Synchrotron Radiation Background for FCC-ee

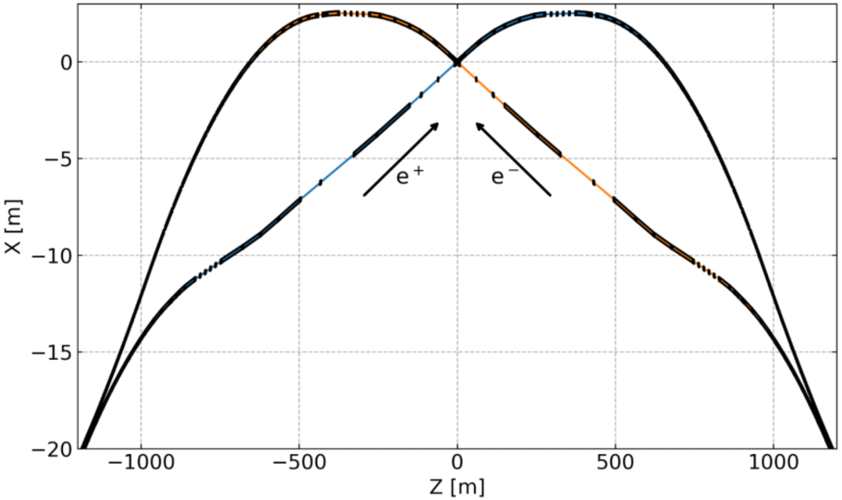
K.D.J. André for the MDI study group

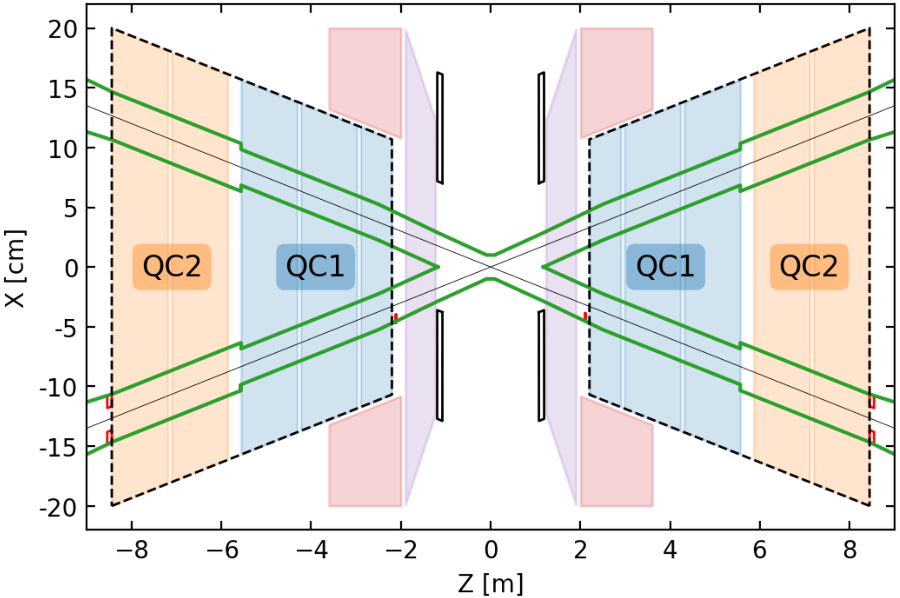
FUTURE
CIRCULAR
COLLIDER

Outline

- FCC-ee lattice, aperture profile, masks and collimators
- Beam model: core and tail transverse distributions
- The characteristics of the different FCC-ee operation modes
- Synchrotron radiation collimation scheme and knobs
- Focus on the Z operation mode mask and collimator settings
  - Beam misalignment along X and Y before QC2L2
  - Comparison with wakefield heat load
- 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.

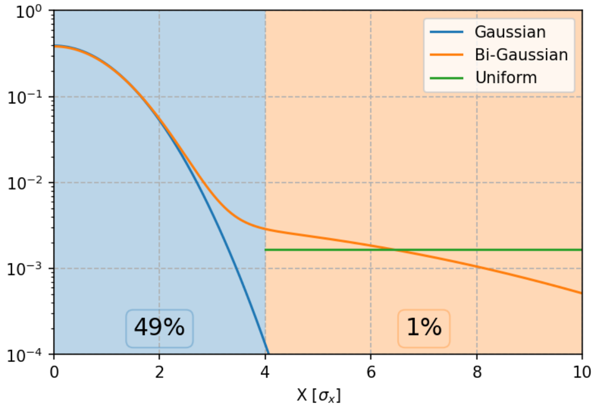
Masks: s=-2.12m with **8.5mm** horizontal aperture, s=-5.58m with **15mm** aperture radius.

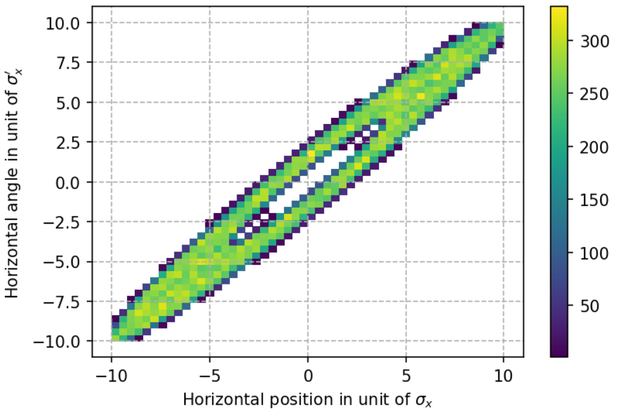
Collimators: after BWL (s=-144m), after QC3L (s=-112m), after QT1L (s=-39.7m) shields the aperture reduction downstream from (⌀70→⌀40), at PQC2LE (s=-8.4m) shields the aperture reduction downstream at MSK.QC2L (⌀40→⌀30).

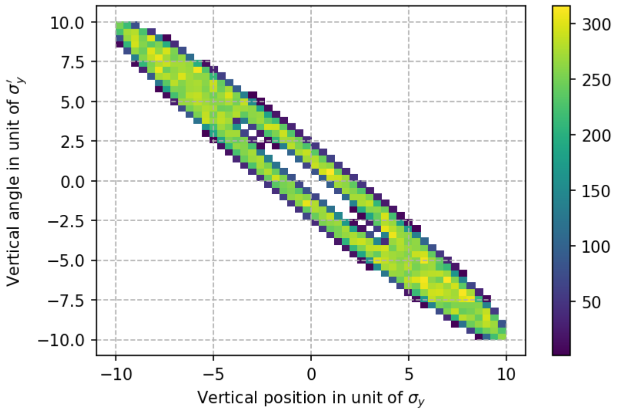
Beam model | Core and tail

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 studied.

Gaussian distribution for the beam core extends to around 4(5) sigmas then a **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**.



