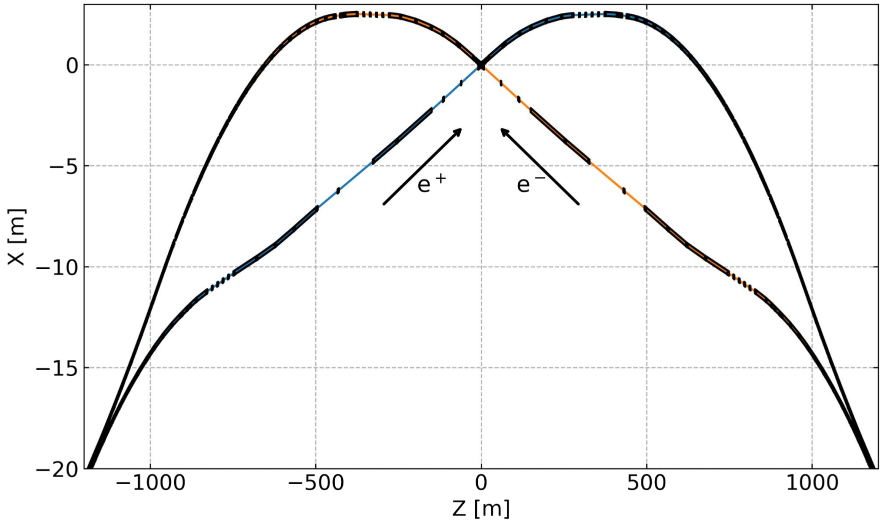
Synchrotron Radiation Background @ FCC-ee

K.D.J. André for the MDI study group

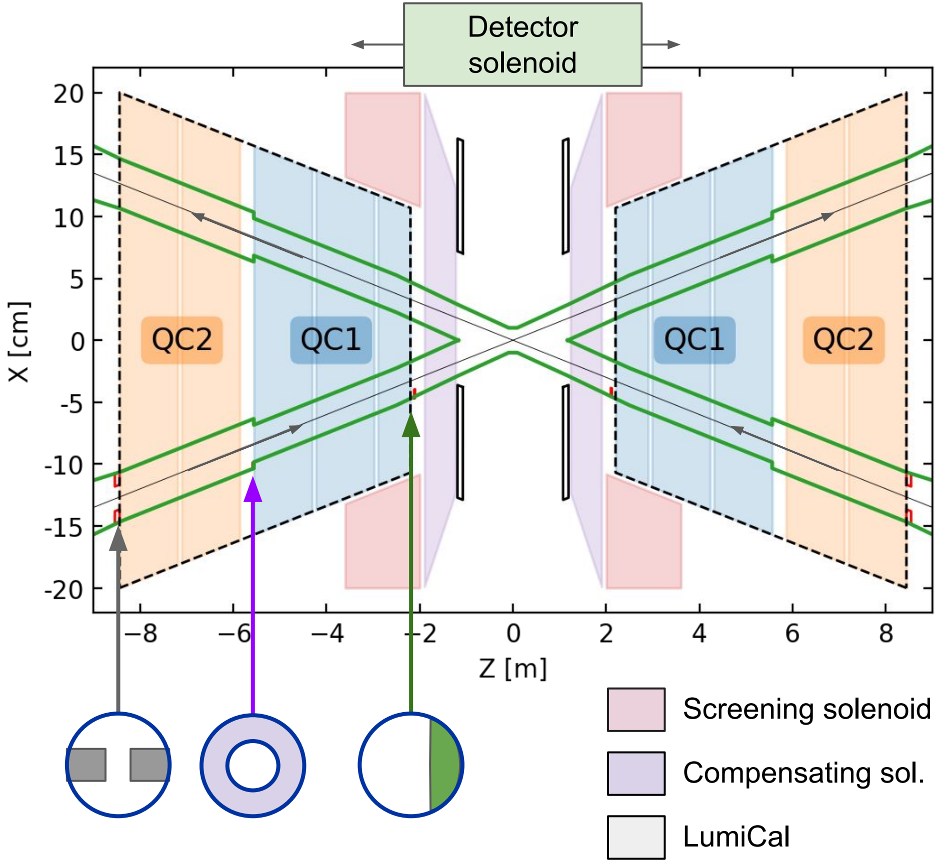
Outline

- FCC-ee lattice, aperture profile, masks and collimators
- Simulation tool, physics and field map
- Synchrotron radiation collimation scheme
  - At the Z operation mode
- Other on-going studies
  - Top-up injection
  - HFD lattice

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 and is tapered to 15mm in QC1.



Simulation tool, field map and physics

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 990 eV (default in GEANT4) to prevent infrared divergence.

Implementation of the solenoid and anti-solenoid field map.

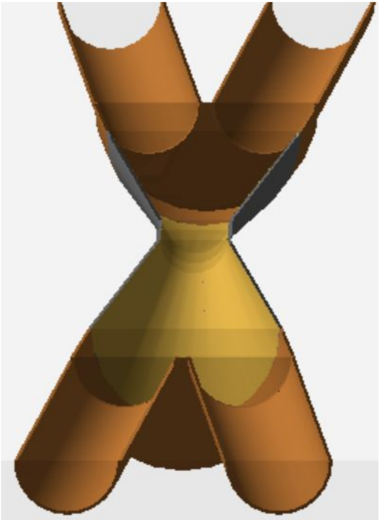
Implementation of a realistic central beam pipe in a GDML format.

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).

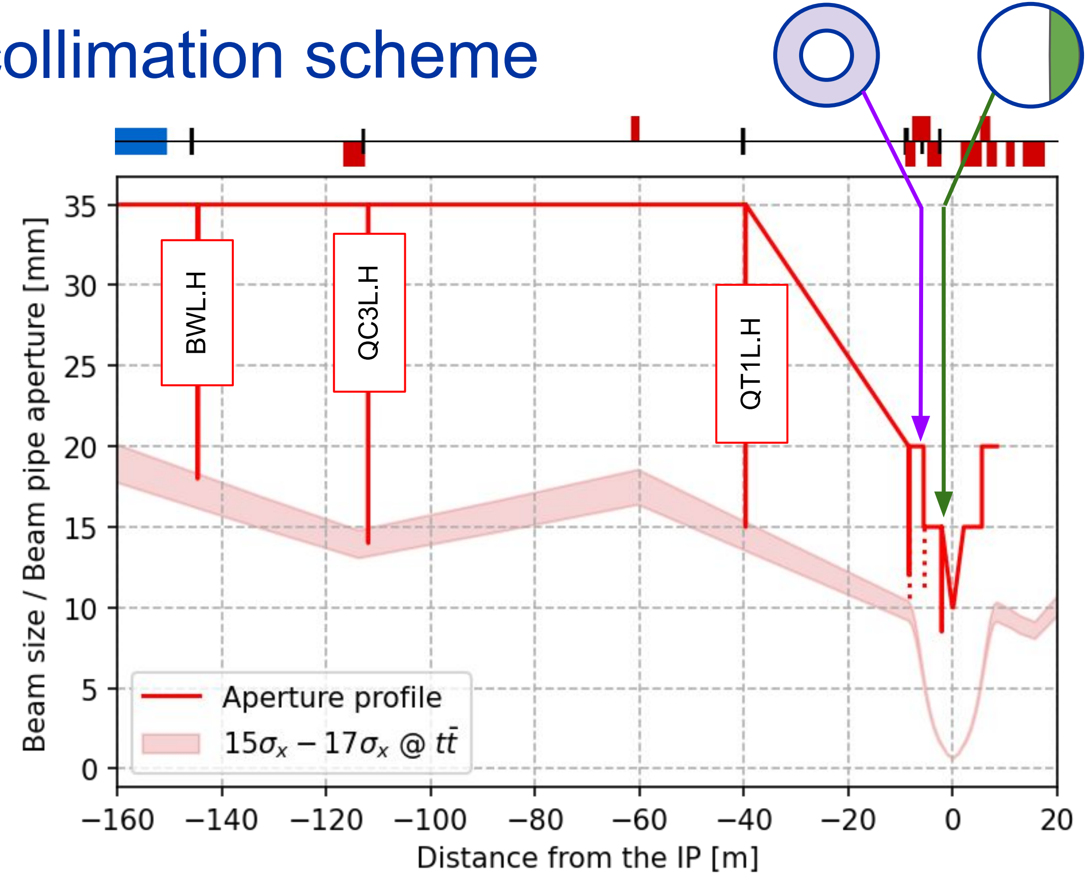


Synchrotron radiation collimation scheme and beam halo collimation

Synchrotron radiation collimation scheme

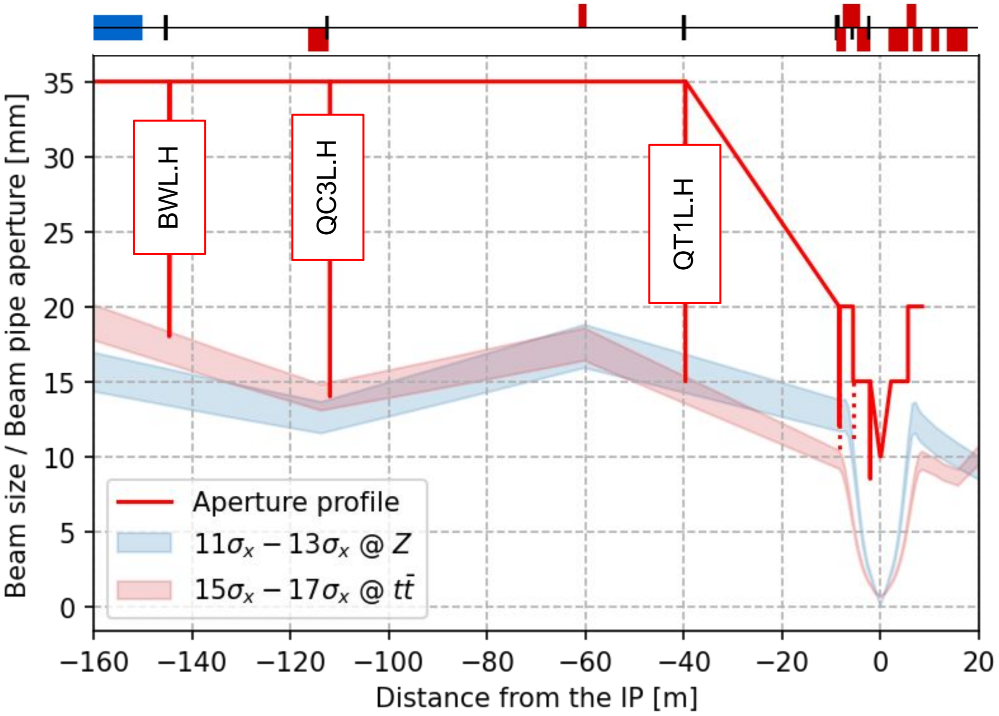
Name	s [m]	half-gap [m]	plane
BWL.H	-144.69	0.018	H
QC3L.H	-112.05	0.014	H
QT1L.H	-39.75	0.015	H
PQC2LE.H	-8.64	0.011	H
MSK.QC2L	-5.56	R = 0.015	H&V
MSK.QC1L	-2.12	0.0085*	H

15 sigmas corresponds to the aperture of the **primary** collimators, **17 sigmas** corresponds to the aperture of the **secondary** collimators.
→ See A. Abramov talk for more details.



Synchrotron radiation collimation scheme

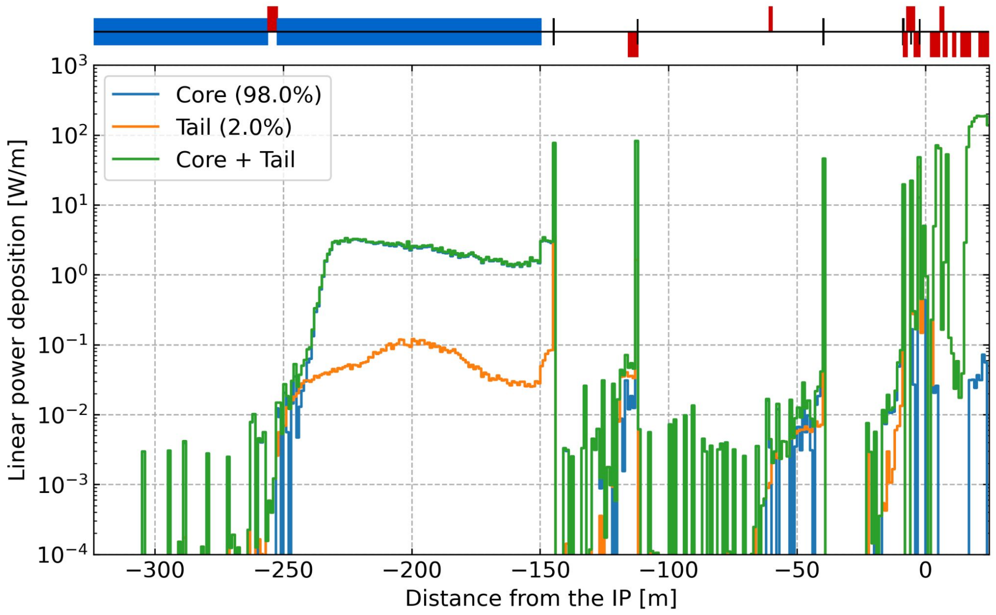
Name	s [m]	half-gap [mm]	plane
BWL.H	-144.69	18	H
QC3L.H	-112.05	14	H
QT1L.**H**	-39.75	15	H
QT1L.**V**	-39.65	15	V
PQC2LE.**H**	-8.64	11→12	H
PQC2LE.**V**	-8.54	11	V
MSK.QC2L	-5.56	R = 15→11	H&V
MSK.QC1L	-2.12	8.5→7.0	H



The collimators closer to the IP need wider apertures from tt to Z. One could adapt the aperture of the mask MSK.QC2L set to 15mm (18.0 σ_x@Z) could be decrease to 11mm (13.3 σ_x@Z). There are no issues in the vertical plane.

