FUTURE CIRCULAR COLLIDER
Innovation Study

INFN LNF
Istituto Nazionale di Fisica Nucleare

INTERACTION REGION DESIGN OF THE FUTURE CIRCULAR COLLIDER FCC-EE

Manuela Boscolo (INFN-LNF)

Particular thanks to A. Abramov, K. André, A. Ciarma, F. Fransesini, A. Novokhatski, Frank Zimmermann

Second ECFA Workshop on e+e- Higgs / Electroweak / Top Factories
Paestum, 11-13 October 2023

Outline

- FCC-ee 4IPs design
- IR design
- Mechanical model of the IR
- Beam losses, Synchrotron Radiation, Beamstrahlung : impact and mitigation
- Next Steps

FCC-ee layout

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

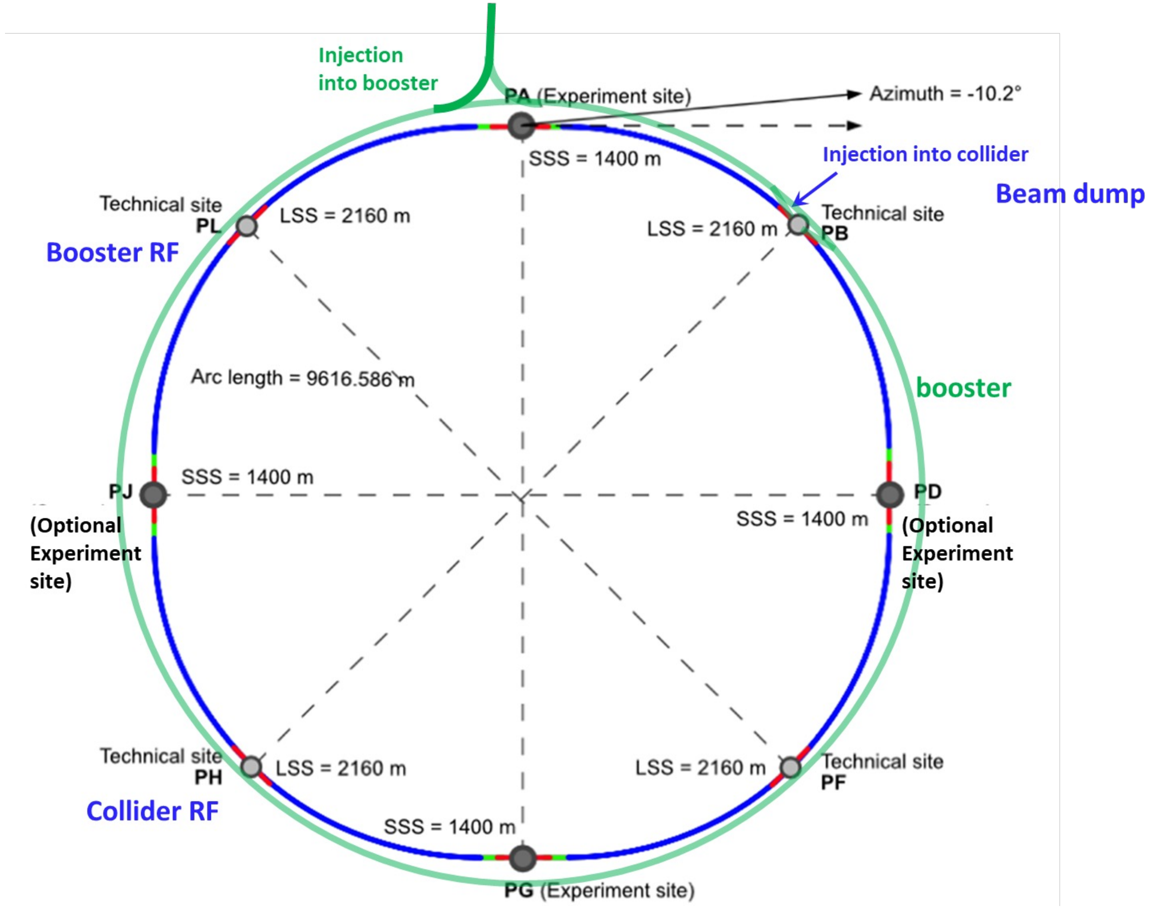
Common footprint with FCC-hh, except around IPs

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)

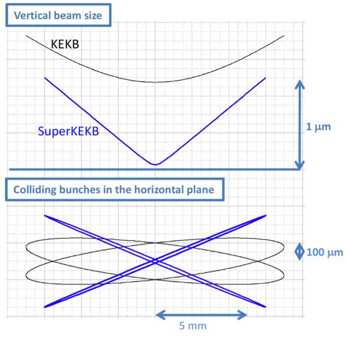


Figure 2: Schematic view of the nanobeam collision scheme.

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
	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

Accelerator Design

Well developed layout that will deliver (extremely) high luminosity Z → t-tbar

Design benefits from LEP, LHC, DAFNE, and B-factory experience as well as LC, EIC and CEPC development

Have detailed lattices for collider rings and booster
Full simulations of beam-beam effects
Working on alignment and correction strategies

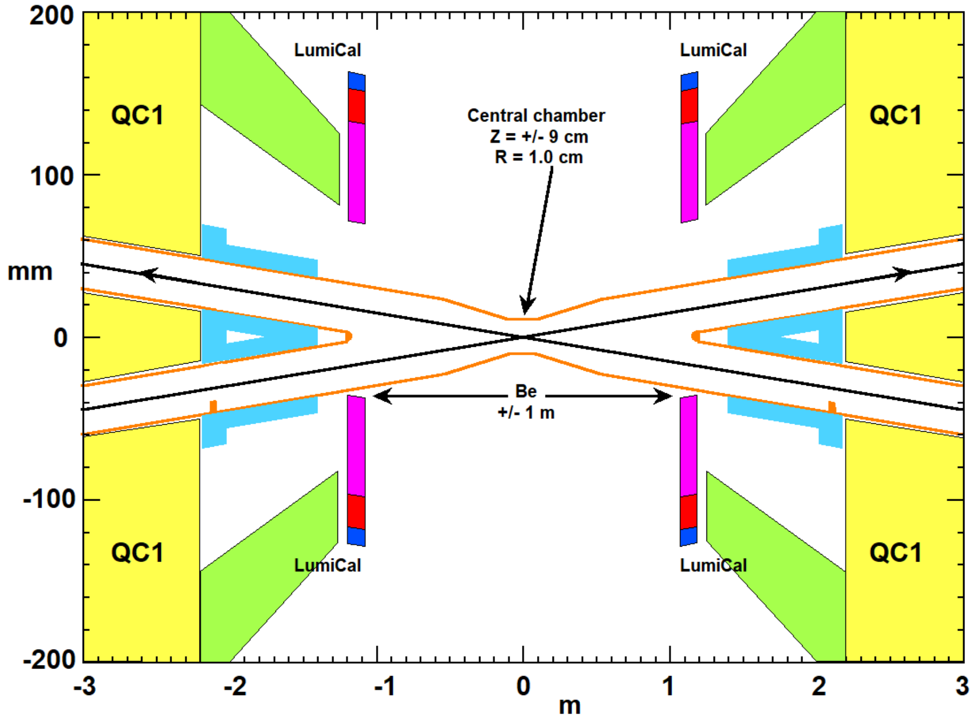
The accelerator has highly repetitive Arcs with challenging IRs