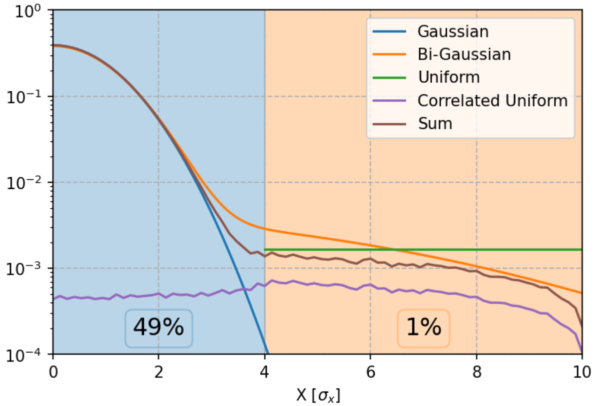


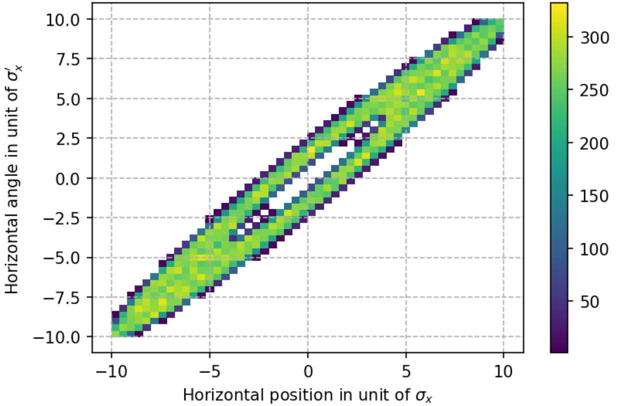


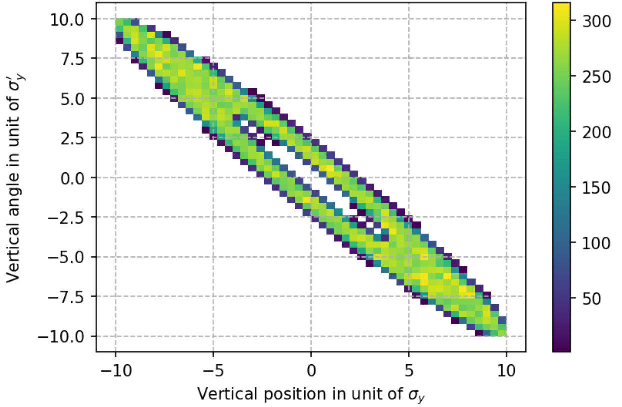
Beam model | Core and tail

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 studied.

Gaussian distribution for the beam core extends to around 4(5) sigmas then a **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**.

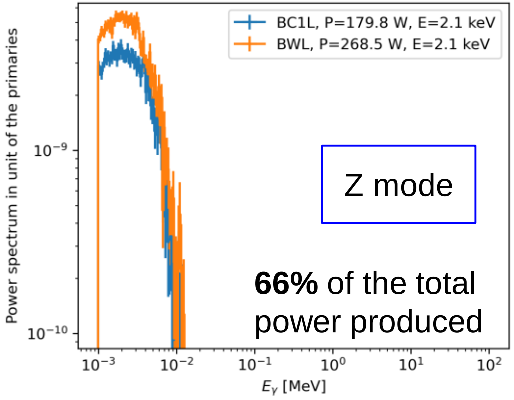


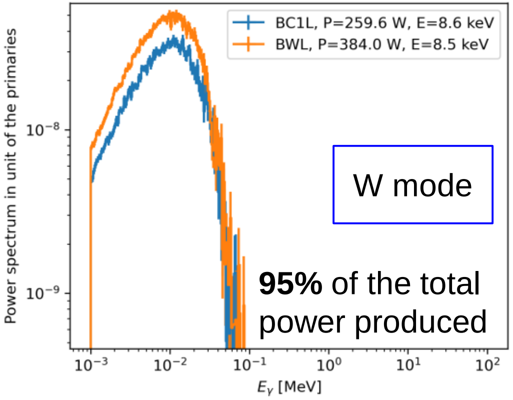


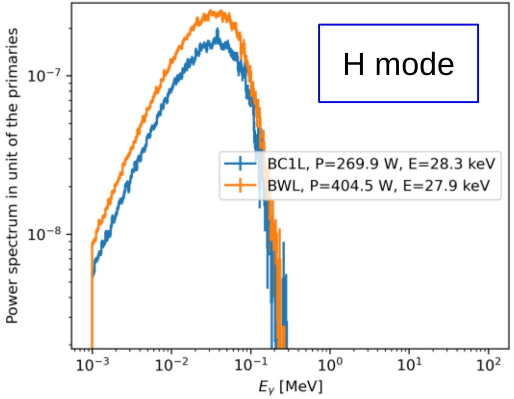


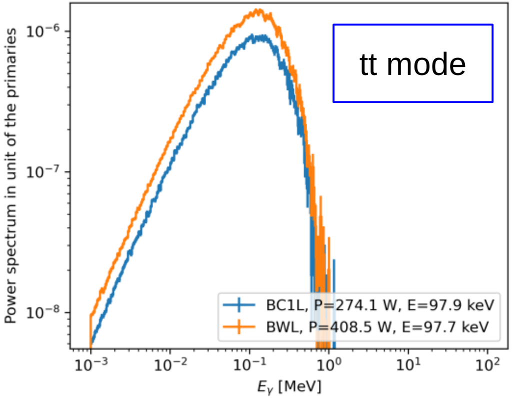
Characteristics of the various operation modes: **Z, W, H, tt**

Synchrotron radiation from upstream dipoles

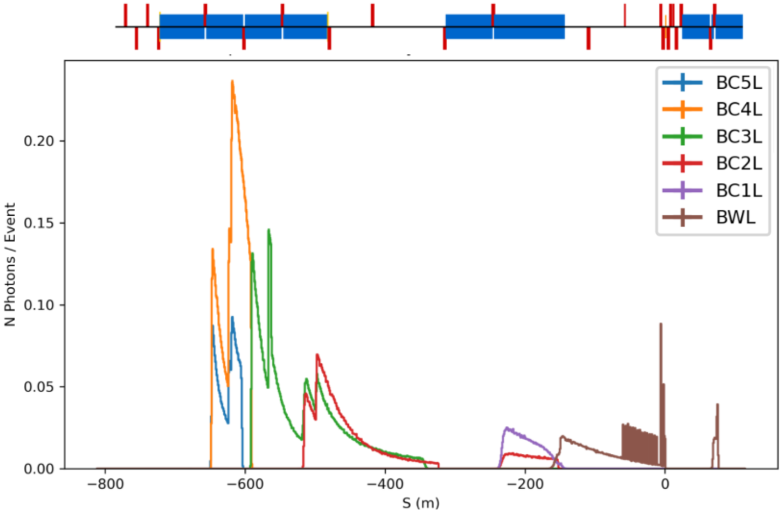








All SR power should be the same. The critical energy is slightly too high at the Z mode (low energy photon missing due to a cut at E = 990 eV). The other modes have the expected critical energies.

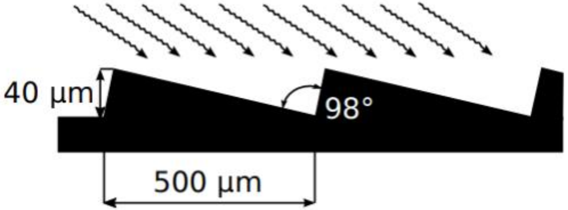


Synchrotron radiation from dipoles and x-ray reflection

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.

Preliminary conclusions:

1. The new “X” IP chamber designed at Frascati, with new integrated IP absorber (half-moons) seem to be able to shield most of the IP from direct-hit photons generated upstream from the last weak dipole (91.7 keV crit. energy at 182.5 GeV)
2. A very small fraction of the dipole radiation (and the last non-FF quad as well) SR hits the external wall of the +/-9 cm Be pipe
3. The critical energy of this photon flux is very low, ~90 eV for both Z and ttbar energies