Z operation mode

Synchrotron radiation collimation at the **Z mode** - Core and tails

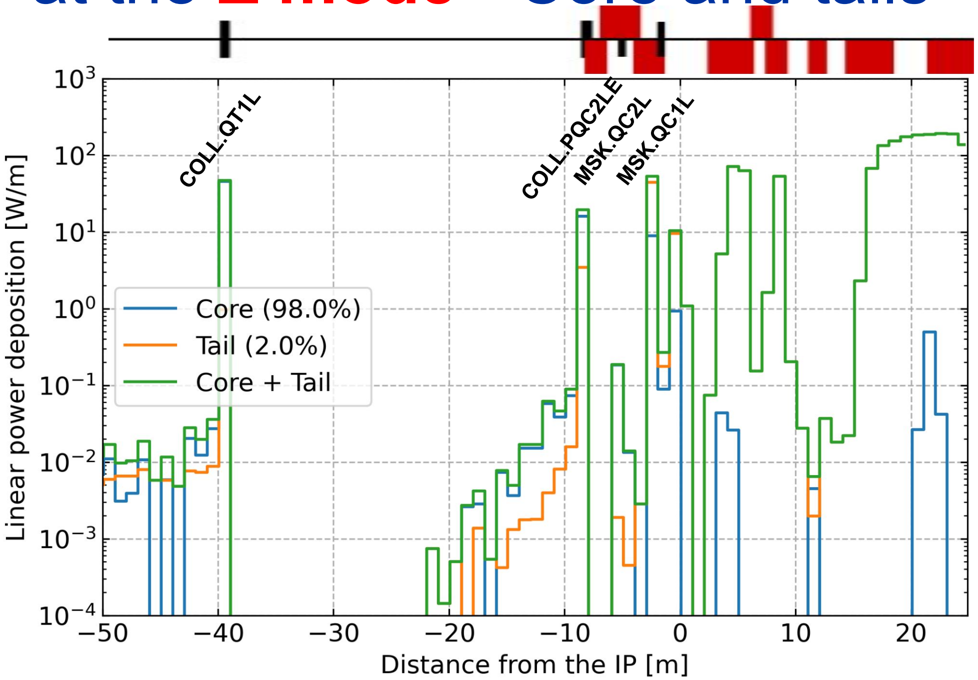


Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

Name	s [m]	nsigma	half-gap [m]	plane
bwl.h	-144.692	14.8	0.018	H
qc3l.h	-112.054	13.3	0.014	H
qt1l.h	-39.747	11.6	0.015	H
qt1l.v	-39.647	199.2	0.015	V
pqc2le.h	-8.64	11.3	0.012	H
pqc2le.v	-8.54	156.3	0.012	V
msk.qc2l	-5.56	18.0/161	R = 0.015	Radial
msk.qc1l	-2.12	47.5(39.1)	0.0085(7)	H

COLL.BWL is 10cm of tungsten absorbing **76W**
COLL.QC3L is 10cm of tungsten absorbing **82W**
COLL.QT1L is 10cm of tungsten absorbing **46W**
COLL.PQC2LE is 10cm of tungsten absorbing **19W**
MSK.QC2L is 2cm of tungsten absorbing **37mW**
MSK.QC1L is 2cm of tungsten absorbing **56W(143W)**

Synchrotron radiation collimation at the **Z mode** - Core and tails



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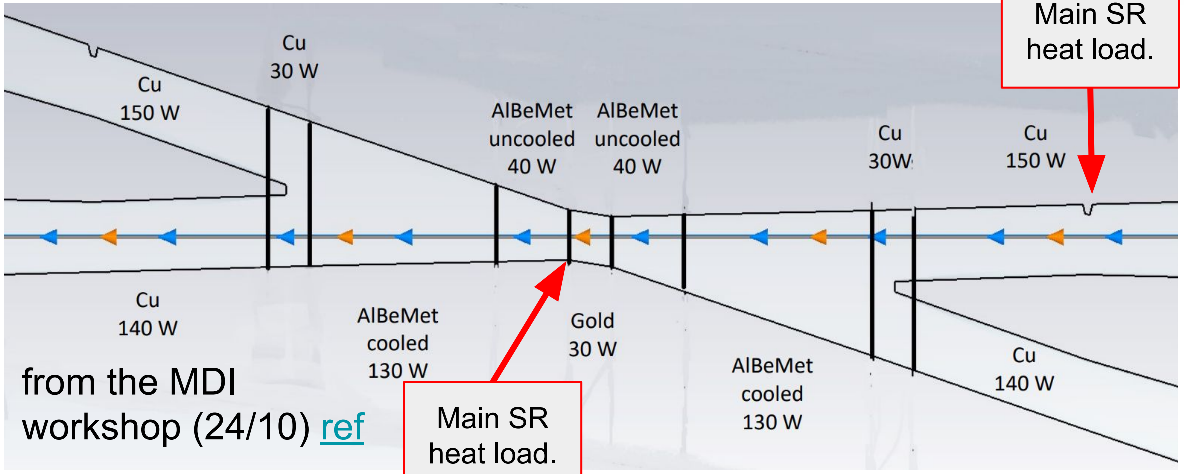
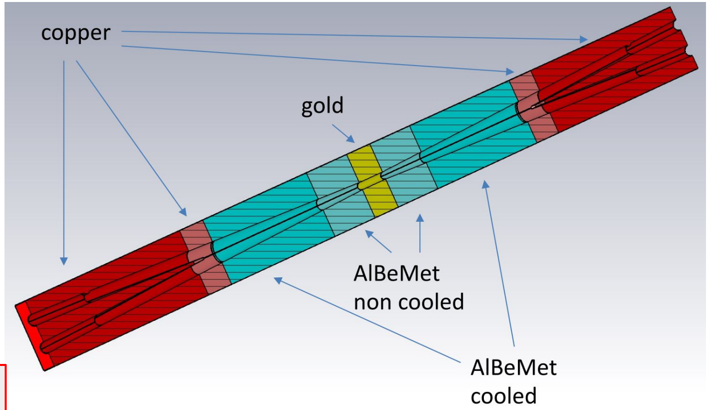
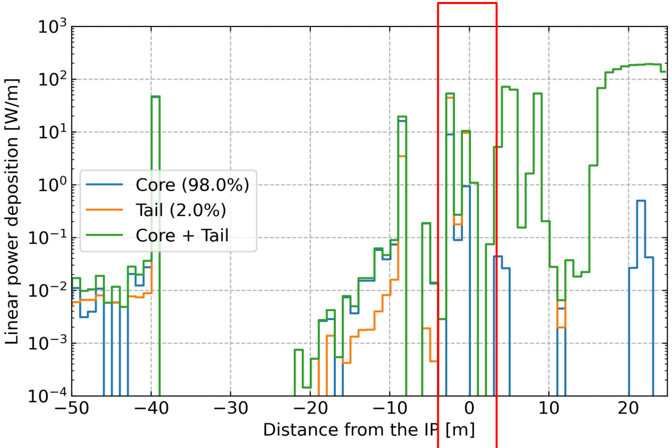
Comparison with wakefield heat load

The synchrotron radiation heat load on the beam pipe is smaller than the heat load due to the wakefields. It depends a lot on the transverse tail distribution.



from the MDI workshop (24/10) ref



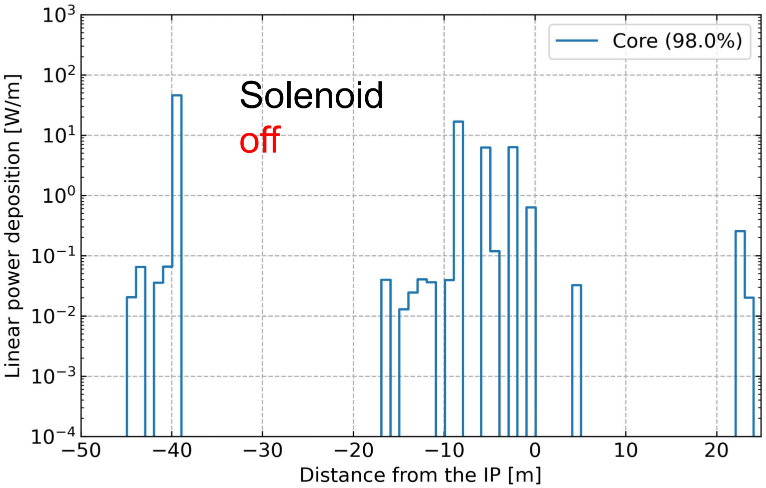


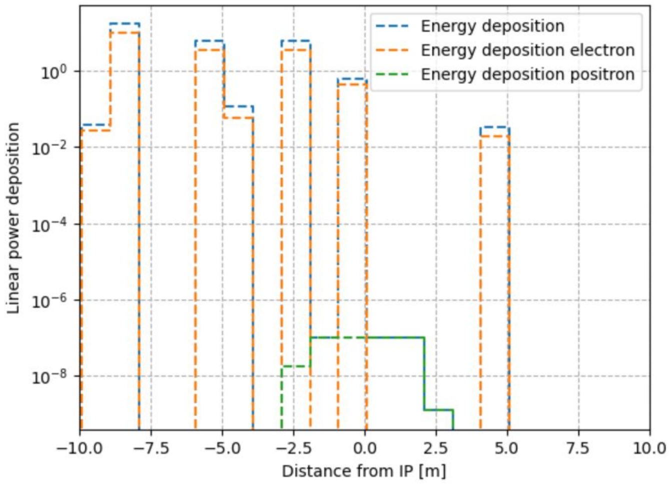
Effects of (anti-)solenoid at Z energy

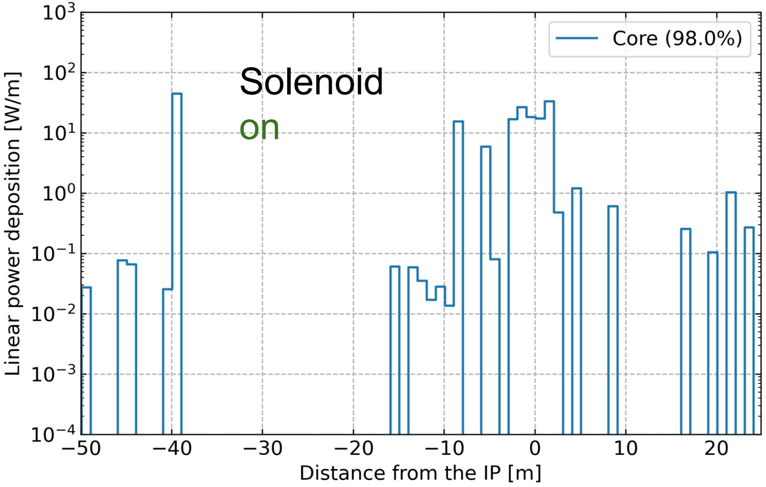
Effects of solenoid

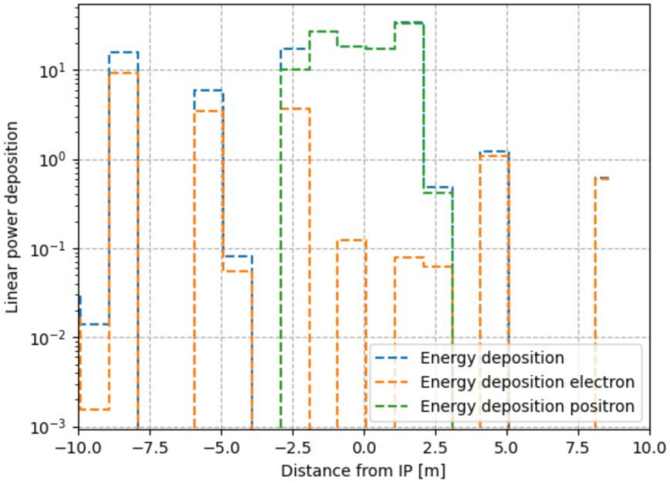
Energy deposited via positrons in the central chamber.

