Synchrotron Radiation Background Studies @ FCC-ee

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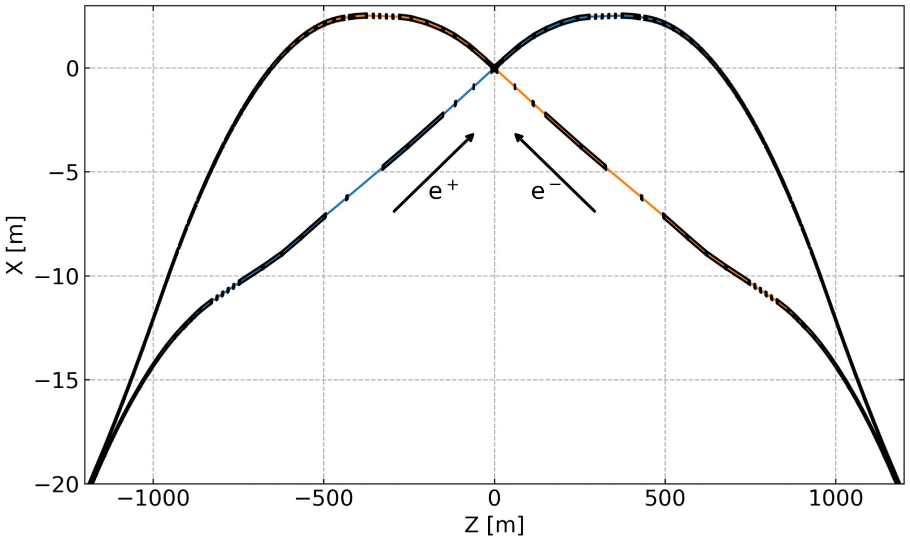
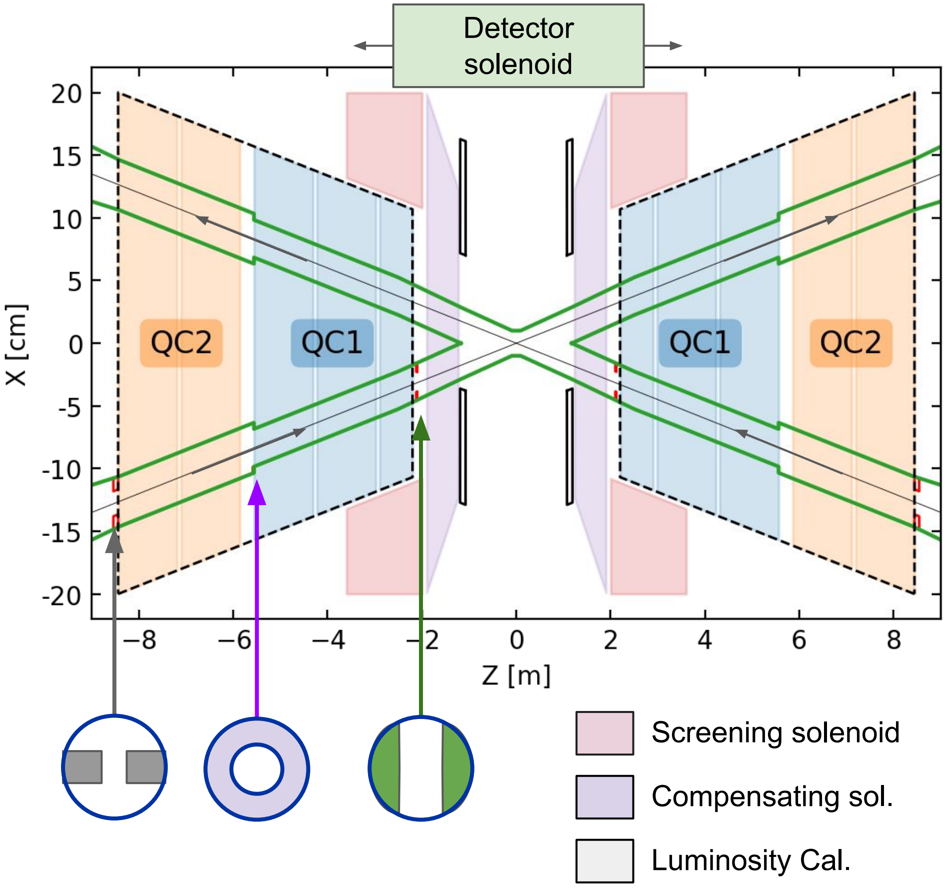
Outline

- FCC-ee lattice, aperture profile, masks and collimators
- Synchrotron radiation collimation scheme
- Results from SR background simulations
  - at the Z operation mode
  - at the tt operation mode
- Update on SR background from top-up injection
- Summary

Mode	Z	W	H	$t\bar{t}$	Unit
Energy	45.6	80	120	182.5	GeV
Beam current	1280	135	26.7	5.0	mA
Bunches / beam	10000	880	248	40	
Bunch population	2.43	2.91	2.04	2.37	10^{11}
Horizontal emittance	0.71	2.16	0.64	1.49	nm rad
Vertical emittance	1.42	4.32	1.29	2.98	pm rad
$\beta^*_{x/y}$	100/0.8	200/1.0	300/1.0	1000/1.6	mm

FCC-ee lattice | IR design



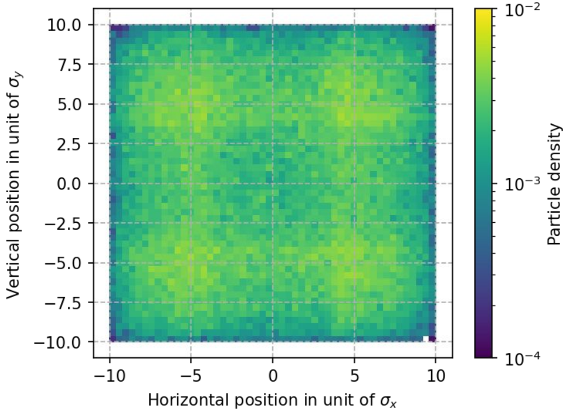


The lattice design upstream the IP is based on weak dipoles and long straight sections. There is a **30 mrad crossing angle** at the IP. The central beam pipe radius is **10mm** over **18cm** along the Z axis. The beam pipe radius is 15mm in QC1 and 20mm in QC2.

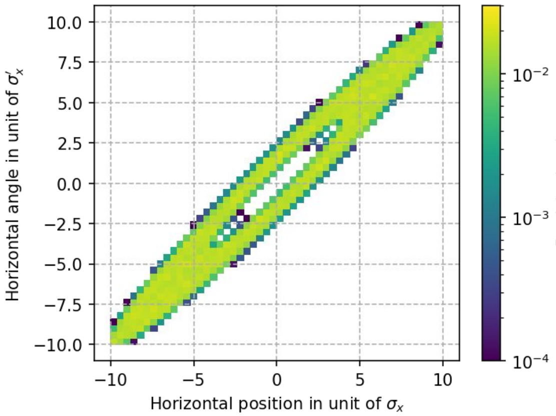
Beam model | Core and tail description

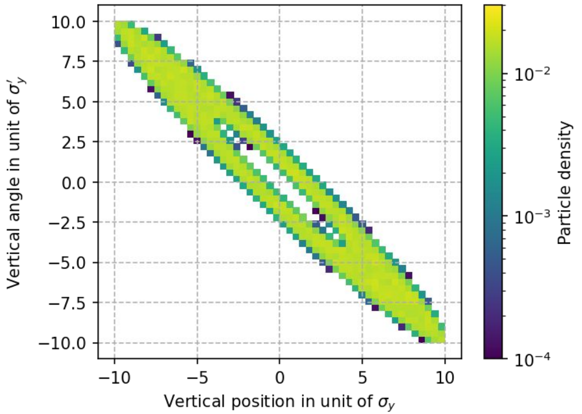
Previous studies from M. Sullivan [1, 2] showed that the non-gaussian beam tails will create a large amount of photons especially in the final focus quadrupoles, hence it needs to be modeled and studied.

Gaussian distribution for the beam core extends to around 4(5) sigmas and a **correlated uniform distribution** is used to fill the X-X' (and Y-Y') phase space from **3.5 σ_x to 6 (8 or 10) σ_x** along the horizontal positions and angles and from **3.5 σ_y to 30 (50 or 60) σ_y** along the vertical positions and angles. Assuming **98%** of the particles **in the core** and **2% in the tails**.



