Requirements and constraints of EIR design option on WP2, WP4, WP5: Milestone M3.3

Seryi, Andrei (University of Oxford (GB)) et al.

28 April 2017

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

The research leading to this document is part of the Future Circular Collider Study

The electronic version of this FCC Publication is available on the CERN Document Server at the following URL:
<http://cds.cern.ch/record/2261545>
Abstract:
In this document we will review the design task of the WP3 (EIR), namely EIR optics (task 1), Machine Detector Interface (task 2), and Beam-Beam effects (task 3) and map the related challenges into the constraints and requirements for the other work packages – arc design (WP2), cryogenic beam vacuum (WP4) and magnet design (WP5).
We will also include a section on how the EIR WP3 constraints and design optimization issues may affect the design of the Experimental Detector (this is outside the scope of EuroCirCol, but is one of the key activity area of FCC-hh community design efforts).
The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. EuroCirCol began in June 2015 and will run for 4 years. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

Delivery Slip

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>Partner</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authored by</td>
<td>Andrei Seryi</td>
<td>Oxford/JAI</td>
<td>26/04/17</td>
</tr>
<tr>
<td>Edited by</td>
<td>Julie Hadre, Johannes Gutleber</td>
<td>CERN</td>
<td>28/04/17</td>
</tr>
<tr>
<td>Reviewed by</td>
<td>Michael Benedikt, Daniel Schulte</td>
<td>CERN</td>
<td>26/04/17</td>
</tr>
<tr>
<td>Approved by</td>
<td>EuroCirCol Coordination Committee</td>
<td></td>
<td>28/04/17</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

1. **EIR EFFECTS ON ARCS (WP3 ON WP2)** ................................................................. 4  
   1.1. EIR AND FF DESIGN AND LENGTH ................................................................. 4  
   1.2. CRAB CAVITY SPECS .................................................................................... 4  
   1.3. DYNAMIC APERTURE STUDIES ................................................................. 5  
   1.4. BEAM-BEAM EFFECTS ON BEAM DYNAMICS ......................................... 6  
   1.5. TRIPLET AND COLLIMATION ..................................................................... 7  

2. **EIR EFFECTS ON VACUUM (WP3 ON WP4)** ...................................................... 8  
   2.1. EIR OPTICS AND VACUUM IN EIR ............................................................ 8  

3. **EIR EFFECTS ON MAGNETS (WP3 ON WP5)** .................................................. 9  
   3.1. EIR OPTICS AND TRIPLET SURVIVAL ..................................................... 9  
   3.1.1. Alternative optics ....................................................................................... 9  
   3.2. EIR OPTICS AND SEPARATION DIPOLES ............................................... 11  

4. **EIR EFFECTS ON DETECTOR** .......................................................................... 12  
   4.1. EIR PERFORMANCE REACH ...................................................................... 12  
   4.2. “EL STAR” AND DETECTOR ....................................................................... 12  
   4.3. PROTON CROSS-TALK ............................................................................. 12  
   4.4. BACKGROUND FROM MUONS ................................................................... 15  
   4.4.1. Simulations ............................................................................................. 16  
   4.5. BACKGROUND FROM PHOTONS ............................................................. 17  

5. **LOW LUMINOSITY EXPERIMENTS** .................................................................... 20  
   5.1. OPTICS ...................................................................................................... 20  
   5.2. MINIMUM TRIPLET APERTURE .................................................................. 20  
   5.3. MAGNETS .................................................................................................. 20  

6. **CONCLUSIONS** .............................................................................................. 22  

7. **REFERENCES** ............................................................................................... 23  

8. **ANNEX GLOSSARY** ....................................................................................... 24
1. EIR EFFECTS ON ARCS (WP3 ON WP2)

1.1. EIR AND FF DESIGN AND LENGTH

Two versions of the FF EIR optics are presently under detailed investigation – the baseline optics with the longer triplet described in the following paragraph and the so-called flat optics with somewhat shorter triplet discussed thereafter.