- 20 to 30 W in the CC.
- Positrons ?

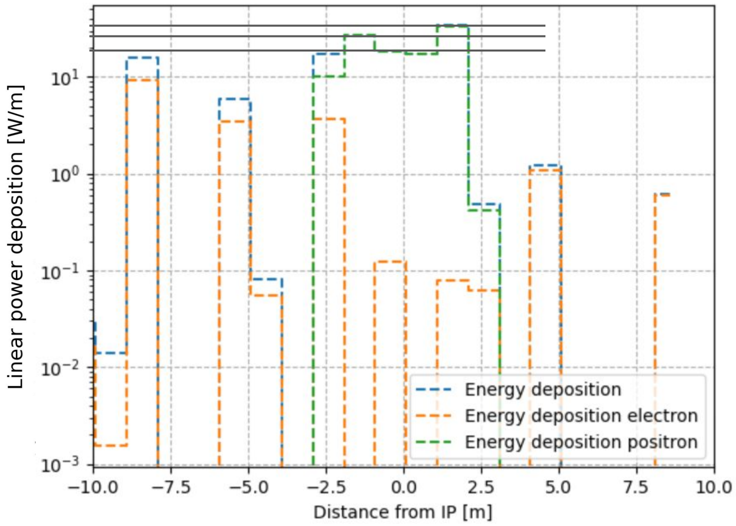


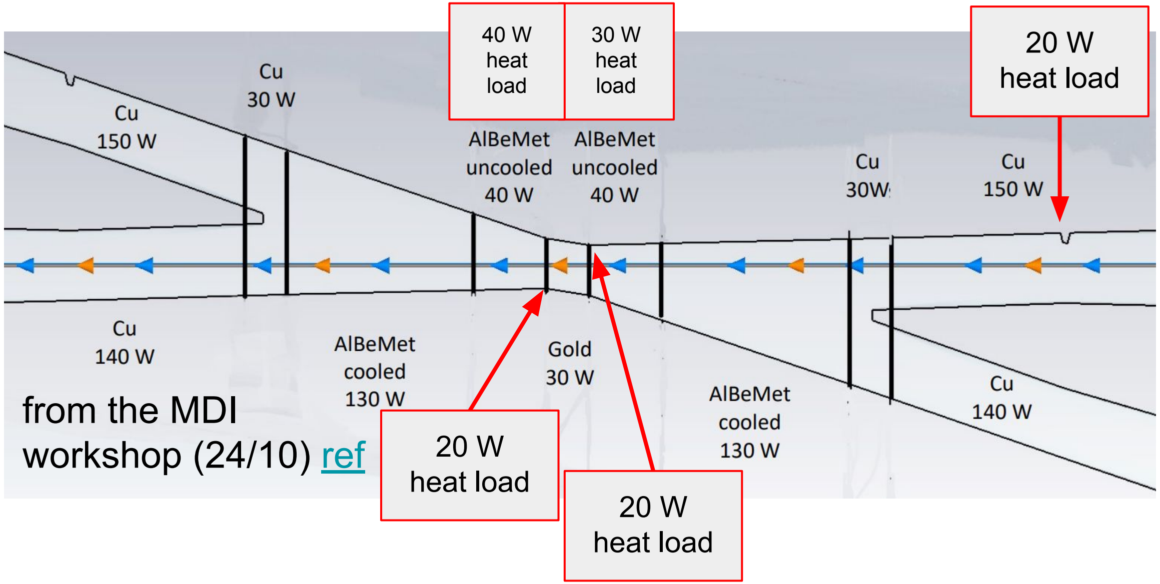






Effects of (anti-)solenoid





Low-energy positrons from photoelectric effects upstream the IP in a strong solenoid field

On-going studies: off-axis top-up injection (ref)

Parameters for the SR background study due to off-axis beam injection

The 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 beam current.

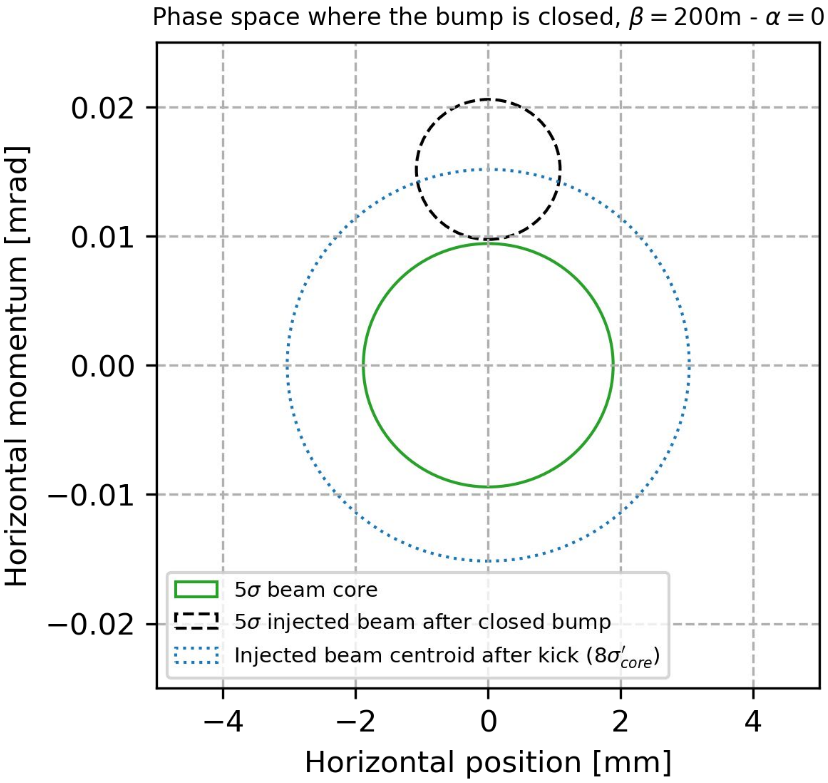
The horizontal damping time is **2336 turns**; 120 turns → 5%, 520 turns → 20%.

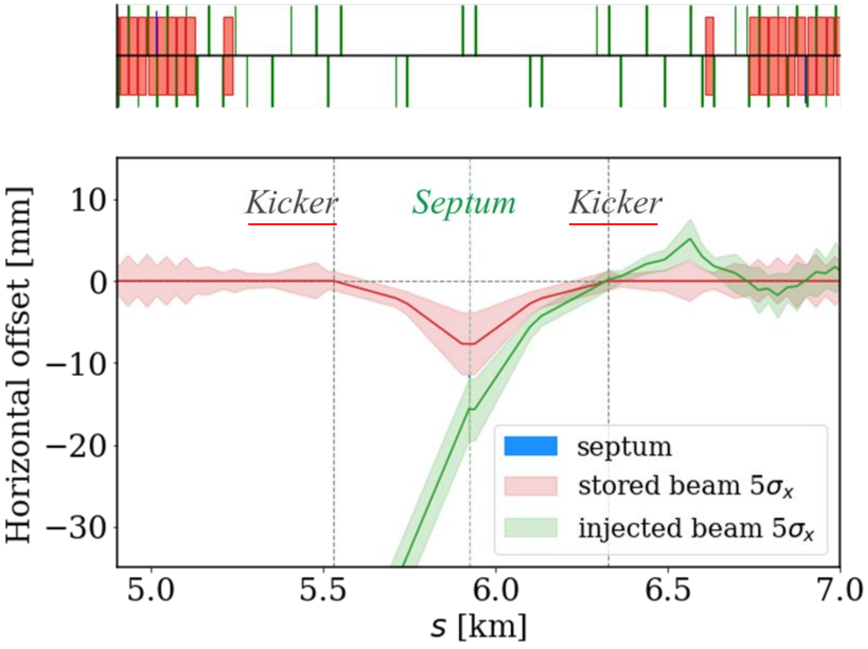
Injected beam centroid evolves along a **5** σ^{core} + **5** σ^{inj} + septum (0.2 σ^{core}) ≡ **8** σ^{core} trajectory in the horizontal phase space.

Tracking from QC2L 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

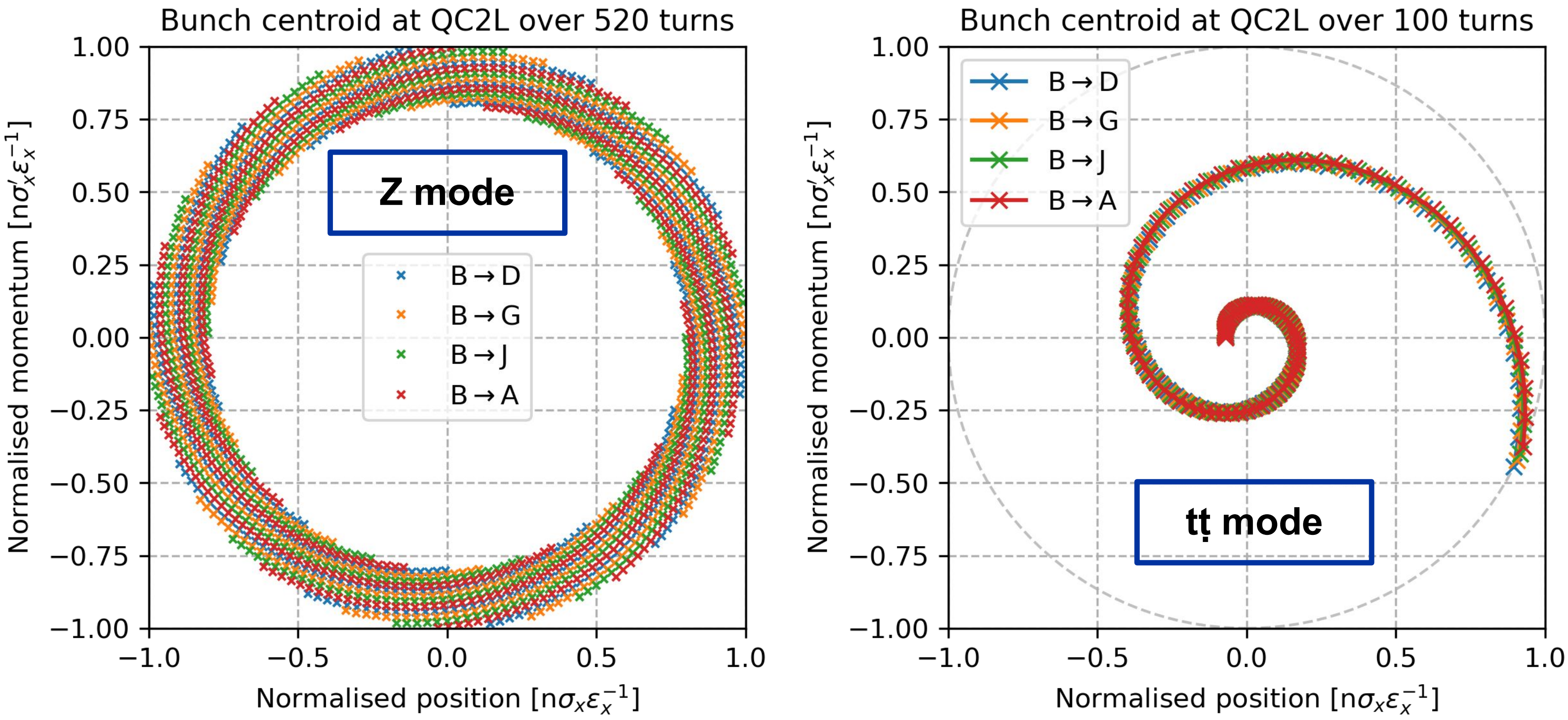




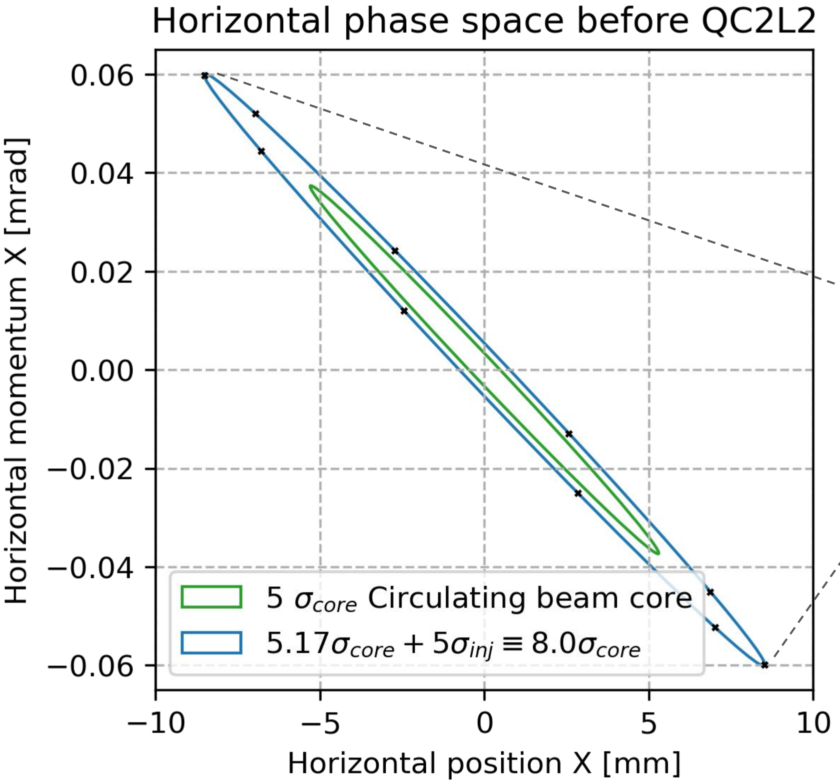
Optics design at point B with V18 lattice