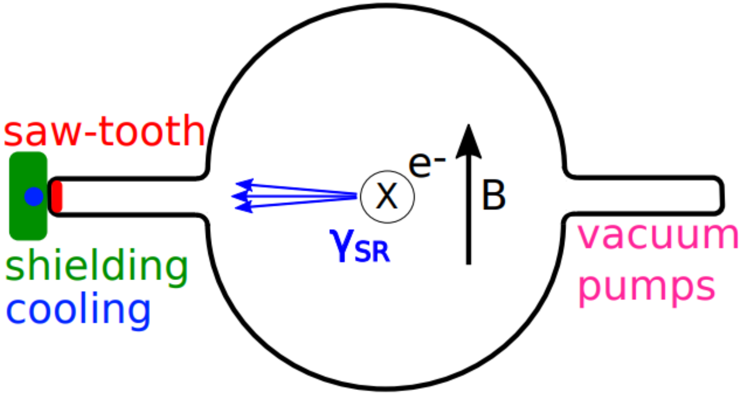
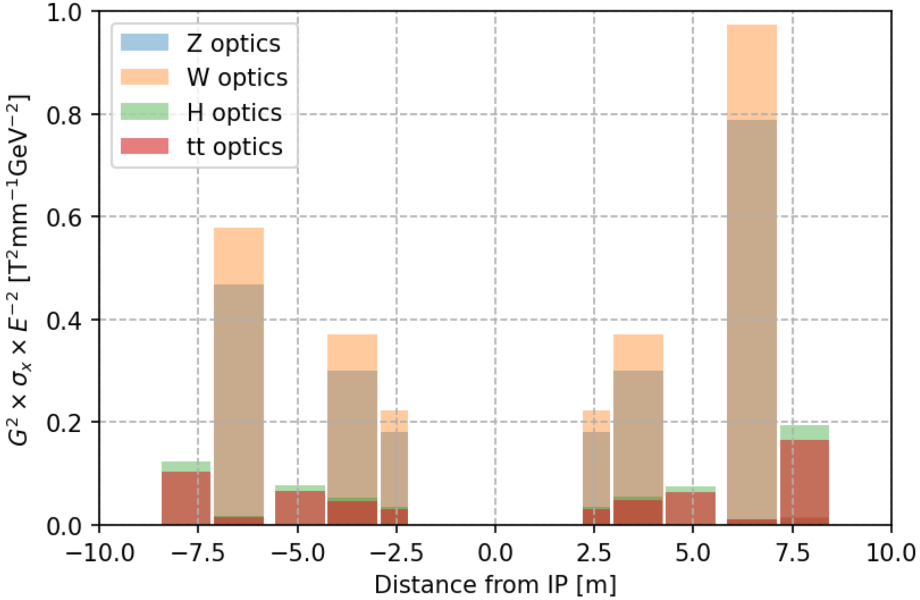


Figure of merit, synchrotron radiation from FF quadrupoles

N. Bernard 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 $G^2\sigma_x E^{-2}(s)$ represents a figure of merit to estimate SR from quadrupoles. As the beam current is scaled according to E^4 for the various operation modes of FCC-ee.

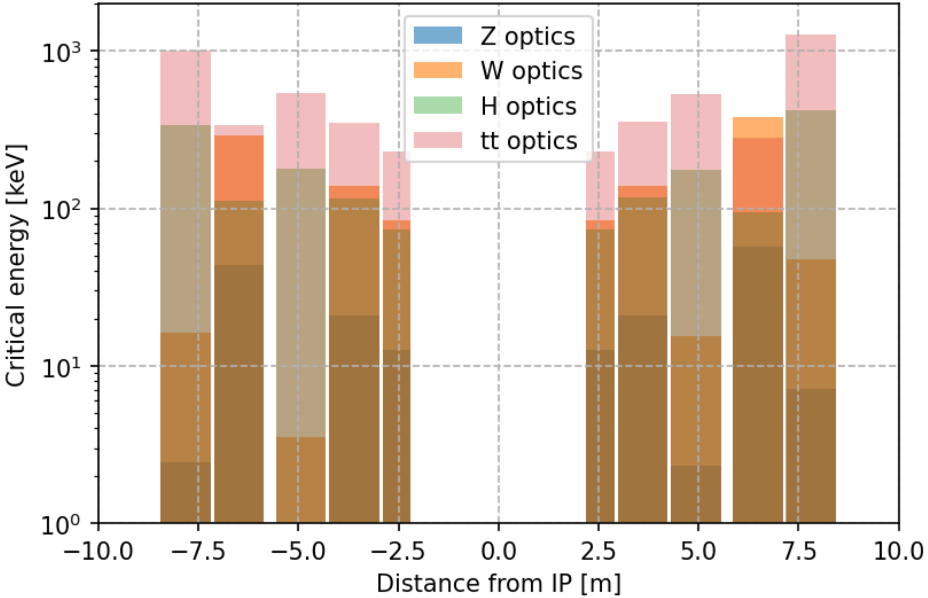
The amount of synchrotron radiation emitted in the FF quadrupoles strongly depends on the optics designs and quadrupole gradients.

	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

Figure of merit, synchrotron radiation from FF quadrupoles

Critical energy analytical estimate from SR in quads:

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

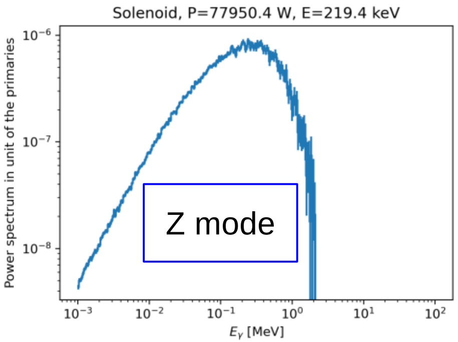


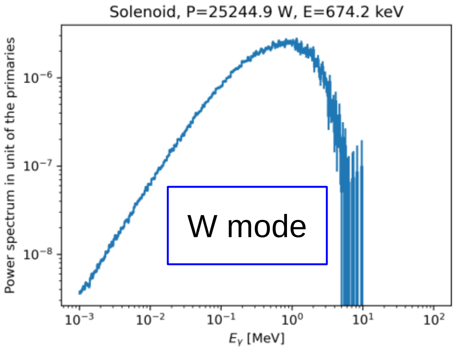
The function $G\sigma_x E^2(s)$ represents a figure of merit to estimate the critical energy from quadrupoles. It does not depend on the beam current and scales with E^3.

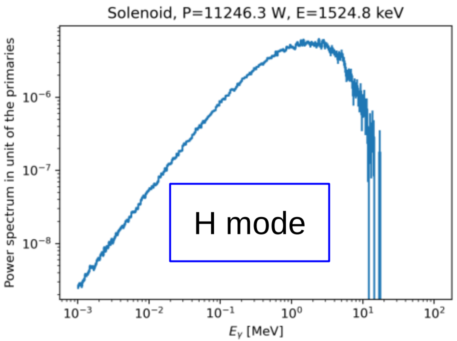
The different operation modes will produce different photon energies with the higher beam energy producing higher photon energies.

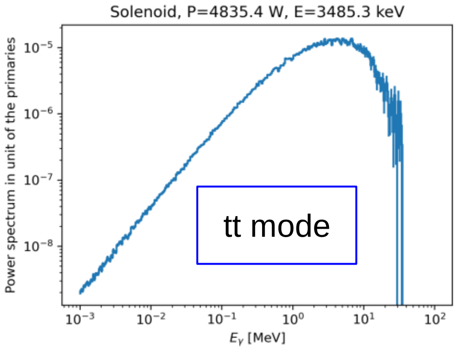
	E/ keV	E/ keV	E/ keV	E/ keV
Mode	Z	W	H	tt
QC2L2	3	18	**373**	**1127**
QC2L1	48	**321**	**128**	**389**
QC1L3	1	4	**219**	**695**
QC1L2	26	**179**	**154**	**523**
QC1L1	12	83	78	**278**
QC1R1	12	83	78	**278**
QC1R2	26	**176**	**157**	**533**
QC1R3	3	18	**216**	**687**
QC2R1	62	**417**	**107**	**325**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

