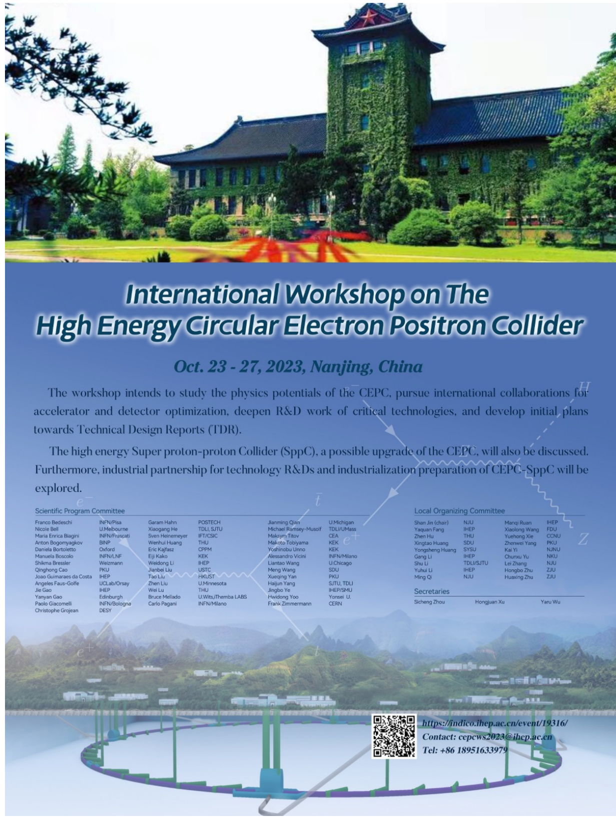
FUTURE CIRCULAR COLLIDER
Innovation Study

INFN LNF
Istituto Nazionale di Fisica Nucleare

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.



FCC-EE MDI OVERVIEW

Manuela Boscolo (INFN-LNF)

for the MDI team

2023 International Workshop on CEPC
23-27 October 2023, Nanjing, China

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.

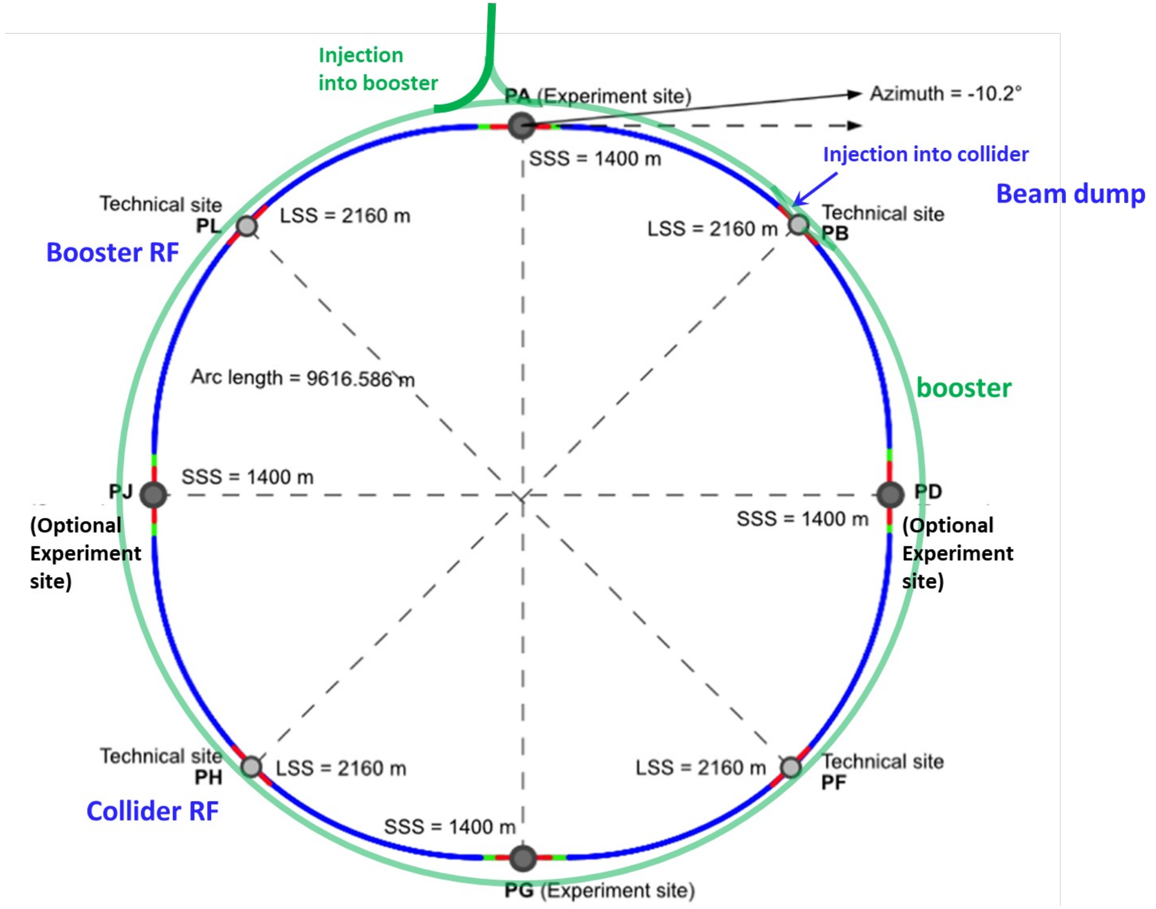
Common footprint with FCC-hh, except around IPs

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)

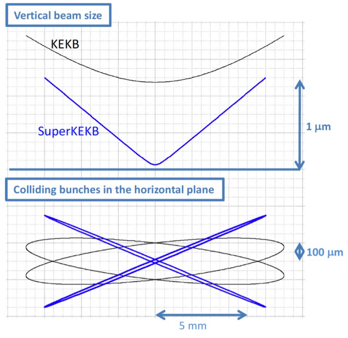


Figure 2: Schematic view of the nanobeam collision scheme.

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	$t\bar{t}$
4 years 5×10^{12} Z LEP x 10^5	2 years $>2\times10^8$ WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs

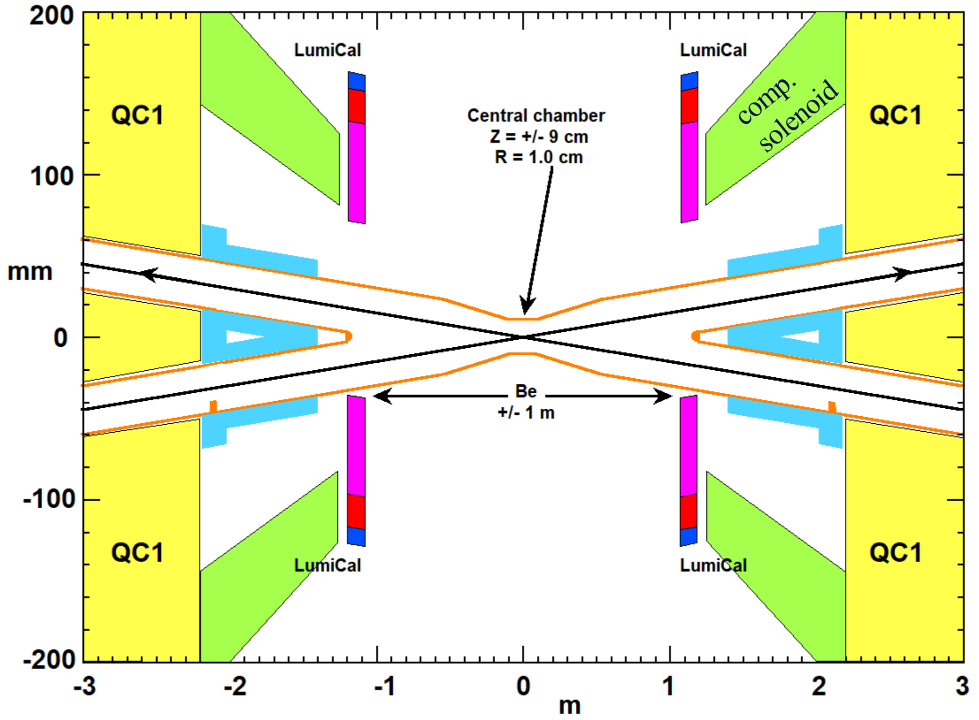
- Very high luminosity at Z, W, and Higgs
- Accumulate > luminosity in 1st 10 years at Higgs, W, and Z than ILC at Higgs
- Accommodates up to 4 experiments → robustness, statistics, specialized detectors, engage community
- Run plan naturally starts at low energy with the Z and ramps but could be adjusted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

