THE MDI OF THE FCC-EE

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for the MDI team

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FUTURE CIRCULAR COLLIDER Innovation Study

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

INFN LNF Istituto Nazionale di Fisica Nucleare

Outline

- Interaction Region design
- Progress on the mechanical model of the IR and integration of detector
- Progress on the backgrounds simulations
- Machine-detector-Interface study

FCC-ee layout

Double ring e+e- collider with 91 km circ.

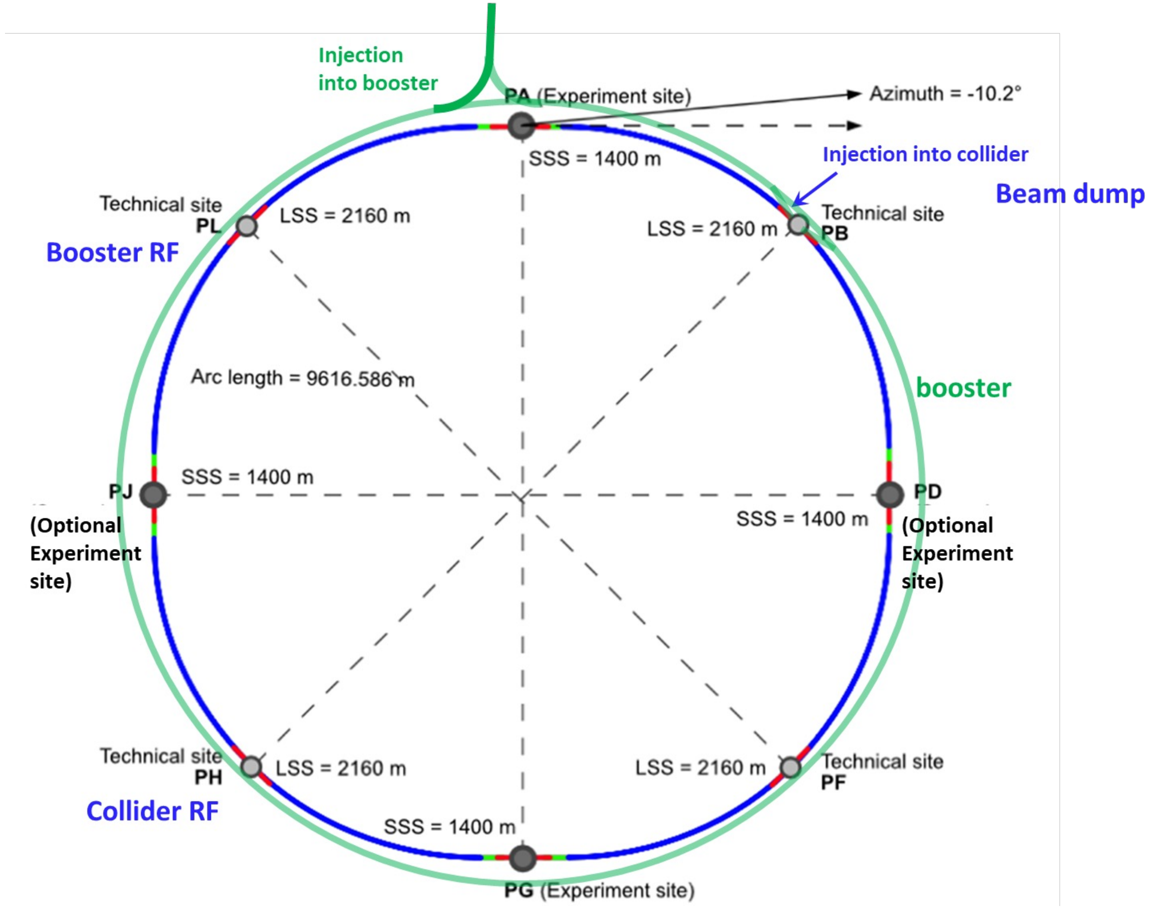
Common footprint with FCC-hh, except around IPs

Perfect 4-fold super-periodicity allowing 2 or 4 IPs; large horizontal crossing angle 30 mrad, crab-waist collision optics (*)

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity

Requires booster synchrotron in collider tunnel and 20 GeV e+/e- source and linac



(*) **Crab-waist** scheme, based on two ingredients:

- concept of **nano-beam scheme:** vertical squeeze of the beam at IP and large horizontal crossing angle, large ratio σ_z/σ_x reducing the instantanous overlap area, allowing for a lower β_y*
- **crab-waist sextupoles**

SuperKEKB https://arxiv.org/pdf/1809.01958.pdf; DAFNE, PRL 104, 174801 (2010)

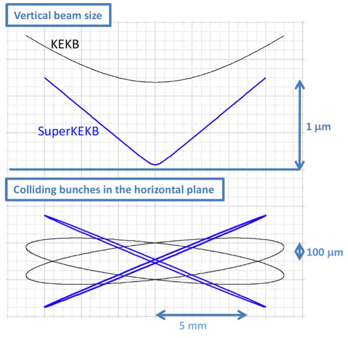


Figure 2: Schematic view of the nanobeam collision scheme.

FCC-ee: main machine parameters and run plan

Running mode	Z		W	ZH	$t\bar{t}$
Number of IPs	2	4	4	4	4
Beam energy (GeV)	45.6		80	120	182.5
Bunches/beam	12000	15880	688	260	40
Beam current [mA]	1270	1270	134	26.7	4.94
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	180	140	21.4	6.9	1.2
Energy loss / turn [GeV]	0.039	0.039	0.37	1.89	10.1
Synchr. Rad. Power [MW]			100		
RF Voltage 400/800 MHz [GV]	0.08/0	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	5.60	3.55	2.50	1.67
Rms bunch length (+BS) [mm]	13.1	12.7	7.02	4.45	2.54
Rms hor. emittance $\varepsilon_{x,y}$ [nm]	0.71	0.71	2.16	0.67	1.55
Rms vert. emittance $\varepsilon_{x,y}$ [pm]	1.42	1.42	4.32	1.34	3.10
Longit. damping time [turns]	1158	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	110	200	300	1000
Vertical IP beta β_y^* [mm]	0.7	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	250	—	<28	<70
Beam lifetime (lum.) [min.]	35	22	16	10	13

	Z	W	ZH	$t\bar{t}$
Run plan	4 years 5×10^{12} Z LEP x 10^5	2 years >2×10^8 WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs

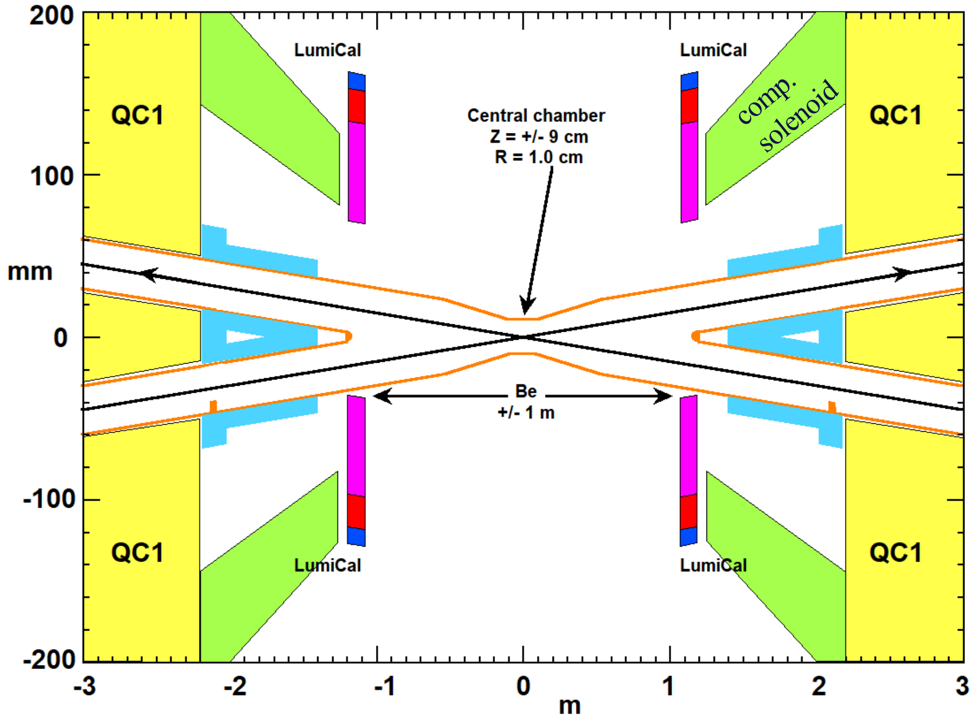
- Very high luminosity at Z, W, and Higgs
- Accumulate > luminosity in 1st 10 years at Higgs, W, and Z than ILC at Higgs
- Accommodates up to 4 experiments → robustness, statistics, specialized detectors, engage community
- Run plan naturally starts at low energy with the Z and ramps but could be adjusted using an RF Bypass to start at Higgs

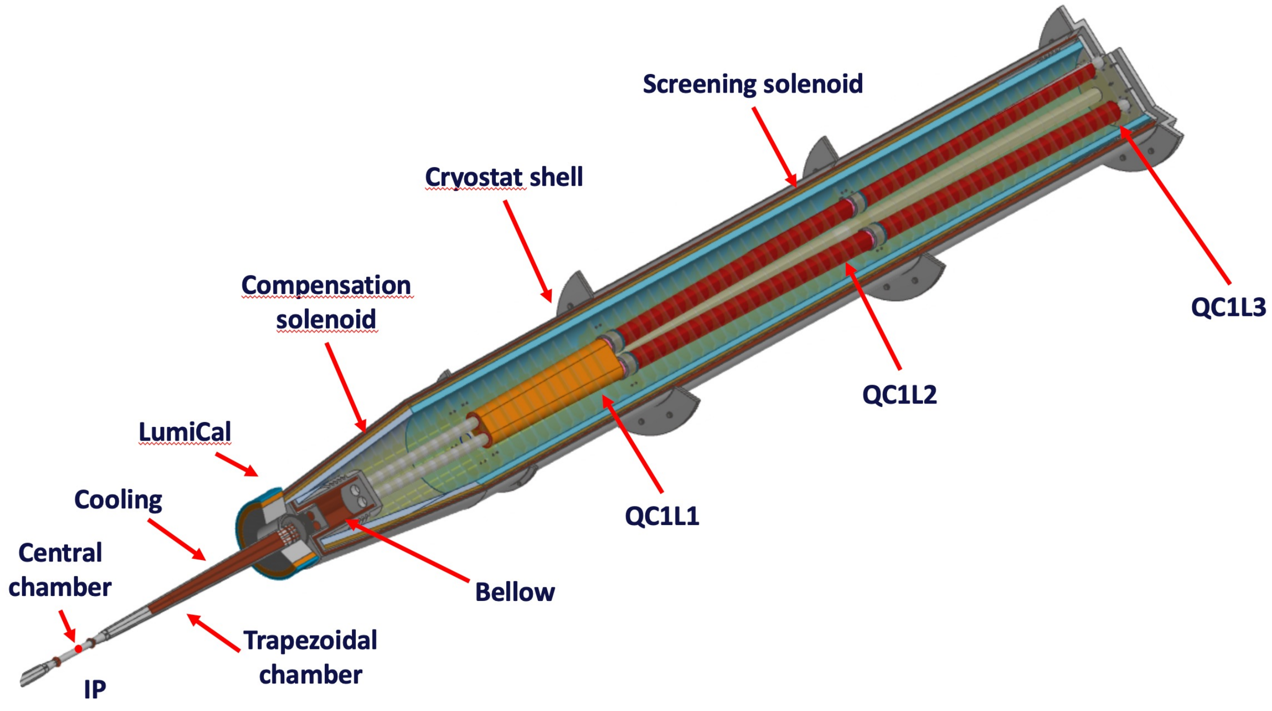
High-level Requirements for the IR and MDI region

