

SYNCHROTRON RADIATION BACKGROUNDS FOR THE FCC-hh EXPERIMENTS*

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Abstract

In this paper we present a detailed analysis of the Synchrotron Radiation emitted by the 50 TeV protons of the FCC-hh in the last bending and quadrupole magnets upstream of the interaction region. We discuss the characteristics of this radiation in terms of power, flux, photon spectrum and fans with and without crossing angle for comparison. We mainly focus our study on the fraction of photons that may hit the detector, with a full tracking in GEANT4 that simulates the interaction within the central beam pipe.

INTRODUCTION

The international Future Circular Collider (FCC) study [1] aims at a design of p-p, e^+e^- , e-p colliders to be built on a new 100 km tunnel in the Geneva region. The final goal is a hadron collider at centre-of-mass energies of the order of 100 TeV, the intermediate steps being a e^+e^- collider for the 90 to 400 GeV centre of mass energy range. To reach such unprecedented energies, in addition to the requirement for ultra high luminosities, a careful study of all the background sources both in the machine and in the experimental area must be performed, including the evaluation of Synchrotron Radiation emitted by hadrons.

MOTIVATION AND SCOPE

The amount of power radiated by Synchrotron Radiation (SR) strongly depends on the relativistic γ factor of the particle, and thus on its mass: $P \propto \gamma^4 \rightarrow P \propto m^{-4}$.

For this reason, SR power emitted by protons is several orders of magnitude lower than the one emitted by electrons, and has been so far an almost negligible contribution to the background also for high energy hadron colliders like LHC.

However, as we aim at unprecedented centre-of-mass energy as high as 100 TeV, the amount of SR power should be also evaluated. In fact, even if the increase of FCC-hh in the centre-of-mass energy with respect to LHC is of about a factor 7, the increase in SR power is of about a factor 170. On the other hand, the *critical energy* of the photons emitted by the proton beam goes with γ^3/ρ , and thus for FCC-hh turns out to be about a factor 100 greater than the one in LHC. This shifts the spectrum from hard ultraviolet for LHC which is easily absorbed into the X-ray range for FCC, for which the Beryllium of the inner beam pipe starts to become transparent. In this paper we present the study of the SR produced in the bending magnets upstream of the

Interaction Region and we investigate the SR that may reach the detector passing through the main absorber that protects the insertion quadrupoles from collision debris, called TAS as for the LHC, which stands for *Target Absorber Secondaries*. The goal of the study is to understand the impact in the experiments in terms of photon energy or flux. In Fig. 1 we show the present design of the FCC-hh Interaction Region [2]. To perform this study, we used two different software tools: *MDISim* [3] and *SYNRAD+* [4], quite different in their approach.

MDISim is a toolkit that combines existing standard tools (MAD-X, ROOT and GEANT4). It reads the MAD-X optics files, and uses its twiss output file to generate the geometry and the magnetic field information in a format which can be directly imported in Geant4 to perform full tracking, including the generation of secondaries and detailed modeling of the relevant absorption processes. Current limitations in GEANT4 are that the generation of the angular distribution is approximate ($1/\gamma$ cone) and that hard photon optical mirror reflection is not included [5].

SYNRAD+ takes as input a geometry of arbitrary complexity either from CAD or STL format, and magnetic fields, and uses them to simulate the beam, whose starting characteristics at a certain point must be provided, generating and tracking SR photons (no $1/\gamma$ approximation is performed). *SYNRAD+* is able to perform a full simulation of the optical interaction (reflection, absorption) of the incident radiation with the pipe material, and has been benchmarked against peer-reviewed literature [6].

We find that results are consistent with each other, as discussed in the next paragraph.

SIMULATION STUDIES

MDISim

MDISim simulation study has been performed on the FCC-hh optics named LATTICE_V8 [7]. This optics foresees a $\beta^* = 0.3$ m and $L^* = 45$ m. After running MAD-X on the lattice file, *MDISim* creates the ROOT file for the geometry of the beam pipe around the IP, as shown in Fig.1, where the vertical dimension has been zoomed by a factor 1000 in order to gain visibility. The apertures shown are those present inside the optics file, with the exception of the ones in proximity to the IP (i.e. behind the TAS), that were not provided in the optics description and instead added by hand to match the current design of the pipe (Beryllium pipe radius of 2 cm). The trajectory of the beam generated by MAD-X within the twiss file is also visible in Fig.1 as a continuous line inside the pipe.

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Its displacement from the centre is due to the fact that the picture represents the case with the $89 \mu\text{rad}$ crossing angle between the two beams turned on. At this first level of the analysis, we calculate with MDISim the total amount of SR power produced by these magnets, from magnet strength, length and particle energy. The results are shown in Tab.1, which shows that the total SR power radiated towards the IP is about 100 W.