Uniform along X-Y





Correlated in X-X' and Y-Y'

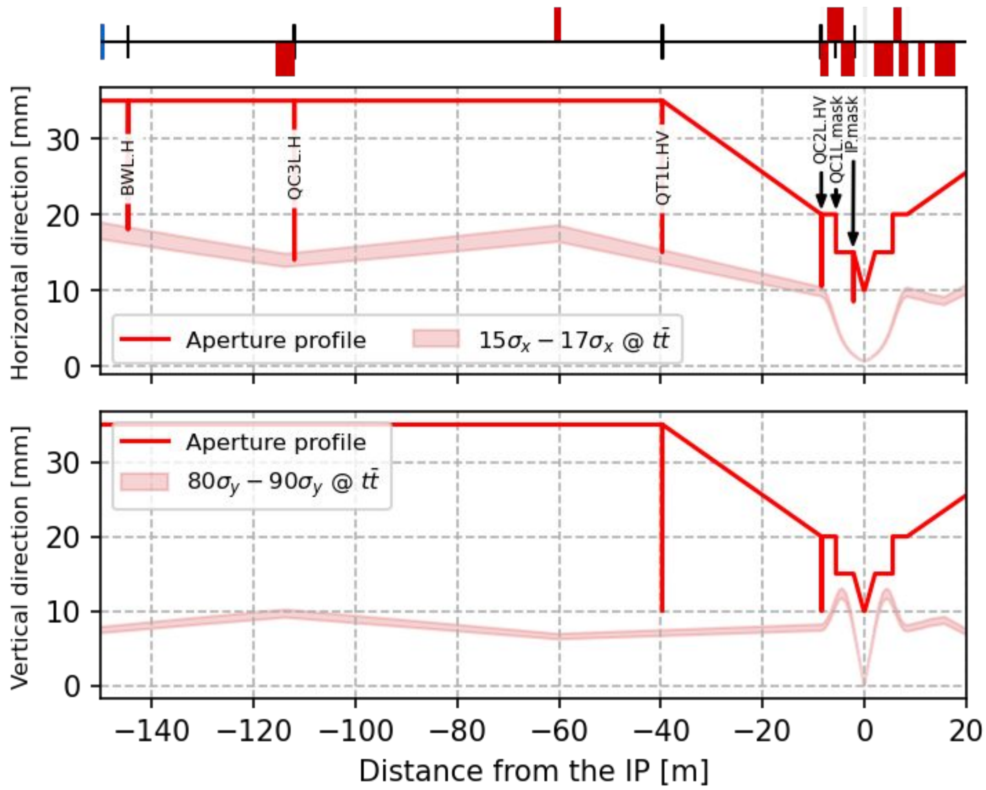
Synchrotron radiation collimation scheme and beam halo collimation

Synchrotron radiation collimation scheme

Name	s [m]	half-gap [m]	plane
BWL.H	-144.69	0.018	H
QC3L.H	-112.05	0.014	H
QT1L.H	-39.75	0.015	H
PQC2LE.H	-8.64	0.011	H
MSK.QC2L	-5.56	R = 0.015	H&V
MSK.QC1L	-2.12	0.007	H

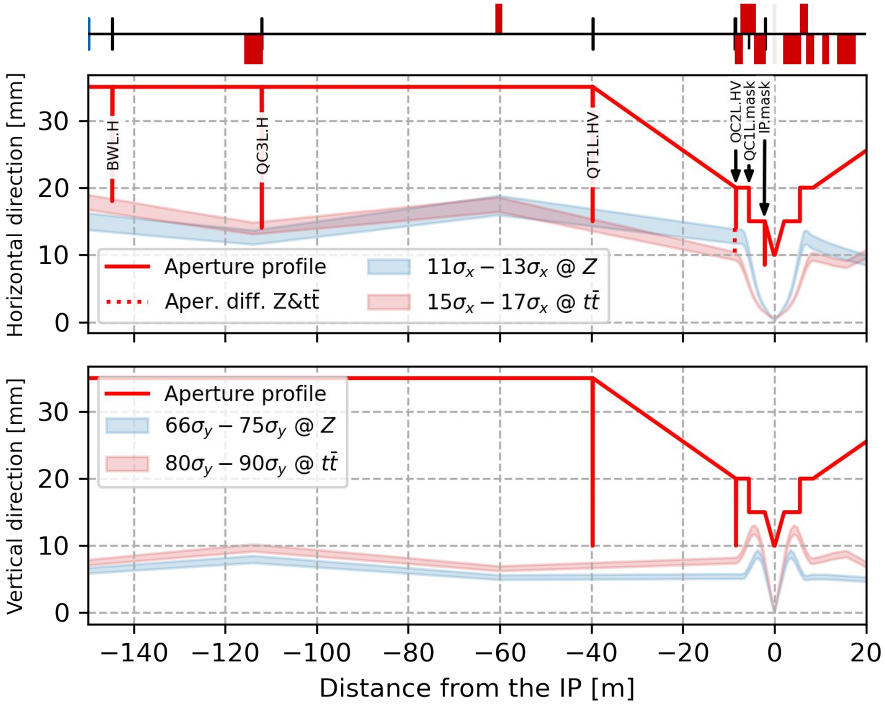
15 σ_x corresponds to the aperture of the **primary** collimators, **17 σ_x** corresponds to the aperture of the **secondary** collimators.

→ See A. Abramov talk for more details.



Synchrotron radiation collimation scheme

Name	s [m]	half-gap [mm]	plane
BWL.H	-144.69	18	H
QC3L.H	-112.05	14	H
QT1L.**H**	-39.75	15	H
QT1L.**V**	-39.65	10	V
PQC2LE.**H**	-8.64	11→12	H
PQC2LE.**V**	-8.54	10	V
MSK.QC2L	-5.56	R = 15	H&V
MSK.QC1L	-2.12	7 to 8	H



The collimators closer to the IP need wider apertures from tt to Z operation mode. The reduction in aperture covered by the mask QC1L.mask is protected by the collimator upstream. There are no issues in the vertical plane. The synchrotron radiation collimation schemes are shown for the two other energy modes in annex.

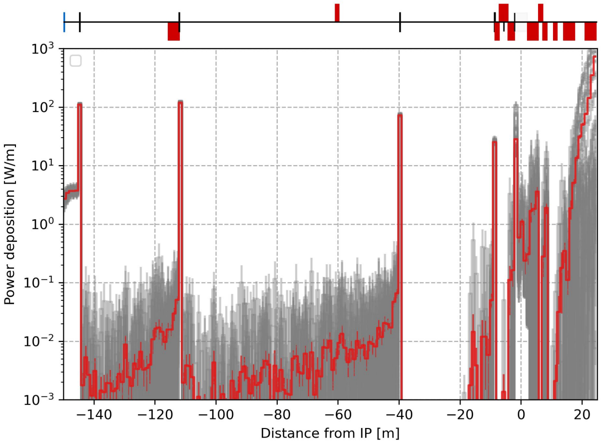
Z operation mode

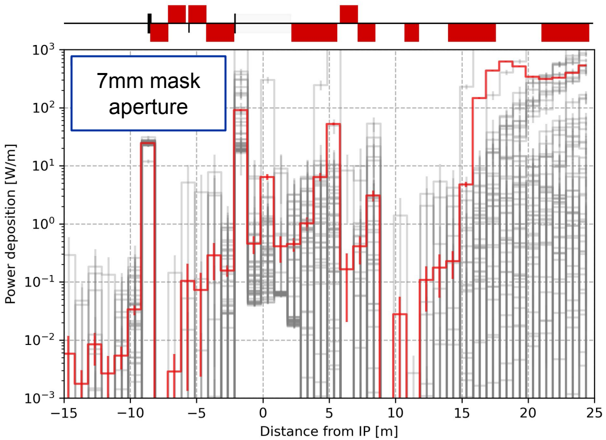
Synchrotron radiation collimation at the Z mode - Jitter

Hor. & Ver. beam jitter **only** with $\sigma_{x,y}$ = 100 microns do not show significant difference with the case without beam jitter.

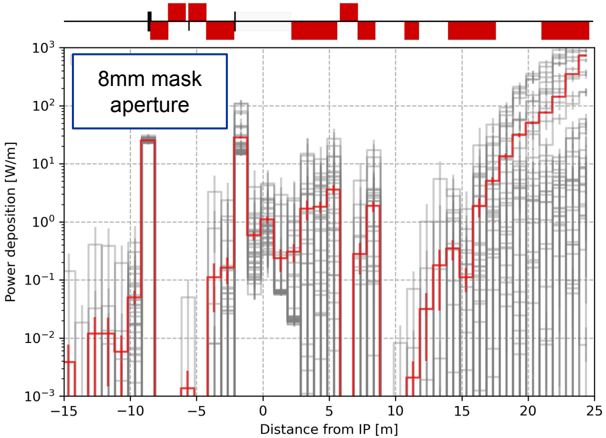
However, a value of the transverse beam direction jitter beyond ± 15 µrad.

Beyond this number a large amount of SR power is deposited near the IP, mostly due to SR created in the FF quadrupoles upstream or the solenoid.





Simulations made with a Gaussian positron beam with jitter of $\sigma_{x,y}$= 100 microns and $\sigma'_{x,y}$= 10 microradians. The grey color highlights 50 simulations, the red is the average.