→ Develop prototype of half arc-cell

→ Develop IR mock-up

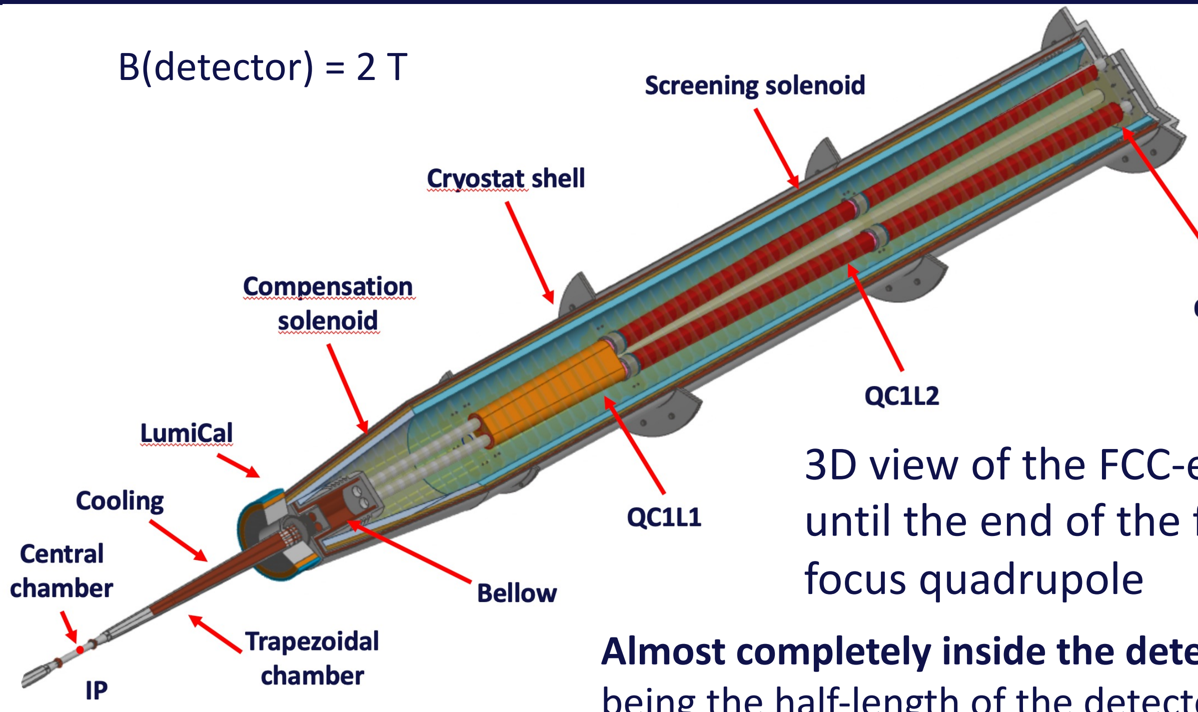
Most R&D is focused on optimizing systems for power efficiency & cost

FCC-ee Interaction Region



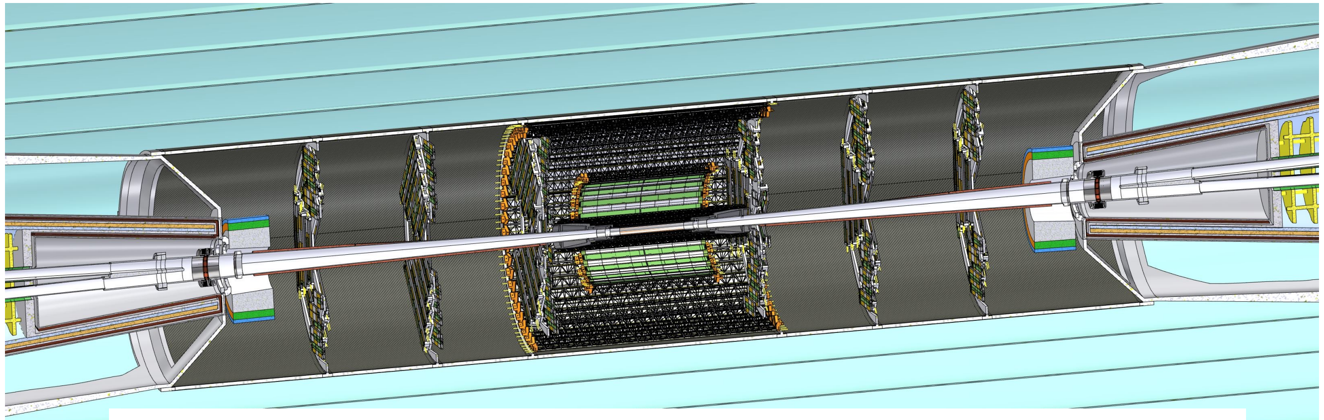
FCC-ee IR layout. The face of the first final focus quadrupole QC1, and the free length from the IP, L*, is 2.2 m. The 10 mm central radius is foreseen for ± 9 cm from the IP, and the two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP.

B(detector) = 2 T



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

Almost completely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at about 8.4 m.



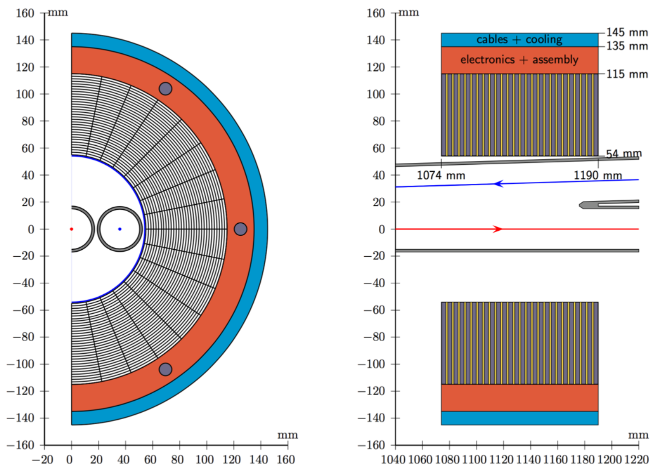
3D view of FCC-ee IR including the rigid support tube, vertex detector and outer trackers.

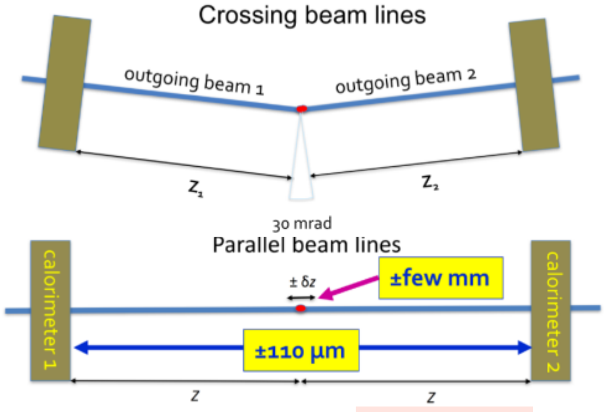
LumiCal constraints & requirements

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** wrt the outgoing pipe
- Requires **50-120 mrad clearance to avoid spoiling the measurement**
- The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines
- Requirements for alignment
  - few hundred μm in radial direction
  - few mm in longitudinal direction