- **One common IR for all energies, flexible design** from 45.6 to 182.5 GeV with a constant detector field of **2 T**
  At Z pole: Luminosity ~ 10^{36} $cm^{-2}s^{-1}$ requires crab-waist scheme, nano-beams & large crossing angle.
  Top-up injection required with few percent of current drop.
  Bunch length is increased by 2.5 times due to beamstrahlung
  At **ttbar threshold**: synchrotron radiation, and beamstrahlung dominant effect for the lifetime
- **Solenoid compensation** scheme
  Two anti-solenoids inside the detector are needed to compensate the detector field
- **Cone angle of 100 mrad cone between accelerator/detector** seems tight, trade-off probably needed
  Addressed with the implementation of the final focus quads & cryostat design, (e.g. operating conditions of the cryostat, thermal shielding thickness, etc.)
- **Luminosity monitor** @Z: absolute measurement to 10^{-4} with low angle Bhabhas
  Acceptance of the lumical, low material budget for the central vacuum chamber alignment and stabilization constraints
- **Critical energy below 100 keV** of the Synchrotron Radiation produced by the last bending magnets upstream the IR at tt_{bar}
  Constraint to the FF optics, asymmetrical bendings

FCC-ee Interaction Region layout

B(detector) = 2 T at all energies





- L* is **2.2** m (L* is the face of the first final focus quadrupole QC1, and the free length from the IP).
- Central vacuum chamber has 10 mm radius, 180 mm long.
- Crotch at about 1.2 m, with two symmetric beam pipes with radius of 15 mm.

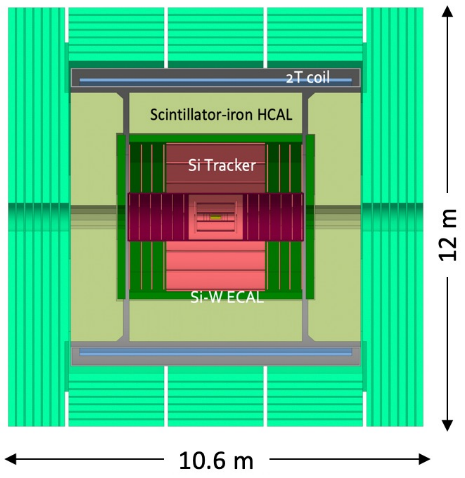
3D view of the FCC-ee IR until the end of the first final focus quadrupole

QC1 almost entirely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at 5.6 m.

The IR layout depends on the IR optics and on the solenoid compensation scheme

FCC-ee Detector Concepts

CLD

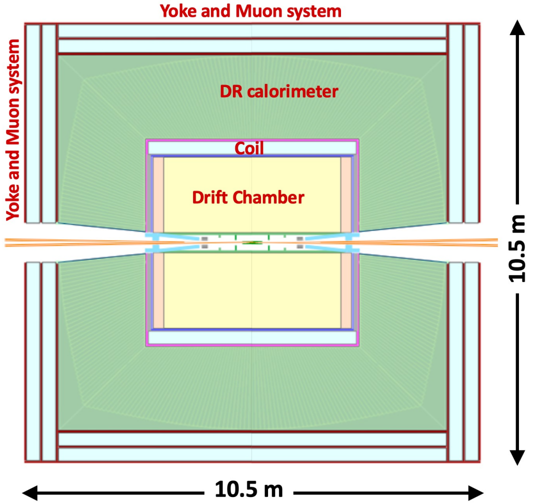


CDR

- Full Silicon vertex detector + tracker;
- Very high granularity, CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system;

- Possible optimization for
  - Improved momentum and energy resolutions
  - PID capabilities

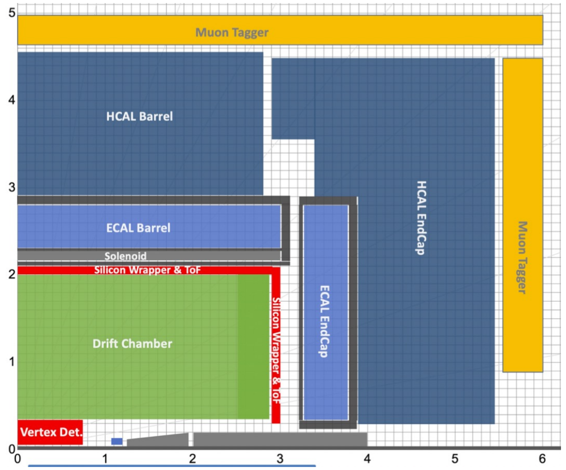
IDEA



- Si vertex detector;
- Ultra light drift chamber w. powerfull PID;
- Monolitic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;

- Possibly augmented by crystal ECAL in front of coil;

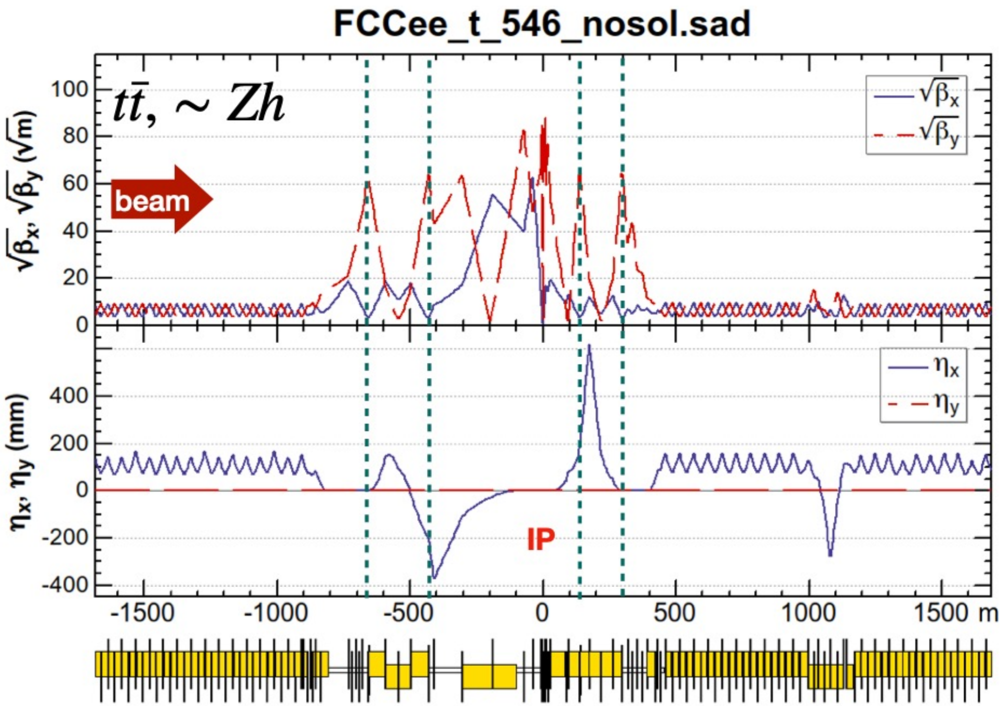
Noble Liquid ECAL based



- High granularity Noble Liquid ECAL as core;
  - PB+LAr (or denser W+LCr)
- Drift chamber (or Si) tracking;
- CALICE-like HCAL;
- Muon system;
- Coil inside same cryostat as LAr, possibly outside ECAL.

Baseline IR optics

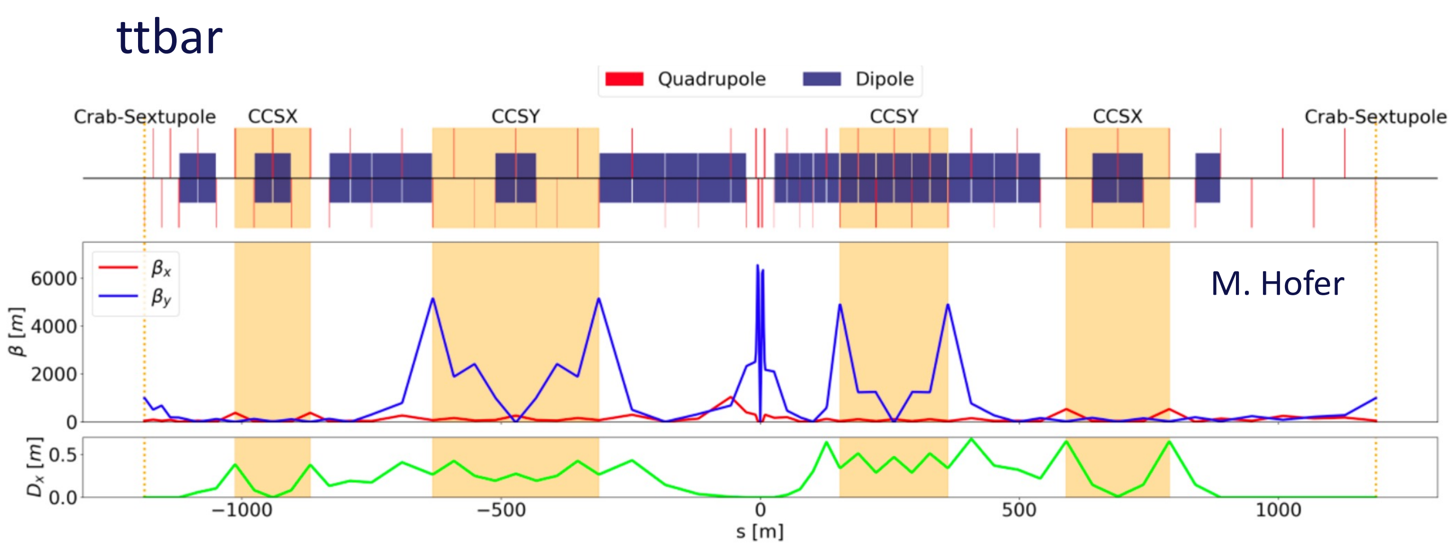
K. Oide



- Crab waist/vertical chromaticity correction sextupoles are located at the dashed lines, they are superconducting.