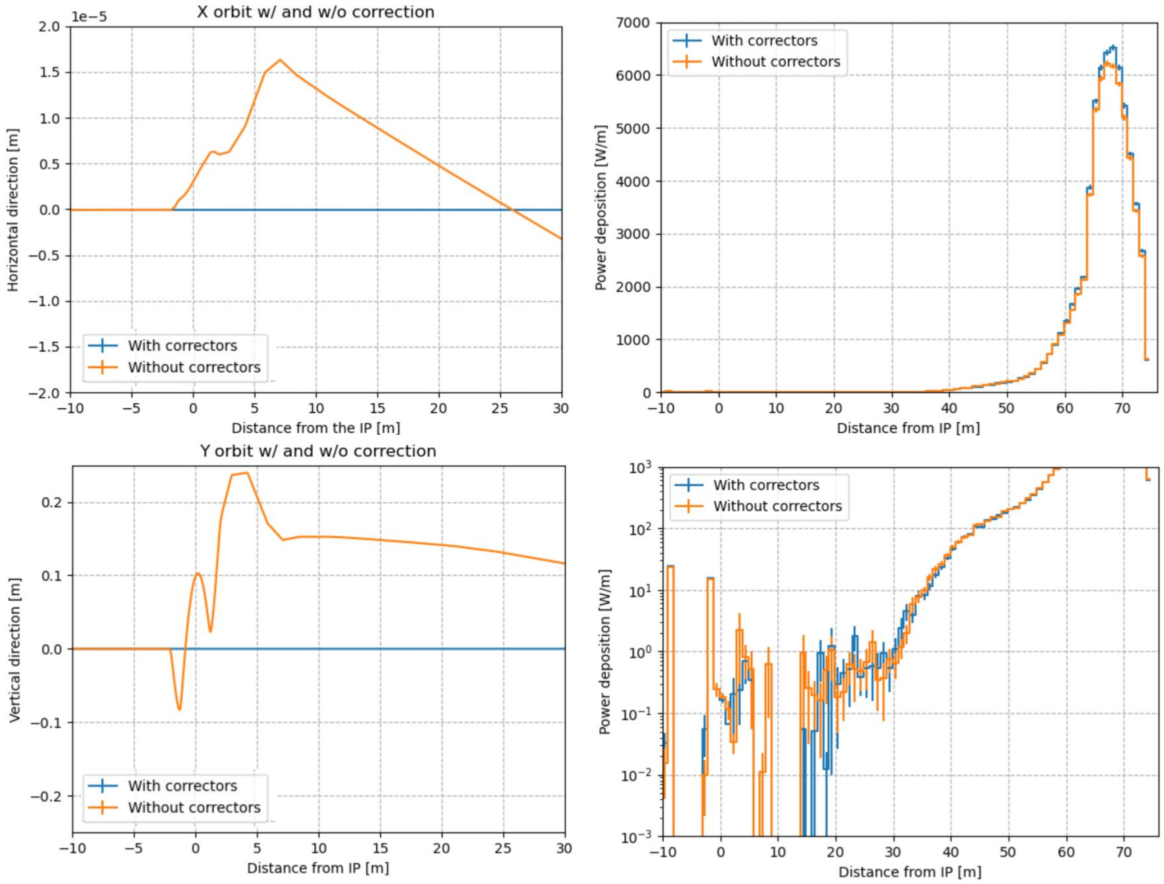
Effect of orbit correctors around the IP - H. Burkhardt

The original (anti-)solenoid field map has been modified by H. Burkhardt with 2 correctors on either side of the IP to correct the orbit in position and angle.

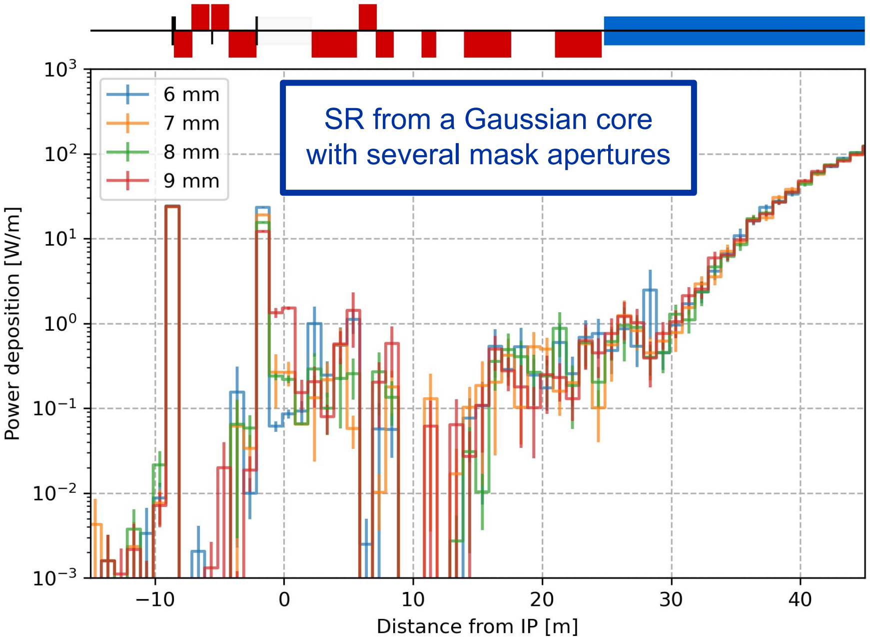
The orbit is corrected to the nm and nrad levels.
The field map with orbit correctors included radiate **3.2 kW** additional SR power (at Z energy).

Next steps:

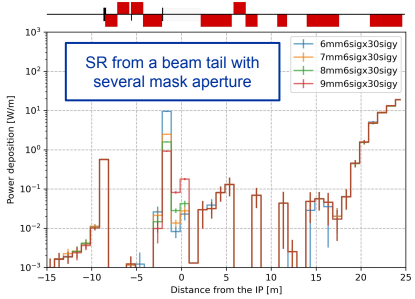
- Does it reduce the SR from quadrupoles downstream ?
- Impact considering transverse beam tail.

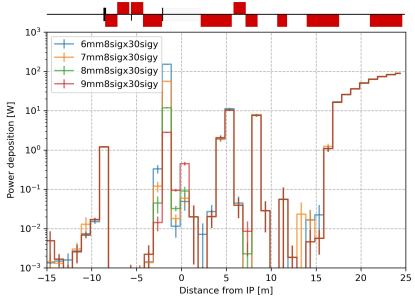


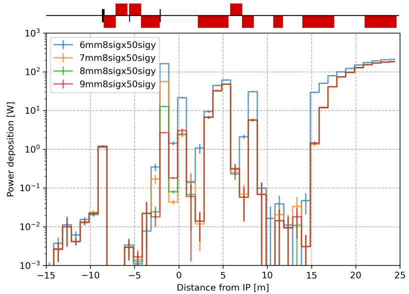
Synchrotron radiation collimation at the Z mode - Core/Tail

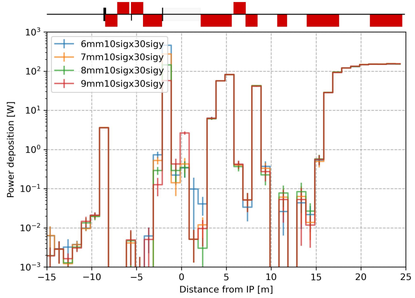


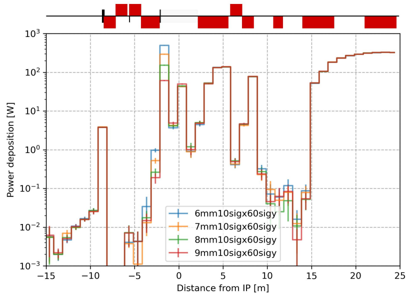
A smaller aperture of the last mask reduces the power deposited in the central chamber. Leaving only the SR from the solenoid fringe field. 6 mm is better than 7 and 8 mm with same result and 9 mm is not sufficient.











With increasing horizontal tail width the mask gets more SR heat load.
With increasing vertical tail width more SR photons hit the central chamber.

Estimate of SR power deposition from transverse tail

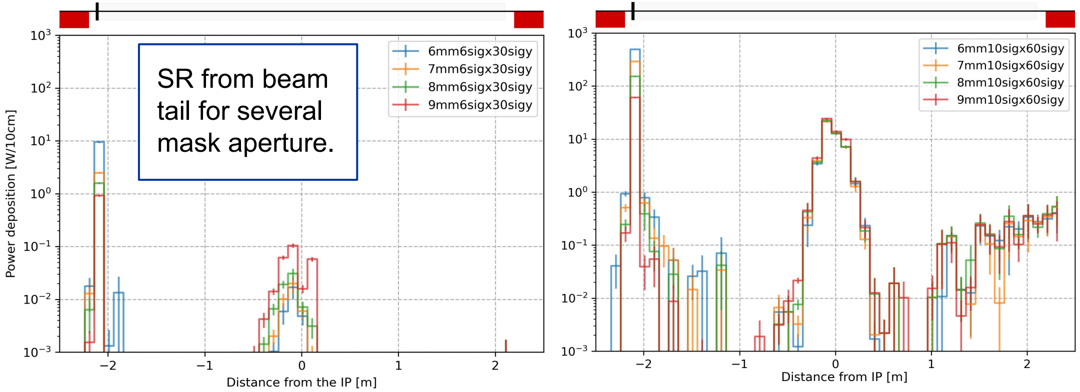
Which tail distribution (assuming 2% of the particles in the tail) causes equivalent SR power deposited w.r.t. SR from the beam core ?

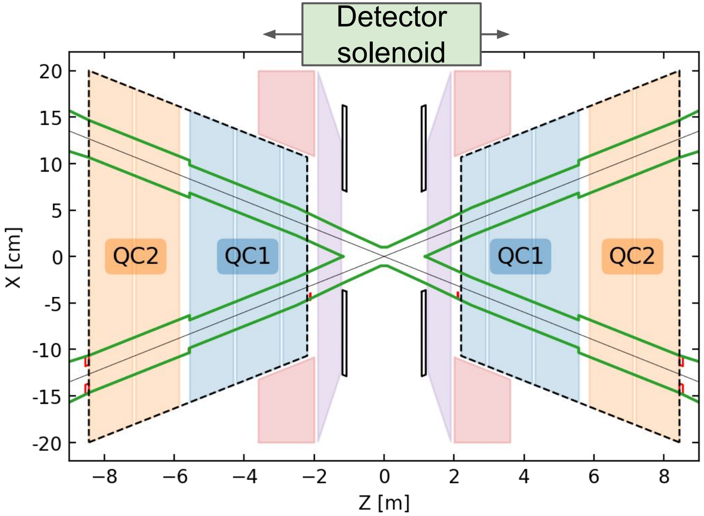
- Power deposited in the **last mask**, it is between 6 and 8 σ_x equivalent to 50 to 75% of the primary collimator aperture.
- Power deposited in the **CC**, it is 10 σ_x and 30 σ_y equivalent to 90% horizontally (the mask gets large heat load protecting the CC and 50% of the vertical primary collimator aperture because the solenoid and FF quadrupoles do not radiate too much vertically.
- Power deposited in the **FF quadrupole beam pipe** downstream the IP between 6 and 8 σ_x equivalent to 50 to 75% of the primary collimator aperture.