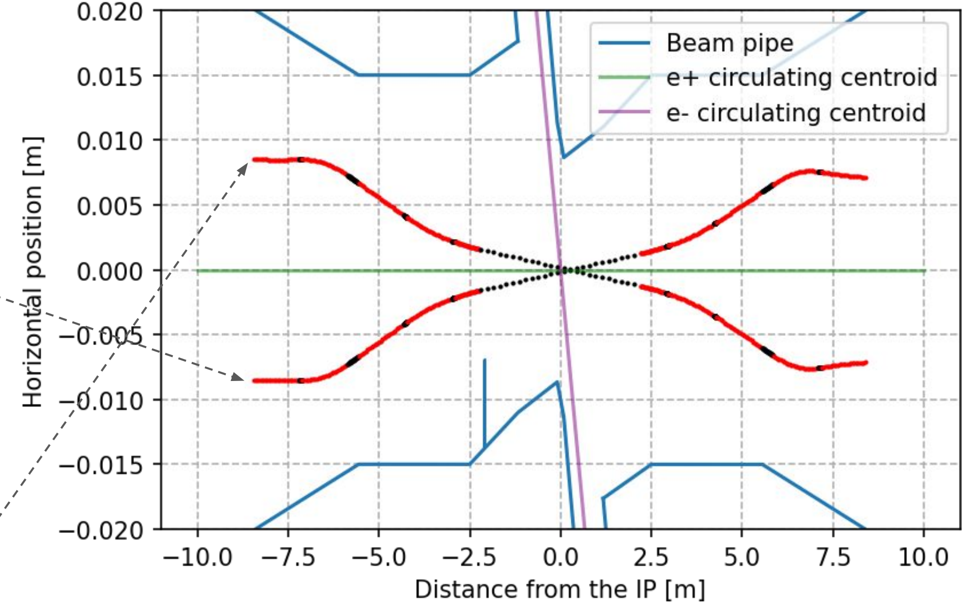
from eeFACT2022, R. Ramjiawan

Top up injection in the normalised horizontal phase space



Top up injection in the horizontal phase space

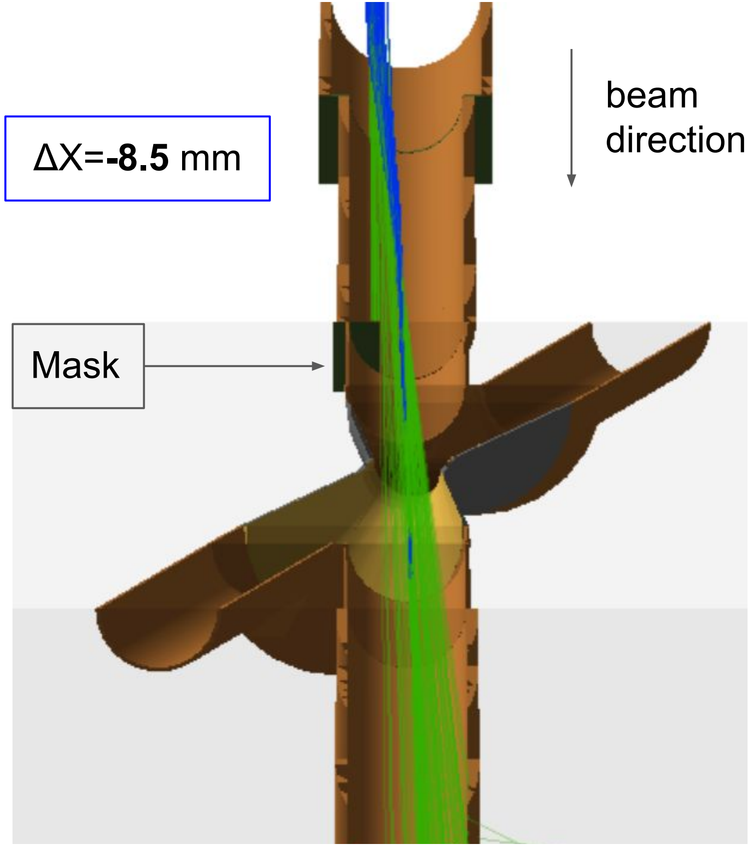


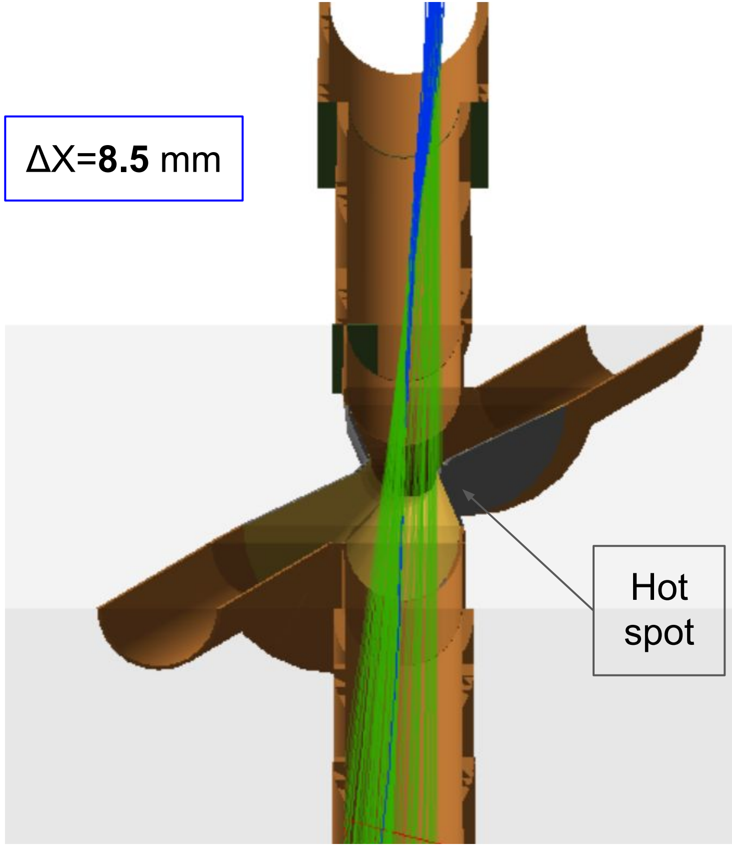


Repeats every **11 turns** with a damping of **~0.5%/11 turns**

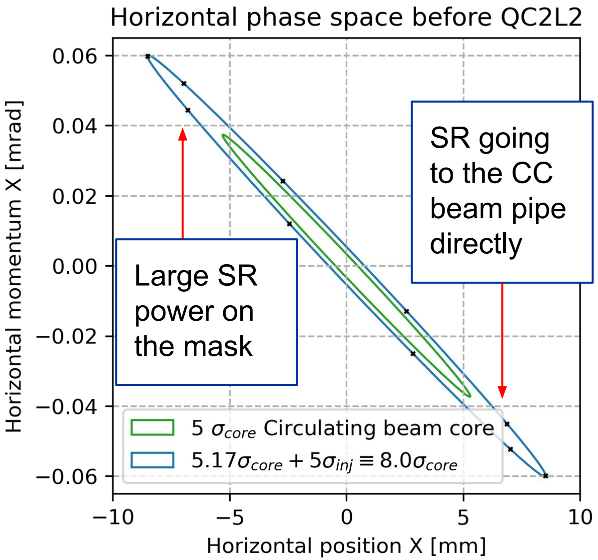
100-110 times per injection ⊂ [-8.5, -7.0]∪[7.0, 8.5]

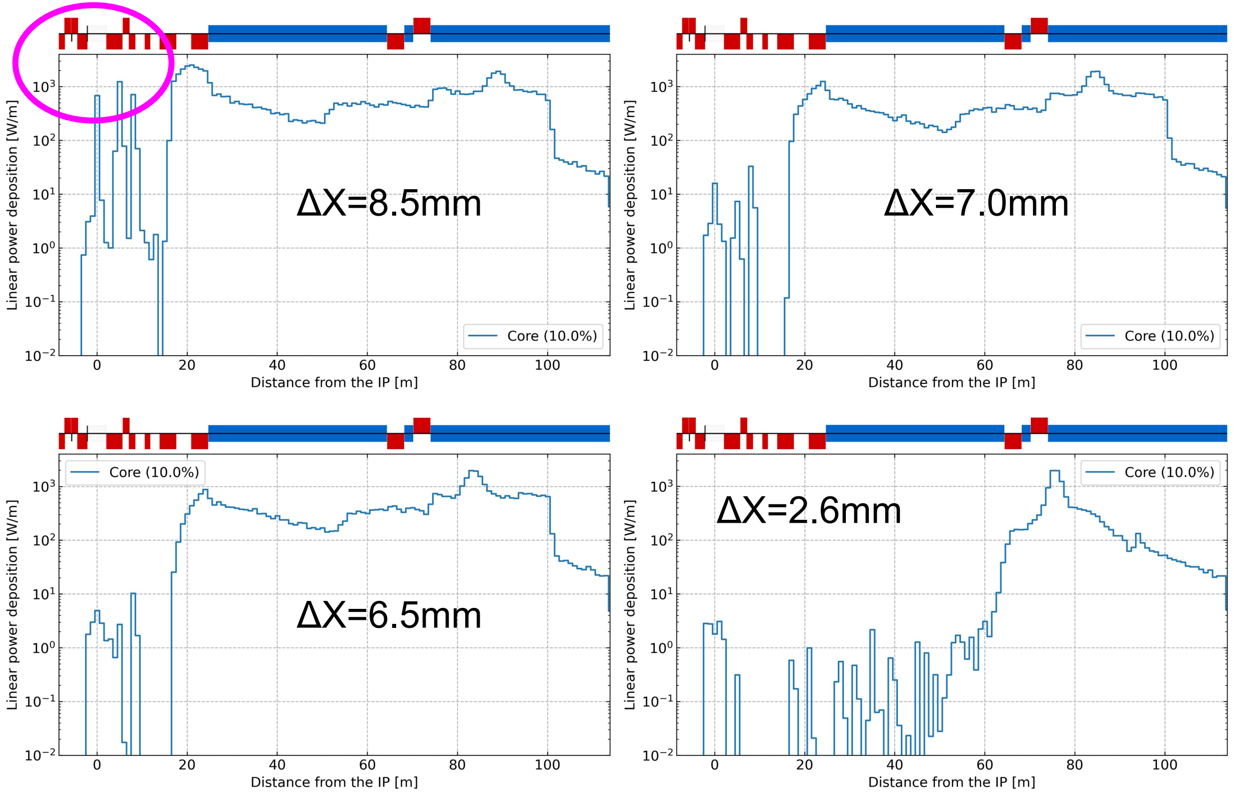
Illustration of the two extremes at Z





Positive horizontal displacement (away from the mask)

