SIMULATING PROTON SYNCHROTRON RADIATION IN THE ARCS OF THE LHC, HL-LHC, AND FCC-hh

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Outline

Introduction

We use the Synrad3D code, developed at Cornell, to simulate the photon absorption distributions in the arcs of the LHC, HL-LHC, and FCC-hh.
Specifically,

- for the LHC we study the effect of the "sawtooth" in chamber
- for the HL-LHC the consequences of the ATS optics with large beta beating in the arcs
- for the FCC-hh the effect of a novel beam-screen design, with a long slit surrounded by a "folded" antechamber.

Motivation

At high proton-beam energies, beam-induced synchrotron radiation is an important source of:

1. Heating
2. Beam-related vacuum pressure increase
3. Primary photoelectrons
   - Electron clouds

Software

- The simulation code Synrad3D developed at Cornell [1] generates and tracks synchrotron radiation photons in the beam lines of accelerators.
- It includes both specular and diffuse reflection on the chamber surface.
- The photons are generated randomly at any point in the lattice with a distribution appropriate for the local bending radius.
- When a photon hits the chamber wall the reflection probability depends on the energy and angle of incidence as well as the material and its surface roughness.
  - Reflectivity tables provided by the LBNL Center for X-Ray Optics.

Simulations

- The lattice for the accelerators were taken from CERN's repositories.
- The wall
  - The reflectivity was taken from LBNL for a 10 nm C layer over Cu.
  - Shape of the vacuum pipe was taken from technical drawings for the LHC and from a design of R. Kersevan for the FCC-hh.
- Photons with an energy lower than 4 eV are ignored.

