PBC CONVENTIONAL BEAMS

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Report from the Conventional Beams Working Group to the Physics beyond Collider Study and to the European Strategy for Particle Physics

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Abstract

This document summarises the main conclusions of the Conventional Beams Working group, which has analysed the beam related and technical requirements and requests in the proposals to the Physics Beyond Colliders study for the North Area at the CERN SPS. We present results from studies on feasibility, requirements, compatibility between proposals and, where possible, the order of magnitude of the costs. The physics interest, sensitivity reach and competitiveness worldwide of the proposals is discussed in the BSM and QCD physics working groups, which work in synergy with the Conventional Beams group.
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1. Introduction

The Conventional Beams Working Group (CBWG) is part of the Accelerators and Facilities Committee within the framework of the Physics Beyond Colliders study. This study shall provide input for the future of CERN’s scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS, spanning the period from now till 2040. The Conventional Beams study is complementary to and works in synergy with the Beyond Standard Model (BSM) and Quantum Chromodynamics (QCD) physics working groups in the Physics Beyond Colliders study, with emphasis on proposals in the North Area at the SPS.

During the PBC kick-off workshop in September 2016, a large number of fixed target proposals was presented. It was deemed important to perform pre-proposal studies in order to allow the working groups to make progress with their evaluation. The list of proposals for the CBWG is shown in Table 1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Comments</th>
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<tr>
<td>NA61++</td>
<td>Run NA61/SHINE at higher intensity and with better protection</td>
</tr>
<tr>
<td>NA64++ (e, h)</td>
<td>Increase electron flux and optimise hadron beams in the H4 line</td>
</tr>
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<td>NA64++ (µ)</td>
<td>Study the possibility to install and run a NA64-like experiment with muons in EHN2</td>
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<td>NA62++</td>
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<td>KLEVER</td>
<td>Study a new beam for a $K_L \rightarrow \pi^0\nu\nu$ experiment at very high proton flux in ECN3</td>
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<td>DIRAC++</td>
<td>Study implementation options for a DIRAC follow-up experiment at the SPS</td>
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<tr>
<td>NA60++</td>
<td>Study implementation options for a NA60 follow-up experiment with heavy ion beams</td>
</tr>
</tbody>
</table>

*Table 1: The list of proposals to be followed by the Conventional Beams Working Group*
The North Area comprises two surface halls, EHN1 and EHN2, and an underground cavern, ECN3. EHN1 is the biggest surface hall at CERN (~330 by 50 m²) and houses the H2, H4, H6 and H8 beam lines. EHN2 is served by the M2 beam line for muon, hadron and electron beams and houses at present the COMPASS experiment. In ECN3 the NA62 experiment for rare kaon decay measurements is served by the K12 line. The CBWG has grouped the proposals per experimental hall.

2. EHN1 proposals

2.1 Introduction

In EHN1 the NA61/SHINE experiment, installed on the H2 beam line, is for the moment driving the SPS heavy ion program. So far it has explored the phase transition to Quark Gluon Plasma. It proposes to continue after LS2 with open charm measurements as well as studies for cosmic ray physics and particle production measurements with neutrino beam replica targets. The program would profit from a significant increase (x10) of the beam intensity in the H2 beam line.

NA64 proposes to continue its search for dark photons (A’) and dark matter with pure electron beam and also with various types of hadron beams in the H4 line. In order to minimize beam time, they will try increasing the electron beam intensity as much as possible, while maintaining a similar beam purity and quality. To reduce setting-up time, they have requested a dedicated beam zone for a quasi-permanent installation in the H4 line.

2.2 NA61++

NA61++ wants to continue measurements with ion and hadron beams as before, but for which 10 times higher beam intensity is necessary. Radiation measurements and simulations have been performed and it has been shown that for higher intensity the shielding around the new PSD calorimeter has to be significantly reinforced. Furthermore, NA61++ foresees several upgrades of their detectors, which imply some local modifications to the infrastructure. The SPSC committee has recommended allocating beam time to NA61/SHINE in 2021, for which part of these modifications are necessary, but the final decision is subject to NA61/SHINE funding.

In order to protect the vertex detector and TPCs from high-intensity bursts, the collaboration requests a new fast (within 1 spill) interlock that will cut the beam rapidly in case of significant intensity or position changes of the beam, to protect the new vertex detector. This system is under study and an economical solution seems feasible.

At a later stage a low-energy beam serving the NA61++ detector would be helpful. A preliminary design exists, but would imply the construction of a number of new magnets and power converters, as well as the associated cabling and cooling. A detailed cost estimate remains to be prepared, along with the NA61++ physics proposal.
2.3 NA64++

NA64 has been running successfully with secondary electron beams in the H4 beam line, relying on synchrotron radiation tagging and tracking, as well as calorimetry to eliminate contamination by other particles in the beam line, usually present at the percent level. The intensity has been ramped up over the years, up to $10^7$ electrons per spill. The main limitation is the setting up time at the beginning of each run, due to the non-availability of a permanent location. It has been decided to prepare a new user zone PPE144, just downstream of the present NA64 location. If approved by the SPSC for 2021, NA64++ will become the first user of this new beam zone and leave the critical detectors in place and connected, eventually on rails for in/out movements.

3. EHN2 proposals

3.1 Introduction

In the EHN2 hall COMPASS proposes to continue on the shorter term a program with the existing M2 beam options, but with different physics goals from the past, such as a measurement of the proton radius $R_p$. For a later stage they propose using a new RF separated anti-proton and kaon beam. The feasibility and design of such a beam line must be investigated.

The NA64++ collaboration proposes to use also the M2 muon beam for dark matter searches. The required muon beam properties are within reach of the present M2 muon beam line. However, the compatibility with COMPASS++ needs detailed studies.

MuonE aims at a measurement on $\mu$-e elastic scattering, which would provide an essential input to precision measurements of $g$-2 of the muon. The muon beam requirements are again within reach of the existing M2 beam line. Scenarios for installing MuonE without dismantling COMPASS have been investigated.

3.2 COMPASS

Members of the COMPASS collaboration, reinforced by some additional groups, are finalising an Expression of Interest for a QCD facility (COMPASS++), which includes a large number of possible measurements with many different beam conditions. The initial ones are standard operational conditions of the existing beam line, either hadron or muon beams. The only beam line upgrade, which is under way, is an improvement of the efficiency and rate capability of the CEDAR Cerenkov counters. A run with muon beams has been approved for 2021 by the Research Board.

One of the future options is a low-energy negative hadron beam, 12 to 20 GeV/c. As at those energies many of the pions and kaons decay over the length of the beam line (more than 1.1 km) at those energies, such a beam is quite enriched in antiproton content, hence allowing a higher antiproton rate without exceeding radiation limits due to an excessive total beam flux. However, at these low momenta, the vacuum needs serious improvement.
At present the 9 magnetic collimators, each more than 5 m long, are under air and the total length of air is between 70 and 80 m.

In case of a decision to abandon the muon beam option, the magnetic collimators could be replaced by standard vacuum tubes, at modest cost. This will also greatly improve the rate of tertiary electron beams.

For the long term, COMPASS members propose to design and build an RF-separated antiproton and kaon beam at high rate and possibly at a momentum of 100 GeV/c or higher. A study has been launched to investigate the feasibility and possible performance of such a beam line. In particular for kaons, the intensity requirement is challenging as most of the kaons decay before they reach the experiment. This is a complex and long study, which will require more time to come to a plausible conclusion. A first version of a beam optics, fitting in the existing tunnel, has been developed and will serve as basis for discussions with the CERN RF group.

3.3 NA64-mu

The NA64 collaboration has started a measurement of the invisible decay mode of the dark photon $A'$ with an electron beam in the H4 beam line. NA64-mu proposes a similar measurement, based on a similar concept, in the M2 muon beam. The existing M2 muon beam satisfies the requirements in terms of beam momentum and flux. The contamination by other particles has been measured to be at the required level, i.e. below $10^{-6}$.

However, the proposed experiment is at least 20 m long and does not fit inside the existing experimental zone without removing at least a large part of the COMPASS setup. A possible solution has been found upstream of COMPASS, at the end of the beam tunnel. By moving two quadrupoles and adding two dipoles, a 20 m long free region can be created in zone PPE211, which can house the experiment. Detailed optics calculations and simulations show that the required beam parameters can be provided, profiting from improved momentum resolution from the Beam Momentum Station. However, because of different rate requirements and lack of focusing in between NA64-mu and COMPASS++ simultaneous operation is excluded. The order of magnitude of the beam modification is about 100 kCHF, dominated by cabling cost. The change-over for the beam line is estimated to take about two weeks. If ever required, additional infrastructure can be designed and built to speed up the change between experiments, but at additional cost.

On the longer term a higher rate version of the experiment could be housed in and around the SM2 spectrometer magnet in the COMPASS++ experiment. Such an experiment could and must profit from synergy with the COMPASS++ detector.

3.4 MuonE

The MuonE collaboration proposes a measurement of $\mu$-e elastic scattering with a detector of about 40 metres length, using the M2 muon beam at standard operating conditions. The constraints for the beam parameters are similar, though not identical to the NA64-mu requirements, although the length of the experiment is slightly longer.
The proposal is to locate the experiment at the same location that is proposed for NA64-mu, but with some additional modifications. Simultaneous operation of MuonE with either COMPASS++ or NA64-mu is excluded, not only because of layout issues but also because of conflicting beam rate requirements. Similarly, MuonE and NA64-mu cannot be operated simultaneously.

4. ECN3 proposals

4.1 Introduction

The NA62 experiment is now in production mode for measuring the branching ratio of $K^+ \rightarrow \pi^-\nu\nu$ with the aim to collect about 100 Standard Model signal events. In a few short runs (typically less than a day each) they have operated the beam line in ‘beam dump mode’, by which a relatively clean condition is created for Hidden Sector searches. One question is whether these conditions can be further optimized in terms of background rejection (e.g. by changing beam settings) and proton flux. It is also considered to accumulate $10^{18}$ pot in 3 months of data-taking in beam dump mode at the highest possible intensities, e.g. in 2023.

KLEVER is an independent proposal aiming at collecting a useful sample of $K_\ell \rightarrow \pi^-\nu\nu$ decays in a new set-up, ideally located in ECN3. This requires the design of a completely new neutral K12 beam line. A 7 times higher proton flux is needed on the T10 target, namely $2 \times 10^{13}$ ppp. This has potentially major implications for radiation protection, ventilation, machine protection and equipment design.

Two other experiments are proposed for high proton or heavy ion beam intensities, namely DIRAC++ or NA60++. For radiation protection reasons they can realistically only be installed in an underground facility, de facto in ECN3. One option is to install them in place of or after the completion of NA62, in which case they compete with NA62 follow-ups or KLEVER.

4.2 NA62 beam dump

The NA62 beam and experiment are designed and optimised for a measurement of the very rare decay $K^+ \rightarrow \pi^-\nu\nu$ with a branching fraction below $10^{-10}$. A muon sweeping system has been installed to significantly reduce the muon rate in the main NA62 detectors, but this magnetic system is limited by the fact that it must preserve the charged kaon beam.

The NA62 experiment can also be operated in a beam dump mode, where the $K^+$ production target is moved out of the beam (and therefore avoiding production of kaons and pions that can decay into muons). The full primary proton beam from the SPS is dumped directly in the TAX (Target Attenuator eXperimental areas) dump-collimators, made of massive copper and steel blocks. This condition allows searching for decays of Hidden Sector particles. However, also here muons form a potentially limiting background that must be minimised. In this case the constraint from the kaon beam no longer exists.
The muon sweeping system consists of a series of three dipoles with the gap filled with iron, except for a 40 mm diameter field-free hole for the kaon beam passage. In normal beam operation these sweep muons away sideways without affecting the main beam. The positive muons from K⁺ and π⁺ decays downstream of these dipoles are in turn swept by a 5 m long magnetic collimator with a toroidal field. This condition is also occasionally used as such for short ‘axion runs’.

It is proposed to operate for at least 3 months in beam dump mode at a later stage to collect a competitive dataset corresponding to at least 10¹⁸ pot. Simulations have shown that the muon background can be reduced by a factor 4 by removing the iron inserts from the dipole sweeping magnets and by changing polarities (by re-cabling) of the 3rd and 4th magnet of the so-called first achromat, a series of 4 dipoles that creates a dogleg in which the beam momentum is defined.

It has been proposed to install a new beam dump further downstream. As that dump is closer to the experiment, the angular acceptance would increase. However, extensive simulations with G4Beamline have demonstrated that the muon background will increase by at least a factor 3 and this option is not considered baseline and would need further study.

4.3 KLEVER

KLEVER is a proposal for a measurement of the rare decay K_L → π⁰νν with a SM branching ratio of about 3·10⁻¹¹. The measurement is extremely delicate and necessitates very high beam rates, requiring 2·10¹⁵ protons per spill and 5·10¹⁹ protons on target over 5 years. One potential background from Λ → π⁰n has been identified. Detailed simulations with FLUKA have demonstrated that this background can be mitigated by increasing the production angle from 2.4 to 8 mrad. This reduces the Λ production rate much more than the K_L rate and softens the Λ momentum spectrum significantly. Consequently, most Λ’s will decay before the start of the fiducial region. Similarly, this shortens the average K_L decay length such that a higher fraction of K_L decay inside the length of the fiducial region. Unfortunately, the K_L production rate per incident proton decreases, but by increasing the angular acceptance of the neutral beam, the total K_L decay rate can be restored. For this one would have to bear the cost of replacing the LKr calorimeter of NA62 by a new calorimeter with larger inside aperture for the beam passage.

The FLUKA simulations have been extended to include the neutral beam line itself and to optimise the muon sweeping. A detailed design has been made. A primary proton beam sloping down at an angle of 8 mrad impinges on a new T10 target with 2 mm radius producing the K_L beam and other secondaries. It is immediately followed by a vertical sweeping magnet that bends the protons further downward by 5.6 mrad, and a TAX dump-collimator with a hole for the K_L beam passage. Another horizontal sweeper reduces the background further.

Two more passive collimators, followed by sweeping magnets and a final active collimator define the neutral beam. The sweeping fields have been optimised to minimise muon backgrounds.
An oriented tungsten crystal, located at the level of the TAX converts the photons into electron positron pairs, which are swept away. The overall beam performance is considered adequate for the experiment.

The main issues are related to the high proton flux required on the T10 target. FLUKA and ANSYS simulations have shown that the present T10 target design would be unsuitable, since its thin aluminium mounting cannot stand the desired rate of $2 \cdot 10^{13}$ ppp. However, there exist designs capable of fulfilling the requirements of KLEVER beam. For instance, some concepts of the target design developed for the fast extracted CNGS beam of $4 \cdot 10^{13}$ ppp can be implemented.

Similar calculations show that the K12 TAX are already close to the limit in K12 beam dump mode with $3 \cdot 10^{12}$ ppp hitting the TAX. The same arguments apply to the P42 TAX. Here a new design is needed with optimised block materials and optimised cooling. This is not considered a fundamental show-stopper, as the TAX in the M2 beam has survived many years of operation with $1.5 \cdot 10^{13}$ ppp impinging on the T6 target upstream of it. But a re-design of the TAX and its construction is needed and will require additional investment of resources.

The beam to T10 passes through the T4 target. It is proposed to not focus the primary beam on T4, but to have a wide and parallel beam in the vertical plane that mostly misses the 2 mm thick T4 target plate. The small fraction that hits the target will be sufficient to produce the H6 and H8 beams without damaging the target head. On the other hand, most of the beam is not attenuated by T4 and therefore the total beam intensity on T4 is not nearly as high as for a focused beam. Depending on the requirements on the other targets, this could be within reach for a 4.8 second flat top.

There was initially a concern that the air containment in the TCC8 cavern would be insufficient for KLEVER operation with the existing ventilation approach. However, the air flow inside the TCC8 target cavern was measured to be very small, thus explaining the low air activation measured outside. The current expectation is that the air contamination can be kept under control, possibly at the cost of installing an air lock in the access gallery to the TCC8 target cavern (like in the accesses from the NA62 control room to ECN3).

However, for the charged beam for NA62, the prompt dose on the surface is still within limits for a supervised area, but would exceed the limits if scaled up to KLEVER intensities. On the other hand, the primary proton beam for KLEVER incident on the T10 target has a downward angle of 8 mrad and is further deflected downward by an additional sweeping magnet following the target. This is much more favourable than the 0 mrad production angle for NA62 today. FLUKA simulations for the prompt dose on the surface above ECN3 are under way. If necessary, it can presumably be mitigated by more front-end shielding inside TCC8 or by better fencing outside around the ECN3 area.
4.4 NA60++ and DIRAC++

As long as the NA62 or KLEVER beam lines and experiments are installed, all the lateral space is taken, in particular along the T10 target and front-end where massive shielding is required. There is no way to transport a second beam line into ECN3 without seriously limiting the front-end shielding, excluded by radiation protection constraints. However, one can revive the old H10 beam towards the old NA60 location and also, in parallel, re-establish a new beam line in place of the present K12 beam, but the NA62 beam and experiment must then be dismantled. A design for a new P12 primary proton beam for a new DIRAC-like experiment has been prepared and has the required parameters. There will be an associated cost for new magnets and power converters that remains to be estimated.

New beam dumps must be installed inside ECN3 and their design must be carefully studied to minimise activation of the air and equipment inside ECN3. It may require a modification of the ventilation system in ECN3.

5. Costs

Cost estimates are mostly very preliminary. In Table 2 the present estimates are listed in four cost categories as a first indication. Consolidation costs are not included (e.g. consolidation of electrical, cooling, ventilation or civil engineering infrastructure). Also, these costs refer only to beam and infrastructure upgrades and do not include the experiments themselves.

The cost categories are defined as follows:

- **C1**: Up to a few 100 kCHF
- **C2**: From few 100 KCHF to 1 or 2 MCHF
- **C3**: From 1 or 2 MCHF to 5 to 10 MCHF
- **C4**: Of the order of ≥ 10 MCHF

<table>
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<th>Building</th>
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<th>Proposal</th>
<th>Upgrades foreseen</th>
<th>Cost</th>
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</thead>
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<td>EHN1</td>
<td>H2</td>
<td>NA61++</td>
<td>Shielding, interlocks</td>
<td>C1</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>NA61++</td>
<td>New very low energy beam (2nd phase)</td>
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<td></td>
<td>H4</td>
<td>NA64-e</td>
<td>New permanent location</td>
<td>C1</td>
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<tr>
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<td>M2</td>
<td>NA64-mu</td>
<td>New location on beam</td>
<td>C1</td>
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<td>Phase 2</td>
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<td>M2</td>
<td>MuonE</td>
<td>Installation on M2 beam</td>
<td>C2</td>
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<td>M2</td>
<td>COMPASS++</td>
<td>Low-energy beam</td>
<td>C2</td>
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<td>C4</td>
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<td>ECN3</td>
<td>K12</td>
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<td>Re-cabling for µ sweeping</td>
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<td></td>
<td>K12</td>
<td>DIRAC++</td>
<td>New K12 beam line</td>
<td>C3</td>
</tr>
</tbody>
</table>

**Table 2**: Preliminary cost estimates where available. Cost categories are explained in the text.
6. Final remarks and conclusions

The CBWG has made studies for all future options attributed to this working group. A common feature of all the proposals is the need for ever higher proton fluxes, with the exception of EHN2. In the framework of the BDF study, significant progress has been made by the SLAWG working group, in reducing losses in the region of extraction and splitting. However, if the Beam Dump Facility is operated, there will be competition for the SPS duty cycle. In the CNGS era this was mitigated by doubling the flat top length. This will again be an option, but not so much with KLEVER in case the same instantaneous rate has to be maintained over much more than 4.8 seconds.

The Conventional Beams Working Group has made significant progress in the specific studies of all proposals submitted to the group and concepts are available or in many cases worked out. Only the RF-separated beam study is still in early stages, but making steady progress. Detailed information and conclusions are described in the full report of the working group, which is available in [1]. It is also clear that, as expected, most of the many studies need further work, in particular studies leading to more precise cost estimates.

Among the BSM (Beyond Standard Model) proposals, the NA62 beam dump run for dark matter searches is rather straightforward to set up, at modest re-cabling cost. It could be combined in the same year with a low-intensity neutral beam test run for KLEVER.

The beam line for KLEVER itself, a measurement of the very rare decay $K_L \to \pi^0\nu\bar{\nu}$, is a new installation, mostly with existing equipment. However, the target and TAX have to be replaced and adequate machine protection systems must be implemented.

On the other hand, the ventilation system and civil engineering infrastructure can be maintained in its present form, apart from very minor local improvements. This would have an associated cost for the installation of the charged beam lines.

NA64-e can continue running in the H4 electron beam for an A’ search without significant upgrades, but it is foreseen to move the setup to a new zone, further downstream, which will allow much faster reinstallation and recommissioning. NA64-mu can be integrated rather easily in the M2 muon beam upstream of COMPASS++ for a complementary A’ search, but cannot operate simultaneously with COMPASS++. The changeover time is a few weeks. The same holds for MuonE, which could use the same location as NA64-mu. It will measure $\mu$-e elastic scattering that provides an essential input for $\alpha_{\mu}-2$. The cost of the beam line modifications remains at a modest level. At a later stage, NA64-mu could use higher fluxes, once installed in and around the SM2 spectrometer magnet of COMPASS++ and in synergy with part of the COMPASS++ apparatus and readout.

For the QCD physics, a new Expression of Interest is in preparation for a COMPASS++ QCD Facility, exploiting initially the M2 muon and hadron beam in basically its present form. Once the muon beam operation is completed, the 9 magnetic collimators could easily be replaced by standard vacuum to allow better electron beams and in particular a low-energy hadron beam, enriched (by the decay of pions and kaons before they would reach the experiment) in antiproton content.
At a later stage an RF-separated kaon or antiproton beam would greatly enhance the physics potential of the QCD facility, but its feasibility, performance and (high) cost are still under evaluation.

In EHN1, NA61++ can continue the NA61/SHINE hadron program, for particle production for cosmic ray studies and neutrino beams, as well as its ion beam program for open charm production and fragmentation studies, with local improvements of shielding and interlocks against intensity and beam position variations. A dedicated and local low-intensity beam is under study to improve somewhat the beam characteristics at low beam momenta, but the cost-benefit ratio remains to be evaluated.

DIRAC++, a study of pionic atoms (and similar systems), and NA60++, open charm measurements with ion beams, can only be housed in an underground area, but are both incompatible with the presence of the NA62/NA62++ or KLEVER installation. However, they can be installed, at the same time, in case none of the kaon experiments would be present. But their operation must be in alternation.
1. D.Banerjee et al., Report of the Conventional Beams Working Group to the Physics Beyond Collider Study and to the European Strategy for Particle Physics, in preparation, advanced draft available as EDMS No. 2053962
1. Introduction

1.1 The Physics Beyond Collider Study

The Physics Beyond Collider (PBC) study [1] at CERN is an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments.

This study should provide input for the future of CERN’s scientific diversity programme, which today consists of several facilities and experiments at the Booster, PS and SPS, over the period until ~2040. Complementarity with similar initiatives elsewhere in the world should be sought, so as to optimize the resources of the discipline globally, create synergies with other laboratories and institutions, and attract the international community.

The proposed project or experiments would typically:

1. Enrich and diversify the CERN scientific program,
2. Exploit the unique opportunities offered by CERN’s accelerator complex and scientific infrastructure,
3. Complement the laboratory’s collider programme (LHC, HL-LHC and possible future colliders).

Examples of physics objectives include searches for rare processes and very weakly interacting particles, measurements of electric dipole moments, etcetera.

The PBC study consists of two main working groups:

- A physics oriented working group composed of two subgroups focused on specific projects, namely the BSM and QCD physics working groups,
- An accelerator oriented working group (PBC-AF committee). This working group consists of several sub-working groups and is complemented with a number of study groups, including the Conventional Beams working group.

The overall organization of PBC is illustrated in Figure 1.1.

In Figures 1.2, 1.3 and 1.4 we show pictures of the experimental hall EHN1, of the COMPASS experiment in EHN2 and of the NA62 experiment in ECN3, respectively.
Figure 1.1: The overall organization of the Physics Beyond Colliders study

Figure 1.2: Overview picture of the experimental hall EHN1
Figure 1.3: The COMPASS experiment in the EHN2 hall

Figure 1.4: The NA62 experiment in the ECN3 underground cavern
1.2 The Conventional Beams Working Group

During the PBC kick-off workshop in September 2016 a large number of fixed target proposals were presented. It was thought important to perform pre-proposal studies in order to allow the working groups to make progress with their evaluation.