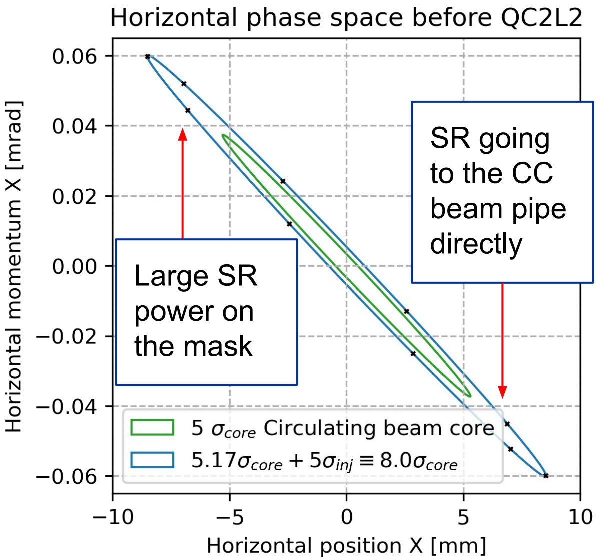


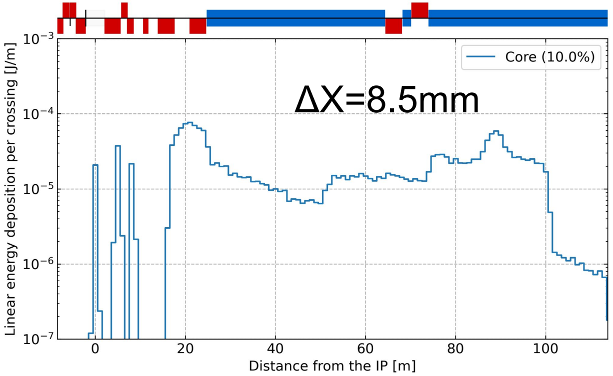


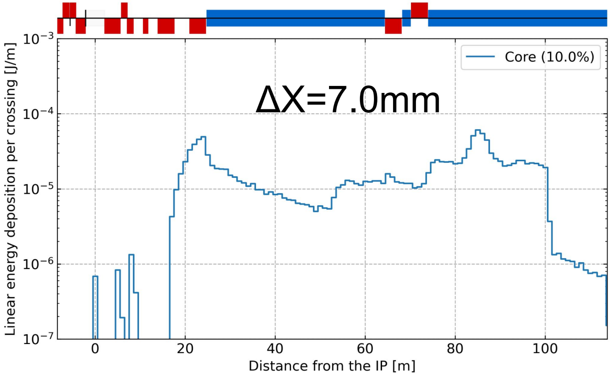
Large power deposition:

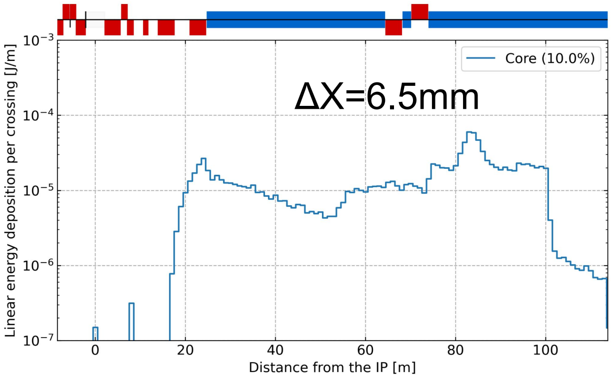
- In the central chamber
- In the FF downstream

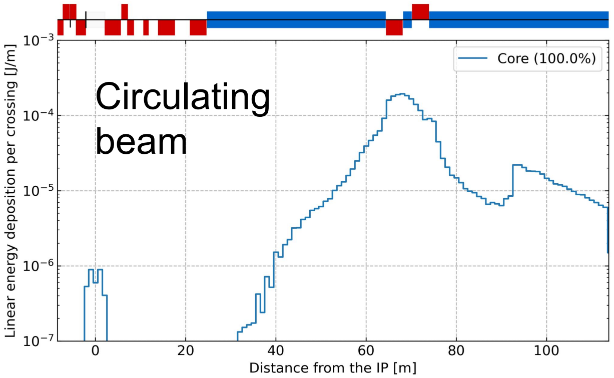
Positive horizontal displacement (away from the mask)







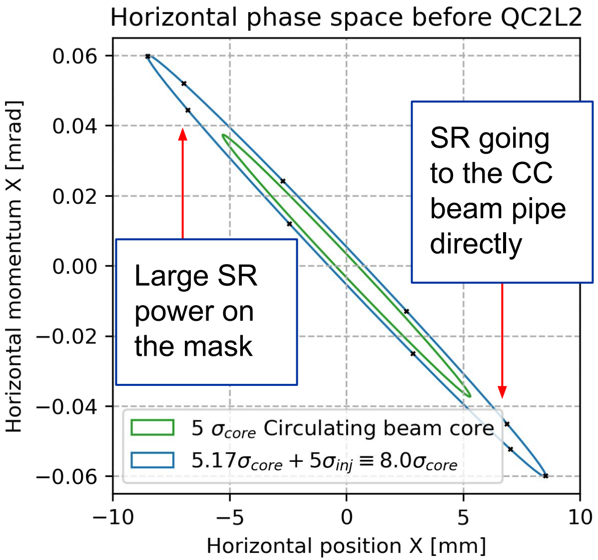


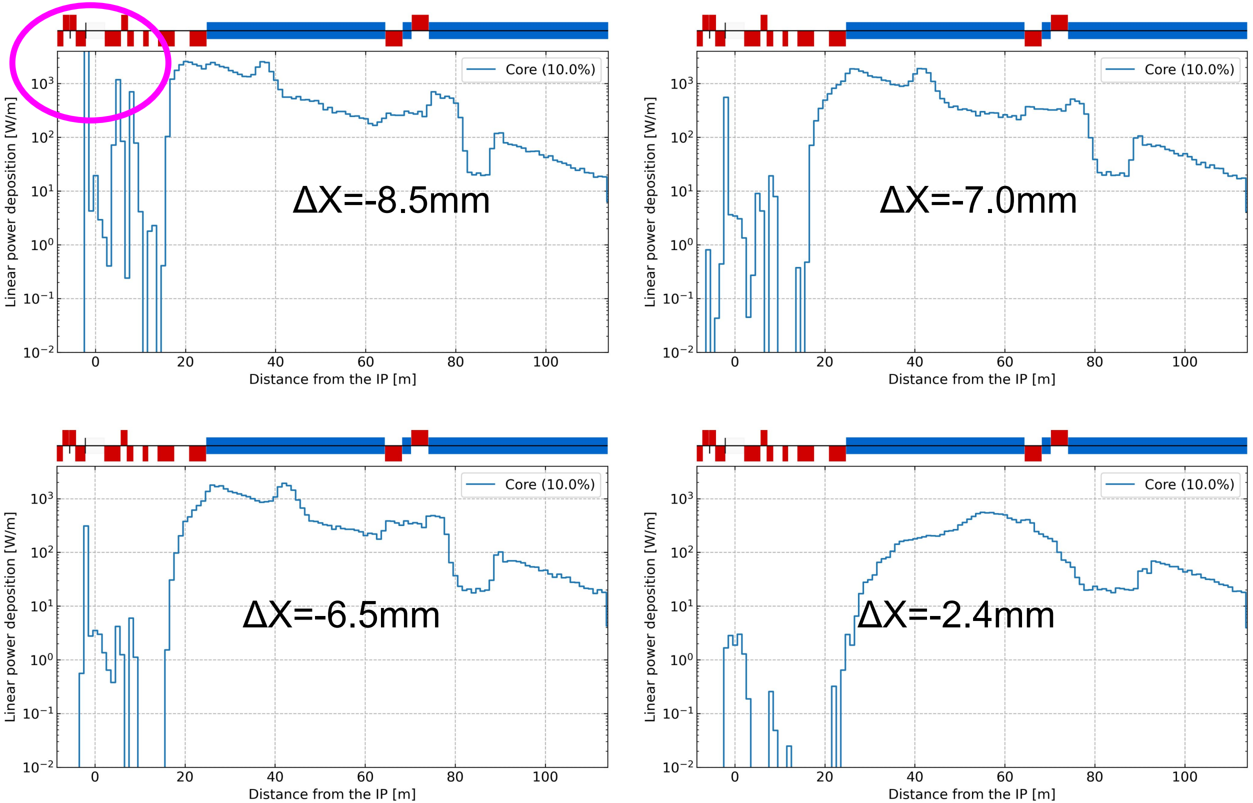


Energy deposition:

- In the central chamber
- In the FF downstream

Negative horizontal displacement (towards from the mask)

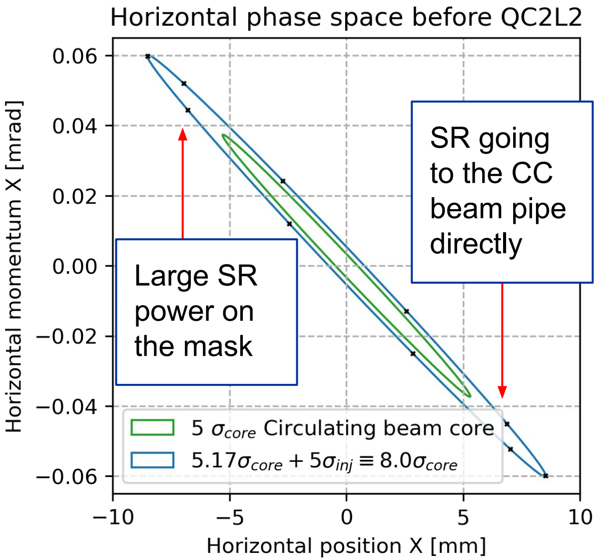


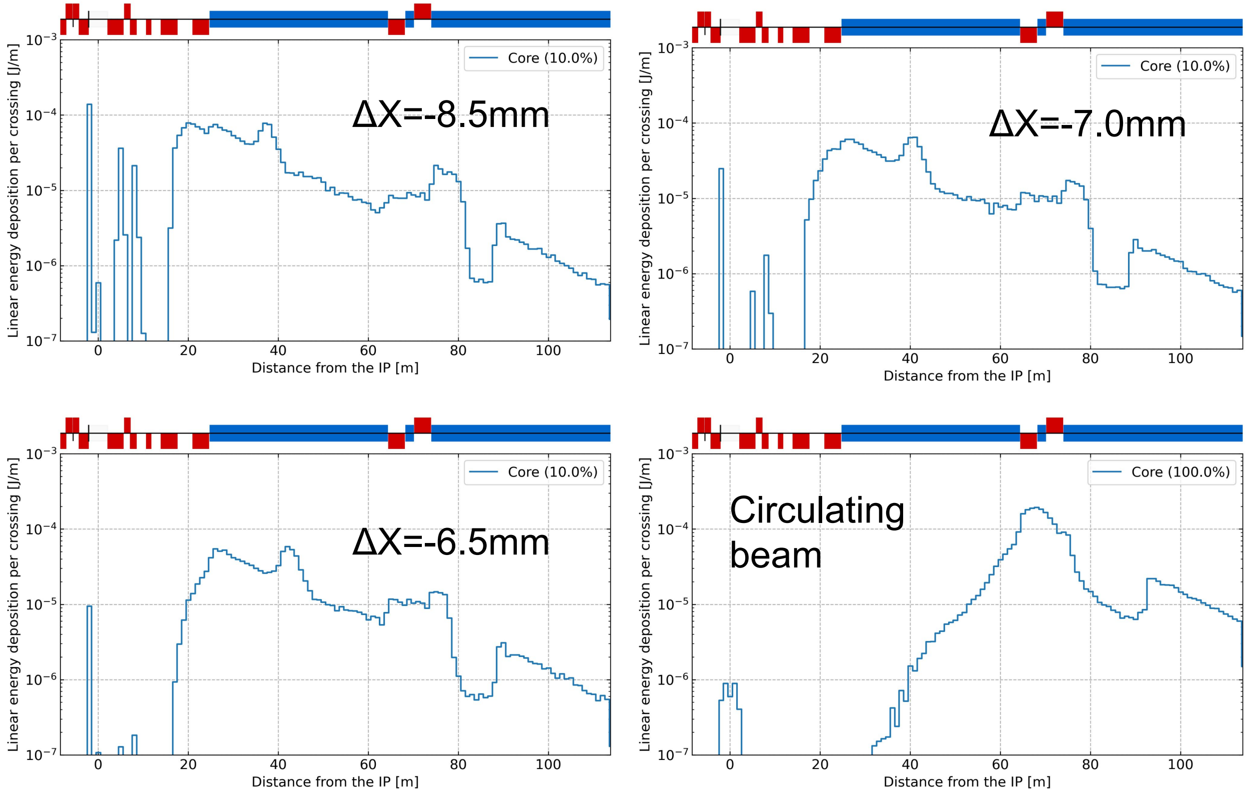


Large power deposition:

- In the mask
- In the FF downstream

Negative horizontal displacement (towards from the mask)



