Synchrotron Radiation Background @ FCC-ee

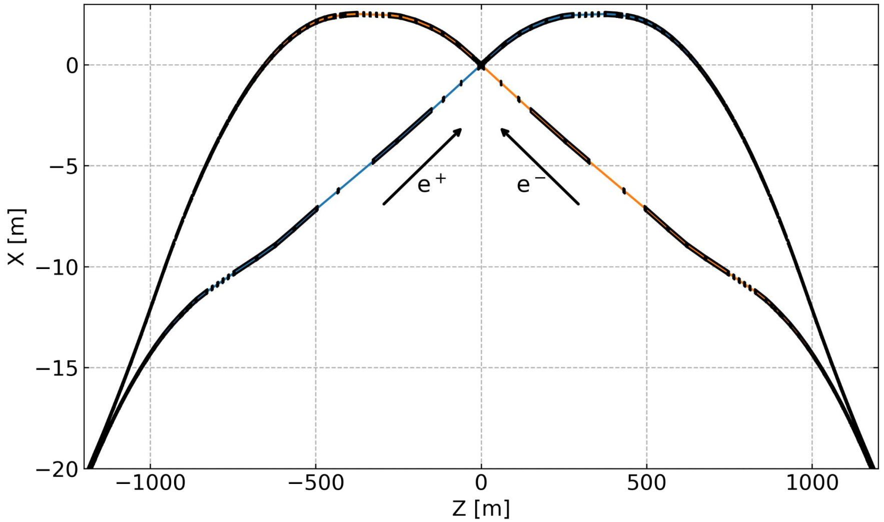
K.D.J. André for the MDI study group

FUTURE
CIRCULAR
COLLIDER

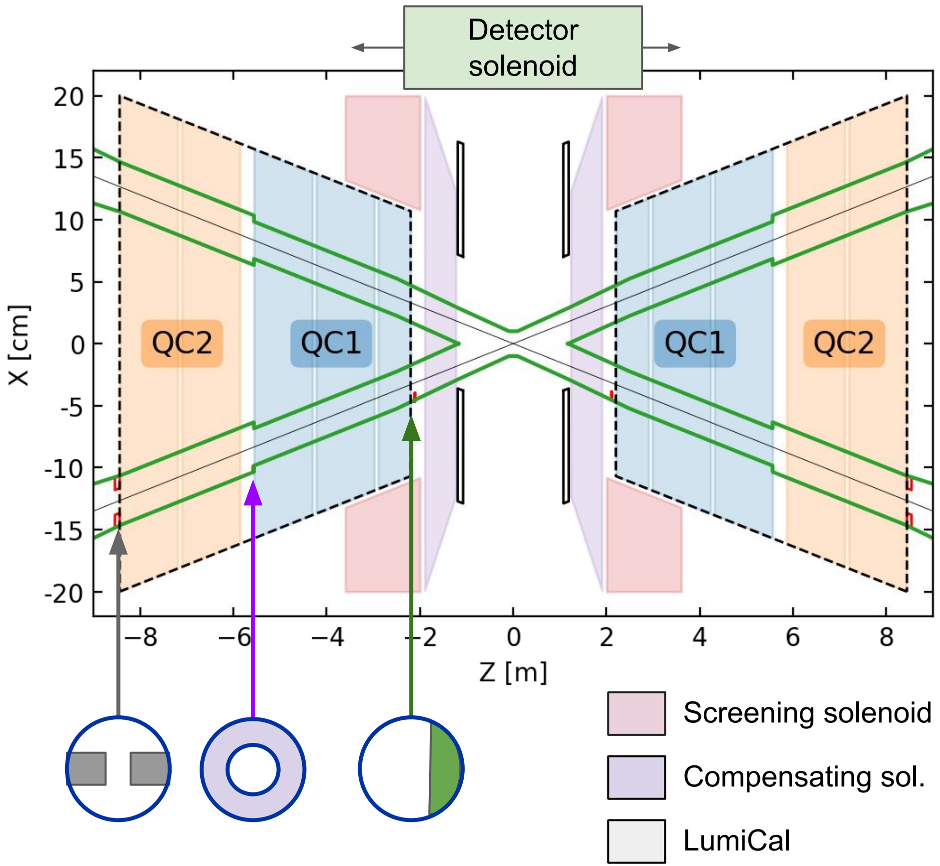
Outline

- FCC-ee lattice, aperture profile, masks and collimators
- Beam model: core and tail transverse distributions
- Synchrotron radiation collimation scheme
  - At the Z operation mode
  - At the $t\underline{t}$ operation mode
- On-going studies
- Summary

FCC-ee lattice | IR design



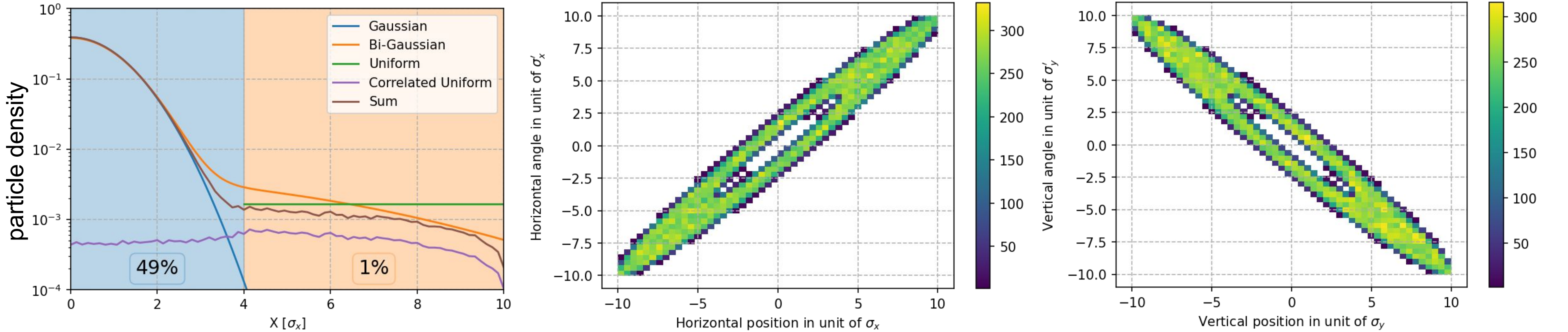
The lattice design upstream the IP is based on weak dipoles and long straight sections. There is a **30 mrad crossing angle** at the IP. The central beam pipe radius is **10mm** over **18cm** along the Z axis and is tapered to 15mm in QC1.



Beam model | Core and tail

Previous work from M. Sullivan (ref) 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 **4 σ_x to 10 σ_x** along the horizontal positions and angles and from **4 σ_y to 10 (30 or 50) σ_y** along the vertical positions and angles. Assuming **98%** of the particles **in the core** and **2% in the tails**.



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.

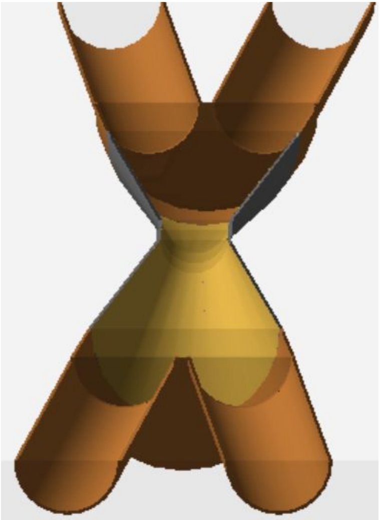
Implementation of a realistic central beam pipe in a GDML format.

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.

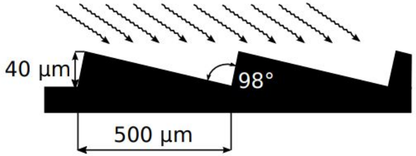
The beam parameters can be found in (ref).

