Interface Machine-Experiments
Definition and Time Plan

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# MILESTONE REPORT

## INTERFACE MACHINE-EXPERIMENTS DEFINITION AND TIME PLAN

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**Abstract:**

In this document we summarize the components and equipment defining the machine-experiment interface for HL-LHC. The corresponding time-line for their design, construction and installation is outlined.
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Executive summary

In this report we give an overview of the machine-experiment interface topics for the HL-LHC operation. The topics addressed cover the three aspects: beam design (optics, layout parameters, apertures), beam operation (signal exchange, machine-experiment protection, background conditions), and specialized equipment (experimental beam pipe, fixed shielding forward absorbers for charged and neutral particles TAXS and TAXN). The corresponding time-line for their design, construction and installation are described.

1. INTRODUCTION

The High Luminosity LHC (HL-LHC) project aims to increase the integrated luminosity of LHC by a factor 10 beyond its design value. The upgrade efforts, which are shared between the machine and the experiments, aim at operating the LHC machine with a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with levelling, and deliver 250 fb$^{-1}$ per year to achieve 3000 fb$^{-1}$ in twelve years of operation.[1] The machine-experiment interface in this high-luminosity operation of LHC extends to several aspects that can be grouped in three categories with obvious links between them:

- **Beam design**: definition of beam optics, layout and parameters, apertures, performance that lead to the set goal of the integrated luminosity as described above.
- **Beam operations**: signal exchange, machine and experiment protection, background conditions to assure the safe, high-efficiency operation of the machine and the experiments.
- **Equipment**: experimental beam pipe, shielding layout, passive absorbers for charged and neutral particles to protect equipment exposed in the high-flux of debris from the interaction point or from secondary’s produced at the beam impact on collimators.

Several of these aspects have already been treated during the initial operation of LHC, and will be followed after LS1 for Run II and Run III with the higher energy beams at 14 TeV centre of mass operation. However, the layout around the Interaction Regions for the two experiments ATLAS and CMS will change substantially for HL-LHC operation. This implies that many of these aspects will have to be revisited and optimised. In particular, new forward shielding absorbers for charged (TAS) and neutral (TAN) particles must be designed to operate at the expected higher absorbed power to replace the existing ones, taking account of the overall space and access constraints.

The follow-up of the machine-experiment interface issues is done principally within WP8, and in several working groups in other work-packages of the project. For sake of compactness, in the FP7-DS-HiLumi LHC the machine-experiment interface is a task in WP1. The foreseen activities within the project addressing the challenges in the machine-experiment interface are described in the next sections.
2. BEAM DESIGN

To maximise the physics reach of the high-luminosity experiments ATLAS and CMS, an increased integrated luminosity is envisaged during the HL-LHC operation. The HL-LHC project goal is to operate at nominal (ultimate) peak luminosity of \(5(7.5) \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\) with levelling, delivering 250(330) \(\text{fb}^{-1}\) per year, to achieve 3000(4'000) \(\text{fb}^{-1}\) in twelve years of operation for the high-luminosity experiments ATLAS and CMS. Achieving these high-luminosities is a key challenge for the machine and the experiments.

For the LHC machine, a new collision beam optics scheme is envisaged for IP1 and IP5, with modifications in the magnet layout to allow operation in a reduced \(\beta^*\) at the interaction of 0.15 m for either 25 or 50 ns bunch spacing. New crab cavities will be installed in the straight section around IP1 and IP5 to allow optimized collision schemes and luminosity leveling.

Upgrades in the ATLAS and CMS detectors are foreseen to allow operating in these conditions. Besides the high-luminosity experiments the other two LHC experiments LHCb and ALICE will also be upgraded and continue operations during HL-LHC. In Table 1 the targeted luminosities for HL-LHC proton operation are shown. The increased luminosity operation for LHCb of \(2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\) would only be possible with a major detector upgrade scheduled for LS2, but remains compatible with the magnet layout of the machine in LSS8. However, the introduction of a TAN is planned to protect the first cryogenic magnets of the machine in the region downstream D2 from the collision debris.