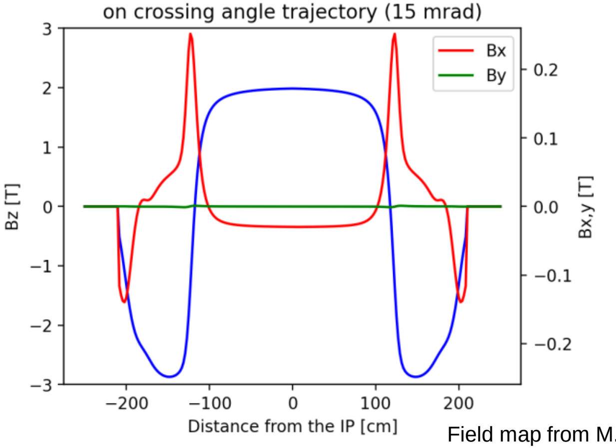
Solenoid synchrotron radiation emission

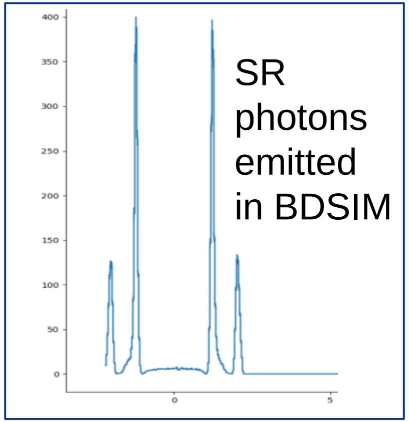


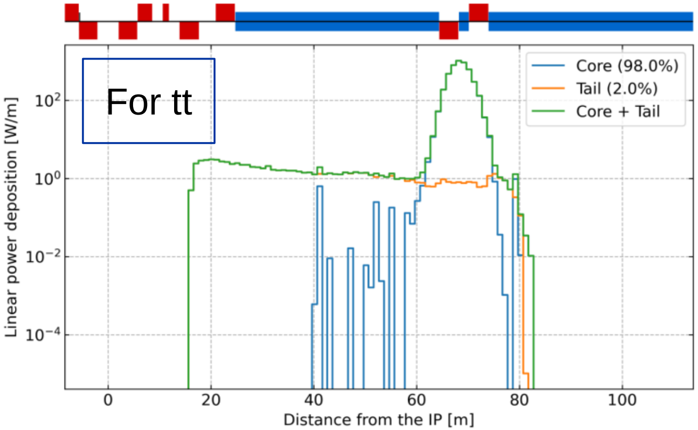








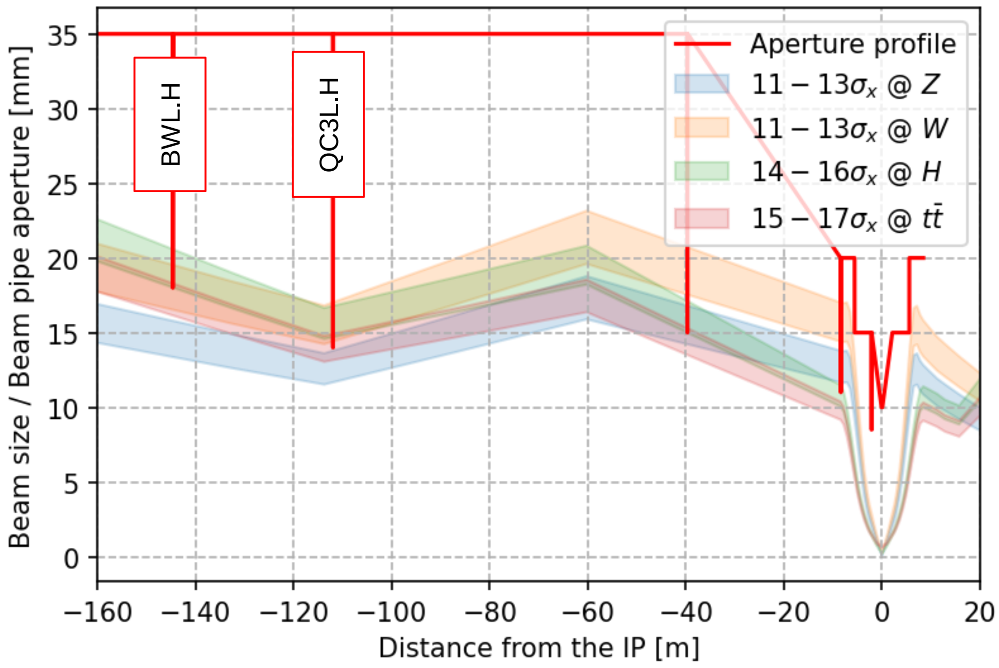




Field map from M. Koratzinos

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
QT1L.V	-39.65	0.015	V
PQC2LE.H	-8.64	0.011	H
PQC2LE.V	-8.54	0.011	V
MSK.QC2L	-5.56	R = 0.015	H&V
MSK.QC1L	-2.12	0.0085*	H



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

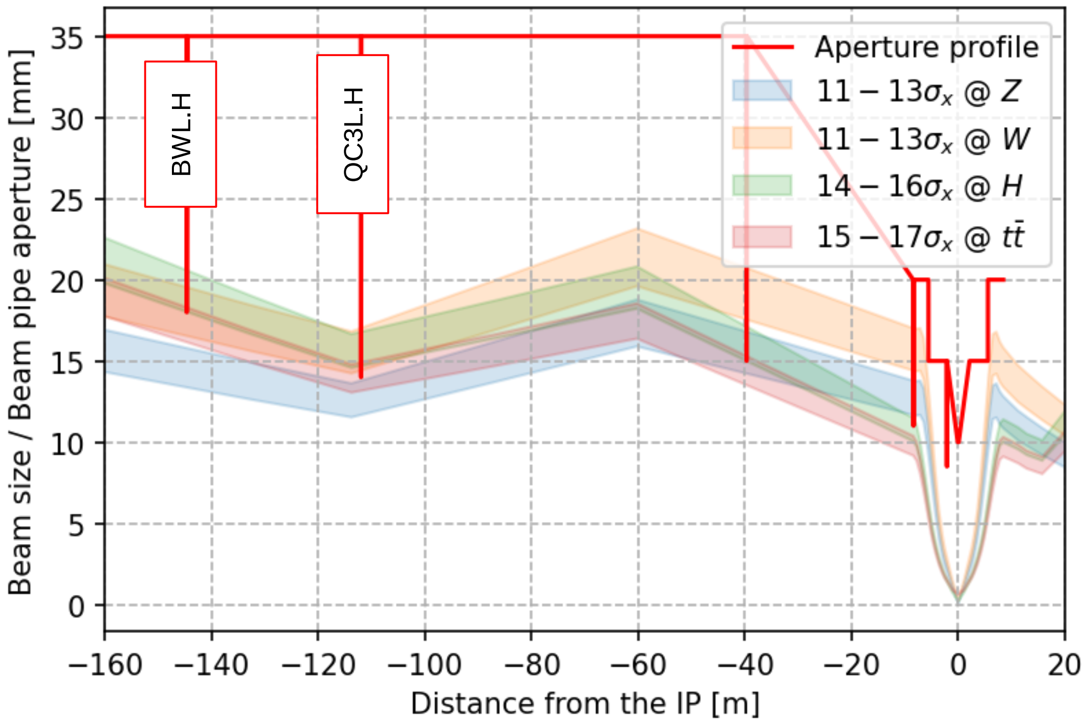
Synchrotron radiation collimation scheme

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).



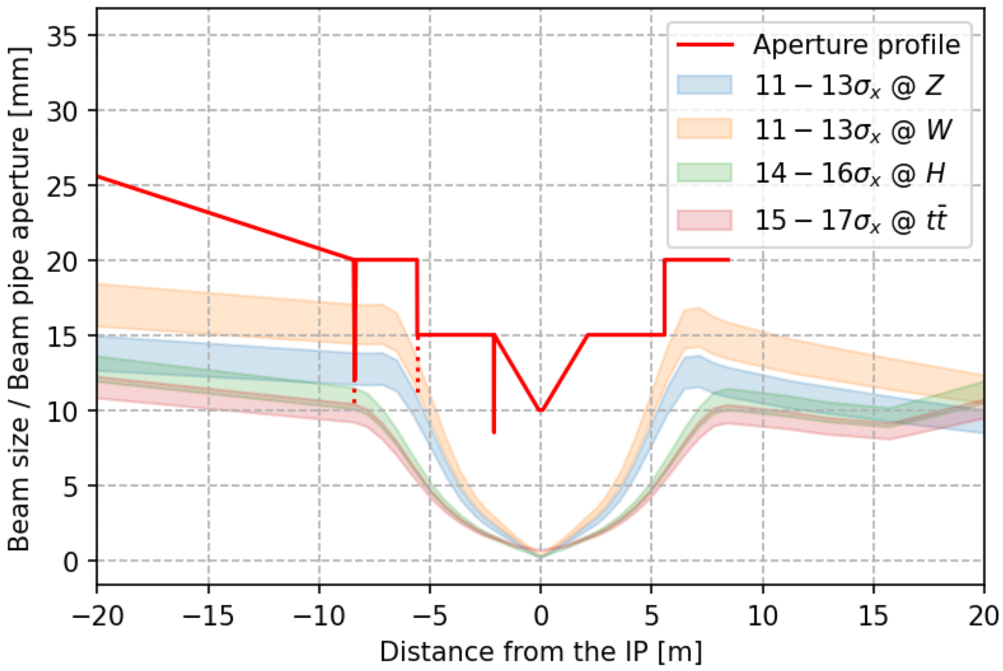
The primary and secondary collimator settings for **W** and **H** are speculative. There are no issues in the vertical plane.