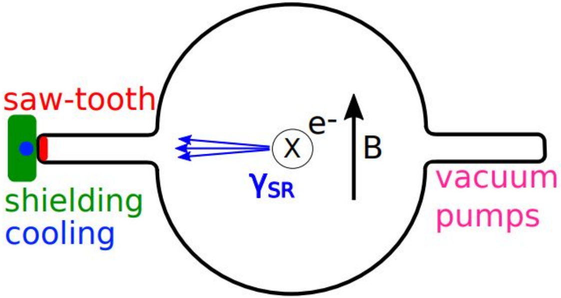


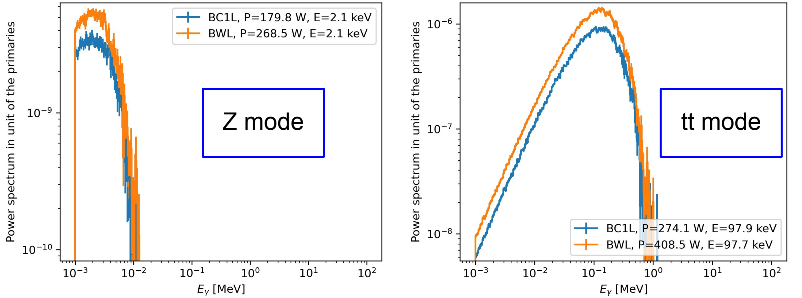
Characteristics of the various operation modes: **Z, W, H, tt**

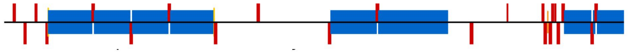
Synchrotron radiation from upstream dipoles

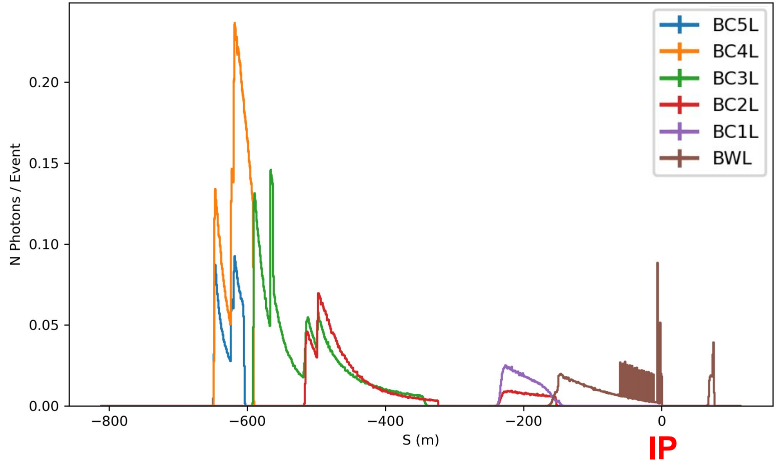
D. Arominski PhD thesis on the x-ray reflection mitigation in the CLIC BDS by adjusting the beam pipe roughness with a saw-tooth pattern on the beam pipe. Similarly, R. Kersevan presented during the FCCee MDI meeting #4 (ref) and proposed a winglet geometry with saw-tooth pattern until the first FF quadrupole, to mitigate the x-ray reflection.



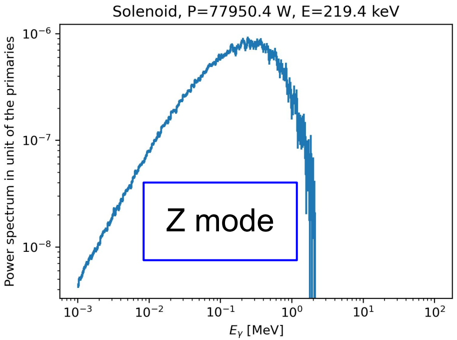


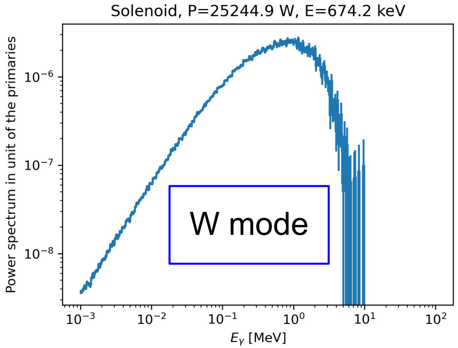


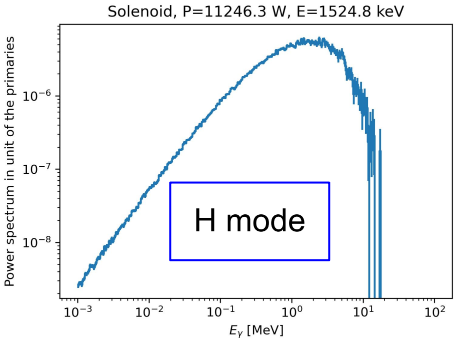


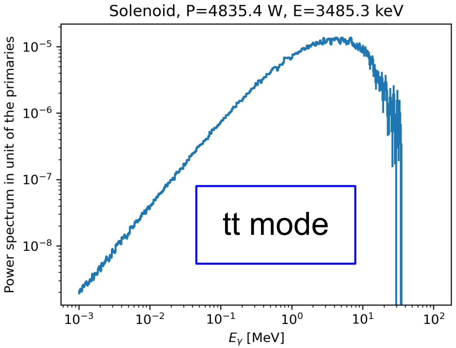


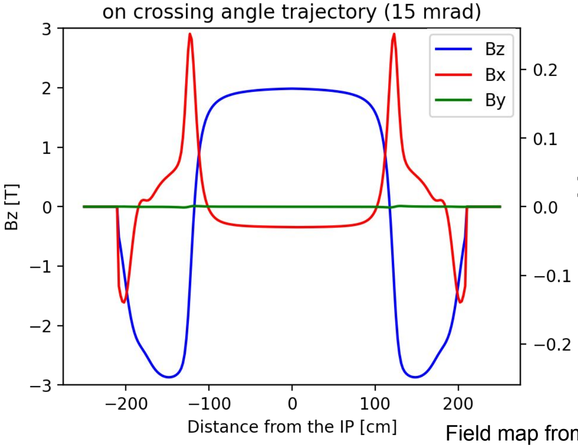
Synchrotron radiation from the solenoid field map



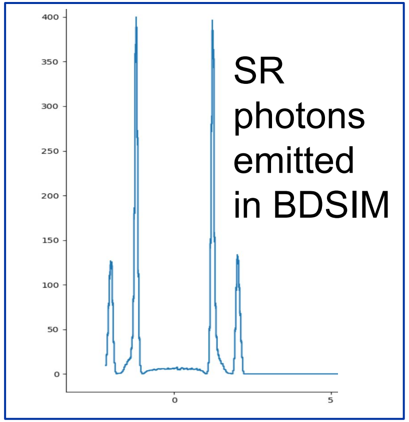


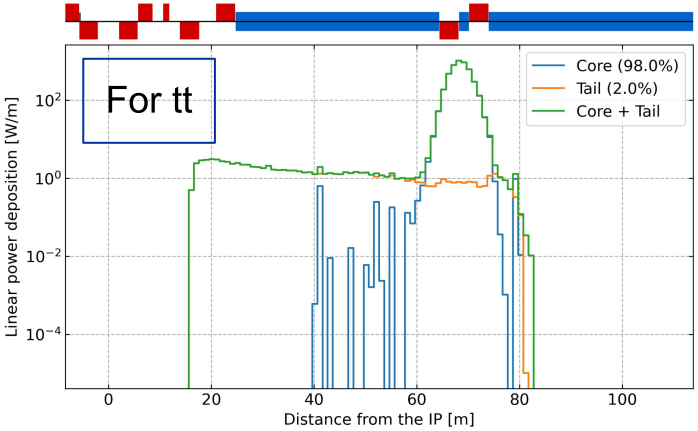






Field map from M. Koratzinos

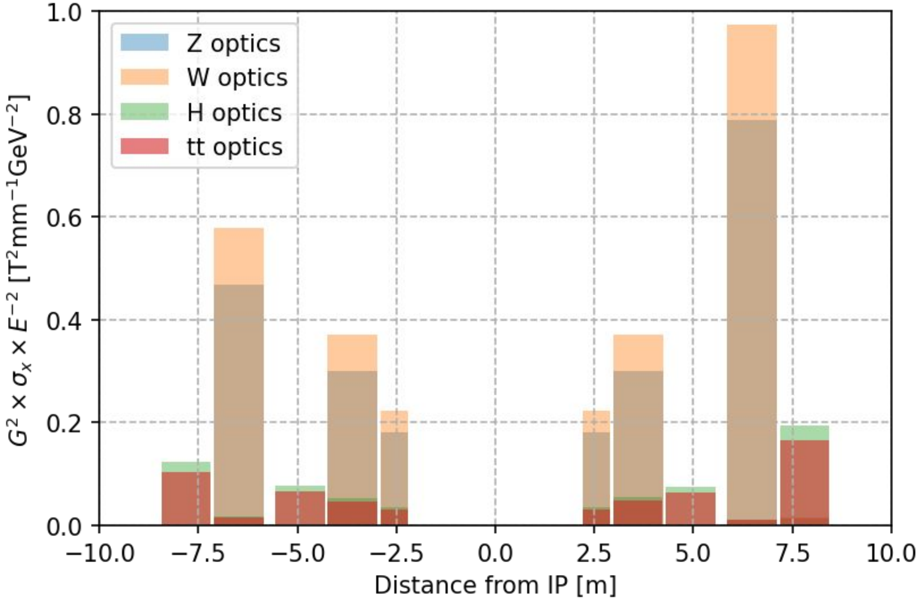




Synchrotron radiation from FF quadrupoles - I

Power analytical estimate from SR in quads [ref]:

$$P = P_0 I_0 G^2 \left[\varepsilon_x \int_0^L \beta_x(s)ds + \varepsilon_y \int_0^L \beta_y(s)ds\right]$$



The function $\mathbf{G^2\sigma_x E^{-2}}$ represents a figure of merit of the SR power from quadrupoles. One notes that beam current is scaled according to E^4 for the various operation modes of FCC-ee.