In summary, horizontal tails even large can be intercepted by the last mask and produce equivalent power deposition as the beam core provided the mask withstand the heat load.

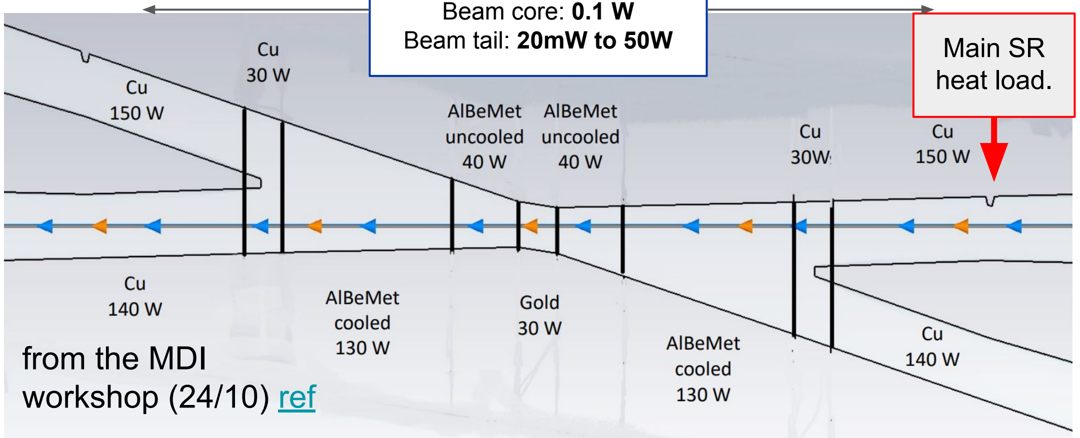
However, large vertical tails cause SR photons emitted mostly vertically and cannot be stopped before the CC unless the central chamber is widened. (up to the same heat load as the wakefield contribution).

Comparison with wakefield heat load





s = +/- 2m
Beam core: **0.1 W**
Beam tail: **20mW to 50W**



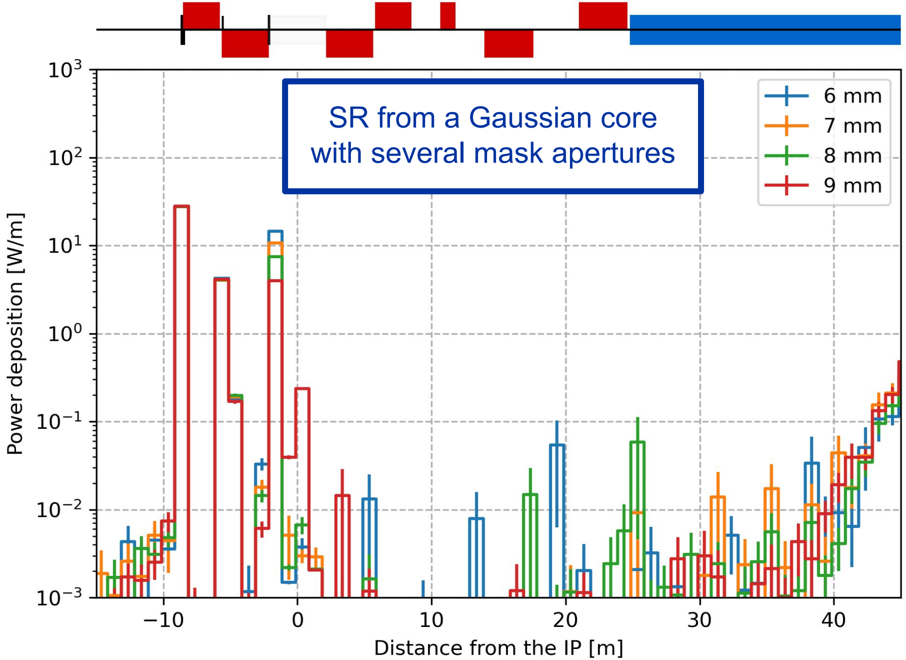
from the MDI workshop (24/10) ref

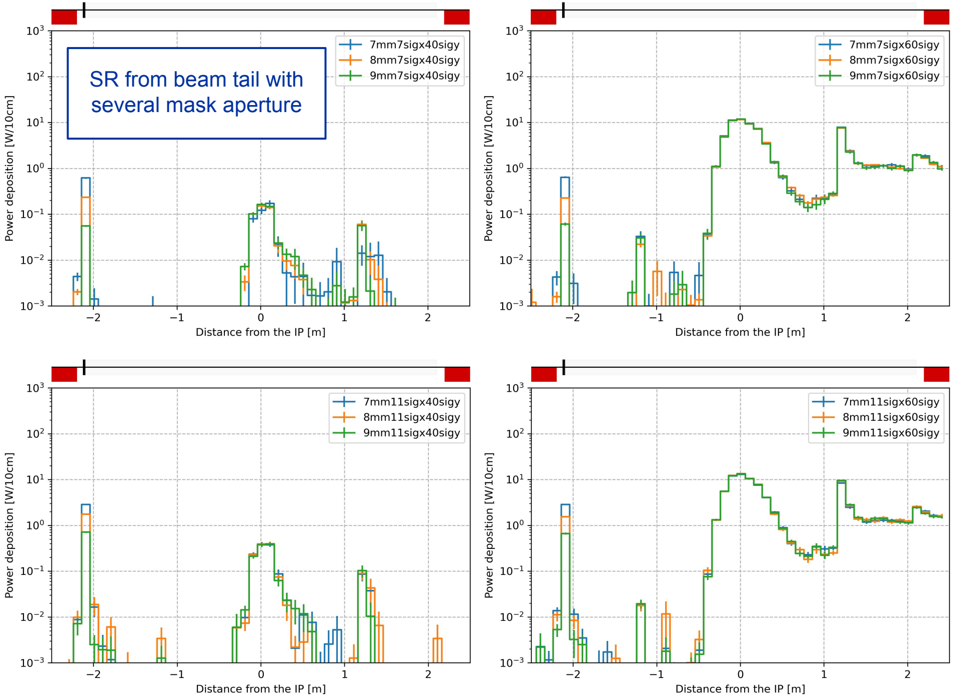
Most of the SR power is deposited in the tungsten mask and in the Gold and AlBeMet sections **uncooled**, ∓35cm around the IP.

In case of large vertical tails and 2% of the beam current outside the beam core; the SR heat load can be equivalent to the wakefield heat load.

tt operation mode

Synchrotron radiation collimation at the **tt mode** - Core/Tail

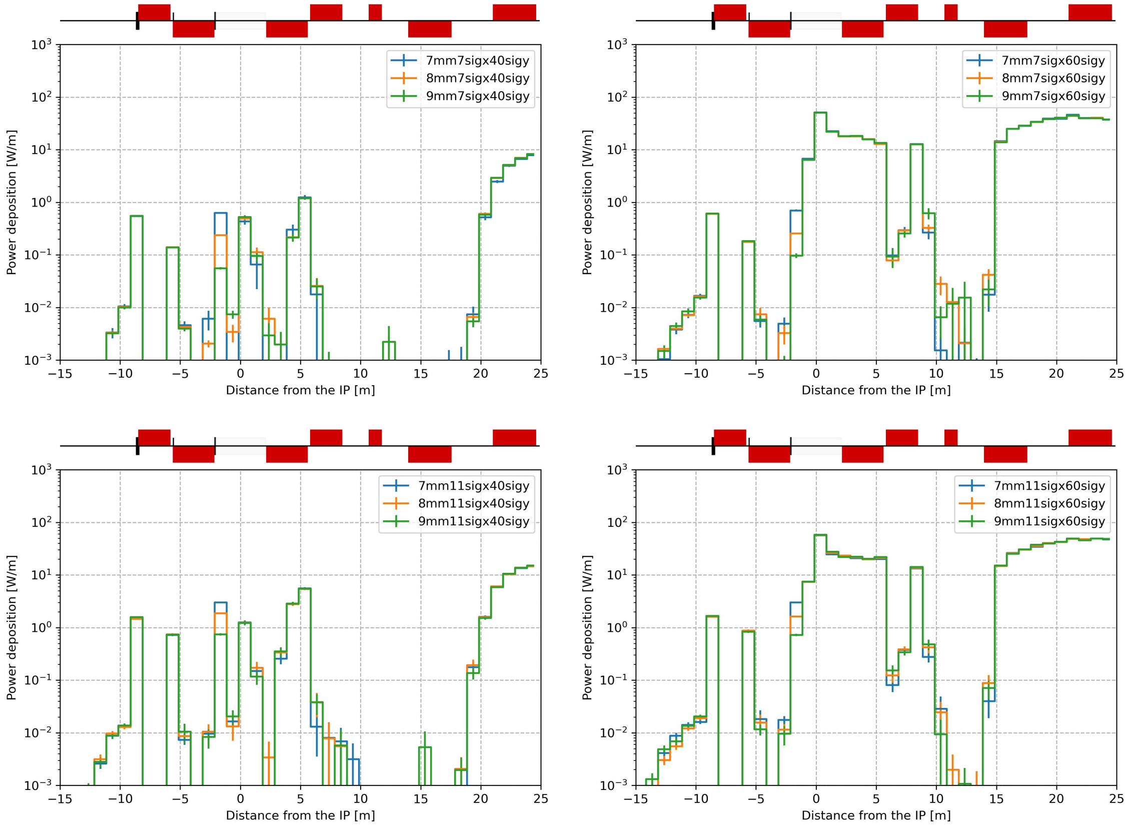




A smaller aperture of the last mask reduces the power deposited in the central chamber. Mask aperture of 6, 7 and 8 mm provide the same heat load in the CC. Similarly to the Z energy, 9 mm is not sufficient.