Synchrotron radiation collimation knobs

Zooming in, PQC2LE collimator, located before QC2L, requires to be more opened at the Z mode by at least a millimeter compare to the tt mode settings implying less protection downstream.

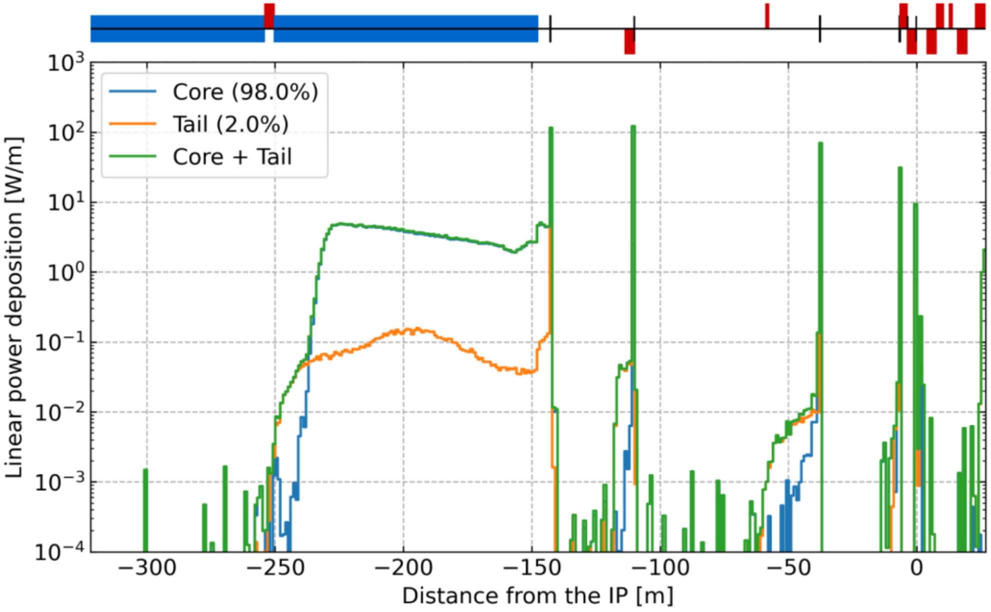
Potential countermeasures :

- Adapt MSK.QC2L aperture actually 15mm (18.0 σ_x) could be decrease to 11mm (13.3 σ_x).
- Displace horizontally COLL.QT1L closer to the IP as the horizontal beam size decreases.



$t\bar{t}$ operation mode

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

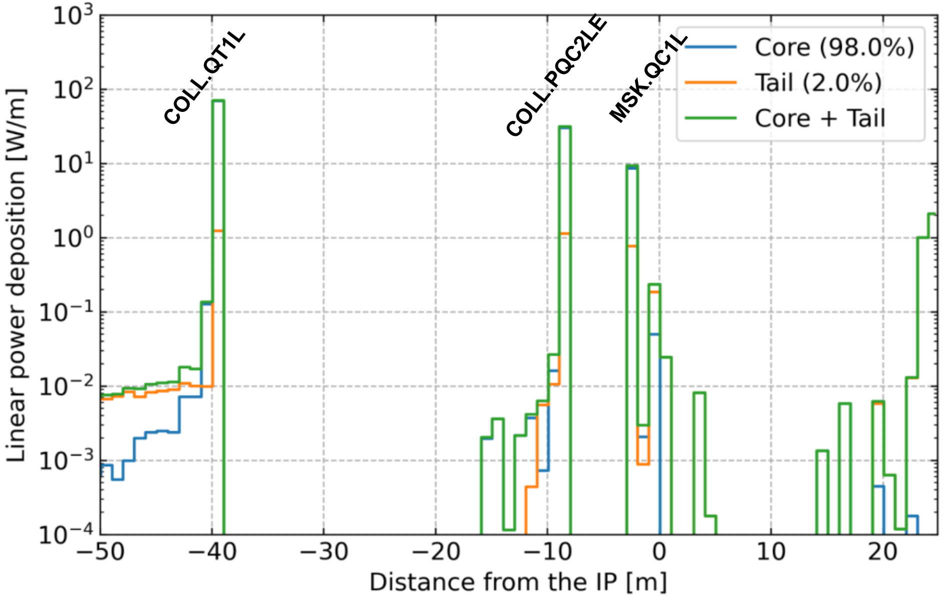


Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

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** - Sum



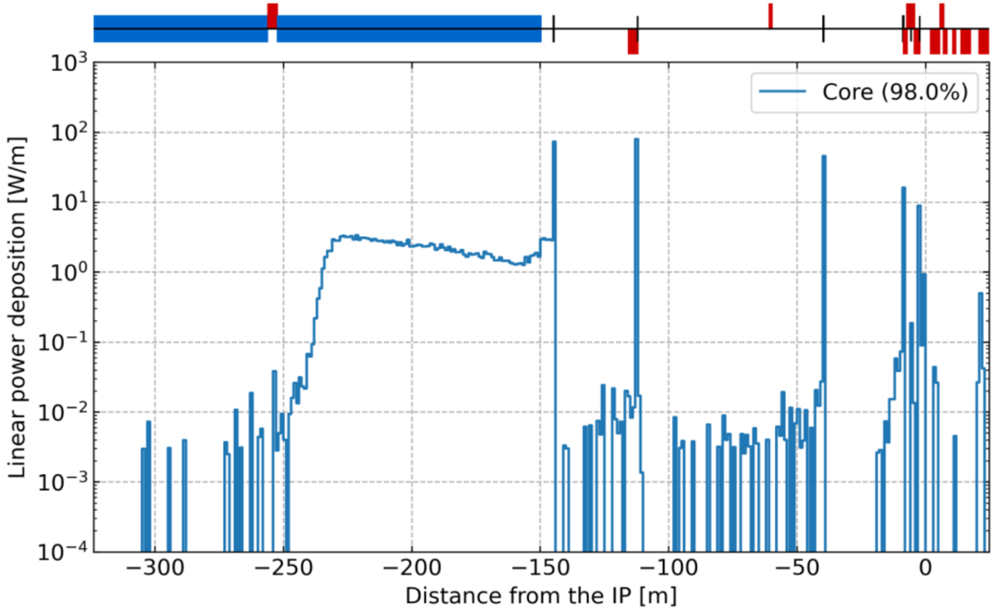
Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

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**

Z operation mode

Synchrotron radiation collimation at the Z mode - Gaussian core

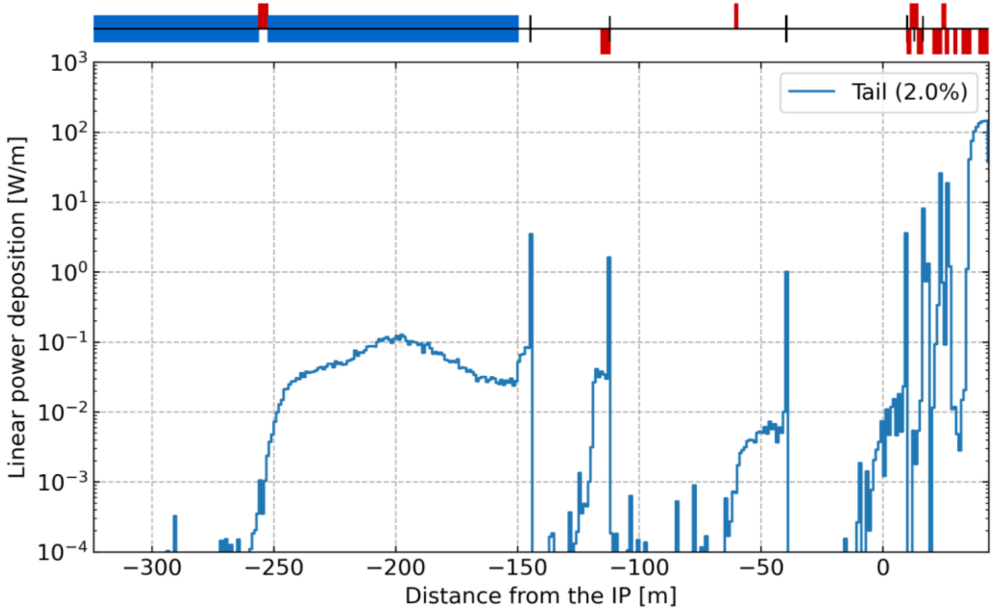


Simulations made with a Gaussian positron beam and without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