Studies of earlier IR versions suggested that L* has little influence on the minimum beta* which is mainly determined by the length of the final focus triplet. In the present baseline optics the current baseline IR features an L* of 45 m, a value determined by requirements of the detector design. The final focus triplet has a total length of 137 m. It is made up of two quadrupoles of 15 m length for Q1 and Q3 each, while Q2 consists of four 13.2 m long submagnets with 2 m spacing in between. Between Q1 and Q2 as well as Q2 and Q3 a 7 m drift space is left to accommodate orbit correctors, BPMs and vacuum equipment. To match the large beta functions at the end of the triplet to the arcs, the matching section needed to be lengthened, leading to a total straight section length of 1500 m. The possibility of reducing the length to the foreseen 1400 m is currently under study. If the IR cannot be shortened to 1400 m, the additional length will have to be compensated with shorter arcs, increasing the required dipole field strength (thus affecting other work-packages – arcs WP2 and magnet WP5). Experiences from the matching process suggest that the main obstacle is matching the dispersion from the separation and recombination dipoles and phase advance needed for the spurious dispersion correction at the same time. Consequently, an ATS or partial ATS scheme could be beneficial as it allows for a dispersion beating and possibly a beta beating that is corrected in the matching section of the adjacent IRs. Furthermore the chromatic properties of the ATS scheme give hope that beta* can be decreased below the “ultimate” beta* of 0.3 m while keeping the sextupole strengths in the arcs feasible.

Simultaneously, an alternative shorter triplet design has been drawn up using a dedicated optimisation code. The triplet consists of seven identical 15 m sub-magnets – Q1 and Q3 are each made of two sub-magnets, whilst Q2 is made of three. The three quadrupole groups have slightly different shielding and currents. Like the baseline, this triplet was designed for a 45 m L* and the spacing between sub-magnets and quadrupole groups are 2 m and 7 m respectively, however, varying the spacing has shown that longer drifts would not have a negative effect on the aperture. A beta* below 0.3 m would require some compromises in collimation or shielding, but the triplet can also be used for a flat 0.2 m by 1 m beta* optics. Moreover, preliminary studies have shown that this triplet is compatible with a 1400 m length.

1.2. CRAB CAVITY SPECS

A local crabbing scheme is foreseen. Due to leakage of the deflection into the arcs, correct specifications can only be obtained when the lattice is integrated into the full ring, several iterations might be required. For the IR lattice currently integrated in the ring (L*=45 m, total length 1500 m), a crab cavity voltage of 10.4 MV is necessary to accomplish full crabbing in one plane at beta*=0.3 m. The goal was set to reach full crabbing at beta* = 0.1 m in one plane. By scaling with the crossing angle, the required crab cavity voltage was determined to be around 18 MV. With technology foreseen in the HL-LHC design report, 1 MV/m can be achieved. This figure includes cryostats, connections, space for the cavities of the opposing beam, etc. Thus 20 m of space have been allocated to the crab cavities between the recombination dipole D2 and the first quadrupole of the matching section Q4. Should the integrated optics or the change in optics for a shorter IR call for more voltage, it is possible to move D2 or Q4 by a few meters. Limits can arise from the aperture need in D2 and flexibility of the matching section. In the case of even smaller beta* partial crabbing can be considered. In the current scenario, crossing angle gymnastics for radiation mitigation will require a hardware exchange of the crab cavities. A crab kissing scheme is not foreseen.
1.3. DYNAMIC APERTURE STUDIES

To ensure that at collision the DA is dominated by the errors in the triplet the DA due to main dipole field quality must be above 30σ. First evaluation of DA at collision due to first table of main dipole multipole errors gives a minimum DA of 10σ, mostly due to the high systematic b3 component. The same correction strategy applied in LHC using spool pieces attached to each main dipole with 3 times the field gradient of LHC ones are able to fully correct up to 6 units of systematic b3. Therefore, a first tolerance on the systematic b3 component has been set to 3 units, as illustrated in Figure 1.

\[ \text{Figure 1: Dynamic Aperture (DA) in number of}\ \sigma\ \text{of the beam as a function of the phase space angles explored for the collision energy of 50 TeV and errors in the main dipoles.} \]

Separate dynamic aperture studies have also been done to study the impact of the errors of the inner triplet. For these studies 60 different realisations (seeds) of the errors in the inner triplet have been considered. Several corrections are also used for the tracking studies: a chromatic and tune correction with the sextupoles and trim quadrupoles along the ring respectively, correction of the horizontal crossing in IRA and vertical crossing in IRG, correction of the spurious dispersion generated from the crossing angle, and finally a coupling correction. In order to correct the spurious dispersion two different methods have been proposed: the LHC-like and the SSC-like correction.

The best result for the LHC-like correction was obtained using a chromatic correction excluding the sextupoles located in the orbit offset around IRG, the minimum dynamic aperture for all 60 seeds was of 1.9σ. On the other hand the SSC-like correction used a chromatic correction using all sextupoles obtaining a slightly better minimum dynamic aperture of 2.3σ.