The Conventional Beams working group is a subgroup of the PBC-AF committee mandated to study a wide set of proposals that could fit in the existing non-LHC experimental areas. Given the relatively long list of studies, we will focus first on those leading to a possible short and medium time-scale implementation and with limited resources, as well as on those which seem to be the most advanced and competitive (based on the available input after the initial kick-off event and on a first feasibility analysis regarding the FT implementation). The list of proposed experiments is shown in Table 1.1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA61++ [2,3]</td>
<td>Run NA61 at higher intensity and with better machine protection</td>
</tr>
<tr>
<td>NA64++(e,h) [4,5]</td>
<td>Increase electron flux and optimise hadron beams in H4</td>
</tr>
<tr>
<td>NA64++ (µ) [6]</td>
<td>Study possibility to run NA54-like experiment with muons in M2</td>
</tr>
<tr>
<td>COMPASS++ [7-9]</td>
<td>Study new requests from COMPASS; including RF separated beams</td>
</tr>
<tr>
<td>MuonE [10]</td>
<td>Study possibility to implement experiment in M2 beam with µ and e</td>
</tr>
<tr>
<td>KLEVER [12]</td>
<td>Study beam for $K_L \rightarrow \pi^0\nu\nu$ at very high proton flux, ideally in ECN3</td>
</tr>
<tr>
<td>DIRAC++ [13]</td>
<td>Study implementation options for DIRAC follow-up at SPS</td>
</tr>
<tr>
<td>NA60++ [14]</td>
<td>Study implementation options for NA60 follow-up at SPS</td>
</tr>
</tbody>
</table>

Table 1.1: The list of proposals to be followed by the Conventional Beams Working Group

1.3 Existing beams and experimental areas

Following the list of proposals in Table 1.1, the Conventional Beams Working Group is mainly concerned with the North Experimental Area at the CERN Super Proton Synchrotron (SPS). The North Area receives a primary proton beam at 400 GeV/c from the CERN SPS. The full SPS proton beam is slowly extracted to the North Area during a flat top of typically 4.8 seconds, which could be modified in case the physics program requires a shorter (e.g. Beam Dump Facility) or longer flat top (e.g. in case of cohabitation with the Beam Dump Facility) in the same super-cycle (i.e. the overall sequence that is repeated). A typical duty cycle (defined as the ratio between useful flat top length and super-cycle) is between 20 and 30%. The recent maximum extracted proton flux was about $3.5 \times 10^{13}$ ppp, but the aim is to reach $4 \times 10^{13}$ ppp in the future. This proton flux is transported and shared through two series of splitter magnets onto three primary targets, T2, T4 and T6, from which the North Area beam lines are derived.
The North Area comprises two surface halls, EHN1 and EHN2, and an underground cavern, ECN3. EHN1 is the biggest surface hall at CERN (330 by 50 m$^2$) and houses the H2, H4, H6 and H8 beam lines. EHN2 is served by the M2 beam line [15] for muon, hadron and electron beams and serves at the moment the COMPASS experiment [16, 17]. In ECN3 the NA62 experiment for rare kaon decays [18] is served by the K12 beam line. A schematic layout of the North Area complex is shown in Figure 1.5.

![Figure 1.5: A schematic layout of the North Area complex.](image)

The T2 target produces the H2 and H4 beam lines. They are normally operated as versatile secondary or tertiary beams but may occasionally be configured as attenuated primary beams. The two beams leave the target at a relative angle of 11.2 mrad and the momenta of the two beam lines are coupled through the angle of incidence of the primary proton beam onto the production angle with respect to the H2 and H4 beams.

This angle and the subsequent distribution of different momenta between the two beam lines can be varied through different settings of the T2 wobbling station, which consists of two dipoles upstream and one dipole downstream of the primary target itself. The H4 beam is a particularly clean electron beam but can also serve its users with high-quality hadron or muon beams. At present the main physics experiment in H4 is NA64 [19], a dark photon search with high purity electron beams [20]. The H2 beam line is the home of the NA61 experiment [21, 22], which has a rich and varied physics program with hadron and heavy ion beams.

From the T4 target the H6 and H8 lines are derived. These are versatile hadron and electron beams, that also can provide low or medium intensity muon beams. They are mostly used for test beam activities. Occasionally the H8 beam can be operated as a low-intensity, low-emittance attenuated primary proton beam. UA9 exploits the good parallelism of this so-called micro-beam option for crystal channeling and collimation experiments.
However, most of the time the protons impinging on the T4 target are pointed towards the P42 beam line and the secondaries produced in the target provide secondary or tertiary beams in H8 and H6. The non-interacting protons are transported to the T10 target, located almost 900 metres downstream of T4. From T10 the K12 beam is derived, which produces a high-intensity mixed secondary beam for the NA62 rare kaon decay experiment, located in the ECN3 underground cavern. The KTAG detector tags the kaon component (about 6%) in the beam.

The T6 target produces the M2 beam for the COMPASS experiment in the EHN2 hall. The M2 beam is a world-wide unique high-energy high-intensity muon beam, which can also be operated as a high-intensity hadron beam. A possibility to operate it as a tertiary electron test beam exists, but the rates are very low. In Table 1.2 we show a summary of the characteristics of the North Area beam lines.

The maximum intensities in all beam lines are limited by radiation protection guidelines, in particular in the surface halls. Depending on beam momentum, production angle and particle type, particle production may limit the intensities even further.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>H2</th>
<th>H4</th>
<th>H6</th>
<th>H8</th>
<th>M2</th>
<th>K12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. momentum (GeV/c)</td>
<td>400/380</td>
<td>400/380</td>
<td>205</td>
<td>400/360</td>
<td>280</td>
<td>75</td>
</tr>
<tr>
<td>Max. acceptance (µSr)</td>
<td>1.5</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Δp/p (%)</td>
<td>±2.0</td>
<td>±1.4</td>
<td>±1.5</td>
<td>±1.5</td>
<td>±4.0</td>
<td>±2.0</td>
</tr>
<tr>
<td>Typical max. intensity/spill</td>
<td>10^7/10^5</td>
<td>10^7/10^5</td>
<td>10^7/10^5</td>
<td>10^7/10^5</td>
<td>5 10^8</td>
<td>2 10^9</td>
</tr>
<tr>
<td>Particle types</td>
<td>p/h,µ,e</td>
<td>p/h,µ,e</td>
<td>h,µ,e</td>
<td>p/h,µ,e</td>
<td>h,µ,e</td>
<td>h,µ</td>
</tr>
</tbody>
</table>

Table 1.2: Overview of the characteristics of the North Area beam lines.
NA62 is now running in production mode for its search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with the aim to collect about 100 signal events. This is expected to remain its main activity until LS3. In a few short runs (typically less than a day) they have operated the beam line in beam dump mode. In this condition the T10 primary target is put in OUT position and the full proton beam of up to $3 \times 10^{12}$ ppp is dumped on the K12 dump collimators (TAX). The muon sweeping is left activated. With these settings a relative clean condition is created for Heavy Neutral Lepton and axion searches. One question is whether these conditions can be further optimized in terms of background rejection (by changing beam settings) and proton flux. It is also considered to run for a full year in beam dump mode. It has been suggested to look then for an optimal position of the beam dump with a view to increasing the acceptance of the experiment and maintaining a good muon background rejection. This involves detailed beam and RP studies.

KLEVER is an independent proposal aiming at collecting a useful sample of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decays in a new set-up, ideally located in ECN3. This requires the design of a new neutral K12 beam line. As the angular acceptance is smaller in the absence of focusing, a 7 times higher proton flux is needed on the T10 target, namely 2 to $2.4 \times 10^{13}$ ppp, to be compared with a nominal proton flux of $3 \times 10^{12}$ ppp for NA62. This has potentially major implications for radiation protection, ventilation, machine protection and equipment design. The beam line is supposed to integrate a crystal-based photon converter which must be carefully matched to the $K_L$ production angle and target characteristics. Some test with a neutral beam in K12 beforehand may be required, in some synergy with a beam dump run. KLEVER could also be considered in the Beam Dump Facility, but it would then have to compete with SHiP.

Two other experiments are proposed for high proton or heavy ion beam intensities, namely DIRAC++ or NA60++. For radiation protection reasons they can realistically only be installed in an underground facility, de facto in ECN3. One option is to install them in place of or after NA62, in which case they compete with NA62 or KLEVER. In the past a second beam line, the H10 beam, served the NA50 and NA60 experiments, located next to NA48. Now the space requirements for the K12 beam and for the NA62 experiment are much more stringent. The lateral space available for a second experiment is much reduced. The front-end shielding, required to cope with air activation around the T10 target and K12 TAX, and with prompt dose above ECN3, interferes strongly with a second beam line. Detailed RP studies, in synergy with the ones for KLEVER, may be required to demonstrate the feasibility of removing or severely reducing the front-end shielding. A new and probably costly approach to ventilation of the target and experimental caverns may have to be considered.

In the EHN2 hall COMPASS wishes to continue on the shorter term a program with the existing M2 beam options, but with different physics goals. At a later stage they propose using a RF separated anti-proton and kaon beam. As they are limited (by RP constraints) in total hadron flux, the only way to increase the useful anti-proton or kaon flux is by increasing the anti-proton or kaon component in the beam. The feasibility and design of such a beam line, as well as its rate capability, must be investigated, at least at a conceptual level. It would in any case require a complete rebuild of the more than 1100 meters long M2 beam line and will have a long lead-time.
Also, the NA64 collaboration has proposed to use the M2 muon beam for dark matter searches. The required muon beam properties are within reach of the present M2 muon beam line. However, the compatibility with COMPASS or MuonE is a more complicated issue that needs discussion and possibly detailed studies. Possibilities have to be explored for running NA64-µ in parallel with COMPASS operation. The initial proposal describes a rather long set-up, very similar to the electron beam dump experiment layout, presently used in the H4 beam. Alternative possibilities, more easily compatible with certain parts of the COMPASS program will be explored.

MuonE aims at a measurement on µ-e elastic scattering, which provides an essential input to precision measurements of g-2 of the muon. The proposal describes an experimental set-up of about 30 metres length, but rather small in lateral dimensions. The muon beam requirements are again within reach of the existing M2 beam line. However, it is not possible to install such an experiment inside EHN2 or the tunnel leading towards it without dismantling or modifying substantially at least a part of the beam line or the COMPASS experiment. Scenarios for combining MuonE with COMPASS operation, either in parallel or in annual alternation, have to be worked out. A test of the contamination in the muon beam is a useful input and must be prepared. In general, several test beam campaigns, both for MuonE and NA64-mu must be organized, already in 2018.

In EHNI the NA61 experiment is for the moment the main user of the heavy ion program. So far it has explored the phase transition to Quark Gluon Plasma and searched for the critical end point in the phase diagram. It proposes to continue with a program dedicated to open charm measurements. The program would profit from a significant increase of beam intensity. Shielding studies are requested to see how and by how much the ion rate can be increased. In addition, they ask for improved beam stability and the implantation of a beam interlock to protect their detectors against possible movements of the beam. The NA61 experiment has also an important component with hadron beams, for cosmic ray studies and for particle production measurements with neutrino beam replica targets. Those will also profit from higher rates.

NA64 proposes to continue its search for the A’ and dark matter with pure electron and also with various types of hadron beams in the H4 line. In order to minimize beam time, they try increasing the electron beam intensity as much as possible while maintaining a similar beam purity and quality. To reduce setting-up time, they have requested a dedicated beam zone for a quasi-permanent installation in the H4 line. An Engineering Change Request has been approved by IEFC (pending funding).

Ideally all these studies shall include an evaluation of feasibility and a rough estimate of the associated cost.

Additional studies concern the delivery of a sufficient number of protons and the compatibility of the existing North Area with SHiP [23-25]operation. These studies will be done in synergy with the Proton Production and BDF study groups within the PBC Accelerators and Facilities section.
1.5 REDTOP

In the course of the study, the Conventional Beams working group was consulted concerning
the REDTOP proposal, mainly a search for very rare η decays and including future possibilities
to search for other very rare decays. The REDTOP approach is to produce the rare mesons at
rest and therefore the experiment requests a high-intensity proton beam at 2 GeV kinetic energy
and a very high duty cycle of 80%. With the valuable input from machine experts we looked
at possibilities at LEIR, at the PS Booster and at the PS itself [26].

At LEIR, major R&D and upgrades would be required to reach the requested kinetic energy.
The PSB and PS are in the main injector chain for the LHC and also serve a large number of
other major physics programs at CERN. A very high duty cycle would be difficult to reconcile
with continued operation of those physics programs. The most realistic and economical
solution would be to install REDTOP at an extracted 2 GeV beam from the PS into a heavily
shielded facility like the CHARM irradiation facility. Even in this case the duty cycle would
have to be reduced considerably. That option is considered by the collaboration.

However, the technical follow-up of these discussions falls beyond the scope of the CBWG
and our recommendation is therefore to discuss this proposal in a different study group or in a
dedicated working group.

References for Chapter 1

1. See http://cern.ch/pbc/
2. M.Gazdzicki, NA61/SHINE physics and facility beyond 2020,
   https://indico.cern.ch/event/523655/contributions/2246414/
3. NA61 Collaboration and the CERN team, Addendum to the NA61/SHINE Proposal
   SPSC-P-330, Study of Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN
   SPS, Early Post-LS2 Measurements and Future Plans, CERN-SPSC-2018-008,
   SPSC-P-330-ADD-10.
4. S.Gninenko, Search for Dark Sector physics in missing energy events at the CERN SPS,
   https://indico.cern.ch/event/523655/contributions/2246865/
5. S.Gninenko et al., Addendum to the NA64 Proposal: Search for the \( A' \rightarrow \text{invisible} \) and
6. D.Banerjee et al., Addendum to the Proposal P348: Search for dark sector particles
   weakly coupled to muon with NA64μ, CERN-SPSC-2018-024, SPSC-P-348-ADD-3.
7. O.Denisov, COMPASS, A universal facility for hadtron structure and spectroscopy
   studies, https://indico.cern.ch/event/523655/contributions/2246412/
8. K.Augsten et al., d-Quark transversity and proton radius, CERN–SPSC–2017–034,
   SPSC-P-340-ADD-1
10. G. Venanzoni et al., MuonE, A high-precision measurement of $a^\mu_{\text{HLO}}$ with a 150 GeV muon beam on $e^-$ target at CERN, https://indico.cern.ch/event/644287/contributions/2724482/
12. M. Moulson et al., Perspectives for an experiment to measure $\text{BR}(K_L \rightarrow \pi^\nu\nu\nu)$ at the CERN SPS, https://indico.cern.ch/event/523655/contributions/2246866/.
13. L. Nemenov et al., Experimental checks of precise QCD predictions by studying the $\pi^+K^-$, $K^+\pi^-$ and $\pi^+\pi^-$ atoms, https://indico.cern.ch/event/523655/contributions/2246870/
14. G. Usai et al., Investigating the QCD phase transition with dileptons: new opportunities at the CERN SPS, https://indico.cern.ch/event/523655/contributions/2247739/
18. E. Cortina et al. (the NA62 collaboration), The beam and detector of the NA62 experiment at CERN, 2017 JINST 12 P05025.
22. N. Abgrall et al., NA61/SHINE facility at the CERN SPS: beams and detector system, JINST 9 (2014) P06005
2 Organisation of the Conventional Beams Working Group

From the previous chapter it appears that the different proposals to the Conventional Beams working group have correlations and synergies that naturally allows combining them in three independent groups:

1. NA62-Beamdump, KLEVER, NA60++ and DIRAC++ all can only be considered for ECN3, due to the high intensities requested,
2. COMPASS++, MuonE and NA64-Mu share the same request for a high-intensity muon beam, which can reasonably only be provided by the M2 beam serving the EHN2 hall,
3. NA61++ and NA64++ are closer to standard operation and call for improved shielding and some improvements to the beam line. They are located in EHN1.

Conveniently these groups match perfectly the available experimental halls and caverns: ECN3, EHN2 and EHN1, respectively.

The projects in EHN1 all share similar requests for improved shielding and some beam improvements and thus require the same approaches and expertise for studies. The EHN2 related projects all compete for the same real estate and for the same beam line. In ECN3 again the experiments are all requiring similar and correlated radiation protection and ventilation studies and they all want to be installed in the same narrow underground cavern.

Consequently, we have decided to organize the Conventional Beams working group in three subgroups as illustrated in Figure 2.1.

**Figure 2.1:** The internal organization of the Conventional Beams working group.
The main regular activities take place inside the three sub-working groups. They organize meetings with the individual experiments or with all experiments concerned, as required. The overall Conventional Beams working group organizes a few meetings per year, typically with all experiments followed by the working group and with the technical experts involved. In parallel regular dedicated meetings take place inside the EN-EA-LE section (the NA beam physicists) to ensure optimal exploitation of the available resources and synergies.

The main deliverable of the Conventional Beams working group is the present report. In addition, detailed documentation of the studies is published in ATS reports and/or on the EDMS site http://edms.cern.ch/. The meeting agendas and the material presented are available on the Indico site at https://indico.cern.ch/category/8813/.
3. EHN1 related projects

3.1 Introduction

The North Area Experimental Halls are multipurpose facilities hosting large fixed-target experiments as well as numerous test beam stands. The EHN1 experimental hall is a general-purpose industrial building, hosting four secondary beam lines named H2, H4, H6 and H8. The H2 and H4 beam lines, of particular interest here, emerge from the T2 target and are approximately 600 m in length, with the last ∼ 250 m inside the EHN1 experimental hall.

3.2 NA61++

NA61 [1] is a fixed-target experiment located permanently in zone PPE152 of H2 beam line. A top-view of the hall including the beam lines is shown in Figure 1. The location of the NA61 experiment is also indicated.

![Figure 1: The EHN1 experimental hall. The four beam lines (H2, H4, H6, H8) are shown, as well as the newly constructed EHN1-extension [2]. NA61 is located in the PPE152 zone.](image)

The NA61 beyond 2020 program (“NA61++”) includes three main parts:

1. Open charm measurements in Pb+Pb collisions for studying onset of deconfinement
2. Hadron production measurements from thick and thin targets, in the range from below 10 up to 120 GeV/c
3. Measurements of fragmentation cross-sections of light nuclei and anti-nuclei.

3.2.1 High Intensity Pb beam for open charm measurements in Pb+Pb collisions

The H2 beam line has been designed to transport ion species to the experimental areas. The ion species must have a magnetic rigidity $P \left(\frac{\text{GeV}}{c}\right) \cdot \left(\frac{A}{Z}\right) < 380$, for safety reasons. For fully stripped Pb ions this maximum is equivalent to 150 GeV/nucleon. The maximum intensity of primary ions that can be transported in the hall is limited to about $10^9$ heavy ions per 10 second spill. Higher intensities should be possible; they however require extra studies and subsequent re-enforcement of the shielding, in particular in the zone where the PSD calorimeter is located. A photo of PPE152 area is shown in Figure 2.
In the same context, a hardware interlock can be implemented in the beam line to protect the detector from intensity and/or steering variations. A similar protection system has been already implemented in COMPASS. Based on a signal from the experiment, a relay switch will set the power supply of magnet MBNH.021.405 (B6) to “STANDBY” mode (zero current) within a time window of 1 spill (~ 5 seconds). The switch will be remotely resettable by the beam line physicist and the CCC control center. Such relay switches are readily available on the market. Subsequently, a few cables from the detector to the BE/BI control room and from there to the power supply in BA81 would be sufficient for the implementation of the system.

3.2.2 Hadron production measurements at low momenta, below 10 GeV/c.

In order to provide a low-energy beam for NA61, a short tertiary beam branch is necessary. The implementation of a similar branch has been done elsewhere in the past for the CMS [3] and ATLAS [4] experiments, as well as more recently for the Neutrino Platform experiments NP02 and NP04 [5]. The low energy branch for NA61 would be located in zone PPE132/42 (just upstream of NA61), which is already a fully shielded zone allowing high intensities on a secondary target. A possible location depicting the position of this tertiary beam line is shown in Figure 3:
Figure 3: A possible location of a tertiary low-energy beam line serving NA61, located in PPE132. The zone is already shielded, thus allowing for maximum intensity in the secondary target.

A preliminary design of such a tertiary branch has been studied. An optics design for such a beam is shown in Figure 4.

Figure 4: A preliminary first-order optics design for the low energy tertiary branch serving NA61. The red line corresponds to the sine-like ray, the green and dashed lines respectively to the magnification and dispersive terms. The deflection angle of the bends is equal to 120 mrad.
A secondary beam of medium momentum (60-80 GeV/c) will impinge on a secondary target. This target will be a cylinder of copper or tungsten, with a length of ~30 cm and a diameter of ~30 mm. Following the target, a quadrupole triplet of high-acceptance, consisting of large-aperture QPL-type quadrupoles (aperture radius 100 mm) will focus the low-energy particles at the center of a momentum-selection collimator. A ‘dogleg’ configuration consisting of four MBPL magnets (aperture: 420 x 140 mm) will define the central momentum of the low-energy particles, with a maximum momentum of 9 GeV/c. The four bending magnets can be in series. In addition, the final focusing triplet will be in series with the front-end one. The total length of the beam line is ~45 meters, thus allowing most of the low-energy particles to reach the experiment without decaying beforehand. A beam dump consisting of iron and concrete will be placed close to the collimator, with the purpose of stopping off-momentum particles and in particular dumping the high-energy secondary particles that do not interact with the target, thus stopping them or their interaction products from reaching the experiment.

A model of the H2 beam line as well as of the future tertiary branch has been designed in the GEANT-4 simulation package, G4BeamLine®. A detail of the model is shown in Figure 5.

Figure 5: Monte-Carlo model of the tertiary branch providing low-energy particles in NA61. The beam line consists of 10 magnets (6 quadrupoles and 4 dipoles) and is ~45 m long.
Assuming $10^7$ secondary particles (75% pions, 20% protons and 5% Kaons) of 80 GeV/c momentum impinging on the secondary target and tuning the magnetic fields of the bends and the quadrupoles for 9 GeV/c, the simulated spot sizes of the beam in the horizontal and vertical plane are shown in Figure 6.

Figure 6: Simulated horizontal and vertical profiles of a very low energy beam at NA61 target. The particles have a momentum within 15% (3 sigma) of the design momentum of 9 GeV/c. Better momentum resolution can be achieved either by closing the momentum selection collimator or by means of a tracking spectrometer placed around one of the bending.

More quadrupoles or and possibly sextupoles could be considered to allow for better control of the horizontal spot size, if necessary for the experiment.

In order to meet the experimental requirements, the background must be minimized. The most important source of background are high-energy muons from the secondary pion decays reaching the experiment. These high-energy muons (> 30 GeV), that practically cannot be stopped by any reasonable shielding, have been simulated and they correspond only to ~3% of the triggering particles. At the same time, lower energy halo muons originating in the last straight section of the secondary beam line and travelling outside the beam-pipe, could be hitting the detector. In addition, some low-energy muons from the decays of low-energy pions within the apertures of the VLE line dipoles can also find their way to the detector. The latter, however, with an optimization of the shielding or implementation of magnetized iron blocks (MIBs) could be deflected away. More studies are necessary for the final optimization of this beam-line and for its possible future implementation and associated costs.

3.2.3 Measurement of fragmentation cross-sections & fragmented beams

Fragmented ion beams have been delivered to NA61 in 2010 and 2011 [6]. No special changes are necessary in the beam line, apart from the extra experimental Time of Flight and $Z^2$ detectors that have to be installed in addition to the beam-line instrumentation.
3.3 NA64++

The proposed future NA64++ research program is significantly extended with respect to the on-going runs by the inclusion of searches for dark sector physics, new sub-GeV states coupled to leptons and/or quarks, new symmetries etcetera. The proposed program will use leptonic (e,μ) and hadronic (π, K, and p) beams provided by the CERN SPS.

More specifically, the requirements and the necessary modifications in the secondary beam lines are summarized below:

- **Muon beam**: main physics motivation being the search for missing energy events: Discussions for installation and test run of the experiment in M2 beam line in EHN2, are discussed in chapter 4;
- **Electron beams**: The A’ Invisible and visible decay searches will remain the main physics motivation, using electron beams in H4 with the purpose to accumulate $10^{13}$ protons on target. A priori no modifications are necessary in H4 beam line.
- **Hadron beams**: The main physics motivation will be to measure invisible decays of $\pi^0$, $\eta$, $\eta'$, $K_S$ and $K_L$, through measurements of the meson charge-exchange production. For this purpose, middle-energy (20-50 GeV/c) hadron beams are necessary. No modifications are necessary in H4 beam line in order to provide these beams.

Concerning the NA64++ proposals, in the framework of PBC, no changes in the beam line are necessary, hadrons of sufficient energy and intensity can be delivered already to NA64.

However, a very complete and therefore time-consuming commissioning and calibration program is required at the start of each running period. Most of the time is related to the re-installation from scratch of the experiment each time. Preparations for equipping zone PPE144 as a user zone have launched already during 2018. This zone would perfectly match the needs of NA64 and allow for a quasi-permanent installation. It is therefore proposed to allocate that zone to NA64 as a first main user. The proposed layout of the new area is shown in Figure 7.

**Figure 7**: Layout of the new zone PPE-144 zone that will serve as a quasi-permanent
References for Chapter 3

3. S. Abdullin et al., CMS NOTE 2008/034
5. N. Charitonidis et al., TUPVA124, Proceedings of IPAC-17, Copenhagen, Denmark
6. I. Efthymiopoulos et al., THPS051, Proceedings of IPAC-11, San Sebastian, Spain
4. EHN2 related projects

4.1 Introduction

The M2 beamline [1] at the North Area delivers high-energy and high-intensity muon and hadron beams towards the experimental hall EHN2 as well as low-intensity electron beams for calibrations. The schematic layout of M2 is depicted in Figure 4.1.

Today the M2 line transports secondary particles from the T6 target over a distance of about 1130 m. The front-end of the beamline consists of six high-gradient quadrupoles for a high acceptance for secondary hadrons. Then, a momentum selection in the horizontal plane with a maximum momentum bite of ±10% Δp/p is performed using a set of horizontal dipoles and collimators. The beam is then matched to a long FODO section of about 600 m length to allow pions and kaons to decay. Depending on the operational mode, a set of up to 9 motorised Beryllium absorbers of 1.1 m length each can be inserted (inside a series of 3 vertical dipole magnets) to absorb the remaining hadrons, which results in a muon beam with a remaining hadron contamination of about 10^{-6} to 10^{-5}. Following these absorbers, a 400 m long section comprising motorised magnetised collimators (“Scrapers”) and magnetised iron blocks (“MIBs”) serves to select the final muon momentum and to clean the beam from muon halo. Once the beam has arrived on surface, it is made horizontal. The last section comprises beam instrumentation for momentum measurements (“BMS”) and beam particle identification (“CEDARs”) and is followed by a final quadrupole triplet to focus the beam on the target of the COMPASS experiment. The different modes of operation are summarised in Table 4.1.