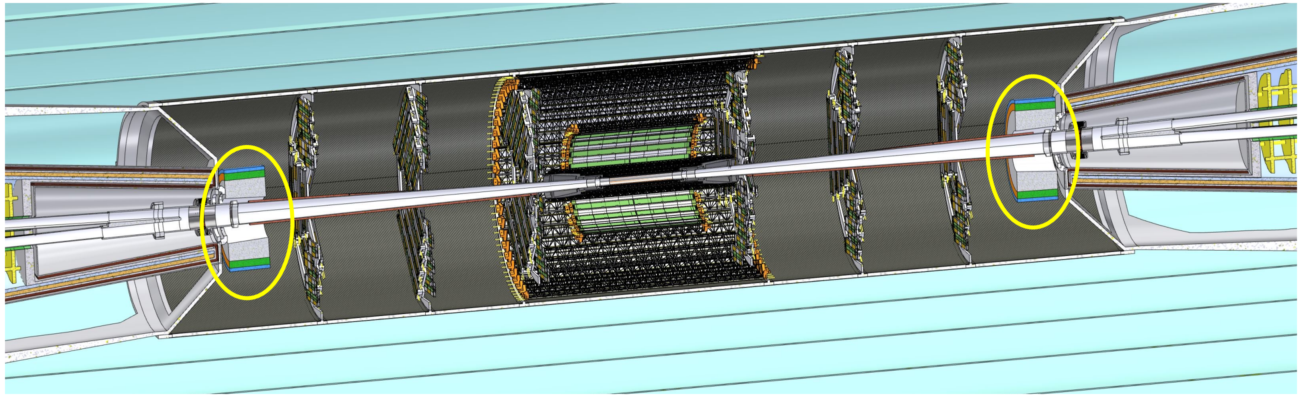




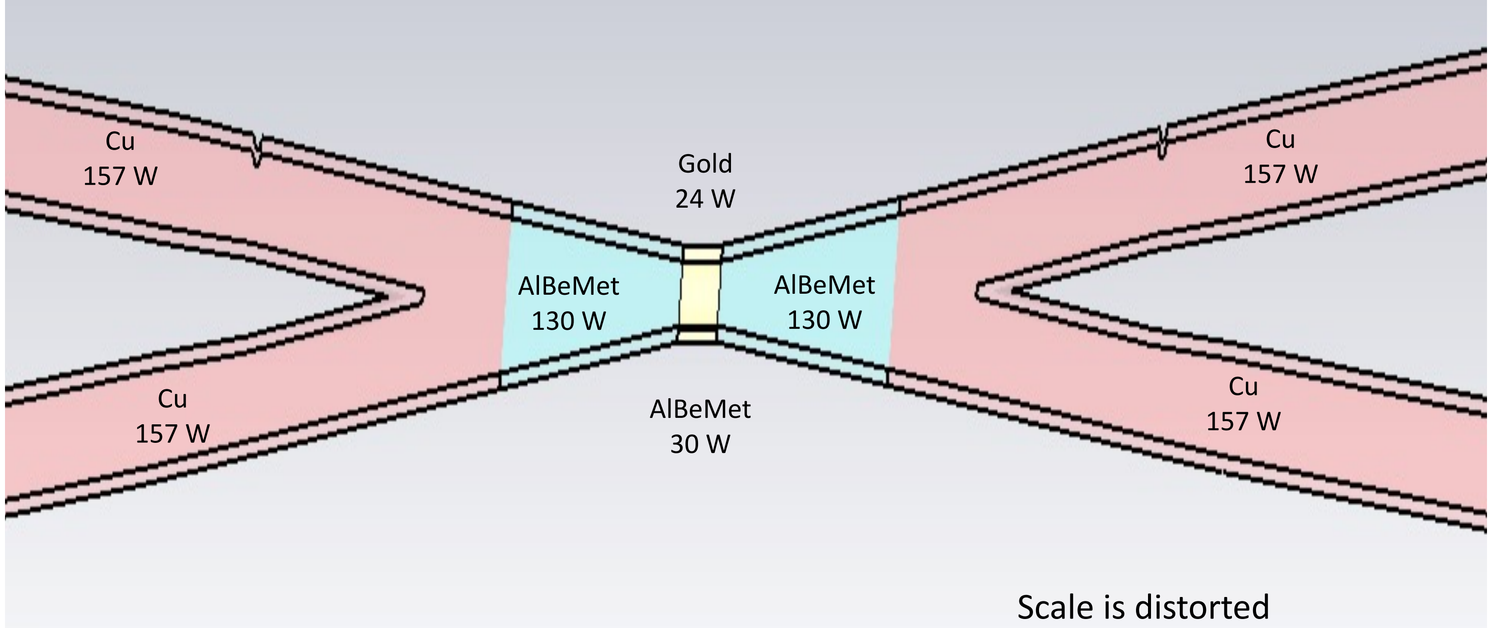
M. Dam

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



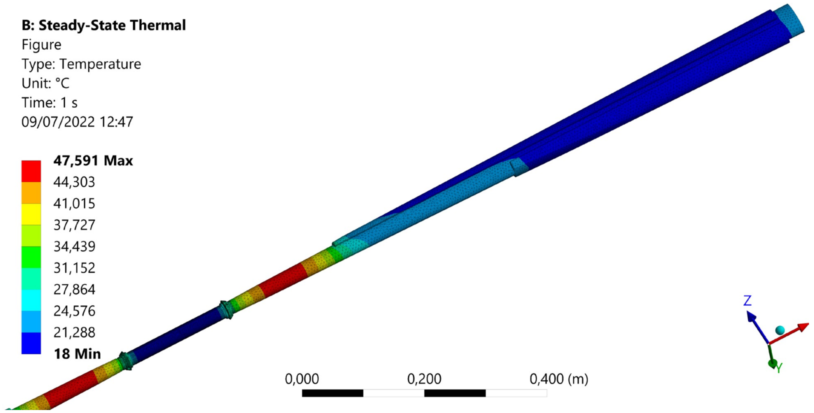
parameter	value
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

CST wakefields evaluations

Estimate heat load

⬇

Fed into ANSYS to dimension the cooling system

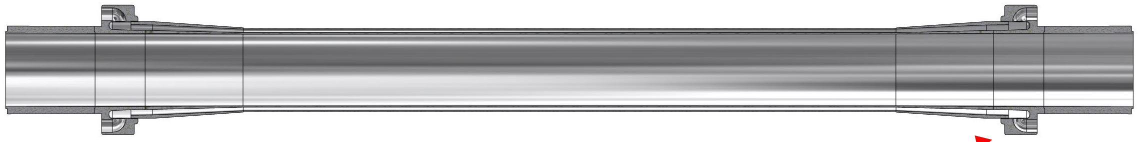


	trapezoidal chamber	central chamber
T_{max}	48°C	33°C
$T_{coolant}$	20.5 °C (paraffin)	20 °C (water)

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

Low impedance vacuum chamber warm and cooled

Central chamber

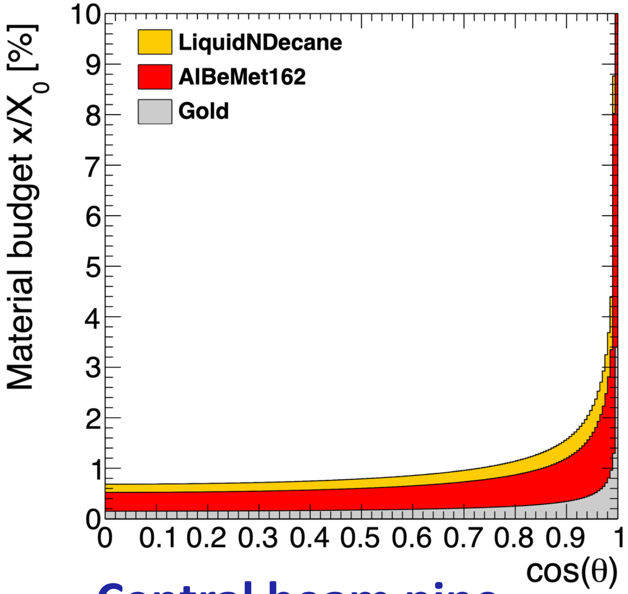


Inlet/outlet for paraffin cooling , all AlBemet, 180 mm long

Inner / Outer radius 10/ 11.7 mm

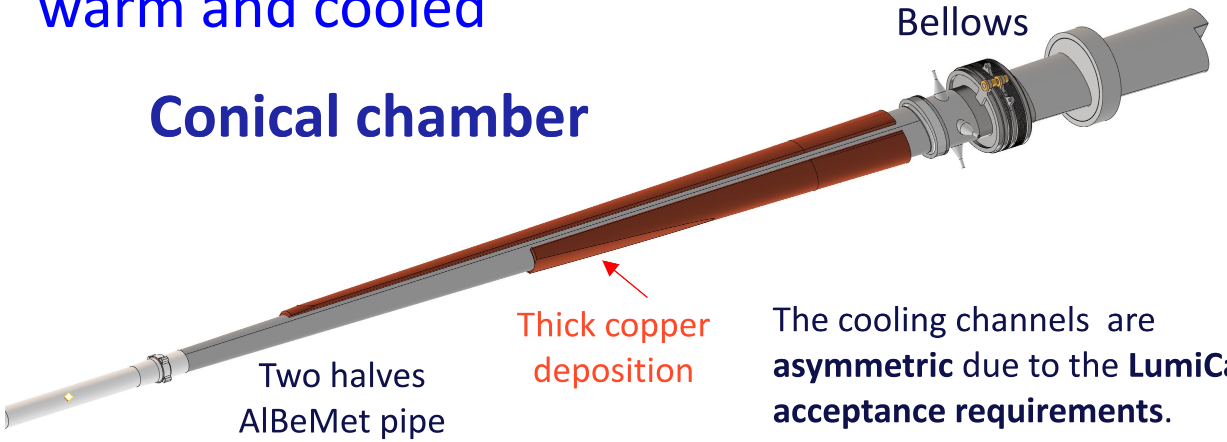
Material	thickness
AlBeMet162(*)	0.35 mm
Paraffin (coolant)	1 mm
AlBeMet162	0.35 mm
Au	5 µm