In order to increase the minimum dynamic aperture non-linear correctors have been added to the lattice to compensate for the errors in the inner triplet. These correctors were installed after the inner triplet (next to Q3) on either side of the IR and with similar lengths as the ones considered for the HL-LHC lattice. The strengths of the non-linear correctors are chosen to minimize the corresponding resonance driving terms. Figure 2 presents the minimum dynamic aperture with respect to the non-linear correctors used, all performed with the LHC-like spurious dispersion. The benefits of including non-linear correctors are clear, increasing the minimum dynamic aperture up to 10.1σ with the use of a3, b3, a4, b4 and b6 correctors.
1.4. BEAM-BEAM EFFECTS ON BEAM DYNAMICS

Dynamic aperture (DA) studies have been performed for different machine configurations. The newest FCC optics and lattice model as described in Section 1.3 has been studied together with the beam-beam effects. For the studies only two Interaction Points (IPs) have been evaluated. Assuming an alternating horizontal and vertical crossing scheme to profit of the passive compensation of the long-range tune and chromaticity shifts the DA of $6\sigma$ is ensured for a crossing angle of 170 $\mu$rad resulting in a separation of 14.5 $\sigma$ at the first long-range encounter as shown in Figure 3. These results confirm the baseline scenario choices but highlights the fact that no margins are left for the negative effects of multipolar errors, Landau octupoles spread, and high chromaticity operation and for the two low luminosity experiments recently added to the baseline.

The two low luminosity experiments should be designed to stay in the shadow of the mains, this could be granted by defining that luminosity should be levelled by separation, to reduce the effect of the head-on collisions, and by increasing the long-range separations (larger $\beta^*$ of larger crossing angles) to values above 28 $\sigma$. Detailed studies are needed to quantify the impact of such experiments on the dynamics and performances together with the final separations.
Round and flat optics are still under study since a first evaluation of the two optics confirms the need for a roughly 35% larger normalized separation for the flat optic respect to the round despite the correction of the tunes shifts due to the broken passive compensation.

1.5. TRIPLET AND COLLIMATION

The long triplet of the baseline IR option was chosen to allow for large quadrupole apertures in order to accommodate enough shielding to protect the magnets from collision debris. The resulting apertures are 190 mm inner coil diameter in Q1 and 240 mm in Q2 and Q3. With the baseline shielding thickness of 15 mm, the large apertures of the triplet quadrupoles allow for significant margin to the “ultimate” beta* of 0.3 m, leaving 38 sigma beam stay clear. Two uses for these margins are considered: it is possible to minimize beta* below 0.1 m and still have enough beam stay clear compatible with the current collimation constraints. Alternatively, the shielding thickness can be increased from 15 mm up to 48 mm. In that case beta* can still be reduced to about 0.2 m with 15σ beam stay clear. Note that these figures do not include mechanical tolerances.

Other potential aperture bottlenecks are the recombination dipole D2 that requires large apertures but also has significant cross talk, as well as the dispersion suppressor region that can become the aperture bottleneck at injection energy as it features the same magnets as the arcs but also larger beta functions to allow enough flexibility for matching the optics.

The possibility of correcting the chromaticity for beta* below 0.3m needs to be studied.
2. **EIR EFFECTS ON VACUUM (WP3 ON WP4)**

2.1. **EIR OPTICS AND VACUUM IN EIR**

In the triplet region, 2 m of drift space are left between the submagnets of Q1, Q2 and Q3 to connect the cryostats. The possibility to install vacuum equipment in these drifts has not yet been addressed, but is limited as shielding needs to be installed in the interconnects. Furthermore, these drifts need to be kept as short as possible. Currently three locations are foreseen to house vacuum equipment: a space of 2 m between TAS and Q1 that also must include the end of the cryostat of Q1. Furthermore 7 m of space between Q1 and Q2 as well as Q2 and Q3 are reserved for orbit correctors, BPMs and vacuum equipment. The required length for the BPMs will have a significant impact on the space left. Additionally 20m of space are currently available between Q3 and D1 but the required length for higher order multipole correctors has yet to be determined. In the section between D2, crab cavities and Q4 some margins have been left but a final statement can only be made after the shorter IR has been fully integrated in the ring. The drifts between the triplet quadrupoles in the alternative triplet are equivalent to the ones in the baseline with the only difference being D1 moved 7 m away from Q3 to be consistent with the 7 m spacing.
3. **EIR EFFECTS ON MAGNETS (WP3 ON WP5)**

3.1. **EIR OPTICS AND TRIPLET SURVIVAL**

The main interaction region layout, considered for energy deposition simulations, is characterised by an L* value of 45 m, which enables enough space for detector installation and maintenance, and by 50% longer magnets with respect to previous cases. Q1 and Q3 have a length of almost 31 m, while Q2A and Q2B of 26 m. A constant tungsten shielding of 15 mm has been put all along the triplet with tentative gaps in the interconnects. Both vertical and horizontal crossing has been considered with a half crossing angle of 89 µrad.