![Figure 4.1: Schematic layout of the M2 beamline. The specific momenta for the most common mode of operation are given, i.e. 160 GeV/c muon beams](image)

<table>
<thead>
<tr>
<th>Beam Mode</th>
<th>Momentum (GeV/c)</th>
<th>Max. Flux (ppp / 4.8s)</th>
<th>Typical Δp/p (%)</th>
<th>Typical RMS spot at target</th>
<th>Polarisisation</th>
<th>Absorber (9.9 m Be)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>+208/190</td>
<td>-10^4</td>
<td>3%</td>
<td>8 x 8 mm</td>
<td>80%</td>
<td>IN</td>
</tr>
<tr>
<td></td>
<td>+172/160</td>
<td>2.5 x 10^8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadrons</td>
<td>+190</td>
<td>10^8 (RP)</td>
<td>-</td>
<td>5 x 5 mm</td>
<td>-</td>
<td>OUT</td>
</tr>
<tr>
<td></td>
<td>-190 Max. 280</td>
<td>4 x 10^8 (with dedicated dump)</td>
<td>-</td>
<td>&gt; 10 x 10 mm</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>-10 to -40</td>
<td>&lt; 2 x 10^4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>OUT</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of the available operation modes of the M2 beamline
4.2 Organisation of the EHN2 Working Group and List of Experimental Proposals

The EHN2 Working Group is a sub-group of the Conventional Beams WG to which it reports regularly. The proposals followed by this subgroup include COMPASS continuations [2], a new QCD Facility [3], MuonE and NA64µ. Four different work packages have been set-up:

- **WP1**: Muon Beams
- **WP2**: Conventional Hadron and Electron Beams
- **WP3**: RF-separated Beams
- **WP4**: Beam Instrumentation

Work package **WP1** comprises studies for a future QCD facility at M2 (i.e. COMPASS experiment successor with proposals for a proton radius measurement and DVCS/DVMP measurements), the MuonE experiment (proposal to measure the hadronic vacuum polarisation contribution to \(g_{\mu}-2\)), and the NA64µ experiment (proposal to search for dark matter coupling specifically to the muon). These studies are based on the current muon beam optics and deal mostly with questions of compatibility between the three proposals in terms of space allocation, required muon momentum and muon intensity.

**WP2** includes studies based on the existing hadron and electron beam options with minimal upgrades for a future QCD facility proposing measurements of antimatter production cross sections, pion PDFs with the Drell-Yan process, and low-energy spectroscopy with antiproton beams.

The study for **WP3** is focussed on the idea of the implementation of a RF-separated beam in the M2 tunnel that would deliver high-intensity antiproton and/or kaon beams, again for proposals of a future QCD facility. These proposals contain measurements for kaon PDFs and Nucleon TMDs with the Drell-Yan reaction as well as kaon polarisabilities with the Primakoff effect, the lifetime of the neutral pion, meson and gluon PDFs with prompt photons, spectroscopy with kaon beams, and studies of vector meson SDMEs, see Table 4.2.

<table>
<thead>
<tr>
<th>Program</th>
<th>Physics Goals</th>
<th>Beam Energy (MeV)</th>
<th>Beam Intensity (A²)</th>
<th>Trigger Rate (Hz)</th>
<th>Beam Type</th>
<th>Target</th>
<th>Estimated Start Time, Duration</th>
<th>Hardware Additions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muonic atomic spectroscopy</td>
<td>Precision proton radius measurements</td>
<td>200</td>
<td>1.0</td>
<td>100</td>
<td>(\mu^+)</td>
<td>High-Pt, low</td>
<td>2022, 1 year</td>
<td>Electron tagging, high P5e</td>
</tr>
<tr>
<td>Muon decay</td>
<td>(g\mu-2)</td>
<td>300</td>
<td>10</td>
<td>10</td>
<td>(\mu^+)</td>
<td>NA48</td>
<td>2022, 2 years</td>
<td>4He target, high-energy Electron tagging</td>
</tr>
<tr>
<td>Electron production cross-sections</td>
<td>30-200</td>
<td>5-10</td>
<td>25</td>
<td>(\mu^+)</td>
<td>E866</td>
<td>2022, 1 month</td>
<td>4He target, high-energy Electron tagging</td>
<td></td>
</tr>
<tr>
<td>(g\mu-2)</td>
<td>High-Pt, low, low Pt</td>
<td>12.0</td>
<td>5-10</td>
<td>25</td>
<td>(\mu^+)</td>
<td>HERA</td>
<td>2022, 3 years</td>
<td>High intensity, momentum calibration, electron tagging</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>Polarisation studies</td>
<td>190</td>
<td>7-10</td>
<td>25</td>
<td>(\mu^+)</td>
<td>CW</td>
<td>2022, 2 years</td>
<td>Beam booster, vector detector</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>Kaon PDFs, Nucleon TMDs</td>
<td>-500</td>
<td>10</td>
<td>25-50</td>
<td>(K^+, K^-)</td>
<td>NA48</td>
<td>2020, 2.5 years</td>
<td>Beam booster, vector detector</td>
</tr>
<tr>
<td>Polarisation</td>
<td>Kaon polarisation studies</td>
<td>-500</td>
<td>5-10</td>
<td>&gt; 10</td>
<td>(K^-)</td>
<td>NA48</td>
<td>2020, 2.5 years</td>
<td>Beam booster, vector detector</td>
</tr>
<tr>
<td>Forward Physics</td>
<td>High-Pt, low Pt</td>
<td>2.0</td>
<td>10-200</td>
<td>100</td>
<td>(K^+, K^-)</td>
<td>P5e</td>
<td>2020, 1.5 years</td>
<td>Beam booster, vector detector</td>
</tr>
<tr>
<td>(K)-enhanced</td>
<td>High-Pt, low Pt</td>
<td>30-100</td>
<td>5-10</td>
<td>25</td>
<td>(K^+, K^-)</td>
<td>HERA</td>
<td>2022, 3 years</td>
<td>Beam booster, vector detector</td>
</tr>
<tr>
<td>Vector meson</td>
<td>Spectroscopy</td>
<td>10-200</td>
<td>5-10</td>
<td>10-200</td>
<td>(K^+, \pi^0)</td>
<td>from P5e to P5s</td>
<td>2020, 1 year</td>
<td>Beam booster, vector detector</td>
</tr>
</tbody>
</table>

Table 4.2: Summary table of requirements by the COMPASS successor experiment ("Future QCD facility"). WP1-related proposals are in blue, WP2-related ones in green, and WP-3 related proposals in red. Courtesy of the COMPASS Collaboration.
WP4 includes studies for an upgrade of the beam instrumentation for both muon and hadron beams. The first step is an upgrade of the differential Cherenkov detectors (CEDARs) for the beam particle identification, which has already been studied and implemented under the direction of Serge Mathot (EN-MME) and comprises a new thermal housing of the detectors for an operational stability within ±0.1°C as required by the original design specifications. The second part of WP4 comprises studies for an upgrade or replacement of the existing beam momentum station (BMS) around Bend 6.

The meetings of the working group were scheduled about once per month with the aim to continuously track the progress on both the experimental and the beam-related studies. Presentations have been archived via Indico and minutes of the meetings will be made available with EDMS. The overall study follows the OpenSE framework for project management. Parts of the reported studies have been included in Reference [3].

4.3 Work Package WP1: Muon Beams
4.3.1 User Requirements for Muon Beams at a Future QCD Facility (“COMPASS++”)

The proposal for a future QCD facility with muon beams [3] contains two planned measurements, i.e. a Deep Virtual Compton Scattering / Deep Virtual Meson Production experiment and a measurement of the proton radius. For the former, the standard M2 muon beam as used in the years 2016 and 2017 shall be provided. For the proton radius measurement, the collaboration requests a standard muon beam with lower intensities of $10^5$ to $10^7$ muons/sec, depending on the rate capabilities of a future trigger system and TPC. The focussed beam shall have a divergence of less than 1 mrad in both planes with a beam spot size of less than 1 cm RMS. The hadron contamination of the muon beam shall be less than $10^{-5}$.

4.3.2 User Requirements for MuonE

The MuonE experiment requires [4] a parallel 150 GeV/c muon beam with maximum intensity, i.e. $5 \times 10^7$ muons/sec. The beam shall have a small divergence of less than 300 µrad RMS in both planes and shall fit the tentative detector dimensions of 10 cm x 10 cm. The experimental set-up requires 40 m of space along the beam. The hadron contamination of the muon beam shall be less than $10^{-5}$.

4.3.3 User Requirements for NA64µ

NA64µ request muon beams for two experimental phases [5]. Phase 1 requires a parallel muon beam of 100-160 GeV/c with a small divergence of less than 500 µrad RMS in both planes. The beam spot size shall be adjusted to the final active target design. The beam intensity shall be in the order of $10^5$ – $10^6$ muons/sec. The available space along the beam shall be 20 m and two MBPLs shall be available as spectrometer magnets, along with the possibility to use the existing beam momentum station (BMS) around Bend6 as used by COMPASS to define the incoming beam momentum with a resolution of 1 %. For the second phase, an installation of the set-up inside the SM2 spectrometer magnet is requested. The
A muon beam of 150 GeV/c shall have a similar beam spot as before and divergence with an intensity of $10^7$ muons/s. A magnetic spectrometer shall be set-up in the COMPASS target region consisting of a MBPL magnet.

### 4.3.4 Compatibility and Integration

Given these user requirements, the implementation of each experiment as a stand-alone installation in EHN2 should bear no technical difficulties, as all set-ups are well compatible with the available space, also leaving enough flexibility for dedicated optics and necessary modifications to the M2 beamline elements. The question of simultaneous installation and even operation of two out of three proposals is important for obvious reasons, the latter under the condition that both beam momentum and intensity are the same for all experiments under consideration. Hence, different possibilities were studied with the aim of having a minimum amount of changes to the installations and thus the flexibility to change in between the proponents on time scales of weeks. As the removal of the COMPASS spectrometer would impose major works, the baseline was chosen to only remove parts of the existing spectrometer if no other solution could be found. In general, two spaces for experiments were studied: Upstream of COMPASS, starting from Bend 6 in zone PPE211, and downstream of COMPASS, in place of the existing hadron beam dump with an option to enlarge the EHN2 hall if deemed necessary.

The **downstream option** was found to be a natural choice for a test beam or demonstration run location as short set-ups in the order of up to 7 m could be placed without significant modifications to the COMPASS spectrometer. Only the removal of the HI05 hodoscope was considered in order to facilitate the test beam campaign for the COMPASS TPC that would be required for the proton radius measurements and a test set-up for the MuonE proposal, cf. Section 4.3. In case of removal of the downstream hadron absorber another 7.5 m could be gained, which would lead to an absolute available longitudinal space of 14.5 m, see Figure 4.2. For this mode of operation, M2 has to be limited to muon beams only while the final beam dump is not present. This would require blocking the beamline absorbers at the end of the decay section (at Z=600 m) to the IN position and would need to be agreed upon by radiation protection. The disadvantage of this location is the limited space that in addition does not allow re-shaping the beam with means of quadrupoles. Thus, experiments at this location would not be compatible with the simultaneous operation of an experiment with a beam that is focussed more upstream, e.g. at the COMPASS target location or at the SM2 location as the large divergence would lead to a very wide beam spot. As an alternative, the EHN2 building could be extended more downstream to obtain the required space for both beamline elements and a downstream experimental area, respectively. This would require extensive civil engineering and infrastructure investments in an order of magnitude that would need to be studied with the help of SMB, EN-CV, TE-EPC and TE-MSC if necessary. In addition, the amount of material present in the COMPASS spectrometer leads to energy loss and thus to a wider spread of the beam momentum. Given the sensitivity of both NA64μ and MuonE proposals, this would require another spectrometer stage to re-measure the incident beam momentum, hence even more space and one or more additional dipole magnets.
Figure 4.2: Downstream option for the installation of test beam equipment or a demonstration run. With the removal of the final beam dump a total length of 14.5 m would be available. The upstream option is depicted in Figure 4.3 and involves a re-shuffling of the presently installed beamline elements. With limited efforts, about 15 m of space can be freed if the CEDAR detectors are removed (left side of Figure 4.3), which is in any case the standard procedure for a change-over from a measurement with hadron beams to a measurement with muon beams. In order to achieve the 20 m for the first phase of NA64µ (NA64µ-1), a minor rearrangement would be required including removal of Quad34, shifting Bend7 upstream by 20 m to be used as the first spectrometer (MS1) and placing two additional MBPLs of aperture 140 mm 3 m downstream of the first MBPL to be used as the 2nd spectrometer (MS2).

Figure 4.3: Upstream option for the installation of the final NA64µ or MuonE experiment. With the rearrangement of the presently installed beamline elements, a total length of up to 40 m would be available.

The currently proposed layout is shown in Figure 4.4. Given the limited proposed period of data taking for NA64µ-1, a fast changeover would be desirable. A common mechanical platform with preinstalled detectors could reduce installation and alignment times significantly, in the order of weeks towards days. In addition, the required stability for NA64µ-1 might not be given in vicinity of the tunnel exit given the large temperature gradient that is present, which led to the construction of the new thermal housing for the CEDAR detectors.
A common platform would also mitigate this problem. A preliminary design and cost estimate for such a mechanical platform, possibly with auto-aligning fixation ("plugin"), is currently being performed by EN-EA.

Figure 4.4: Currently proposed layout of NA64m phase 1.
The beam arrives from the lower left side.

Figure 4.5: Tentative optics for NA64µ phase 1 in the so-called upstream location.
Another advantage of the given location for NA64µ-1 would be the possibility to use the existing beam momentum station ("BMS") of COMPASS around Bend 6 that allows measurement of the beam momentum with a precision in the order of 1%. The MBPLs requested in addition for NA64µ-1 would be used for a small spectrometer (MS1) that would either crosscheck or improve the BMS measurement. Since Bend7 is planned to be used for MS1, its power supply can be reused. For the two additional MBPLs requested for the second spectrometer (MS2), the power supply of Quad34 can be used. As the full infrastructure for the operation of these MBPLs exist nearby, only minor investments of a few tens of kCHF for the prolongation of cables and cooling lines plus some small expenses for the installation itself would have to be considered. NA64 uses a downgraded version of the COMPASS DAQ with an expected data flux of 40 MB/s. For phase 1 they would require space for 1-2 DAQ racks near the setup, which can be accommodated, and gas connections for their tracker detectors using an Ar-CO2 gas mixture. For this option, optics has been calculated as depicted in Figure 4.5, which are compatible with the requirements mentioned in Section 4.3.3. This optics would also preserve focusing at the COMPASS target location, however with a slightly deteriorated spot size or divergence, mostly due to the material presented by the NA64µ-1 HCAL. Results of simulations for a 100 GeV/c muon beam with Halo are shown in Figures 4.6 to 4.9. The obtained spot size has a Gaussian shape with $\sigma_x = 17$ mm and $\sigma_y = 28$ mm. The corresponding divergence is 0.2 mrad in x and 0.3 mrad in y with a momentum spread of about 4.5 GeV/c.

**Figure 4.6:** Beam spot for NA64µ phase 1 in the so-called upstream location with $\sigma_x = 17$ mm and $\sigma_y = 28$ mm.

For the installation of the full MuonE set-up in the upstream location, up to 40 m of space would have to be freed. This would require a modification of about 60 m of beamline from Quad 32 up to Bend 8. Optics fulfilling the requirements stated in Section 4.3.2 has been calculated and is depicted in Figure 4.10. This optics offers the option to either focus the beam on the COMPASS target location (thus being compatible with the proton radius measurement) or to focus the beam on the possible NA64µ phase 2 location inside SM2 (see Figure 4.7), however for this optics options one would require the Quad34-36, as shown, which limits the available space for MuonE to 30 m. In case 40 m is the lower limit for MuonE, the downstream quadrupoles would have to be removed and parallel running is not possible.
Figure 4.7: Proposed set-up for NA64µ phase 2 inside the SM2 spectrometer magnet and surrounding COMPASS detectors.

Figure 4.8: Divergence of beam for NA64µ phase 1 in the so-called upstream location with $\sigma_x' = 0.2$ mrad and $\sigma_y' = 0.3$ mrad.

Figure 4.9: Momentum distribution of beam for NA64µ phase 1 in the so-called upstream location for a 100 GeV/c nominal beam momentum with $\sigma_p = 4.5$ GeV/c.
Figure 4.10: Tentative optics for MuonE in the upstream location with the example of a focused beam on the NA64μ phase 2 location inside SM2. For MuonE up to 30 m of longitudinal space would be available.

Figure 4.11: Example of phase space change for the beam in Y co-ordinate for MuonE in the upstream location at the entrance (left) and at the end of the experimental setup (right) taking into account tracker (Si+Be) and Muon ID material (3 m of Fe).
However, the installations can still be compatible with minor rearrangements e.g. removing parts of MuonE (mainly its MuonID) and reinstalling the quadrupoles to focus the beam to COMPASS or NA64µ thus reducing the change-over time. Another drawback is that the material of the MuonE installation including a 3 m iron block for muon identification and requiring a parallel beam lead to a non-negligible growth of phase space due to multiple scattering and also to a larger momentum spread in combination with either a larger spot size or divergence depending on the chosen focussing. This effect is illustrated in Figure 4.11, where a clear enlargement of the trace space after passing of MuonE taking into account all materials can be seen. As a mitigation measure, the material of the MuonE muon filter could be optimised\footnote{The optimum choice for reducing multiple scattering would be Beryllium, but the total length needed would increase by 4.5 m. Beryllium is furthermore too expensive: With the current cost of about 7.5 kCHF/kg, the material for the absorber alone would cost in the order of 20 MCHF.}: One possibility, at the cost of increased length, could be using Carbon instead of Iron. In addition to the multiple scattering, a contamination of the muon beam due to particle production or bremsstrahlung processes might be possible. A dedicated study with both FLUKA and Geant4 has been performed and shows a negligible hadronic component in the beam below 10 ppm. As expected, mostly photons, electrons and positrons are produced at lower momenta in the order of 1 GeV/c and below, \textit{cf.} Figure 4.12. The charged component does not reach the COMPASS target location due to the sweeping effect of the following dipoles. With the help of a thin lead or tungsten foil, the photon component can be converted to electrons and positrons and thus be swept away. Another possibility would be introducing a horizontal dipole downstream of Bend 6 that would offer a different incident angle to MuonE. In this case, the beam subsequently would be deflected back by Bend 9 to the nominal axis after passing the last MuonE detector and produced photons would be dumped inside Quad 36. Such a possibility would allow for an installation of another dipole magnet (e.g. MBPL) at the COMPASS target location that could be used as a magnetic spectrometer for NA64µ phase 2, but would be also compatible with the proposed proton radius measurement. For DAQ MuonE plans to use the baseline solution for the CMS upgrade with an acquisition rate of 40 MHz. The data flux expected is 0.5 Tb/s requiring around 10 servers to handle this, based on the experience and solutions from LHCb. The system is planned trigger-less. Due to the required stability of the tracking detectors a very precise alignment is required, which might benefit from a single platform support. In addition, cooling of the detectors necessitates either dedicated gas or cooling water infrastructure.

NA64µ phase 2, proposed to be installed inside SM2, requires a spectrometer upstream near the COMPASS target location, consisting of a MBPL at the highest current (for most precise momentum reconstruction) which will have a deflection of 6 mrad for an incoming 150 GeV/c beam. This will result in an offset of 12 cm from the nominal beam axis near SM2 which may not be acceptable for the COMPASS downstream trackers planned to be used for NA64µ phase 2 as well. In order to resolve these issues, we propose a chicane as shown in Figure 4.13 consisting of Bend7, Bend9 (in the beamline) and an additional MBPL installed near the COMPASS target to exploit the maximum capability of a MBPL and also to deflect the beam back to the nominal axis down the COMPASS and NA64µ setup. A similar setup is currently used by COMPASS, but consisting of the target dipole instead of the proposed MBPL.
The obtained beam parameters at MuonE, the COMPASS target location, and at the NA64µ phase 2 position are summarised in Table 3. The corresponding distributions are illustrated in Figure 4.14 TO 4.18.

![Graph showing produced particles after passing MuonE (FLUKA / Geant4)](image)

**Figure 4.12:** Produced particles after passing MuonE (FLUKA / Geant4)

![Diagram of proposed chicane](image)

**Figure 4.13:** Proposed chicane to be used by NA64µ phase 2 consisting of Bend7, Bend9 and an additional MBPL near the COMPASS target. T1-T6 shows the tentative positions of the spectrometer trackers.
Figure 4.14: Spot Sizes at MuonE (A) with $\sigma_x = 26$ mm and $\sigma_y = 27$ mm, COMPASS Target (B) with $\sigma_x = 22$ mm and $\sigma_y = 21$ mm and NA64$\mu$ (C) with $\sigma_x = 30$ mm and $\sigma_y = 31$ mm.

Figure 4.15: Beam Divergence at MuonE with $\sigma_x' = 0.3$ mrad and $\sigma_y' = 0.2$ mrad.
Figure 4.16: Beam Divergence at the COMPASS target with $\sigma_x = 1.2$ mrad and $\sigma_y = 1.4$ mrad.

Figure 4.17: Beam Divergence at the NA64 with $\sigma_x = 0.8$ mrad and $\sigma_y = 0.6$ mrad.

Figure 4.18: Momentum distributions at MuonE (A) with $\sigma_p = 5.9$ GeV/c, COMPASS Target (B) with $\sigma_p = 5.8$ GeV/c and NA64 (C) with $\sigma_p = 5.5$ GeV/c for incident 160 GeV/c muon beam.
4.4 Beam Tests 2018

During the 2018 beam time, the main user of the M2 beam was the COMPASS collaboration with a Drell-Yan physics run [5-6], for which a 190 GeV/c negative hadron beam was used. The running-in time included several days of 190 GeV/c muon beams for calibration. The 2018 COMPASS set-up is shown in Figure 4.19 including the additional hadron absorber in the COMPASS target region as required for the measurement, which was placed downstream of the polarised target.

![Figure 4.19: The 2018 COMPASS setup. Courtesy of the COMPASS collaboration](image)

The MuonE collaboration requested to run parasitically with a test beam set-up downstream of the COMPASS experiment close to the original hadron beam dump as shown in Figure 4.20. In parallel, COMPASS also tested a TPC prototype for the proposed proton radius measurement, which was placed about 3 m upstream of the MuonE set-up. Infrastructure such as electricity, network connections, racks and concrete platforms were installed coordinated by the EN-EA group. COMPASS used a hydrogen TPC as an active target for the incident muon beam. The TPC was used to measure the energy of recoil protons between 0.5 and 100 MeV. Silicon telescopes placed upstream and downstream of the TPC were used to measure the muon scattering angles. The test beam time was planned to i) establish the performance of the TPC in the muon beam, ii) investigate the need or benefit of a higher
Figure 4.20: Overview of the test beam installations close to the EHN2 final hadron beam dump

Figure 4.21: COMPASS TPC Setup. The beam enters from the right into two Silicon tracking stations and ten impinges on the TPC in the middle. The Silicon stations on the left are used to measure the scattered muons. Courtesy of the COMPASS collaboration

granularity readout plane and iii) correlate events in the silicon detector with those in the TPC. Figure 4.21 shows the 2018 test beam setup for the TPC measurements. MuonE used two modules as shown in Figure 4.22, each made of 4 Silicon tracker planes with a size of 9.5 cm x 9.5 cm and a Carbon target with 8 mm thickness. The set-up included an electromagnetic calorimeter as well at the downstream end. The aim was to use the muon beam for an indication on the trigger strategy and to check for a correlation between $E_e$ and $\theta_e$ with the aim to validate the possibility suppressing electrons with energy of less than 1 GeV. In
addition, the cross section $\sigma (\mu + e \rightarrow \mu + e)$ was supposed to be measured given enough statistics. Figure 4.23 shows the test beam set-up for MuonE during the 2018 run. For both test beams, dedicated electrical infrastructure and IT was made available by EN-EA. The EHN2 WG and experiments acknowledge with gratitude the help of B. Veit and P. Boisseaux-Bourgeois.

4.4.1 Beam studies

In order to estimate the muon beam distributions at the test location, studies with the beam simulation software *Halo* were performed. The simulation used optics for 190 GeV/c muon beams as well as hadron beam that were both used respectively in 2018 for the COMPASS
data taking. Halo is able to simulate the beam trajectory taking into account all beamline elements (quadrupole, bending magnets, collimators and magnetic collimators) with the aim to estimate beam-related distributions at specified locations. It takes into account energy loss introduced by the hadron absorber present in the 2018 COMPASS set-up and the magnetic fields of both spectrometer magnets SM1 and SM2.