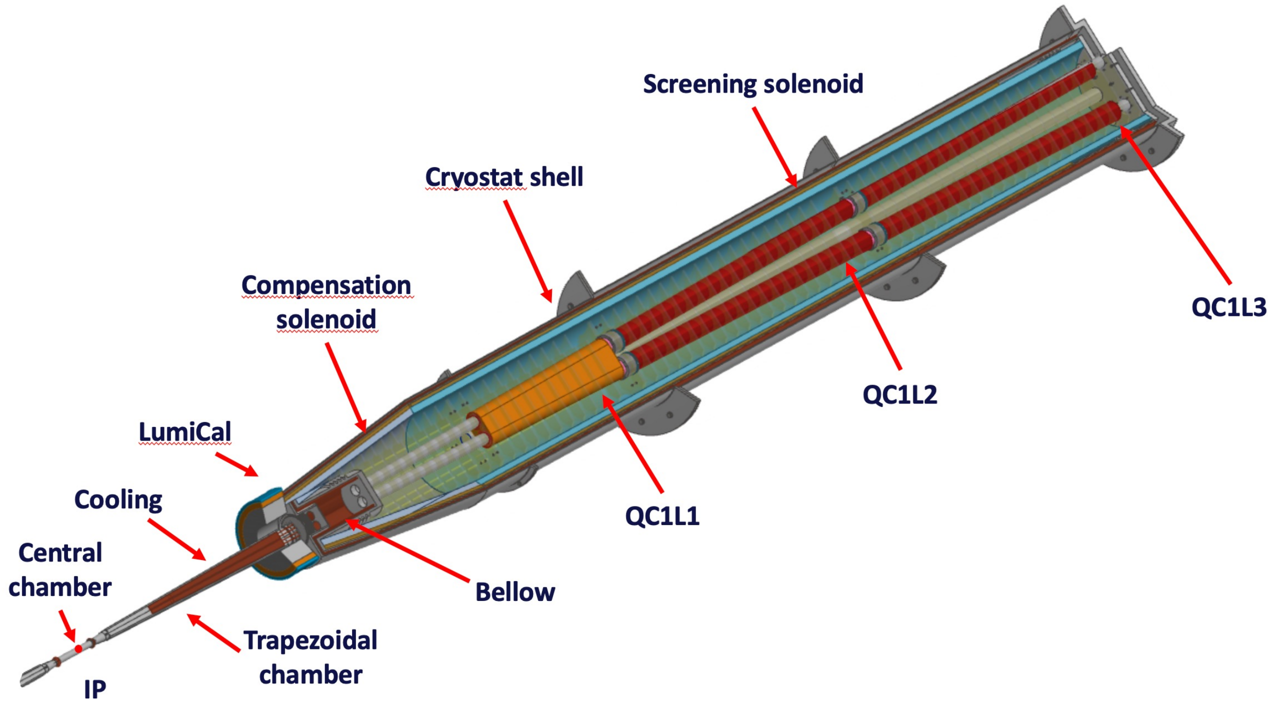
High-level Requirements for the IR and MDI region

- **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

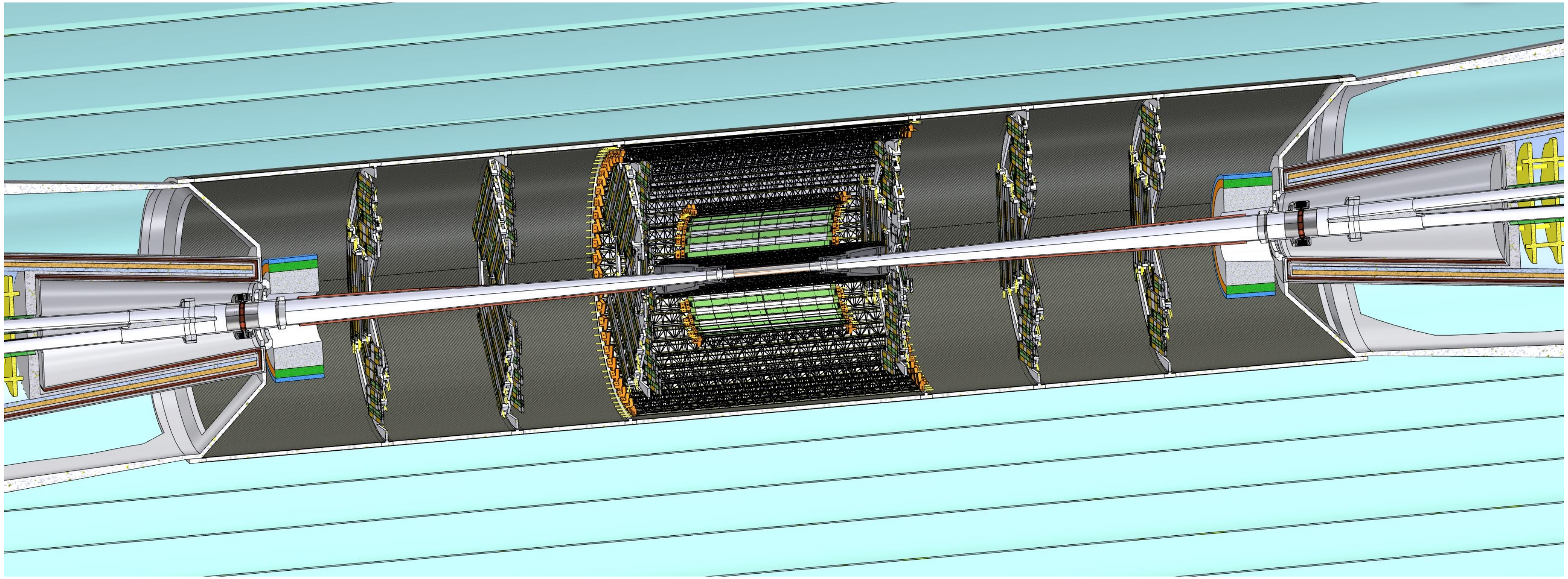
QC1 almost entirely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at 5.6 m.

P. Raimondi recently proposed a non-local solenoid compensation scheme that greatly modifies this design.

FCC-ee Interaction Region

see talk by F. Palla

3D view of FCC-ee IR: zoom at the very central region about 2.4 m



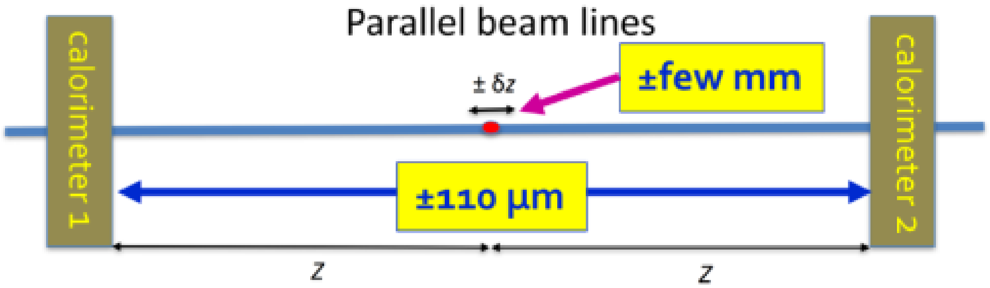
View including the rigid support tube, vertex detector and outer trackers