The considerable increase of the triplet magnet lengths leads to a decrease of the magnet gradients and a consequent increase of the coil apertures to 205 mm in Q1 and 248 mm in Q2 and Q3. The larger aperture has a positive impact on the expected radiation load on the triplet. The maximum peak power density on the magnet coils reaches 2.5 mWcm$^{-3}$ (2 mWcm$^{-3}$) for vertical crossing (horizontal crossing), significantly below the expected quench limit. After an integrated luminosity of 5 ab$^{-1}$, the maximum peak dose in the coils is at the end of Q1 and it is equal to 42 MGy and 33 MGy, for vertical and horizontal crossing respectively. This is 45% lower than what was obtained for the L*=36 m case with the same shielding thickness, thanks to the more than doubled magnet coil aperture. As mentioned in Section 1.1, these magnets are too long and they need to be split to reach values of about 15 m. In addition to this, a minimum gap of 2 m needs to be considered between them. Numbers will be updated with the final layout.

The azimuthal position of the dose peaks is very well localised, reflecting in Q1 the crossing angle direction. This feature can be exploited by changing the crossing plane and the vertical angle polarity during the run, in order to share the maximum impact among different mid plane positions. This would imply hardware changes for the crab-cavities. Assuming to run 50% of the time in vertical crossing (25% with an upward angle and 25% with a downward angle) and 50% in horizontal crossing, the maximum peak dose is reduced to 25 MGy for both high luminosity insertions. Considering the present limit of 30 MGy, the triplet could survive a long luminosity run.

As an exploratory study towards a sustainable integrated luminosity of 20-30 ab$^{-1}$, the shielding inside the triplet magnets has been increased to 55 mm thickness. With this amount of shielding the beam stay clear is reduced to 15.5 σ at a minimum β* of 0.2 m. While this is still lower than the “ultimate” parameter, it considerably limits the luminosity that the long triplet could offer beyond that. The resulting peak doses are reduced by a factor of 10, compared to the 15 mm thick shielding case. Therefore, if the available aperture offered by the length increase is used for shielding, the triplet could already survive the entire integrated luminosity, while offering some limited margin in the value of β*

or beam stay clear.

Finally, when splitting the first quadrupole, the apertures and gradients of the different components can be optimized in order to distribute the radiation load longitudinally and reduce the maximum peak dose value at its end.

3.1.1. **Alternative optics**

Apart from the length and strength of the magnets, the optics choice influences the energy deposition by two main facts: the crossing angle and the maximum beta. The larger the crossing angle, the higher the dose received by the magnet coils. On the other hand, the maximum beta limits the absorber thickness and therefore the energy deposited in the coil. A flat optics with an increased beta* in the crossing plane can afford a smaller crossing angle for the same normalized separation and therefore the dose can be reduced.

The advantages of a flat optics are also a breakdown of the beta functions between Q1 and Q2 and Q3. As Q1 shows a reduced beam size, it can afford more shielding than Q2 and Q3. This shielding reduced
the dose not only in the coils in Q1, but also in Q2 and Q3 as it shadows the particle debris from the IP. Figure 4 shows the Twiss functions for the alternative flat optics.

![Twiss functions for alternative flat optics](image)

*Figure 4: Flat optics for betax* = 1.0, betay* = 0.2.*

![Maximum dose in MGy per 10 inverse attobarn](image)

*Figure 5: Maximum dose in MGy per 10 inverse attobarn in the alternative flat optics.*

The maximum dose is shown in Figure 5.
3.2. EIR OPTICS AND SEPARATION DIPOLES

As a general requirement, the D1 should have similar aperture and shielding as the inner triplet magnets in order to be protected by radiation. Dedicated studies will be needed, which will consider both NC and SC options as presently discussed by the project team.
4. **EIR EFFECTS ON DETECTOR**

4.1. **EIR PERFORMANCE REACH**

The “ultimate” beta* of 0.3m has been reached in the baseline IR design and leaves significant margin in beam stay clear even if a very thick shielding option is chosen (see above). Options beyond the “ultimate” parameters include the thick shielding and beta* = 0.2 m leaving just enough beam stay clear or decreasing beta* below 0.1m. From the detector point of view, the pile-up of 1000 events per crossing in the nominal “ultimate” option represents a great challenge. The 5 ns option preferred by the experiments on the other hand has a challenging normalized emittance goal. Thus the significant margins in terms of beta* can be used as leverage to keep the goal for integrated luminosity realistic. Dynamic aperture and chromaticity correction for beta* below 0.3m have to be studied yet.

