Future Circular Collider

PUBLICATION

Report on design option for machine detector interface: Milestone M3.5

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MILESTONE REPORT

DESIGN OPTION FOR MACHINE DETECTOR INTERFACE

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Abstract:

Report on the machine-detector-interface requirements and constraints considering all studies carried out so far. Report on the impact of synchrotron radiation on detector and machine components in the interaction region and on the effects of debris onto magnets close to the detector. Report on radiation shielding and space constraints for experiments.

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1. MACHINE DETECTOR INTERFACE REQUIREMENTS AND SPACE CONSTRAINTS FOR EXPERIMENTS

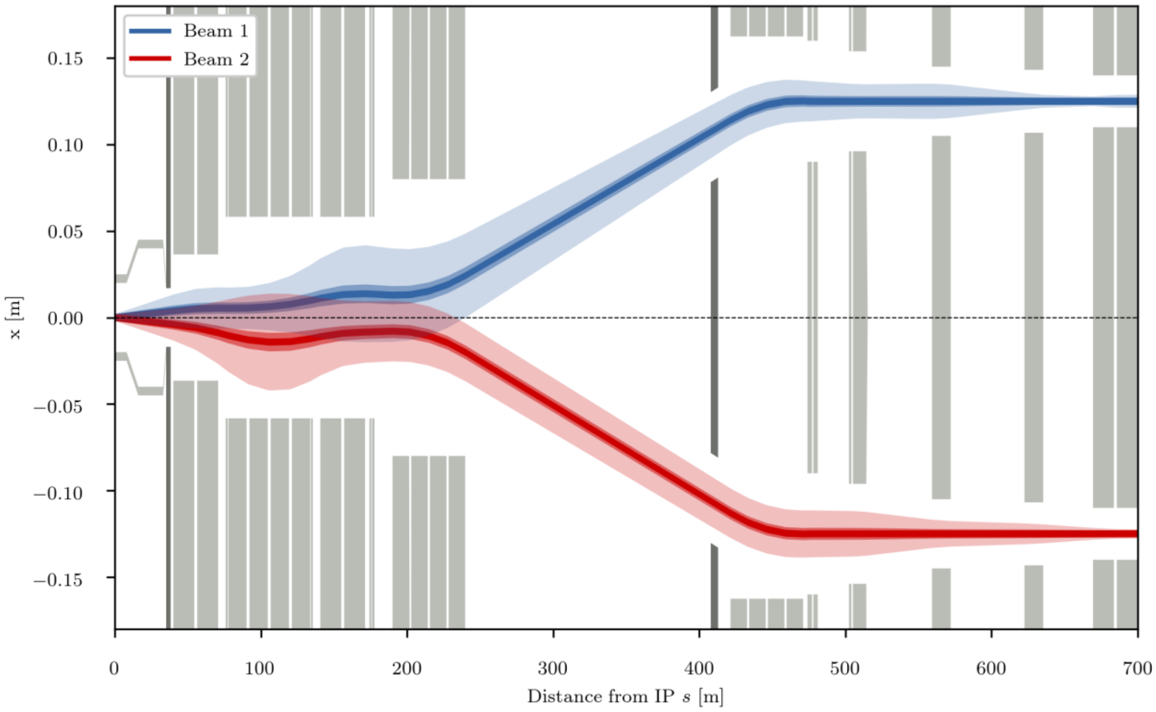

Figure 1: High luminosity EIR apertures. Magnets are depicted in light grey, absorbers (TAS and TAN) in dark grey. At s<40 m the detector beam pipe is shown.

The Machine-Detector Interface (MDI) components considered so far are the experimental beam pipe and absorbers for the collision debris of the high luminosity EIR. The dimensions of the experimental caverns are governed by the needs of the experiments. A cavern length of 66 m (33 m on either side of the detector) is required for the opening of the detectors. Apart from the beam pipe, no accelerator elements are currently foreseen to be placed inside the cavern.