The 190 GeV/c muon beam was used for the commissioning of the COMPASS spectrometer during the first days of the 2018 beam time. The flux was in the order of $10^8$ muons per spill for $1.2 \times 10^{13}$ protons on T6. The estimated beam spot at the COMPASS target location was found in the simulation to be $\sigma_x = 7.7$ mm and $\sigma_y = 6.4$ mm as depicted in Figures 4.24 and 4.25. The calculated momentum is 189 GeV/c with a spread of $\sigma_p = 7.5$ GeV/c. The angular divergence is $\sigma_x' = 0.5$ mrad and $\sigma_y' = 0.7$ mrad as expected. At the test location 47'844 mm downstream of the COMPASS target, the muon beam degrades slightly due to the presence of the hadron absorber. The integrated flux within the typical size of a device under test of 10 cm x 10 cm was of the order of $10^7$ muons per spill. The spot on the MuonE set-up was simulated to be $\sigma_x = 77.3$ mm and $\sigma_y = 81.4$ mm (see Figure 4.26). The momentum distribution is shifted to a lower value of 186 GeV/c due to energy loss in the hadron absorber whereas the width remains at $\sigma_p = 7.5$ GeV/c. The beam divergence increased due to multiple scattering in the absorber material to $\sigma_x' = \sigma_y' = 1.5$ mrad.

![Graphs showing beam parameters from Halo of the 2018 muon beam at the COMPASS target location, as it was used for the COMPASS commissioning run. Upper row: Horizontal and vertical size, lower row: horizontal and vertical divergence.](image-url)
Figure 4.25: Beam parameters from Halo of the 2018 muon beam at the COMPASS target location, as it was used for the COMPASS commissioning run. Left: 2D distribution of the beam spot, right: calculated momentum distribution.

Figure 4.26: Beam parameters from Halo of the 2018 muon beam at the test beam location, as it was used for the COMPASS commissioning run. Upper row: Horizontal and vertical size, middle row: horizontal and vertical divergence, lower row: 2D distribution of the beam spot and calculated momentum distribution.
The **190 GeV/c hadron beam** was used after commissioning with muon beam for the data taking of COMPASS through the full beam time in 2018. Due to the thickness of the COMPASS hadron absorber, only muons from pion and Kaon decays were reaching the downstream test area, which turned out useful for the continuation of the tests in spite of having only $10^6$ muons per spill at the COMPASS target for $3.8 \times 10^8$ hadrons per spill. There, the beam spot parameters of the muon component in the beam were found to be $\sigma_x = 11.7$ mm and $\sigma_y = 19.8$ mm, while the divergence is $\sigma_{x'} = 0.16$ mrad and $\sigma_{y'} = 0.26$ mrad (see Figure 4.27). The simulated momentum distribution peaks at 174 GeV/c with a width of 20.1 GeV/c (see Figure 4.28). After propagation through the hadron absorber and the field of both SM1 and SM2 spectrometer magnets, the beam parameters at the test location were found to be $\sigma_x = 92.8$ mm and $\sigma_y = 89.6$ mm (see Figure 4.29). For the MuonE active area of 10 cm by 10 cm, the integrated flux was calculated to be in the order of $10^5$ muons per spill. The resulting momentum distribution shows a slightly lower peak value at 173 GeV/c due to energy loss in the absorber material, however the width was calculated to be the same as before. The divergence increased considerably due to multiple scattering, i.e. $\sigma_{x'} = 1.5$ mrad and $\sigma_{y'} = 1.4$ mrad.

**Figure 4.27:** Beam parameters from *Halo* of the 2018 muon component of the hadron beam at the COMPASS target location, as it was used for the COMPASS data taking in 2018. Upper row: Horizontal and vertical size, lower row: horizontal and vertical divergence.
Figure 4.28: Beam parameters from Halo of the 2018 muon beam at the COMPASS target location, as it was used for the COMPASS commissioning run. Left: 2D distribution of the beam spot, right: calculated momentum distribution.

Figure 4.29: Beam parameters from Halo of the 2018 muon beam at the test beam location, as it was used for the COMPASS commissioning run. Upper row: Horizontal and vertical size, middle row: horizontal and vertical divergence, lower row: 2D distribution of the beam spot and calculated momentum distribution.
4.4.2 First experimental conclusions

COMPASS was able to test their high-pressure TPC and reported good performance of the detectors. The time coincidence of both proton and muon signals in both the TPC and silicon modules, respectively, was observed. This was a major challenge due to the use of two different data acquisition systems.

MuonE reported a successful test beam time so far and took data until the end of the M2 operation in 2018. The beam conditions in M2 were reported to be so useful that the test beam in H8 could be cancelled. Analysis of the data is still ongoing. As of June 11th, MuonE reported 220 M recorded events with a continuing data taking of 7 M events per day. A few ten thousand elastic candidate events were observed so far.
4.5 Work Package WP2: Conventional Hadron and Electron Beams

4.5.1 User Requirements for Input to Dark Matter Searches at a Future QCD Facility

The proposal for a future QCD facility includes a measurement of antimatter production cross sections, in particular antiproton production, as an input for Dark Matter Searches with AMS and others. The standard M2 hadron beam as used in the years 2008 and 2009 shall be provided. The proponents request intensities of $5 \times 10^5$ hadrons/sec in the range of 20 to 280 GeV/c. The focussed beam shall have a divergence of less than 1 mrad in both planes with a beam spot size of less than 1 cm radius.

4.5.2 User Requirements for Antiproton-induced spectroscopy at a Future QCD Facility

Another proposal is the measurement of heavy quarks exotica (XYZ) with the help of low energy antiproton beams. Hadron beams with energies between 12 and 20 GeV/c and highest possible content of antiprotons shall be provided. The proponents request intensities of $10^7$ hadrons/sec. The focussed beam shall have a divergence of less than 1 mrad in both planes with a beam spot size of less than 1 cm radius. Means of identification of the antiproton component in the beam shall be provided such as CEDAR or threshold Cherenkov detectors.

4.5.3 User Requirements for Drell-Yan measurements at a Future QCD Facility

The measurement of Pion Parton Distribution Functions by the Drell-Yan process on nuclear targets is proposed with positive and negative pion beams of 190 GeV/c. The proponents request intensities of $7 \times 10^7$ hadrons/sec. The focussed beam shall have a divergence of less than 1 mrad in both planes with a beam spot size of less than 2 cm radius. Means of identification of the beam contamination or an identification of the pion component shall be provided such as CEDAR or threshold Cherenkov detectors that are capable to deal with high intensities.

4.5.4 User Requirements for Prompt-Photon measurements at a Future QCD Facility with conventional pion beams

The measurement of Gluon Parton Distribution Functions for Mesons by production of prompt photons is proposed with positive and negative pion beams of 190 GeV/c. A comparison to results obtained from a RF-separated Kaon beam is desirable, thus the use of the modified beamline is an option. The proponents request intensities of $5 \times 10^6$ hadrons/sec. The focussed beam shall have a divergence of less than 1 mrad in both planes with a beam spot size of less than 1 cm radius. Means of identification of the beam contamination or an identification of the pion component shall be provided such as CEDAR or threshold Cherenkov detectors.

4.5.5 Low-energy antiproton beams

In a first step, the production of antiprotons at several desired energies has been estimated using the so-called Atherton parameterisation, based on results of production measurements on Beryllium targets in the North Area. In Figure 4.30, the flux of secondary particles at 0 mrad production angle versus the secondary momentum is shown. The two study cases at 12 (20) GeV/c are below the accepted validity for an extrapolation of the Atherton parameterisation, but were used for an initial estimate of the correct order of magnitude. The flux is expected to be about 0.41 (0.20) antiprotons per interacting proton per steradian per GeV/c momentum bite. This corresponds to about 4.4% to 4.8% of the total negative hadron flux.
Based on the experience of operating the West Area in the 1990s, the main background contribution to the beam was identified as electrons. As depicted in Figure 4.30, the electrons at lower energies contribute with more than 90% to the total flux. Hence, a suppression of the electron background has to be included, most probably by the insertion of a thin lead sheet at a focal point in the beam optics in order to keep the contribution by multiple scattering to the beam divergence at the CEDAR counters low. Given a 99% suppression of electrons and including the decay of hadrons along the M2 line, this would result in a fraction of 18.2% (11.3%) of antiprotons at the Compass target location for 12 (20) GeV/c beams. With a typical solid angle of $\pi \times 10^{-5}$, a target efficiency of 40% for the 500mm T6 target head, a flux of $10^{13}$ protons on T6, and assuming a 2% momentum bite for new low-energy optics, the resulting antiproton flux would be $10^8$ ($5 \times 10^7$) for 12 (20) GeV/c beams. As the intensity in EHN2 is limited by radiation protection to about $10^8$ particles per 4.8 sec spill, the total antiproton flux thus is limited by the purity of the beam. For the calculated purity of antiprotons of 18% (11%), an upper limit of the antiproton flux at the Compass target is estimated to be $1.8 \times (1.1) \times 10^7$ antiprotons per spill.

For an efficient transport of low-energy antiprotons, several optimisations of the M2 beamline could be envisaged. Besides dedicated low-energy optics, a completion of the vacuum in the line would be necessary. So far, the M2 beamline is optimised for muon transport, which implies that several elements specific to muon beams were not designed for operation in vacuum, such as the magnetic collimators (“scrapers”), Collimator 5, and 9.9 m of Beryllium absorbers inside Bend 4. Therefore, a total of about 80m of the beamline remain without vacuum. Depending on the operational conditions, two solutions would be preferred. For a full year of operation without muon beams, the above-mentioned elements could be removed from the beamline and/or be exchanged by standard magnets and absorbers, which are compatible with the vacuum requirements. In this case, the removal of scrapers will have

Figure 4.30: Atherton parameterisation for the production of different particle species given in flux per solid angle [steradian], per interacting proton, and per dp [GeV/c] as a function of secondary momenta for a 0 mrad production angle. Negative values for momenta are used to indicate negatively charged particles.
the consequence of a large muon component in the beam in the order of 3-5% and an increased muon halo due to the M2 geometry. If this background cannot be tolerated or an intermediate operation of muon beams is envisaged, another solution could be a fitting of vacuum tanks inside the scrapers with an estimated cost of about 150 kCHF (material + work). The fitting work would have to be done after setting up the scraper positions and the motors would need to be blocked as was done for the scraper in K12. In addition to the optics change and vacuum optimisation, the beam instrumentation has to be adapted as outlined in Section 4.5.7.

4.5.6 High-intensity pion beams

The currently used high-intensity pion beam for Drell-Yan measurements at COMPASS is limited in intensity by radiation protection considerations to about 4 $10^8$ hadrons per 4.8 sec spill. These high intensities are only allowed in a special configuration of the COMPASS spectrometer, for which a hadron absorber is installed directly behind the polarised target and several layers of concrete shielding are added to the nominal Salève wall shielding. A FLUKA study has been launched in collaboration with HSE-RP in order to understand better the origins of radiation stemming from the beam tunnel taking into account the material of the two installed CEDAR detectors. As a preliminary result, the current radiation levels at the entrance of the beam to EHN2 could already be confirmed by the simulation. The radiation map is shown in Figures 4.31 and 4.32: As expected, the main origin of radiation are hadrons lost in Bend 6 and the considerable interaction of the hadron beam in the CEDAR vessels, which are filled with Helium gas at 10.5 bar. As a next step, magnetic field maps will be included for higher precision of the results. Then, a study for the optimisation of the surrounding shielding at the CEDAR location is planned as well as a study to understand how the so-called “sky-shine” radiation in EHN2 could be reduced. HSE-RP has furthermore launched a measurement campaign at different locations in EHN2 and the results will be used to benchmark the simulations.

Besides the possibility to increase the total intensity in EHN2, another prospect for higher pion intensities would be an enrichment of the fraction of pions in the positive hadron beam with the help of differential absorption. For this, a filter target would be installed in an upstream focus of the beam with a material for which the attenuation of pions is less than for protons, e.g. polyethylene. During a former test beam in EHN1, an enrichment of pions at 300 GeV/c from 5.8% to 19.1% of the total intensity has been found, however on the cost of losing of about 98% of beam intensity. For M2, a possible location for the installation of a filter target would be 677 m downstream of the T6 target in front of Bend 4 and 5. At this location, a filter target of 5 mm lead already exists that is used for tertiary electrons, see Section 4.5.7. A preliminary GEANT4 study shows that the pion content of the beam at 190 GeV/c could be increased from originally 25% to 29.5% if 2 m of polyethylene would be installed on the cost of losing about 86% of the beam. As the beam rate for the same optics and collimator settings is about a factor 13 higher for positive beams, these losses would impose only a small limitation in terms of available rate from production. An important drawback is the increase of divergence of the beam by multiple scattering in the polyethylene. This might lead to a decreased performance of the CEDAR detectors, which are necessary to tag the positive pions in the beam. In summary, given the moderate enrichment with respect to the lost intensity and degraded performance of the beam PID, it is doubtful whether enrichment by differential absorption would have a significant impact on the Drell-Yan statistics.
Figure 4.31: Preliminary results for the radiation map and their statistical accuracy of the 2018 high intensity hadron beam ($3.8 \times 10^8$ at XION.065.093) at the entrance of the beam to EHN2 in the top view, where the beam is entering from the left side. The two CEDAR detectors and their main structure are marked by the black lines in the centre of the plot. The lower plot is a visualisation of the FLUKA model that has been adapted to include the surroundings, important structures, shielding, beam line elements, and detectors.
Figure 4.32: Preliminary results for the radiation map and their statistical accuracy of the 2018 high intensity hadron beam ($3.8 \times 10^8$ at XION.065.093) at the entrance of the beam to EHN2 in the side view, where the beam is entering from the left side. The two CEDAR detectors and their main structure are marked by the black lines in the centre of the plot.

4.5.7 Electron beams
So far, a low-intensity tertiary electron beam is used for calibration purposes of the COMPASS experiment. The electron beam is derived from a secondary target (5 mm lead), where electrons and positrons are produced by bremsstrahlung and pair production from the electromagnetic cascade that follows the hadronic cascade of the interacting secondary beam and from energy loss of the original electron content of the secondary beam. In general, the low intensity of a few hundred to a few thousand electrons per spill is partly a result of the missing vacuum in the beamline and partly by the production via a secondary target. Upgrades of the vacuum quality as outlined in Section 4.5.5 will help to increase the intensity within the same order of magnitude, especially for low-energy electron beams. A secondary electron beam would be highly polluted by hadrons, however, due to the low bending angles in the M2 line and the consequently low energy loss of electrons by synchrotron radiation that is normally used to separate electrons and hadrons in high-energy secondary beams. If requested, a study of using either a strong achromat or permanent wiggler magnets in the beamline might turn out useful.
4.6 WP3: RF-separated hadron beams

4.6.1 Principle of RF-separated beams and initial study

At higher energies in the order of 100 GeV/c, an enrichment of antiprotons is not naturally given by decays of other particles over the length of a beamline, due to higher lifetimes of particles in the laboratory frame. In addition, the proposal for a new QCD facility [3] includes requirements for a higher content of kaons and positive pions in the beam depending on the measurement to be performed. Starting from studying limitations in terms of production of particles, there are several possibilities to enrich the content of a wanted particle species in the beam, usually by suppression of unwanted particles. Due to the $1/p^3$ dependence of electro-static separators, it is not reasonable to use such a method at beam energies higher than a few GeV. While in principle an enrichment by differential absorption would be feasible, the very low efficiency, high losses, and small suppression factors for unwanted particles as described in Section 4.5.6 leave only the possibility of RF-separated beams.

The method of RF-separation was first employed at CERN in the 1960s based on ideas of Panofski and Schnell as for instance described in Reference [6]. The main idea is based on the different velocities of particle species in a beam with defined momentum. As displayed in Figure 4.33, two dipole RF cavities (RF1 + RF2) with frequency $f$ are implemented at a given distance $L$. The transverse kick of RF1 is either amplified or compensated by RF2 depending on the phase difference between both. This phase difference is given by the difference of velocities of the various particle species. For two species $i (i = 1, 2)$ with masses $m_i$ and velocities $\beta_i$, the phase difference reads $\Delta \Phi = 2\pi \left( L f / c \right) (\beta_1^{-1} - \beta_2^{-1})$. In the limit of large momenta, the phase difference can be expressed as a mass difference between the two species at the beam momentum $p$: $\Delta \Phi = 2\pi \left( L f / c \right) (m_1^2 - m_2^2)/(2p^2)$.

For kaons as wanted particles, the phase difference could be chosen at $\Delta \Phi_{\pi K} = 2\pi$, which results in $\Delta \Phi_{\pi K} = 94^\circ$. This means that the kick for both protons and pions would be compensated by RF2 and they would be absorbed in the beam stopper. The kaons would receive a close-to-maximum transverse kick and mostly go around the stopper. For antiproton beams, the phase difference could be chosen at $\Delta \Phi_{\bar{p} K} = \pi$, which results in $\Delta \Phi_{\bar{p} K} = 133^\circ$ and $\Delta \Phi_{\bar{p} e} = 184^\circ$. In this case, the antiprotons would receive an acceptable deflection while electrons and pions are dumped effectively. Based on a study by J. Doornbos at Triumph for CKM, we assume a similar input for frequency ($f = 3.9$ GHz) and kick strength of the RF cavities ($d_{\pi} = 15$ MeV/c). Given the length of 1.1 km of the M2 beamline, the length $L$ between cavities cannot be chosen larger. In such a study case, the upper momentum limitation for RF-separated kaon beams would be about 75 GeV/c and about 108 GeV/c for RF-separated antiproton beams. In reality, the beam design must include a section for momentum selection and a section to match to the RF cavities before entering the first cavity. In addition, space

Figure 4.33: Panofsky-Schnell method [6] for RF-separated beams. The unwanted particles (red) are stopped by a beam stopper while the wanted particles (green) receive a net deflection by the combination of the RF1 and RF2 dipole RF cavities out of the central axis.
for the dispersion recombination, for the final focus and for beam particle identification has to be included in the design. Hence, the total available length shrinks accordingly. As the phase difference depends quadratically on the chosen momentum, such beams would deliver acceptable separation only in a small momentum band. In addition, the dispersion of the beam $\Delta p/p$ needs to be limited to about 1% within the cavity regions in order to prevent a phase shift of $\Delta \Phi = \Delta \Phi_i (1 - 2 \Delta p/p)$ and thus a lower separation efficiency. As an example, using the given acceptance values and the maximum target efficiency of 40% for the 500 mm T6 target, a calculation was performed for the case of a 100 GeV/c antiproton beam. Assuming that 80% of the antiprotons would pass the beam stopper and an optimisation of the solid angle to $10\pi$ µsterad could be achieved, one would expect about $8 \times 10^7$ antiprotons in EHN2 for $10^{13}$ incident protons at the T6 target. Due to the current radiation protection restrictions for EHN2 of $10^8$ particles per 4.8 s spill for set-ups without a hadron absorber, the limit would be given only by the to-be-achieved purity of the beam. Assuming 50% purity, this would be about $5 \times 10^7$ antiprotons per spill.

### 4.6.2 Optics and beamline design

An important challenge is to fit the new design in the already existing M2 tunnel. The tunnel features different changes of slopes, at which vertical dipoles are located that introduce dispersion. Another challenge is the frontend, which consists in the present configuration of six high-gradient quadrupoles (see Figure 4.34). They provide already a high acceptance as required for the RF-separated beam design. However, the frontend quadrupoles are located in TCC2 at a very close distance to both the T6 target and the two Target Attenuators (TAX), which means the residual dose at this location does not allow for a long installation time and which therefore should be avoided.

As already mentioned, one drawback of the original M2 design for hadron beams are the small and changing slopes of the tunnel that are followed by the main bending magnets. While this is necessary for achieving highest muon fluxes, these small angles do not allow for large dispersion regions in the beamline that could be used for a good momentum selection. Thus, a vertical achromat was introduced in the design as depicted in Figure 4.34. The first vertical magnet BV1 introduces an angle of 14 mrad that is followed by a field lens (Q81). The beam is then deflected by another bend (BV2) to a momentum slit (C1) and the dispersion is re-matched through another field lens (Q8), BV3 and BV4. Studies for the integration of the two RF cavities are continuing, which will be used to provide an input to the RF group in terms of expected beam spot size through the cavities. This is required to provide the maximum available frequency and thus the upper limit for the momentum of the beam.

Following the first cavity, a triplet of quadrupoles is used to match the beam into a long FODO section for transport towards the second cavity. Due to the vertical slope of the tunnel and therefore the presence of two more vertical bending magnets, a source of dispersion arises in the middle of the FODO section. One idea would be splitting the last vertical bending magnet (B6) into two parts and using a field lens quadrupole in between, which would allow for recombining the dispersion before entering the last cavity. The beam is then focussed on the second cavity that is followed by a beam dump for the unwanted particles, which has to be implemented in the design as the next step. Afterwards, a section with parallel beam should follow in order to accommodate beam particle identification, e.g. with CEDAR detectors. Finally, a triplet of quadrupoles is used to focus on the experimental target.
4.6.3 RF requirements
The requirements for the RF system will have to be defined according to the results obtained from the study described in the previous section. It is already clear that only superconducting cavities will allow operation due to the slow extraction and therefore long spill length, over which the system needs to operate. Given the preliminary results of the initial study presented in Section 4.6.1, frequencies in the order of about 4 – 10 GHz seem to favourable. A dedicated study by the BE-RF group would be needed to understand the achievable kick strength and aperture / gap size of the cavities.

4.6.4 Integration
As a first step, the current 2D layout of the M2 beamline has been ported to a 3D model including the tunnel dimensions. When the full design of the RF-separated beam will become available, the beamline elements will be integrated in the model and service needs as well as possible civil engineering requirements will be defined.

Figure 4.34: Preliminary frontend optics up to the first RF cavity (RF1) for an RF-separated beam.
4.7 Beam instrumentation (WP4)

4.7.1 CEDAR upgrade

The CEDAR detectors for beam particle identification are located at the exit of the beamline tunnel and the entrance to the EHN2 hall. One consequence of this particular location is the high temperature gradient between tunnel and hall with considerable day/night and seasonal fluctuations. This leads to a dynamic change of temperature over the gas volume of the CEDAR detectors, which in turn is detrimental for the stability of the detectors as the effective refractive index changes over time. Even a constant temperature gradient smears out the opening angle of the Cherenkov light, while the internal CEDAR optics accept only a very specific solid angle. Due to these reasons, an upgrade of the thermal shielding to an actively controlled environment has been proposed and was implemented by EN-EA and EN-CV at the beginning of 2018. The new system consists of a better insulating layer around the gas vessel that allows for air circulation. Cooled air is constantly circulated in the system and guarantees a temperature gradient of only 0.1°C as depicted in Figure 4.35. During a test in the summer of 2018, the air circulation has been stopped for a few days for a better comparison during real operation. In Figure 4.36, the temperature varies significantly along the CEDAR gas vessels as can be seen by the difference in between the measurements of the several temperature probes. In addition, the day/night variation of temperature is clearly observed. Besides the better thermal housing, the CEDAR detectors were also upgraded with new multi-anode photomultiplier tubes and new readout electronics to cope with the higher beam intensity for the COMPASS Drell-Yan data taking. First results with the upgraded system look promising, however a full performance analysis has still to be performed by the experiment.

Figure 4.35: Measured temperature gradient along the CEDAR1 gas vessel. The min-max variation is below 0.1°C.

4.7.2 Possible upgrades to beam momentum measurements

In context of the NA64μ phase 1 studies, simulations were performed with Halo and Geant4 to check the performance of the BMS and MS1 to define the incoming beam momentum. The BMS consists of beam defining hodoscopes labelled BM01-06 as shown in Figure 4.37. The entire beamline was simulated with HALO and the particle hits were recorded at the BMS hodoscope positions. The BMS hodoscopes have a detector resolution of 1.3 mm for BM01-4 and 0.7 mm and 0.4 mm for BM05 and BM06, respectively. The hodoscopes measure the beam only in the vertical (Y) co-ordinate. The system of bending magnets (Bend 6) consists of three 5 m vertical bends with 3.3 Tm bending power each.
The momentum reconstruction with the BMS was estimated using the TMVA analysis of ROOT with the Boosted Decision Tree method. The vertical hit positions and the direction of the particle in the upstream and downstream part were chosen as the input variables. The detector resolution was taken into account. Figure 4.38 shows the momentum resolution of 1\% as calculated with this method for a 160 GeV/c incoming beam. In order to further improve the BMS resolution, a BMS upgrade could be envisaged by replacing the existing hodoscopes with detectors of much better spatial resolution, such as Silicon detectors ($\sigma_x = 10 \text{–} 50 \mu m$) or gas strip detectors with very high rate capability ($\sigma_x \sim 100 \text{–} 200 \mu m$). Figure 4.38, right, shows the improvement in the momentum resolution for a 160 GeV/c incoming beam using the above method for different detector resolutions keeping the detector positions and the number of detectors same. For a detector resolution of 50 \mu m, achievable with a Silicon detector, a resolution of 0.35\% can be expected. The fit function has been extrapolated up to 500 \mu m resolution in case a detector based on scintillating fibres would be considered.

4.7.3 Particle identification for future hadron beams
For the low-energy antiproton beam, the currently available beam particle identification by the CEDARs is not adequate as the detector optics are optimised for the use of Helium (so-called CEDAR-N). For the use of Nitrogen, another type of CEDAR exists, but all of the two available detectors are used in NA61 and NA62 and Nitrogen would not be suitable for the very low momenta. For low-energy test beams, usually threshold Cherenkov detectors are used. They consist of a beam pipe that is filled with gas (e.g. CO2) at a chosen pressure, in which Cherenkov light is emitted and reflected perpendicular to the beam axis by a mirror at the downstream end. The light is collected with the help of a Winston-like cone and detected by a monolithic photomultiplier tube. This system is not capable of high beam intensities. A
possible upgrade would need to address the rate issue by either spreading out the collected light on a large surface detector or a direct detection of the light within the gas volume, for instance with a windowless gas detector that would use the radiator gas also for amplification as proposed by INFN Trieste [9].