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

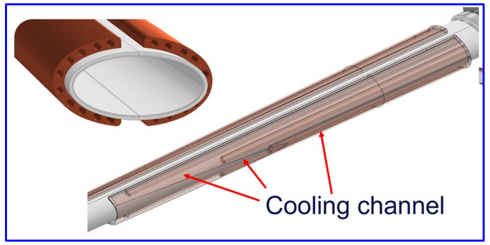


Central beam pipe material budget

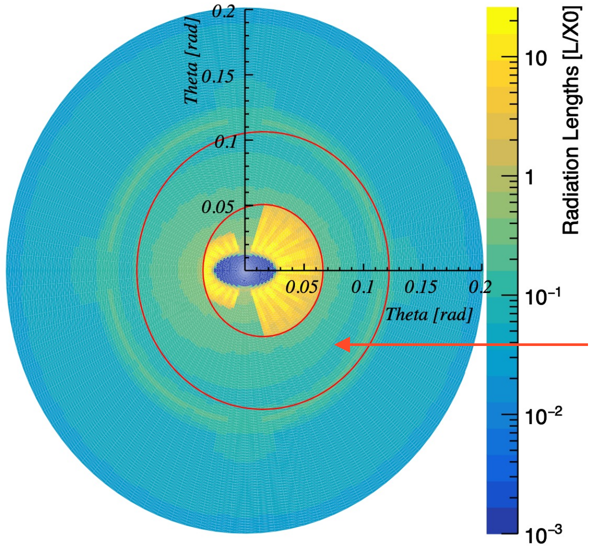
Conical chamber



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

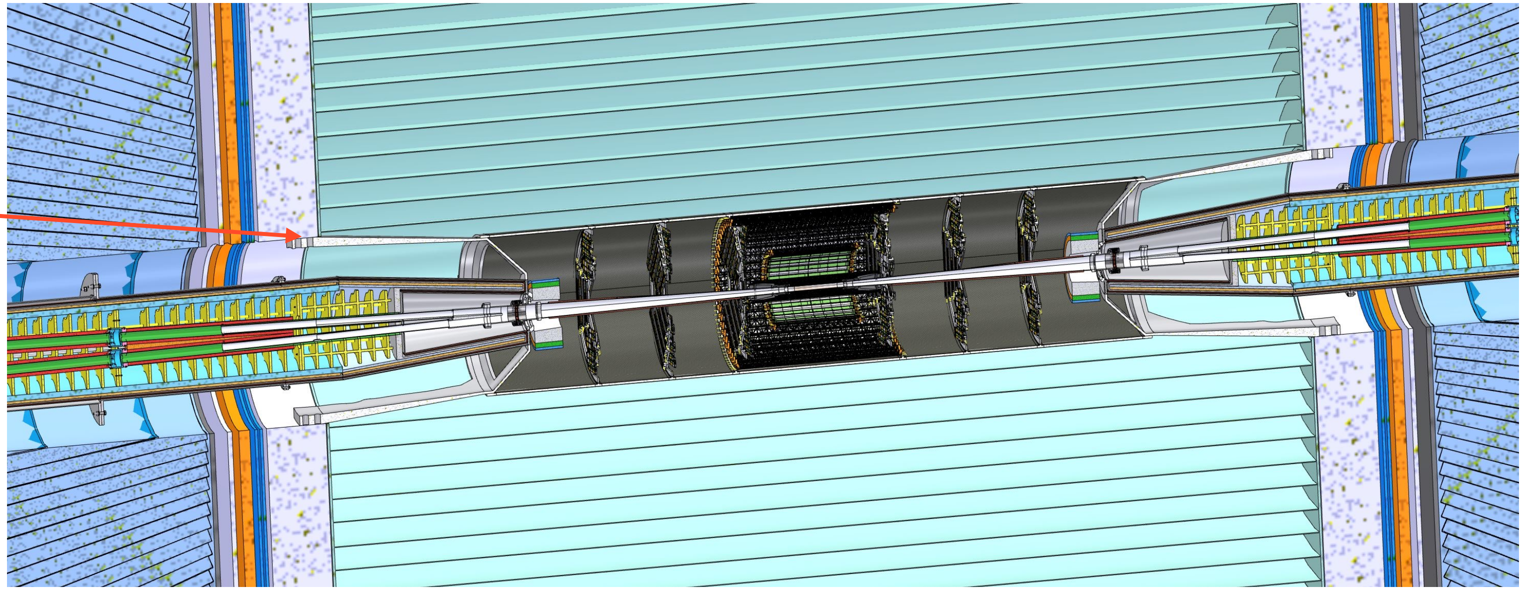
see talk by F. Palla

Central Support tube with endcaps

- **All elements in the interaction region -beam pipe, vertex, tracker disks, LumiCal- are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment**.
- The support tube is a **carbon-fiber lightweight rigid structure**.
- This study has been performed for the **IDEA** detector, and it works also for ALEGRO (ECAL based)

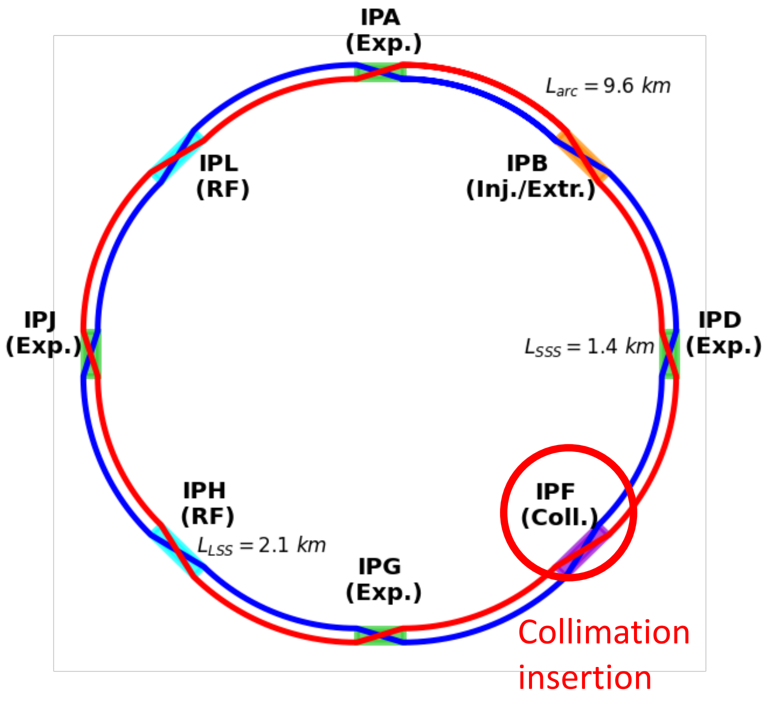
Integration of the support tube with the detector