LCCO (or HFD) Optics

P. Raimondi



LCCO: Local Chromatic Correction Optics
HFD: Hybrid FODO

- Weak chromatic correction sextupoles allow to be normal conducting.
- The crab sextupole is placed at the beginning of the FF to minimize its impact on Momentum Acceptance (MA)

The beam optics are asymmetric between upstream/downstream due to crossing angle & suppression of the SR upstream to the IP

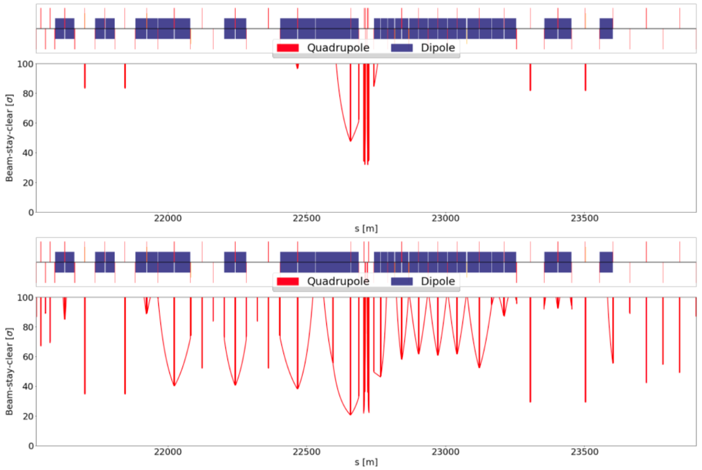
LCCO Final Focus - Impact to IR design

- The Final Focus is optimized to have the **largest possible beam stay clear (BSC) and minimum losses** in the final focus system and all the way through the IR
- The goal of the FF design is to have the **dynamic aperture larger than the physical aperture**

Beam Stay Clear

Z-pole

ttbar



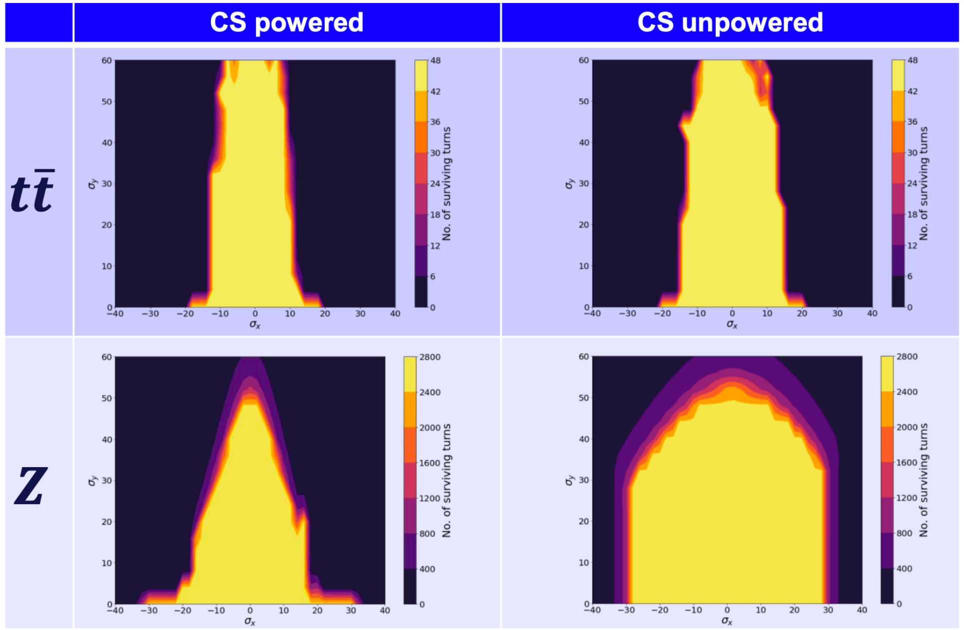
Preliminary aperture model same as baseline,
r=35 mm everywhere, but: r=15 mm at QC1; r=20 mm at QC2

Bottlenecks:

- **baseline Z: 14.5 σ_x / tt_{bar}: 14.4 σ_x**
- **LCCO Z: 31 σ_x / tt_{bar}: 20 σ_x**

Dyn. Apert. with SR and Crab sextupoles (CS)

- DA tracking performed using Xsuite and Xdyna
- Crabsextupoles (CS) powered to 80% (Z)/ 40% (tt) of their geometric strength
- Tracking performed for ~ one damping time 2500 turns (Z)/ 45 turns (tt)
- CS have small impact on DA at Z,



Standard solenoid compensation

Coupling compensation

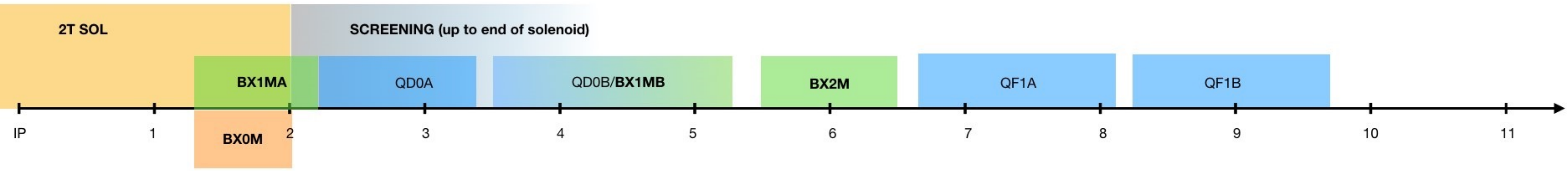
After a few iterations the best compromise between performances and feasibility, under finalization by A Ciarma seems to be:

- no compensating solenoid
- zero the Bs (solenoid) field with starting from 2mt from the IP until the end of the detector solenoid
- zero the Sum(Bs*l) with antisolenoids (2 per beam) outside the IR quads.
- corrects residual coupling with weak skew quads wrapped around the IR quads.
- correct orbit with weak correctors in several locations around the IR
- correct dispersion with standard tuning knobs

Correctors and skew are no matter what needed for orbit and coupling correction (tuning knobs)

This solution is "optics independent", could be applied to the baseline or the LCCO optic

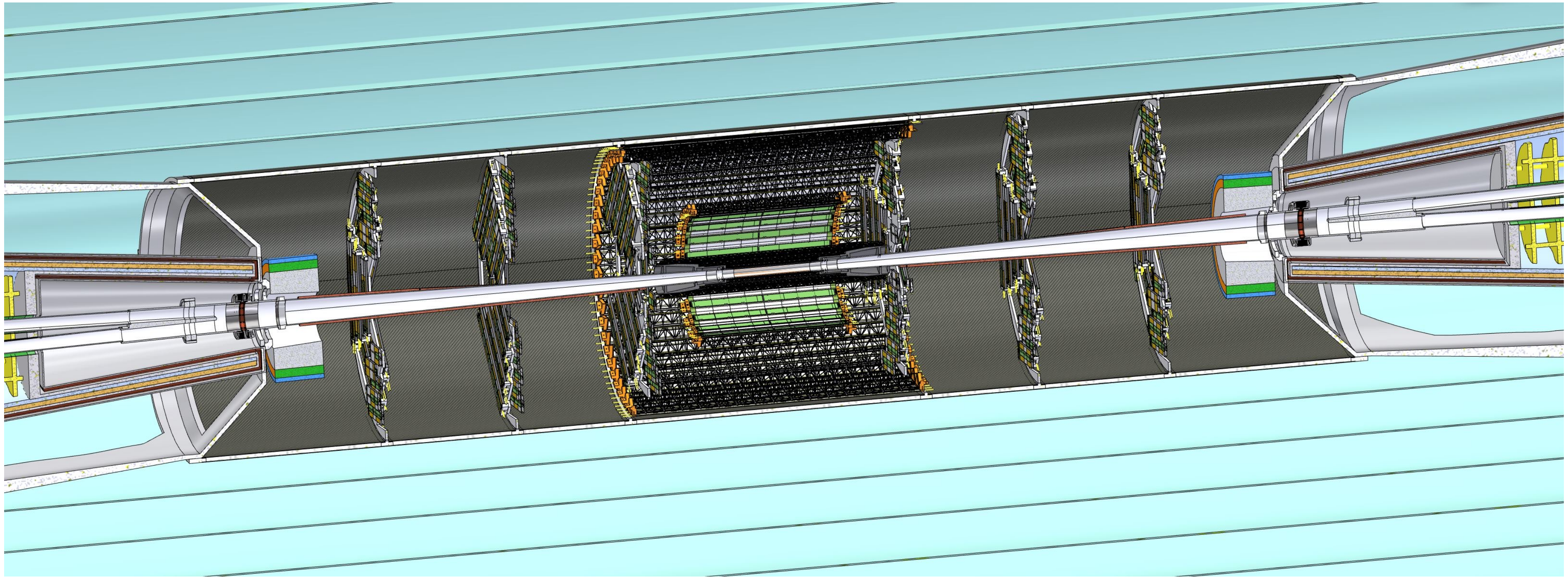
Standard solenoid compensation scheme layout



Screening solenoid wishes/possibilities"
Since its field is 2T, could it have a smaller outer radius to increase detector AA (M Koratzinos)
Could it be tapered in order to minimize the detector end-field effects (probably different for each detector)
Could it be generated by QD0A?

FCC-ee Interaction Region

zoom at the central region about ± 1.2 m



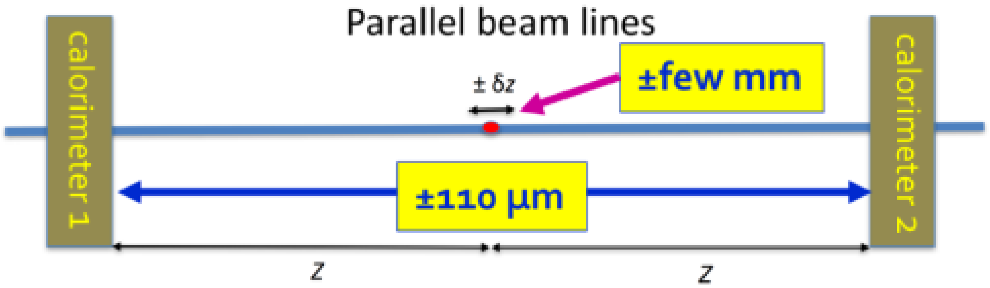
View including the rigid support tube, vertex detector and outer trackers

Ref: M. Boscolo, F. Palla, et al., *Mechanical model for the FCC-ee MDI,* EPJ+ Techn. and Instr., https://doi.org/10.1140/epjti/s40485-023-00103-7

LumiCal constraints & requirements

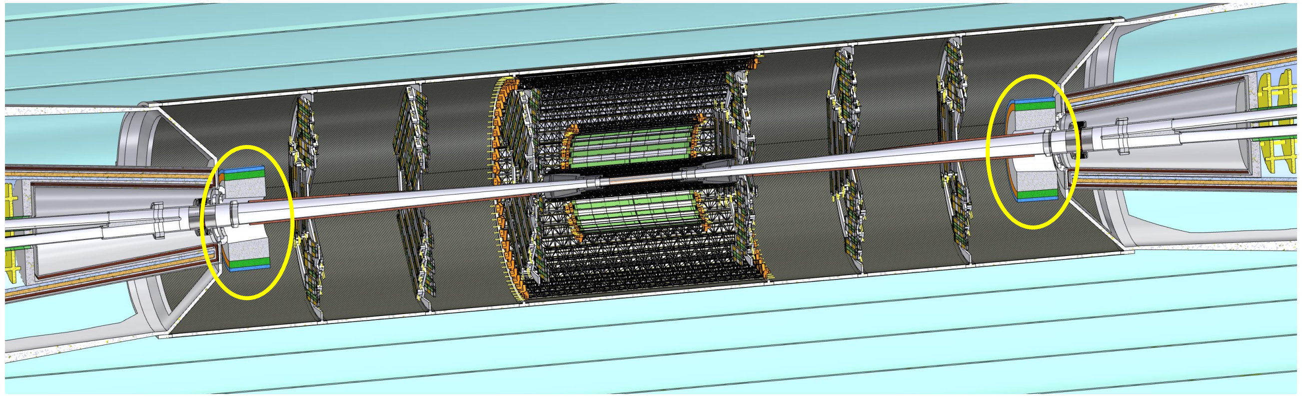
Goal: absolute luminosity measurement 10^{-4} at the Z
Standard process Bhabha scattering