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

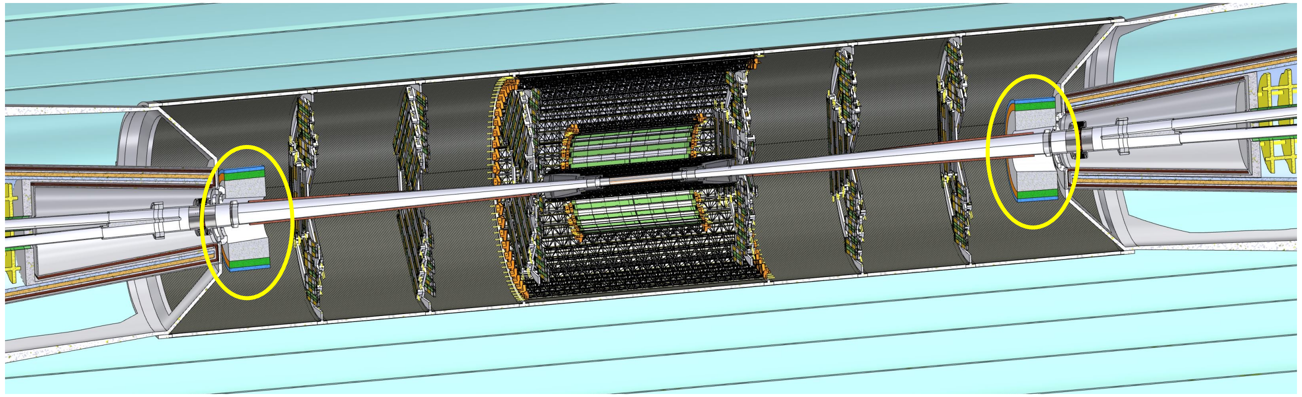
Goal: absolute luminosity measurement 10^{-4} at the Z
Standard process Bhabha scattering

- 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:

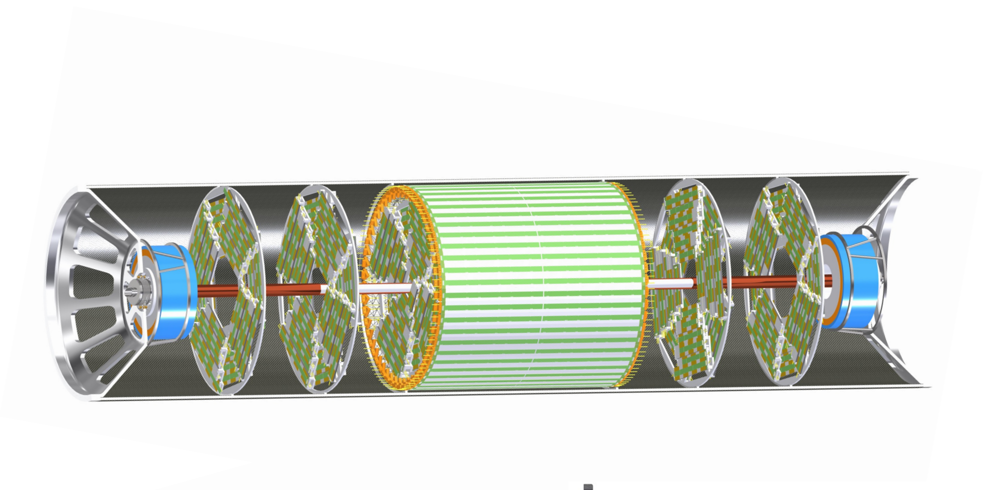
- **Asymmetrical cooling system** in conical pipe to provide angular acceptance to lumical
- **LumiCal held by a mechanical support structure**



Progress IR mechanical design

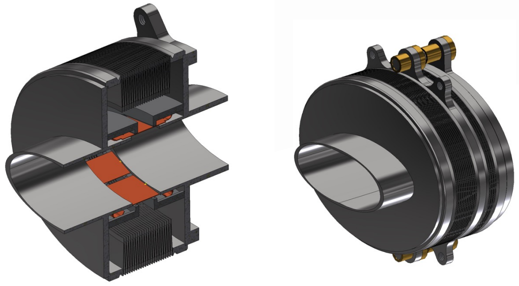
- The **central chamber** geometry was studied to integrate the central chamber with the **vertex detector.**

- The **support tube** has been designed to :
  - Provide a cantilevered support for the pipe
  - Avoid loads on thin-walled central chamber during assembly or due to its own weight
  - Support LumiCal
  - Support the outer and disk tracker



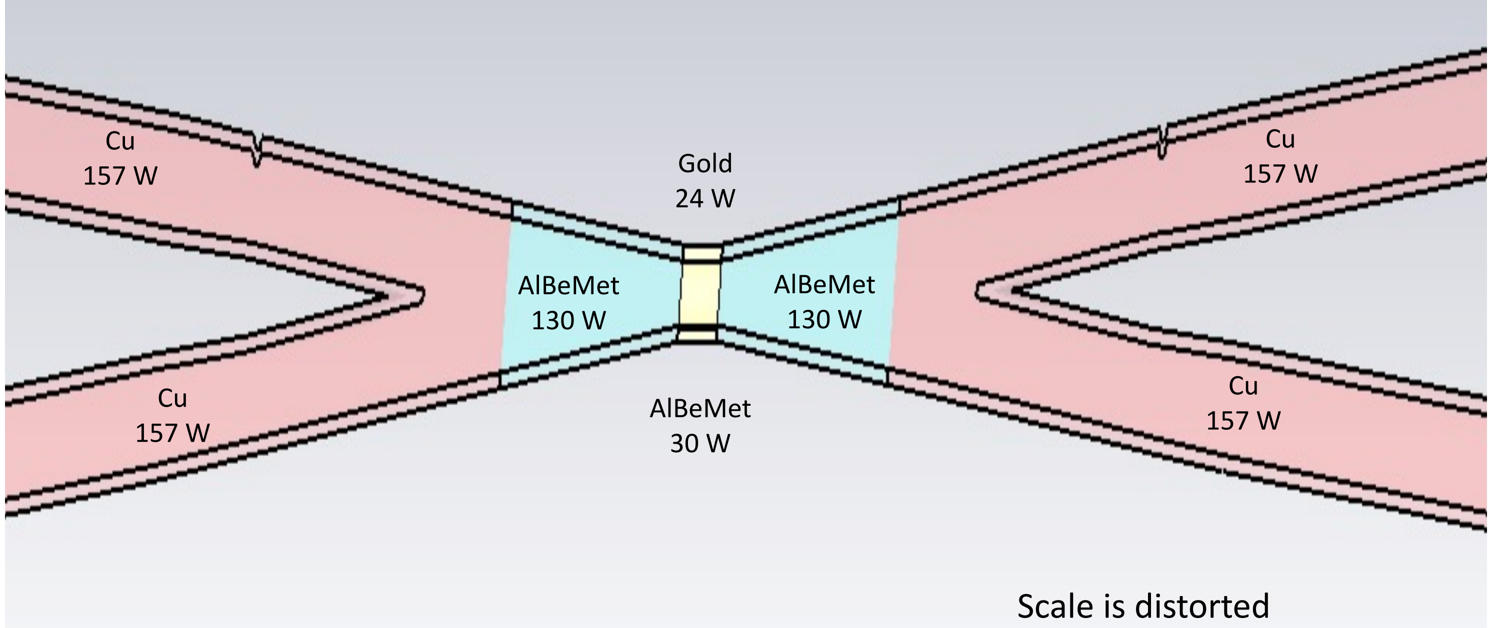
- The **crotch chamber** design has been started, evaluating different solutions.

- **Two different type of bellows** have been proposed.
  Adaptation of ESRF bellows.
  Optimization design is in progress with CST calculation.



- The **assembly procedure** is in progress and the rail solution has been proposed.

Impedance-related heat load distribution

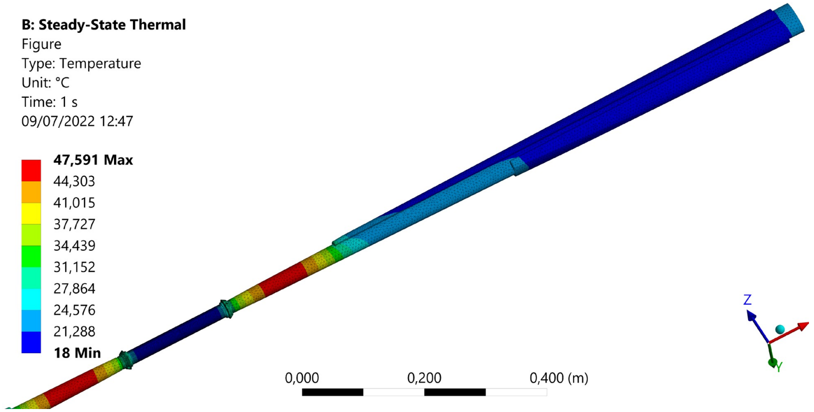


parameter	value
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

CST wakefields evaluations
Estimate heat load

↓

Fed into ANSYS to dimension the cooling system



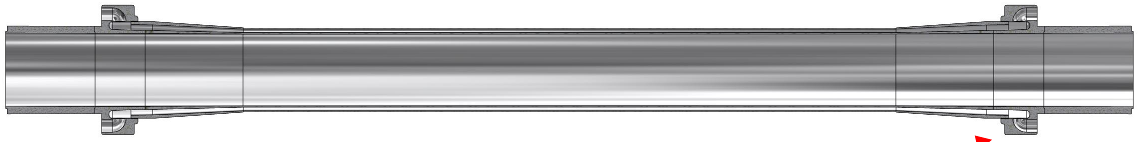
	trapezoidal chamber	central chamber
T_{max}	48°C	33°C
$T_{coolant}$	20.5 °C (paraffin)	20 °C (water)