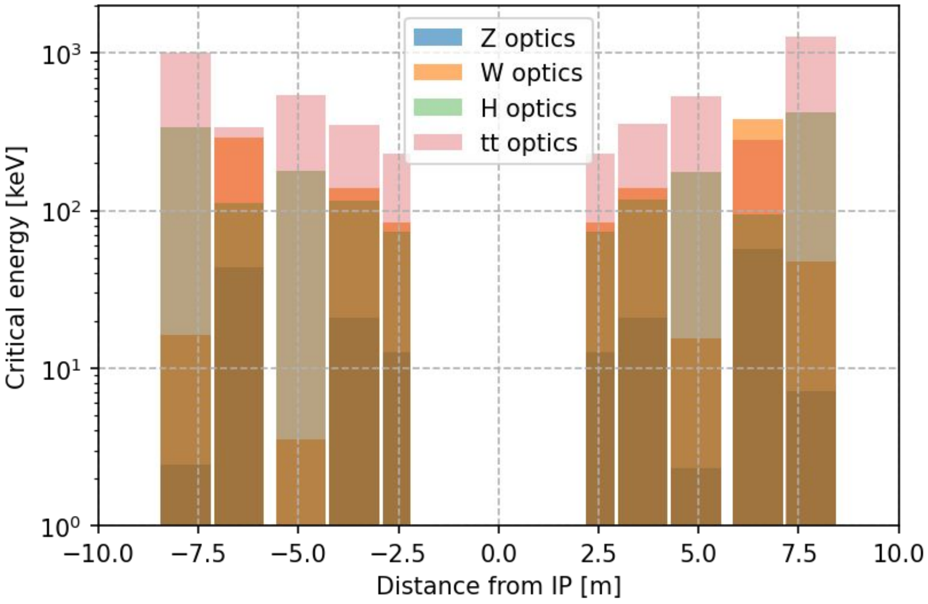
The amount of synchrotron radiation emitted in the FF quadrupoles strongly depends on the optics designs and quadrupole gradients.

	P /W	P /W	P /W	P /W
Mode	Z	W	H	tt
QC2L2	13	20	742	547
QC2L1	**4101**	**6266**	86	65
QC1L3	1	1	249	204
QC1L2	**1125**	**1812**	124	116
QC1L1	242	410	32	33
QC1R1	242	410	32	33
QC1R2	**1127**	**1815**	129	120
QC1R3	12	19	243	199
QC2R1	**6939**	**10599**	60	45
QC2R2	111	169	**1176**	866

Synchrotron radiation from FF quadrupoles - II

Critical energy analytical estimate from SR in quads:

$$E_{crit} = \frac{3\hbar c E^3}{2(m_e c^2)^3} \frac{G}{B\rho} \sqrt{\left[\varepsilon_x \int_0^L \beta_x(s)ds + \varepsilon_y \int_0^L \beta_y(s)ds\right]}$$



The function $\mathbf{G\sigma_x E^2}$ represents a figure of merit to compare the critical energy from quadrupoles. It does not depend on the beam current and scales with E^3.

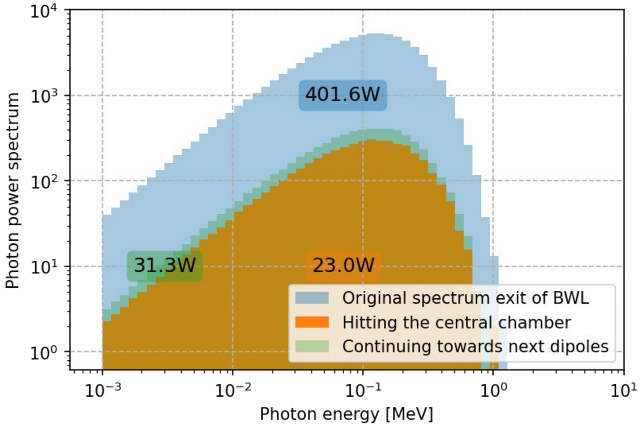
The different modes will produce different photon energies with the higher beam energy producing higher photon energies.

	E/ keV	E/ keV	E/ keV	E/ keV
Mode	Z	W	H	tt
QC2L2	3	18	**373**	**1127**
QC2L1	48	**321**	**128**	**389**
QC1L3	1	4	**219**	**695**
QC1L2	26	**179**	**154**	**523**
QC1L1	12	83	78	**278**
QC1R1	12	83	78	**278**
QC1R2	26	**176**	**157**	**533**
QC1R3	3	18	**216**	**687**
QC2R1	62	**417**	**107**	**325**
QC2R2	8	53	**470**	**1417**

Synchrotron radiation collimation scheme

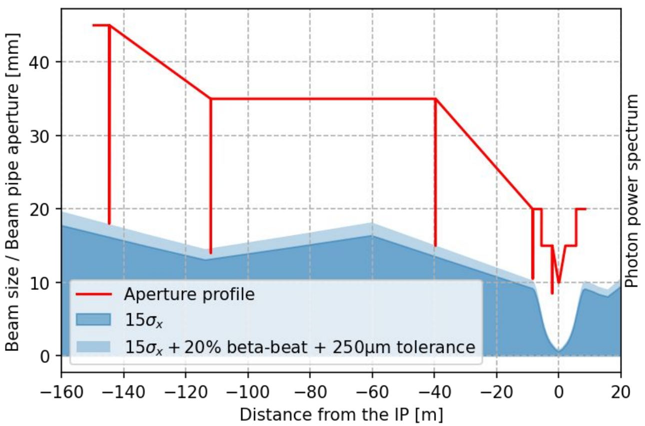
Synchrotron radiation power deposition from BWL (last dipole before the IP)

Unshielded study



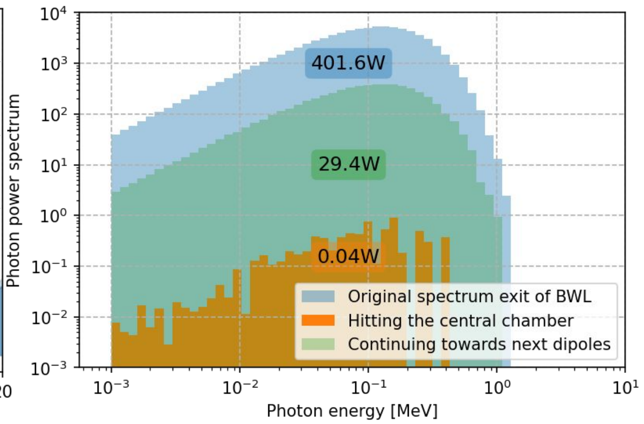
A total of **23W** is deposited in the CC region and **347W** are distributed along the beam line before the IP.
31W continue towards BC1R-BC3R.

Mitigation method



Study of the SR from the last dipole, tracked past the IP to record the photon hits and confine them at specific locations as well as possible.

Shielded study

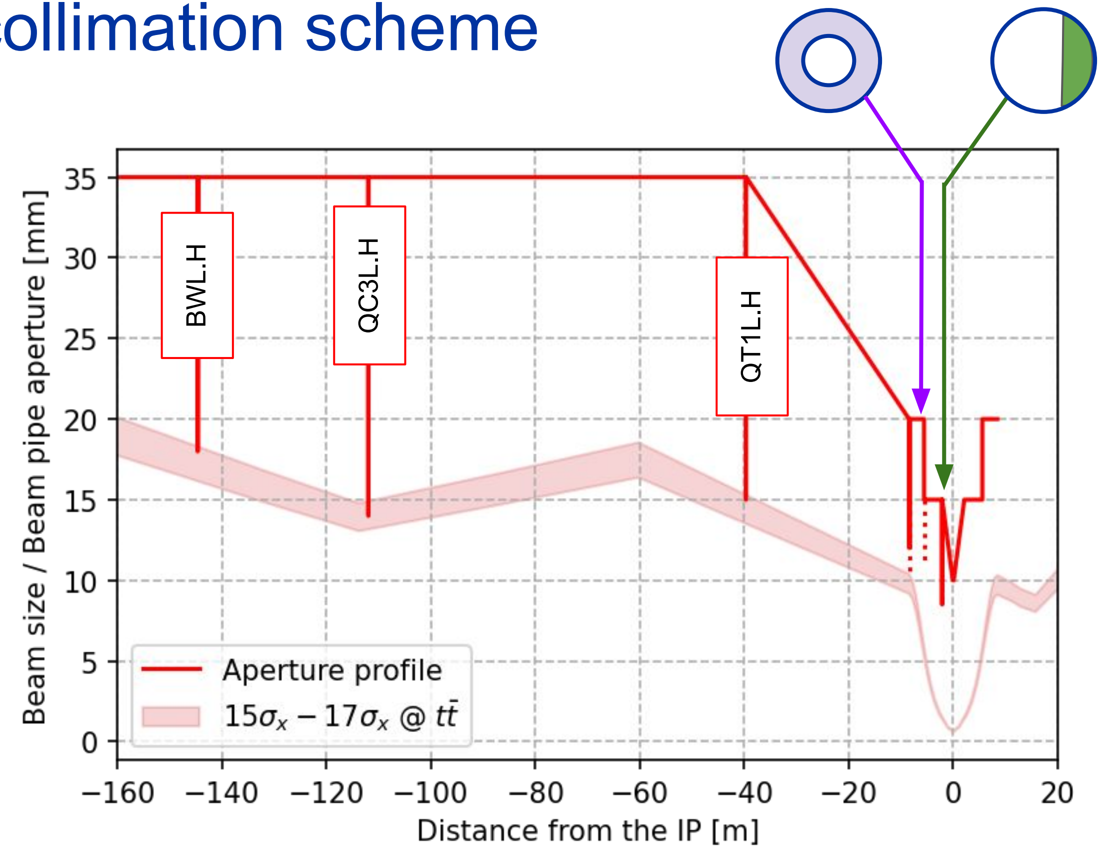


Power spectrum of the photons hitting the beam pipe or continuing towards the dipoles BC1R-BC3R.