The extension of the horizontal tail increases the heat load on the mask. Vertical tail extending to 60 σ_y create a non negligible heat load on the CC.

Synchrotron radiation collimation at the **tt mode** - Tail



The heat load from SR created by particles in the tail on the mask does not reach the same, large value, with respect to the Z energy.

However, considering vertical tail extending to 60 σ_x (eq. to 75% of the primary vertical halo collimator), rather large SR power can be deposited.

The variation of the mask aperture has little impact on the power deposited on the CC.

Off-axis top-up injection (ref)

Parameters involved in the SR background studies from off-axis beam injection at 45.6 GeV

The horizontal emittance of the injected beam is **0.235 nm.rad** (ref) as opposed to 0.71 nm.rad for the circulating beam.

The injected beam has **10%** of the circulating colliding beam current.

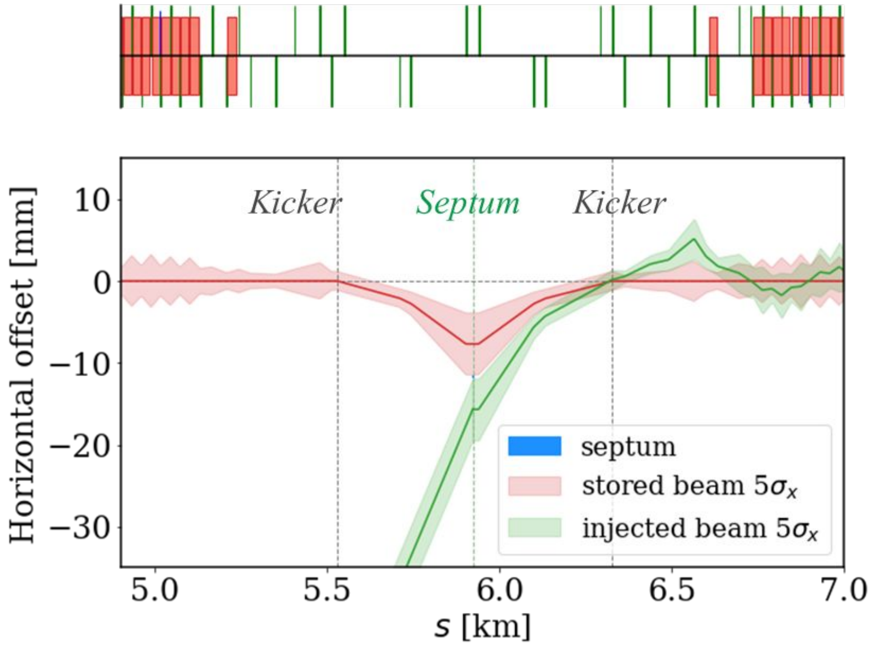
The horizontal damping time is **2336 turns**; 120 turns → 5%, 520 turns → 20%.

Injected beam centroid evolves along a **5** σ^{core} + **5** σ^{inj} + septum (0.2 σ^{core}) ≡ **8** σ^{core} trajectory in the horizontal phase space.

Tracking simulations from QC2L (s=-8.4m) onwards with the latest 4 IPs lattice (V22); 2 masks available to protect the FF quads and central chamber.

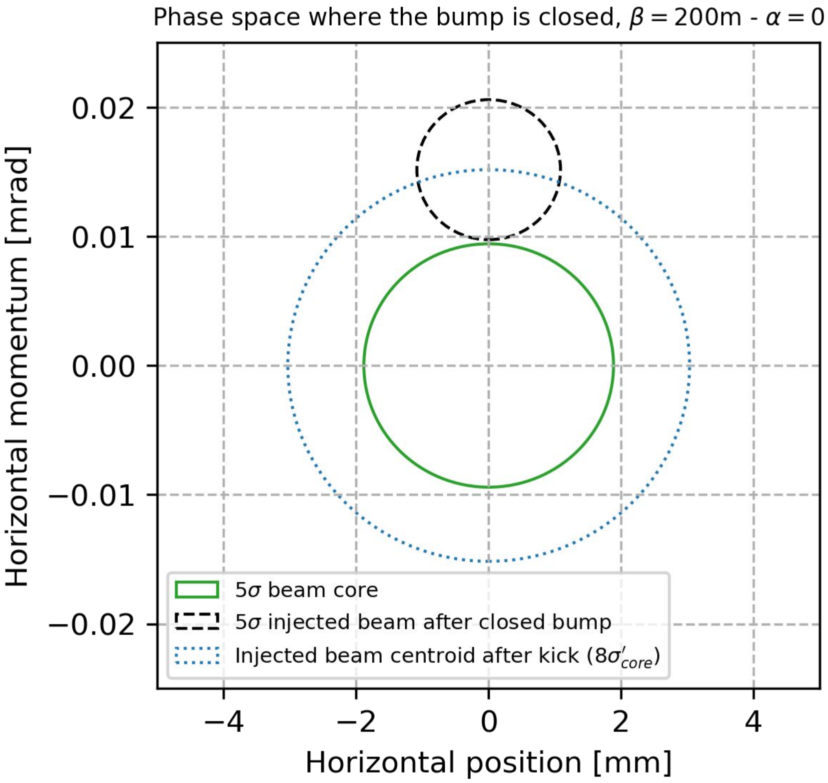
The injected beam is **perfectly aligned** and **Gaussian** *i.e.* **no tails**.