Studied cases

1 LHC

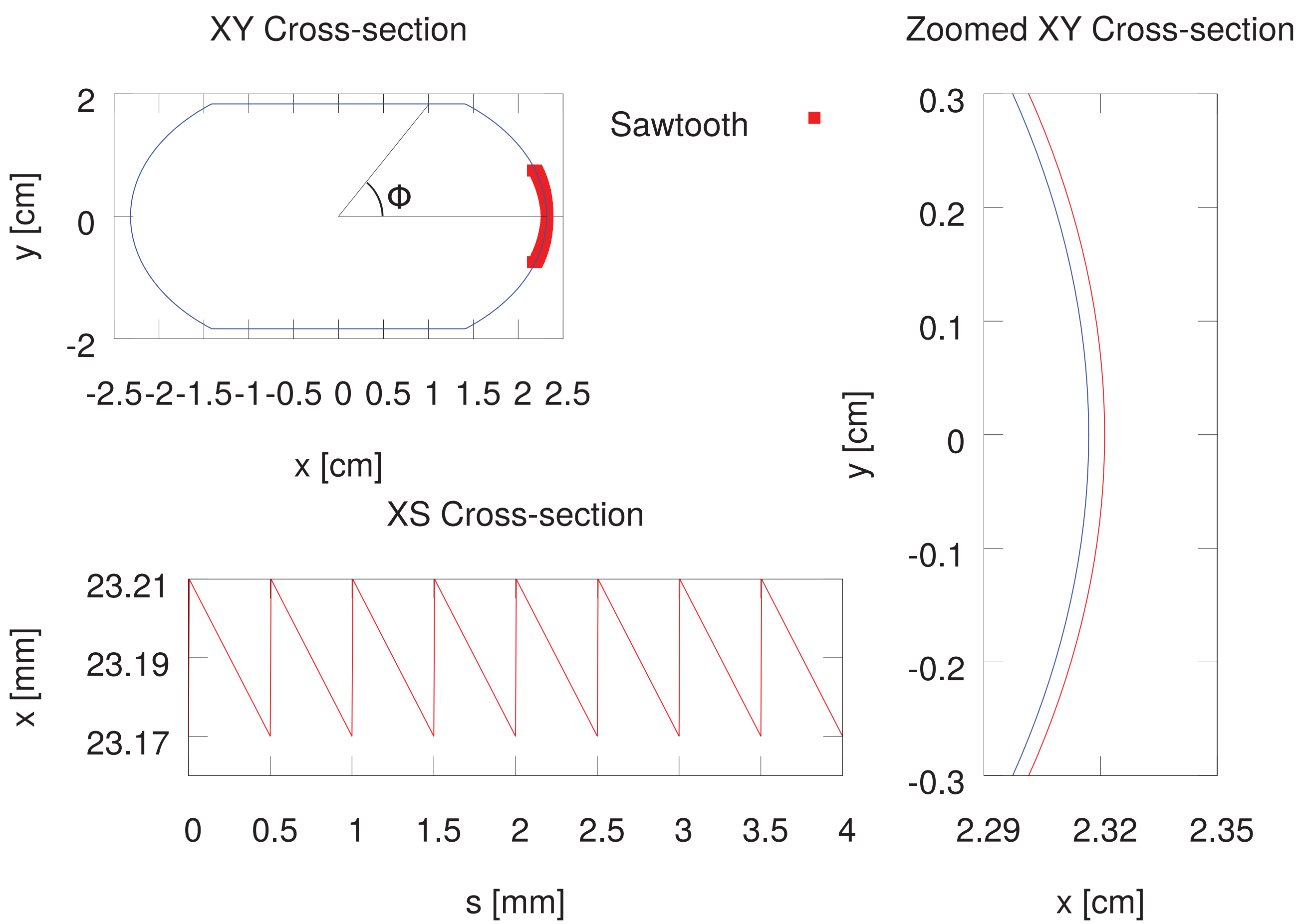
2 HL-LHC

3 FCC-hh

LHC

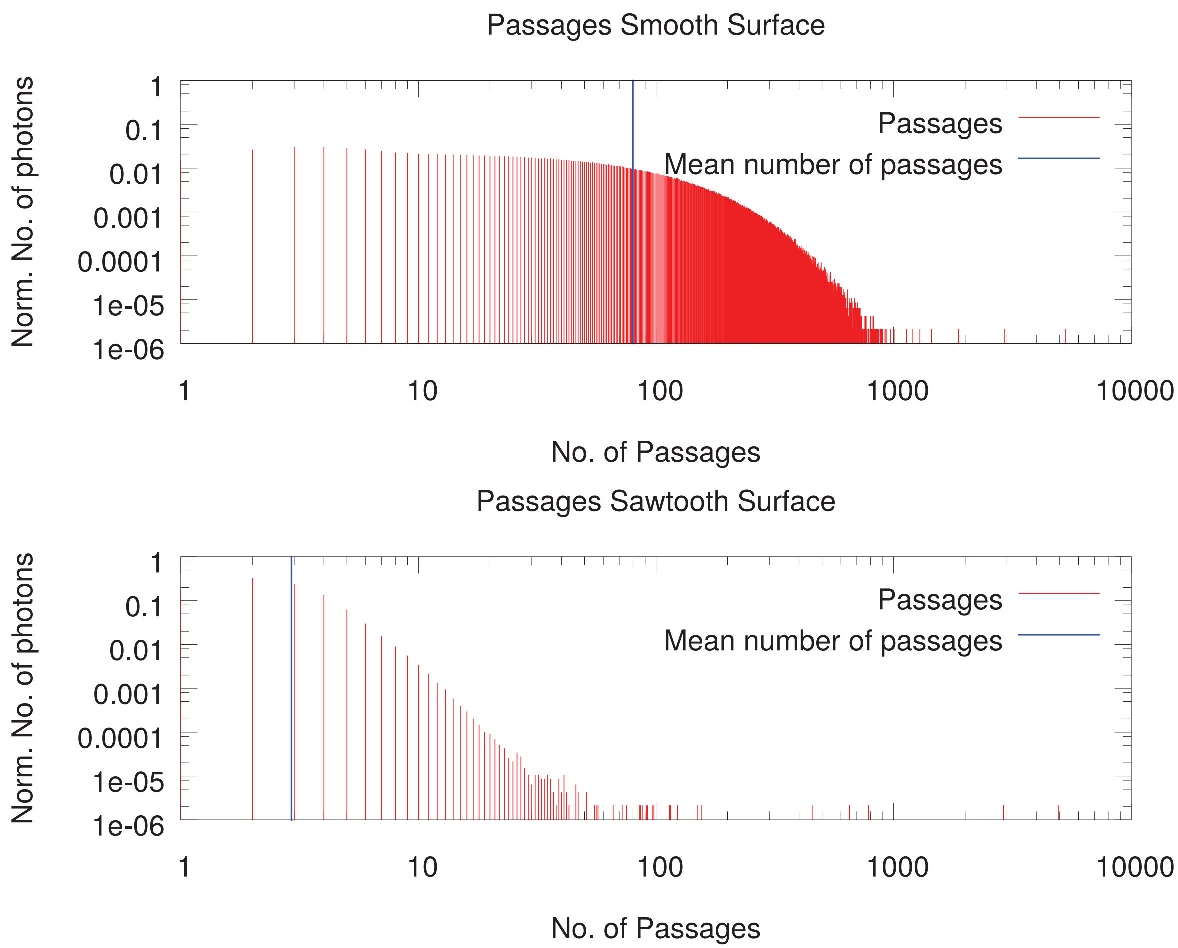
- Two cells of the LHC were simulated and periodic conditions were set.
- To see the effect of the sawtooth pattern on the wall of the LHC simulations were run with and without the sawtooth pattern.