Figure 4.37: Schematic of the beamline showing the BMS and MS1.

Figure 4.38, left: Momentum resolution of 1 % estimated for the current BMS setup with simulation. Right: Estimated momentum resolution dp/p [%] as a function of detector resolution.
References for Chapter 4


4. S. Gninenko et al., Addendum to the NA64 Proposal: Search for the $A' \to$ invisible and $X \to e^+e^-$ decays in 2021, CERN-SPSC-2018-004, SPSC-P-348-ADD-2.


8. COMPASS collaboration, COMPASS-II proposal, CERN-SPSC-2010-014, SPSC-P-340 (2010).

5. ECN3 related projects

5.1 Introduction

For ECN3 four proposals have been assigned to the Conventional Beams working group: NA62 in beam dump mode (hereafter called NA62-BD) [1], KLEVER [2], NA60++ [3] and DIRAC++ [4]. At the moment the NA62 experiment [5], aiming to collect 100 events of the very rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$, is the sole user of the ECN3 cavern.

With special settings of the existing beam line, the $K^+$ production target T10 being moved out of the beam, the full proton beam can be dumped in the existing massive dump collimators (XTAX) and the muons produced are swept away by the existing muon cleaning system. In this mode NA62-BD, has a competitive sensitivity to dark sector candidates, such as Heavy Neutral Leptons and the dark photon $A'$. A first step of the study is to understand if the beam dump conditions can be further optimized for short runs (~1 day) by different settings, without changing the installation. For a possible long run (e.g. 1 year), layout changes can be considered, such as a more downstream position for dumping the protons, which would enhance the acceptance for dark matter candidates.

KLEVER is the $K_L \rightarrow p\pi\nu\nu$ counterpart, which requires a new, neutral beam line, a new detector and significantly higher proton flux on the T10 target due to the lower angular acceptance. This requires optimization of the beam parameters in terms of signal and background rates, radiation protection related studies, equipment protection and proton delivery studies.

NA60++ and DIRAC++ need standard ion or proton beams at intensities that nowadays can only be provided in underground areas, such as ECN3. These can be provided with beam if none of the kaon experiments is present in the hall. However, new beam lines need to be constructed (although rather standard ones) and the cohabitation with NA62-BD or KLEVER is not obvious and needs further detailed study.

5.2 NA62-BD

5.2.1 Some principles of the present set-up of NA62

The NA62 beam line follows grossly a straight line from the $K^+$ production target T10 to the NA62 main detectors. This exposes the NA62 detectors potentially to a high muon background flux. A muon sweeping system has been designed and optimized, using an old simulation program, called HALO [6]. This program stems from 1974, is therefore well benchmarked and runs quite fast on modern computers. However, it only allows to simulate muon backgrounds and no other particle backgrounds such as hadrons (including neutrons), photons and electrons, which are also present. The beam line for NA62 with its optics is schematically shown in Figure 5.1.

The mixed beam is produced in the 400 mm long Beryllium production target, T10. The outgoing particles are captured and focused by a quadrupole triplet onto a pair of dump collimators (XTAX) with two 1 cm diameter holes each. Before the TAX two dipoles make a parallel downward displacement of 75 GeV/c beam particles by 110 mm.
The TAX are positioned and offset such that an overall ±2.5 mm aperture provides a 1% RMS momentum selection for the transmitted beam. Another pair of dipole magnets puts the beam back on the original horizontal axis for further collimation. The rest of the beam line serves to clean the beam, identify the kaons and measure the momentum, position and direction of each beam particle at a rate of 750 MHz.

![Schematic layout and optics of the K12 beam for the NA62 experiment](image)

**Figure 5.1:** Schematic layout and optics of the K12 beam for the NA62 experiment

Muons originate mostly from the decay of pions and kaons produced by interactions in the T10 target and TAX. Muons can thus be positive or negative. A first stage of muon sweeping consists of a series of three 2 m long dipoles which have their gap filled with iron, except for a 40 mm diameter hole which is almost field free to allow the passage of the beam. Both signs of muons are swept sideways out of the detector acceptance. From then only positive pions and kaons are transported and the muons from their decays are only positive.

In the centre of a second ‘achromat’ (a set of 4 dipoles housing the momentum spectrometer), a toroid, called ‘scraper’, sweeps the muons outside the main beam away from the detector. The remaining muon background is dominated by unavoidable pion and kaon decays downstream of the scraper. This system is well described by the HALO simulation program. As the rates in the detectors also comprise a significant rate of other particles (hadrons, electrons, photons, etc), background estimates for dark sector searches must take those rates into account as well. Therefore, a G4-Beamline simulation [7], based on Geant4, has been implemented and subsequently used to optimise settings and possibly an optimized layout for dark matter searches.
5.2.2 Benchmarking of the G4-Beamline simulations

The present status of the G4Beamline model is illustrated in Figure 5.2. The proton beam is injected from the bottom left leaving the P42 beamline and entering the T10 target section followed by a set of collimators. Magnet models have been developed to describe the physical geometries of the yokes and coils according to dimensions given in the SPS Magnets Kit [8].

![G4Beamline model of the K12 beam line serving the NA62 experiment](image)

**Figure 5.2:** G4Beamline model of the K12 beam line serving the NA62 experiment

Approximate descriptions of the magnetic fields including the fields in the iron yokes exist within the HALO software. For this particular study they have been extracted and converted for the use within the G4Beamline model. Examples of the MCB and QNL magnets used in the K12 beam line are shown in Figure 5.3.

![Cross-section of the MCB and QNL magnets and their magnetic field lines](image)

**Figure 5.3:** Cross-section of the MCB and QNL magnets and their magnetic field lines (coils are not drawn).

The G4Beamline model is completed by a simplified geometry of the NA62 experiment. Most detectors, i.e. the four Straw trackers, the CHODs, the Liquid Krypton (LKr) calorimeter and the hadron calorimeters / muon vetoes MUV1 to MUV3, have been implemented as simple planes, scoring the coordinates of passing particles.
The required acceptance cuts as provided by NA62 are applied subsequently in the analysis of the particles scored. Additionally, the big vacuum tank and the twelve large angle vetoes (LAVs) have been included to also simulate the material interactions in the detector region. The full model has been placed in a simplified description of the TCC8 and ECN3 cavern including the concrete walls surrounded by a thick layer of soil.

In order to validate the new G4Beamline model, a set of simulations has been conducted and the results have been compared to existing particle flux estimates as well as to measured data sets from the NA62 collaboration. Both the nominal configuration for NA62 and the proposed NA62-BD beam dump configuration have been considered. All simulation studies are based on the G4Beamline version 3.04 using the default Geant4 physics list FTFP_BERT and a kinetic energy cut-off of 1 GeV/c.

5.2.2.2 Simulation of the nominal NA62 configuration

The initial benchmarking test was performed using the nominal configuration for NA62 using the vertical TAX positions of -107.5 mm and 112.5 mm respectively. The hole of the TAX is located at about y=-110 mm to perform the selection of a 75±0.75 GeV/c momentum bite of the beam, which is vertically displaced by this amount using an achromat surrounding the TAX. The momentum selection is completed by collimator 3, located at a vertical focus downstream of the TAX, for which a vertical gap of 4mm was chosen in the simulations. The primary proton beam was modelled assuming a beam waist at the T10 target with a width of ($\sigma_x, \sigma_y$) = (0.4 mm, 0.3 mm) and a divergence of ($\sigma_x, \sigma_y$) = (0.2 mrad, 0.15 mrad).

The secondary particle beam, created in the interactions of the proton beam with the T10 target, has been tracked through the entire K12 beam line and finally scored at a (virtual) plane located 102 m downstream of the T10 target.

![Figure 5.4: Simulated pion content at 102 meters after the T10 target for the nominal NA62 configuration.](image)
The pion distribution and the momentum spectrum obtained at this location are shown in Figure 5.4. Similar results for pions and kaons were obtained. The beam distribution agrees with the distributions illustrated in the NA62 design report. The central momentum is about 75 GeV/c and validates the description of the magnetic fields in the simulation. The momentum spread is slightly larger than 1%, but could be fine-tuned by adjusting the collimator 3 gap. The total rates of the scored protons, pions and kaons are shown in Table 5.1. A very good agreement of the pion and kaon rates have been obtained, while a slightly enhanced proton rate is observed in the G4Beamline simulation.

<table>
<thead>
<tr>
<th>Fluxes at 102m from target per $1.1 \cdot 10^{12}$ incident protons per s</th>
<th>NA62 Technical Design Report</th>
<th>G4Beamline simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons ($\cdot 10^6$)</td>
<td>173</td>
<td>308</td>
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<tr>
<td>Kaons ($\cdot 10^6$)</td>
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<td>547</td>
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Table 5.1: Comparison of fluxes between the NA62 Technical Design Report and the G4Beamline model at 102m downstream of the T10 target.

5.2.2.3 Simulation of the NA62-BD configuration

After validation of the results in nominal configuration, the main study case of NA62-BD (Beam Dump mode) has been investigated. Since muons are considered as the primary background for the experiment, the following studies focus on their creation and transport. For this case, the T10 beryllium target has been removed and the TAX has been placed in dump mode (140 mm, 140mm). The model of both regions (target and TAX) is illustrated in Figure 5.5.

Figure 5.5: Models of the residual material in the T10 region (left) and the TAX (right)

The green area represents an air volume, which was included to simulate the interactions of the primary proton beam with the residual material after removal of the T10 beryllium target. Furthermore, the titanium secondary emission foils within the TBIU (Target Box Instrumentation Upstream) and the vacuum windows have been implemented. Pions and kaons produced in this region can subsequently decay into muons and lead to a considerable background for dark sector searches in NA62-BD.
The interactions of the primary protons that are dumped in the TAX are taken into account as the second major contribution of background muons within the studies described below.

The simulated proton beam spots at T10 and the TAX are shown in Figure 5.6. While the beam at the T10 target location has a waist with the predefined widths and divergences, the beam size increases at the entrance of the TAX by a factor 10 using the nominal optics of the K12 beamline. A new beam dump located further downstream of the beam line would require the beam to pass cleanly through the holes in the existing TAX and the present widths would be too large for a loss-free passage. For that reason, a change of the quadrupole settings was studied as described in the following section.

The muon simulation is performed using a two-step approach and the contributions arising from the region before the TAX and in the TAX are treated separately. For this purpose, a scoring plane is placed behind the TAX to score all muons reaching this plane. To simulate the muons created before the TAX, a sample of $10^{11}$ protons were launched to interact in the target region and all muons reaching the scoring plane were recorded, while other particles were stopped before interacting with the TAX to reduce the computational effort for this sample. The second contribution (muons from the TAX) was produced by impinging $10^9$ protons and simulating their full interactions with the TAX. For this sample only the muons created in the TAX region were scored.

The combination of both samples with the correct weights allows the representation of the full muon population. The full set of muons scored behind the TAX is shown in Figure 5.7.

The spatial distribution shows a cylindrical symmetry around the proton impact point on the TAX. Due to the tungsten inserts below and above the proton impact point, the rate is reduced at these locations. Most of the muons scored in the plane behind the TAX are produced by interactions within the TAX. The production of higher energetic muons in the TAX is strongly suppressed. Consequently, the number of events for higher momenta is very low. To generate a higher statistics sample for the larger momenta, the scored TAX muon sample has been parametrized analytically. An example is shown in Figure 5.8.
Figure 5.7: Spatial distribution, momentum spectrum and place of creation of the muons scored at z=23.7 m, directly after the TAX.

Figure 5.8: Parametrization of the muons created in the TAX. The left figure shows the horizontal phase space for the momentum slice of 20-30 GeV/c muons. The right figure illustrates the difference in production rates between 10 and 200 GeV/c by four orders of magnitude.

The muons are sorted in 10 GeV/c momentum bins and a two-dimensional Gaussian is fitted respectively for the x-p_x and y-p_y phase spaces to parametrize the distribution. The change of the fit parameters for different longitudinal momentum characterizes the full spectrum. Analytical functions are used to describe the fit parameter dependence and to further extrapolate the muon distribution to higher momenta up to 350 GeV/c. Based on this parametrization a larger statistics sample of positive and negative muons is created and transported through the beam line downstream of the TAX in order to benchmark the G4beamline model and subsequently improve the magnet configuration to suppress the muon background [9].
In collaboration with the NA62 experiment a common benchmarking scenario was chosen to validate the simulation with data already measured in this configuration. For this purpose, all tracks within the acceptance of the NA62-CHOD and with a time-associated hit in the MUV3 are selected. The (reconstructed) coordinates and momenta of these tracks at $z=180$m are compared between measurement and simulation.

Figure 5.9 shows the simulated distributions of positive muons, for which these selection criteria have been applied. As seen, the muons stemming from the target region have a smaller radius and a larger momentum around 75 GeV/c, while the muons created in the TAX have a larger radius and significantly smaller momenta mostly below 50 GeV/c.

![Figure 5.9: Simulated distributions of positive muons at 180 m and within NA62-CHOD acceptance with origin before the TAX (let) and in the TAX (right). The color scale indicates the number of muons per billion POT per bin.](image)

Both distributions have been merged with the correct scaling factors and compared to a measured data sample provide by B. Dobrich and T. Spadaro from the NA62 collaboration.
The results are shown in Figure 5.10 for positive and negative muons. The characteristics of the data are reproduced to a large extent. Both, positive and negative muons contain a large accumulation at larger radii and lower momenta, which originate from the TAX, while the cluster at about $R=200\text{mm}$ and $p=75\text{ GeV/c}$ for positive muons originating from upstream decays can be also seen in the data. In summary, a satisfactory qualitative agreement has been achieved, allowing the pursuit of optimization studies of muon background suppression. To reduce the systematic influence of the quantitative discrepancy (the number of scored tracks in the analysed data sample is about a factor five larger than the simulated muon sample for the same number of POT), the estimated muon rates for different beam line configurations have been compared to the nominal configuration that has been used in earlier beam dump runs.

**Figure 5.10:** Measured distribution of charged tracks (left) and simulated distribution of muons at 180 m and within NA62-CHOD acceptance (right) in beam dump mode. The upper (lower) row represents the positive (negative) charged particles. The colour scale indicates the number of muons per billion POT per bin. The data has been downscaled by a factor five.
5.2.3 Optimisation studies with unmodified layout

Based on the model validated above, studies to further reduce the existing muon flux for the NA62-BD experiment have been conducted. First possibilities to adjust the proton beam spot on the TAX are discussed. Subsequently, optimization of the NA62-BD configuration, still using the existing TAX at its nominal location as proton dump, is discussed. For this purpose, the magnet configuration of the magnets downstream of the TAX is varied to explore the possibilities of a further reduction of the muon background in the NA62-BD setup.

5.2.3.1 Study of the proton beam transport

The primary 400 GeV/c proton beam is transported from the P42 beam line to the T10 target, which is at the beginning of the K12 beam line. The default P42 optics aims for a focus at the T10 target, while the present K12 optics is optimised for the transport of a 75 GeV/c positively charged beam from T10 to the experiment. For the NA62-BD configuration these constraints to the beam optics are not mandatory. Instead, a loss-free transport of the proton beam to the TAX (or a new dump) needs to be guaranteed. The nominal beam size at the TAX location shown in Figure 5.6 does not fulfill this requirement for a new dump location downstream of the TAX, since the holes of the TAX have a diameter of only 10 mm.

To study a new set of quadrupole settings, the descriptions of P42 and K12 have been implemented to the program MAD-X [10], using the nominal quadrupole currents for the P42 beam line with a magnification from T4 to T10 of (0.5,-1) and the nominal settings of the K12 beam line. Subsequently, the currents of the last four quadrupoles of the P42 beam line and the first six quadrupoles of the K12 beam line have been adjusted to reduce the beam spot size at the TAX location and for a possible new dump location at about z=51m accordingly.

Figure 5.11 illustrates the horizontal and vertical beta functions before and after the fitting procedure for the 400 GeV/c proton beam with the assumed dimensions given in the last section. The beam waist, originally at the T10 target location, is moved further downstream to reduce the beam sizes at the TAX location, while simultaneously passing through the copper collimator behind the T10 target.

The simulated beam sizes of the proton beam at the TAX and at a possibly new dump location at z=51m are shown in Figure 5.12. The beam size at the TAX location has been reduced such that more than 3σ could pass through the TAX holes. The transmission of the proton beam to a new location is significantly exceeding 99% using this configuration. This enables the transport of the proton beam through the existing TAX for studies of a possible new beam dump.
5.2.3.2 Definition of the Figure of Merit

The muon rate scored the muon veto detector MUV3 at the end of the beam line has been chosen as figure of merit for the optimization of the magnetic configuration. Figure 5.13 shows the spatial distributions and momentum spectrum for positive and negative muons with the nominal setup used in beam dump runs up to now.

In this setup, muon tracks can be observed in the entire geometrical acceptance of the detector and at all momenta. Furthermore, an increased density of muon tracks can be observed close to the beam pipe. The total muon rate in the simulations amounts to 67 kHz, from which 55 kHz have a momentum above 15 GeV/c, assuming a nominal intensity of $1.1 \cdot 10^{12}$/s.
Figure 5.13: Spatial and momentum distributions of the muons reaching the muon veto MUV3 in the nominal beam dump setup of the K12 beamline before optimization. The left plot shows the number of muon hits per bin normalized to $10^9$ protons injected to the K12 beamline. The right plot shows the simulated muon (red) and antimuon (green) rate vs. momentum, assuming an intensity of $1.1 \cdot 10^{12}$/s.

5.2.3.3 Variation of the achromat magnets around the TAX

Figure 5.14 shows the geometrical arrangement of the four magnets of the first achromat surrounding the TAX. In the present setup, these magnets are powered by four power supplies.

Figure 5.14: Achromat magnets around the TAX

For a possible optimization of the muon suppression, a possible re-cabling of these magnets is investigated. In this setup, the first magnets are turned off in order to transport and dump the proton beam without vertical deflection on the TAX. The two power converters would be consequently available to power the last two magnets after the TAX individually to optimize the muon sweeping. Additionally, the magnets of the second achromat and the quadrupoles downstream of the TAX have been turned off for these studies.
Figure 5.15: Remaining rate w.r.t. the nominal configuration discussed in section 5.2.3 for different magnetic fields of the two magnets after the TAX. The left figure shows the relative change of all momenta, the right figure for $p>15$ GeV/c

Figure 5.15 shows the remaining muon rate for different values of the two magnets. In nominal configuration the two magnets have equal field strengths but opposite polarities. Therefore, the deflections inferred by these two magnets tend to cancel each other and the muon sweeping is significantly reduced. Instead, the operation of these magnets with same polarity is beneficial and allows reducing the muon rate above 15 GeV/c by almost two orders of magnitude. For large field strengths, the low-momentum muons ($p<15$ GeV/c) are strongly deflected in the first magnet and then pass the yokes of the second magnet. The opposite field direction in the yokes deflects them back into the geometrical acceptance of the MUV3 detector and leads to a drastically increased rate.

Figure 5.16: Remaining rate w.r.t. the nominal configuration for positive (green) and negative muons (red) and their sum (black). The left figure shows the relative change of all momenta, the right figure for $p>15$ GeV/c
A more granular variation of the magnetic field of the second bending magnet has been performed to illustrate this effect. For this purpose, the first magnet behind the TAX was set to its maximum field of $B = -1.82$ T. The results are illustrated in Figure 5.16. The total muon flux can be reduced to about 25% using a field strength of -0.3T in the second magnet, while the optimum for muons of $p > 15$ GeV/c is found at the maximum field strength of -1.82T for which the total rate is decreased to below 5%. In the following these two configurations will be referred to as:

- Scenario 1: $B_{1B} = -1.82$T, $B_{1C} = -0.3$T
- Scenario 2: $B_{1B} = -1.82$T, $B_{1C} = -1.82$T

### 5.2.3.4 Variation of the muon sweeping magnets BEND3

In the present configuration three muon sweeping magnets (BEND3) are installed at about z=50 m – 60 m in the K12 beam line. These magnets are MBPL type magnets with a length of 2 m respectively and have a vertical magnetic field. For the nominal NA62 rare kaon decay measurements, the gaps with an aperture of 20 cm are filled with iron slabs, in which a 40 mm diameter, almost field-free bore is drilled. The nominal field strength in the iron is approximately -1.8T. Due to the crucial observed impact of the return yokes, the first two magnets have been varied in series, while the strength of the third magnet was varied individually in the simulations.

![Figure 5.17](image.png)

**Figure 5.17**: Remaining muon rate w.r.t. the nominal configuration for different magnetic fields of the BEND3 magnets in scenario 1 (left) and scenario 2 (right).

Figure 5.17 shows the remaining muon rates scored in MUV3 and obtained in scenario 1 and scenario 2. For scenario 1 the best suppression is observed, when the three sweeping magnets are operated with the same polarity and maximum field. In scenario 2 the rate is dominated by low-momemta muons, which are deflected by the return fields of the last achromat bend. In this case the muon sweeping magnets have no impact on the remaining total muon rate. On the contrary, the spatial distributions significantly change for different configurations. This is illustrated in Figures 5.18. In both scenarios the deflection in the vertical field of the sweeping magnets introduces a horizontal asymmetry in the distributions. For scenario 2 the large contribution of the low-momentum muons is observed as spread points with large weighting factors in the entire detector area.
For the following optimization studies, the magnetic field strengths have been kept at their nominal values of -1.8T.

![Figure 5.18](image)

**Figure 5.18**: Spatial distribution of remaining muons at MUV3 for the field configurations (-2T, -2T), (0T, 0T), (2T, 2T) in scenario 1 (upper row) and scenario 2 (lower row).

5.2.3.5 Variation of the magnetic field of the scraping magnet and a possible replacement using magnetized iron blocks MIBs

A further magnet for muon halo suppression is the so-called scraper magnet located in the centre of the second achromat of the K12 beam line. Due to the large deflections upstream of this magnet, its dimensions are rather small compared to the distances of the muon trajectories from the beam axis at this location. For that reason, a possible replacement by much wider magnetized iron blocks (MIBs) could be considered. To investigate the effect of these MIBs, a specific study, in which the scraper magnet has been replaced by two MIBs similar to the ones used in the M2 beam line, has been conducted. The outer dimensions of these MIBs are 1.8m x 1.9m with a hole of 0.2m x 0.2 m and a length of 1.6 m, respectively. The simulated model is shown in Figure 5.19.

![Figure 5.19](image)

**Figure 5.19**: Scraper magnet (yellow, left) and possible replacement with MIBs (red, right)
Considering first the use of the scraper magnet, the variation of the magnetic field has no significant impact on the remaining muon rate in both scenarios. The total rate remained constant within their fluctuations varying the field strength between hypothetical -2T to 2T. Considering scenario 2, muons below 150 GeV/c are mostly passing beside the scraping magnet, while for momenta above 150 GeV/c the positive muon rate is decreased for more positive fields, while the negative muon rate increases.

A similar effect can be observed using the MIBs instead of the scraper. Figure 5.20 shows the remaining muon rate in scenario 2 for muons above 15 GeV/c. The described field value is taken at x=440 mm and y= 0 mm. Due to the toroidal field configuration of the MIBs, these magnets are well suited to suppress efficiently particles with either positive or negative charge, but not both simultaneously. The minimum total muon rate is even observed for a disabled magnetic field of the MIB magnets.

In conclusion, the main reduction of the muon rate could be achieved by tuning the setup of the first achromat surrounding the existing TAX. For this operation two scenarios have been established, which require a re-cabling of the existing power converters that are currently used for these magnets.

**Figure 5.20:** Remaining rate w.r.t. the nominal configuration for positive (green) and negative muons (red) and their sum (black) in case of the scraper magnet (left) or the replacement by MIBs for p>15 GeV/c in scenario 2.

### 5.2.4 Studies for an optimized layout

A possible long run of the NA62-BD experiment allows considering bigger modifications to the beam line layout. To enhance the acceptance of the BSM searches, the proton dump location could be moved further downstream and thus closer to the fiducial volume of the experiment. One idea is the removal of the first of three muon sweeping magnets of the BEND3 group. A new dump can be mounted at this location, while the two other muon sweeping magnets, that are located directly behind the new dump, can be optimized to reduce the muon background created in the dump. In this location the beam dump would still be located upstream of the separation between the air volumes of the target cavern and the experimental hall itself.
This idea has been implemented and studied in the G4Beamline model. The modifications are shown in Figure 5.21.

**Figure 5.21:** G4Beamline model showing a possible new setup with a new dump. The 10 mm diameter hole of the existing TAX is aligned to the reference axis to allow for the passing of the muon beam.

The bores of the existing TAX have been aligned to allow the passage of the 400 GeV/c beam on a straight reference beam axis up to the new dump location, which is illustrated in red. The quadruple changes required for a loss-free proton transport (see section 5.2.3) have been applied. Furthermore, the three collimators in front of the new dump have been removed from the model. The new proton dump has been modelled as a 3.2 m long massive copper block with a quadratic transversal cross-section of 80x80 cm$^2$.

For this particular configuration the muon background rate has been simulated for different magnetic configurations downstream of the new dump.