Top-up injection in the horizontal phase space

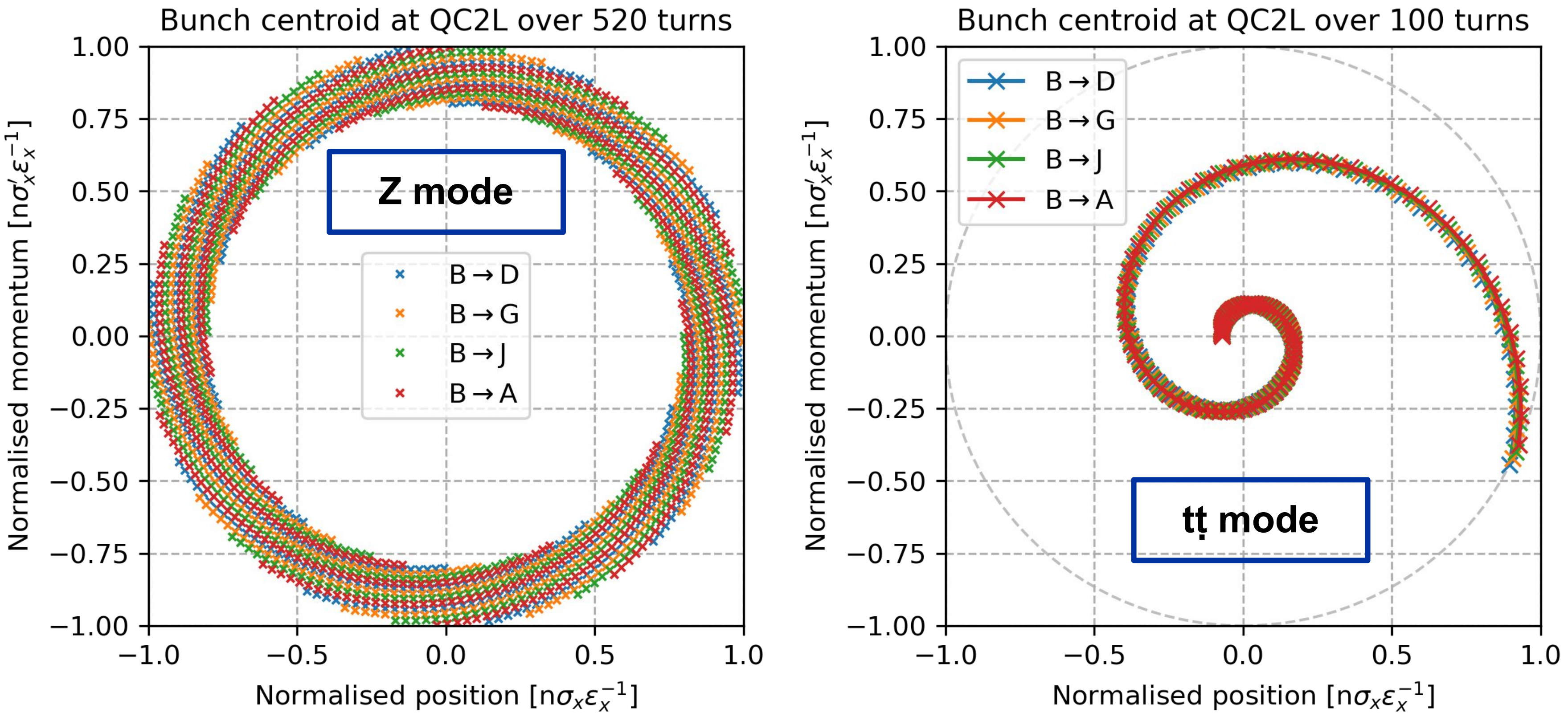


Optics design at point B with V18 lattice

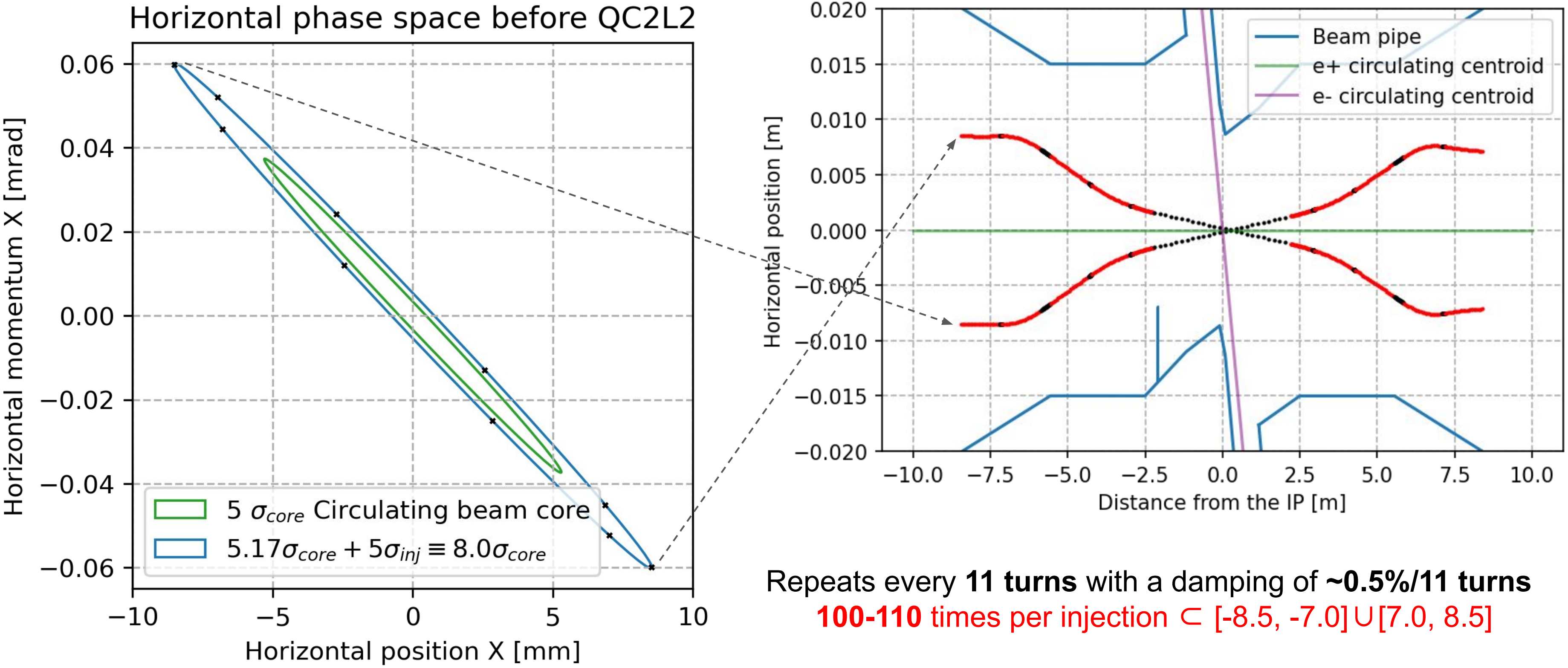
from eeFACT2022, R. Ramjiawan



Top-up injection in the normalised horizontal phase space



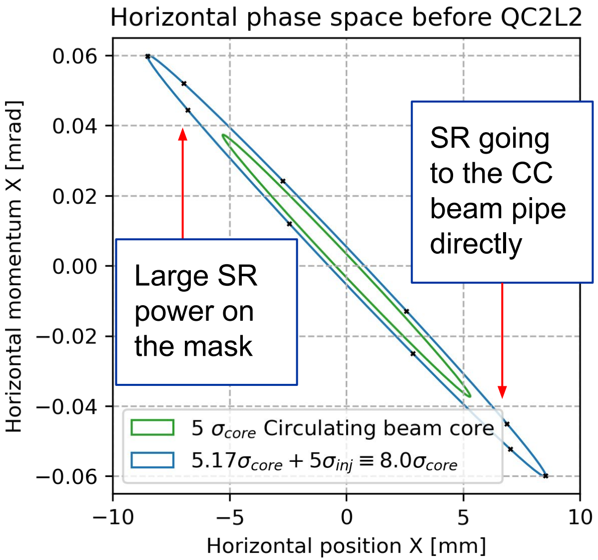
Top-up injection in the horizontal phase space

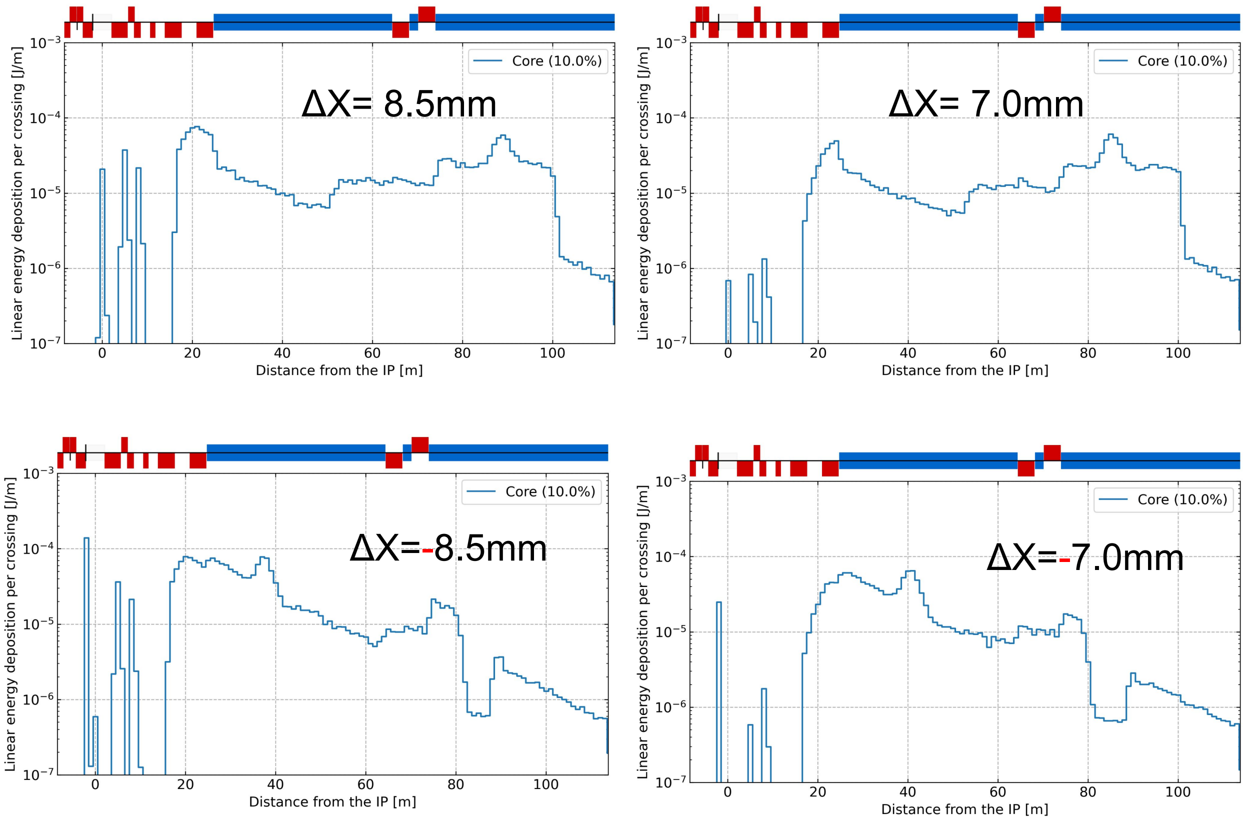


Repeats every **11 turns** with a damping of **~0.5%/11 turns**

100-110 times per injection ⊂ [-8.5, -7.0]∪[7.0, 8.5]

Horizontal displacement (asymmetric 7mm mask aperture)