- Bhabha cross section 12 nb at Z-pole with acceptance **62-88 mrad**
- Requires **50-120 mrad clearance to avoid spoiling the measurement**
- Requirements for alignment
  few hundred μm in radial direction
  few mm in longitudinal direction

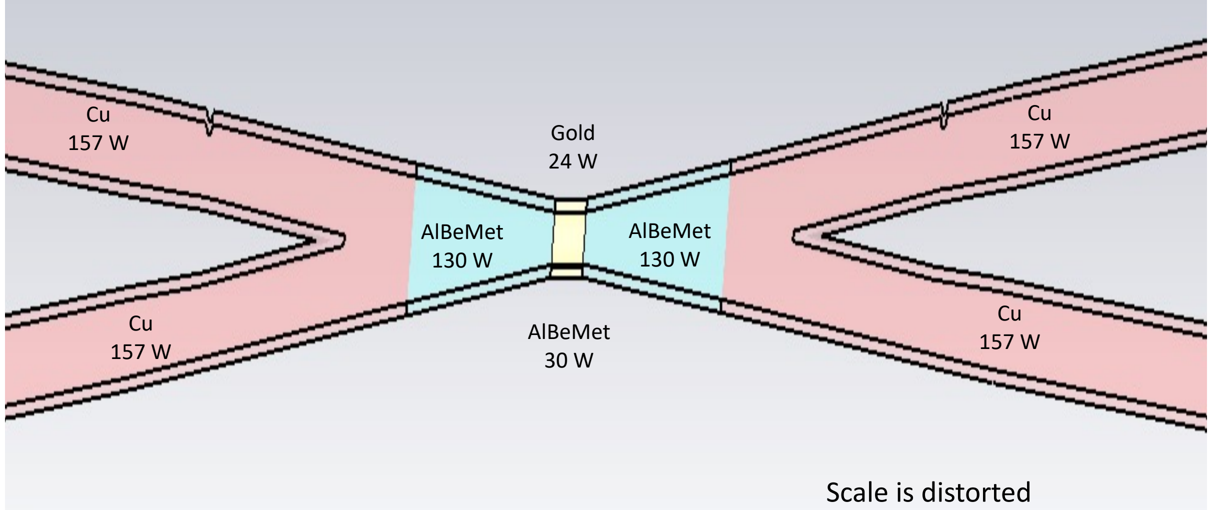


Lumical integration:

- **Asymmetrical cooling system** in conical pipe to provide angular acceptance to lumical
- **LumiCal held by a mechanical support structure**



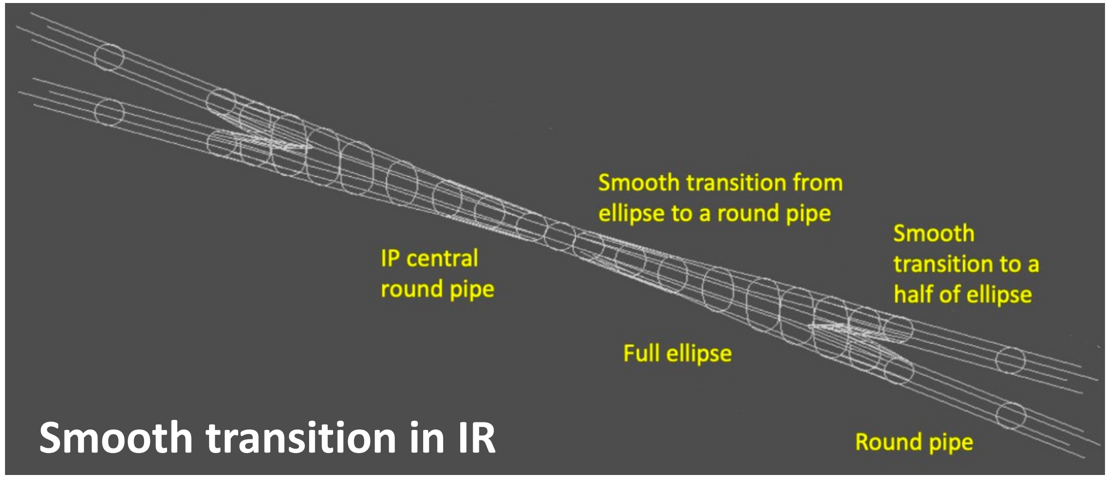
Impedance-related heat load distribution

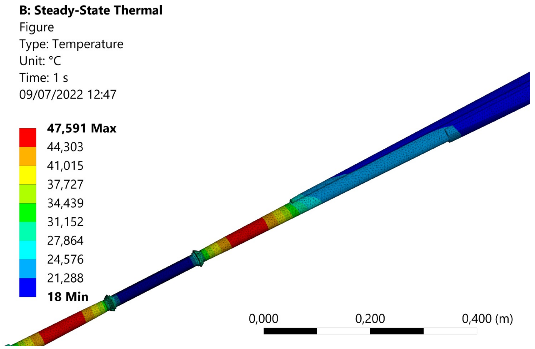


parameter	value
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

CST wakefields evaluations
Estimate heat load

Fed into ANSYS to dimension the cooling system





	trapezoidal chamber	central chamber
T_{max}	48°C	33°C
$T_{coolant}$	20.5 °C (paraffin)	20 °C (water)

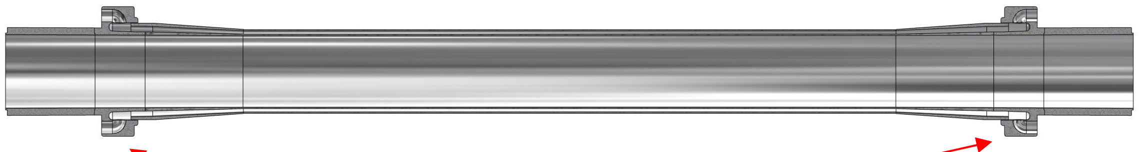
Crotch position slightly shifted from IP to house BPM next to lumical, allowing the integration of the lumical as a single object.
CST simulations performed confirm the modification (update presented in Frascati)

Ref. A. Novokhatski, F. Fransesini, *et al*. "*Estimated heat load and proposed cooling system in the FCC-ee IR beam pipe*", MOPA092, IPAC23

Low impedance central vacuum chamber

warm and cooled

Prototyping planned with the IR mockup

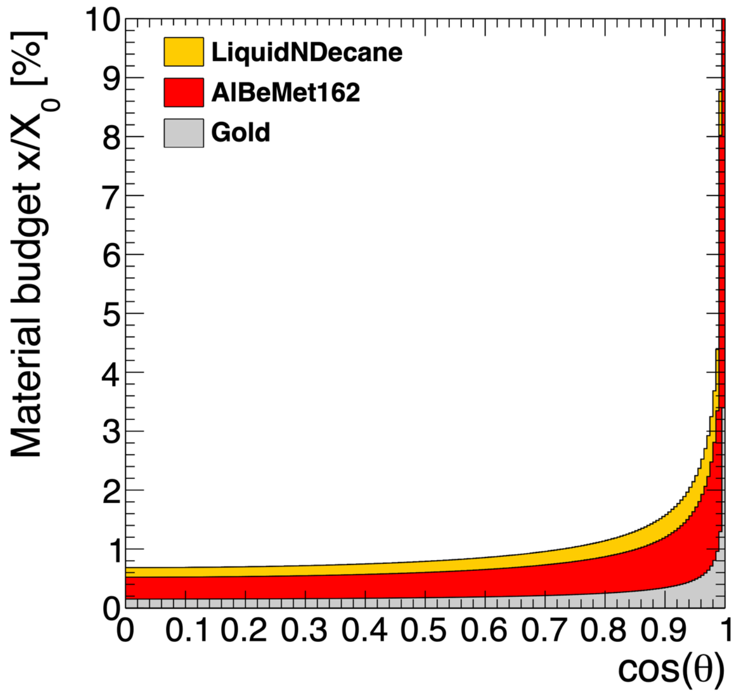


Inlet/outlet for paraffin cooling , all AlBemet, 180 mm long

Inner radius 10 mm

AlBeMet 162
62% Be and 38% Al alloy

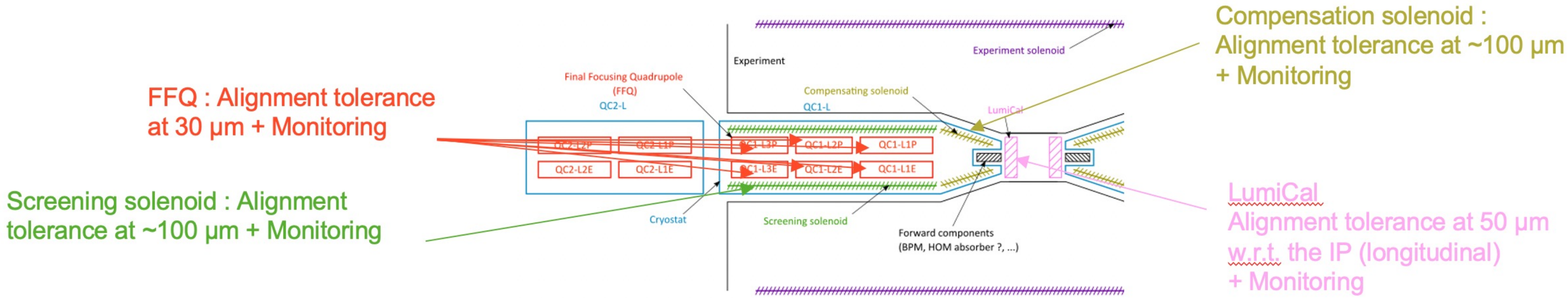
Central beam pipe material budget



All AlBeMet due to the constraints from the lumical acceptance.