Runs with ion beams are also envisaged, mainly for ALICE but with the other experiments taking data as in the past.

Table 1 Target luminosities for \(p-p\) operation for the HL-LHC. The luminosities for the LHC Run-2 are also included for comparison. Total targeted integrated luminosity in CMS and ATLAS is 3000 \(\text{fb}^{-1}\) after 12 years of operation.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Peak Luminosity [cm(^{-2}) s(^{-1})]</th>
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<tr>
<td></td>
<td>HL-LHC</td>
</tr>
<tr>
<td>ATLAS</td>
<td>(5 \times 10^{34})</td>
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<tr>
<td>CMS</td>
<td>(5 \times 10^{34})</td>
</tr>
<tr>
<td>ALICE</td>
<td>(1 \times 10^{31})</td>
</tr>
<tr>
<td>LHCb</td>
<td>(2 \times 10^{33})</td>
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2.1. BEAM DESIGN CONSTRAINTS AND IMPACT TO EXPERIMENTS

The following guidelines for the beam design studies are included in the project that relate to the short straight sections and experiments.

- The LHC layout modifications at IP1 and IP5 and detector upgrades are planned during LS3.
- The layout of the short straight section around the experiments will change significantly with the introduction of the new large-aperture inner triplet quadrupoles Q1-Q3, the new superconducting dipole D1 and the installation of crab cavities. The foreseen HL-LHC...
layout of the magnetic elements around IP1 and IP5 is shown in Figure 1 and Figure 2 compared to that of LHC.

Figure 1 Layout of the high-luminosity regions of HL-LHC compared to that of LHC for the region up to D1.

Figure 2 - Layout of the high-luminosity regions of HL-LHC up to Q4. The new D1 superconducting dipole and the crab cavities following D2 are shown. The thick boxes indicated the magnetic lengths and the thin ones the cryostat assemblies. Courtesy E. Todesco [Daresbury 3rd HL-LHC collaboration meeting]
The layout changes and beam optics optimizations are discussed in joint meetings with the experiments as part of WP1, WP2 and WP8 and in dedicated project workshops. Details of the magnet configuration and aperture are still under discussion.

The layout changes concern the area beyond the present TAS starting at the first quadrupole Q1 at 23m from the interaction region. That way the forward shielding arrangement of the detectors remains unchanged, and modifications may arise only to minimize the background to the experiments.

From discussions with the experiments it was agreed that the LHC operation after LS3 will be dedicated to high-luminosity operation, and high-β* optics (>>30 m) as well as the forward detectors and experiments installed in the LHC tunnel are not planned, and if proposed should remain compatible with the high-luminosity operation and layout.

2.2. INTERACTION REGION (SINGLE BEAM PIPE)

A key upgrade of the ATLAS and CMS experiments for the HL-LHC operation is that of the inner tracker detectors. The change to a smaller radius Al pipe is already done during LS1. [2] This is important for the detectors to deal with high pile-up and should be kept for the HL-LHC operation. The addition of new tracker modules for larger rapidity coverage up to |η| = 5.0 is also envisaged, should an adequate technology is validated as well as handling and integration issues that remain compatible with the forward detector and shielding layout. The ALICE and LHCb experiments also plan modifications to their experimental beam pipe to a reduced inner radius. The present and foreseen experimental beam apertures are summarized in Table 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Experimental beam pipe inner radius R_{\text{min}} /mm</th>
<th>When</th>
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<tbody>
<tr>
<td>ATLAS - IP1</td>
<td>29.0</td>
<td>23.5</td>
</tr>
<tr>
<td>CMS – IP5</td>
<td>29.0</td>
<td>21.7</td>
</tr>
<tr>
<td>ALICE – IP2</td>
<td>29.0</td>
<td>18.2</td>
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<tr>
<td>LHCb/VELO –IP8</td>
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3. BEAM OPERATION