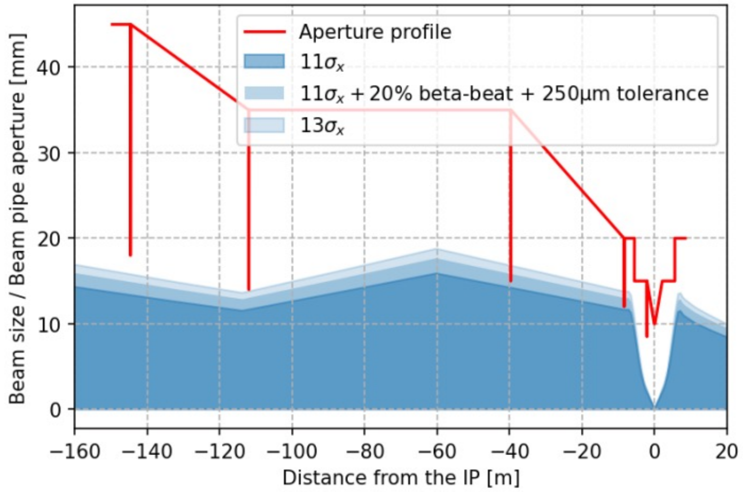
- Anchoring points with the detector is under study → we are investigating the anchorage to the calorimeter
- Required space for vertex and tracker detector services is under study

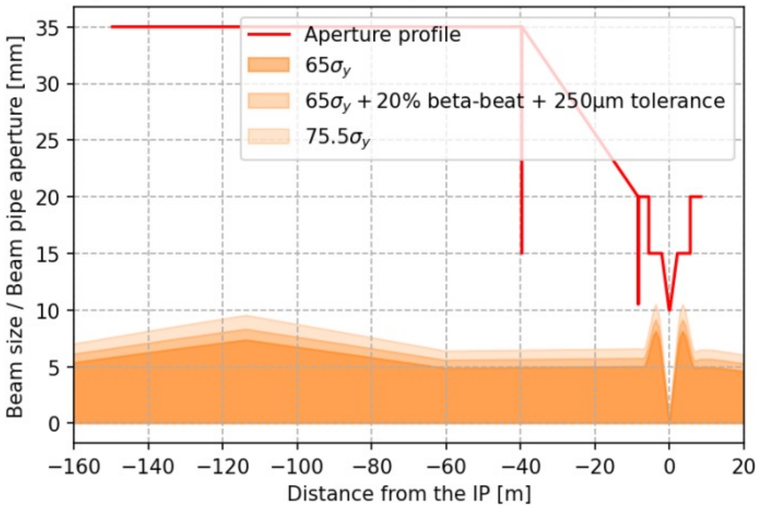


Main Ring Collimation

- **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

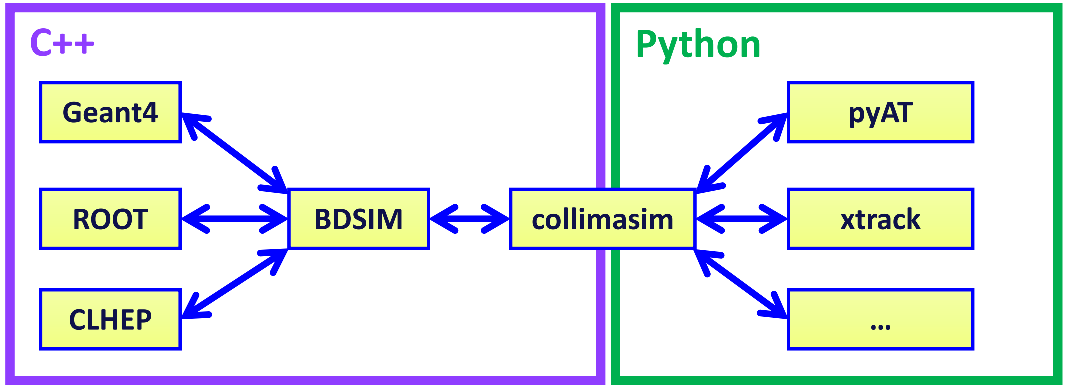






Main Ring Collimation

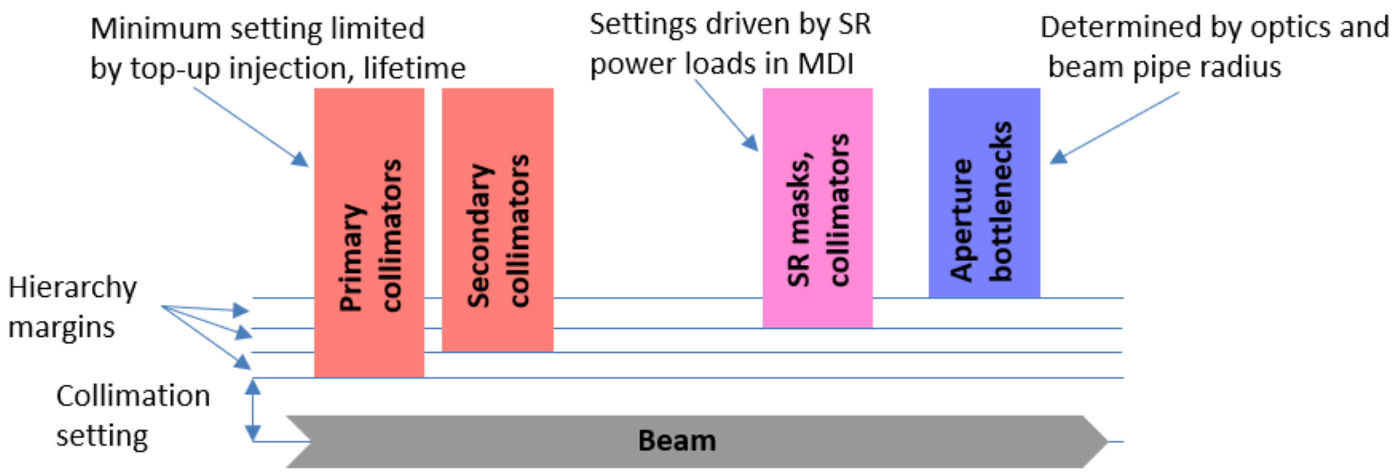
Complete simulation package for modeling performance in FCC-ee and FCC-hh (these tools are now being used at EIC as well)



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



Synchrotron Radiation backgrounds

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

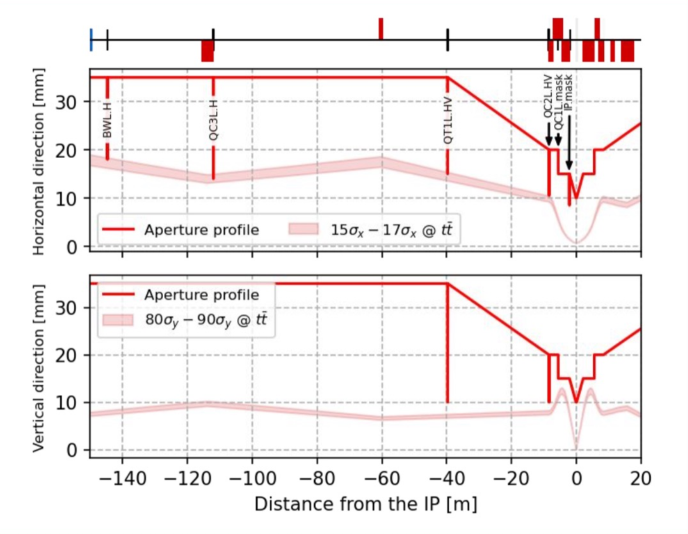
Characterisation of the SR produced for **all beam energies**.