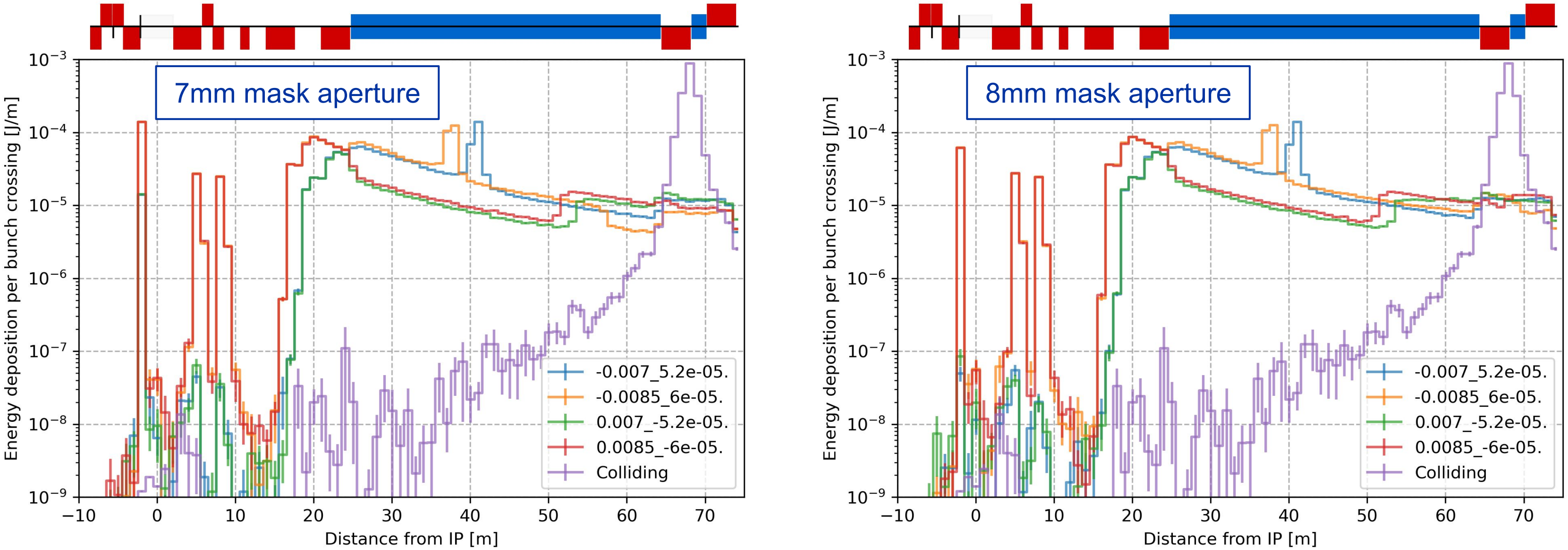




With **positive** horizontal excursion, direct SR hits on the CC.

With **negative** horizontal excursion, there is SR energy deposition on the CC.

Horizontal displacement (symmetric mask aperture)



Equivalent protection of the CC with a 7 or 8 mm mask aperture enabling a reduction from **0.2mJ/Xing** to **0.06mJ/Xing** in the mask. The reduction is better for smaller orbit excursions.

Peak heat load over one turn from consecutive injected bunches with maximal excursion is > 500 W. Average heat load on the mask is small between injection because the injected beam orbit is damped.

Summary

- Simulations with beam core jitter have been performed at Z energy. A transverse position jitter with 100μm standard deviation (eq. to $0.03\sigma_x$ and $3.5\sigma_y$ at BWL), is “harmless”. Conversely, a transverse angular jitter causes excessive SR beyond 15μrad (eq. to $3.5\sigma_{x'}$ and $33\sigma_{y'}$).
- SR from beam tail studies highlight that a **7 or 8 mm** mask aperture provides equal (or better) SR collimation performances allowing a reduction of the mask heat load if necessary.
- Effective SR collimation for **Z** and **tt** operation modes including transverse tails provided they do not extend too far vertically (<75% of the vertical halo collimators).
- Off-axis top-up injection is challenging at Z because of the **large orbit excursion** and **slow damping**. The SR intercepted by the last mask causes high energy deposition per bunch crossing (~**0.2mJ**/Xing) w.r.t. (~**0.8μJ**/Xing) from the colliding beam. The central chamber is well protected by a **symmetric** mask.

Thank you
for your attention.

Simulation tool, field map and physics models

BDSIM simulation tool (ref & website) that is based on GEANT4.

Use of the synchrotron radiation (*G4SynchrotronRadiation*) and low-energy electromagnetic physics (*G4EmPenelopePhysics*) from GEANT4.

Production energy cut at 10 eV (below the default in GEANT4) to prevent infrared divergence.

Implementation of the solenoid and anti-solenoid field map.

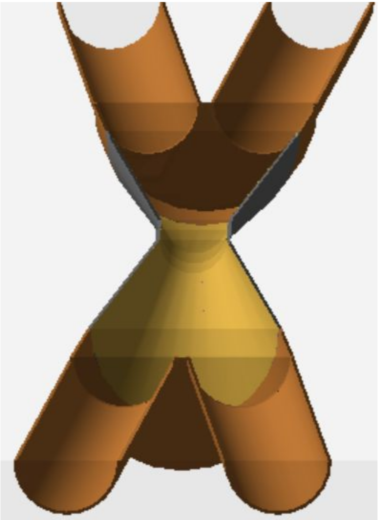
Implementation of a realistic central beam pipe in a GDML format.

The beam pipe is made of Copper.

The collimators (10cm) and masks (2cm) are made of Tungsten.

The MAD-X sequences (link) are converted as input files for BDSIM.

The beam parameters can be found in (ref).



Annex: SR collimation for the other energy modes

Assuming the same beam sizes as the Z operation the beam halo collimator apertures for W should be (9-11 σ_x) and (66-75 σ_y).

Assuming the same beam sizes as the tt operation the beam halo collimator apertures for H should be (13-15 σ_x) and (80-90 σ_y).

The collimation for W and H energies are subject to evolve with further development of the optics and lattice designs, *e.g.* V23.

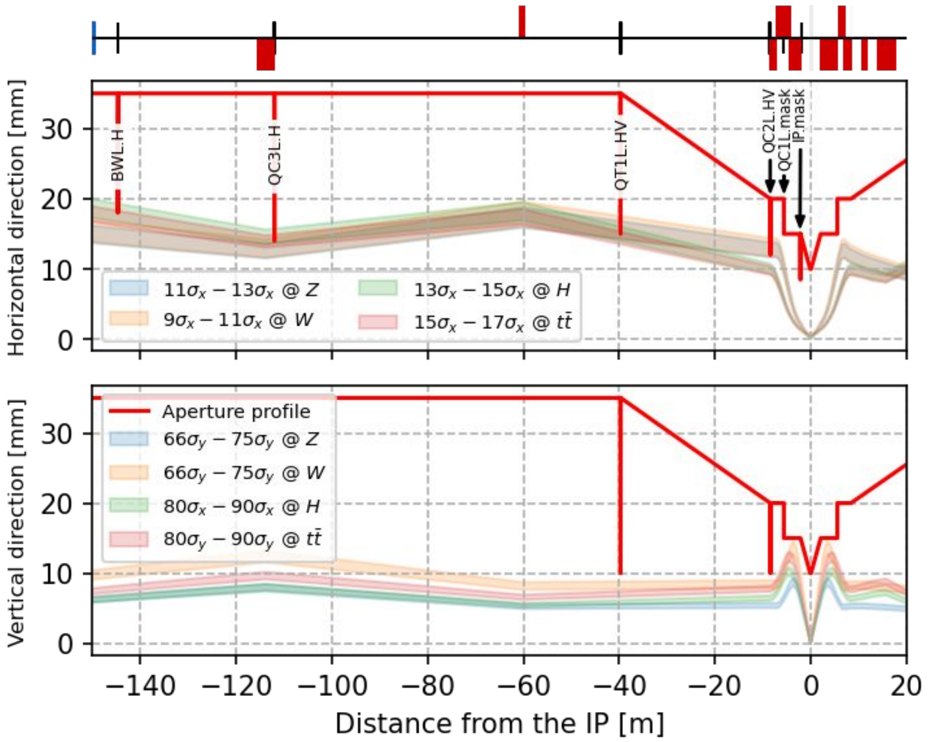
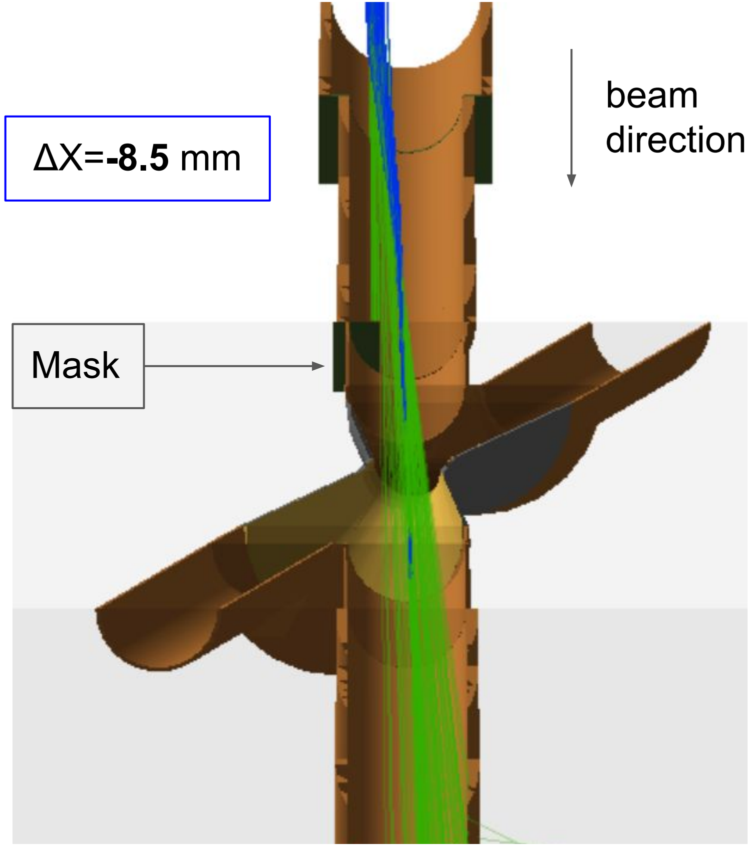