The material and shape of the experimental beam pipe are mandated by the needs of the detector. It comprises of a 0.8 mm thick beryllium beam pipe with 40 mm aperture diameter extending to 8 m on either side of the interaction point, followed by an 8 m long conical beryllium beam pipe with an inner diameter increasing to 80 mm. From s = 16 m to s = 33 m a straight aluminum beam pipe with 80 mm diameter is needed, after which a short conical cone reduce the aperture to the 34 mm diameter of the TAS absorber.

The absorbers include the TAS, placed at s = 35 m before the first final focus quadrupole to capture most of the secondary particles, as well as the TAN, situated in front of the recombination dipole D2 about 410 m from the IP, protecting it from neutral particles from the IP.

For the low luminosity EIR, no cavern or beam pipe requirements are known so far. First studies of the collision debris show that a simple tungsten mask is sufficient to protect the triplet magnets. As the D2 recombination magnet is superconducting, a TAN will also be required, but no studies on heat load or needed specifications have been done so far.

2. SYNCHROTRON RADIATION BACKGROUND FROM PHOTONS

Due to their mass, Synchrotron Radiation (SR) 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 50 TeV, 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_V9. 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 2).

In this full simulation we compared the two cases, with or without the 89 μrad horizontal half crossing angle foreseen in the design.

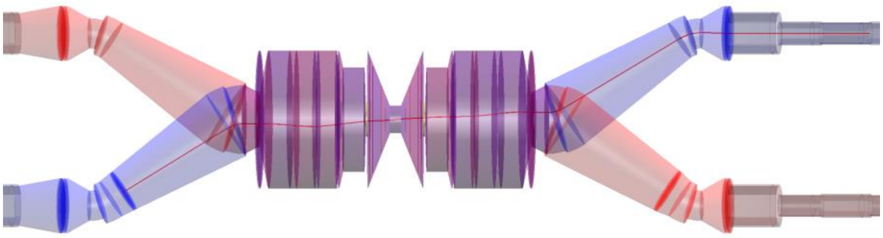

Figure 2: Top view of the FCC-hh IR reconstructed in Root, used for the Geant4 simulation (not in scale, transverse dimensions enlarged by a 1000 factor). In red the beam trajectory with crossing angle.

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 1: Summary of SR power emitted in the last 500m upstream the IP that enters the TAS (P_{TAS}) or hits the Be pipe (P_{Be}), with or without crossing angle. Values are per bunch.

CrAn	$N_{\gamma TAS}$	E_{mean} [keV]	P_{TAS} [W]	P_{Be} [W]
Yes	$2.9*10^9$	1.28	20.8	0.95
No	$1.6*10^9$	1.38	8.1	0.62

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 1 keV 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 3). 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.

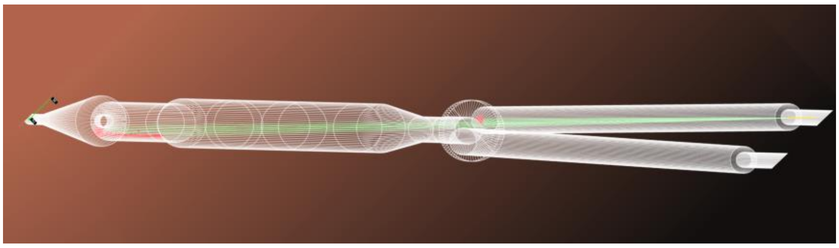

Figure 3: SYNRAD simulation of the last 700m of pipe upstream the IP. In green the photon tracks.

Table 2: Summary of SR power emitted in the last 500m from the IP that enters the TAS, with SYNRAD.

Element	$\mathbf{P}_{\not{C}r}$ **[W]**	$\mathbf{P}_{Cr}$ **[W]**
$Q1$	0.01	10^{-6}
$Q2_A$	0	10^{-4}
$Q2_B$	0.1	2.2
$Q3$	0	1.2
$D1_A$	5.0	5.8
$D1_B$	0	4×10^{-5}
$D2_A$	0.1	10^{-3}
$D2_B$	0	0
TOT	**5.3**	**9.2**

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.