LHC Beam Pipe Cross-Section



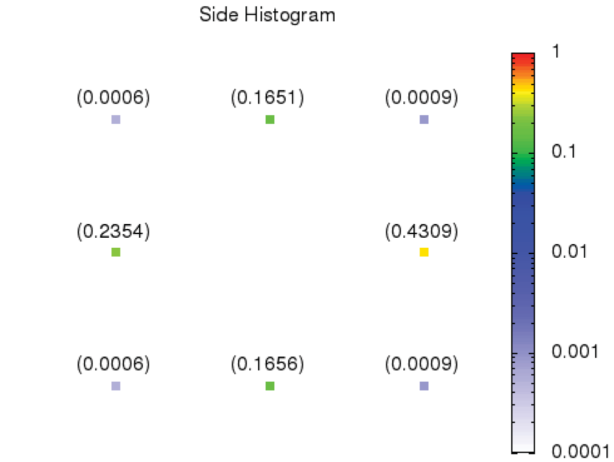
Passages

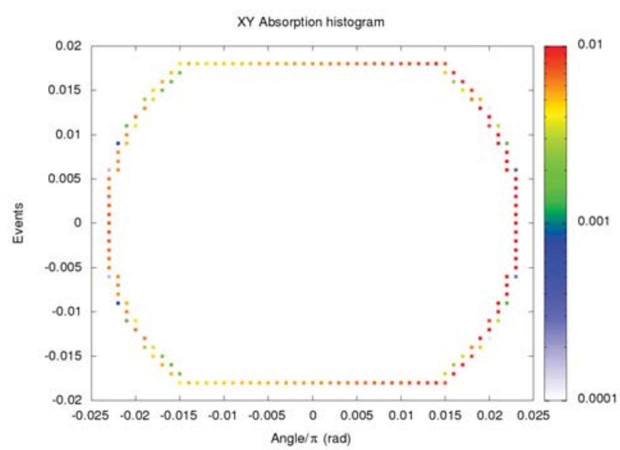
Passages=Reflections+1



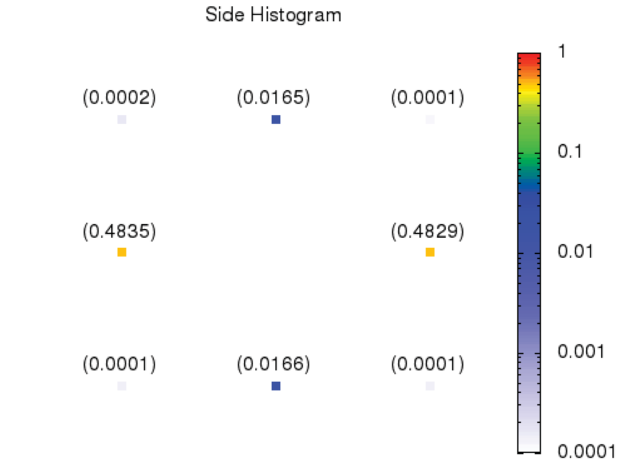
Photon absorption

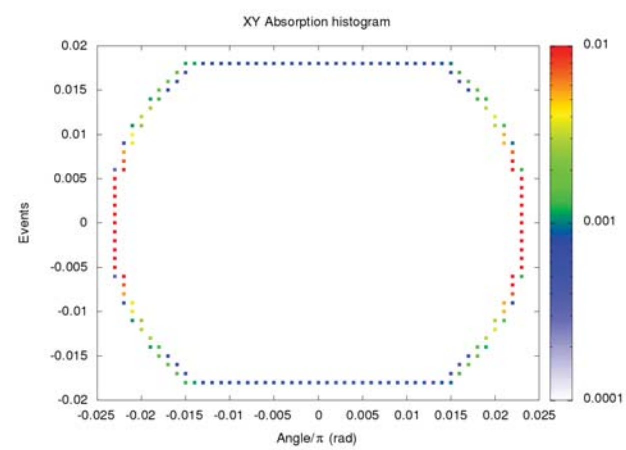
Smooth surface



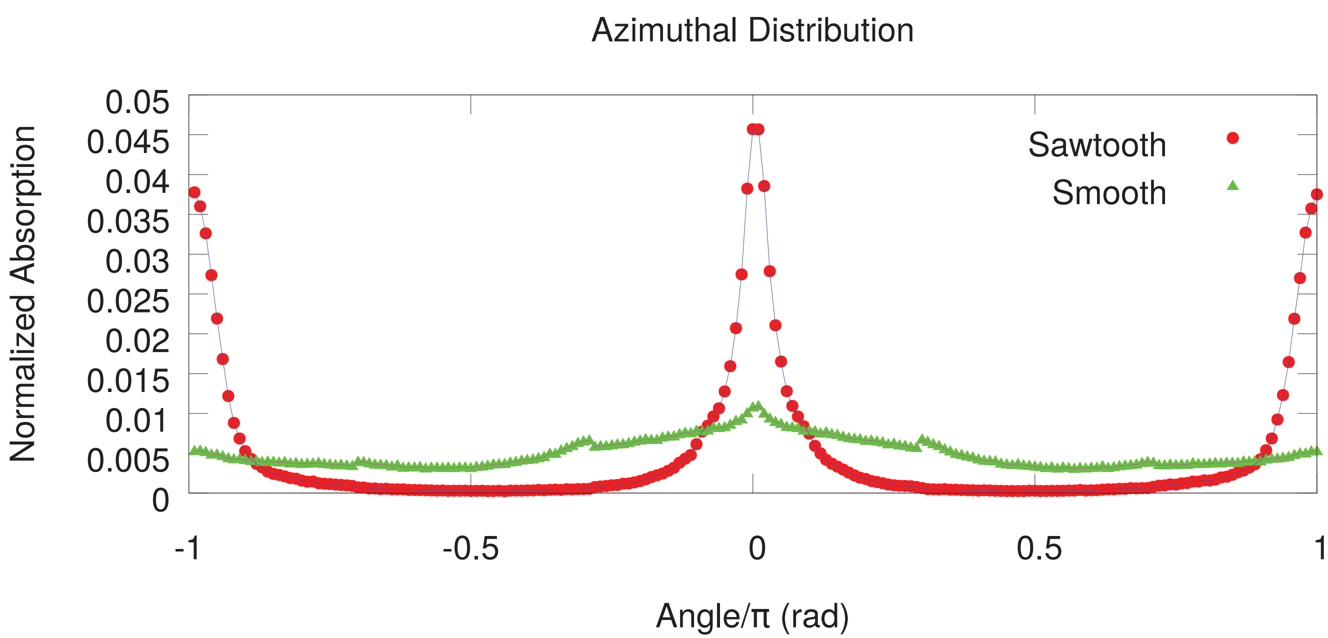


Sawtooth Pattern





Angular Distribution



Results

- With the sawtooth present, only 2% of the photons were absorbed on each of the top and bottom surfaces
- Without the sawtooth 16% of the photons were absorbed on each on the top and bottom of the chamber.

	% of absorption		
Simulation	**top,bottom**	primary impact side	opposite side
Sawtooth	**2%**	48%	48%
Smooth	**16%**	43%	24%

Results

- These results, in particular the change in the azimuthal distribution due to the sawtooth surface, are roughly consistent with experimental measurements in open setups (i.e., with a limited length of test chamber) at VEPP-2M [8, 9, 10] and ELETTRA [11].

Comparison with experiments (smooth)

- The VEPP-2M measurements for a smooth copper-coated chamber without sawtooth at 20 mrad grazing incidence revealed a photon forward reflectivity R of up to 95%[9]. This would correspond to an average number of $n_{\mathrm{pass}} = 1/(1 - R) \approx 20$ photon passages through the chamber until absorption. Adding another 2–4% diffusely reflected photons [9], the average number of photon passages in the measurements would be between 33 and 100, which is consistent with the value of about 80 found by the Synrad3D simulations.

Comparison with experiments (sawtooth)

- For the sawtooth surface a much lower total reflectivity of about 10% was measured [11]. This translates into an average number of passages not much above 1, while the Synrad3 simulations predict a value below 3

Conclusions

- The almost 10-fold reduction of photons hitting the top and bottom of the chamber confirms the intended effect of the sawtooth structure: to greatly decrease the number of photoelectrons generated above and below the beam in the arc dipole magnets, where, following the vertical field lines, they could approach the beam and contribute to further electron-cloud build up.

Studied cases

1 LHC

2 HL-LHC

3 FCC-hh

HL-LHC

- The HL-LHC will have nearly twice the beam current of the LHC, which will approximately double the photon flux.
- In the arcs, a second main difference between the LHC [4] and the HL-LHC [12] is a beta wave introduced through the long adjacent arcs in order to squeeze the β^* at the two high-luminosity collision points.
  - This scheme for the optics is called the achromatic telescopic squeeze (ATS) [13].