Illustration of the two extremes at Z



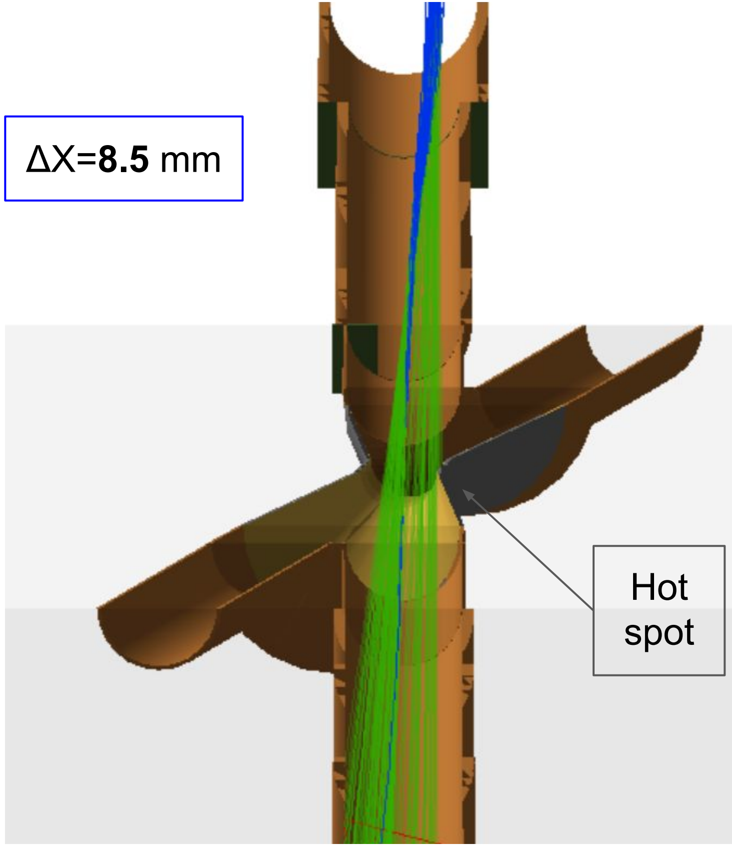
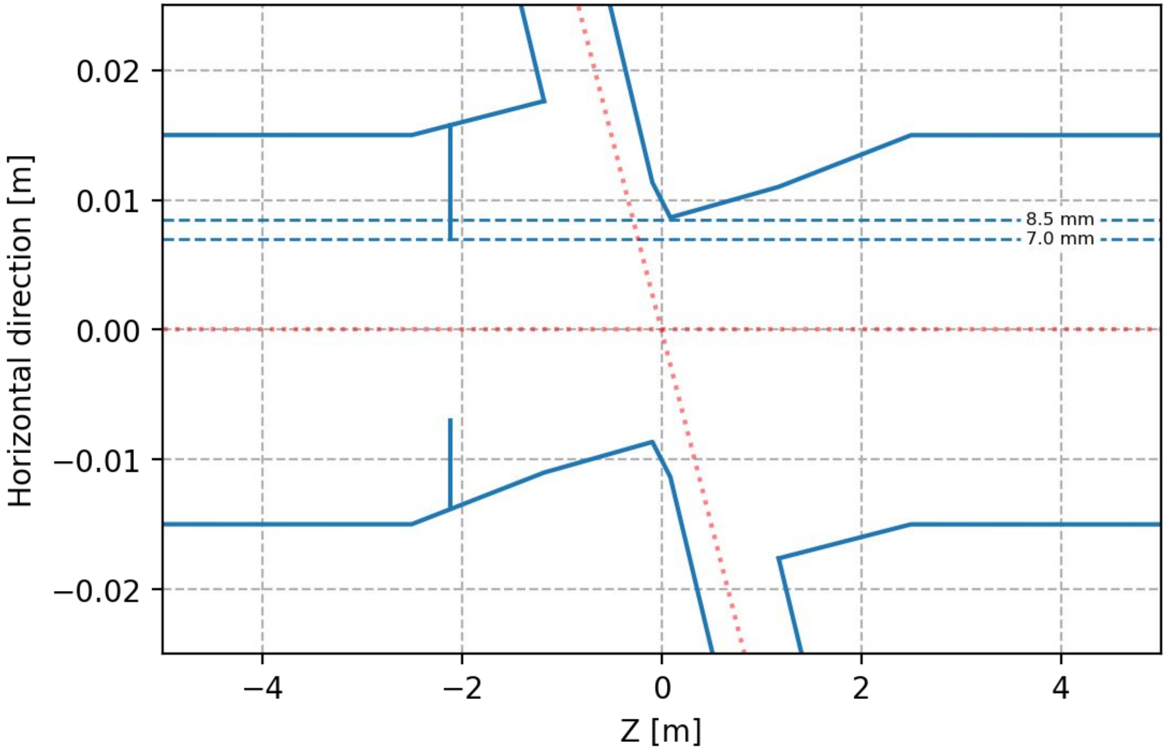
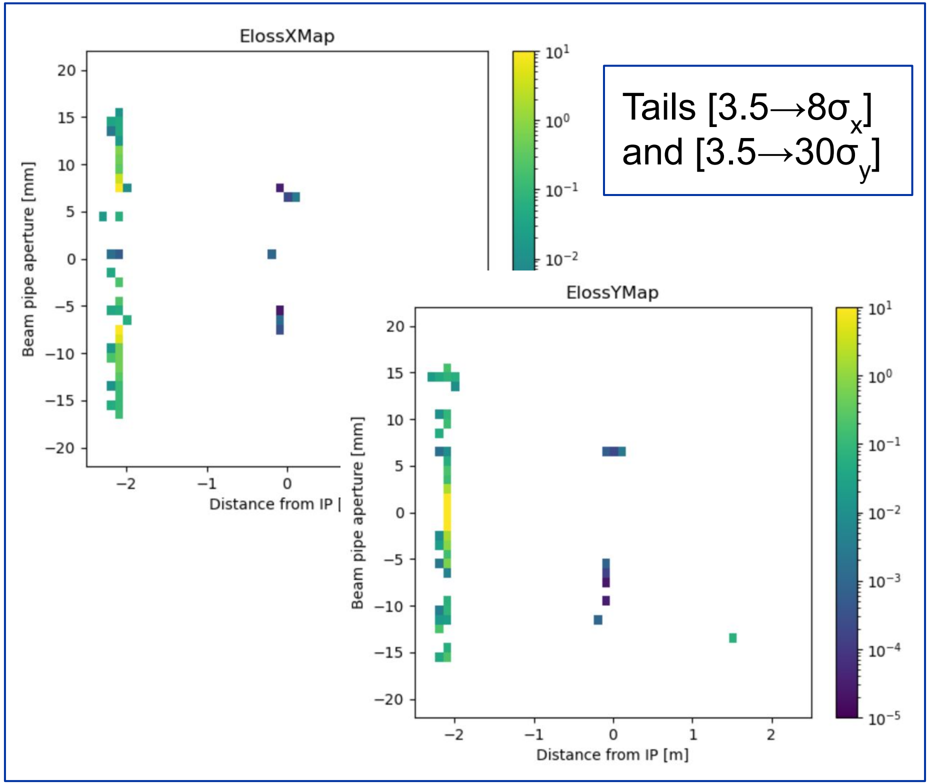
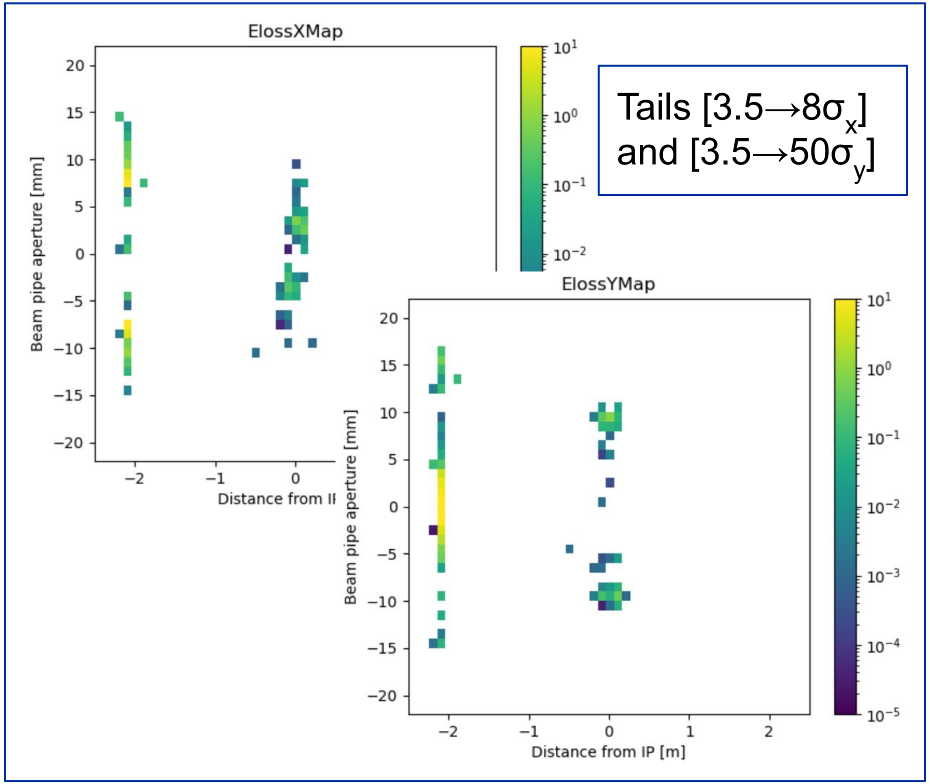


Illustration of the mask aperture with respect to the central chamber aperture.



Effect of symmetric mask on SR caused by transverse tails





Power deposition in the range [-2.5m, 2.5m] around the IP