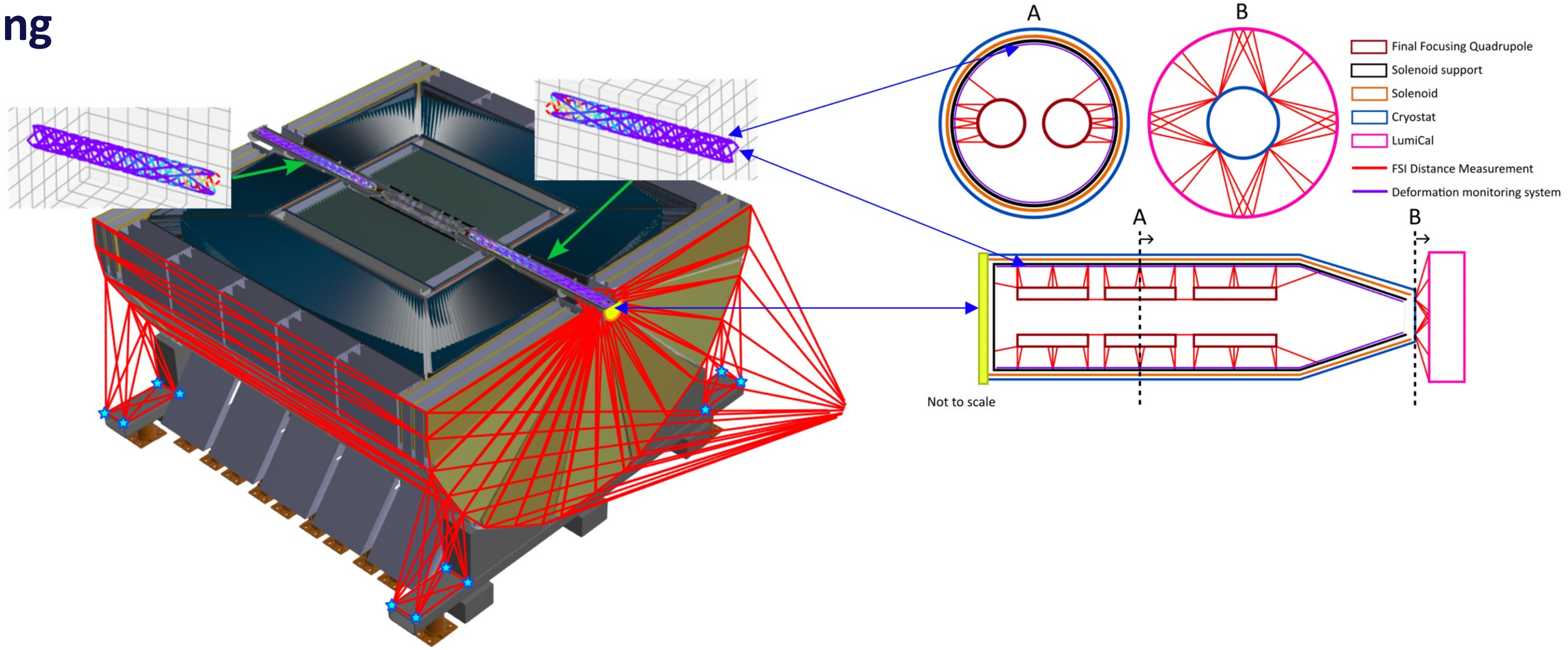
MDI Alignment and monitoring system

- Monitoring of the interface at the end of **QC1**
- Monitor the alignment **between QC1 and QC2.**
- Monitor the alignment **between the inner components and the experiment solenoid**.
- Monitor the alignment **between the two sides of the experiment**.
- Monitor the alignment of the **lumical**.



Permanent network of interferometric distance measurements based on Frequency Scanning Interferometry (FSI).

https://iopscience.iop.org/article/10.1088/1361-6501/acc6e3

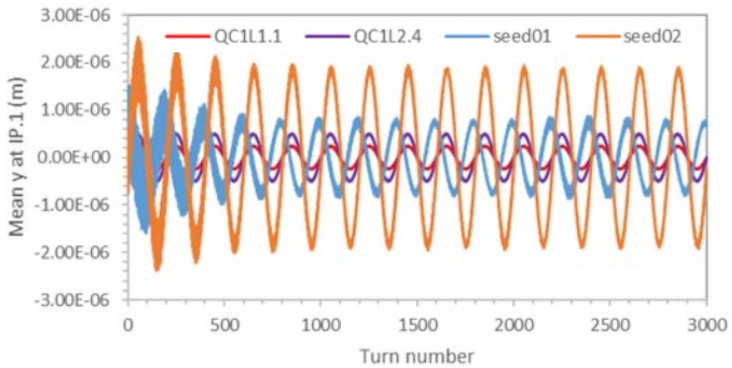


Internal alignment using optical fibers and deformation monitoring.

Simulations shown **micrometric accuracy** for the alignment between final focusing quadrupoles on both sides.

Towards mechanics and optics evaluation of the vibration effects for the MDI

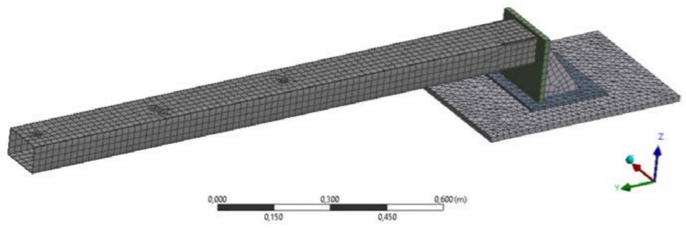
Optics: beam tracking studies



Setup tracking simulation:

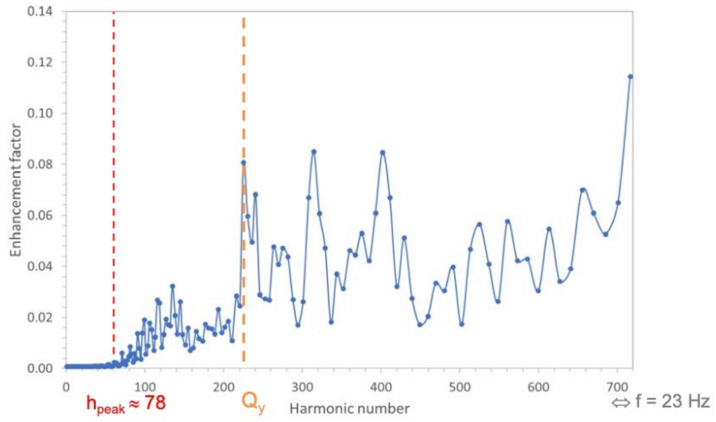
- sinusoidal vibration of all FFQs at 15 Hz with 1 µm of amplitude (first mode of vibration for SuperKEKB)
- Each FFQ contributes to the mean vertical offset at the IP.

Mechanics



validation of the method on a cantilever beam prototype

Effect of plane ground waves on the closed orbit



study performed with MADX, each quad of the ring is assumed with a vertical misalignment

Plans & Beam induced Background

Single Beam particles effects (e^+, e^-)

- Inelastic beam-gas scattering (Bremstrahlung)
- *Elastic beam-gas scattering (Coulomb)*
- Synchrotron Radiation
- Thermal photons
- *Touschek*

Luminosity induced background (e^+e^-)

- Radiative Bhabha
- Beamstrahlung photons and spent beam
  - Incoherent/ Coherent e^+e^- Pair Creation
  - $\gamma\gamma$ to hadrons

Fluka model for the MDI region is starting to evaluate **radiation doses (TID) and neutron fluences**

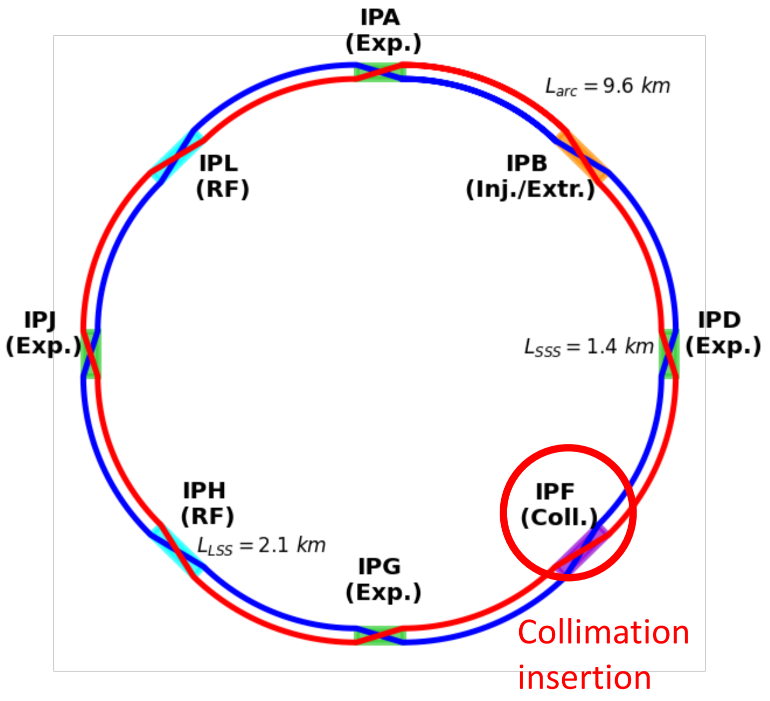
We have performed first evaluations of these effects for the CDR.

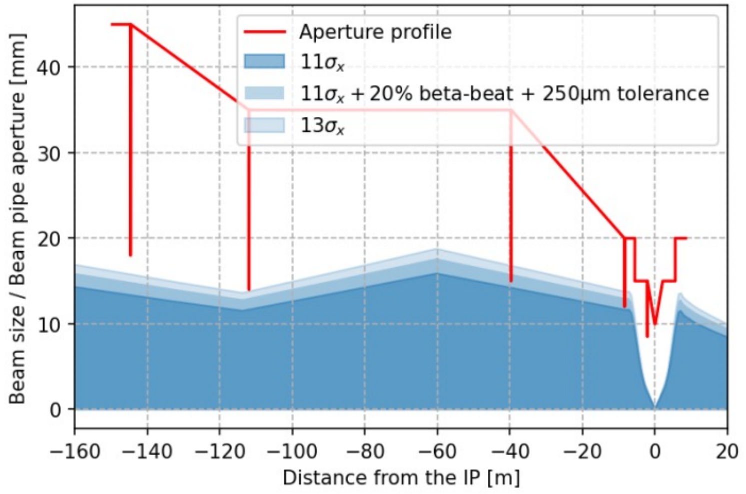
For the feasibility study the topic was tackled starting from developing a new code for particle tracking and study the **halo beam**, with an LHC-like approach. **A collimation region was implemented for halo beam.**

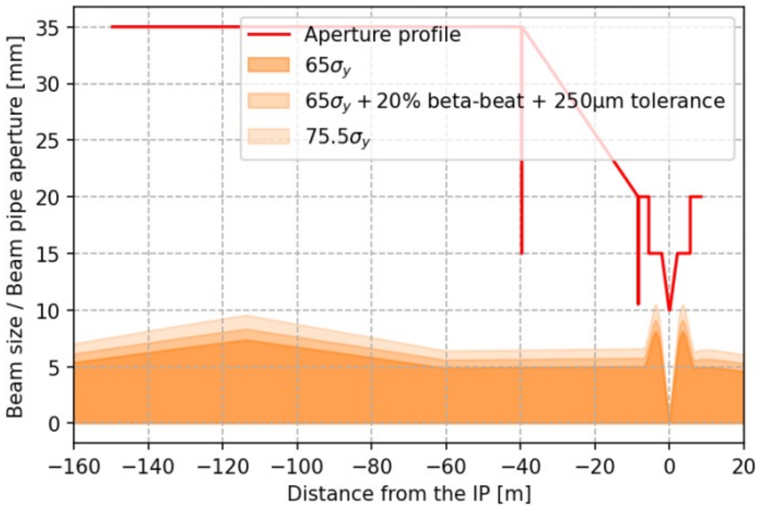
The MDI region is now improved as more realistic, and software model developed.
We plan to update and complete those studies.