Extensive experience is gained so far with the operation of the LHC and the experiments during Run I. The major operational issues on the machine-experiment interface are addressed, and viable solutions are found on issues like:

- signal exchange, for experiment and machine status and information,
- beam tuning for luminosity optimization during operations,
- safety interlock signals to protect sensitive experimental equipment from failure cases,
- beam induced background to the experiments.
Until the HL-LHC operation, further experience will be gained in particular with the operation of the beams at nominal luminosity and top beam energy during Run II. The active beam monitoring system using the BLMs and fast 3-turns beam dump will be maintained and further improved for HL-LHC possibly including signals from the inner or near-beam detectors from the experiments.

With the upgraded layout of the machine around the high-luminosity regions IP1 and IP5 substantial effort must be invested to estimate the expected background to the experiments and possibly reduce their impact to the physics performance of the detectors. The LHC background-working group brings together experts from the four LHC experiments (ATLAS, CMS, LHCb, ALICE) and coordinates the studies. Particular effort is made to develop common tools and share the knowledge and experience from the present LHC operation. The impact of the expected aperture model for background to the experiments is evaluated and feedback is given to the beam design teams. The operation of the LHC machine in Run II after LS1 with the increased beam energy and 25 ns bunch spacing would provide important feedback for the understanding of the expected backgrounds and the simulation results for HL-LHC.

Within WP8, studies involving experts from the machine and the experiments are ongoing on the possible operation scenarios including crabbing schemes, luminosity levelling, collision crossing angles, etc. The goal is to evaluate the limits from the detectors like the pile-up density that can be afforded whilst maintaining the high-efficiency for the physics signals.

Finally, studies on possible accident scenarios and associated risks for the machine and experiments are initiated. The studies address using particle tracking codes through the LSS magnetic elements failure scenarios of machine components during operation like: crab cavity failures, asynchronous beam dumps, or more rare events like mechanical failures with obstacles in the beam, failures of D1 or D2 magnets, kicker or orbit errors with the beam scraping on collimators around the high-luminosity IPs, beam scraping on the experimental beam, to name the major ones.

The induced background and radiation to the experiment in the case of these events will be evaluated and protection measures will be suggested and followed to mitigate the risks. In the collaboration with WP10, RP experts and experts from the experiments the radiological impact in these scenarios will be evaluated and when required mitigation solutions like correct choice of material, special tooling and optimized procedures for maintenance and repair actions will be developed. This work will be part of the subject of the Working Group “Interventions in Radioactive Areas of HL-LHC” attached to WP8 setup to provide the forum for exchange of information and expertise towards developing common optimized approaches within the project.

4. EQUIPMENT

The hardware and equipment involved in the machine-experiment interface for HL-LHC operation include:

- The experimental beam pipes, covering in particular the part around the interaction region but more widely the design, handling and operation procedures for the vacuum sector from Q1-to-Q1.
• The **passive absorbers for charged** (TAXS) and **neutral** (TAXN) particles designed to primarily protect the nearby superconducting magnet from the radiation coming out from the interaction point

• The **forward shielding** in the experimental caverns, in particular the part that is close to the LHC machine tunnels.

The design considerations and foreseen upgrades in these are briefly described here.

### 4.1. THE EXPERIMENTAL BEAM PIPE

As discussed above, in all four experiments proposals for new experimental beam pipes are considered with reduced inner radius.

For the ATLAS and CMS experiments the new inner beam pipes are already implemented during LS1 and will be in operation from Run-2. The new beam apertures are listed in Table 2 and schematically shown in Figure 3.

In the baseline scenario, the inner chamber aperture of ATLAS and CMS remains unchanged (i.e. the same as the one after LS1) for the HL-LHC operation. However, the remaining vacuum parts must be changed to match the upgraded configuration of the experiments in the forward region and to the new TAXS aperture.