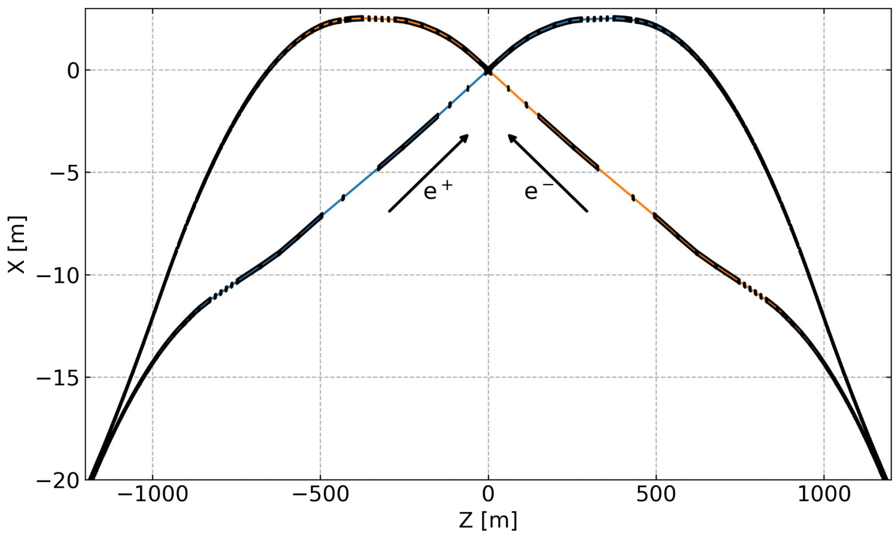


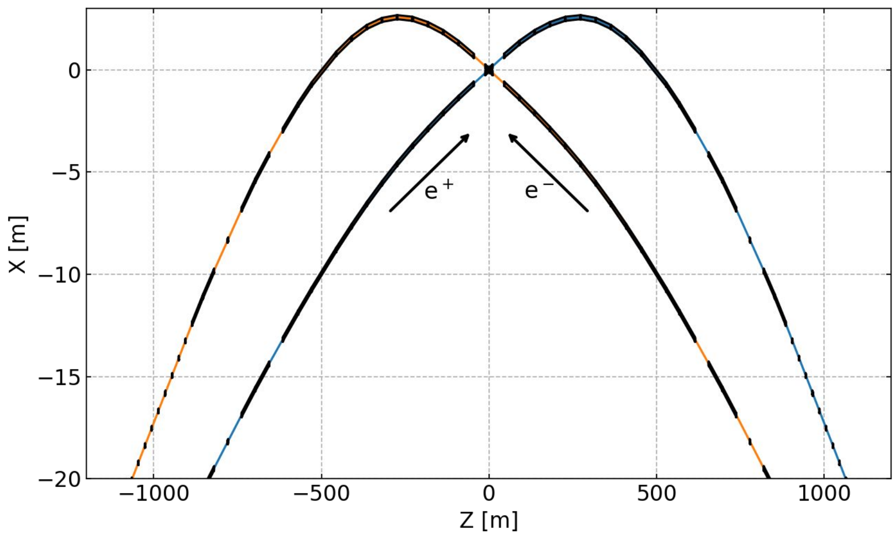
Energy deposition:

- In the mask
- In the FF downstream

On-going studies: HFD lattice (ref)

Comparison with the HFD lattice





Asymmetric interaction region beam optics to accommodate a long straight section with the last dipole (100keV critical energy) **150m** from the IP.
Optics design at the IP: β_x^*=10cm, β_y^*=0.8mm

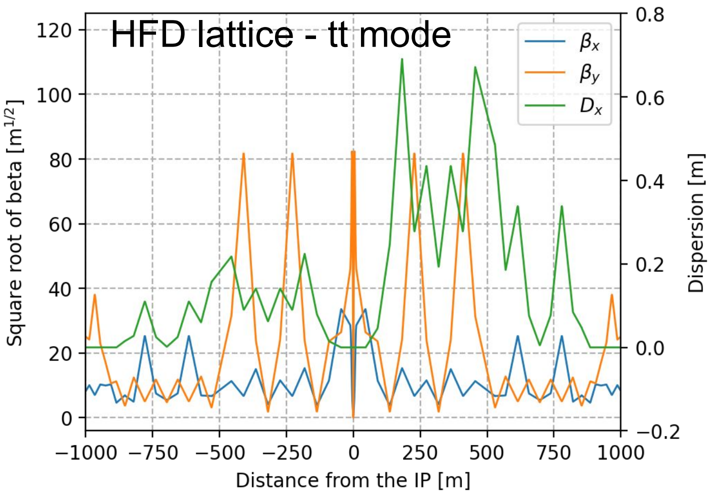
Symmetric interaction region beam optics to accommodate a short straight section with the last dipole (200keV critical energy) **48m** from the IP.
Optics design at the IP: β_x^*=13cm, β_y^*=0.5mm

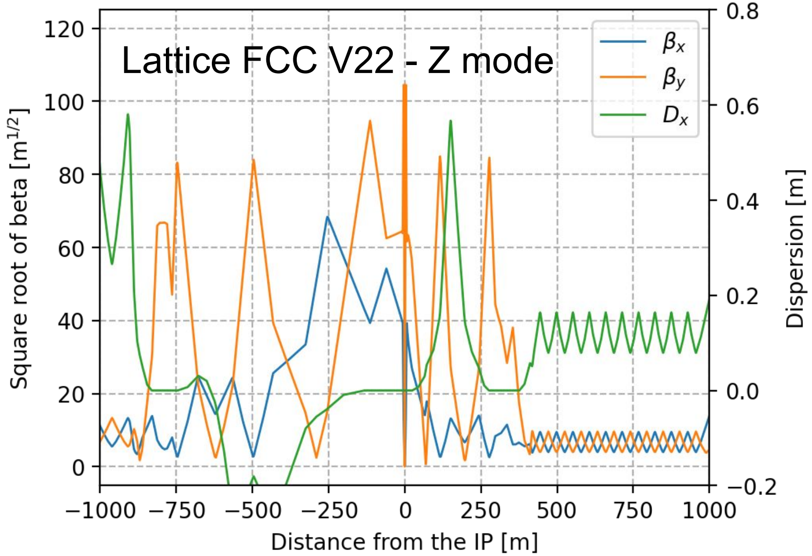
Beam parameters comparison

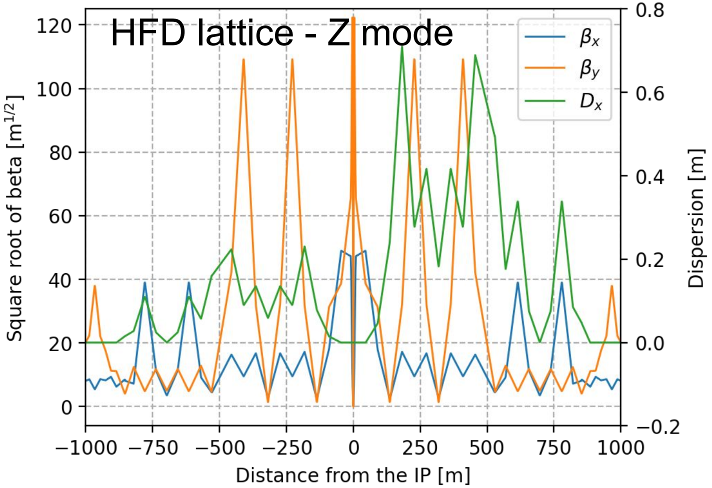
Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam $\xi_x/\xi_y{}^a$		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS)	[sec]	–		1065	4062
Lifetime (lum)	[sec]	1129	1070	596	744

(Bold: computed values)		FCCee Z	FCCee W	FCCee H	FCCee ttbar
Parameter	Units				
LUMINOSITY	**cm^{-2} s^{-1}**	**1.83E+36**	**1.95E+35**	**6.93E+34**	**1.21E+34**
Pinch effect Shatilov		**1.93E+36**	**2.05E+35**	**7.27E+34**	**1.27E+34**
Energy	**GeV**	45.6	80	120	182.5
Circumference	**m**	91170	91170	91170	91170
X-Angle (full)	**mrad**	30	30	30	30
β_x @ IP	**m**	0.13	0.16	0.2	0.52
β_y @ IP	**mm**	0.5	0.8	1.1	1.6
Coupling (full current)	**%**	0.1	0.1	0.1	0.1
Emittance x (without IBS)	**nm**	0.19	0.57	1.24	2.83
Emittance x (with IBS)	**nm**	0.19	0.57	1.24	2.83
Emittance y	**pm**	**0.188**	**0.57**	**1.24**	**2.83**
Momentum compac	**mm**	1.78E-05	1.78E-05	1.78E-05	1.78E-05
Bunch length (zero current)	**mm**	3.7	3.9	4.2	4.7
Bunch length (in collision)	**mm**	10.9	7.02	6.1	5.3
Beam current	**mA**	720	70	23	4
Number of bunches	**#**	16000	1000	200	20
RF frequency	**Hz**	4.00E+08	4.00E+08	4.00E+08	4.00E+08
Revolution frequency	**Hz**	**3.29E+03**	**3.29E+03**	**3.29E+03**	**3.29E+03**
Harmonic number	**#**	**121644**	**121644**	**121644**	**121644**
N. Particle/bunch	**#**	**8.553E+10**	**1.330E+11**	**2.186E+11**	**3.801E+11**
σ_x @ IP	**microns**	**4.94**	**9.55**	**15.75**	**38.36**
σ_y @ IP	**nm**	**9.70**	**21.35**	**36.93**	**67.29**
σ_x @ IP	**cm**	**0.000494**	**0.000955**	**0.001575**	**0.003836**
σ_y @ IP	**cm**	**0.00000097**	**0.00000214**	**0.00000369**	**0.00000673**
$\sigma_{x'}$ @ IP	**microrad**	**38.0**	**59.7**	**78.7**	**73.8**
$\sigma_{y'}$ @ IP	**microrad**	**0.019**	**0.027**	**0.034**	**0.042**
Piwinski angle	**rad**	**33.07**	**11.03**	**5.81**	**2.07**
σ_x effective	**microns**	**163.59**	**105.74**	**92.85**	**88.28**
σ_x effective	**cm**	**0.0164**	**0.0106**	**0.0093**	**0.0088**
Hourglass reduction factor		0.950	0.950	0.950	0.950
Tune shift x		**0.0021**	**0.0055**	**0.0100**	**0.0392**
Tune shift y		**0.1354**	**0.1354**	**0.1356**	**0.1426**
Energy Loss/turn	**MeV**	31.8	300	1530	8150
SR power loss	**MW**	**22.90**	**21.00**	**35.19**	**32.60**
RF Wall Plug Power (SR only)	**MW**	**45.79**	**42.00**	**70.38**	**65.20**