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.



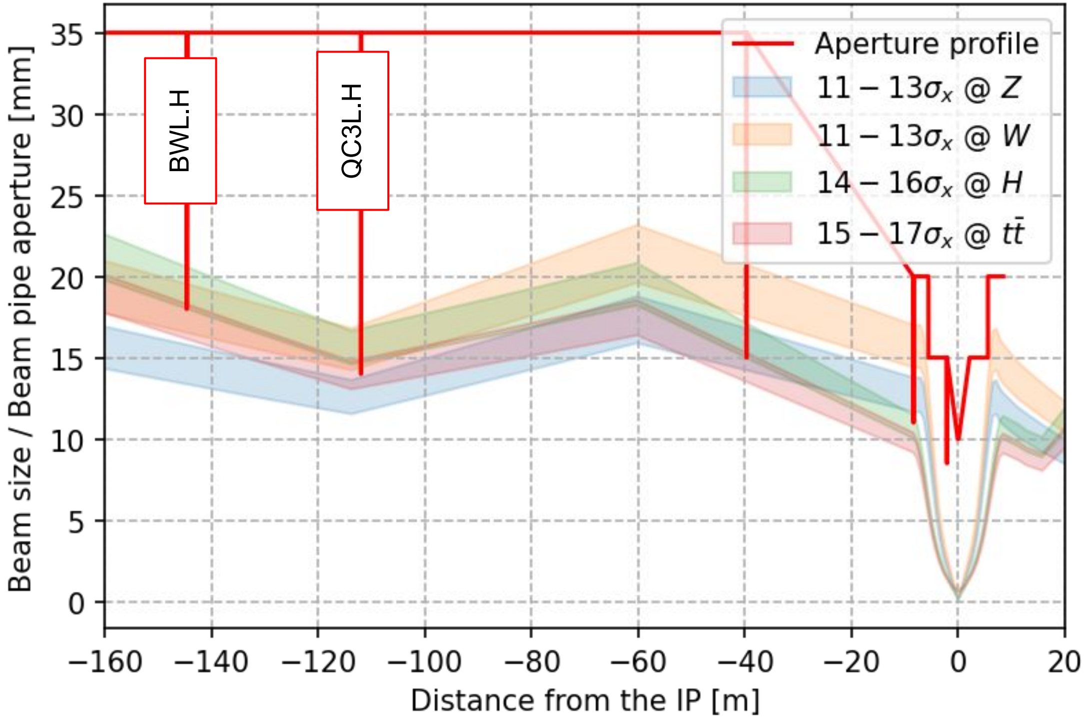
Synchrotron radiation collimation scheme

BWL: might be a problem @ H, but can be re-optimised once BWL dipole will be split. *Not critical*.

QC3L: Ok @ Z and tt, but difficult @ W and H. Could be more opened but more SR power would be deposited in the beam pipe. *Not critical*.

QT1L: Ok @ tt, *difficult for Z, W and H.* Can be opened more but more SR will propagate to PQC2LE and will represent an issue for Z and W modes.

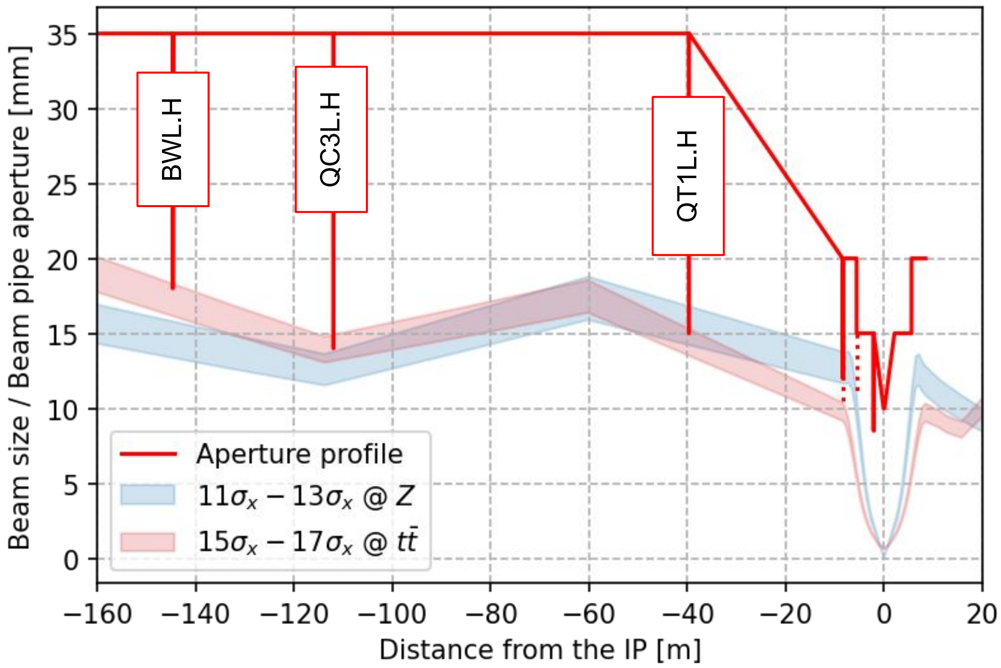
PQC2LE: Ok @ H and tt, but requires more opening @ Z and W. Less protection of QC2L and may require to close MSK.QC2L further (radial mask).



The primary and secondary collimator settings for **W** and **H** are speculative. There are no issues in the vertical plane.

Synchrotron radiation collimation scheme

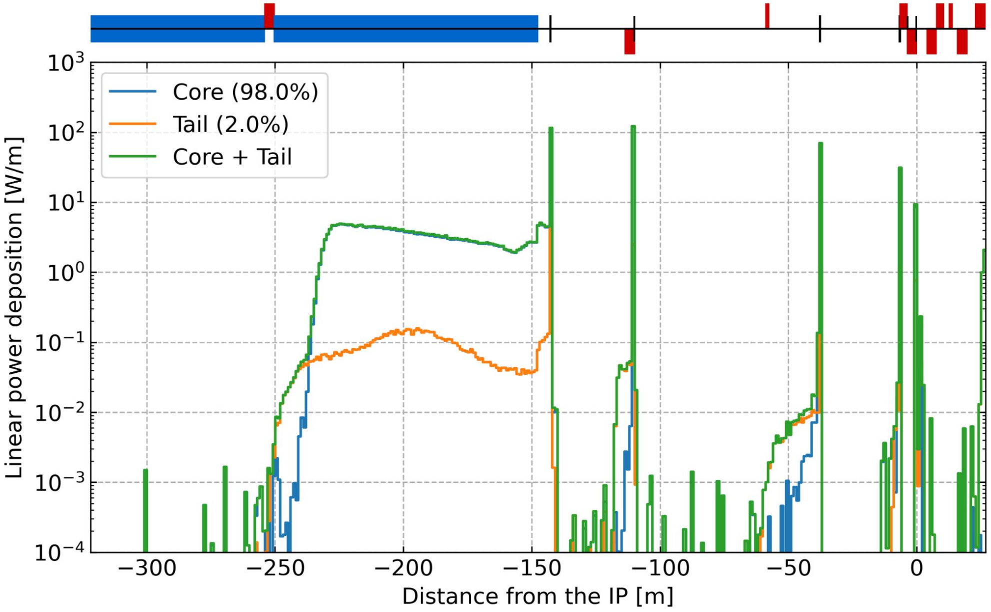
Name	s [m]	half-gap [mm]	plane
BWL.H	-144.69	18	H
QC3L.H	-112.05	14	H
QT1L.**H**	-39.75	15	H
QT1L.**V**	-39.65	15	V
PQC2LE.**H**	-8.64	11→12	H
PQC2LE.**V**	-8.54	11	V
MSK.QC2L	-5.56	R = 15→11	H&V
MSK.QC1L	-2.12	8.5→7.0	H



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.