Main Ring Collimation

- **Dedicated halo collimation system in point PF**
  - Two-stage betatron and off-momentum collimation in PF
  - Defines the global aperture bottleneck
  - First collimator design
- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs
  - Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses

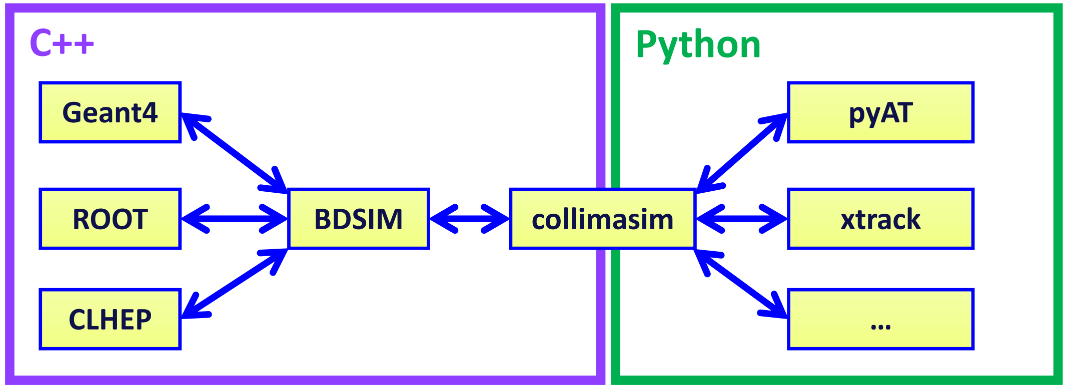






Main Ring Collimation

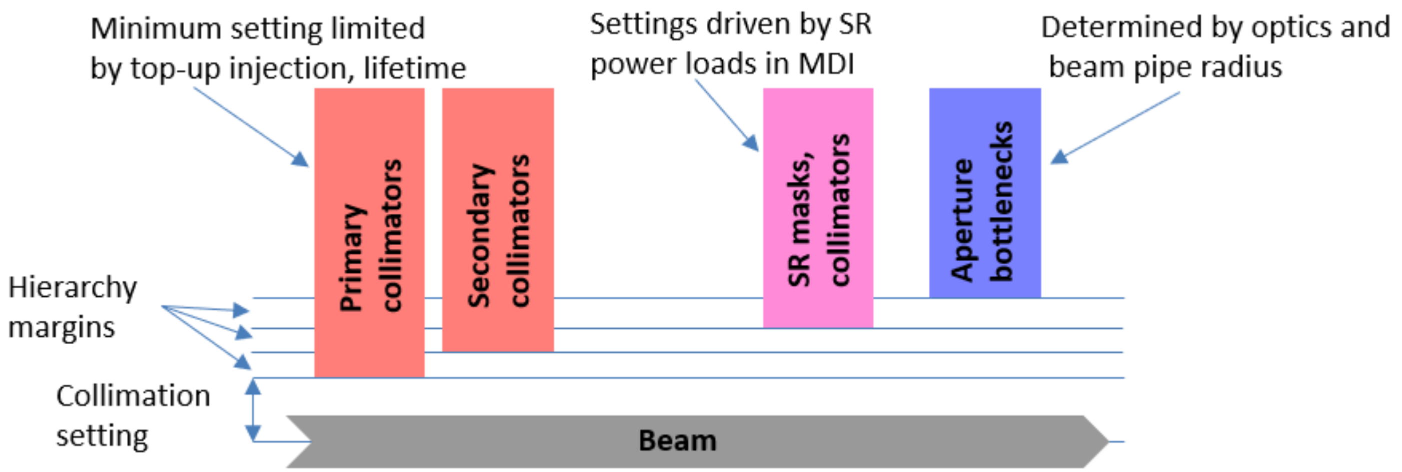
Complete simulation package for modeling performance in FCC-ee and FCC-hh (these tools are now being used at EIC as well)



Three layered collimation system has excellent performance

With a pessimistic 5-minute lifetime at Z → 59.2 kW absorbed in PF while < 2 W reach experimental IRs

Super KEKB observations of ‘fast beam loss’ needs to be understood as it would be hard to protect against

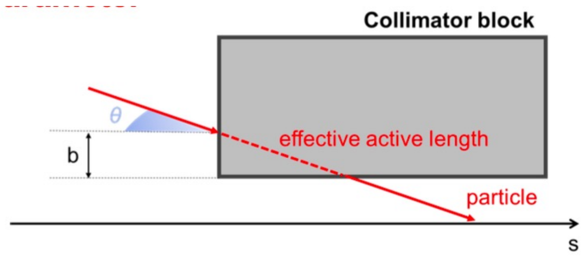


Beam losses in the MDI

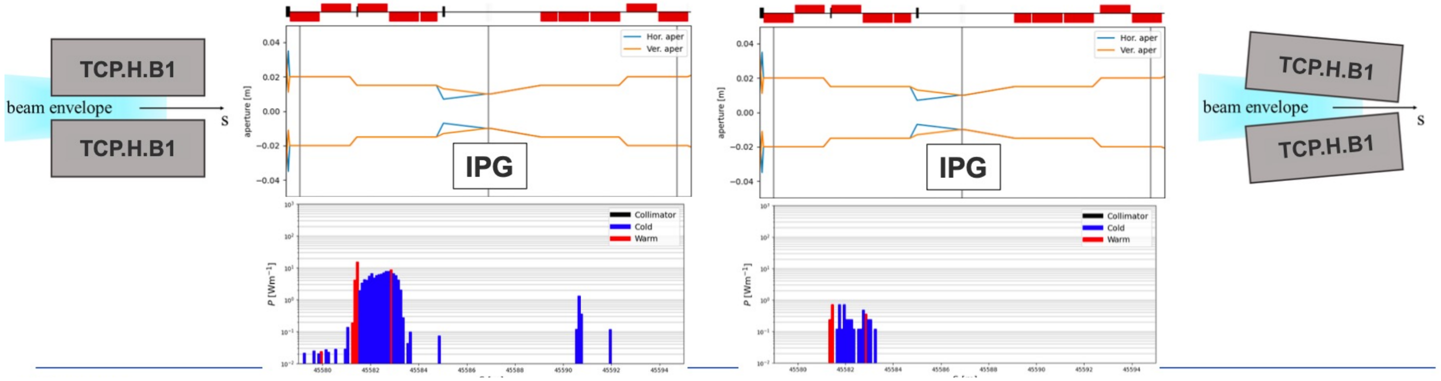
Evaluation of the halo collimation system performance
MDI beam losses (Xtrack-BDSIM)

- **Parametric scan of the primary collimator length** indicates 25-30 cm TCP (Two radiation-length primary collimators)
- **Impact parameter scan** study

b: impact parameter
θ: angle of incidence



- Two scenarios
  - **TCP.H.B1 parallel to the closed orbit**
  - **TCP.H.B1 aligned to the beam envelope** (loss mitigation strategy) - **"tilted TCP.H.B1"**



Synchrotron Radiation backgrounds

Simulations with **BDSIM** (GEANT4 toolkit), featuring SR from Gaussian beam core and transverse halo.

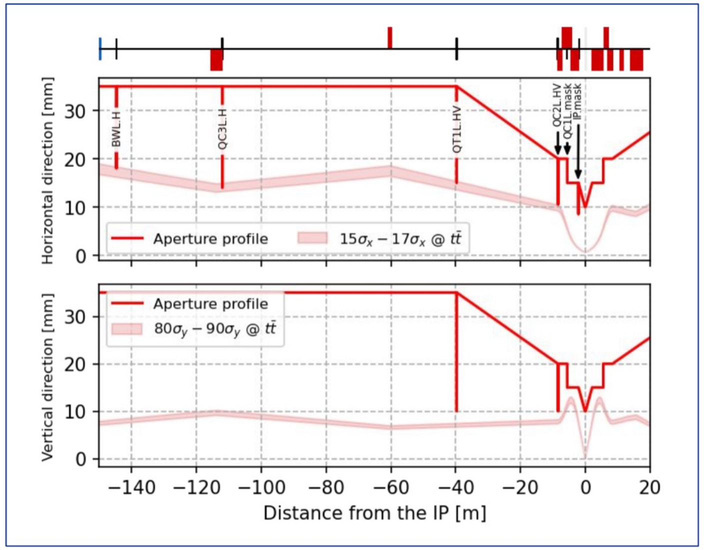
Characterisation of the SR produced for **all beam energies**.

SR produced upstream the IP:

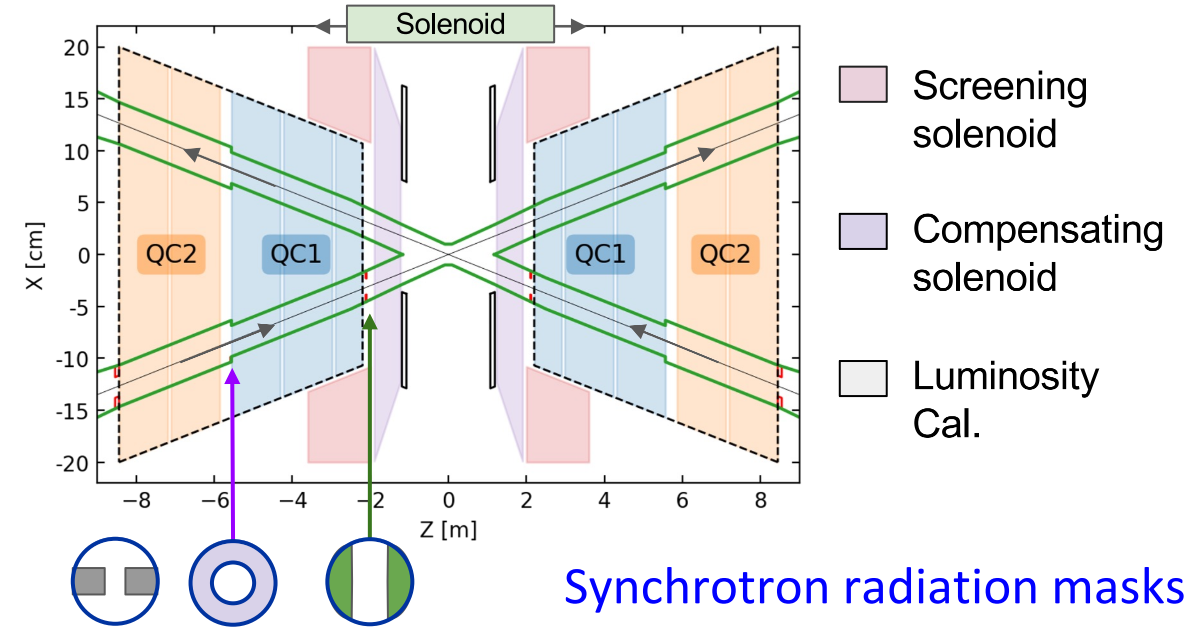
- by the **last dipoles and quadrupoles upstream the IR** can be a background source, to be collimated and masked
- by the **IR quads and solenoids** collinear with the beam and will hit the beam pipe at the first dipole after the IP.

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.