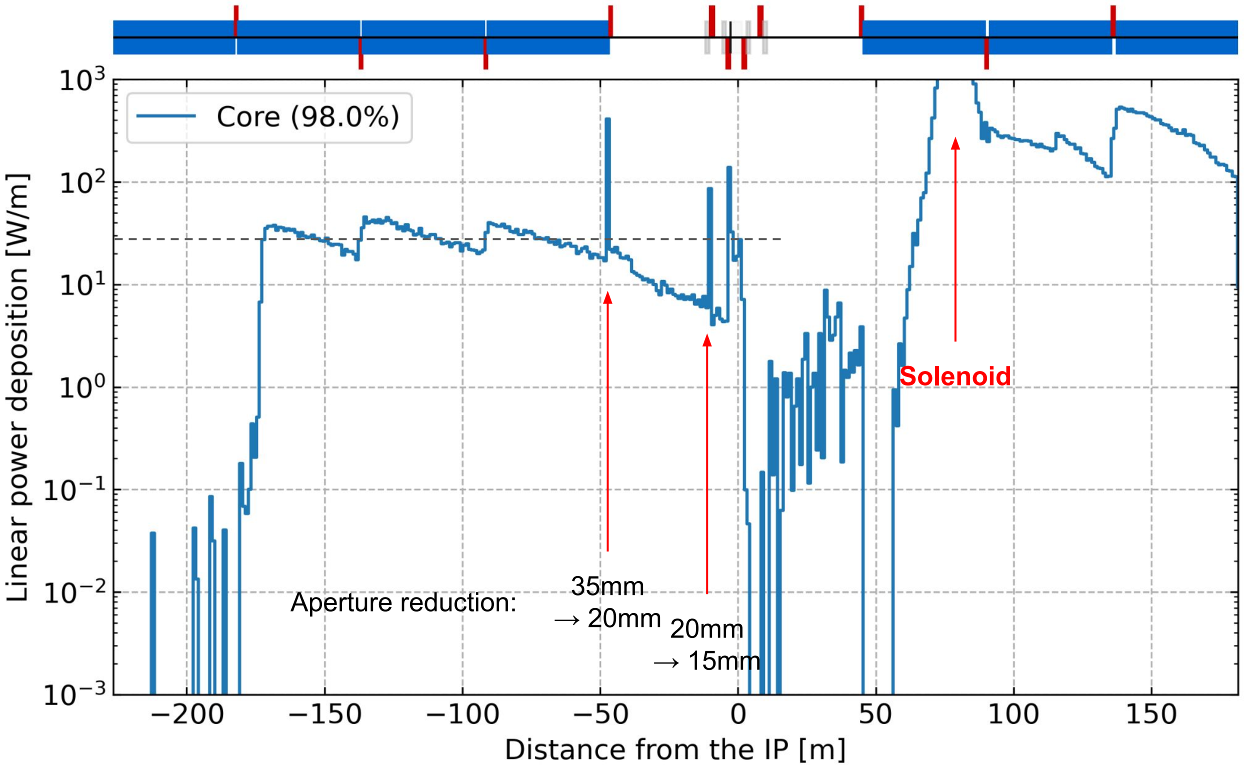
Comparison with the HFD lattice





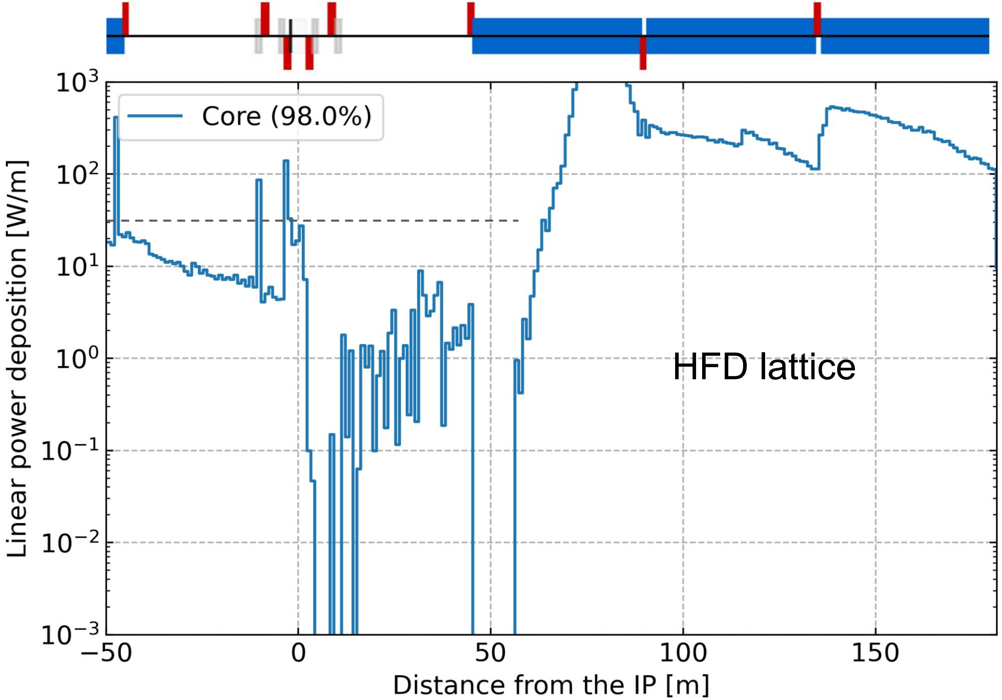


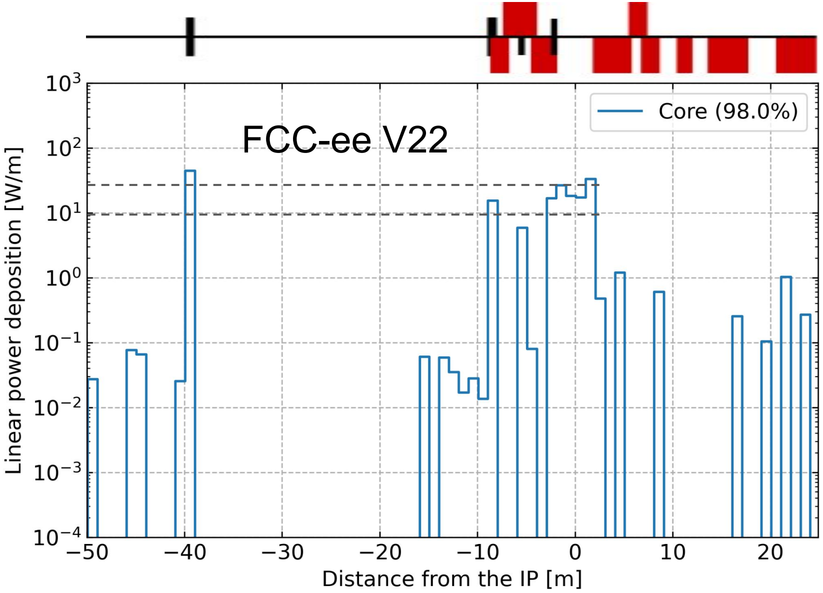
SR power deposition at Z energy 45.6 GeV



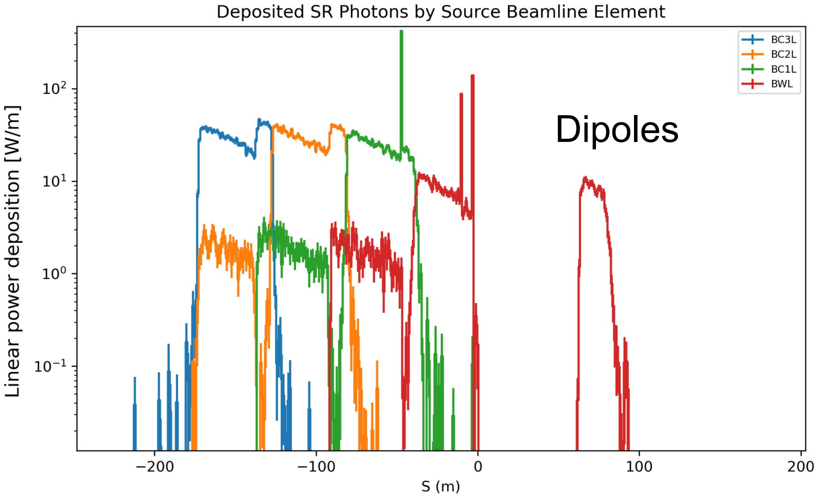
- Only one mask present in the design at s=-2.1m
- Peaks of SR power deposition present at aperture reductions.
- High power deposited in the mask because there are no collimators upstream.
- Power deposited in the CC around 20 to 30W due to the solenoid.

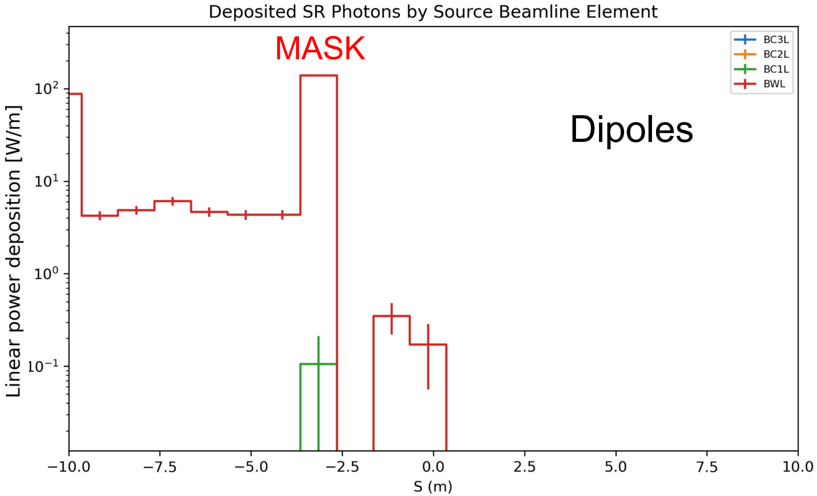
SR power deposition at Z energy 45.6 GeV

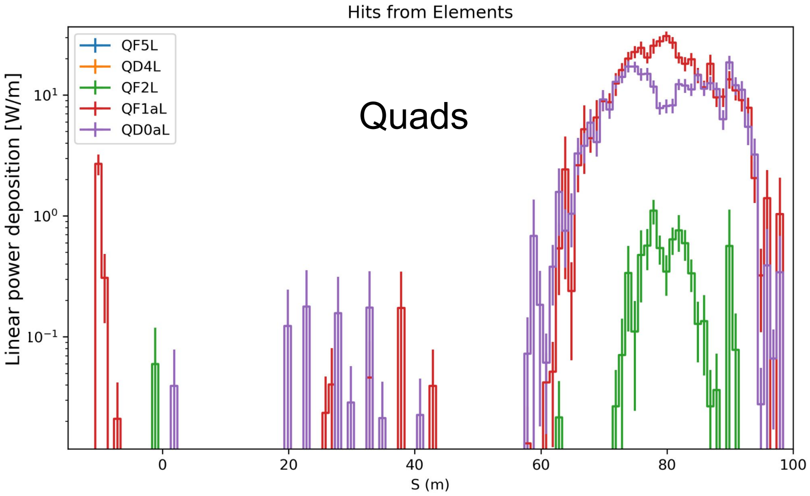


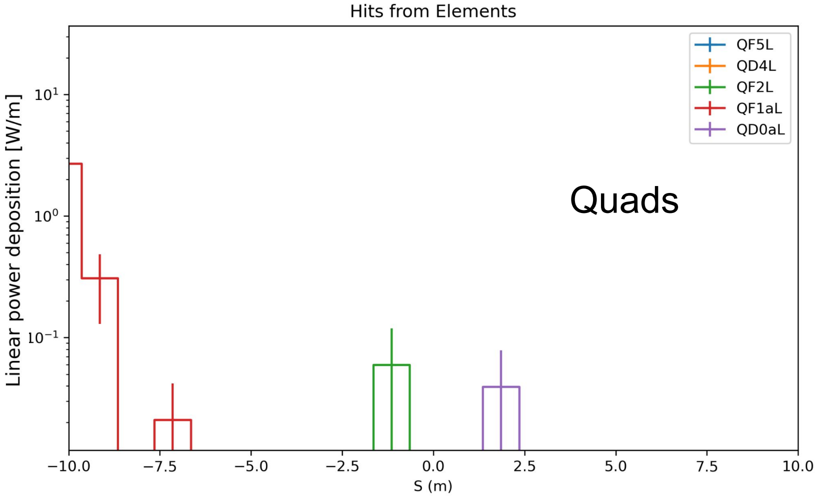


Similar order of magnitude in terms of SR losses. The HFD lattice needs SR collimators to have a conclusive comparison.


Deposited SR Photons by Source Beamline Element
BC3L
BC2L
BC1L
BWL
Dipoles
Linear power deposition [W/m]
S (m)

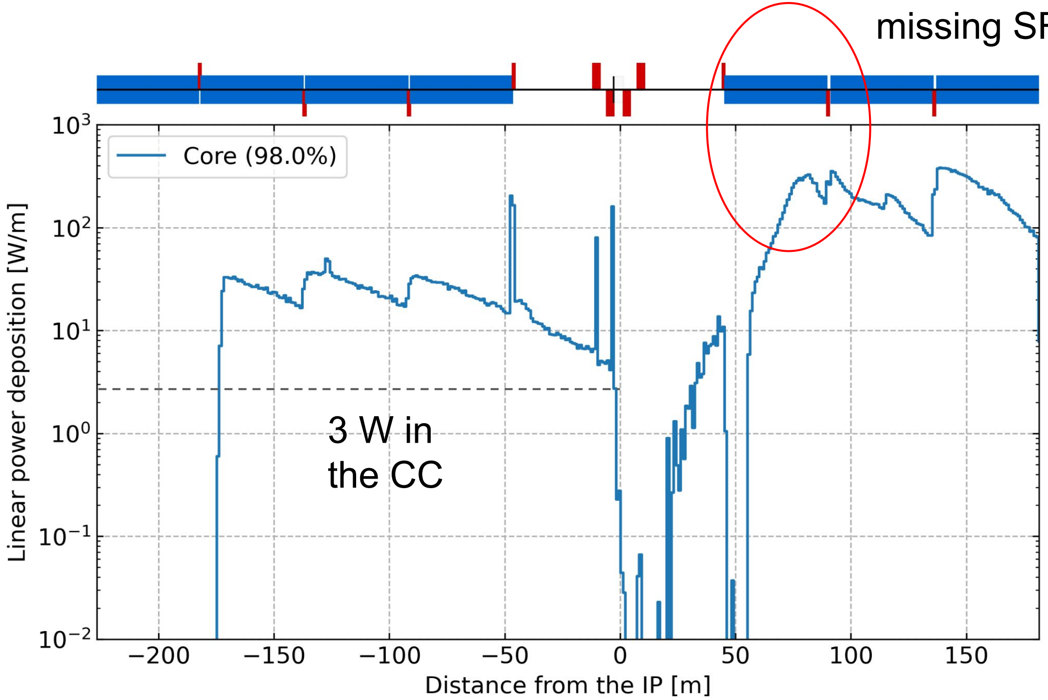

Deposited SR Photons by Source Beamline Element
MASK
BC3L
BC2L
BC1L
BWL
Dipoles
Linear power deposition [W/m]
S (m)

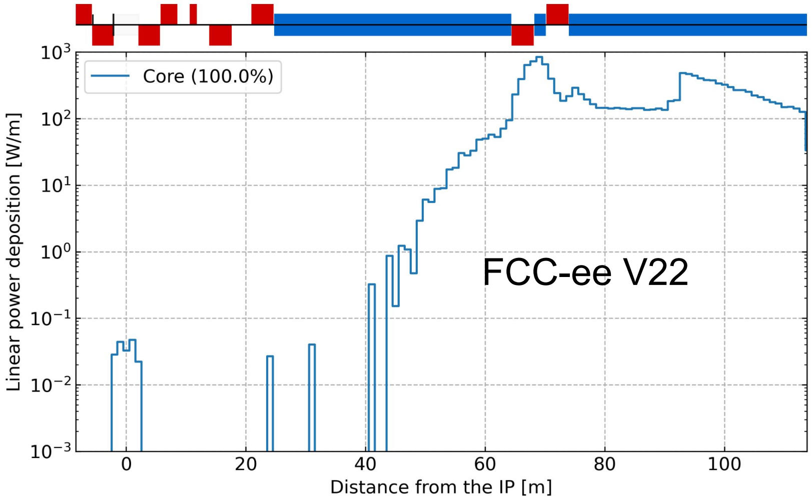

Hits from Elements
QF5L
QD4L
QF2L
QF1aL
QD0aL
Quads
Linear power deposition [W/m]
S (m)