The contribution of a possible last spectrometer magnet has been estimated to be of the order of 1 W.

Table 1: Summary of s position along the lattice, length, strength, magnetic field, SR critical energy and total power for the last 4 bending magnets

Element	S [m]	l [m]	B [T]	E_{crit} [keV]	P [W]
$D1_A$	231	12.5	-4.3	1.15	32
$D1_B$	245	12.5	-4.3	1.15	32
$D2_A$	427	15	3.6	0.96	27
$D2_B$	443	15	3.6	0.96	27

As a second step of the analysis, we calculate the SR radiation cones for each magnetic element and illustrate them using the visualization provided by MDISim-ROOT TEvent interface, shown in Fig.1. We can see that only a fraction of the radiation emitted towards the IP will impact on the TAS absorber.

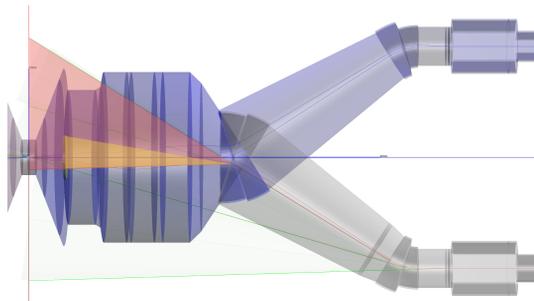


Figure 1: Top view of the geometry of the pipe around the IP as generated by MDISim and shown in ROOT. The transverse dimension has been zoomed by a factor 1000 in order to gain readability. The red area shows the angular distribution of SR photons emitted by the bending elements, the yellow the fraction reaching the TAS. The ratio of the two angles gives the fraction of produced power that actually enters the TAS.

The numbers are summarized in Tab.2, evaluated both with and without crossing angle scheme. The power load on the TAS corresponds to about 20 W.

As third and final step, we perform the full tracking simulation for the last ± 700 m around the IP using the magnet geometry and fields imported into GEANT4. This is illustrated in Fig. 2 for 10 protons starting on axis at a distance of 700 m from the IP.

The Geant4 simulation has then been used to evaluate the amount of power entering the TAS. The spectra of SR

Table 2: Summary of solid angle for SR photons emitted by the last 4 bending magnets and total power that enters the TAS, with (Cr) and without ($\mathcal{C}r$) the crossing angle. P is the total power emitted, while f is the fraction of it entering the TAS.

El.	P [W]	$f_{\mathcal{C}r}$ [%]	$P_{\mathcal{C}r}$ [W]	f_{Cr} [%]	P_{Cr} [W]
$D1_A$	32	40	13	77	25
$D1_B$	32	0	0	0	0
$D2_A$	27	15	4	17	5
$D2_B$	27	0	0	0	0
TOT	-	-	17	-	30

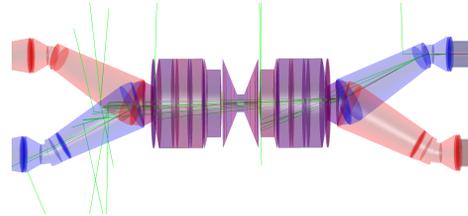


Figure 2: Output of a simple 10 protons simulation, shown again in ROOT with the usual 1000x enlargement on the vertical scale.

photons entering the TAS region for both cases (with and without Crossing Angle) are shown in Fig. 3, while the summary of the power load is reported in Tab.3.

A similar approach has been used to evaluate the particles reaching the 16 m long Beryllium pipe surrounding the IP, and thus the power load on it, also shown in Tab.3. In summary, the SR power hitting the Be pipe is less than 1 W with crossing angle, a safe value in term of power. However, also the abundant flux of these low energy photons may play a role.

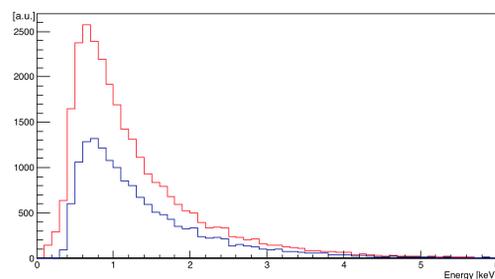


Figure 3: Spectrum of photons entering the TAS region with (in red) and without the Crossing Angle scheme (in blue).