3. COLLISION DEBRIS AND RADIATION

Proton-Proton inelastic collisions taking place in the FCC-hh, in particular inside the two high luminosity detectors, generate a large number of secondary particles. Most of these particles are intercepted by the detector and its forwards region shielding, releasing their energy within the cavern. However, the most energetic particles, emitted at small angles with respect the beam direction, travel farther inside the vacuum chamber and reach the accelerator elements, causing a significant impact on the magnets along the Experimental Insertion Region (EIR), in particular in the final focusing quadrupoles and the separation dipoles. At ultimate instantaneous luminosity conditions (30E34 $cm^{-2} s^{-1}$) the power released toward each side of the IP is 260 kW, that is inevitably impacting upon the FCC-hh elements and consequently dissipated in the machine, the nearby equipment (e.g. electronics racks), and the tunnel walls. It is important to study how these particles are lost in order to implement the necessary protections for shielding sensitive part of the magnets and the machine. In this context, Monte Carlo simulation plays a crucial role being able to simulate particle interaction with matter by relying on a detailed implementation of physics model and an accurate 3D description of the region of interest. In particular, the FLUKA code [1,2] is extensively used in this conceptual design study, also thanks to the experience collected in the LHC and HL-LHC design [3] as well as the benchmarks already available in literature for these machines [4].

The model of the EIR presented in the following includes the latest optics available at the time of the simulation (with L*=40m) and 500m of accelerator elements such as the inner triplet, the two separation dipoles (D1 and D2), the Target Absorber Secondaries (TAS) and the Target Absorber Neutrals (TAN). The following coil apertures (in diameter) were implemented in the model: Q1 164mm, Q2 and Q3 210mm, orbit correctors 210mm. To protect the inner quadrupoles coils, a 35mm thick tungsten shielding was implemented in the mechanical design of the triplet magnets and the orbit correctors: the shielding thickness reported in this study is the maximum allowed in order to match optics requirements and aperture limitations. Finally, p-p collisions at 100 TeV c.m. with a vertical half crossing angle of 89 μrad have been simulated and the particle shower was tracked all along the accelerator elements [5].

The total power deposited in the cold magnets (Table 3) is shared between the cold mass and the tungsten shielding, with a ~15-85 ratio. In particular, the Q1B results as the most impacted element of the triplet with a total power of 12.6 kW in the shielding that need to be extracted from the cryogenic system. Being the TAS the first protecting element of the EIR, the power deposited in this component is 26.5 kW. Finally, the TAN results the most critical element of the simulated line with 112 kW that need to be suitably dissipated.

Table 3: Total power distribution in the EIR elements.

Total Power [kW] - Vertical Crossing							
Element	***Cold shielding***	***Cold mass***	***Warm mass***	***Element***	***Cold Shielding***	***Cold mass***	***Warm mass***
TAS			**26.5**	**Q3A**	5.38	0.71	
Q1A	4.7	0.78		**Q3B**	7.57	0.92	
Q1B	**12.6**	**1.89**		**C3**	0.87	0.15	
C1	0.06	0.06		**D1A**			5.06
Q2A	1.47	0.22		**D1B**			3.74
Q2B	0.77	0.11		**D1C**			3.58
Q2C	4.54	0.61		**TAN**			**112**
Q2D	6.40	0.89		**D2A**			0.080
C2	0.71	0.08		**D2B**			0.012
				D2C			

A maximum peak power density of 4.5 mW/cm^3 was evaluated at the end of the Q1B: the value is below the save limit of 5 mW/cm3 specified by the magnet experts, but the remaining margin is limited. Studies on the quench limit are currently ongoing to better determine the maximum value allowed [6].

To estimate the insulator lifetime, the absorbed dose in the magnet coils was calculated. Figure 4 shows the peak dose profile considering the ultimate integrated luminosity goal (30 ab^{-1}). Assuming an operational limit of ~30 MGy for conventional radiation resistant insulator materials, the most critical element (Q1B) exceeds by about a factor 2 this limit. As already mentioned, the model is already considering the maximum shielding thickness allowed (35mm). Given that:

- crossing polarity and plane alternation are known to significantly reduce the maximum dose, by more equally distributing the radiation load in the coils and this way increasing the lifetime of the triplet [5];
- in addition, this limit is likely to be increased by using more radiation hard insulator, e.g. epoxy/cyanate-ester blends [6];
- alternatively, the replacement of the inner triplet once during the FCC-hh lifetime might be considered.