### 5.2.4.1 Variation of the muon sweeping magnets BEND3

The largest benefit is expected from the two remaining magnets of the BEND3 group, since they are directly located behind the new dump. In the nominal setup the gap of the BEND3 muon sweeping magnets are filled with iron, which has an almost field-free bore of 40 mm diameter. These iron inserts have been removed to model the BEND3 magnets as regular MBPL magnets with uniform vertical magnetic fields and maximum field strengths of about 1.8 T.

The strengths of both magnets have been varied individually to explore the effect of the return fields in the yokes in the simulation. Figure 5.22 shows the simulated total muon rate for different field configurations of these two magnets.

If these magnets are turned off, the muon rate is increased by almost a factor 60 compared to nominal beam dump setup. An effect from the deflection in the return fields cannot be observed, since these magnets are shorter than the bending magnets used for the first achromat (2 m (MBPL) vs. 3.6 m (MTR)). Thus, the maximum muon suppression is achieved for an operation at maximum field strength.
Figure 5.22: Remaining muon rate w.r.t. the nominal configuration for different magnetic fields of the two remaining BEND3 magnets in the new proton dump scenario.

Nevertheless, the rate in this setup is still significantly enhanced with respect the nominal configuration. The amount of negatively charged muons is more than an order of magnitude larger than the positively charged ones, since the scraper magnet located further downstream is optimized for the suppression of positive muons only. As a consequence, the negatively charged muons deflected in the BEND3 magnets see the toroidal field of the scraper magnet, which deflects them back towards the beam pipe. The resulting spatial distributions of the muons reaching the MUV3 detector are illustrated in Figure 5.23 for three different magnet configurations.

Figure 5.23: Spatial distribution of remaining muons at MUV3 for the field configurations (-2T, -2T), (0T, 0T), (2T, 2T) of the two remaining BEND3 magnets in the new proton dump scenario.
5.2.4.2 Influence of the Scraper magnet

The impact of the aforementioned scraper magnet is discussed below. Now the magnetic field of the BEND3 sweeping magnets has been set to -1.8T, respectively. The momentum spectra of the muons at the MUV3 plane are shown in Figure 5.24 for a variation of the scraper magnetic field strength.

![Figure 5.24: Simulated muon (red) and antimuon (green) rate vs. momentum simulating scraper magnetic field of -2T, 0T and 2T and assuming an proton beam intensity of $1.1 \cdot 10^{12}$/s](image)

In case the scraper is turned off, the spectra of positively and negatively charged muons are almost identical. For positive field strengths, the suppression due to the toroidal field reduces significantly the amount of positive muons. At the same time, the amount of negatively charged muons is enhanced. For negative field strengths, the effect is the opposite. A similar behaviour can be observed for a replacement of the scraper by MIBs as discussed in section 5.2.3.5.

Summing up the muon contributions, the total muon rate is minimized for a disabled scraper magnet. Simultaneously, the accumulations of muon hits at the MUV3 detector plane occurs at larger distances from the beam pipe.

5.2.4.3 Extension of the BEND3 group

As discussed earlier the integrated magnetic field and thus the integrated sweeping strength of the two MBPL magnets is significantly smaller than the potential sweeping strengths of the two MTR magnets behind the existing TAX. To increase the integrated field strength the replacement of one of the QNL magnets by a third MBPL magnet is considered in this section. Figure 5.25 shows the model of the new proton dump and the three MBPL magnets used for this particular study.

The field strengths of all three magnets have been set to the maximum field of -1.8 T and the scraper magnet has been turned off as discussed in the previous section. The spatial distribution and momentum spectra of the simulations with two and three MBPL magnets are compared in Figure 5.26. Due to the introduction of a third magnet, the spatial separation of positive and negative muons and their distance to the beam pipe could be further increased.
Furthermore, the rates of high-momenta muons could be significantly reduced by the addition of a third dipole, while the impact of the return field becomes visible for the low-momenta muons. The latter significantly enhances the total simulated muon background below 5 GeV/c. A full overview of the rates for different momentum ranges is given in the following section.

**Figure 5.25**: New proton dump scenario with a third MBPL magnet added to the remaining two BEND3 magnets after the dump. For this purpose the first QNL magnet has been removed.

### 5.2.5 Summary

Based on a new G4Beamline model, the muon background of the proposed NA62-BD experiment has been extensively studied. During this study five different scenarios have been identified, which are compared and discussed in the following:

- **Scenario 0**: This is the baseline setup of the NA62-BD experiment. The 400 GeV/c proton beam is dumped on the TAX, which is set to “dump mode”. The magnets of the K12 beamline are operated at their nominal configurations used for the currently running NA62 experiment.

- **Scenario 1**: The first two magnets of the first achromat are turned off to impinge the proton beam without vertical offset on the TAX. The main field of the third and fourth magnet (B1B, B1C) are set to -1.82T and -0.3T, respectively. This maximizes the muon suppression considering the entire momentum range. The quadrupoles and the magnets of the second achromat are turned off. The BEND3 magnets and the Scraper are operated at their nominal currents.

- **Scenario 2**: Similar to the Scenario 1, except that the magnets B1B and B1C are set to their maximum field of -1.82T. This minimizes the muon rate for p>15 GeV/c.
Figure 5.26: Simulated muon (red) and antimuon (green) rate vs. momentum (upper row) simulating two (left) vs. three MBPL magnets (right) at their maximum field of -1.8 T and assuming an proton beam intensity of $1.1 \times 10^{12}$/s. The lower row shows the spatial distributions of the scored muons at MUV3 in these scenarios, respectively.

- **Scenario 3:** The quadrupoles of P42 and K12 have been tuned to transfer the proton beam through the bores of the TAX, which are aligned on the central axis. The first BEND3 magnet has been replaced by a 3.2 meter copper dump, to simulate the NA62-BD scenario with a dump closer to the fiducial volume of the experiment. The iron slabs in the remaining BEND3 magnets have been removed, transforming them to regular MBPL magnets available for the muon sweeping after the new dump. The maximum field of -1.8 T has been applied to these magnets. The Scraper magnet is turned off, since a minimal total muon rate has been observed in this scenario.

- **Scenario 4:** Similar to Scenario 3, except that an additional MBPL magnet has been added to the BEND3 magnet to increase the integrated magnetic field and thus the sweeping strengths directly behind the new proton dump. For that purpose, the first QNL magnet behind the new dump location needs to be removed.
Table 5.2 shows the scored muon rates at the MUV3 plane for different momentum ranges and the scenarios described above.

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<td><strong>5.5 (9%)</strong></td>
<td><strong>1.7 (3%)</strong></td>
<td><strong>1.6 (3%)</strong></td>
</tr>
<tr>
<td>3</td>
<td>109.5</td>
<td>97.0</td>
<td>95.6</td>
<td>93.0</td>
<td>89.7</td>
</tr>
<tr>
<td></td>
<td>110.2</td>
<td>102.2</td>
<td>100.9</td>
<td>97.9</td>
<td>94.5</td>
</tr>
<tr>
<td></td>
<td><strong>219.7 (333%)</strong></td>
<td><strong>199.2 (319%)</strong></td>
<td><strong>196.5 (335%)</strong></td>
<td><strong>190.9 (350%)</strong></td>
<td><strong>184.2 (365%)</strong></td>
</tr>
<tr>
<td>4</td>
<td>216.6</td>
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<td>3.2</td>
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<td></td>
<td>187.0</td>
<td>30.4</td>
<td>8.7</td>
<td>7.4</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td><strong>403.6 (611%)</strong></td>
<td><strong>61.0 (98%)</strong></td>
<td><strong>12.7 (22%)</strong></td>
<td><strong>10.9 (20%)</strong></td>
<td><strong>9.9 (20%)</strong></td>
</tr>
</tbody>
</table>

Table 5.2: Remaining muon rate (positive, negative, total) in kHz cored in the MUV3 detector plane for different momentum ranges and the scenarios described in the text.

Using a new cabling situation of the first achromat, the total muon rate could be reduced by a factor four in the entire momentum range as shown by Scenario 1. Large-momentum muons (p > 15 GeV/c) can be further reduced to below 5% of the baseline setup, by operating the two magnets after the first TAX with same polarity and maximum current (Scenario 2). Due to the return fields the rate of low-momenta muons is significantly increased in this scenario. The balance between those contributions needs to be optimized experimentally.

The simulation of the new proton dump replacing the first magnet of the BEND3 group shows a significantly increased muon rate in the studied configuration. In Scenario 3, in which the remaining BEND3 magnets are operated at their maximum field, the total muon rate detected at the MUV3 plane is more than a factor 15 higher than in Scenario 1. Adding a third MBPL dipole to the BEND3 group (Scenario 4) reduces the muon rate for large momenta (p>15 GeV/c) to a similar level as in Scenario 1, but due to the return fields the low-momenta muons are drastically increased. Applying a similar scheme for the existing TAX situation (Scenario 2), the muon rate in this scenario is about a factor 5 smaller than in Scenario 4. In summary, the simulated muon background using the existing TAX as proton dump could be efficiently reduced by a factor four. For the new proton dump location considered in this study, a drastically increased muon rate is expected and the option seems therefore not interesting.
5.3 Studies for KLEVER

5.3.1 Introduction

KLEVER proposes a measurement of the branching ratio of the very rare decay $K_L \rightarrow \pi^0 \nu \nu$, which is a counterpart of the present NA62 measurement of $K^+ \rightarrow \pi^+ \nu \nu$. This decay mode is even more rare (SM prediction $\sim 3 \times 10^{-11}$). Also, as the neutral beam acceptance cannot profit from focusing, the angular acceptance will be smaller than for a charged beam. Consequently, the required proton flux for KLEVER is at least $2 \times 10^{13}$ protons per 4.8 s spill, about a factor 7 higher than for the nominal NA62 beam.

The beam will transport all long-lived or stable neutral particles, including $K_L$ but also $K_S, \Lambda, n$ and $\gamma$’s. A non-zero production angle will reduce the fraction of $\Lambda$’s and neutrons in the beam, relative to the $K_L$ component, but also the $K_L$ rate per proton on target. In addition, a larger production angle will soften the spectra of the particles. For a start of the decay volume at a sizeable distance from the production target ($\sim 100$ m), this implies an increase of the $K_L$ decay rate per produced $K_L$ over the length of the fiducial volume, but a decrease of $K_S$ and $\Lambda$ decays over that same length, as they will more often decay before the start of the fiducial volume.

A first study addresses the optimal production angle, based on FLUKA [11,12] and Geant 4 simulations, starting with benchmarking compared to (sparse) existing data. The baseline target material will be beryllium, but in the future alternative materials could be studied. A benchmark study for the simulation performance and the impact of the production angle for the beam to KLEVER has been completed [13]. High-Z target materials would reduce the $\gamma$ content in the beam (relative to the $K_L$), but suffer from higher local temperature rise. In general, all questions related to the high intensities and their impact on equipment and radiation protection will be addressed in section 5.4.

The production angle must be implemented in the last section of the P42 beam line, which transports the primary proton beam over almost 900 m from the T4 target in TCC2 to the kaon production target T10 in TCC8 (in its present location). The proposal is to have the protons impinging onto the T10 target downward at the required angle (the neutral beam axis being horizontal). This is an also essential factor in reducing the prompt muon flux outside, above and behind the ECN3 cavern.

Finally, the study addresses the design and optimization of the neutral beam itself, in particular the background reduction, collimation and muon sweeping.

5.3.2 Benchmarking of FLUKA simulations

Measuring the particle content emerging from a target is difficult, and requires a very different approach for charged and for neutral particles. Efforts were undertaken at CERN for measuring the charged particle content of the secondary beam driven by 400 GeV/c protons [14] and at Fermilab a neutral beamline was constructed in order to measure the production spectra of several of neutral particles: $\Lambda^0, K_S$ and neutrons [15].
To compare the simulation to reality, the choice has to be made for a thin or a thick target. The thin target allows for direct interpretation of the primary interaction cross section at production, but is not representative for the thick target (400 mm beryllium) foreseen for KLEVER operation. The full-length target introduces two complicating factors: scattering of secondary particles inside the target and additional (tertiary) production. In Figure 5.27, the relation between the thickness of a target and the total (normalized) production of long-lived charged particles is shown, split according to the generation of the parent particle (primary and secondary) and restricting to particles with a production angle less than 10 mrad relative to the incoming primary protons.

For a 400mm long (~1λ) beryllium target, typically around 40% of the particles (excluding particles with momentum less than 1 GeV/c) was not directly generated by the incoming primary proton. Each subsequent generation of particles will naturally carry less momentum, and therefore the produced spectrum is very different from a thin and a thick target. Measurements on thin targets were used to benchmark the FLUKA and Geant simulation codes, which were then used to compute and parameterize a complete set of particle production for thick targets. The former gives confidence that the simulation adequately reflects reality. The latter is the input required by the experiment, combining the effects of particle production with re-scattering and tertiary production, and will be detailed further in the Section 5.3.3.

![Figure 5.27 Origin of positive (left) and negative (right) charged particles as a function of beryllium target thickness](image)

Limited data is available for charged particles at high momenta; at the specific momentum that KLEVER is expected to run at, only the NA20 dataset [14] is available, where reasonable agreement was found for both Geant and FLUKA. The NA20 study includes a parametrization
(to be referred to as the Atherton parametrization), which agrees with the data but will not reflect reality well at low momenta (for which no data was recorded). In Figure 5.28, the Atherton data is shown together with the same distributions sampled from Geant and FLUKA.

Extensive studies have been made of the charged particle production in FLUKA and Geant [16] but for KLEVER the neutral particles are of particular importance. Three data sources were used, recording datasets for $\Lambda^0$, $K_s$ and neutrons over a wide range of secondary momentum and production angles, taken at Fermilab [15, 17, 18]. As before, a full dataset was generated in FLUKA and Geant and analyzed with ROOT to check the agreement with the data. Figure 5.29 shows the curves as recorded after analysis of the FLUKA and Geant data, compared to the available experimental data.

Figure 5.28 Measured data (symbols), Geant simulated data (continuous histogram), FLUKA simulated data (broken histogram) and the Atherton parametrization for charged particles, at 0 and 0.5 GeV/c transverse momentum
The data for $K_s$ shown in Figure 5.29 can be interpreted as a direct benchmark for the production of $K_L$, since for fundamental reasons they are produced at identical rates. Special attention was paid to the $\Lambda^0$, which features as a crucial background for the experiment: if it decays $\Lambda^0 \to n\pi^0$ (BR 0.358) in the sensitive volume and the neutron is not detected, it fakes the signature of the signal decay $K_L \to \pi^0\nu\bar{\nu}$. Finally, the total production of neutrons is of interest because, even with limited detection efficiency, they form a large fraction of the particles detected in the final (small angle) calorimeter, which is located on the beam axis with direct line of sight of the target.

Figure 5.29 Results simulated in FLUKA (circles) and Geant (squares), compared to series of measurements at specific production angles (continuous lines) for $\Lambda^0$ (top left, top right), $K_s$ (bottom left) and neutrons (bottom right)

There are some regions of discrepancy between the simulation and the experimental data, in particular at very low angles for high-momentum neutrons. Additionally, the experimentally
recorded spectrum differs strongly between Geant and FLUKA at low angles and high momenta (where Geant has a peak close to the primary momentum). The experimental data at very low angles disagree with both of the simulations, peaking at significantly higher momentum. As the angles increase, it is found that both simulations predict more neutrons than are observed in the data, which, while not ideal, means that any predicted rates will be conservative estimates for backgrounds for KLEVER. No large disagreements are found between the simulations in Geant and FLUKA.

5.3.3 Conclusions on targeting

The initial proposal for the design of KLEVER, as described in [19], had the protons impinging on the target at an angle of 2.4 mrad, in other words the neutral beam is derived at a production angle of 2.4 mrad. It was found that under these conditions, the rate of background Λ^0 decays (in particular into π^0n) occurring in the fiducial volume of the detector was prohibitive. A solution was found by using a larger production angle, and in parallel opening up the angular acceptance of the neutral beam (from 0.3 mrad to 0.4 mrad) to compensate for the reduced K_L flux per proton at this higher production angle.

The effect of the production angle on the particles emerging from the target was studied extensively. To ease and speed up studying the particle spectra, in particular the impact of decays over the long distance between the target and the detector, a series of fits was made to the produced particle spectra. These were fitted over the full angular and momentum space simultaneously, using the Malensek parametrization, described in [20]. A detailed description of the methods used, as well as the fit parameters extracted from the Geant and FLUKA simulations, can be found in the full note [13]. It was found that this model reasonably describes the simulated production of all hadron species. The use of this parametrization then allows for quick refactoring of the impact of lifetime of the particle (notably in the case of the Λ^0, which in its frame of rest only has a lifetime of 263ps). The change to higher production angle has several different important consequences the total production rate reduces, but also the momentum spectrum changes. The production at the target and the average momentum of lambda and KL are shown in Figure 5.30.

![Figure 5.30](image-url) Production per proton on target (left) and mean momentum (right) of K_L and Λ^0
The impact of the change in production angle is large indeed. The production of $K_L$ drops by a factor 2.6, and the production of lambda drops by a factor 8.3. However, the fraction of $K_L$ that decays inside the fiducial volume actually goes up by a factor 1.6, owing to the smaller decay length at lower momenta combined with the specific long lifetime of the $K_L$ (51ns). The fraction of $\Lambda^0$ decays in the fiducial volume goes down by a factor 48. The net effect of the change in opening angle (0.3 mrad to 0.4 mrad) and production angle (2.4 mrad to 8 mrad) is generating 1.1 times more $K_L$ decays in the fiducial volume and suppressed the number of $\Lambda^0$ decays by a factor 220. With this additional suppression, the amount of background represented by the $\Lambda^0$ is acceptable for the KLEVER measurements. The total number of decays in the fiducial volume, after the change to 8 mrad, is $4.1 \times 10^{-6}$ and $1.32 \times 10^{-10}$ per proton on target, for $K_L$ and $\Lambda^0$ respectively. The remaining suppression required comes from kinematic cuts applied in the detector and has been shown to adequately reduce the number of background decays of the $K_L$ and $\Lambda^0$ [21].

Simultaneously with the studies concerning the production angle, an assessment was made of the impact of the target material. For targets of identical length in terms of nuclear interaction length $\lambda$, no large differences were found in terms of hadronic production. However, there is strong suppression of the photon content of the beam, since higher-Z materials have a significantly smaller conversion and radiation length. With the current rate of high energy photons (>5 GeV) in the beam, it is necessary to put a significant quantity of material directly in the beam as a photon absorber, which then simultaneously adds extra scattering for the incident $K_L$. However, if the choice is made for a higher-Z target, this absorber could be made substantially thinner. Two target materials (lead and copper) were assessed in the same way as the beryllium target benchmarking described above, and it was found that they are similarly well simulated in FLUKA and Geant. It is expected that tungsten would be a more suitable high-Z material than lead because of its superior thermomechanical properties. However, the technical feasibility remains to be studied, as the energy deposit per unit of volume is much higher than in beryllium. The impact of the target material on the thickness of the photon absorber is studied further by means of a full beamline simulation in Section 5.3.5.

5.3.4 P42 modifications

The P42 beam transports primary protons traversing and not interacting in the T4 target to the T10 target, located almost 900 m further downstream. At the end of the present P42 beam three dipoles allow to control the vertical angle of incidence onto the T10 target and therewith the production angle of the secondary beam. However, in the present layout this angle is limited to less than about 3 mrad. The present charged kaon beam for NA62 is operated at 0 production angle and the $K_L$ beam for the NA48 experiment at 2.4 mrad. Both options can thus comfortably be covered with the present layout. The production angle can be controlled by adjusting the fields in the three last dipoles. However, for the KLEVER experiment the required production of 8 mrad implies a downward slope of the incoming beam of 8 mrad with respect to the (horizontal) beam axis of the outgoing kaons. This can be achieved by replacing the last dipole, BEND12 (MCW type with maximum bending strength $BL = 4.63$ Tm) by a stronger MTR magnet with a nominal BL of up to 7.5 Tm.
two preceding MBN magnets (up to 10.8 Tm each) need to be realigned. See Figure 5.31 for the new layout. The second one, BEND11, needs to run at a current higher than the maximum RMS current of 1340 Amps, but for pulsed operation it is well below the allowed maximum for reasonable duty cycles. The optics for proper focusing on T10 is shown in Figure 5.32.

**Figure 5.31:** the layout of the end of the P42 beam with 8 mrad production angle.

**Figure 5.32:** The optics of the last section of the P42 beam line with 8 mrad production and focus at the T10 target with the same magnification as in the old layout and negligible dispersion at the T10 target.
Alternatively, the non-laminated BEND12 magnet can be operated at about 1 kA (well above the nominal maximum current of 820 Amps) and the BEND11 current reduced. The MTR has the same coils and cooling circuits as a MTN magnet (which has only a larger gap, thanks to extra shim plates), which can run at up to 1365 Amps. Therefore there should be no cooling issue. However, at 1 kA the field would be 2.2 Tesla. The magnet group checked that this field can indeed be achieved, albeit at the cost of a slightly degraded field quality. In case even larger production angles would be requested one day, one would have to install an extra dipole upstream of the quadrupole pair preceding BEND10 (i.e. QUAD21) and realign all beam elements between that new dipole and the T10 target.

In Table 5.3 we show the fields and currents for the solution with nominal BL for BEND12, In Table 5.4 for the solution with higher current in BEND12.

<table>
<thead>
<tr>
<th>Bend</th>
<th>Deflection (mrad)</th>
<th>P_t-kick (GeV/c)</th>
<th>BL (T.m)</th>
<th>Magnet type</th>
<th>Current (Amps)</th>
<th>I for NA62 (Amps)</th>
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<tr>
<td>BEND10</td>
<td>4.785</td>
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<td>879.6</td>
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<td>7.396</td>
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<td>1117.4</td>
</tr>
<tr>
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<td>5.472</td>
<td>2.1888</td>
<td>7.30111</td>
<td>MTR</td>
<td>815.1</td>
<td>Was MCW</td>
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Table 5.3: Fields and currents for the solution with nominal BL in BEND12

<table>
<thead>
<tr>
<th>Bend</th>
<th>Deflection (mrad)</th>
<th>P_t-kick (GeV/c)</th>
<th>BL (T.m)</th>
<th>Magnet type</th>
<th>Current (Amps)</th>
<th>I for NA62 (Amps)</th>
</tr>
</thead>
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<tr>
<td>BEND10</td>
<td>5.093</td>
<td>2.0372</td>
<td>6.79542</td>
<td>MBN</td>
<td>936.2</td>
<td>1339.6</td>
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<td>2.6496</td>
<td>8.83819</td>
<td>MBN</td>
<td>1252.9</td>
<td>1117.4</td>
</tr>
<tr>
<td>BEND12</td>
<td>5.936</td>
<td>2.3744</td>
<td>7.9202</td>
<td>MTR</td>
<td>995</td>
<td>BL_{max} 7.5?</td>
</tr>
</tbody>
</table>

Table 5.4: Fields and currents for the solution with BEND12 at almost 1 kA

5.3.5 Neutral beam design

Following the change of production angle to 8 mrad, an optimized design was made for the neutral beamline after the target. This design uses four collimators. The first of these is the TAX (Target Attenuator) collimator (located from about 5.6 m downstream of the target), which serves the dual purpose of absorbing the primary proton beam emerging from the target and initial preselection of the beam particles. Second is the defining collimator, at 40 m distance from the target, which defines the beam acceptance by stopping all particles beyond a certain radius. This generates additional background (in particular at the edge of the aperture), which is removed by a third collimator, the cleaning collimator, located at 80 m from the target. The active final collimator is at the same time a detector, with a LYSO inner ring extending outward from 60mm to 100mm radius and a lead / plastic shashlik calorimeter extending out to a radius of 1m. It serves to define the upstream limit of the fiducial volume, and vetoes all unwanted particles from the upstream region that would otherwise trigger the detector. The current beamline design is shown in Figure 5.33.
It should be noted that with the 8 mrad production angle, the design calls for a calorimeter around 250 m from the target, extending from 130 mm radius outward; this implies that the existing krypton calorimeter (featuring a vacuum pipe of 80 mm radius) will not be suitable for KLEVER.

The decay fiducial region extends from about 130 to 170m from the target. The KLEVER detector consists of a large number of large angle photon vetoes (LAVs), constituting hermetic coverage as viewed from the fiducial region, which reject any decay for which a photon is detected that would not hit the main detectors at the end of the beamline.