To evaluate the effect of the interaction of these photons in the Be pipe, a devoted simpler simulation has been set up, in order to avoid the unneeded complexity of the full one and obtain a much quicker response for a high number of primaries. The geometry is simply represented by a Be tube of 2 cm radius and 1.2 mm thickness on which photons generated with the right SR spectrum (taken from the previous full simulation) impinge with a $70 \mu\text{rad}$ grazing angle.

Table 3: Summary of SR power emitted by the last 500 m from the IP that enters the TAS (P_{TAS}) or hits the Be pipe (P_{Be}), coming from the full Geant4 simulation, with or without Crossing Angle. Values are per bunch.

CrAn.	$N_{\gamma TAS}$	\bar{E} [keV]	P_{TAS} [W]	P_{Be} [W]
Yes	2.9×10^9	1.28	14.6	0.8
No	1.6×10^9	1.38	8.6	0.5

The main conclusion from the GEANT4 simulations is that the energy spectrum of the photons hitting the Beryllium pipe remains in the few keV range where only a tiny fraction, of order 10^{-9} corresponding to one photon per bunch crossing would traverse the beam pipe and enter the detector region.

SYNRAD+

SYNRAD+ generates and traces SR photons emitted by a given beam in a given magnetic field. The user has thus to provide the magnetic fields (dipoles, quadrupoles and so on), the beam parameters (emittance, energy spread and so on) at the entrance of each magnetic element, since the program does not track beam particles outside magnetic elements (i.e. in drifts), while it performs a full track of the emitted photons. Also the actual beampipe geometry has to be provided, since the program is able to perform a full simulation of the optical interaction (reflection, absorption) of the incident radiation with the pipe material, based on the the appropriate optical properties provided to SYNRAD+. For this part of the study, the optics version *fcc_hh_v6_45* was used [8]. In particular, the twiss file generated by MAD-X was used to input the characteristics of the beam at each point, while geometry and magnetic fields for the last ~ 700 m of pipe were manually created from optics apertures. All the materials were assumed to be perfect absorbers of the incident radiation, to be coherent with the MDISim part of the study.

There is a significant difference between the SYNRAD+ geometry and the MDISim one, given by the fact that some unphysical situations arise when simply importing optics apertures, in particular in the recombination chamber between the two beams, as shown in Fig. 4. In the SYNRAD+ simulation, a “LHC-like” geometry for the recombination chamber has been used, as visible in Fig. 4, where SR photons are also shown.

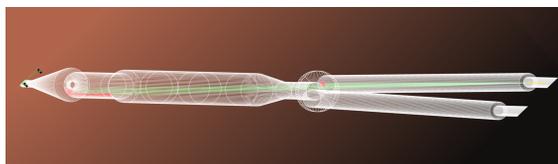


Figure 4: SYNRAD+ simulation of the last 700m towards the IP. In the middle it is visible the “LHC-like” recombination chamber, discussed in the text.

Once the 3D model is built, SYNRAD+ allows us to calculate power and spectrum of radiation hitting a certain surface by simply selecting it. The study was performed independently for the different magnetic elements (dipoles and quadrupoles), and for both cases with or without crossing angle. The results are summarised in Tab. 4.

Table 4: Summary of SR power emitted in the last 500 m that enters the TAS , coming from the SYNRAD+ simulation.

Element	P_{Cr} [W]	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

SUMMARY

In the development of a Future Circular Collider with unprecedented energies and luminosities a careful study of all the background sources is crucial, also regarding Synchrotron Radiation entering the Interaction Area. In this paper, a systematic study has been presented, following two different and independent programs, MDISim and SYNRAD+. Both models predict that the power load inside the TAS will be close to 10 W, with small differences between the case with crossing angle and without it. Concerning the load on the inner Be pipe, about 0.5 W are expected, with a very low number of photons traversing the beam pipe.

Both programs allow for a fast update of the SR estimate to be performed after optics changes. However, we do not expect significant lattice modifications that could change our conclusions on the SR in the experiments.

The difference between the two approaches for the power entering the TAS can be attributed to differences in the vacuum chamber geometry implemented in the two codes. While MDISim uses the horizontal and vertical apertures provided in the optics files, with circular/elliptical apertures, SYNRAD+ implements more detailed vacuum chamber geometries similar to the ones used in the LHC and foreseen for HL-LHC, in particular the recombination chamber between the D1 and D2 dipoles. This discrepancy is believed not to affect the conclusions.

It has to be noted that for both calculations no real geometry for the Inner Triplets’ (IT) beam screens (BS) has been considered. At this point in time a geometry envisaging an internal distributed tungsten liner from Q1a to at least D1, similar to what is being done for HL-LHC, is probable, but lack of details at time of writing this paper have not allowed us to formulate a detailed geometry of the FCC-hh IT BS and analyse it.

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