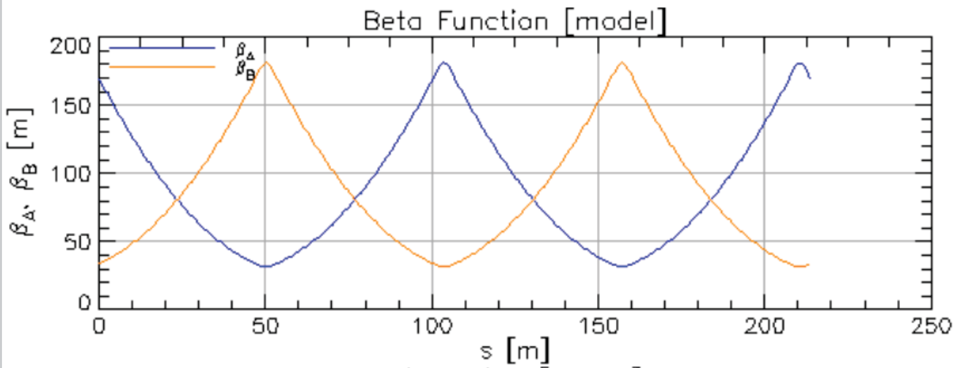
ATS

ATS exists in:

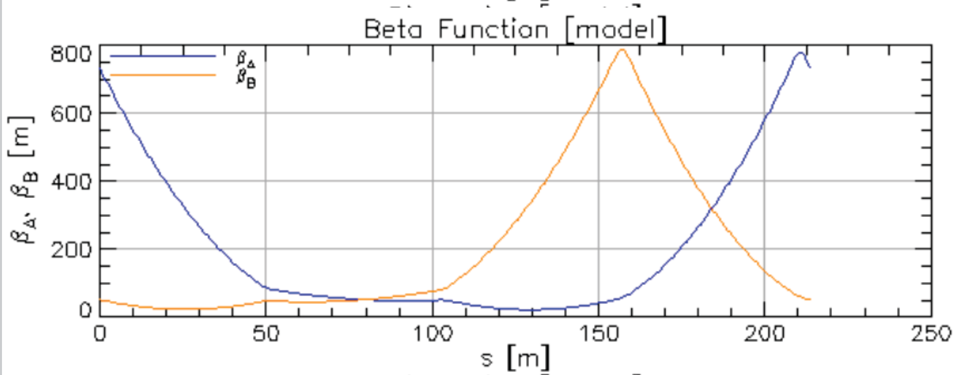
- Round ($\beta_x^* = \beta_y^*$)
- Flat configurations ($\beta_x^* \gg \beta_y^*$ in one IP, and $\beta_x^* \ll \beta_y^*$ in the other).

With a large vertical beta beat in the arcs 45 and 56, the distribution of photons hitting the chamber wall (and being absorbed there) may change.

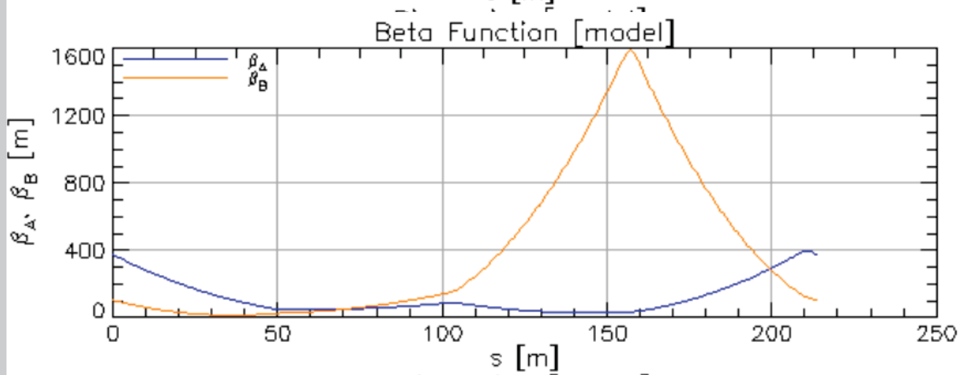
Beta Function at the arcs for different optics



Pre-squeezed ($\beta_{y,min} \approx 32$ [m])



Round($\beta_{y,min} \approx 24$ [m])



Flat($\beta_{y,min} \approx 16$ [m])

Expected Results

Considering that the nominal geometric RMS emittance, ϵ_y, of about 0.3 nm the corresponding maximum RMS divergence of $\sigma_{y',\mathrm{max}} \approx (\epsilon_y/\beta_{y,\mathrm{min}})^{1/2} \approx 5 \times 10^{-6}$ is still much smaller than the RMS angle of the photon emission, $\sim 1/\gamma \approx 1.3 \times 10^{-4}$. Therefore, no large effect of the ATS optics on the photon distribution is expected.