$t\bar{t}$ operation mode

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

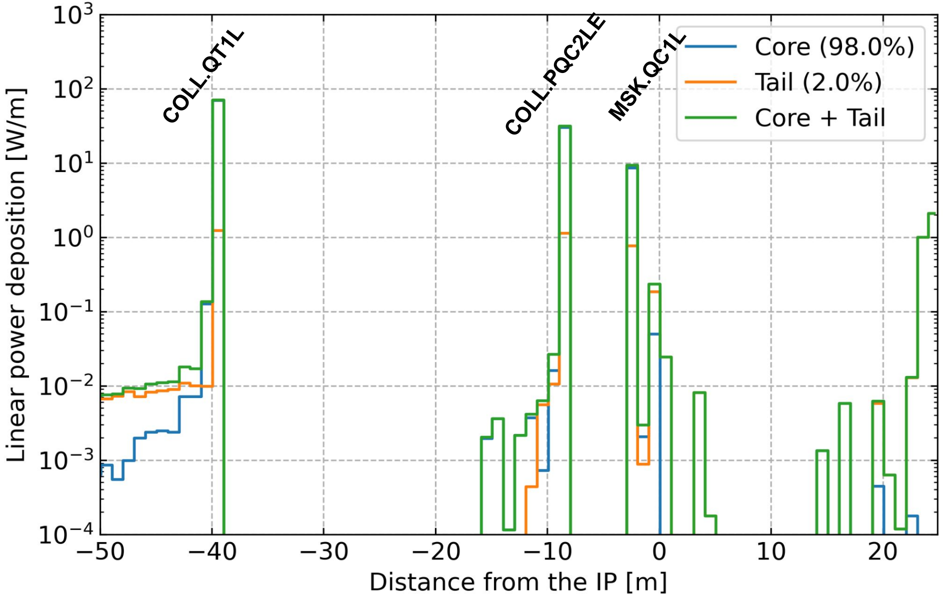


Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

Name	s [m]	nsigma	half-gap [m]	plane
bwl.h	-144.692	16.7	0.018	H
qc3l.h	-112.054	16.1	0.014	H
qt1l.h	-39.747	16.7	0.015	H
qt1l.v	-39.647	180.9	0.015	V
pqc2le.h	-8.64	18.0	0.011	H
pqc2le.v	-8.54	120.0	0.011	V
msk.qc2l	-5.56	43.5/113	R = 0.015	Radial
msk.qc1l	-2.12	93.9	0.0085*	H

COLL.BWL is 10cm of tungsten absorbing **124W**
COLL.QC3L is 10cm of tungsten absorbing **124W**
COLL.QT1L is 10cm of tungsten absorbing **70W**
COLL.PQC2LE is 10cm of tungsten absorbing **25W**
MSK.QC2L is 2cm of tungsten absorbing **0.1mW**
MSK.QC1L is 2cm of tungsten absorbing **10W**

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



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qt1l.h	-39.747	16.7	0.015	H
qt1l.v	-39.647	180.9	0.015	V
pqc2le.h	-8.64	18.0	0.011	H
pqc2le.v	-8.54	120.0	0.011	V
msk.qc2l	-5.56	43.5/113	R = 0.015	Radial
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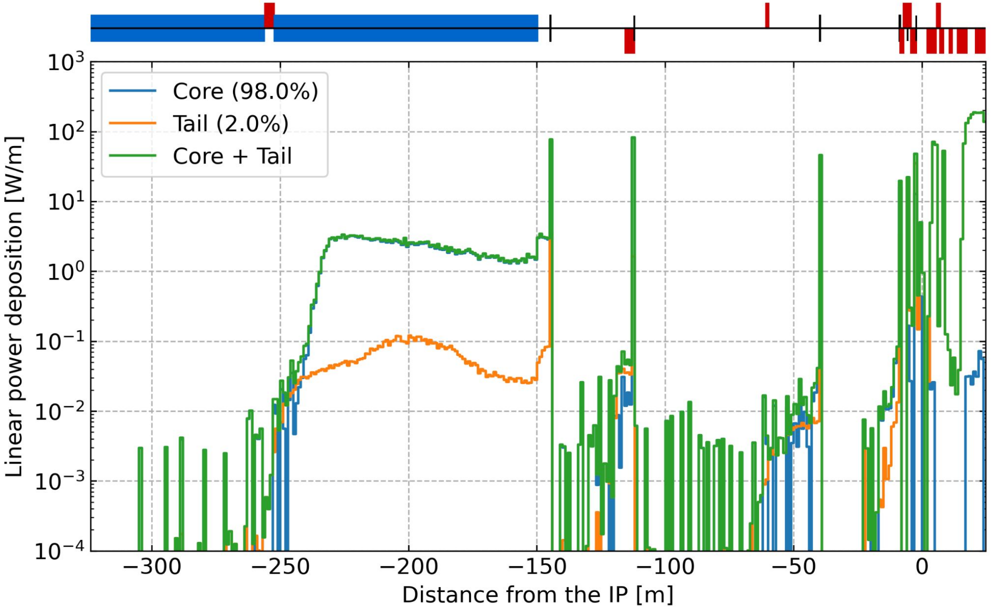
Z operation mode

Synchrotron radiation collimation at the Z mode - Core and tails

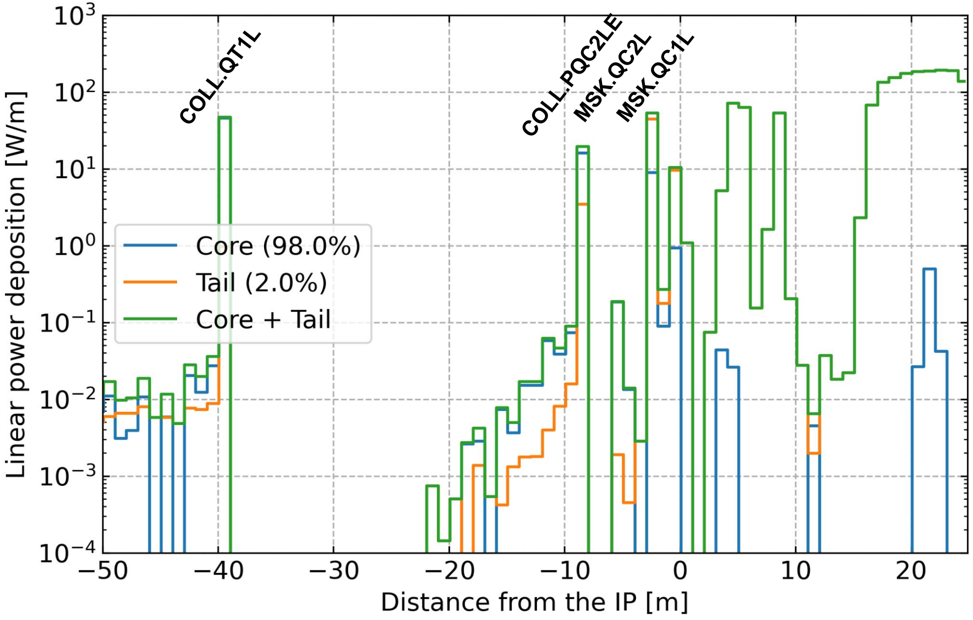


Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

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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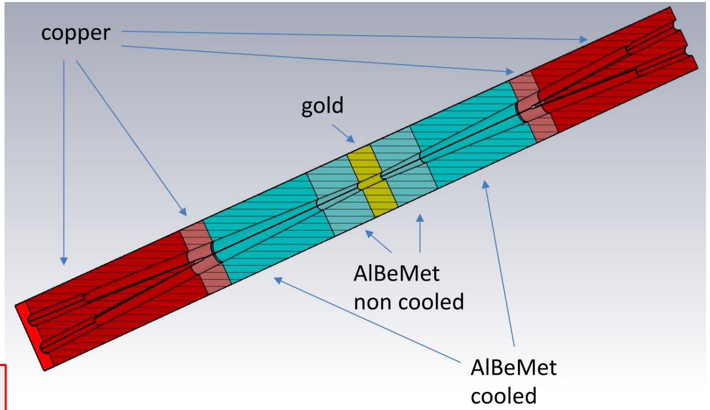
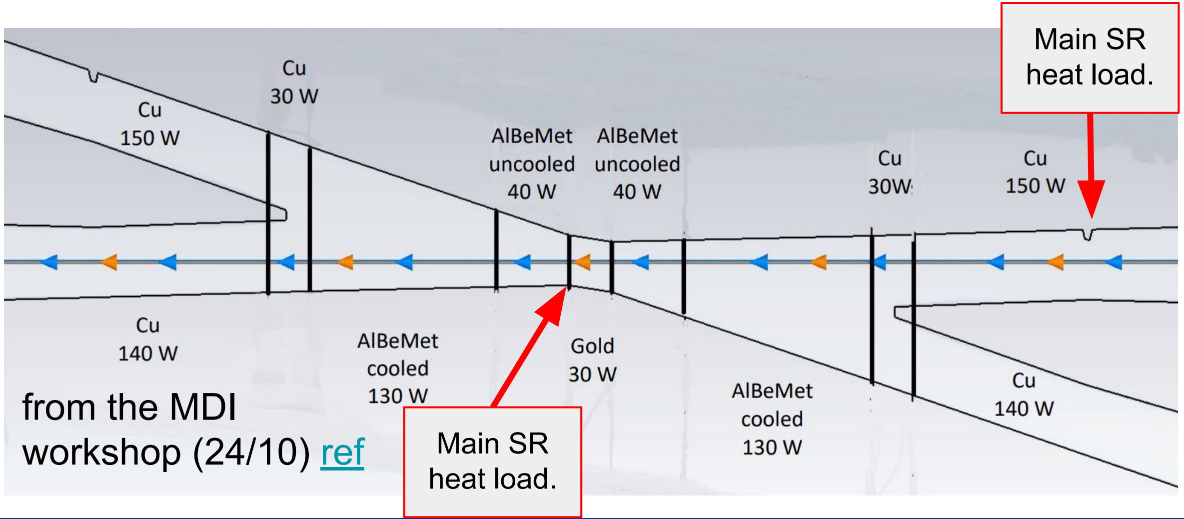
MSK.QC2L is 2cm of tungsten absorbing **37mW**
MSK.QC1L is 2cm of tungsten absorbing **56W(143W)**