SR produced upstream the IP:

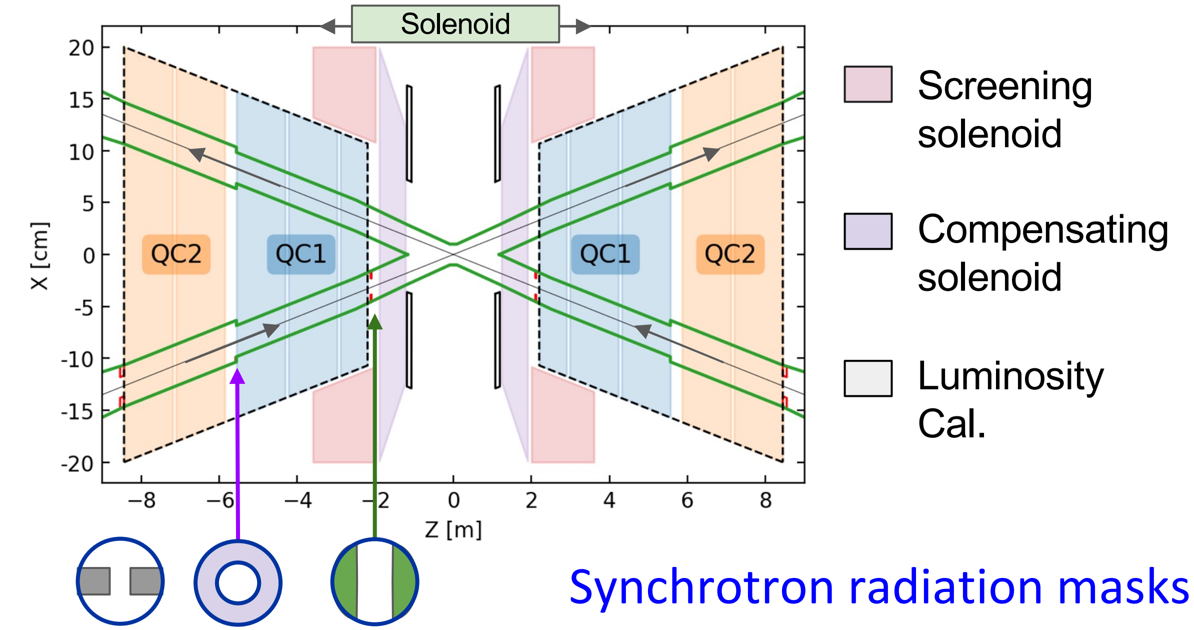
- by the **last dipoles and quadrupoles upstream the IR** can be a background source, to be collimated and masked
- by the **IR quads and solenoids** collinear with the beam and will hit the beam pipe at the first dipole after the IP.

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.

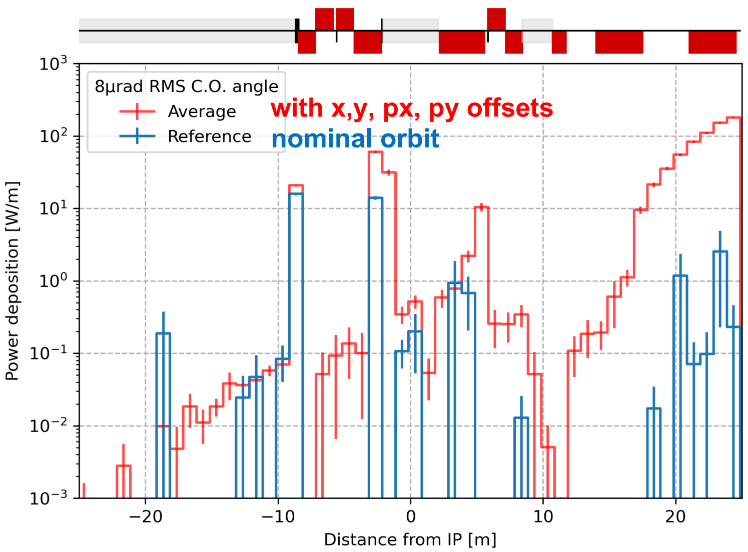


Synchrotron radiation collimators



Synchrotron radiation masks

Synchrotron Radiation backgrounds

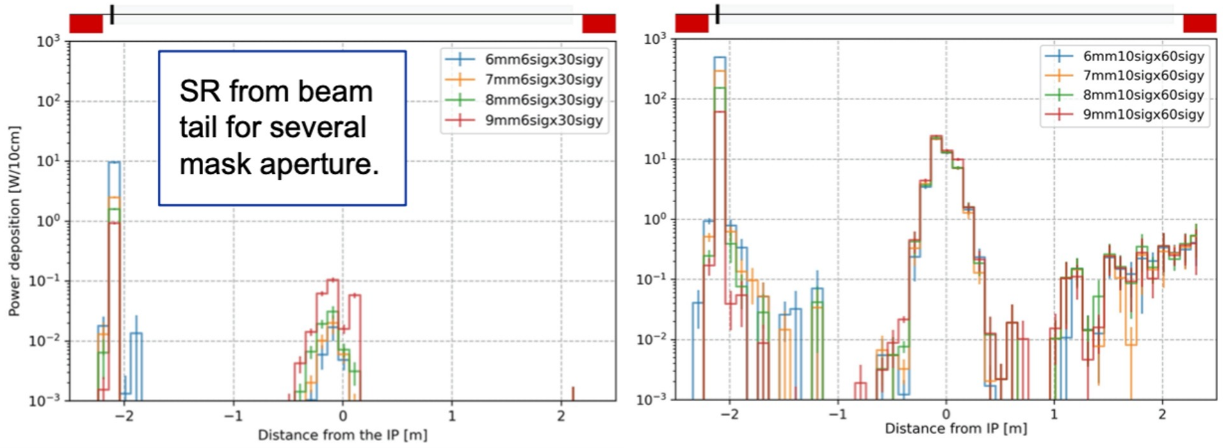


Power deposition from beam core for Z-mode

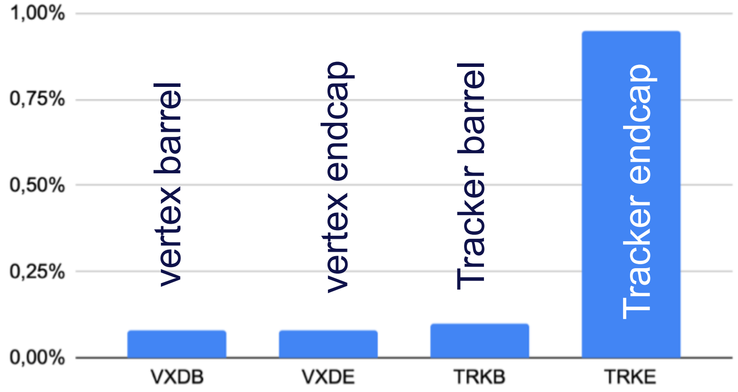
Blue is the reference closed orbit

Red is the average with possible soffsets due to misalignments

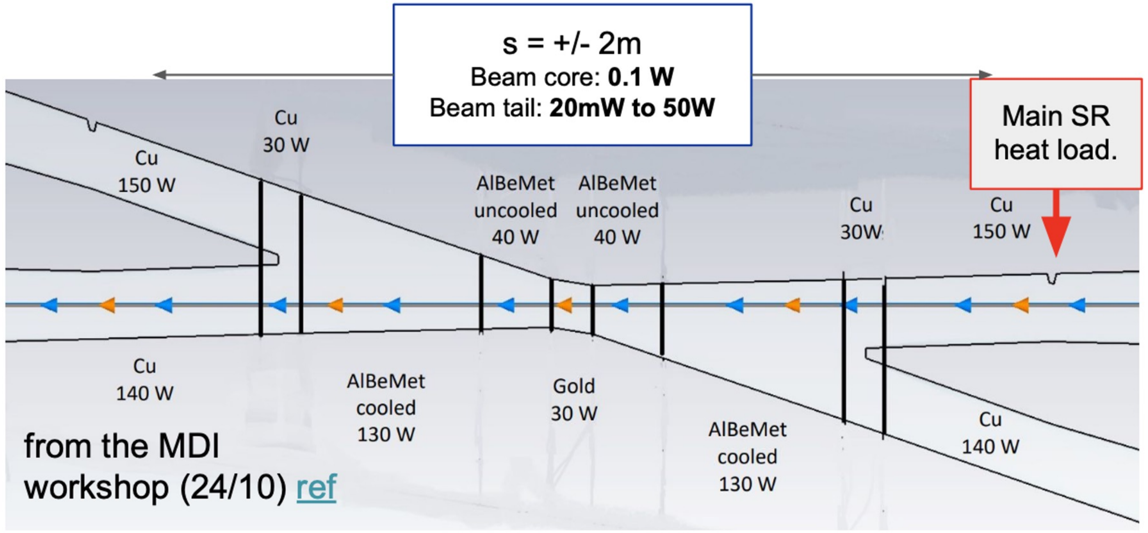
Heat load from beam halo synchrotron radiation