Hits from Elements
QF5L
QD4L
QF2L
QF1aL
QD0aL
Quads
Linear power deposition [W/m]
S (m)

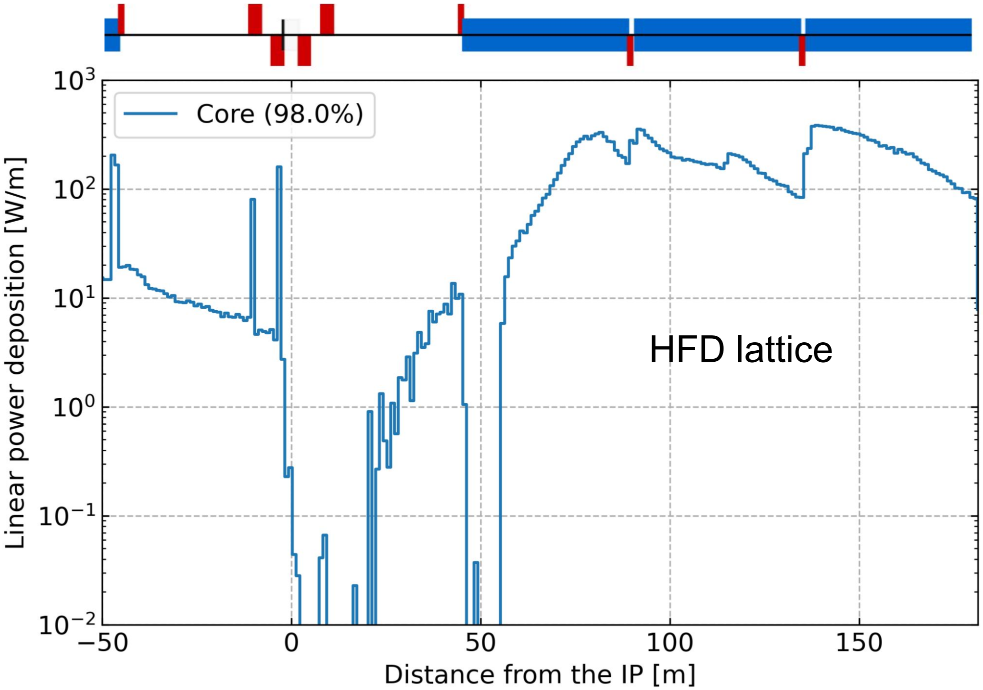
SR power deposition at tt energy 182.5 GeV

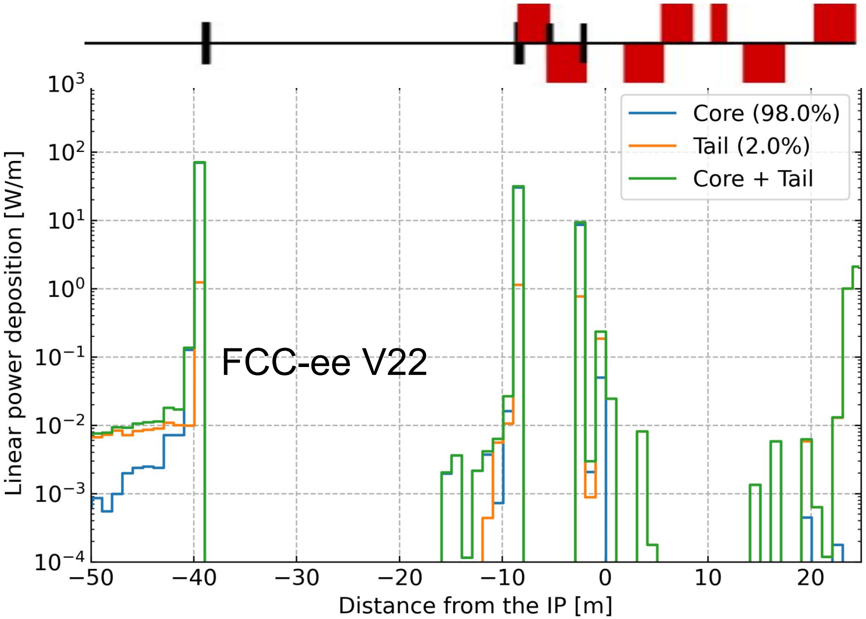
missing SR from solenoid ?





SR power deposition at tt energy 182.5 GeV

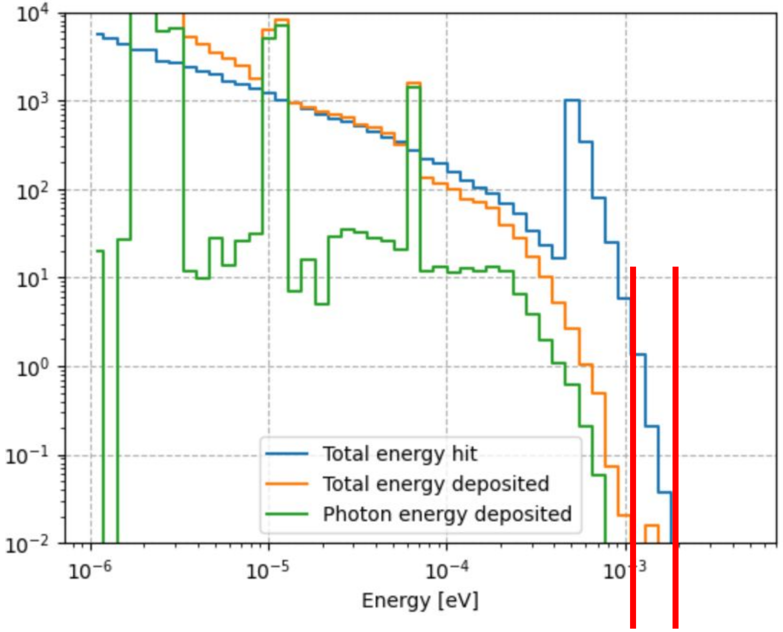




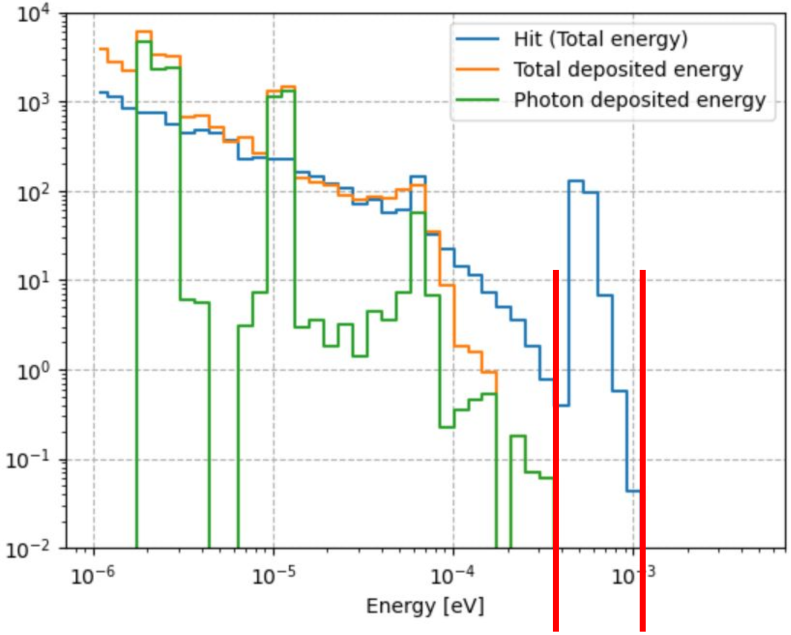
Similar order of magnitude in terms of SR losses. The HFD lattice needs SR collimators to have a conclusive comparison.

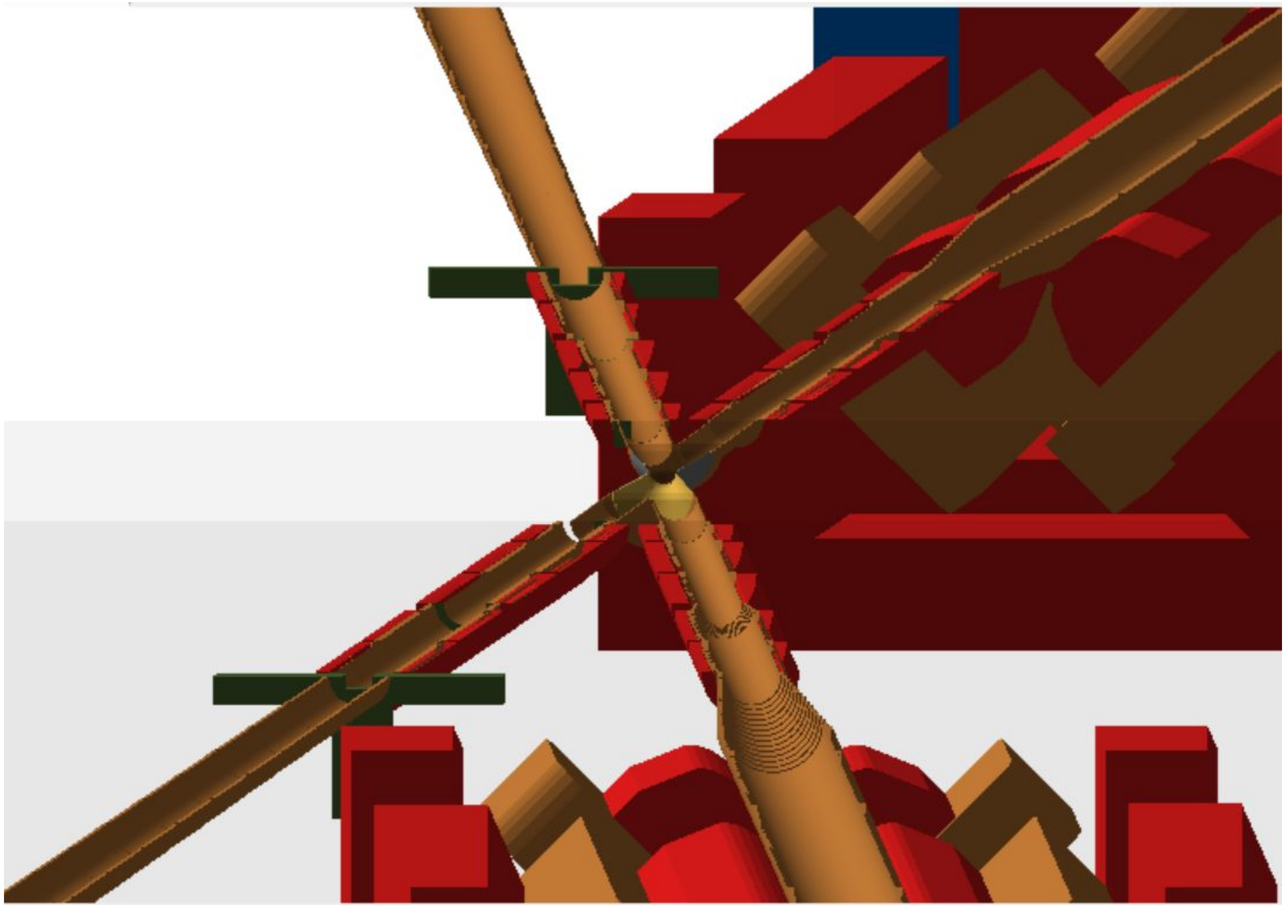
Photon energy spectrum at the mask

MASK_QC1L - FCC-ee HFD



MASK_QC1L - FCC-ee V22





Simulations settings

10 runs of 100,000 primary positrons (or 10 runs of 50,000 primary positrons)

Beam distribution: **Gaussian distribution** from Twiss parameters to represent **the core**

or **Halo uniform distribution** 4 to 10 (or more) σ_x (and σ_y) to represent **the tails**

Physics list : *Synchrotron_radiation* physics and *em_peneloppe* (particle-matter interaction)

Energy / Range cuts:

e+/e- **1 mm** ~ 990 eV (air/vacuum), 2.3 MeV in W, 1.4 MeV in Cu

e+/e- **5 um** ~ 53 keV in W, 60 keV in Cu

gamma **1 mm** ~ 990 eV (air/vacuum), 1 keV in W, 1 keV in Cu

gamma **5 um** ~ 4.8 keV in W, 2.2 keV in Cu