At the end of the beamline (about 250m from the target), three calorimeters are placed. The inner small angle calorimeter (SAC) extends out to a radius of 10cm (set by the angular definition of the beam, 0.4 mrad over 250m), covers the phase space with a direct line of sight to the target. The second is referred to as the main electromagnetic calorimeter (MEC), extending out to 125cm radius, which records the signals of the photons that have a sufficiently large opening angle relative to the beam, allowing $\pi^0$ particles that are generated and decay in the fiducial volume to be reconstructed. An intermediate ring-shaped calorimeter (IRC) sits in between the MEC and the SAC to ensure that no particles escape through the gap between the MEC and the SAC. In Figure 5.34, the detector design is shown.
As discussed in the previous section, KLEVER is expected to operate with $2 \times 10^{13}$ protons per spill. Conservatively, the effective spill is taken as 3 seconds (currently the nominal length is 4.8s), leading to an instantaneous rate of $6.67 \times 10^{12}$ Hz of protons on target, thus accounting for some intensity fluctuations. The rate requirement set on the small angle calorimeter (SAC) is 100 MHz of particles, of which about 40 MHz assumed from high-energy photons (> 5 GeV). This design parameter implicitly determines the thickness of the photon absorber to be integrated in between the TAX, see Figure 5.35. A simulation was performed using three different target materials and a photon absorber made of tungsten. For tungsten, the radiation length $X_0$ is about 3.5mm. The effective photon conversion length (for pair creation, referred to as $X_{\text{eff}}$) is $9/7$ times longer, i.e. about 4.5mm. For each target material (beryllium, copper and tungsten) eleven simulations were made, stepping from zero to ten effective conversion lengths of tungsten photon absorber, and the rate of particles passing into the volume occupied by the SAC was recorded. In order to reduce the computational requirements, charged particles were filtered from the beam just after the target. In Figure 5.35, a detail from the FLUKA simulation shows the TAX region of the beamline design for KLEVER, with the photon absorber inset in the center. In Figure 5.36, the rate of photons >5 GeV passing into the SAC is shown for the three target materials, as a function of photon absorber thickness.
The effect of the photon absorber is twofold - it removes high-energy photons from the beam, but also scatters $K_L$. It is found that for the beryllium / copper / tungsten target respectively, a photon absorber of length $7.3 / 5.2 / 3.8 \times X_{\text{eff}}$ (32.9 / 23.3 / 16.9mm tungsten) is needed. This simultaneously degrades the number of $K_L$ passing the final collimator. Using the copper (tungsten) target, 15% (28%) more $K_L$ passes through the hole in the active final collimator.

To assess the effect of the stages of collimation, the momentum (energy) spectrum of three particle species after each collimation stage is shown in Figure 5.37. The spectrum of photons and neutrons is shown in Figure 5.38.
The amorphous photon absorber could be replaced by an oriented crystal converter, which would have an increased photon conversion rate per unit of length. As a result, the length of the absorber can then be reduced and along with the length the impact on the hadron component of the neutral beam. A test of such a crystal converter has been performed in the H2 beam in the North Area in August 2018.

As a final step, several magnetic elements are expected to be part of the beamline. The first of these is an MTR (7.5 Tm bending power) directly after the target station, giving the primary proton beam an additional 5.6 mrad downward angle before being dumped in the TAX at a sufficient distance from the neutral beam. The other purpose of the magnetic sweeping is to sweep away the charged secondary particles. It is expected that the TAX itself also creates additional charged background, which is to be swept by another MTR (7.5 Tm). The defining collimator is to be followed by an MTN magnet (also 7.5 Tm bending power but it has a larger gap to fit the beam). Finally, the cleaning collimator has two MBPL magnets (3.8 Tm bending power each). These magnets serve to sweep out of the main detector acceptance any background produced on the collimators. The final collimator is not followed by a magnet since it is already an active detector which would thus anyway veto particles crossing it. All the magnets quoted here are already part of the K12 beamline for NA62 and can thus be reused.

An important background for the experiment is formed by muons being swept into the acceptance by the magnets, both through the field in their gap and by the return field in the yoke. To this end a simulation of reduced scope was performed to assess the muon flux passing into the AFC and the MEC. A brief test run of the simulation indicated that the majority of the muons are generated from decays occurring in the upstream region before the TAX.

**Figure 5.38** Momentum distribution of gamma’s and neutrons at the various stages of collimation
To reduce computational cost, a cut was implemented in the simulation, removing non-muon particles hitting material, and leaving the photon absorber transparent. This removes the cascade of the primaries in the collimator inside the target station and in the TAX. A computational cost reduction of around a factor 30 was achieved. This allowed for a more detailed exploration of magnet parameter space. It was assumed that the magnets should be placed as close to the collimators as possible. The first (vertical) sweeping magnet serves for dumping the primary beam, and its position is assumed to be fixed. This leaves the magnets after the TAX, defining and cleaning collimators. Of these, the two MBPLs are varied together; since they have no lever arm with respect to each other. Varying both would just lead to partial cancellations and adding complexity without benefits. It was also assumed that the magnets should be run at maximal field, to optimize the removal of unwanted (non-muon) charged components. Three (sets of) magnets remain, and for each of these there are four cardinal rotations, for a total of sixty-four combinations.

To represent all of these in a relatively simple fashion, a vertical and horizontal weight was attributed to each of these magnets, a factor four for the first, a factor two for the second, and a factor one for the final set. Together with an orientation (+1 vertical, 0 horizontal for up, 0 vertical and -1 horizontal for sweeping towards negative x) these weights now form a two-dimensional parameter space, allowing the total muon rates to be plotted on a colour scale. The result, showing the muon rate for all combinations of rotations, in the AFC and in the MEC, can be seen in Figure 5.39.

**Figure 5.39**: Muon background rate in MHz (total for positive and negative) found in the AFC (left) and in the MEC (right), as a function of geometrically weight of the magnets.

These plots are divided into four quadrants; each of which represents an orientation for the sweeping magnet following the TAX, which has the largest weight. It is observed that placing this magnet in a vertical orientation (top and bottom quadrants), has a severe detrimental effect. There is also a local maximum for the far left and right tips of these plots, indicating that placing all the magnets in the same horizontal orientation results in a local maximum.
The minimum is found at the points just left and right of the origin; representing a fully horizontal set of orientations with the magnet after the TAX sweeping in the opposite direction of the two (sets of) magnets following it. The better of these two is then picked on the basis of considerations of radiation protection. In Figure 5.40, the (local) rate of positive and negative muons is shown, for a plane extending to +/-4m horizontally and vertically, placed just before the AFC (at z=119m). For this particular case, the magnet following the TAX sweeps positive particles to positive x, and the remaining magnets to negative x. The size of the AFC is indicated.

**Figure 5.40:** Local muon rate (in MHz) at z=119m, in front of the AFC, for positive muons (left) and negative muons (right). The black circle indicates the coverage of the AFC.

The directionality of these two groups of muons are set by the first (vertically sweeping) magnet just after the target station and that following the TAX. The first is fixed; thus the positive muons acquire a downward orientation, and the negative muons upward. The magnet following the TAX adds a horizontal component to this, in this case sweeping positive particles to positive x. The critical consideration is that the (currently NA62-) control room is located at positive x. As such, out of the two orientations that were found to be optimal earlier, the one that sweeps the muons away from the control room is chosen. After the optimization, the total muon rates found in the AFC and MEC are about 2.5 and 4.9 MHz respectively, with the increase in the latter being mostly attributed to decays between the two.

### 5.4 Intensity limitations and mitigation measures

#### 5.4.1 The existing situation

For NA62 the nominal beam flux on T10 is $3 \times 10^{12}$ ppp. The nominal beam intensity of the 75 GeV/c secondary beam is $2.2 \times 10^9$ ppp. These intensities are quite similar to the nominal primary and secondary beam intensities for the NA48 experiment (last run in 2002). However, in between the approval of NA48 and operation of NA62 the radiation protection rules and guidelines have changed considerably.
In an underground area like ECN3, with a hermetic zone perimeter excluding physically any access with beam on, the secondary beam intensity for NA62 does not pose particular problems. Activation is limited to the region of the final beam dump and only a part of the small tunnel leading towards that dump is locked with a RP veto. However, the primary beam intensity onto the T10 target leads to significant activation around the target, TAX dump collimators and in general to the front end of the K12 beam line. Also, the air around the front end of the beam line gets activated and might escape into the part of ECN3 where NA62 is installed and, via the access shafts, into the control rooms and into the environment. After weeks of running, the air activation in ECN3 would impose moderately long cool-down times before allowing access into ECN3 (~24 hours or more). Therefore, several mitigation measures had to be implemented before the start of NA62 operation.

A double wall with over-pressure inside had to be installed to separate the air volumes of the target zone in TCC8 from the detector zones in the downstream part of the TCC8 cavern and in ECN3. This reduces the waiting time before access to just the time it takes to access anyway. On top of that air locks were installed in the access galleries towards the control rooms on the surface. In addition, it was considered crucial to install massive shielding around the target region in order to restrict air activation mostly to the air volume inside the shielding. However, it was not clear how quickly the activated air could escape into the environment. The initial conservative estimate was that the system would be sufficient for NA62 operating conditions, but with only a small safety margin.

Also, the front-end shielding should help to reduce the prompt muon dose outside ECN3, by stopping pions and kaons before they decay into muons. For KLEVER-like intensities a study was needed.

The beam elements and also the experiment itself are protected against beam excursions by a system called P0-survey. It checks the magnet currents and their references with respect to a surveillance reference and moves one of the TAX to dump position in case of discrepancy. The acquisition of the currents and the closing of the TAX hole may take more than one spill and this may become critical with much higher intensities than now.

Yet another issue is the delivery of sufficient protons onto the T10 target in the presence of other users of the T4 target (H6 and H8 beams) and at the same time high intensities on T2 and T4. The T4 target serves as an attenuator for the P42 beam to T10 but also to produce the H6 and H8 secondary beams. The longer the target, the higher the production rates for H6 and H8, but the stronger the attenuation for the primary proton beam towards T10 and the higher the radiation dose produced around the T4 target. The high rate needed on T10 would suggest a short T4 target head, but even then, a proton crisis could occur. One solution could be a by-pass beam, where the vertical beam size at T4 would be made much larger than the thickness of the target plate. In that case most of the beam would pass by the T4 target unattenuated. As the overall rate is high, the small fraction hitting the target would still be sufficient for H6 and H8.

All the mitigation measures required may lead to non-negligible costs.
5.4.2 Radiation protection aspects and implications on shielding and ventilation

5.4.2.1 Calculated air activation

In order to estimate the air activation for the NA62 operation, FLUKA studies have been conducted in 2011 [22]. It has been assumed that the intensity on the T10 target would be $2 \times 10^{11}$ protons per second with 150 days of NA62 operation per year. For the simulation the radioactive decay has been assumed without any ventilation or air leakage.

It has been found that most of total isotope production stems from particle interactions in zone between target and TAX, which is now enclosed by a concrete shielding (see Figure 5.41).

![Figure 5.41: Hadron fluence per primary particle on T10](image)

At the time, i.e. before the installation of an airlock, complete mixing of air from TCC8 and ECN3 has been assumed (most conservative scenario), as there was no clear indication of the separation by a ventilation curtain. With that assumption, after 1 month of operation and the air extraction speed of 5400 m$^3$/h after beam stop, a waiting time of about 7.5 h would have to be respected to access ECN3 when satisfying the requirement of < 1 $\mu$Sv per hour for permanent occupation (see Figure 5.42).

![Figure 5.42: Effective dose per h stay in TCC8 + ECN3 air after 30 / 150 d of NA62 operation](image)
In order to reduce the waiting time and to avoid any unjustified exposure of personnel entering ECN3, a clear separation of TCC8 and ECN3 air volumes was proposed.

A double wall with over-pressure inside has thus been installed to separate the air volumes of the target zone in TCC8 from the detector zones in the downstream part of TCC8 and in ECN3 (“SAS” in Figure 5.43). This now reduces the waiting time before access to just the time it takes to access anyway. For cost reasons it was decided to not ventilate the air in the target area at all during beam, but to have a flush during 30 minutes after a 30 minutes cooldown period before an access to TCC8. During the access itself, the ventilation will be on. The absence of ventilation during beam has two purposes:

- It keeps the air flow low and maximizes the time for activated air to escape into the environment and by that the most of the short-lived isotopes will have decayed,
- With additional dampers the ducts from the target cavern to the ventilation unit are blocked. This is important as the ventilation units for TCC8 and ECN3 are installed next to each other in the same volume just above TCC8 and in direct connection to it. The (activated) air from the TCC8 unit would otherwise leak into that volume and be taken in by the ECN3 unit and probably lead to air activation into ECN3.

Figure 5.43: Layout of TCC8 / ECN3

On top of that air locks were installed in the access galleries towards the control rooms on the surface to avoid activated air reaching the control rooms.

It was considered crucial to install a massive shielding around the front end of the beam to somewhat restrict air activation to the air volume inside the shielding\(^1\). However, it was not clear how quickly the activated air could escape into the environment. The initial estimate was that the system would be sufficient for NA62 operating conditions, but with a conservatively expected very small safety margin (could even be of the order of only 50%).

\(^1\) Also, the front-end shielding may help to reduce the prompt muon dose outside ECN3, by stopping pions and kaons before they decay into muons. For KLEVER-like intensities a separate study is needed because of very different conditions in both the primary and secondary beams.
5.4.2.2 Calculated environmental impact of radioactive air

Studies have been conducted in 2011 [23] in order to calculate the impact of the air activation in the cavern on the environment outside of the cavern. This has been performed with the goal of dose minimization and facility optimization (ALARA), having a dose objective of <10 \( \mu \text{Sv/y} \) for members of the public. To remain safely below dose objective annual releases of short-lived radioactive gases shall not exceed several TBq per facility. It has been assumed that there is a complete mixing of air from TCC8 and ECN3 (most conservative scenario), no delay of releases and that there are \( 2.6 \times 10^{18} \) protons on target per year (\( 2 \times 10^{11} \text{ p/s, 150 days per year} \)).

The result of the study was the calculated total annual production of short-lived radioactive gases of 59 TBq in TCC8 and 4.2 GBq in ECN3. Hence, this led to the conclusions that the air leakage from TCC8 to ECN3 must be avoided and releases must be delayed by >0.5 h. This would reduce the environmental impact from TCC8 by a factor ten to 6 TBq, which would still contain 99% contribution of short-lived isotopes after half an hour. It has been also required that two ventilation monitoring stations are installed (TCC8 and ECN3 outlets). All these recommendations have been implemented before the start of the NA62 physics data-taking,

5.4.2.3 Measured releases of radioactive air from TCC8

The simulations described above have been cross-examined with the help of the usual continuous RP monitoring measurements performed in 2017. The measurement has been performed with a gas flushing delay of 0.5 h or longer. Please note that the air from the ECN3 (including TCC8 downstream of the airlock) is constantly released, whereas the air from the target zone only during access (with 30’ purge after a 30’ waiting time). The measured activity level of the short-lived gases has been only 0.2 TBq, so only 3% with respect to the impact studies. This discrepancy may be explained by several reasons.

a) There was no continuous irradiation immediately before the air release measurement. There is quite some time between production at the target and the measurements in the ventilation since the particles need to drift to the location of the monitors. During Machine Development sessions and Technical Stops, short-lived particles will decay. A delay of ~9 hours until access after a beam stop would explain the differences.

b) The total number of protons on target (\( 7.7 \times 10^{17} \)) has been in 2017 by factor 3.4 lower than assumed in the simulation.

c) There are uncertainties in the simulations, mainly due to the geometry.

d) For long-lived radionuclides a direct comparison of estimated and measured values is difficult due to abovementioned points as well as physicochemical state of radionuclides. This is due to the fact that the HEPA filters retain those radionuclides, which attach to aerosols (e.g. Be, Mg, Al, Si, P, S, K).

e) Additional radionuclides (e.g. Co56) may be present, which are originating from air and dust particles activation.

f) There might be outgassing of H\(^3\) and humidity in the air.

The measured total committed effective dose to members of the public in 2017 was 0.05 \( \mu \text{Sv} \).
Consequently, the proposed increase of the beam intensity by a factor of \( \sim 7 \) to \( 2 \times 10^{13} \) protons on target per second, needed for the operation of KLEVER experiment, should lead to an effective dose, which from the air activation point of view is clearly below the environmental dose objective of \(< 10 \, \mu\text{Sv/y}\), but the effect of air activation in the tunnel remains to be seen. Studies of the air activation in the tunnels and/or other areas are discussed in the following sections.

**5.4.2.4 Measured air flow**

Now that NA62 has taken data for some time with beam intensities of around 60% of the nominal one, first measurements of the radiation levels in and around TCC8 and ECN3 have become possible. In particular these address also the air streams to other areas. The monitoring station, measuring air activation outside ECN3, shows rates which are much below the ones initially expected from simulation (see previous sections). One of the possible reasons for this, as stated above, is that the air flow inside the TCC8 cavern would be very different from what has been assumed in the estimates. Therefore, with the help of the EN-CV group, air flow measurements have been done inside several locations inside the cavern.

The possible sources of the air circulation have been assumed to be the air flow from the overpressure air lock in TCC8 as well as the access gallery to TCC8, especially in case of the atmospheric pressure change. Representative locations at which measurements have been made were selected and are shown in Figure 5.44.

![Figure 5.44: Layout of the TDC85 and TCC8 tunnels with the locations of the airflow measurements indicated by yellow ellipses.](image)

<table>
<thead>
<tr>
<th>Location 1</th>
<th>Location 2</th>
<th>Location 3</th>
</tr>
</thead>
<tbody>
<tr>
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<td>03-04-18 14:00</td>
</tr>
<tr>
<td><strong>End date and time</strong></td>
<td>04-04-18 15:11</td>
<td>04-04-18 00:14</td>
</tr>
<tr>
<td><strong>Average air flow (m/s)</strong></td>
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<td>0</td>
</tr>
<tr>
<td><strong>Std dev. of air flow (m/s)</strong></td>
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<td>0.011</td>
</tr>
<tr>
<td><strong>Min. air flow (m/s)</strong></td>
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<td>0</td>
</tr>
<tr>
<td><strong>Max air flow (m/s)</strong></td>
<td>0.1</td>
<td>0.87</td>
</tr>
</tbody>
</table>

**Table 5.5:** Air flow measurement results in the TDC85 and TCC8 tunnels.
To perform the measurements a new piece of equipment has been acquired – an omni-directional probe SOM-900 from KIMO Instruments. It has a measurement range of 0.0 m/s to 5.0 m/s with the resolution of 0.01 m/s across the full measurement range. The results of the measurements are displayed in Table 5.5.

These results demonstrate a very minor to non-existing air flow, hence refuting the hypothesis that the air flow is a contributing factor to the activation levels in the cavern being lower than initially expected with conservative assumptions and before implementation of mitigation measures. It has to be considered, however, that the measurements were performed only during a short period of time, which did not cover very significant changes in the outside atmospheric pressure. A measurement of air pressure has been performed at COMPASS experiment. It is located in a neighbouring hall in which the air pressure is assumed to be equal to the atmospheric pressure outside.

According to this measurement during the period of the air flow data taking the atmospheric pressure at CERN was varying between approximately 950 and 955 mbar (see Figure 5.45). The outside temperature has varied during the same period by 7.85°C.

![Figure 5.45: Measured atmospheric pressure during the time of the air flow measurement in the cavern.](image)

Also, the measurement has been performed with beam switched off, to avoid the activation of the probe, and hence the potential air flow related to the magnet temperature variation could not be measured. However, this effect is expected to be very small as the magnets are water cooled.
5.4.2.5 Calculated prompt dose

Another limitation is the prompt dose above ECN3, presumably dominated by muons. In case of NA62 the secondary beam is produced at 0 production angle, i.e. the protons impinge horizontally on the production target. Pions and kaons are transported horizontally over almost 25 m before they are dumped in the XTAX dump collimators and a large number of muons will be produced there. These muons contribute to the prompt dose above the cavern, while the main share of the dose comprises neutrons.

The dose rate above the cavern has been calculated with the FLUKA software in 2011 [22]. The calculation has been performed for an average beam intensity of $2 \times 10^{11}$ protons per second. Also, standard soil composition and a very conservative estimate of density 1.2 g/cm$^3$ (clay) have been assumed, since at the time no measurements for the local chemical composition and density of the soil were available. According to old civil engineering hand-drawings the soil thickness was modelled with 5 m above P42, 9 m above TCC8 and 11.6 m above ECN3 (see Figure 5.46).

![Figure 5.46: Dose rates above TCC8](image)

The results of the simulation are presented in Figure 5.47. The highest expected dose rates on the surface above TCC8 is in the order of 6-7 µSv/h. Assuming 150 days of NA62 operation per year, 6 µSv/h would lead to an annual dose of 22 mSv. However, it has to be underlined that the soil density used in the study is very conservative. With a more realistic (but still conservative compared to 2.3 g/cm$^3$ measured recently by CENF [24]) assumption of the density to be 1.9 g/cm$^3$ the expected hadron fluence behind 5 m soil is only in the order of 45 µSv per year, so lower by a factor of ~30.

The beam loss scenarios in publicly accessible areas have been studied as well (green-field and bridge above TDC85), those are, however, too conservative as no critical beam line elements could cause a high muon fluence into these areas.

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In order to confirm the expectation that the dose rate with a more realistic soil density assumption is sufficiently reduced, a simulation was performed for the region surrounding the target, implementing the KLEVER beamline elements and detectors within the TCC8 and ECN3 caverns. For the purposes of this simulation, the new 4 mm diameter KLEVER target was placed in the current T10 target shielding with minor modifications to the internal target station collimator to allow for the passage of the primary beam. The target castle was followed by a vertical MTR sweeping magnet, with the TAX placed after that. The elements following the target castle are surrounded on the side and top by 80cm of iron shielding, followed by 80cm of concrete. An overview of the KLEVER target region is shown in Figure 5.48.

**Figure 5.47:** Dose rates above TCC8 along beam axis

**Figure 5.48:** The KLEVER target region.
In the region near the target, three critical points are considered in particular. The first is the rate directly above the ground shield, directly over the target. The second is the road running parallel to the TCC8 cavern, providing access to the current NA62 control room. The final point is the building leading to the access shaft and tunnel leading into TCC8 from the surface, PP851. For these points, the dose from neutrons is used, since at these large angles relative to the target, muons do not play a major role, and other particles are not sufficiently penetrating. For the purpose of this simulation, the soil density was assumed to be 1.9 g/cm$^3$.

The dose rate along the beamline (averaged over $x=-0.5$ to $x=+0.5$ m) is shown in Figure 5.49. Additionally, two transversal cuts are shown in Figure 5.50; one at the access shaft to TCC8 (averaged over $z=\ldots$ to $z=\ldots$, and one where the radiation peaks (averaged over $z=1$ m to $z=2$ m).

**Figure 5.49**: YZ-projection (over $x=-0.5$ to $x=+0.5$ m) showing equivalent dose rate due to neutrons in the KLEVER upstream region, expressed in $\mu$Sv/h. The maximum rate at ground level is observed to be about 0.07 $\mu$Sv/h.

**Figure 5.50**: XY-projections over $z=1$ m to $z=2$ m (left) and showing the TCC8 access shaft, here averaged over $z=-12.1$ m to $z=-11.1$ m) showing equivalent dose rates due to neutrons. The maximum rate observed at the road is 0.2 $\mu$Sv/h, the maximum rate at ground level in the TCC8 access building is about 20 $\mu$Sv/h.
It was found that the rates observed over the target region and at the access road to the control room are acceptable, about 0.07 μSv/h and about 0.2 μSv/h respectively. The rate found at ground level in the access building to TCC8 is too high, and extra mitigation measures must be implemented. The beam steering onto the target at 8 mrad downward angle will account for part of this; and further shielding must be placed as necessary.

Finally, a study is in preparation concerning the dose rate due to muons at ground level near the end of ECN3. Initial results indicate that while dose rates in this region could be significant, they are of a level that can probably be addressed with a series of targeted shielding solutions. The above prompt dose studies are still preliminary and remain to be validated by the radiation protection group.

5.4.2.6 Measured prompt dose

For the purpose of the reports on environmental monitoring several measurements with help of ionization chambers and REM counters have been performed at the locations close to the border of the free access area (see Figure 5.51). According to the reports, the environmental monitoring around TCC8 / ECN3 always remained below dose limits for public areas (<1 mSv/y). The monitor SMS816 is located above the transfer lines to ECN3 and EHN2 and has measured an integrated dose of 0.27 mSv in 2017. The particles contributing to the dose are to approx. 50% electromagnetic particles (particularly muons) and to other ~50% neutrons. The highest dose rates have been measured by the monitors SMS823 (down-beam of EHN2) and SMS824 due to the beam to COMPASS experiment. The measured dose was close to 1 mSv/y limit, hence an additional measurement campaign is currently under planning.

5.4.3 Impact on equipment, protection measures

The neutral kaons for the KLEVER experiment are to be produced by the interaction of the proton beam with the target T10. After passing the collimator used for the control of the transverse beam size and a dipole magnet, the beam is collimated by the target attenuator (TAX) of the K12 beamline, where a large share of beam’s intensity is deposited (see Figure 5.52).
Figure 5.51: Stray radiation monitoring stations

Figure 5.52: The layout of the T10 target and the following beamline elements (collimator, magnet, TAX) of the K12 beamline, as implemented in the FLUKA simulation.
A requirement for the KLEVER operation is that the deployed target and TAX can deal with the power deposited by the KLEVER proton beam intensity without material damage and without deformation of their physical shapes. In this section the studies on the material survival of the T10 target and the K12 TAX are presented. For the simulations it has been assumed that the beam is extracted at a uniform intensity over a period of 4.8 seconds with a 16.8 seconds repetition rate.

### 5.4.3.1 Survival of T10 target

The target is mounted on the target station displayed in Figure 5.53.

![Figure 5.53: Scheme of the T10 target and the target station.](image)

The T10 target currently used for NA62 operation consists of four beryllium rods of 2 mm diameter and 100 mm length. This layout and material have been assumed in the simulation for KLEVER as well. The diameter of target material rods planned for KLEVER is actually larger (4 mm in the current design), but the results of the simulation for the heat deposition are not assumed to differ a lot if this change would be considered. The rods are held in place by 25 μm-thick aluminum sheets with 20 mm radius (see Figure 5.54). The mechanical coupling between rods and sheets has some play. Cooling of the system is performed via an external fan with a power of 600 Nm³/h, which ventilates the complete target box.
Figure 5.54: The geometrical model of the T10 target consisting of beryllium rods and their mounting, consisting of aluminum sheets and flanges around them.