Maximum occupancy in subdetector/BX



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

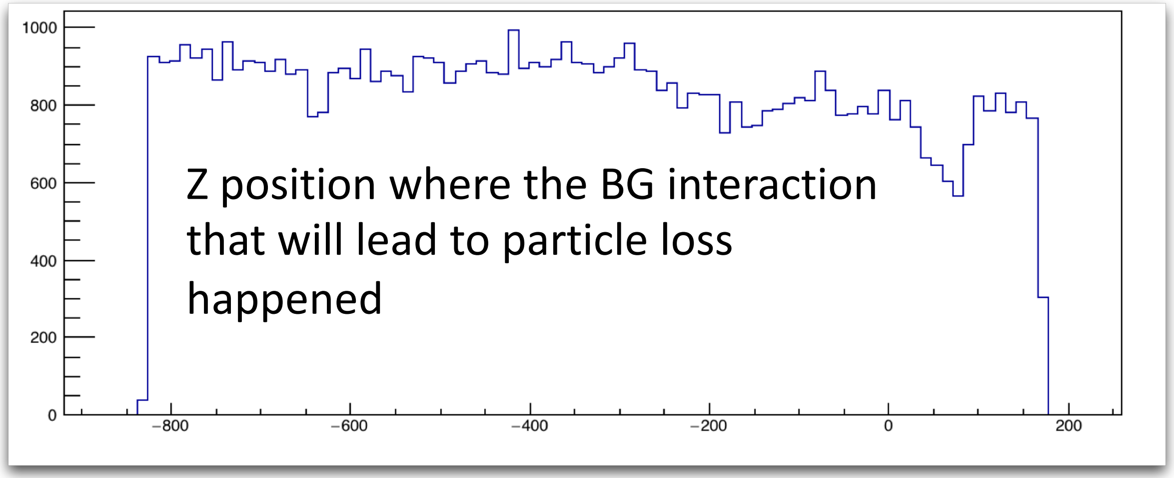


Heat Load from wakefields

Inelastic Beam Gas scattering in the IR

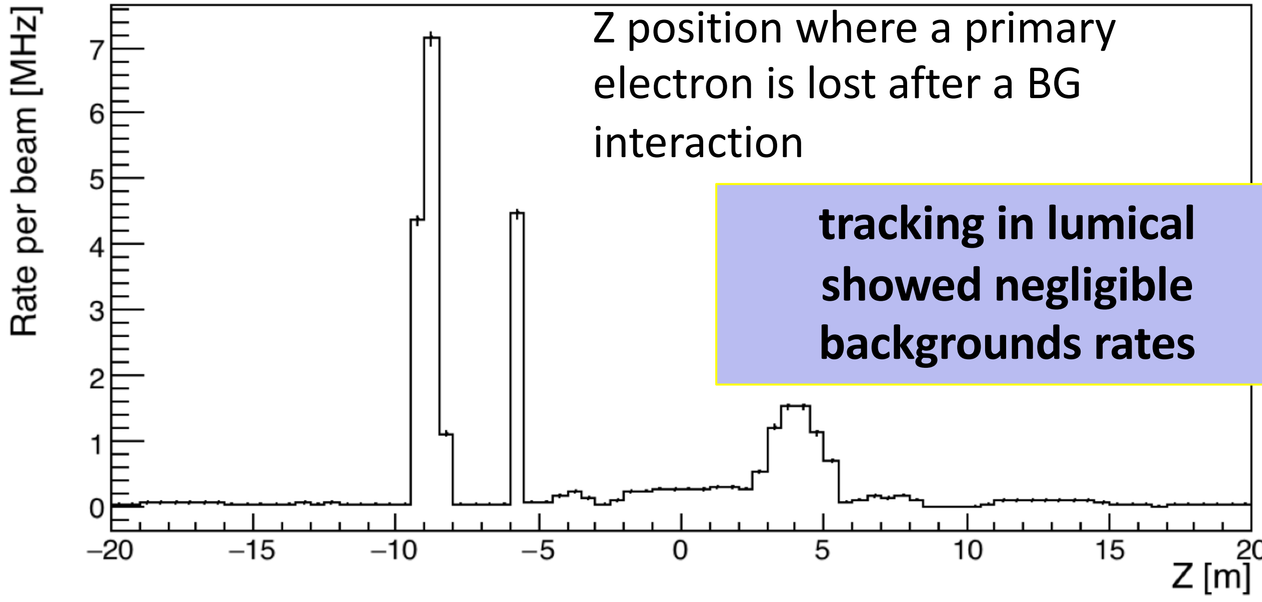
CDR study, to be updated

MDISim was used to import in Geant4 beam pipe geometry + magnetic elements + beam characteristics

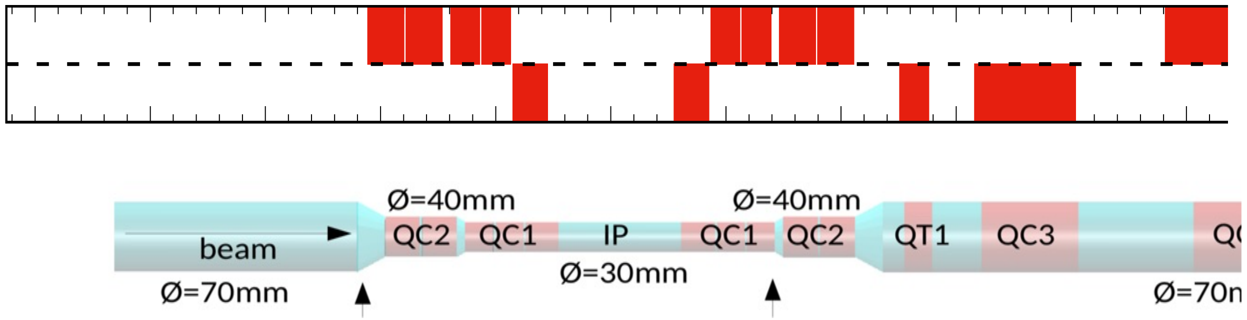


IR Loss map

N_2 and 10^{-7} Pa, 300 K



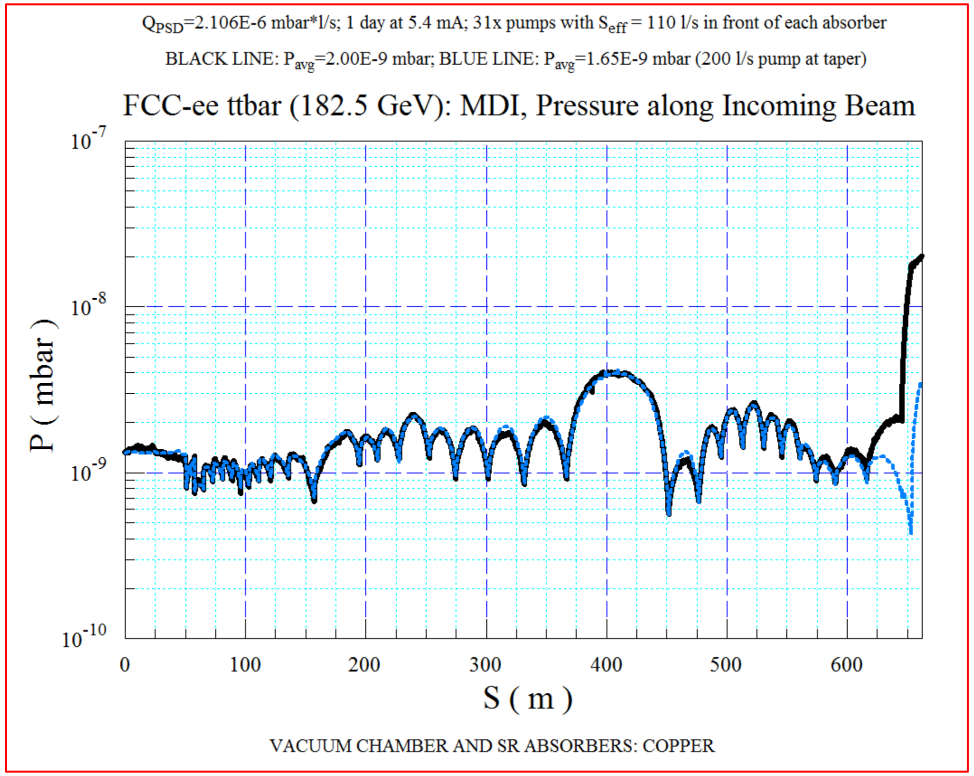
tracking in lumical showed negligible backgrounds rates