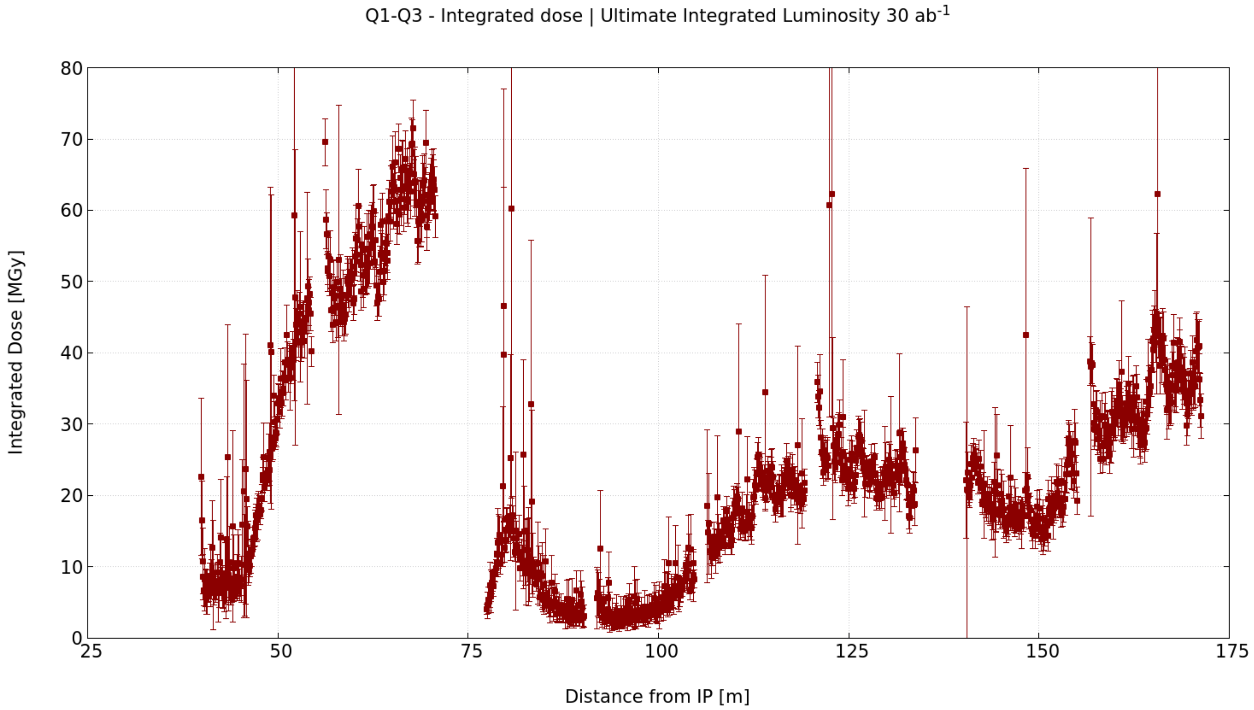

Figure 4: Absorbed dose [MGy] in the triplet cold magnets coils considering the ultimate integrated luminosity conditions (30 ab-1). Statistical errors are indicated. Larger statistical fluctuation should not be considered.

With regard to the separation dipoles, the D1 – with the coils located farther away from the vacuum chamber and no shielding implemented – will face a similar situation with a peak dose a factor ~2 above the current 30 MGy operational limit. To further protect this element, the design of a dedicated mask might be considered. On the other hand, the D2 turns out to be well protected by the presence of the TAN. Nevertheless, the matching section cold quadrupoles, just following the D2, could be more impacted due to their different design. A dedicated study is currently ongoing.