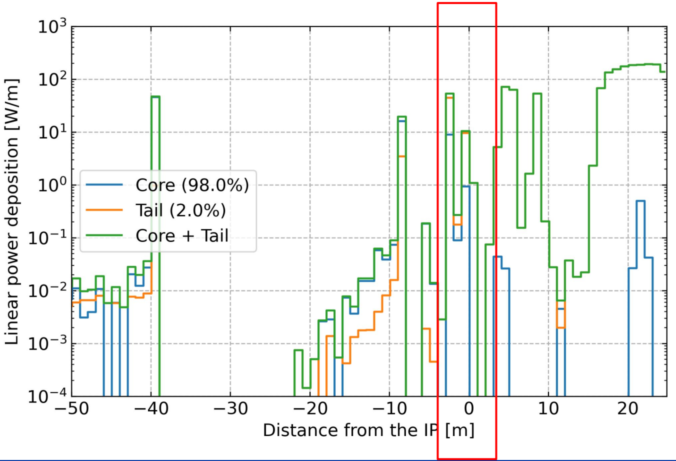
Comparison with wakefield heat load

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.



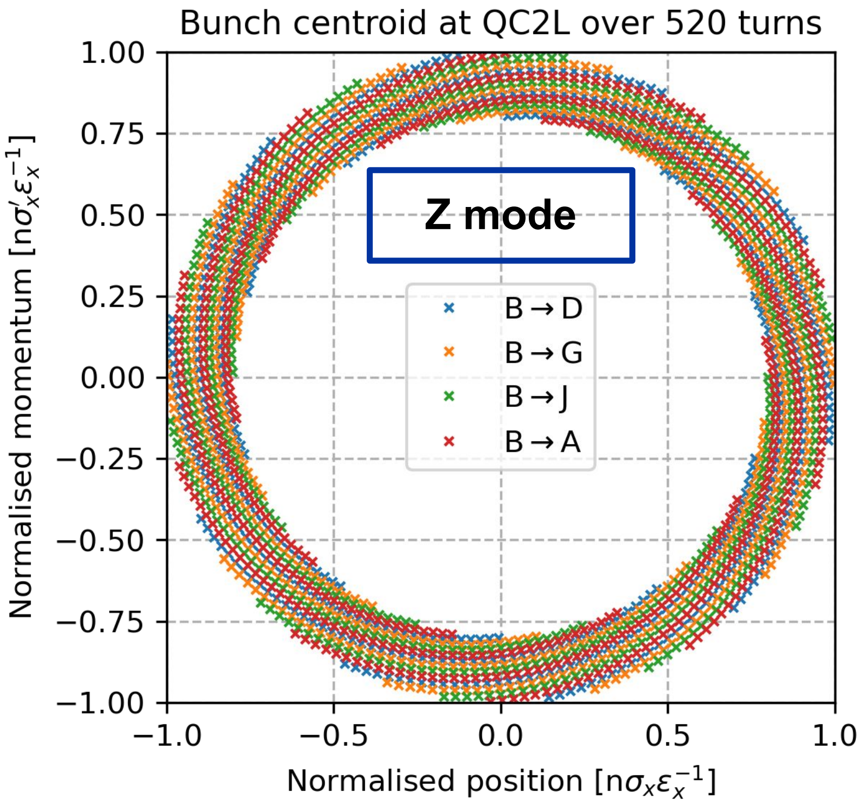


from the MDI workshop (24/10) ref



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

Top up injection



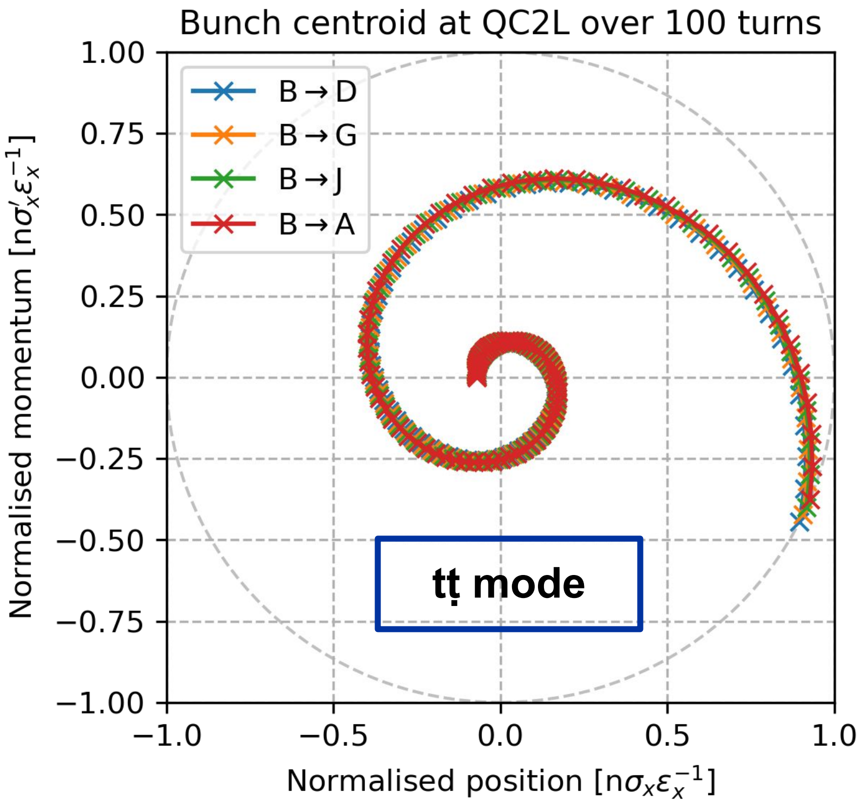
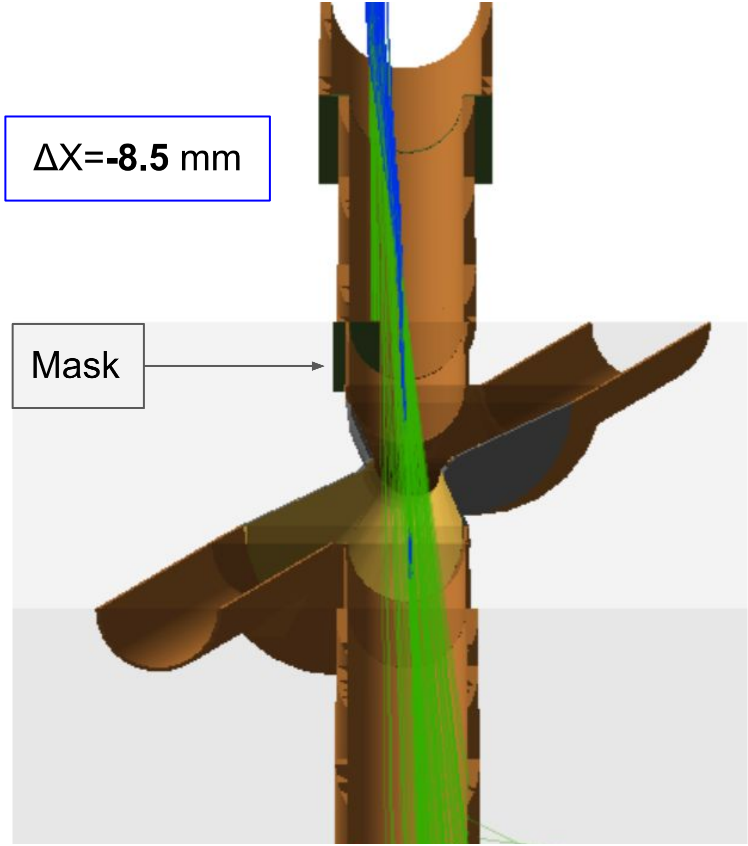
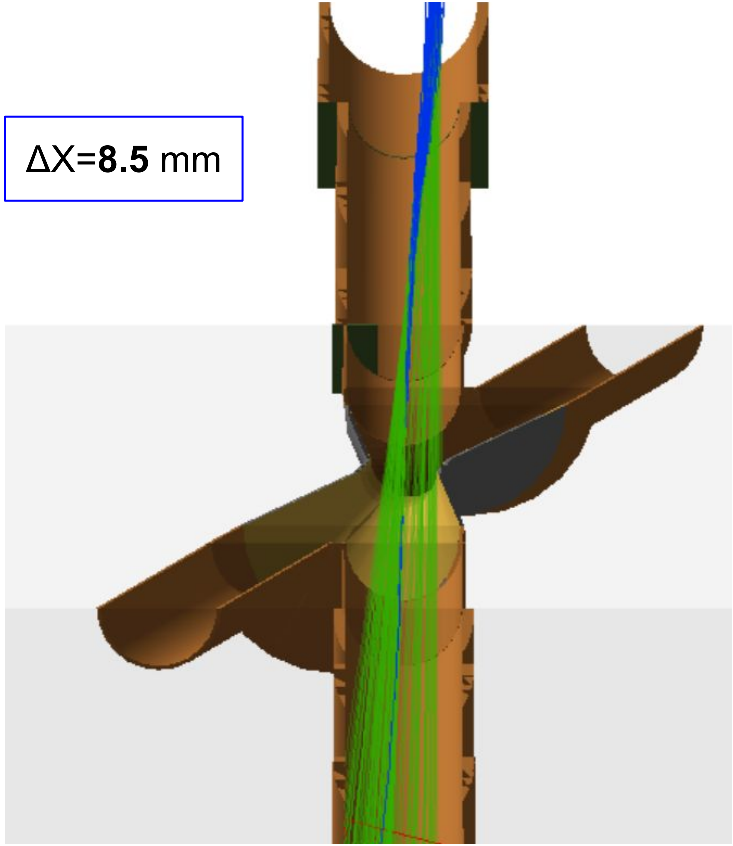
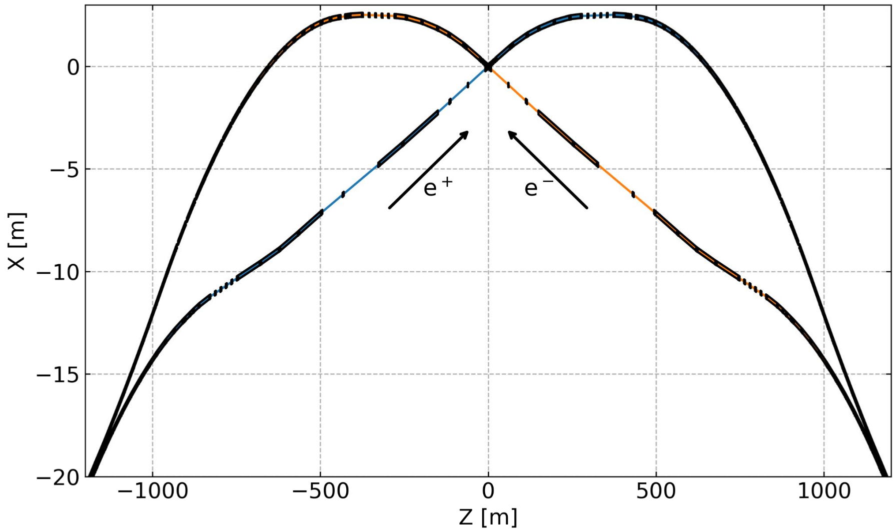