Results

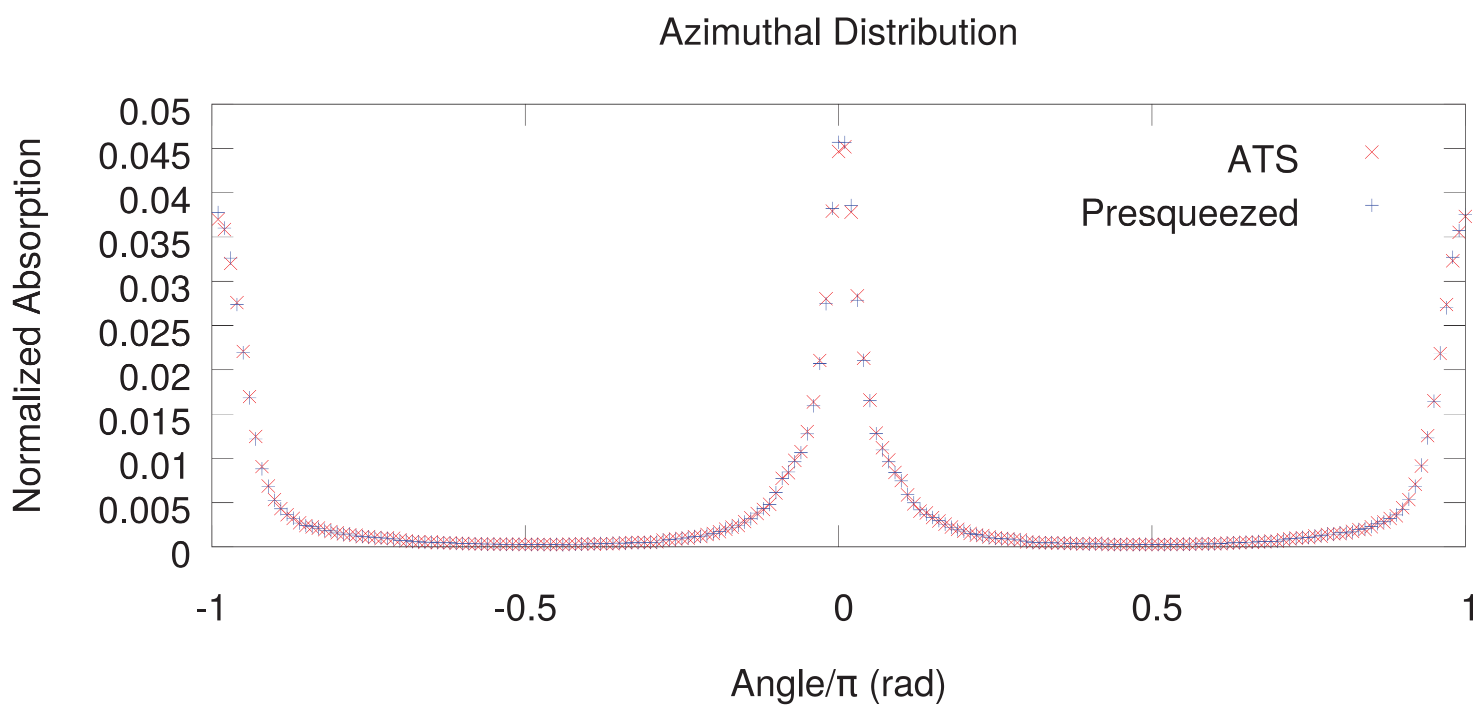
SR Simulations

Guillermo, Sagan, Zimmermann

LHC

HL-LHC

FCC-hh



Conclusions

- The expectation is confirmed by Synrad3D simulations: The ATS optics does not change the photon distribution for the HL-LHC arcs