The alternative triplet can comfortably reach a beta* of 0.3 m with shielding comparable to the thick shielding of the baseline. It also has enough beam stay clear in the triplet at beta* of 0.2 m. As mentioned in section 1 the triplet can also be used for a 1 m by 0.2 m beta* flat optics – this offers several advantages even though the initial luminosity is considerably lower. Simulations that take into account particle burn off show that the theoretical beam-beam total tune shift is always below the upper limit of 0.03 for the ultimate case. Therefore, mitigations such as artificial emittance blow up are not needed. This implies that the emittance damping can be beneficial for the instantaneous luminosity that decays more slowly than for the round optics. This shows a small reduction in integrated luminosity (as opposed to the initial one), but it shows a much more stable production rate with a reduced peak luminosity. However a detailed study with larger normalized separations, required from beam-beam dynamic aperture studies, will be performed to have direct comparison between the two optics cases in terms of luminosity performances.

4.2. **“EL STAR” AND DETECTOR**

The L* of 45m was chosen to comply with the needs of the detector design presented at the FCC week 2016. After the forward spectrometer dipole was dropped from the baseline detector design, the remaining space was used to mitigate the back-scattering from the TAS in the detector and for space for opening the detector. For the alternative detector design, the forward spectrometer is still present but significantly shorter. The potential impact on L*, especially in the light of the thicker shielding wall, has not been discussed yet. A shorter L* would reduce the peak beta functions in the triplet, reducing chromaticity, and potentially making integration of a shorter IR easier. A reduced chromaticity would also require less or shorter sextupoles in the arcs, leaving more space for dipoles and hence potentially increasing the maximum beam energy.

4.3. **PROTON CROSS-TALK**

With the 100 TeV c.m. proton-proton collisions at the FCC-hh, experimental cross-talk is a possible issue. We have investigated elastic and inelastic protons transported through the beam pipe using PTC and MERLIN. The result of the overall study will have implications for experiments and potentially the collimator structure in the machine.

Using an L* of 45 m, and β* of 0.3 m with vertical crossing and a normalised emittance of 2.2 μm, we generate particles at IPA and study particle flow to IPB, as representative of IPG to IPH. The upgraded
version of DPMJET-III in FLUKA is used to generate proton-proton collision events at the FCC-hh c.m. energy. As shown in Figure 6 protons have a large energy range when exiting the IP.

![Figure 6: Energy range of protons having undergone collision at 100 TeV c.m. leaving IPA with crossing on.](image)

For inelastic protons (those with greater than 0.01% energy loss in collision) propagating forward of the IP, the highest losses occur in the inner triplet, and separation and recombination dipoles D1 and D2, which is consistent with findings from the FLUKA team [1]. A loss rate of order $1 \times 10^9$ protons per second was estimated at the start of the arc post IPA for ultimate parameters; this highlights the need for mitigation of losses in this region, as detailed in section 3.

Losses in the long straight section are shown in terms of proton energy in Figure 7. From this it is clear that only higher energy particles will reach the dispersion suppressor (DS) and arc. Protection at loss locations prior to the arc should be considered as not all inelastic protons exiting the IP after collision will be absorbed by the TAS.

![Figure 7: Energy of lost particles at their loss position in the long straight section, where $s=0$ is IPA.](image)
The protons reaching the dispersion suppressor region are of concern, as they are of high energy and may be lost in superconducting magnets, as shown in Figure 8, where the DS region begins at around $s = 800$ m.

Figure 8: Loss rate from protons exiting the IP after collision. As seen in Figure 2, the DS losses ($s > 800$ m) are near top energy and thus of concern.

Two collimators have been added to the post-IP DS in order to intercept the higher energy inelastic protons. The first concern is whether or not they can operate at nominal betatron collimation insertion half gaps (in order to maintain the collimation hierarchy) and still intercept inelastic protons from collision. Using the nominal setting of 35.14 $\sigma$ (horizontal) for the two TCLDs in cell 8 and cell 10 of the DS, we observe that all protons are absorbed in these collimators, as shown in Figure 9.

Figure 9: Loss rate from protons exiting the IP after collision. The DS losses ($s > 800$ m) are now completely absorbed by the TCLD collimators which are set to a half gap of 35.14 $\sigma$ in the horizontal plane.

The TCLD design for betatron and post-IP debris collimation is still under study. FLUKA simulations of particle showers onto the nearby DS magnets are being performed. At this early stage it appears that
these TCLDs will intercept the debris at nominal collimation settings thus maintaining the collimation hierarchy. These collimators must also be used for heavy ion debris, studies of this are planned.

Elastic protons (those with less than 0.01% energy loss in collision) mostly reach the next IP with a spot size similar to that of the beam, and will likely cause some emittance growth. The inelastic protons are mostly lost in the long straight section and DS regions, however a rate of 9 protons per beam crossing at ultimate luminosity, and 1 proton per beam crossing at nominal luminosity, is predicted at the next IP from these studies. The use of crab cavities will likely affect these results, and their inclusion is envisioned in future work.