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

FCC-ee IR mockup and prototyping is planned

Low impedance vacuum chamber warm and cooled

Central chamber

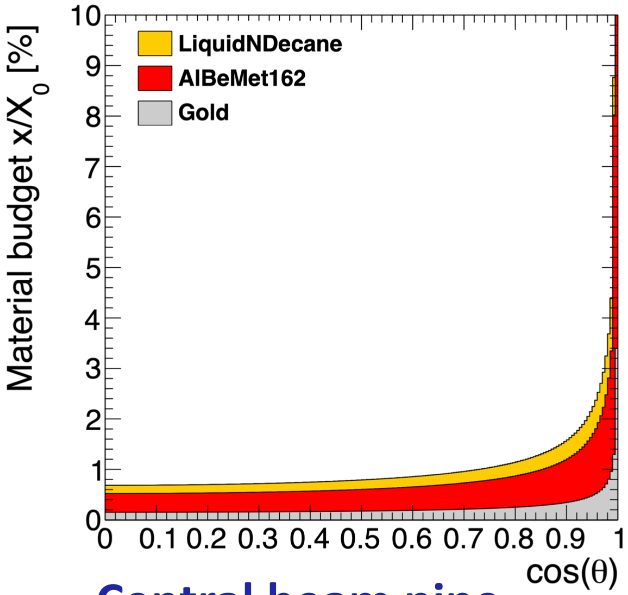


Inlet/outlet for paraffin cooling , all AlBemet, 180 mm long

Inner / Outer radius 10/ 11.7 mm

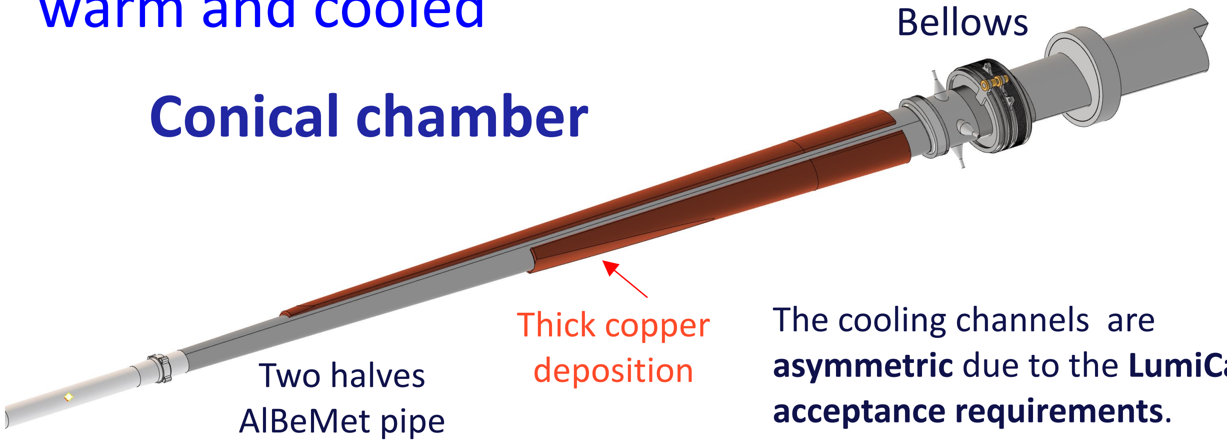
Material	thickness
AlBeMet162(*)	0.35 mm
Paraffin (coolant)	1 mm
AlBeMet162	0.35 mm
Au	5 µm

(*) AlBeMet 162
62% Be and 38% Al alloy

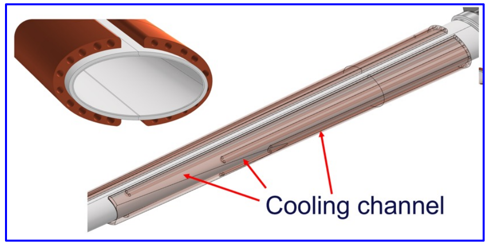


Central beam pipe material budget

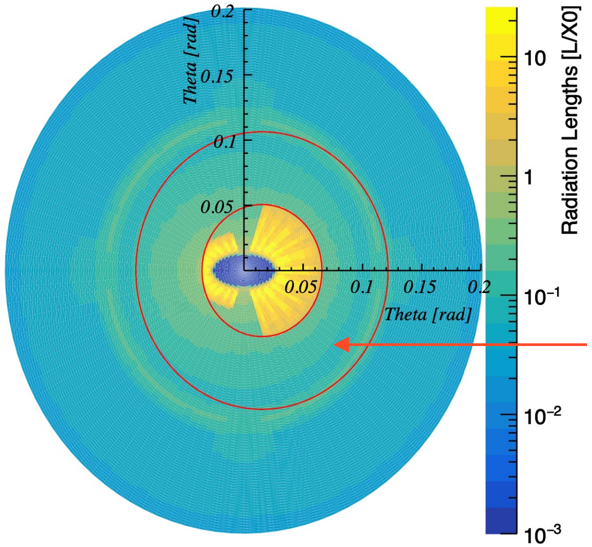
Conical chamber



The cooling channels are **asymmetric** due to the **LumiCal acceptance requirements**.



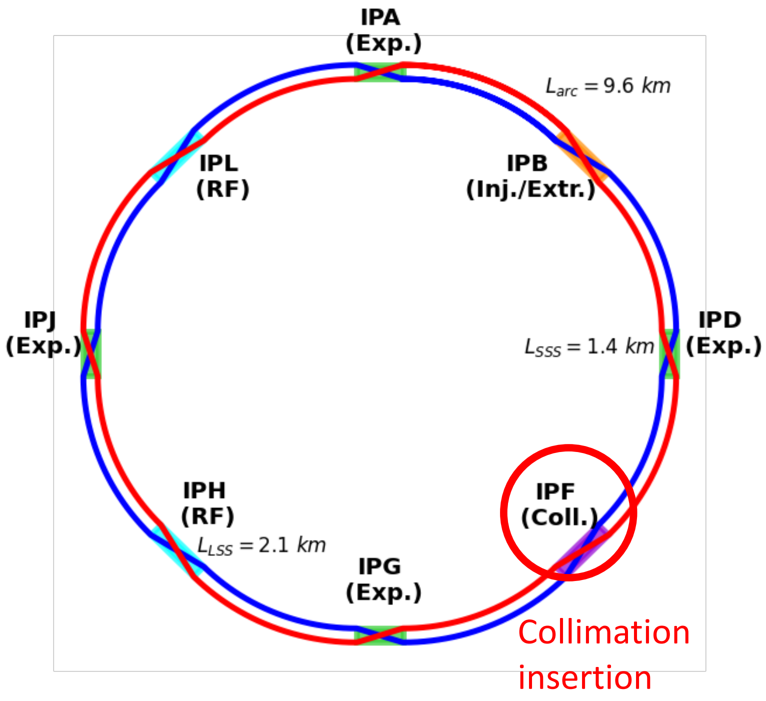
It goes from 90 mm to 1190 mm from IP.