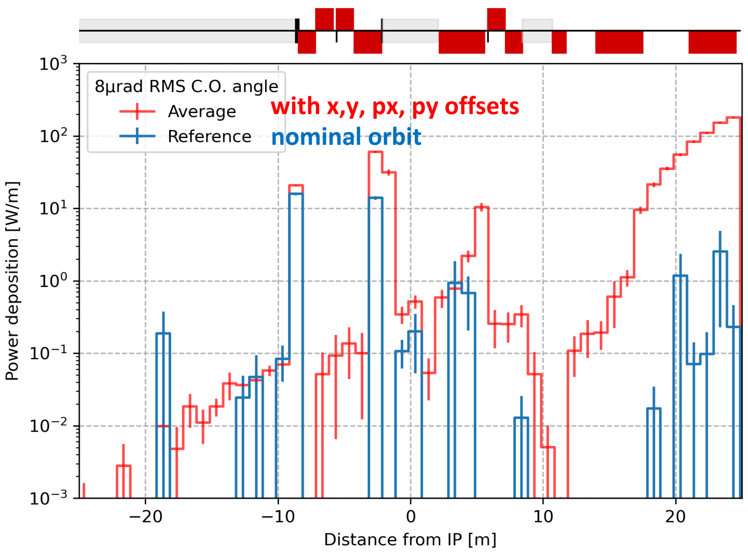


Synchrotron radiation collimators



Synchrotron radiation masks

Synchrotron Radiation backgrounds

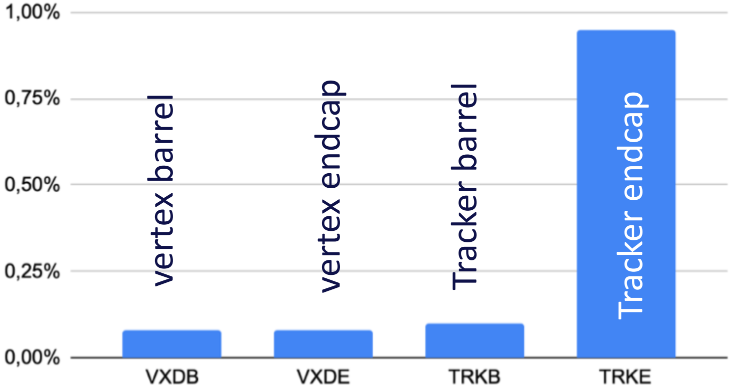


Power deposition from beam core for Z-mode (v22)

Blue is the reference closed orbit

Red is the average with possible offsets due to misalignments

Maximum occupancy in subdetector/BX

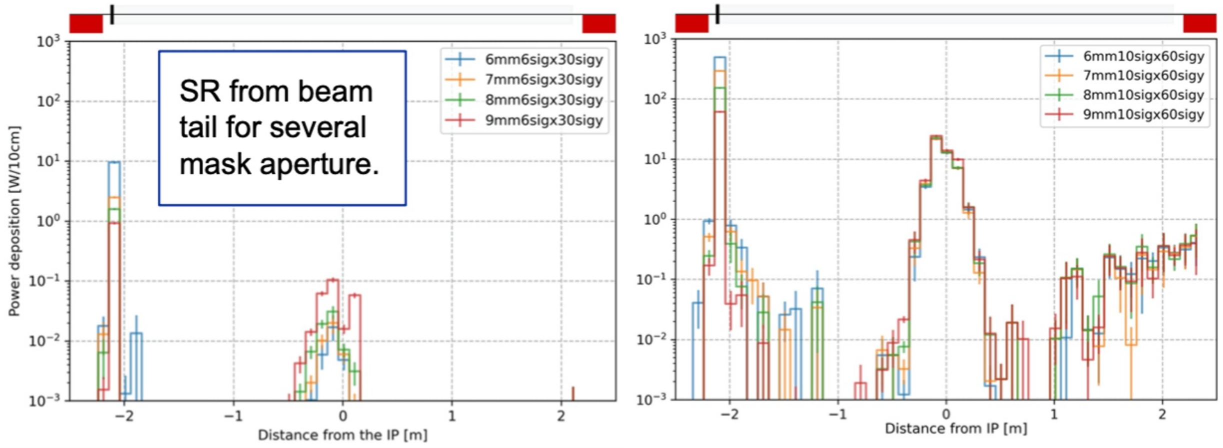


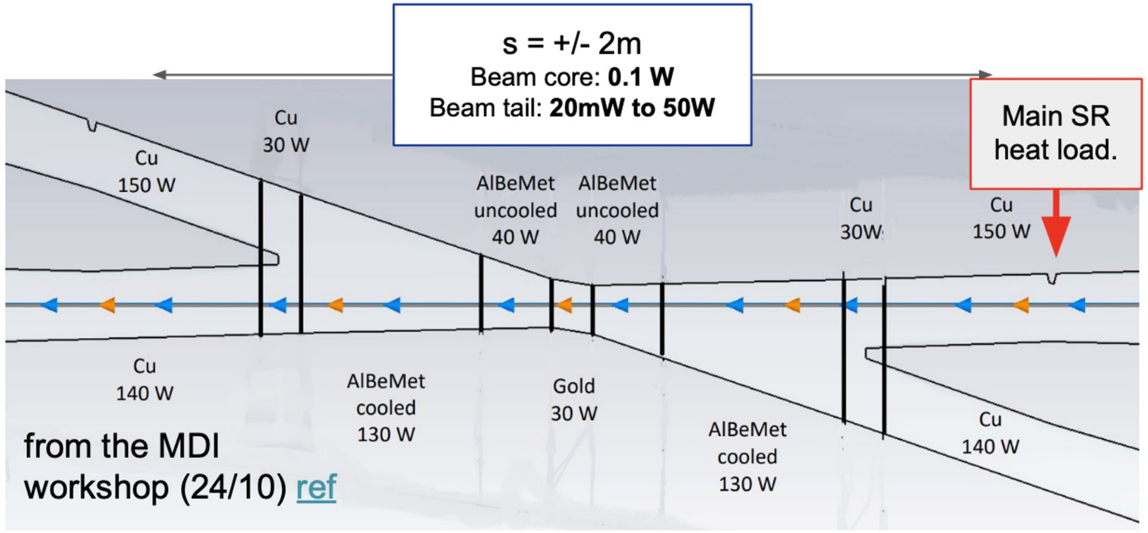
($t\bar{t}$ threshold - CDR beam parameters
CLD detector - NO shieldings)

A. Ciarma

from beam tails hitting SR mask tips

Heat load from beam halo synchrotron radiation

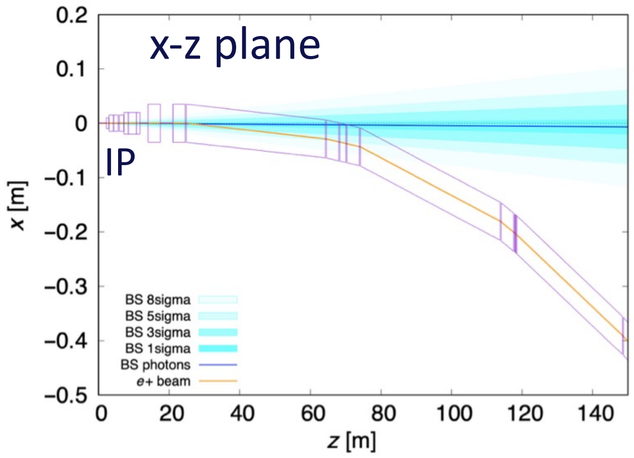


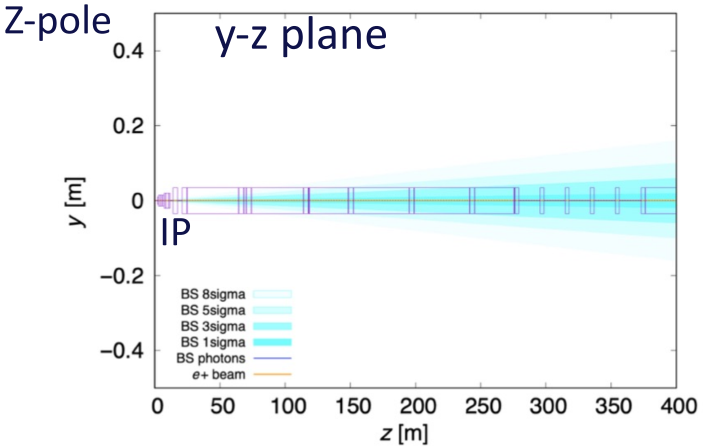


Heat Load from wakefields

Beamstrahlung Radiation

Radiation from the colliding beams is very intense 400 kW at Z
Study performed with GuineaPig.





This BS radiation exits the vacuum chamber around the first bending magnet BC1 downstream the IP

	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

MB and A. Ciarma, PRAB 26, 111002 (2023), link

High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

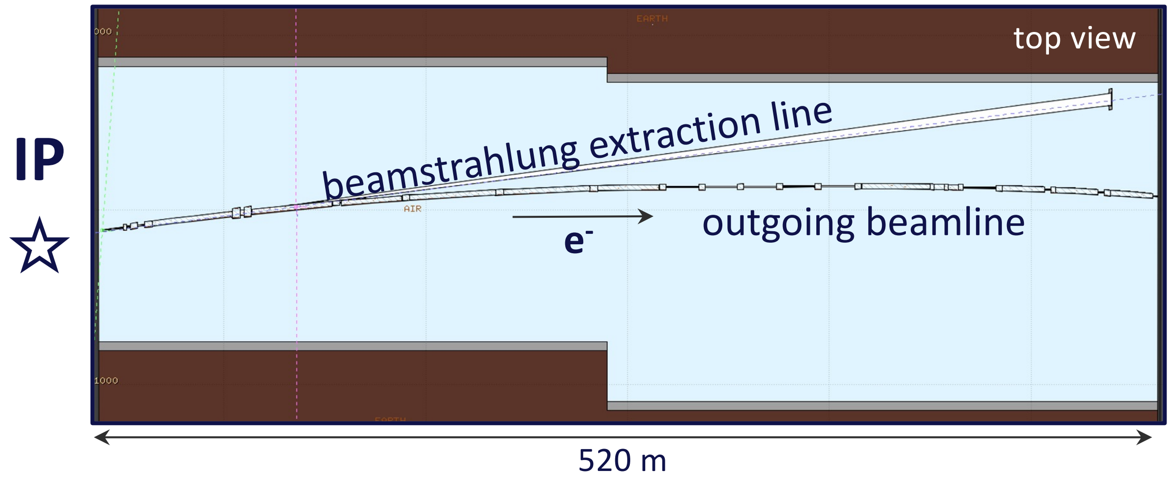
- Different targets as dump absorber material are under investigation
- Shielding needed for equipment and personnel protection for radiation environment