Studied cases

1. LHC
2. HL-LHC
3. FCC-hh

FCC-hh

SR Simulations

Guillermo, Sagan, Zimmermann

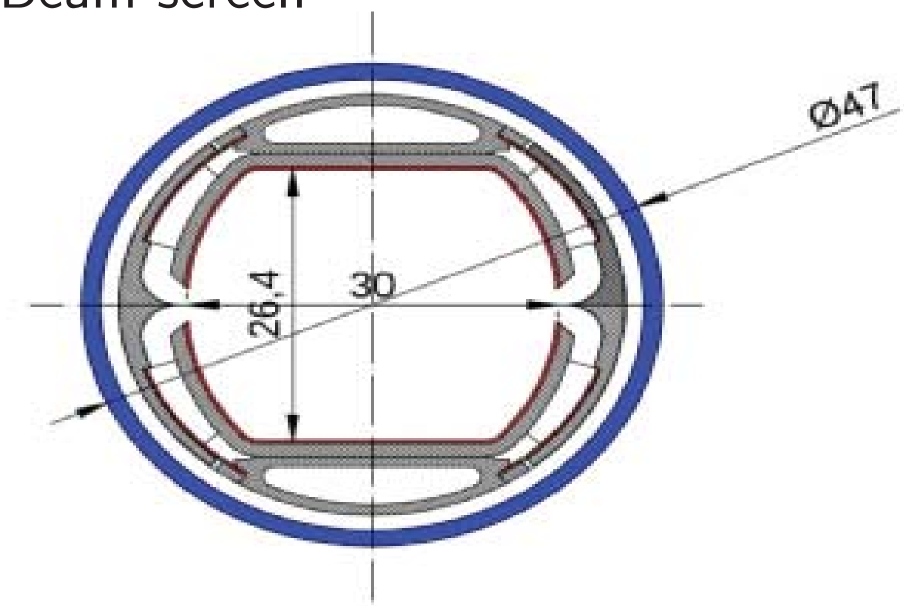
LHC

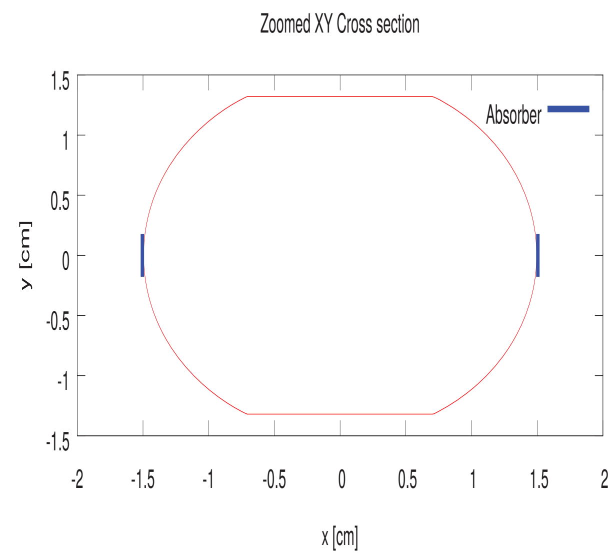
HL-LHC

FCC-hh

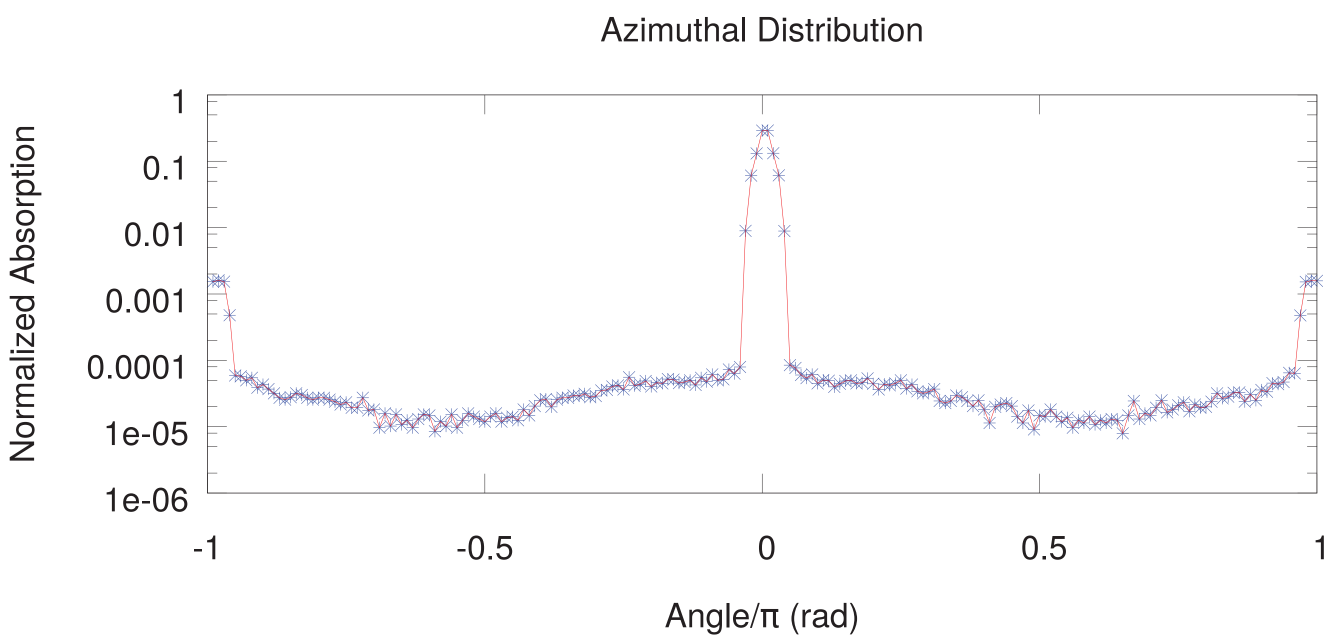
The FCC-hh will feature novel beam-screen shapes with an integrated compact antechamber.
Slots in the equatorial plane with a vertical full height of 3 mm will absorb most of the photons, thereby facilitating the beam-screen cooling and stabilizing the beam vacuum [14, 15].