For the ALICE and LHCb experiments modifications are also foreseen for the experimental beam pipes as shown in Table 2. However, all changes will be implemented during LS2.

Already during Run II but in particular after few years of operation in Run-3 at high-luminosity, the activation levels in the experimental beam pipe would require careful planning and the development of special tooling for maintenance interventions and final dismantling. In particular any opening scenarios where parts of the beam vacuum pipe have to be removed must be prepared and done with remote tools thus minimizing the dose to the people.
4.2. THE PASSIVE FORWARD ABSORBERS

The high-luminosity regions of LHC at IP1/ATLAS and IP5/CMS are equipped with passive absorbers for charged (TAS) [3] and neutral (TAN)[4] particles. They are installed on either side of the interaction region at the join of the experimental caverns to the LHC tunnel. Their prime function is to protect the superconducting quadruples in the straight section, primarily the inner triplet quadrupoles Q1-Q3 but also D2 and Q4, from the collision debris out of the interaction region. In parallel the TAS completes the forward shielding of the experiments and both the TAS and TAN participate in the background reduction to the experiments.

For the low-luminosity experiment IP8/LHCb and IP2/ALICE no such absorbers are installed. For the HL-LHC operation the following modifications are foreseen:

- New TAS and TAN absorbers on either side of IP1 and IP5, called TAXS and TAXN respectively should replace the existing ones. The protection must be extended to D1 magnets that in HL-LHC will be superconducting (while it normal conducting in the present LHC). The new absorbers must have and aperture adapted to the HL-LHC beam optics and operation and should be designed to cope with the increased energy deposition.
- A new TAXN absorber is planned for IP8 designed to operate at the foreseen ×5 higher luminosity operation. The installation of a TAXS absorber around IP8 is not required.

Details of the key design parameters of these absorbers are described below.

4.2.1. The charged particle passive absorber TAXS

The TAS absorber is located at approx. 19 m from the interaction point on either side of IP1 or IP5. Its core is a 0.5 m diameter and 1.8 m long copper cylinder traversed on its axis by a constant aperture beam pipe. The TAS absorbers are embedded in the forward shielding of the experiments as shown in Figure 4 and Figure 5.
The new TAXS absorbers for HL-LHC, should replace the existing ones with the following modifications and improvements:

- The beam pipe aperture increases to 54 mm in diameter from the present 34 mm, to be confirmed by the simulation studies.
• The cooling power should increase to dissipate the approx. 780 W deposited in the TAXS during operation in ultimate conditions including a safety margin.
• The overall design of the TAXS should respect the mechanical and envelop constraints from the surrounding shielding.

Improvements in the alignment mechanism and vacuum exchange should be incorporated in the new design in view of optimized maintenance operations and exposure to radiation.

In the baseline scenario the exchange from the TAS to TAXS is to happen after few months of cool-down period during LS3. The overall procedure must be optimized such to minimize the exposure of personnel to radiation in compliance with the ALARA principle.

4.2.2. The neutral particle passive absorber – TAXN

The TAN absorber is designed to absorb the flux of forward high-energy neutral particles produced at the interaction region of IP1 and IP5. There is a TAN absorber installed in either side of IP1 and IP5 located between the separation/recombination dipole pair D1 and D2 and contains the transition from the single common beam pipe to the two separate pipes for the incoming/outgoing beams. The TAN absorber contains slots in the upstream part where beam luminosity monitors and experimental detectors can be installed. In Figure 6 the TAN absorber as installed in the LHC tunnel is shown.

New TAN absorbers for IP1 and IP5, called TAXN, should be designed and replace the existing ones for the HL-LHC operation, with the following modifications and improvements:

• The position of the TAXN will be different by few meters with respect to the present ones
• The overall design and layout should be adapted to the available space constraints maintain the correct shielding efficiency
• The vacuum chamber layout should be adapted to the new geometry protection efficiently for the adjacent quadrupoles and optimization for the background conditions to the experiment.
• Active cooling will be required to dissipate the expected approx. 1.5 kW of power from the beam expected for the operation at the ultimate luminosity conditions including a safety margin.