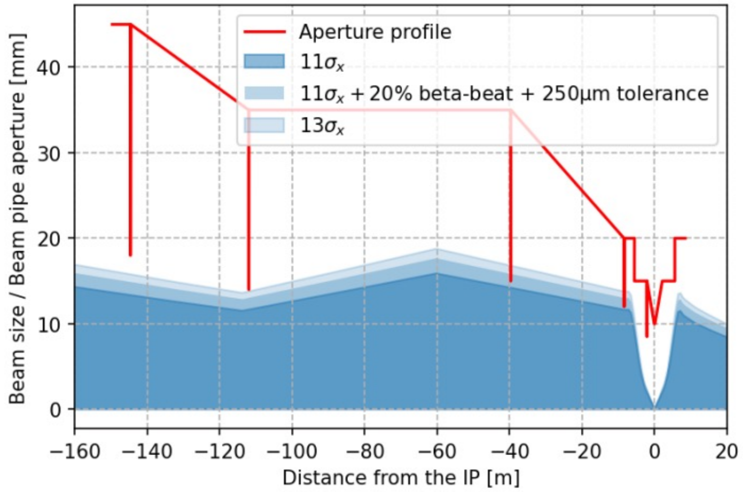


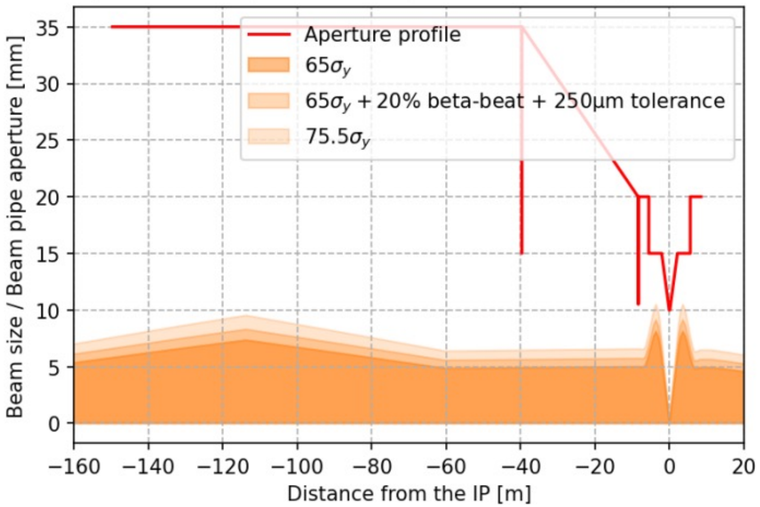
Conical beam pipe material budget

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

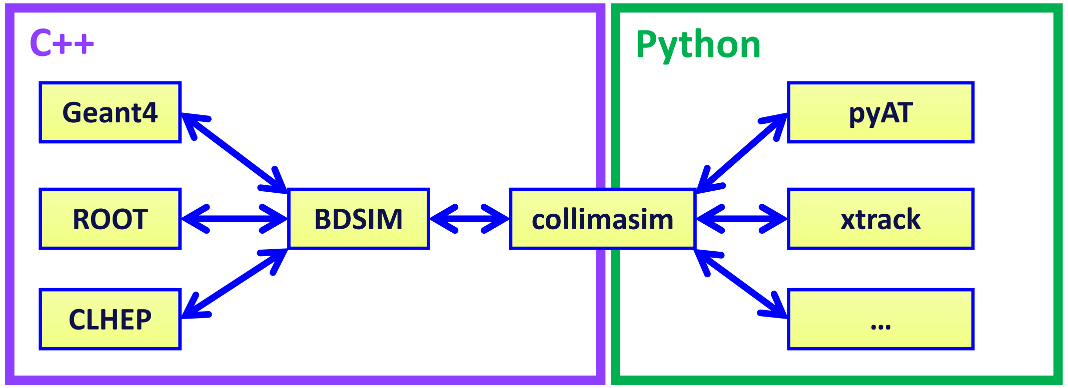






Main Ring Collimation

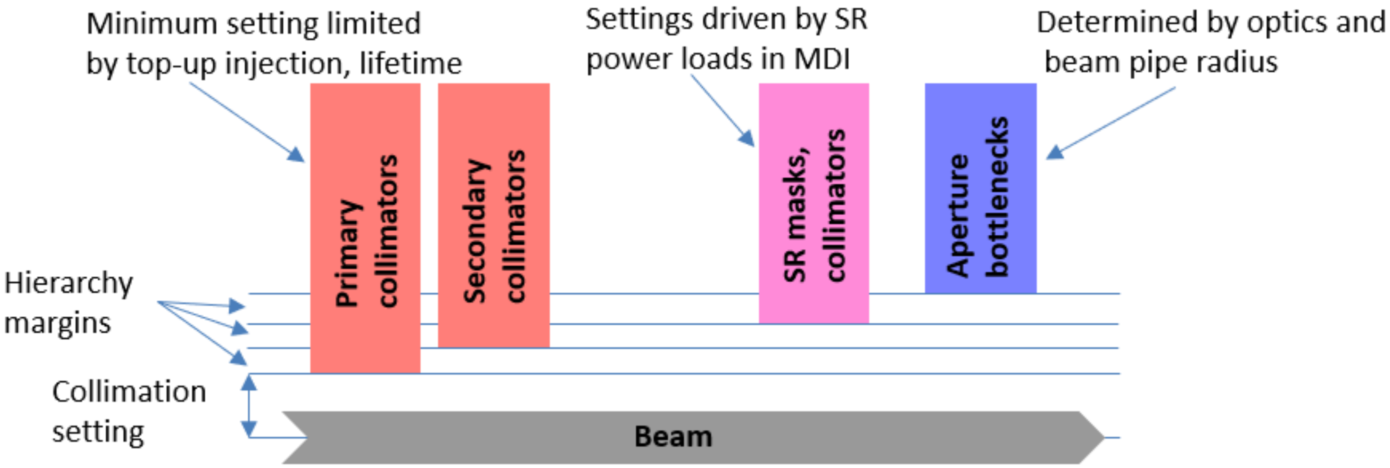
Complete simulation package for modeling performance in FCC-ee and FCC-hh (these tools are now being used at EIC as well)



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

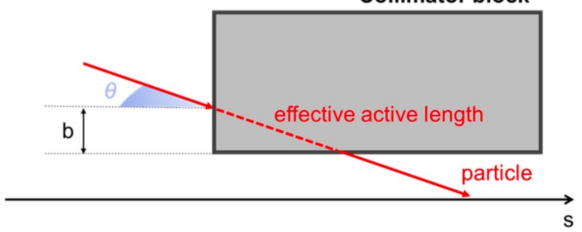


Beam losses in the MDI

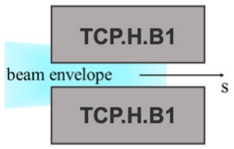
Evaluation of the halo collimation system performance
MDI beam losses (Xtrack-BDSIM)

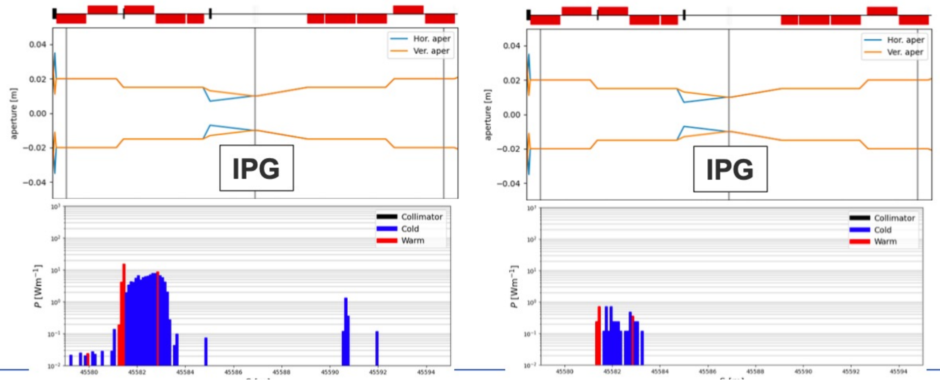
- **Parametric scan of the primary collimator length** indicates 25-30 cm TCP (Two radiation-length primary collimators)
- **Impact parameter scan** study

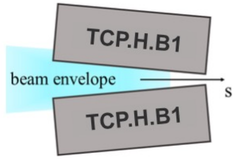
b: impact parameter
θ: angle of incidence



- 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"**







Giacomo Broggi

Synchrotron Radiation backgrounds

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

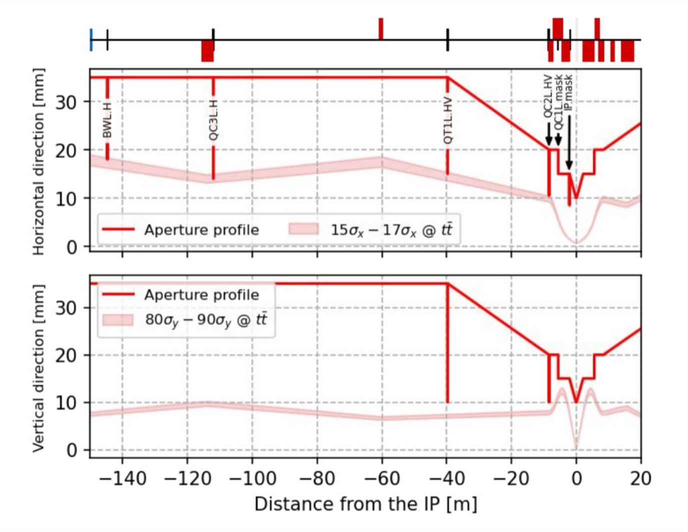
Characterisation of the SR produced for **all beam energies**.