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 **73W**
COLL.QC3L is 10cm of tungsten absorbing **80W**
COLL.QT1L is 10cm of tungsten absorbing **45W**
COLL.PQC2LE is 10cm of tungsten absorbing **16W**
MSK.QC2L is 2cm of tungsten absorbing **35mW**
MSK.QC1L is 2cm of tungsten absorbing **12.7W**

Synchrotron radiation collimation at the Z mode - tail distribution

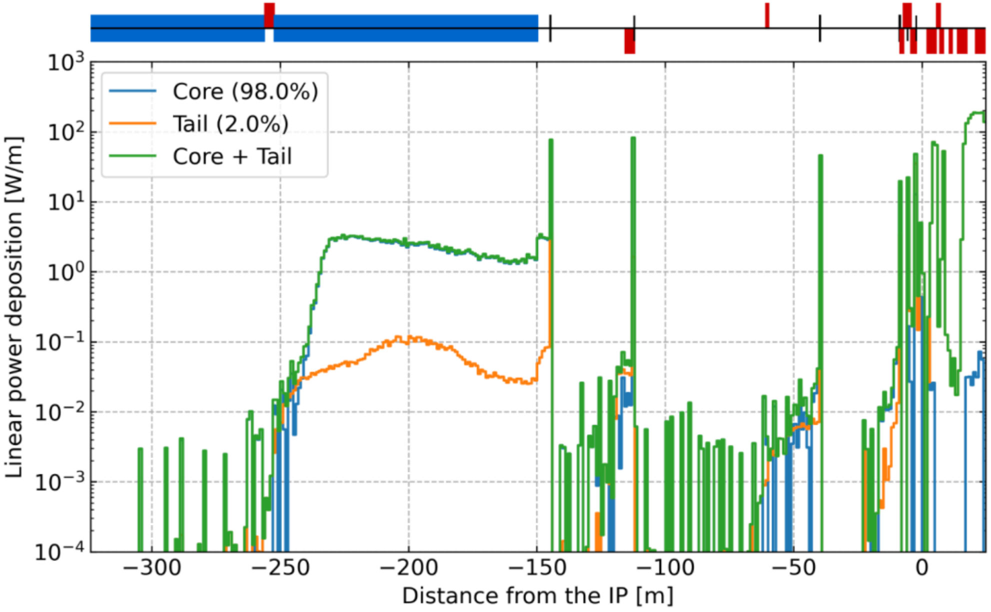


Simulations made with a positron beam with 4 to 10 sigmas uniform distribution (tail) and without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

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)	0.007	H

COLL.BWL is 10cm of tungsten absorbing **3.5W**
COLL.QC3L is 10cm of tungsten absorbing **1.6W**
COLL.QT1L is 10cm of tungsten absorbing **1W**
COLL.PQC2LE is 10cm of tungsten absorbing **3.3W**
MSK.QC2L is 2cm of tungsten absorbing **2mW**
MSK.QC1L is 2cm of tungsten absorbing **43W**

Synchrotron radiation collimation at the Z mode - Sum

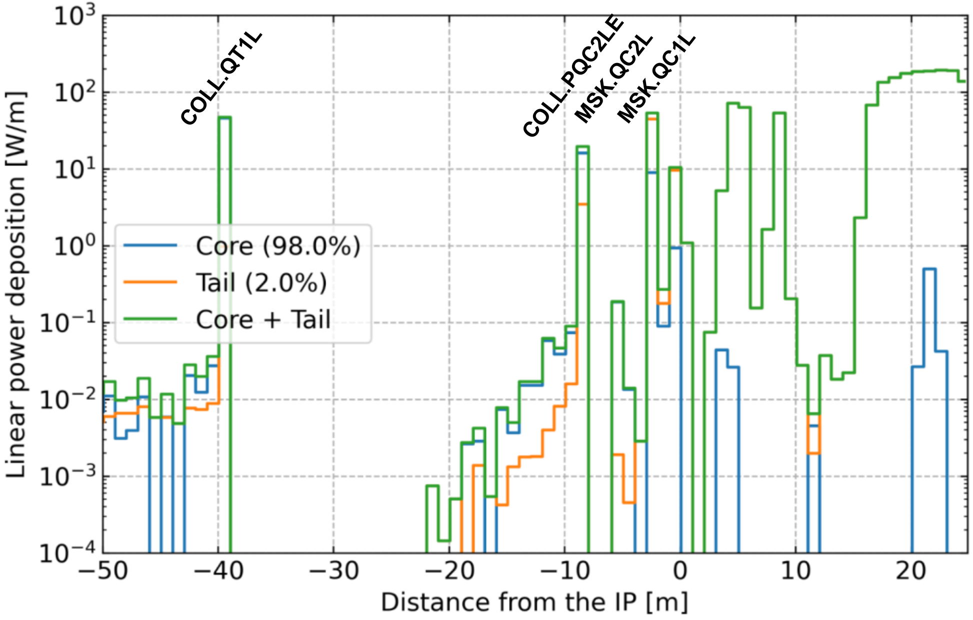


Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail but without the synchrotron radiation from the solenoid as it produce radiation deposited downstream the IP.

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** - Sum



Simulations made with a Gaussian positron beam and 4 to 10 sigmas uniform distribution for the tail but 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)**

Beam misalignment

Beam misalignment

From the entrance of QC2L2 (s=-8.44m) onwards.

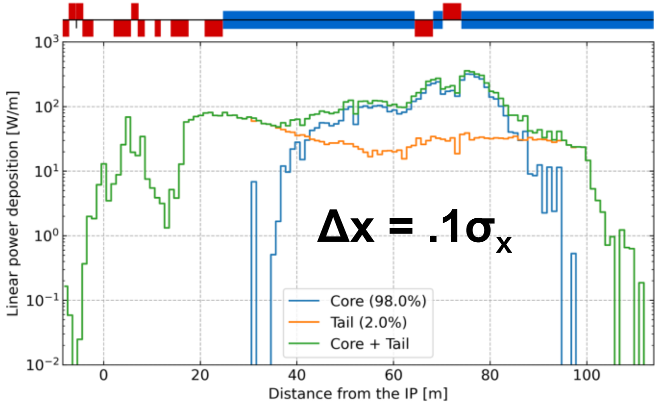
Misalignment in X and Y: σ_x=1.06**mm**, σ_y=76.75**μm**

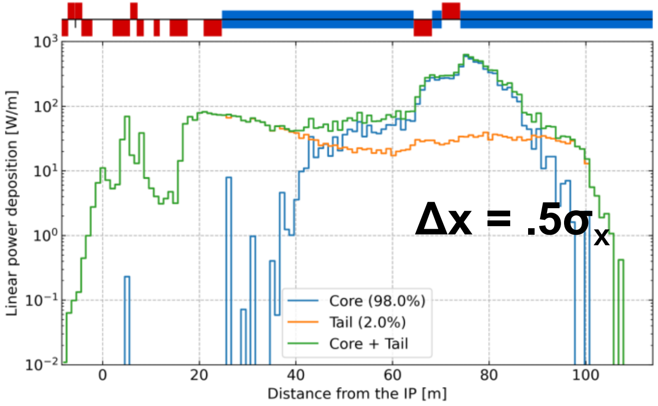
Study of ±0.5σ_x, ±0.1σ_x and ±5σ_y, ±1σ_y