4.4. BACKGROUND FROM MUONS

As a first approach an analytical investigation of the range of muons generated with DPMJET-III was performed. Muons are mostly produced through the decay of collision products, and thus were recorded 3 m from the IP in the forward direction. Around $4 \times 10^5$ muons were produced in the forward direction when generating $1 \times 10^6$ proton-proton collisions after 3 m. The maximum muon energy recorded was $\sim 22$ TeV. The range of these muons is shown in Figure 10, from which it is clear that no muons have the required energy to travel the 5.92 km distance between IPA and IPB. This analytical calculation does not include range straggling or stopping power fluctuations. These effects have been covered in the FLUKA simulations through tunnel, in 4.4.1, including the possibility of muons being guided by the tunnel or vacuum pipe.

![Figure 10: Analytical range of collision debris muons 3 m post IPA through standard rock. IPB is 5.92 km from IPA through rock.](image)

The impact of crossing angle and the detector magnets on the detector cross-talk has yet to be checked, both the muon and proton calculations will benefit from the use of particle shower codes which are envisioned in the near future. The muon distribution at arbitrary distance from the IP will also be checked in order to provide the best range estimates, and FLUKA simulation optimisation.
4.4.1. Simulations
In order to verify the range of muons that will be propagated and may arrive to the other detector, a FLUKA model of the section IPG-IPH of the FCC tunnel was developed (Figure 11).

A muon distribution at the exit of the detector was generated by DPMJET-III in FLUKA (Figure 12). Most of these muons are contained within an energy range 1-2000 GeV. All of these muons, including the high energy ones, were propagated through the tunnel model of Figure 11.

![Figure 11: Horizontal cross section of the FLUKA model for the tunnel section IPG-IPH.](image)

![Figure 12: Initial muon distribution.](image)

![Figure 13: Some muon trajectories through the tunnel rock.](image)

Figure 13 shows some muon trajectories through the rock tunnel.

The muons were tracked to a total of $10^9$ histories. The histograms of the muons at different points within the tunnel are shown in Figure 14. Less than 10 muons were detected at 2.3 km while none was found from 2.7 km on. Further simulations with more statistics will be done to assess these results, but we can say that from what we have analysed, muon cross talk does not seem to be an issue. There are some muons with a considerable energy that can travel in the order of hundreds of meters, but the
curvature of the tunnel combined with the large distance between the adjacent points makes it very hard for a muon to reach the other detector.

\[\text{Figure 14: Muon histograms crossing the tunnel at different distances from the IP.}\]

\[\text{4.5. BACKGROUND FROM PHOTONS}\]

Due to their mass, Synchrotron Radiation emitted by protons is usually a negligible source of background in the experiments, also in very high energy proton beams such as LHC. However, in the case of FCC, were the energy reaches 50TeV, also this possible contribution should be evaluated carefully. For this purpose, we performed a dedicated study with MDISim, which is a set of C++/Root classes that allows to run MADX with a certain lattice, read the MADX output plotting the lattice, and to perform several calculations regarding SR (such as power radiated, number of emitted photons, critical energy for each element) plotting it on the accelerator geometry.

A simple analytical calculation suggests that the power emitted by the last 4 bending magnets upstream the IP is of the order of 100W. However, the fraction of this power that enters the experiment area, defined as “what is after the TAS”, is obviously smaller. To evaluate it, we used MDISim to import the full geometry of the last +/-700m of beam pipe in Geant4, for the optics version LATTICE_V8. We performed a full simulation, including creation and propagation of Synchrotron Radiation photons by the beam protons in the magnets (both dipoles and quadrupoles), to analyze the flux of particles entering the TAS (in yellow in Figure 15).

In this full simulation we compared the two cases, with or without the 80 µrad horizontal crossing angle foreseen in the design.
The results of this simulation, summarized in Table 1, suggest that about 10W are expected to enter the TAS, out of which only about 1W should hit the +/- 8m long inner Beryllium pipe. The contribution of a possible 10 Tm detector spectrometer to be placed after the TAS has been evaluated in 1 additional Watt.

<table>
<thead>
<tr>
<th>CrAn.</th>
<th>N_{TAS}</th>
<th>\bar{E} [\text{keV}]</th>
<th>P_{TAS} [\text{W}]</th>
<th>P_{Be}[\text{W}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>2.9\times10^9</td>
<td>1.28</td>
<td>14.6</td>
<td>0.8</td>
</tr>
<tr>
<td>No</td>
<td>1.6\times10^9</td>
<td>1.38</td>
<td>8.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

On the other hand, to evaluate the effect of the vast flux of low energy photons, a dedicated simulation of the Beryllium pipe has been performed in Geant4. We expect less than 1 photon per bunch with an energy of the order of 1KeV to traverse the Be pipe towards the experiments.