SR produced upstream the IP:

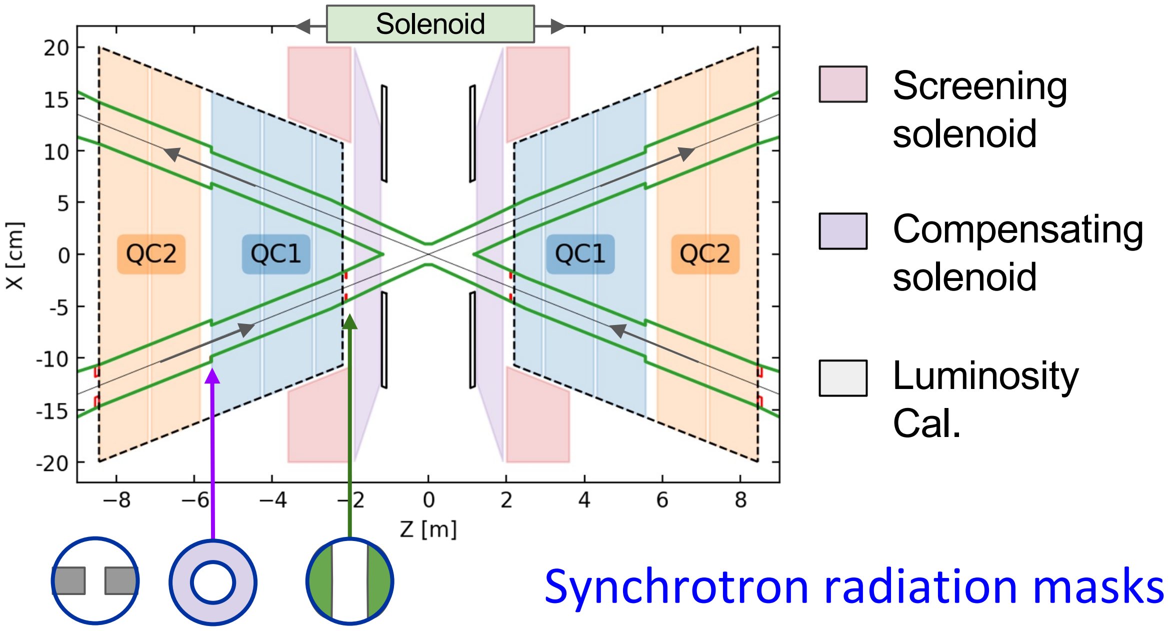
- by the **last dipoles and quadrupoles upstream the IR** can be a background source, to be collimated and masked
- by the **IR quads and solenoids** collinear with the beam and will hit the beam pipe at the first dipole after the IP.

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.