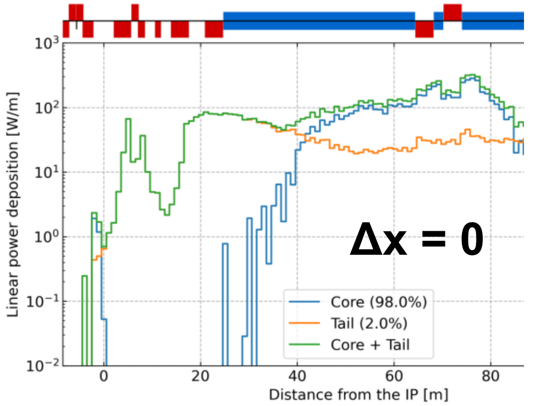
Misalignment in X' and Y': σ_x'=7.5**μrad**, σ_y'=49.5**nrad** propagated to the IP such that it reaches one transverse sigma.

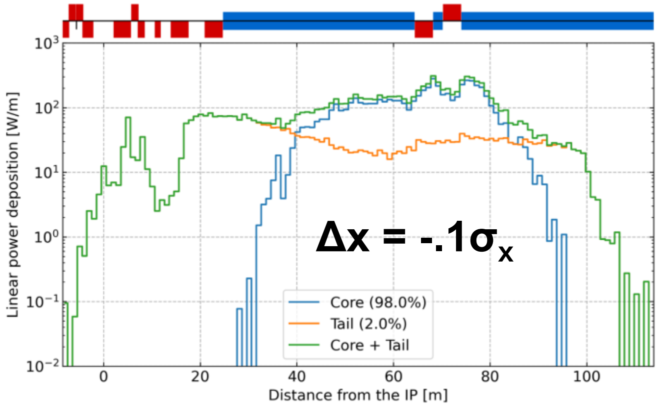
Study of σ_x'=±1μrad (eq. to one $\boldsymbol{\sigma_x^*}$) and σ_y'=±4nrad (eq. to one $\boldsymbol{\sigma_y^*}$)

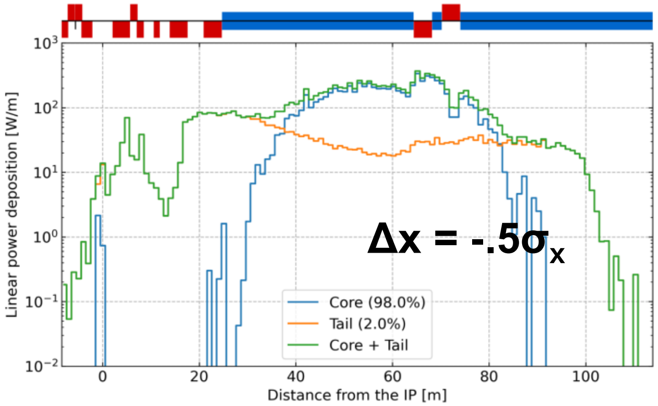
SR from tails in the primary beam @ Z - Quads



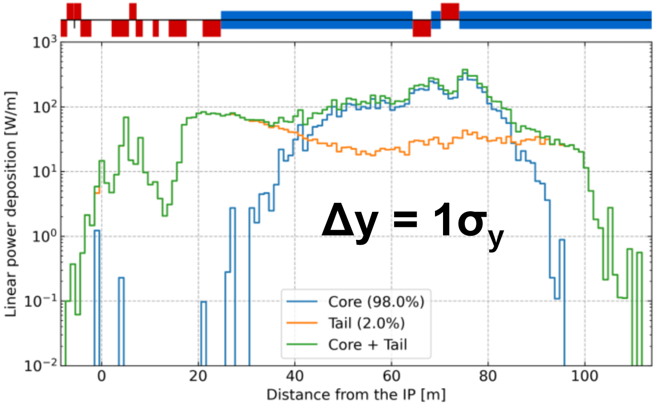


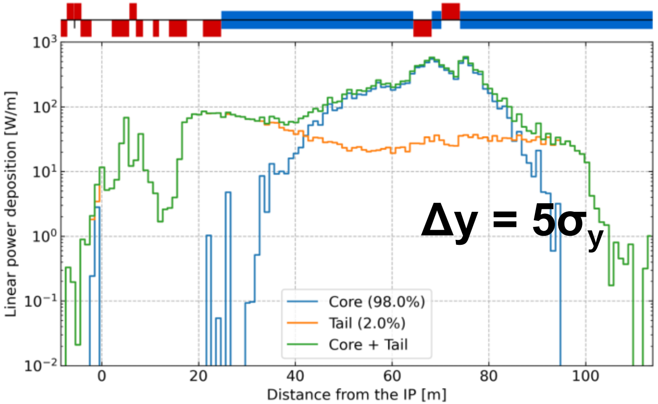


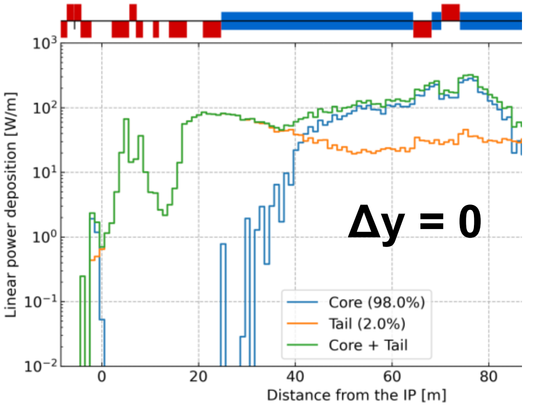


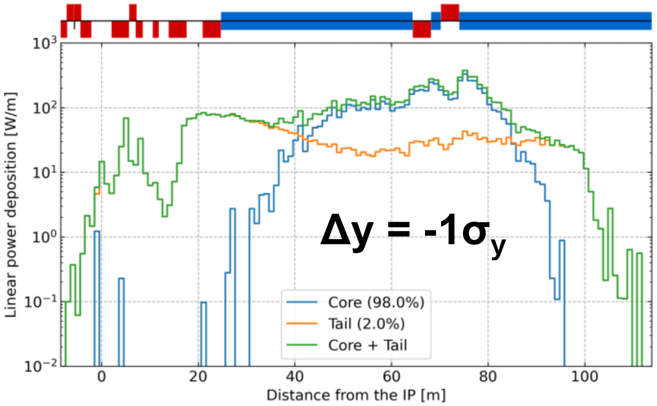


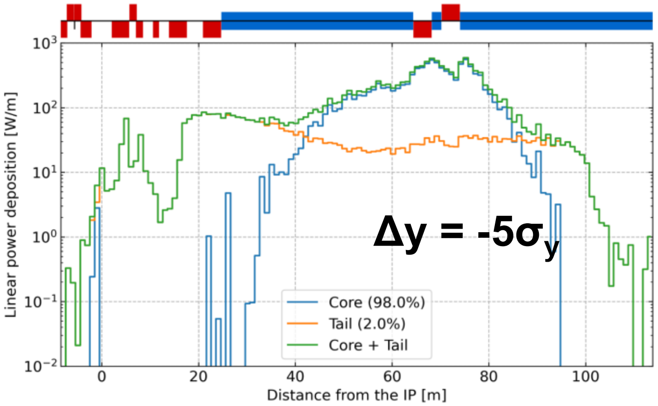
SR from tails in the primary beam @ Z - Quads