Improvements in the mechanical design of the absorber should be incorporated in the design to allow optimized installation and maintenance activities.

The aperture of the vacuum pipes in the TAXN will be defined in combination to the adjacent collimators located upstream D2 to provide maximum protection at all beam optics scenarios.
The locations for beam instrumentation for luminosity monitoring and experimental detectors may be included if easily incorporated in the TAXN design in the design and impose no maintenance constraints.

In the IP8 new TAXN absorbers should be installed in either side of the interaction region in available slots upstream of D2 as shown in Figure 7.

![Figure 7 - 3D layout of LHC showing the foreseen location of the TAXN absorbers around IP8.](image)

The removal of the existing TAN absorbers and the installation of all TAXN absorbers at IP1 and IP5 are scheduled during LS3. The installation of TAXN for IP8 is foreseen already during LS2.

### 4.3. THE FORWARD SHIELDING

The forward shielding of the high-luminosity experiments at IP1 and IP5 was designed for the nominal LHC luminosity of $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, including a safety margin for the ultimate operation conditions. The massive blocks installed provide sufficient absorption of the secondary particles during operation to the experimental detectors and protection of the activated inner parts during maintenance and shutdown activities.

In the project baseline, and given the overall space constraints, no modification to the basic design of the forward shielding arrangement of the detectors is foreseen. However based on studies of the expected radiation and activation levels (see for example Figure 8), local optimisations and shielding enhancements may be done.

In parallel the overall access and maintenance operations for the detectors, and in particular for the innermost parts, must be optimised and if proven useful remote handling tools and methods must be developed.

These optimisation design principles and guidelines for- the interventions in the radioactive areas of HL-LHC including during maintenance activities is the subject of a Working Group combining experts from the machine and the experiments within WP8.
Figure 8 - Ambient dose equivalent profile at IP5 during HL-LHC operation. Courtesy O. Bertamelo, I. Bergstrom, H. Vincze.

5. TIMELINE

In the tables below the timeline for the engineering design, production and installation of the equipment related to machine-experiment interface is shown.

For the TAXS and TAXN at IP1 and IP5 the baseline where the exchange is done during LS3 is defined in Table 3 and Table 5. The removal of the existing TAS and TAN is indicated during the first quarter of LS3, however the actual date will be scheduled to comply with the ALARA principle and the planning of the activities in the accelerator and the experiments.

Table 3 – Timeline for the TAXS baseline scenario for IP1 and IP5. The removal of the existing TAS is indicated during the first quarter of LS3, however the actual date will be scheduled to comply with the ALARA principle and the planning of the activities in the accelerator and the experiments.
6. CONCLUSION

The machine-experiment interface issues for HL-LHC project were presented. The majority of the activities and issues refer to the high-luminosity experiments ATLAS and CMS at IP1 and IP5 respectively, while smaller scale activities for ALICE and LHCb at IP2 and IP8 are described as well. The key issues described refer to the definition of the apertures of the experimental beam pipe and forward absorbers TAXS and TAXN, where a compromise between the beam optics and operation and machine protection and background reduction to the experiments is searched. The major technical issues of the construction of the TAXS and TAXN are described as well. The new equipment will be designed to operate at the ultimate beam parameters for HL-LHC operation. The work is conducted in several working groups within WP8, involving experts from the LHC machine and the experiments.

The experience gained during the Run I operation of LHC and what is expected during Run II with the increased energy of the beams would be a crucial guideline for the studies and design of the equipment for HL-LHC.
7. REFERENCES

   M. Galilee, Reduction of ATLAS VI Diameter, LHC-VC1I-EC-0001, EDMS No:1230222.

ANNEX: GLOSSARY

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<tr>
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<tr>
<td>TAS</td>
<td>Target Absorber</td>
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<tr>
<td>TAN</td>
<td>Target Absorber Neutral</td>
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