This whole study was confirmed by means of the comparison with another software, SYNRAD, able to address the same question but starting from a totally different approach. In fact, Synrad does not simulate the whole physics, but just generates and traces SR photons emitted by a given beam in a given magnetic field (see Figure 16). For the Synrad study we used the optics fcc_hh_v6.45. Despite some differences in the optics version and in some geometrical details (the recombination chamber was assumed here to be “LHC-like”), the results confirm the same order of magnitude for the power entering the TAS, as shown in Table 2.
Table 2: Summary of SR power emitted in the last 500m from the IP that enters the TAS, with Synrad.

<table>
<thead>
<tr>
<th>Element</th>
<th>$P_{Er}$ [W]</th>
<th>$P_{Cr}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q1$</td>
<td>0.01</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$Q2_A$</td>
<td>0</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$Q2_B$</td>
<td>0.1</td>
<td>2.2</td>
</tr>
<tr>
<td>$Q3$</td>
<td>0</td>
<td>1.2</td>
</tr>
<tr>
<td>$D1_A$</td>
<td>5.0</td>
<td>5.8</td>
</tr>
<tr>
<td>$D1_B$</td>
<td>0</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$D2_A$</td>
<td>0.1</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$D2_B$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOT</strong></td>
<td><strong>5.3</strong></td>
<td><strong>9.2</strong></td>
</tr>
</tbody>
</table>

We thus conclude that Synchrotron Radiation emitted by beam protons in the last magnetic elements towards the IP is not a dangerous source of background in the experiments, with the design parameters. In a low luminosity configuration, we expect this effect to be even smaller.
5. LOW LUMINOSITY EXPERIMENTS

5.1. OPTICS

Recent layout modifications consider the combination of the low luminosity experiments with the injection. These combined insertions will still be housed in 1400 m long straight sections located in points B and L. The combination of these two systems imposes certain length constraints in the matching section as space has to be allocated between the matching quadrupoles for the injection hardware like the septum (MSI) and the injection kicker (MKI). To protect the cold elements against miskicked injected beams an absorber (TDI) downstream of the kicker needs to be installed as well. The inclusion of this protection device requires taking into account of an additional phase advance constraint \( \mu_{kicker} - \mu_{TDI} = 90^\circ \) during matching the injection optics in order to guarantee an optimal efficiency of the TDI. Due to constrained space in the straight section and the length requirements of the injection hardware the optics with this layout is not very flexible even in Point L where no phase advance constraint for the protection device needs to be applied during matching the injection optics for Beam 1.

With an \( L^* \) of 25 m, which was suggested by the detector design group, the current design optics is a round optics with a \( \beta^* = 3 \) m.

5.2. MINIMUM TRIPLET APERTURE

For the design \( \beta^* \) of 3 m, a half crossing angle of 19 µrad, and the magnet specifications presented later the minimum beam stay clear in the triplet is 20 σ. The current separation scheme foresees a parallel separation of ± 1.5 mm which leaves a beam stay clear of 17 σ in the triplet. The same separation is currently envisaged during injection where a \( \beta^* \) of 27 m is used. This leaves a beam stay clear value of 15 σ.

5.3. MAGNETS

The magnets used in the current layout are described in the following table.

| Table 3: Magnet Specification for the combined experimental and injection insertions |
|-------------------------------------------------|-----|-----|-----|
| Magnet Type                                      | Length [m] | Gradient [T/m] | Field [T] | Aperture [mm] |
| Triplet Q1/ Q3                                  | 10   | 270           | -         | 64           |
| Triplet Q2                                      | 15   | 270           | -         | 64           |
| Separation Dipole D1                            | 12.5 | -             | 12        | 100          |
| Recombination Dipole D2                         | 15   | -             | 10        | 60           |
| Matching Quadrupole Short Type MQM              | 9.1  | 200           | -         | 70           |
| Matching Quadrupole Long Type MQML              | 12.8 | 300           | -         | 50           |
| Orbit Corrector                                 | 1    | -             | 3         | 64           |

In the presented layout, the triplet quadrupoles have already been split to achieve a more feasible magnet length. After splitting the quadrupole, a considerable gap of 2 m had to be inserted between quadrupole parts.
For the separation and recombination dipoles a rather challenging design was chosen as the limited available space requires a short separation section.

In an effort to reduce the cost of quadrupole manufacturing, a unified magnet model for the triplet quadrupoles was sought after. At this moment, all triplet quadrupoles share the same aperture and maximum gradient while only the length of these modules differ.