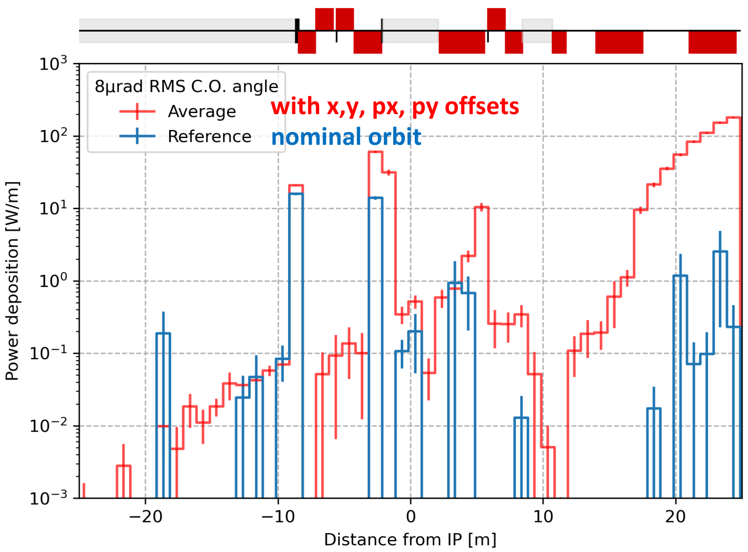


Synchrotron radiation collimators



Synchrotron radiation masks

Synchrotron Radiation backgrounds

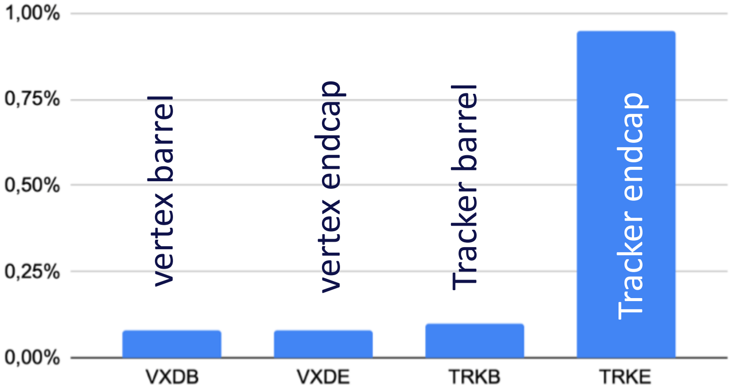


Power deposition from beam core for Z-mode

Blue is the reference closed orbit

Red is the average with possible soffsets due to misalignments

Maximum occupancy in subdetector/BX

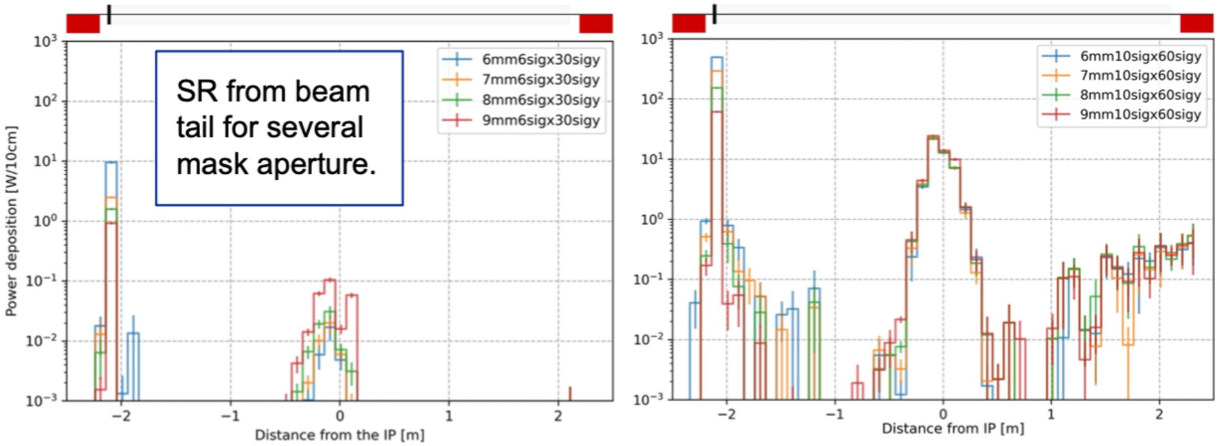


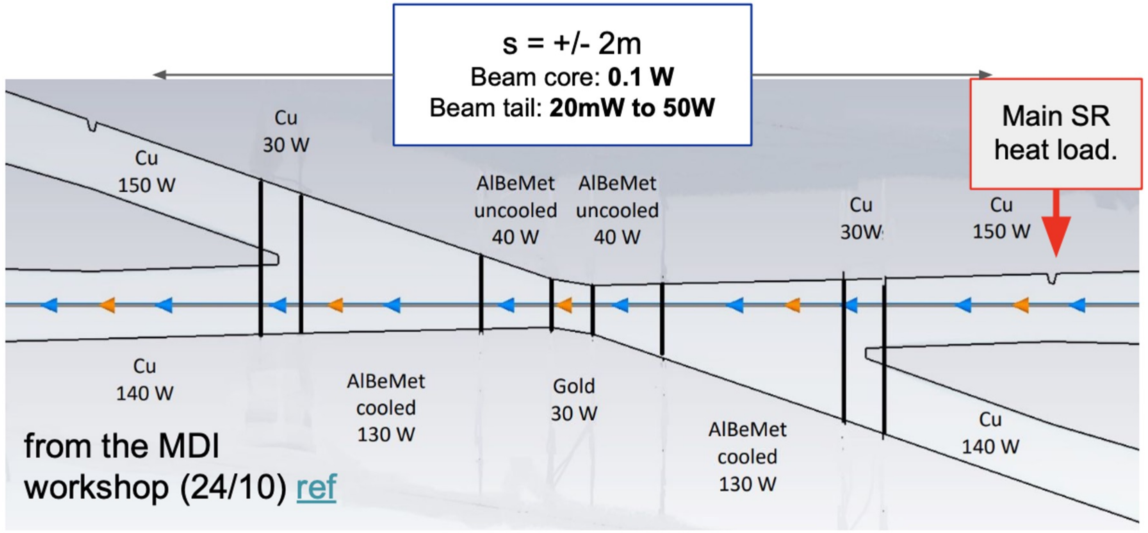
from beam tails hitting SR mask tips

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

A. Ciarma

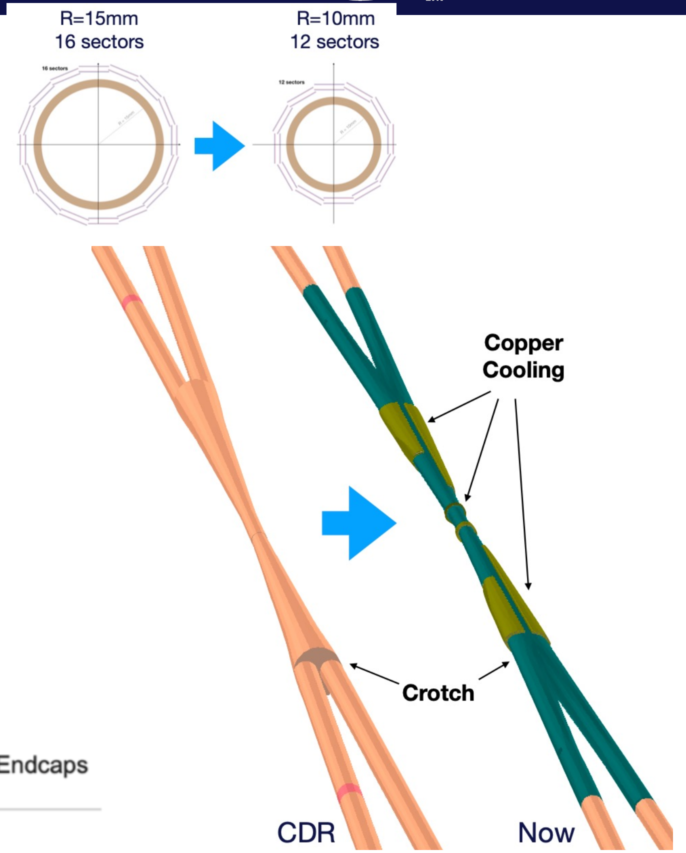
Heat load from beam halo synchrotron radiation





Heat Load from wakefields

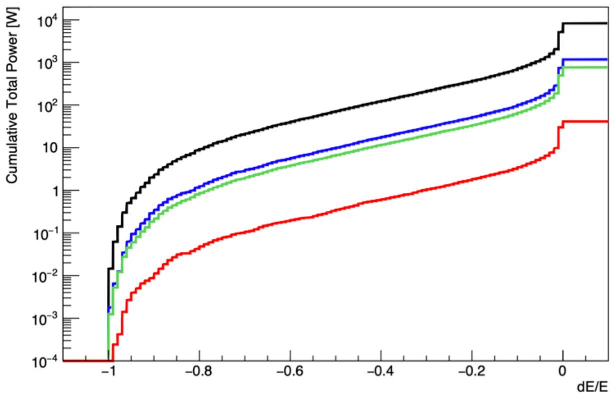
Detector background simulations



More realistic MDI software model implemented in key4hep:

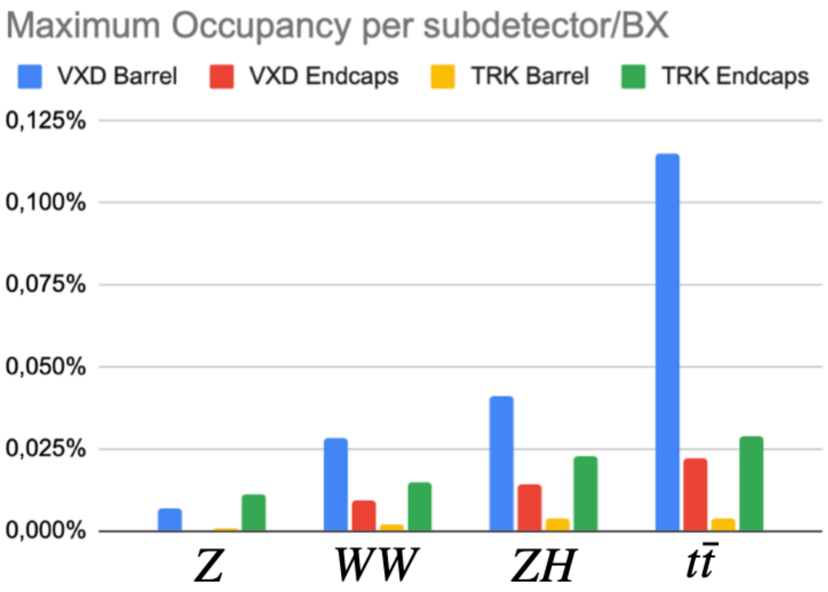
- CAD beam pipe
- lumical
- IR magnet and cryostat hollow shell
- CLD VXD adapted to the smaller 10mm radius beam pipe

Radiative Bhabha



	Energy Radiated [dE/E]	>2%	>10%	>50%
Power Carried by spent beam [W]	Z	1500	650	70
	WW	200	100	10
	ZH	150	60	6
	tt	8	3	0.3