FLUKA studies of the FCC-ee IR

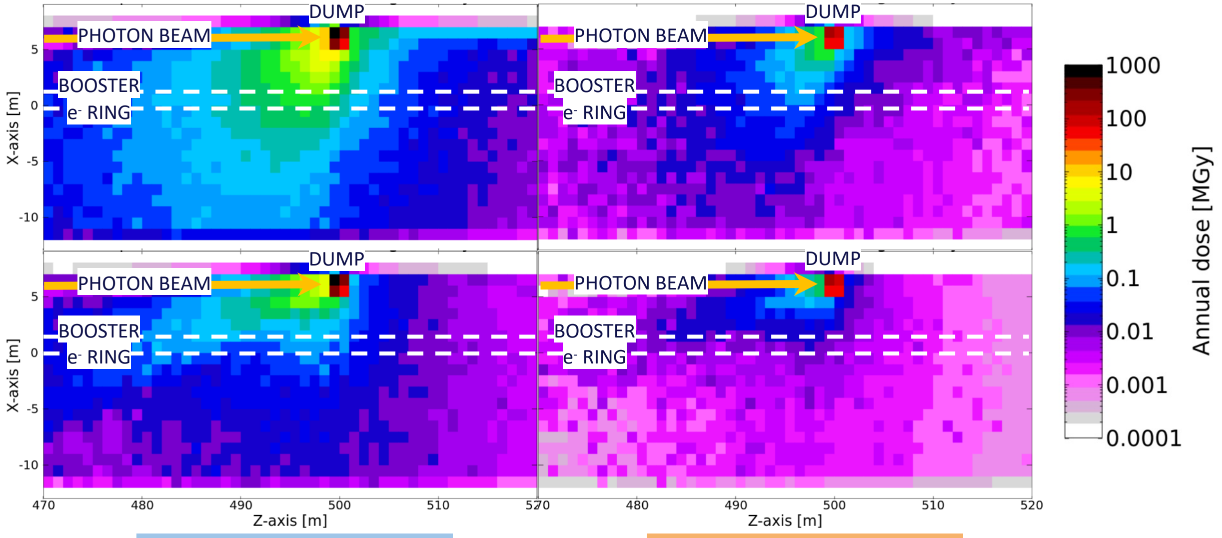
FLUKA model to estimate the radiation levels in the FCC-ee tunnel in the experimental IR

- beamstrahlung dump and synchrotron radiation outgoing from the IP investigated
- no SR absorbers included
- radiation studies for the detector and FFQ to be addressed soon (including beamline incoming to the IP)

FLUKA MODEL

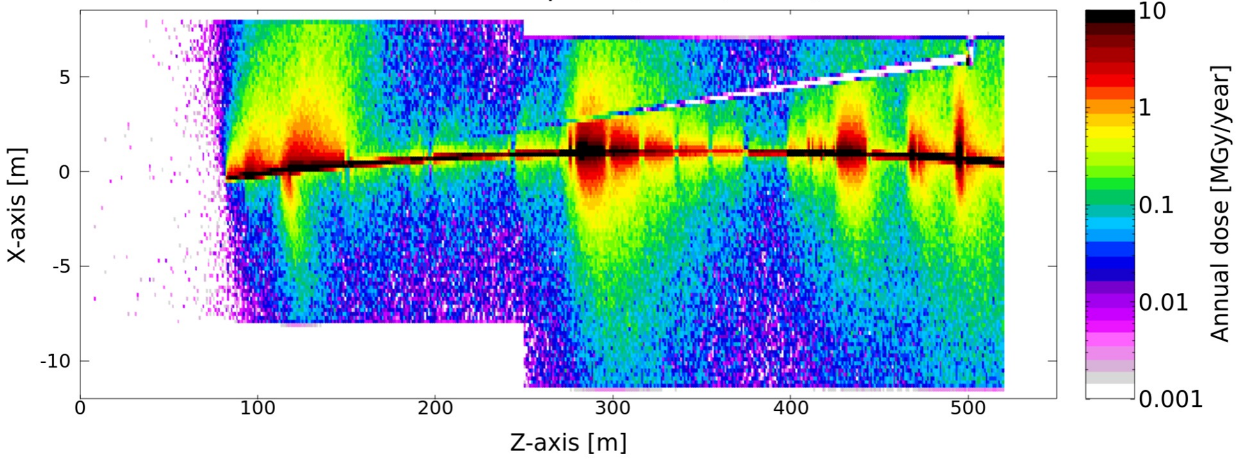


ANNUAL DOSE FROM BEAMSTRAHLUNG DUMP

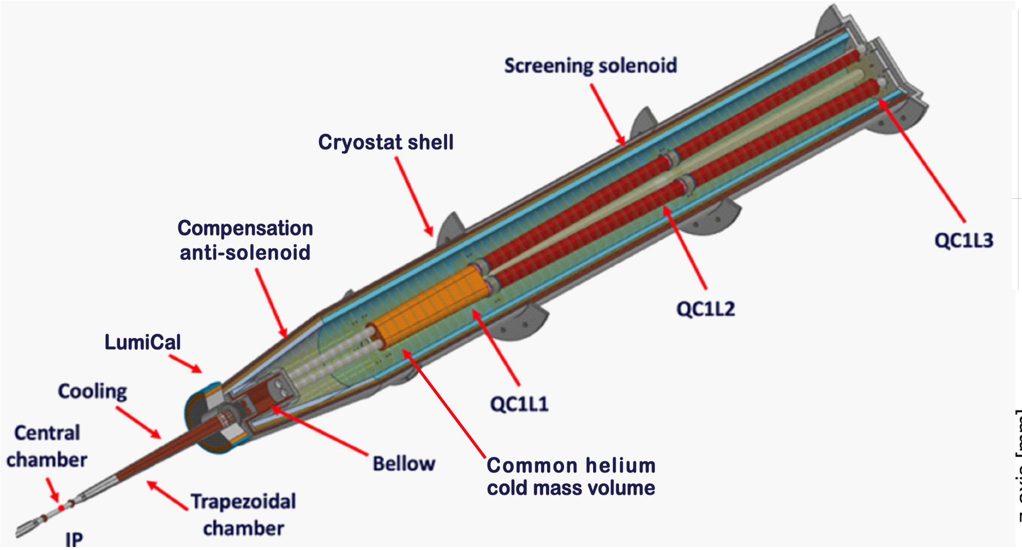


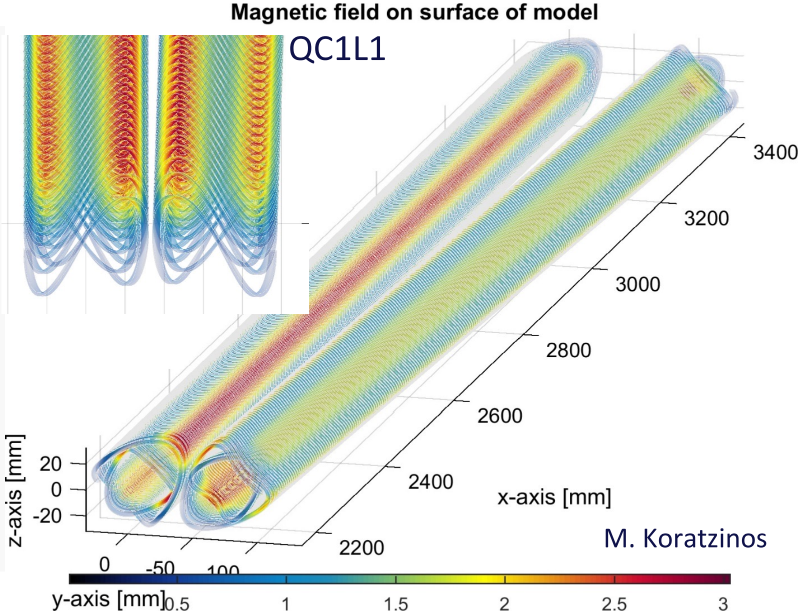
ANNUAL DOSE FROM SR @ttbar

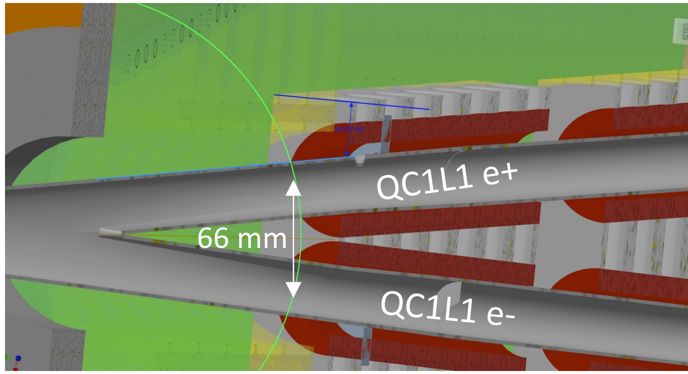
ttbar - horizontal plane (-20cm, 20cm)



FCC-ee IR Final Focus quadrupoles







minimum distance between the magnetic centers of e+/e- for QC1L1 is (only) 66 mm

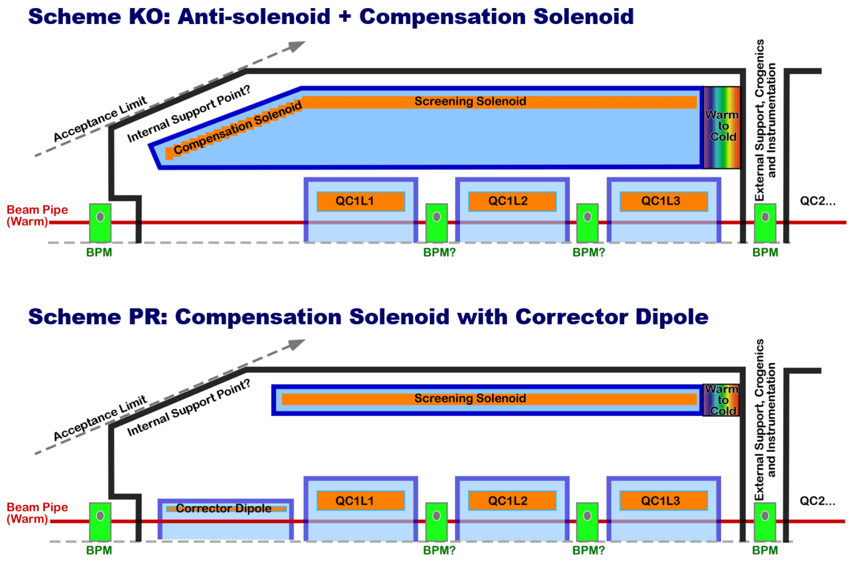
Ongoing work to develop IR quadrupoles with ~100 T/m

QC1 based on Canted Cos theta (CCT) design, with max gradient 100 T/m, NiTi 2.9 K.
The inner radius of the beam pipe at QC1 is 15 mm; at QC2 it is 20 mm.
Other options are also under evaluation to determine the best solution.

Integration of complete cryostat with magnets, correctors, and diagnostics is required.

Efficiency of the IR quadrupole magnets and potential prototype

Two IR Optics Schemes Currently Under Consideration



- For **BPM access** and cryogenic flexibility, it is **useful to separate individual cold masses** within main cryostat.
- Best practice says to provide **inner and outer heat shields** and more space for containment and support.
- Also, preliminary study suggests that some coils likely need **protection** from energy deposition at Z running.
- Thus, both inner and coil radii should increase, but this is not possible for all coils (e.g. QC1R/L1).
- Solutions: higher performance superconductors, lower temperatures, new coil geometries and magnetic yokes.

1. **We must finalize functional requirements for each magnet at every operating point asap in order to develop individual magnetic design solutions (e.g. QC1R1 @ tt is different than QC2R1 @ Z).**
2. **Much of the required R&D is pushing state of the art (e.g. if we need Nb_3Sn or HTS coils) so it is important to integrate magnet prototyping and testing into the project (approval???) schedule.**

Significant progress on key aspects of the MDI design

- Mechanical model, including vertex and lumical integration, and assembly concept
- Backgrounds, halo beam collimators, IR beam losses
- Synchrotron radiation, SR collimators and masking, impact on top-up injection
- Heat Loads from wakefields, synchrotron radiation, and beam losses
- Beamstrahlung photon bump with first radiation levels

And thanks to many people for inputs!