Collision debris studies have an impact also on the civil engineering design of the cavern as well as the EIR tunnel. Indeed, due to the space requirements for the detector and civil engineering constraints, the shape of the cavern is such as the TAS and part of the Q1 are embedded in the experimental hall. As a consequence, to reduce the background signal from the interaction of the collision debris with the EIR elements, particularly the TAS, a concrete blockhouse (2m thick in all directions) was designed. Figure 5 shows a 3D rendering of the experimental cavern, the detector, the blockhouse and the EIR tunnel and magnets as implemented in the FLUKA model. The cut in the 3D rendering shows how the blockhouse allows to protect the detector form the back scattered radiation, in terms of absorbed dose and High Energy Hadrons (HEH) fluence [7].

To summarize the study, the power deposition in the cold mass peaks in Q1B at 12.6 kW. This value is significant but cooling appears to be possible with suitable cooling channels inside the shielding. The maximum peak power density in the coils is close but below the assumed quench limit. Assuming a crossing plane variation is implemented, the insulator lifetime in the triplet comfortably exceeds half of the target integrated luminosity goal, meaning the magnets will need to be exchanged not more than once. The separation dipole D1 is exposed to similar levels of radiation but can be protected by a dedicated mask. Currently simulations are ongoing to confirm this for the latest lattice, considering also the exposition of the matching section quadrupoles.

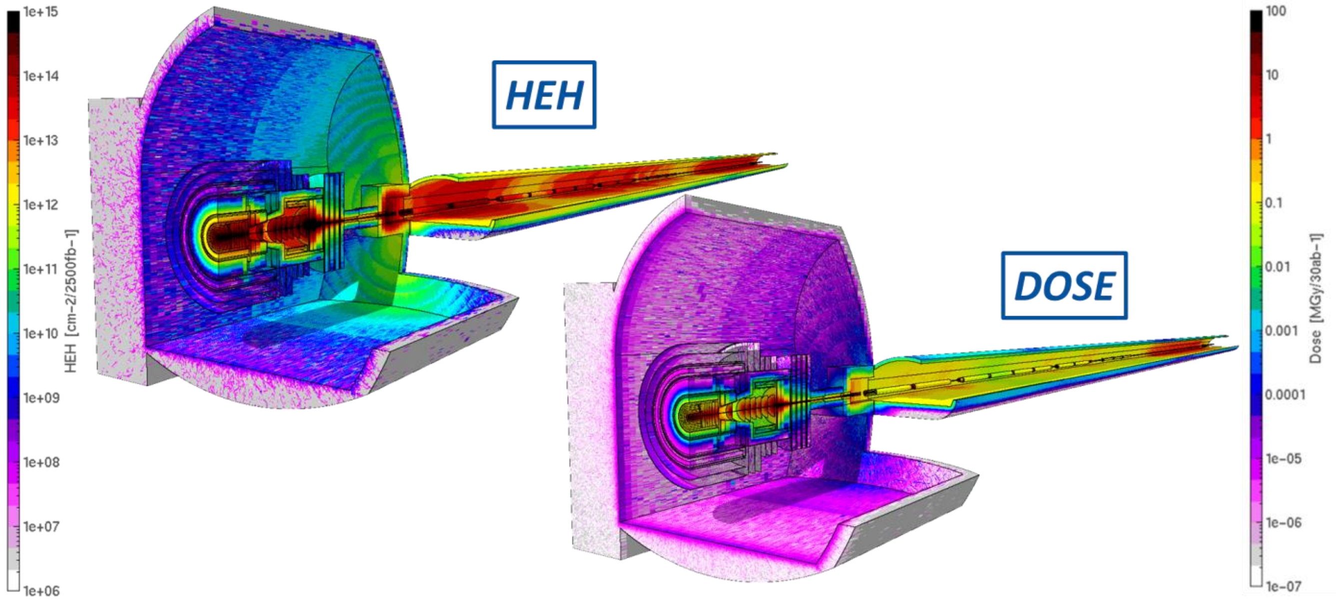

Figure 5: 3D rendering of the experimental cavern and the EIR tunnel. The 2m thick concrete blockhouse allows for a significant protection of the detector from the radiation originated by the interaction of the collision debris with the machine elements, in part

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5. 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
Nb_3Sn	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