Incoherent pairs creation

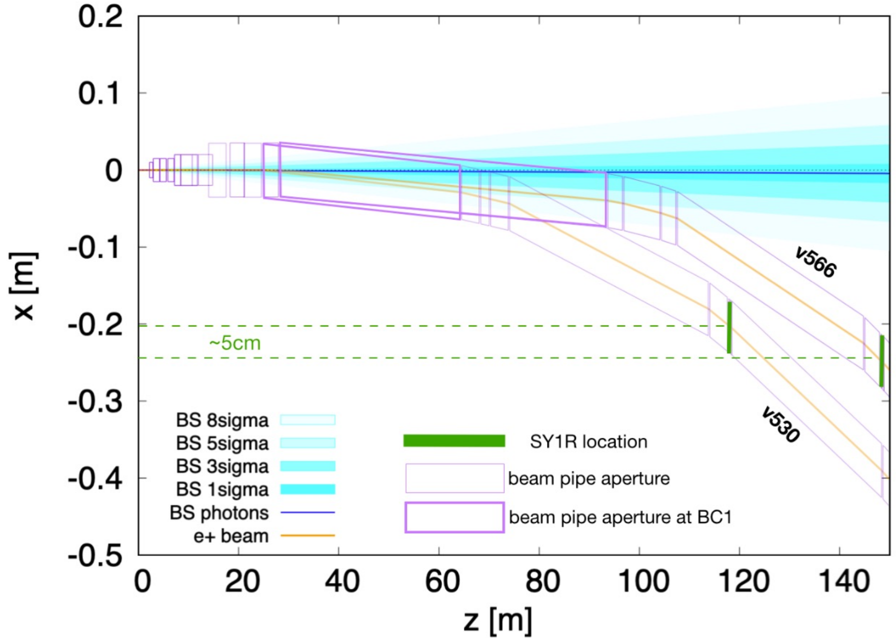


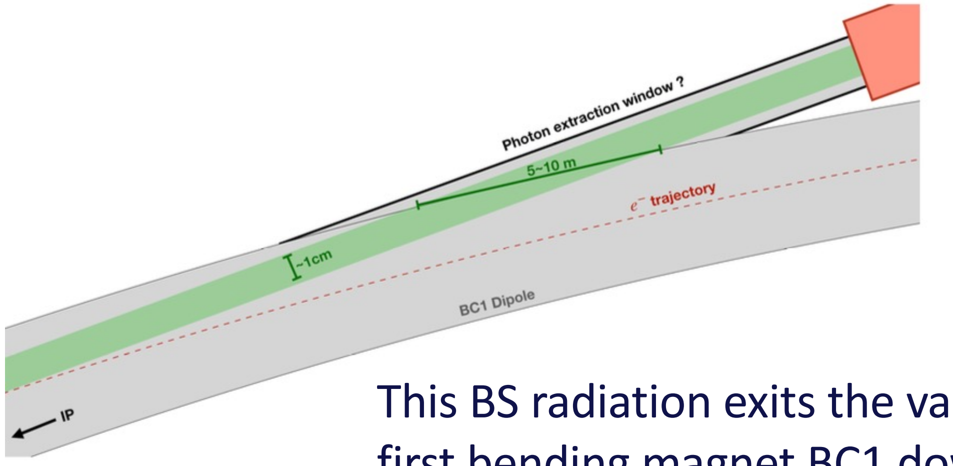
Beamstrahlung Radiation

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

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

Z-pole



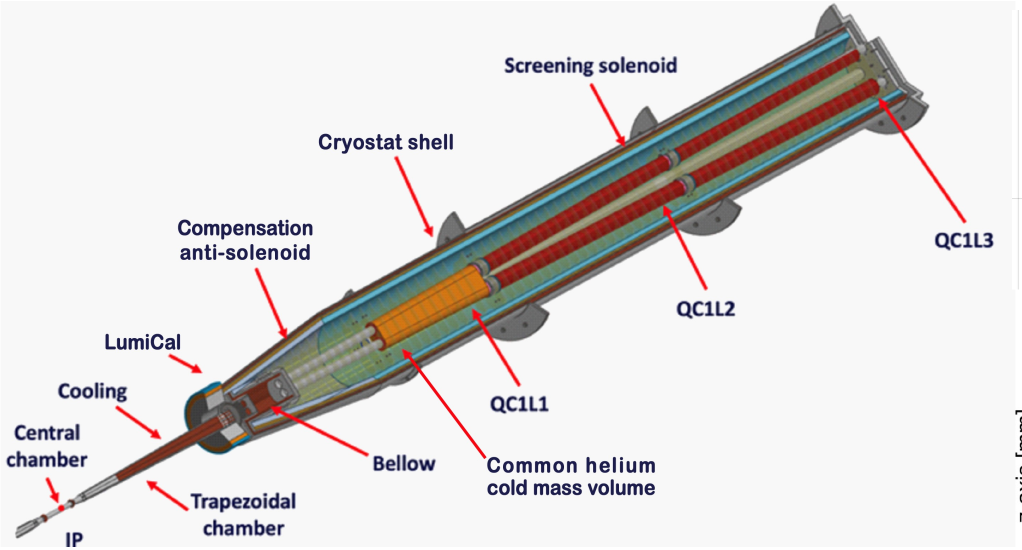


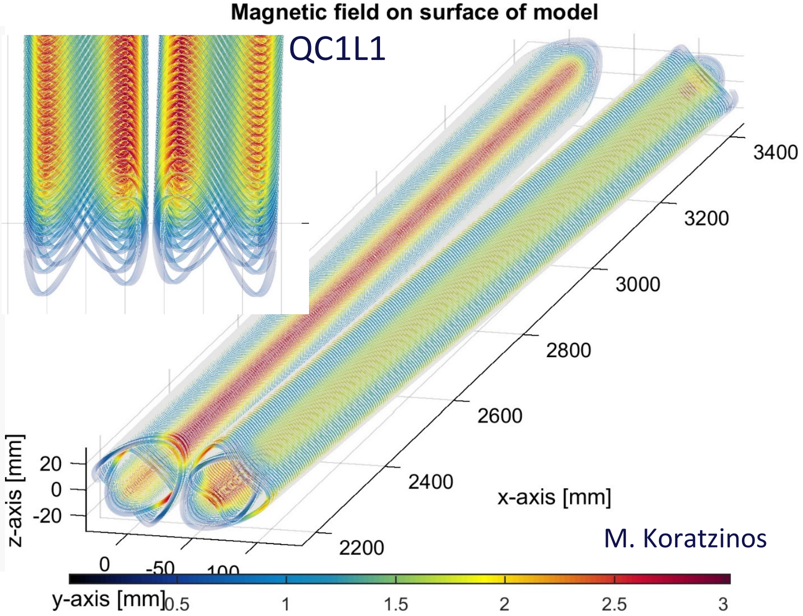
This BS radiation exits the vacuum chamber around the first bending magnet BC1 downstream the IP

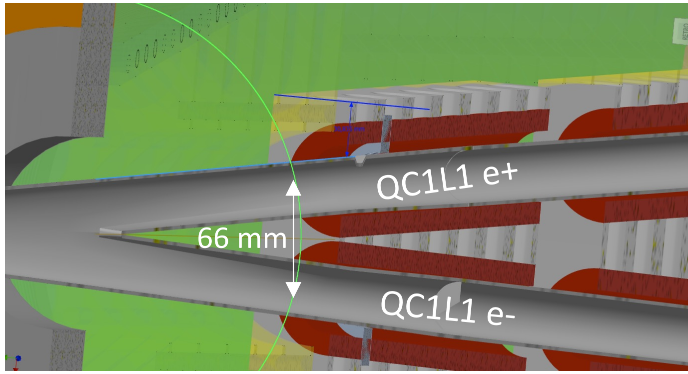
High-power beam dump needed to dispose of these BS photons + all the radiation from IP

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

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.

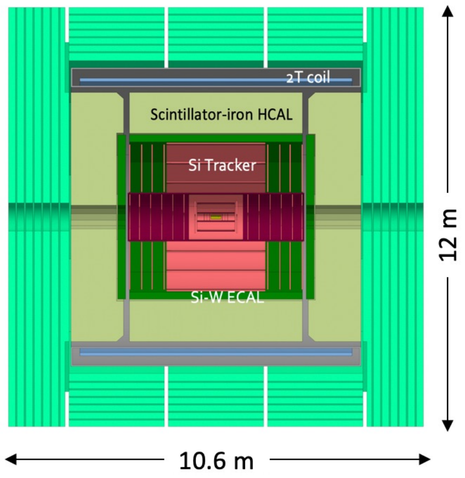
Significant progress on key aspects of the MDI design

- 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

Backup

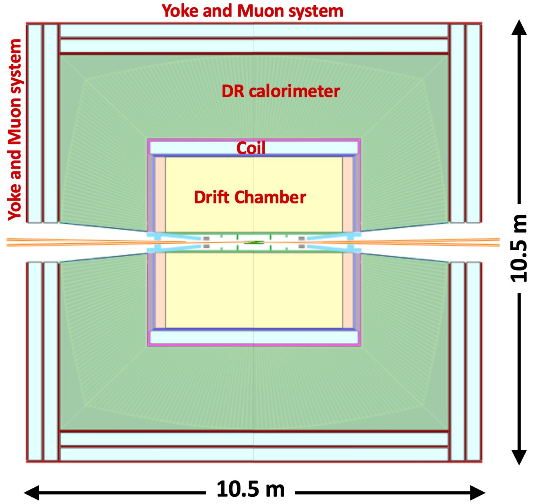
FCC-ee Detector Concepts

CLD

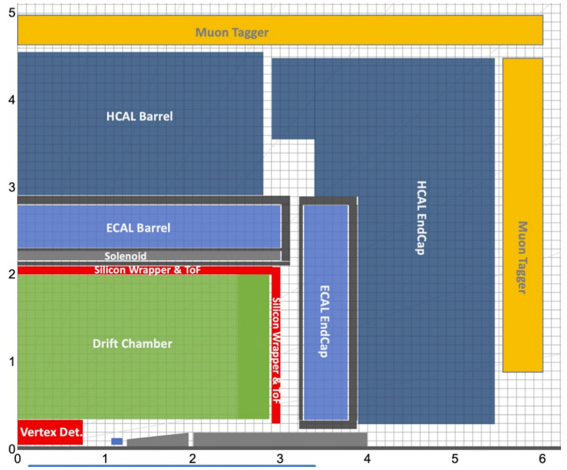


CDR

IDEA



Noble Liquid ECAL based



new

- 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

- 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;

- 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.