The energy deposition in the target has been simulated with help of the FLUKA and ANSYS software codes. The beam parameters of the incoming beam have been imported from the MADX and G4Beamline simulations of the beam optics proposed for the KLEVER beamline. The transverse beam size at the target location is assumed to be $\sigma_x = \sigma_y = 0.4$ mm. The largest share of the beam energy is deposited in the target itself. The energy deposition in the aluminum sheets has been considered in the simulation, but is comparably low due to the small thickness of the aluminum sheets. The energy deposition in the flanges is not included in the model, since these are at radially sufficient distance from the beam.

In general, the thermal expansion of the material along the beam can cause internal stresses, leading to the deformation of the material. However, due to the geometry of the rods being long cylinders (along the beam direction) with a small radius, the beam energy is deposited almost uniformly inside them. Hence, the thermal stresses can be neglected in this simulation.

The following investigation focuses on the steady state temperature of the beryllium rods, in which the power deposited by the beam is equal to the power lost. The energy loss by the beryllium rods is assumed to occur in the two ways. Firstly, there is a heat deposition to air. The heat transfer coefficient (HTC) has been conservatively assumed to be 10 W/m²°C. The heat transfer to the aluminium foils has been assumed to be negligible due to the low physical contact surface between the beryllium rods and the aluminium sheets and due to the mechanical play between the rods and the sheets. Secondly, the rods are losing the energy by black body radiation.

The result of the energy deposition simulation is displayed in Figure 5.55.

Figure 5.55: Temperature in the beryllium rods in the steady state operation of KLEVER. The maximal temperature inside each rod is displayed above its depiction.
As the figure shows, the temperature of the beryllium rods reaches values of up to 769°C. The maximal acceptable operational temperature of beryllium is 830°C, so it can be assumed that the target itself would survive the KLEVER operation. However, such high temperatures can become problematic for the aluminum sheets in contact with beryllium rods, since the material properties of aluminum start changing at the temperatures above 100°C.

In order to address this problem, there are two aspects of the current design that need to be upgraded: the mounting of the rods, currently consisting of 25-µm-thick aluminum sheets, and the cooling system.

The aluminum sheets can be substituted by thicker and more solid supports, made of a material with higher temperature resistance. The assumptions made for selecting a suitable material are that

- as little mounting structure material as possible is hit by the beam,
- the material does not produce too high amounts of long-lived isotopes when exposed to the high-intensity proton beam for a prolonged period of time,
- the geometry of the mounting is rotation invariant (or close to rotation invariant) around the beam axis.

A more efficient cooling can be implemented by the use of pressurized air. This would strongly increase the HTC, and the steady state temperature of the rods is very sensitive to this parameter. The target mounting developed for CNGS experiment can be used as an initial approach for the new design. In this mounting the HTC between the cooling air and the target is higher than at T10 by several orders of magnitude.

5.4.3.2 Survival of K12 TAX

The K12 TAX is a large collimator, currently located 24 meters downstream of the T10 target. For the KLEVER experiment this distance is planned to be reduced to 5.5 m. The primary goal of the TAX is to absorb the part of the beam not propagated into the direction of the detector, including the primary protons not interacting in the target. The TAX currently used for the NA62 experiment consists of two separately movable tables with 4 metal shielding blocks each, which are mounted on two separate cooling plates (see Figure 5.56). The movement of the tables is vertical and the cooling plates are located beneath the collimator blocks. The first two blocks of the first module are made of copper, the following six blocks are made of cast iron.

The primary beam for the KLEVER experiment is designed to propagate through the target at a downward angle of 8 mrad and, after further downward deflection by 5.6 mrad, hit the TAX wall. In order to simulate the energy deposition in the TAX, a FLUKA model has been created (see Figure 5.57).
Figure 5.56: Layout of the K12 TAX collimator currently used for the NA62 experiment.

Figure 5.57: The geometrical models of the first TAX module composed of four blocks (left) and its cooling plate (right).
This model includes the geometry of the TAX modules consisting of four blocks mounted on a water-cooled cooling plate. The result of the energy deposition per unit volume is displayed in Figure 5.58. The total energy deposited in each of the four blocks of the first TAX module is presented in Table 5.6.

![Image](image_url)

**Figure 5.58:** The deposition of energy of one pulse for KLEVER beam in the two modules of the current K12 TAX design.

<table>
<thead>
<tr>
<th>TAX 024</th>
<th>Target IN</th>
</tr>
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<tr>
<td>BLOCK</td>
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</tr>
<tr>
<td>1</td>
<td>120.7</td>
</tr>
<tr>
<td>2</td>
<td>79.7</td>
</tr>
<tr>
<td>3</td>
<td>25.1</td>
</tr>
<tr>
<td>4</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**Table 5.6:** Total energy deposited by one KLEVER beam pulse into each of the four blocks of the first TAX module.

Once the energy deposition in the TAX is known, the potential threats to the TAX structure survival have been analyzed with help of the ANSYS software. Two scenarios have been examined:

a) the beam pulse hitting the cold TAX and hence creating thermal stress due to the expansion of the parts, in which the energy is initially deposited, and

b) the steady state scenario, in which the energy deposited by the repeated beam pulses is in equilibrium with the energy transported away by the cooling water.
The result of the simulation of the first pulse of the beam hitting a room temperature target are shown in Figure 5.59. The figure displays the temperature distribution inside the four blocks of the first TAX module. The maximal temperatures in the individual blocks are displayed above them.

![Temperature distribution](image)

**Figure 5.59:** Temperature distribution within the first module of the TAX at the extraction end of one 4.8 s KLEVER pulse.

This result shows that even after one pulse the temperatures reached in the first copper block of TAX are above 160°C. The operational temperature of the pure copper is not supposed to exceed 100°C, after which a significant creep of the material can occur. Also, the stresses in the material would exceed 250 MPa, which is the limit for copper at room temperature, above which it does not maintain its physical structure.

In the steady state, in which the power deposited by the beam is equal to the power carried off by the cooling water in the plate below the TAX, the temperatures rise to even higher values (see Figure 5.60).
Figure 5.60: The temperature distribution in the four blocks and the cooling plate of the first TAX module during the steady state operation of KLEVER. The maximal temperature reached in each of the four blocks is displayed above the block.

Here, the temperatures of both of the first two copper blocks are far above the allowed limit of 100°C. Also, the temperatures in the third and fourth blocks rise significantly. It is interesting to see that the maximal temperature in the third block is higher than in the second one. The reason for it is the fact that the last two blocks are composed of cast iron, and since their thermal conductivity is lower than the one of copper, the thermal energy is not transported as efficiently downwards towards the cooling plates as in the copper blocks. Iron undergoes some structural modifications at 727°C. So, while these temperatures are not explicitly reached, the margin for the first iron block is relatively small. E.g. in case of the prolonged operation of the beam without the target, in which almost entire beam power is deposited in the TAX, the critical temperature of iron would be reached.

These simulations show that significant modifications of the TAX design are needed in order to accommodate the beam intensity required by the KLEVER experiment. Some of the proposed modifications are listed below:

1) Putting the cooling plate closer to the point of impact of the beam. This modification is particularly important for the temperatures during steady state operation, since it would make the cooling more efficient.

2) A first block (thickness to be defined) could be composed of aluminium. Aluminium has a lower density than Cu, and hence the power of the beam would be deposited in it more gradually over a longer distance along the beam. This would reduce the total energy deposited in the first TAX block.
Currently, there are tungsten inserts in the collimator aperture, which could get extremely hot in case of operation with KLEVER intensity. Tungsten itself has a very high operational temperature limit. However, the high temperature of the inserts could cause thermal deformation/warping of the collimator holes and of the adjoined material of the collimator block. The solution could be to remove the tungsten inserts from the first block and eventually also the second one.

Replace pure Cu by a CuCrZr alloy. CuCrZr is widely adopted at CERN in a variety of beam-intercepting devices. It maintains its mechanical properties (yield strength and ultimate tensile strength) at high temperatures much better than the pure copper. This would increase the temperature limit figure from 100°C to much higher values.

5) Improved cooling plate design. A cooling plate can include a longer cooling coil. This would increase the surface area and hence improve the heat dissipation.

6) The previous point could be brought to an extreme by integrating the cooling coil into the TAX modules.

5.5 Possible implementation of NA60++ and DIRAC++

5.5.1 Stand-alone installation of other experiments in ECN3

NA60++ is proposed as a successor to the NA60 program with studies of di-lepton production and open charm. It will use primary ion beams over a range of energies, with minimum beam intensities of $10^7$ ions per second, i.e. $5 \times 10^7$ per 5 second spill. In addition, they request some periods of a few weeks each with proton beams at $5 \times 10^8$ protons per second. The footprint of the experiment proposed is 8x8x10 m$^3$, see Figure 5.61, but if needed a narrower version could be prepared.

![Proposed layout of the NA60++ detector.](image)
DIRAC++ is a follow-up on the by now dismantled DIRAC experiment in the T8 beam line in the East Area. The experiment would profit from higher production rates of $\pi\pi$, $\pi K$ and $K\pi$ atoms at the SPS and proposes a new experiment with a proton beam intensity of $1.5 \times 10^{12}$ protons per spill. The initially proposed layout needed 10 m width for the detector plus space for passages and access to the equipment. A reduced version of the detector itself fits within 6 m. See Figure 5.62.

![Figure 5.62: Schematic layout of a possible DIRAC++ detector](image)

Both experiments can in principle be installed in the ECN3 cavern, or in a new underground cavern. It would even be possible to install them both simultaneously in ECN3, offset longitudinally and laterally, see Figure 5.63 for a schematic view. It would require the replacement of the K12 beam line by a new proton transport line and to reestablish the end of the P41 and the H10 line, more or less as used by the NA50 and NA60 experiments in the past. The lateral space situation would be manageable and the proton beam time would have to be shared. The design of the proton lines should not pose particular problems. However, there will be an associated installation cost and the availability of power converters and magnets must be verified, following a detailed design. Because of the lower intensities, massive front-end shielding can be avoided. The beam design for the beam to NA60++ could be a straight copy of the original H10 beam. The optics is shown in Figure 5.64. The K12 beam will be completely new and a possible optics is shown in Figure 5.65.

The intensity requirement of NA60++ should not pose major problems. However, DIRAC++ would induce activation of equipment and of the air in the ECN3 cavern. This would have impact on the cooldown time before access and impose ventilation in the ECN3 cavern. However, the DIRAC++ target is almost transparent and no loss points along the beam are foreseen. The beam can be dumped in a properly designed reentrant dump, like was the case for the DIRAC experiment in the East Area. Details remain to be studied.
Figure 5.63: Schematic view of possible implementation of NA60++ (H10) and NA60++ (K12’)

Figure 5.64: The optics as proposed for NA60++, copied from the old H10 beam design
5.5.2 Cohabitation with NA62 or KLEVER

However, the situation changes drastically in case either NA62 or KLEVER is installed in ECN3. The NA62 experiment (and almost certainly the same for KLEVER) occupies the full length of TCC8+ECN3, with even a 12 m extension to find a correct place for the final beam dump. On top of that the experiment is quite wide and in many places lateral space has to remain free for interventions or repairs that require opening the vacuum tank, the RICH or any detector under the electronics room above the last part of the main detectors. All along the vacuum tank the 12 LAV modules may need interventions, which implies that they have to be moved out towards the Jura side. Insufficient lateral width next to NA62 is available, see Figure 5.66.

Apart from these mechanical constraints, there are many questions related to radiation protection constraints. The front-end shielding is considered vital to contain the air activation and the leakage of activated air into the environment, as well as the dose rates above and behind the ECN3 cavern. In Figure 5.67 we show a top view of the layout of the present NA62 installation, including the front-end shielding. The red line indicates the central beam axis of the (now dismantled) H10 beam line towards the old NA50 and NA60 experiments. The incompatibility with the front-end shielding is evident. The dismantling of the front-end shielding would significantly increase the dose above ECN3, as pions from the target and TAX region can travel further and therefore have more time to decay into muons. The air mixing will be much faster and the fear is that much more activated air will escape into the environment.
Figure 5.66: the available space next to NA62.

Figure 5.67: Schematic view of the K12 beam front end. The red line indicates the beam passage of the now dismantled H10 beam to NA60.

Also, the double wall separating the air volumes between TCC8 and ECN3 would have to be modified to provide another hole for the H10 beam passage, which complicates dismantling (for interventions) and makes air tightness more critical. The old T8 target, still highly radioactive must be dismantled and removed from its storage location in the cavern.

In case NA62 and KLEVER would be dismantled, some of the K12 beam elements (e.g. magnets) could be reused to cover part of the needs for the new charged beam lines. In case NA62 stays in place, more magnets have to be found or procured. Finally, the proton beam time for NA60++ or DIRAC++ would have to be shared with NA62 or KLEVER.
References for Chapter 5

2. M.Moulson et al., Perspectives for an experiment to measure BR(KL→πνν) at the CERN SPS, https://indico.cern.ch/event/523655/contributions/2246866/.
5. E.Cortina et al. (the NA62 collaboration), The beam and detector of the NA62 experiment at CERN, 2017 JINST 12 P05025.
6. C.Iselin, HALO a computer program to calculate muon halo, CERN 74-17, Laboratory II, Experimental Areas Group, 29 August 1974.
19. Prospects for an experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) at the CERN SPS. M. Moulson for the NA62-KLEVER project, arXiv 1611.04864, 2016.
21. KLEVER: An experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) at the CERN SPS. M. Moulson for the KLEVER project, arXiv 1812.01896, 2018.
22. C.Theis, Requirements for the TCC8/ECN3 ventilation system due to air activation, EDMS 1176875.
23. P.Vojtyla, Environmental constraints on a ventilation system of NA62, EDMS 1163163.
6. Interfaces to other Working Groups

The Conventional Beams Working Group has profited from input and discussions with other (non-)PBC working groups. Proton delivery is a key issue and there is a significant potential impact from BDF operation due to a reduction of the duty cycle for North Area operation. This has been studied by the proton performance working group [1] within the PBC Accelerators and Facilities study [2] and in synergy with the Beam Dump Facility working group (BDF) [3]. At a lower level, proton delivery is affected by AWAKE [4,5], HiRadMat [6] and LHC operation.

Another restriction comes from high radiation doses at critical locations such as extraction septa, splitters and primary targets. In this domain we profit from excellent progress made by the SPS Losses and Activation Working Group, SLAWG [7].

6.1 Machine performance study group

A common feature of most of the proposals received is the request for higher intensities. Even though requests for primary proton fluxes have not always been precisely formulated (sometimes related to non-availability of detailed beam designs), one may make educated guesses based on previous experience.

In this document we assume a flat top of 4.8 seconds. In case of a longer flat top the proton intensities required to saturate the DAQ rates of the experiments scale linearly with flat top length. The proton performance study suggests a flat top of 6.1 seconds. This would reduce somewhat the impact of BDF on the duty cycle. For the NA fixed target experiments it would allow higher rates per spill for most experiments and lower pile-up and background rates for KLEVER.

For physics experiments in H2 and H4 (NA61, NA63, NA64), typical proton intensities per spill are 40 $10^{11}$ ppp or lower. However, NA64 is increasing its rate capability and, if pile-up can be handled adequately, one may anticipate a request for 60 $10^{11}$ ppp on T2 during their running periods.

The T4 intensity is driven by the requirements for the beams to ECN3. The test beams and R&D experiments in H6 and H8 have modest intensity requirements in most cases and they are typically also limited by radiation protection restrictions. For NA62 and NA62-BD the nominal intensity on the T10 target is 30 $10^{11}$ ppp. With a BE target head in T4 of 100 mm length, this would correspond to between 60 and 70 $10^{11}$ ppp on T4. However, KLEVER aims at taking at least 2 $10^{13}$ ppp on T10. In the present configuration this would require at least 4 $10^{13}$ ppp on the T4 target. As this exceeds any realistic possibility in the foreseeable future, a T4-by-pass option has been proposed in chapter 5. About 25% of the decrease between T4 and T10 is due to attenuation and another 25% due to collimation in the TAX (long tails of the beam). In case 80% of the beam by-passes the target, only 20% would be attenuated by the T4 head. Therefore 0.75x80% + 0.5x20% = 70% of the T4 flux would reach the T10 target. In that case ~280 $10^{11}$ ppp would be needed on T4. A further reduction of the T4 flux would
require reduction or elimination of beam tails or an even shorter target in T4 or a higher fraction bypassing the target.

With a 40 mm target (still ok for H6 and H8) the $280 \times 10^{11}$ ppp would reduce to about $250 \times 10^{11}$ ppp and with 90% bypassing the target to $275 \times 10^{11}$ ppp. If all tails could be removed, the required T4 flux would be between 210 and $220 \times 10^{11}$ ppp.

For T6 the maximum flux is $150 \times 10^{11}$ ppp for a muon program and $\sim 100 \times 10^{11}$ ppp for a hadron beam program with a classical hadron beam. For the RF separated beam not proton flux requirement can be given at this stage.

These numbers are summarized in Table 6.1.

<table>
<thead>
<tr>
<th>Target</th>
<th>Min. flux</th>
<th>Max. Flux</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>$40 \times 10^{11}$</td>
<td>$60 \times 10^{11}$</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>$60 \times 10^{11}$</td>
<td>$280 \times 10^{11}$</td>
<td>Could be reduced to 220 if no more tails at all</td>
</tr>
<tr>
<td>T6</td>
<td>$100 \times 10^{11}$</td>
<td>$150 \times 10^{11}$</td>
<td>For COMPASS today</td>
</tr>
<tr>
<td>Total</td>
<td>$200 \times 10^{11}$</td>
<td>$490 \times 10^{11}$</td>
<td>Could be reduced to 410 or $420 \times 10^{11}$ ppp if no tails</td>
</tr>
</tbody>
</table>

**Table 6.1: Anticipated future proton requests**

Without BDF operation, the fixed target experiments would assume a 4.8 s flat top at the highest possible repetition rate. The Proton Performance group has assumed a flat top of 4.9 seconds. In case of simultaneous operation of SHiP in the same super-cycle, the Fixed Target cycles are alternated with typically 4 BDF cycles of 7.2 seconds each, as shown in Figure 6.1 (here with CNGS cycles instead of BDF cycles). Depending on the number of BDF cycles, the proton flux sharing per year between BDF and the North Area physics is shown in Figure 6.2.

**Figure 6.1:** an example of running the NA fixed target program and CNGS cycles in the same super-cycle. BDF cycles will be similar to CNGS cycles, but with a 1 second slow extraction instead of fast extraction.
Figure 6.2: A possible scenario for proton sharing between SHiP/BDF and the North Area physics program, with a spill duration of 4.9 seconds for the North Area operation.

In this scenario, the FT program would receive about $10^{19}$ pot per year. This corresponds to the request of KLEVER alone. The overall FT request is probably larger by a factor 1.5. Therefore, some prioritization may be necessary in the proton flux attribution in this case.

The scale on the right-hand side of Figure 6.2 indicates the number of 4.9 seconds spills per year. With an increasing number of spills for BDF, the duty cycle and hence the number of spills available for the existing North Area fixed target program decreases by up to about a factor of three. This is still the favoured scenario in case the available proton flux is the main limiting factor and concern. In case the request of proton flux extracted to the North Area would be lower than $4 \cdot 10^{13}$ protons per spill, a solution (also adopted during CNGS operation) would be to lengthen the flat top and increase the proton flux per spill proportionally. The extra time on flat top increases the spill duration significantly and only has a marginal effect on the overall super-cycle length. As an extreme example, the spill length could be doubled, at a slight reduction of the overall proton flux available but with much increased duty cycle. In Figure 6.3 the proton sharing between BDF and North Area physics is shown for this scenario. The number of spills is still the same, but can also be expressed in ‘equivalent spills’ (periods of 4.9 seconds with beam): the number of equivalent spills is doubled and much closer to the 2018 number. Details of these schemes are described very nicely in the report of the Proton Performance working group [8].
Figure 6.3: A possible scenario for proton sharing between SHiP/BDF and the North Area physics program, with a spill duration of 9.7 seconds for the North Area operation

6.2 The SPS Losses and Activation Working Group (SLAWG)

The SLAWG working group in the Accelerator and Technical sector is working on reduction of losses and activation at the extraction, splitting and beam transfer to the North Area. The total requirement is well above the maximum considered feasible today. They have proposed very promising solutions to reduce the losses at extraction and in the proton transfer to the North Area. These efforts will continue after LS2.

6.3 Beam Dump Facility Working Group

The Beam Dump Facility (BDF) working group studies the feasibility, design and costs of a new very-high-intensity facility in the North Area, triggered by the SHiP proposal. SHiP requests several short (~1-second-long) slow-extracted spills of $4 \times 10^{13}$ ppp each. This beam would be transported via the TT20 transfer line up to the first splitter. Instead of splitting off the beam towards the T6 target, the polarity of this magnet would be inverted during BDF cycles and the full beam sent to the BDF facility. In this approach the losses at the splitter should be avoided, but the intensity requirement remains at the limit of what is presently considered feasible, even after a number of improvements. These improvements are studied by the proton performance and SLAWG working groups. The sharing of protons with the fixed target program has been discussed in section 6.1. Ultimately the scientific committees and Research Board will decide the proton sharing in the CERN complex.
6.4 AWAKE WG

AWAKE operation will have another, presumably modest, impact on the duty cycle for the other SPS users. This will have to be understood better in synergy with the AWAKE working group and the future evolution of the AWAKE program.

References for Chapter 6

7. Future studies and Outlook

In the preceding chapters we have shown many results relevant for the evaluation of the long list of proposals submitted to the Conventional Beams Working Group. However, the list was too long to complete all the studies within the time available. In the following sections we indicate what needs to be studied further in the coming years, in case the proposals will be approved and implemented.

7.1 RF separated beam design

The design study for the RF separated beam, as requested by the QCD facility initiated by COMPASS, could only start very late. So far, a first possible optics has been designed, which will allow starting studies of the RF aspects. Further iterations between the RF system design and the beam optics will then allow a detailed study of the dump of unwanted particles and subsequently estimates of the beam acceptance. Finally, absolute rates and the beam composition need to be calculated. In case the results are positive, finally a detailed design, integration and estimation of the cost must be prepared. This whole study could take one or even several years.

7.2 Detailed implementation of KLEVER

A conceptual design of the KLEVER beam has been presented in Chapter 5. Technical implementation details remain to be studied. This includes design of components (inserts in collimators), integration studies, ventilation and possible air containment upgrades, final RP assessment, more refined costing. Also, the infrastructure for the installation of the experiment and the vacuum system need to be studied in great detail.

7.3 Intensity increase in ECN3

The adaptation of critical equipment, such as targets and TAX, must be optimized and designed in detail. Most likely some R&D work and prototyping will be necessary, in particular concerning the target and TAX block materials. Based on the final layout, shielding and ventilation systems must be defined in full detail. In case RP requires a ventilation in ECN3, also the link to the access system must be defined and implemented.

7.4 Detailed design of a H10-like beam

The design of an H10-like beam towards an experiment on the Jura side of the hall was inspired by the now dismantled H10 beam for NA60. A refined cost estimate has to be prepared, as all the infrastructure for the old H10 beam has been dismantled at the time of construction of NA62. A new charged beam line in place of the NA62 location has been designed from scratch. A first layout and optics design is described in chapter 5. Adequate beam instrumentation, RP monitoring and beam loss monitoring must be implemented for a DIRAC++ experiment. Also here a detailed cost estimate remains to be prepared, based on integration studies.
7.5 Beam studies and machine developments needed

Proton delivery is critical, in particular for operation of KLEVER simultaneously with other users in EHN1 and EHN2. Detailed studies have been performed in the framework of the proton production study, of the BDF project and in the SLAWG working group. A key issue is the reduction of the losses at the extraction septa, at the North Area splitters and along the primary proton transfer line TT20 in general. Recently many improvements were proposed and tested with remarkable successes. A prominent example is the use of a crystal diffuser, which affects the steering of the extracted beam to the North Area. More MD studies are required for many aspects. These studies are usually of common interest to all the groups mentioned before.

7.6 Safety

Safety is a very important aspect of every new experiment or facility. Safety aspects can only be studied in detail when one starts to work towards real implementation. For any new experiment and facility Safety Files have to be written.

7.7 Cost estimates

For the time being the cost estimates are rough indications. Final costing requires detailed studies, including integration studies and in some cases further R&D. This will require resources which were not available so far. The present cost estimates are restricted to order of magnitude classes and listed in Table 7.1. The cost categories are defined as follows:

- C1: Up to a few 100 kCHF
- C2: From few 100 KCHF to 1 or 2 MCHF
- C3: From 1 or 2 MCHF to 5 to 10 MCHF
- C4: Of the order of ≥ 10 MCHF

<table>
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<tr>
<th>Building</th>
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<th>Proposal</th>
<th>Upgrades foreseen</th>
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<td>NA64-e</td>
<td>New permanent location</td>
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<td>QCD fac.</td>
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<td>C4</td>
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<tr>
<td>K12</td>
<td>DIRAC++</td>
<td>New K12 beam line</td>
<td>C3</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1: Rough cost estimates for beam and infrastructure, related to the proposals treated by the Conventional Beams working group
7.8 Summary

In almost all cases the studies give good indications of the feasibility and implications of the beams and infrastructure modifications associated with the proposed experiments. However, in view of the implementation, more time and resources are required. These resources include budget for R&D studies, as well as industrial manpower (e.g. for integration studies) and staff, fellows and/or project associates.
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