For the shielding inside the triplet quadrupoles currently an absorber thickness of 10 mm is considered. For the other insets like the beam screen the same thicknesses are assumed as in the Main IR triplet quadrupoles.

First radiation studies are ongoing. Preliminary results show that a 10 mm thick tungsten shielding would guarantee a magnet lifetime of 500 fb⁻¹, assuming a dose limit of 30 MGy. With this shielding thickness, the peak power density is expected be 1mWcm⁻³ for 5x10³³ cm⁻²s⁻¹.
6. CONCLUSIONS

In this document we have highlighted several constraints and dependencies arising from the EIR design onto other work packages as well as on detector design. In general, we find that the current tentative design is consistent with the overall FCC-hh design. In particular the following issues have been studied:

- The separation of the points with experiments A, B and L appears large enough to avoid significant background from one experiment into the other.
- The power deposited by synchrotron radiation in the experimental beam pipe is in the order of 1W, which is considered negligible.
- Preliminary designs of the low luminosity insertions have been made matching current and newly proposed layouts. Their luminosity seems to be limited by beta* and radiation dose to about a factor 20 below that of the main experiments.
- The main experimental insertion length can be made to be 1400 m significantly decreasing the operational margins and flexibility. In particular final quadrupoles might only survive one 5 year run, while with 1500 m 3 runs are at reach. This also motivates R&D to develop more resilient materials to radiation.
- Triplet quadrupoles have been implemented to respect the maximum length of 15m and minimum separation of 2m. These constraints significantly affect operational margins and triplet lifetime. It is therefore important to explore the margins on these values.
- The field quality of the final focusing triplets strongly requires accurate corrections with dedicated coils, challenging machine operational phases before corrections. It should be explored if better field quality can be achieved.
- L*=45m is used but shorter L*, even by 10%, has great benefits in terms of field quality tolerances, operational margins and triplet lifetime.
- Beams are separated in the common beam-pipe with a crossing angle of about 90 μrad. This is assessed sufficient but without considering the impact from triplet non-linearities and the low luminosity experiments.
- Crab cavity specifications have been provided. A space of 20 m has been allocated for them.
- Alternative operational scenarios without crab cavities, using flat beams, have been explored yielding only a small loss on integrated luminosity.

We would like to stress in particular the following dependence – the presently chosen L* (45m) is affecting the length of the EIR straight section (presently 1500m for one of the EIR optics options, i.e. longer than 1400m allocated). A longer insertion could be allocated, but would require significant modifications of the civil engineering. It would also decrease the arc length, which requires to increase the field in magnets in the arcs – this increases their cost or eat up the margin. The value of L* is kept at 45m to preserve the option of the dipole spectrometer in the detector, while the baseline detector is shorter and may live with shorter L*. Therefore, keeping the option of the dipole spectrometer in detector increases the cost of magnets in arcs. Dropping the option of dipole spectrometer may allow some reduction of L*, reduction of length of FF and reducing the risks for arcs and arc magnets. This global dependency will need to be addressed so that the overall performance/cost of the design will be optimized.
7. REFERENCES

8. ANNEX GLOSSARY

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

- **ATS**: Achromatic Telescopic Squeezing
- **BPM**: Beam Position Monitor
- **c.m.**: Centre of Mass
- **DA**: Dynamic Aperture
- **DIS**: Dispersion suppressor
- **ESS**: Extended Straight Section
- **FCC**: Future Circular Collider
- **FCC-ee**: Electron-positron Collider within the Future Circular Collider study
- **FCC-hh**: Hadron Collider within the Future Circular Collider study
- **FODO**: Focusing and defocusing quadrupole lenses in alternating order
- **H1**: Beam running in the clockwise direction in the collider ring
- **H2**: Beam running in the anti-clockwise direction in the collider ring
- **HL-LHC**: High Luminosity – Large Hadron Collider
- **IP**: Interaction Point
- **IR**: Interaction Region
- **LHC**: Large Hadron Collider
- **LLIR**: Low Luminosity Interaction Region
- **LAR**: Long arc
- **LSS**: Long Straight Section
- **MBA**: Multi-Bend Achromat
- **MIR**: Main Interaction Region
- **Nb₃Sn**: Niobium-tin, a metallic chemical compound, superconductor
- **Nb-Ti**: Niobium-titanium, a superconducting alloy
- **RF**: Radio Frequency
- **RMS**: Root Mean Square
- **σ**: RMS size
- **SAR**: Short arc
- **SR**: Synchrotron Radiation
- **SSC**: Superconducting Super Collider
- **TSS**: Technical Straight Section