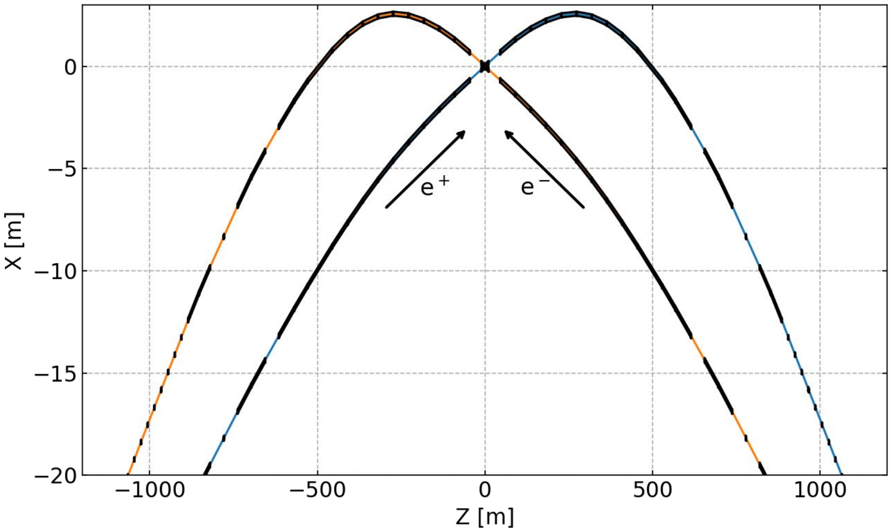
Illustration of the two extremes at Z





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

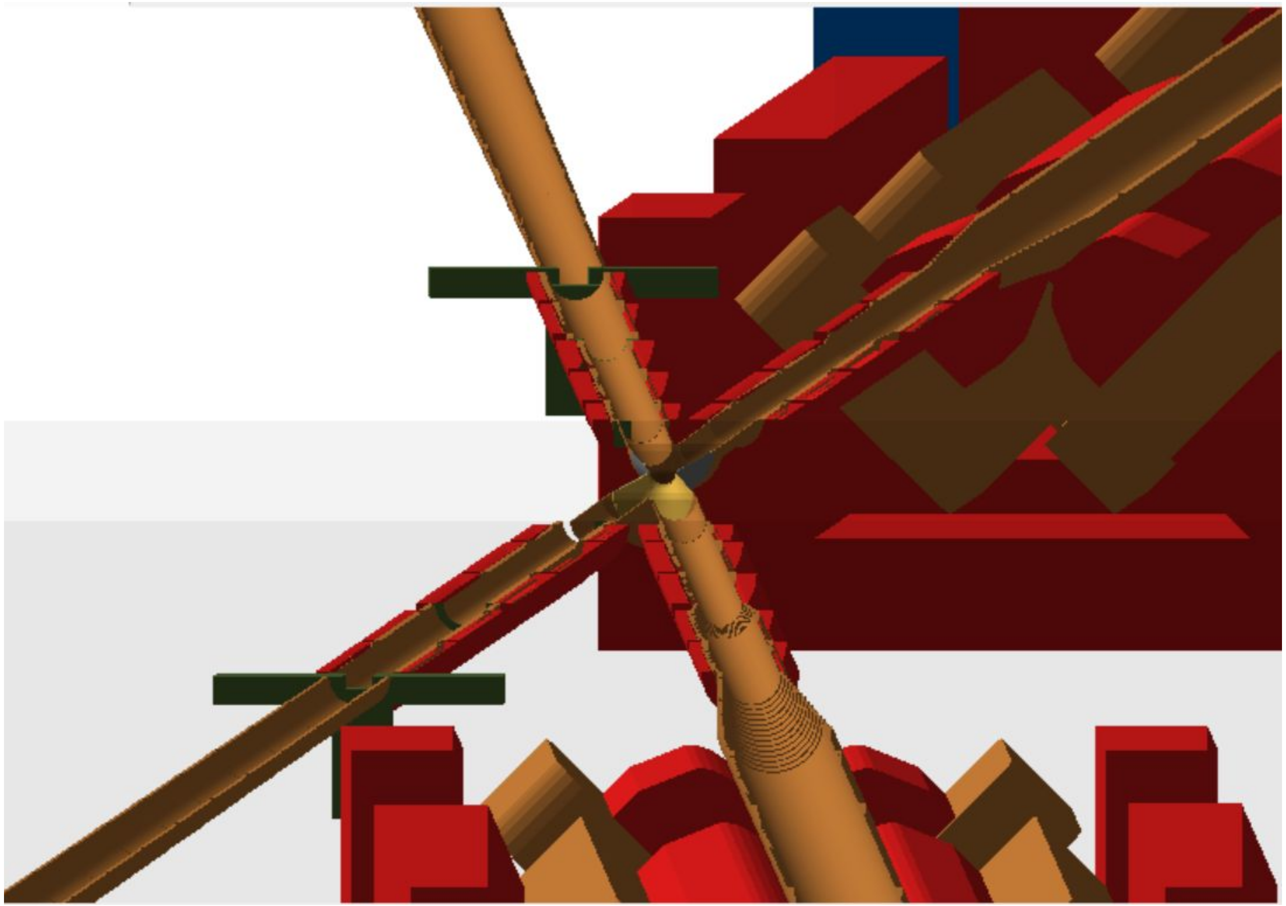
Symmetric interaction region beam optics to accommodate a short straight section with the last dipole (200keV critical energy) **48m** from the IP.
Optics design at the IP: β_x*=13cm, β_y*=0.5mm

Summary:

- **The interaction region lattices for the 4 operation modes have been implemented in BDSIM** with the **solenoid field map** and with a realistic design of the central beam pipe with **10mm radius**.
- The heat load on the central beam pipe due to synchrotron radiation is smaller than the heat load due to wakefields at Z.
- The collimators and masks mitigate the synchrotron radiation hits on the beam pipe from the last dipole (BWL) and quadrupoles in the straight section.
- The **initial synchrotron radiation collimator settings** have been designed for the **Z and tt operation modes** with the objective of being above the primary collimators, if possible above the secondary collimators as well.

Next steps:

- Iteration with A. Abramov on the positions and apertures of the synchrotron radiation collimators within the collimation hierarchy.
- Study the SR collimation performance with the X-Y tail distribution modeling (charge and width).
- Continue the study of the synchrotron radiation background due to off-axis top-up injection.