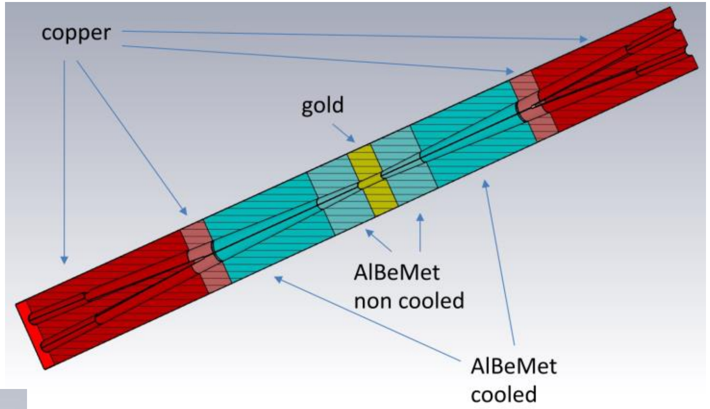


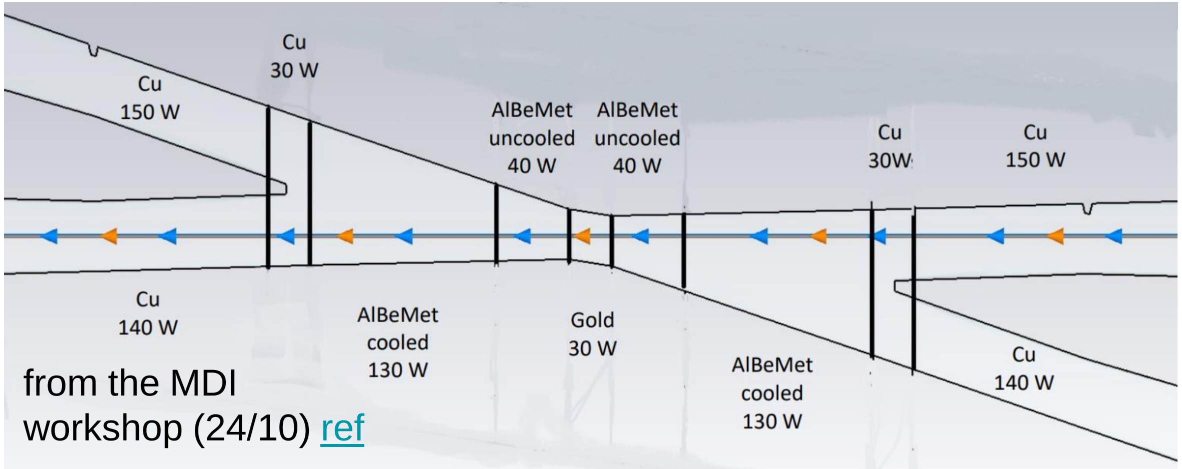




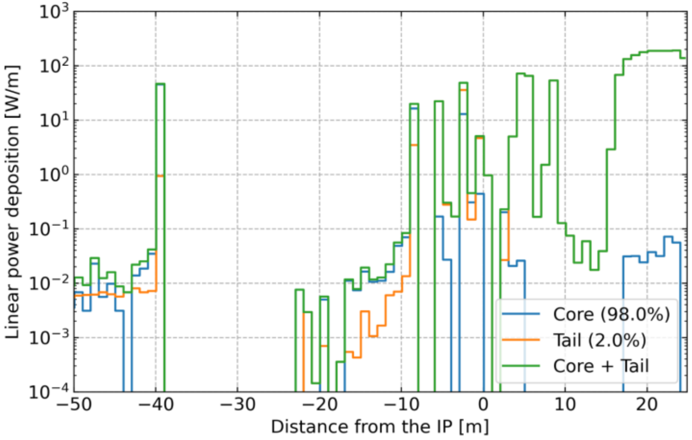
Comparison with wakefield heat load

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



Summary:

- **The interaction region lattices for the 4 operation modes have been implemented in BDSIM** with the solenoid field map and without the installation of the CAD design of the central beam pipe.
- The central beam pipe can be efficiently shielded with collimators and masks from the synchrotron radiation emitted in the last dipole BWL.
- 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 collimator hierarchy. Asymmetric collimators like the mask ?
- Flux of photons hitting the collimators
- Refine the tail distribution model and its influence on the SR collimation performance.
- Continue the study the influence of misalignments and top-up injection on the SR collimation.

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 W, 1.4 MeV Cu

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

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

gamma **5 um** ~ 4.8 keV W, 2.2 keV 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.

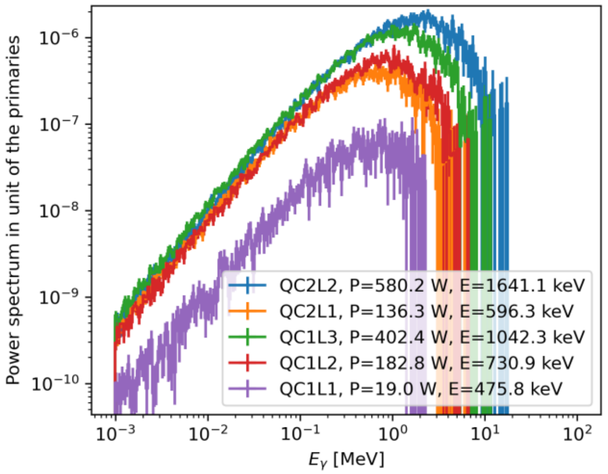
SR from quads for **tt mode**

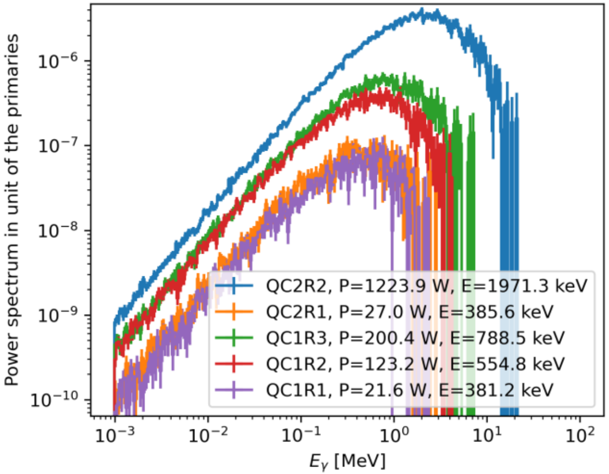
SR photons produced below 30 MeV.

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**





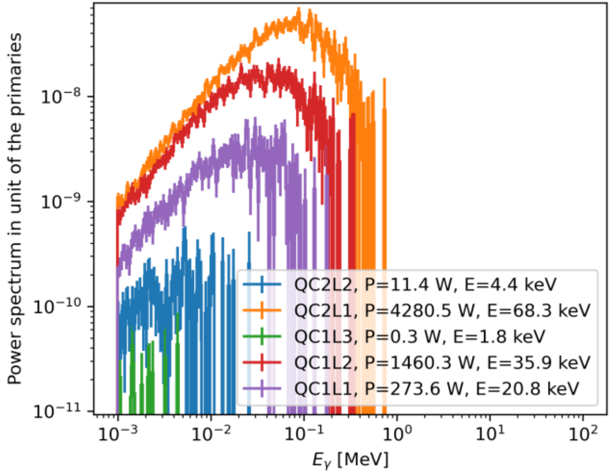
SR from quads for Z mode

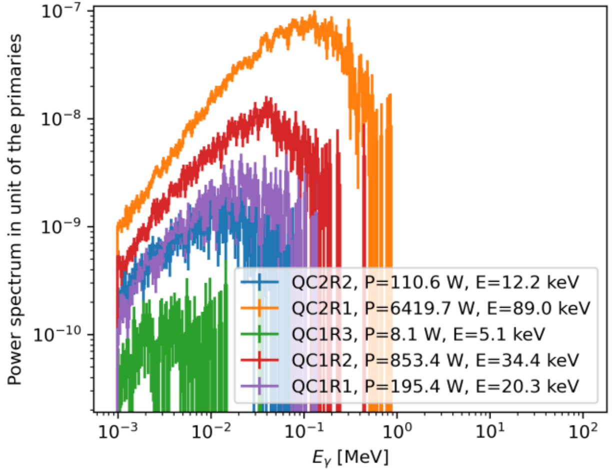
SR photons produced below 1 MeV.

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





Beta function at the IP for the Z operation mode