Beam screen





Results


Azimuthal Distribution
Normalized Absorption
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
-1
-0.5
0
0.5
1
Angle/π (rad)

Results

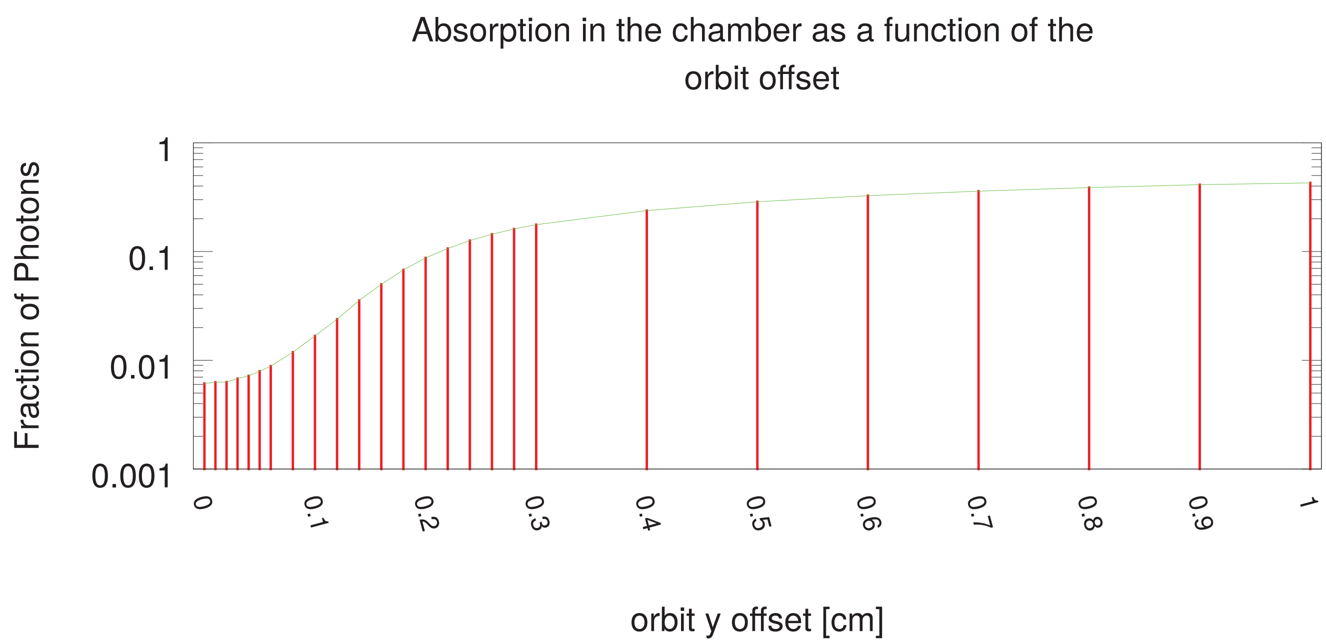
SR Simulations

Guillermo, Sagan, Zimmermann

LHC

HL-LHC

FCC-hh



Conclusions

- For a centered orbit, a fraction of 0.6% of the emitted photons is being absorbed at the beam screen outside of the absorber slots.
- The dependence of this fraction on a vertical orbit offset, sets a tolerance on the acceptable closed-orbit distortions in the FCC-hh of about 1 mm in order to keep the fraction of the emitted photons absorbed at the beam screen below 1%

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