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

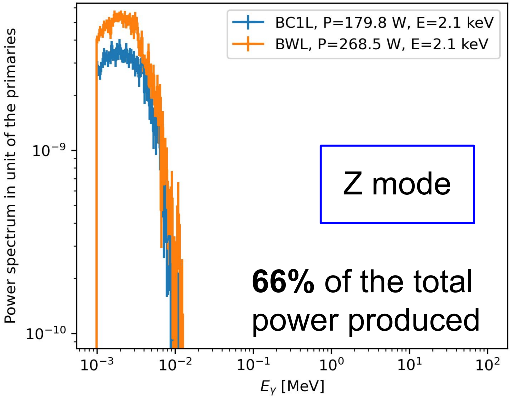
Physics list - em_penelope: https://geant4.web.cern.ch/node/1621

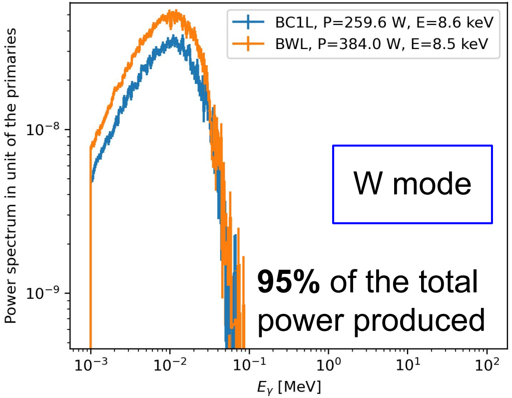
The model approach and the available Penelope model

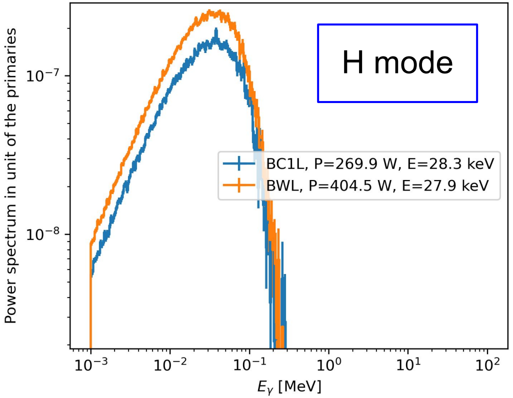
Physics process	Particle(s)	Old Penelope Process	New Penelope Model
Rayleigh scattering	gamma	G4PenelopeRayleigh	**G4PenelopeRayleighModel**
Compton scattering	gamma	G4PenelopeCompton	**G4PenelopeComptonModel**
Photo-electric effect	gamma	G4PenelopePhotoElectric	**G4PenelopePhotoElectricModel**
Pair production	gamma	G4PenelopeGammaConversion	**G4PenelopeGammaConversionModel**
Ionisation	$e^{\pm}$	G4PenelopeIonisation	**G4PenelopeIonisationModel**
Bremsstrahlung	$e^{\pm}$	G4PenelopeBremsstrahlung	**G4PenelopeBremsstrahlungModel**
Positron annihilation	e^{+}	G4PenelopeAnnihilation	**G4PenelopeAnnihilationModel**

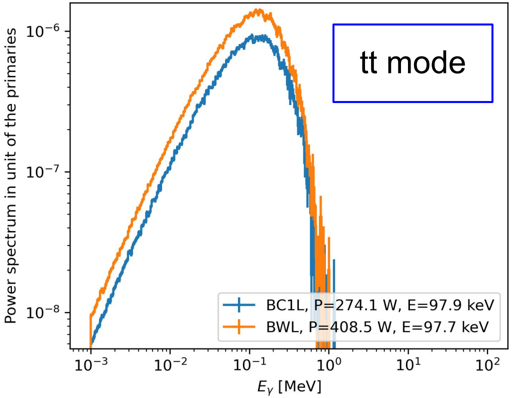
Note that **fluorescence is activated by default** in **G4EmLivermorePhysics, G4EmLivermorePolarizedPhysics and G4EmPenelopePhysics, G4EmStandardPhysics_option3, and G4EmStandardOption4 physics constructors** while Auger production and PIXE are not. For Geant4 10.5 UI commands "auger" and "augerCascade" are fully equivalent, the last will be removed in the next major release.

Synchrotron radiation from upstream dipoles

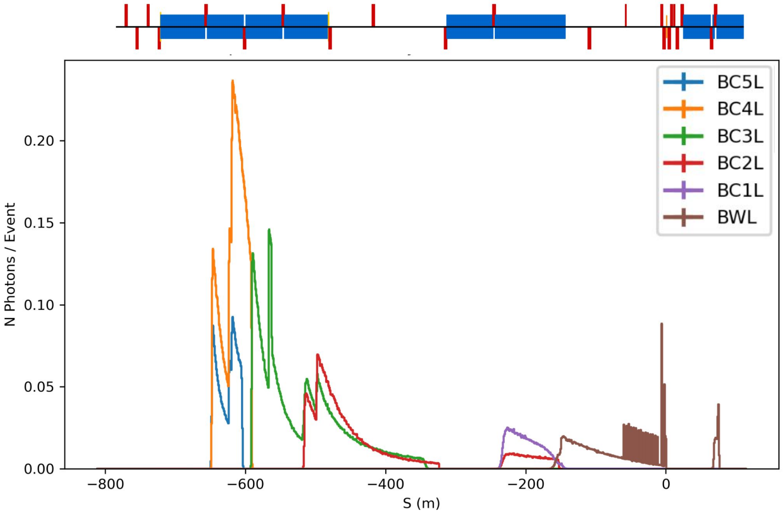








All SR power should be the same. The critical energy is slightly too high at the Z mode (low energy photon missing due to a cut at E = 990 eV). The other modes have the expected critical energies.



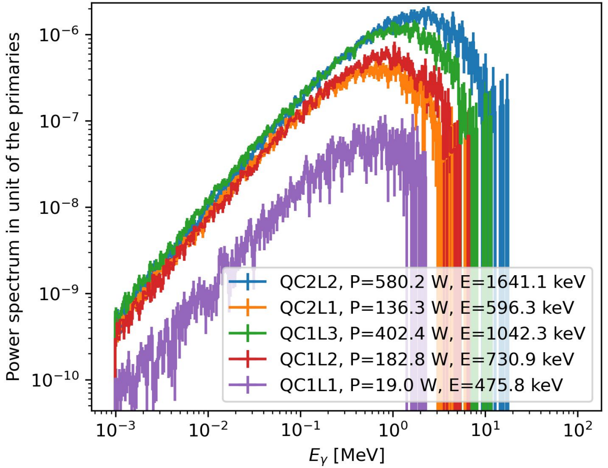
SR from quads for **tt mode**

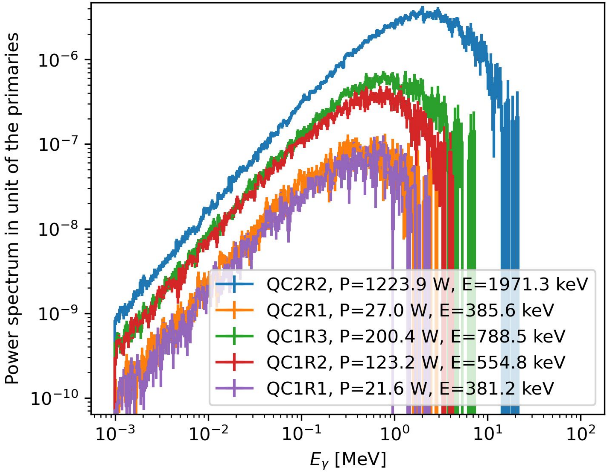
SR photons produced below 30 MeV.

Rather large critical energy for **QC2L2** (before the IP), hence particles in the tail can lead to SR hitting the central beam pipe;

and **QC2R2** mostly producing SR hitting the beam pipe in the dipoles downstream.

	Analytical		BDSIM	
	P /W	E/ keV	P /W	E/ keV
QC2L2	547	**1127**	580	**1641**
QC2L1	65	**389**	136	**596**
QC1L3	204	**695**	402	**1042**
QC1L2	116	**523**	183	**731**
QC1L1	33	**278**	19	**476**
QC1R1	33	**278**	22	**381**
QC1R2	120	**533**	123	**555**
QC1R3	199	**687**	200	**789**
QC2R1	45	**325**	27	**386**
QC2R2	866	**1417**	**1224**	**1971**





SR from quads for Z mode

SR photons produced below 1 MeV.

Rather large SR power for **QC2L1** (before the IP), hence particles in the tail can lead to SR hitting the central beam pipe;

and **QC2R1** mostly producing SR hitting the beam pipe in the dipoles downstream.

	Analytical		BDSIM	
	P /W	E/ keV	P /W	E/ keV
QC2L2	13	3	11	4
QC2L1	**4101**	48	**4281**	68
QC1L3	1	1	1	2
QC1L2	**1125**	26	**1460**	36
QC1L1	242	12	274	21
QC1R1	242	12	195	20
QC1R2	**1127**	26	853	34
QC1R3	12	3	8	5
QC2R1	**6939**	62	**6420**	89
QC2R2	111	8	111	12