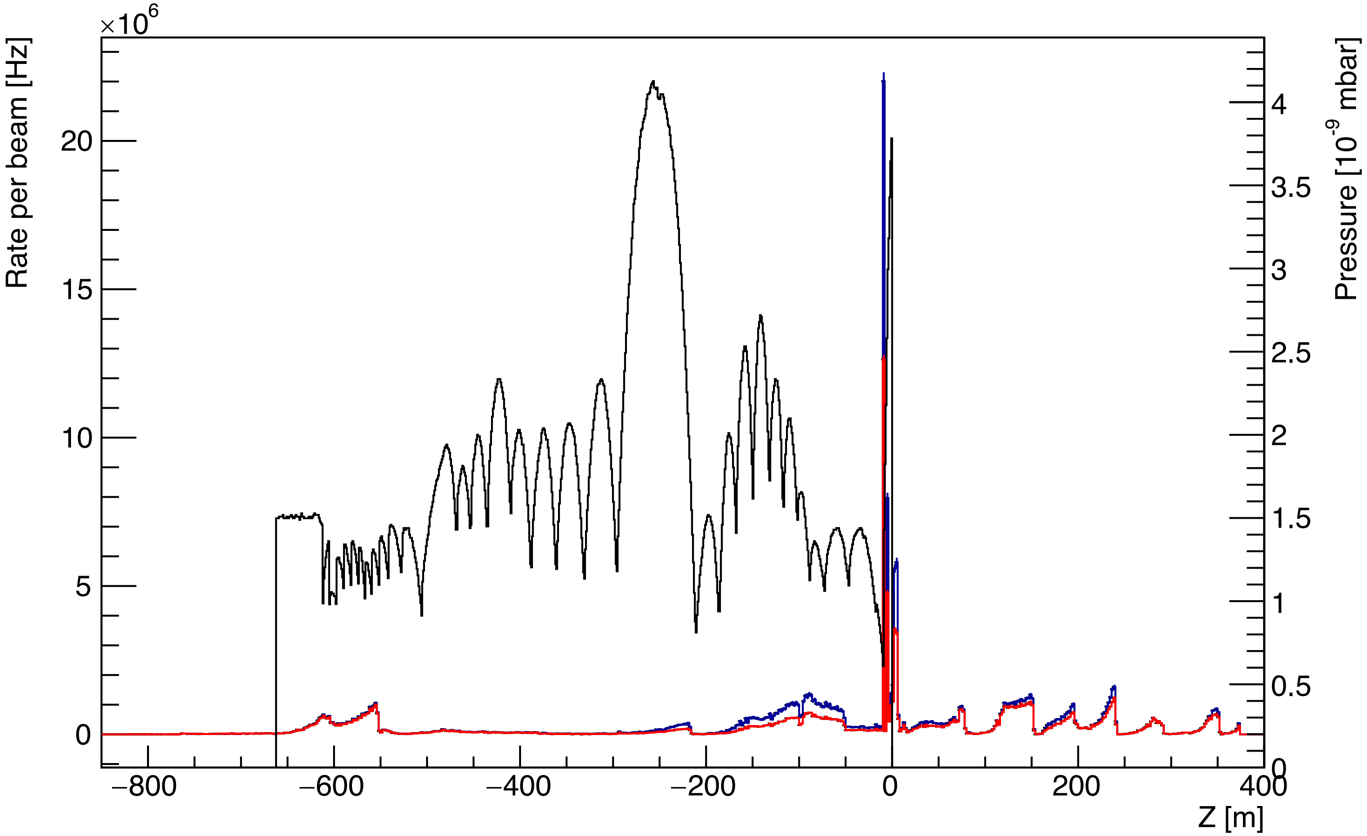


Case	I [mA]	Loss Rate +/-20m from IP [MHz]	Lifetime [hours]
Z	1390	147	42
W	147	16	53
H	29	3	56
ttbar	5.4	0.5	59

Local pressure variations and beam-gas simulation

CDR study, to be updated





- The figure shows the pressure profile for the T-pole at 182.5 GeV, after a vacuum conditioning of 1 day at full current (5.4 mA)
- The blue curve assumes a higher pumping speed at the taper placed immediately before the QC2L2 final-focus quadrupole: it helps decrease the pressure bump near the IP

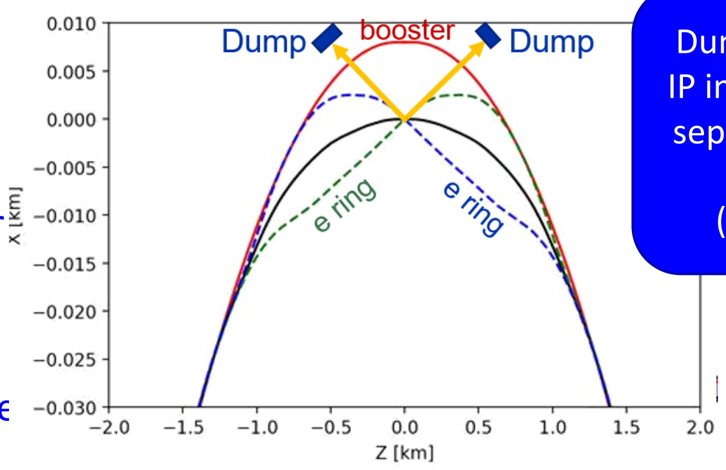
Loss map (left axis):
blue: accounting for local pressure profile
red: constant pressure profile

Beamstrahlung Dumps

FUTURE CIRCULAR COLLIDER

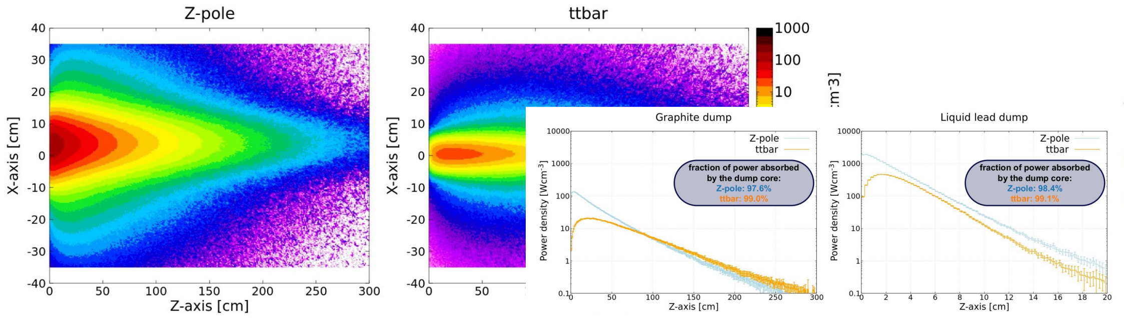
Two 400 kW dumps are needed at each IP to accommodate the high power beamstrahlung

- **High-power dumps needed to safely dispose of the high photon flux from IP**
- **Challenges for the dump design:**
  - High-power density (MeV photons) → challenging for absorber material and windows
  - Activation (through photo-nuclear interactions)!
  - Radiation environment around dump (ionizing dose to equipme radiation to electronics)



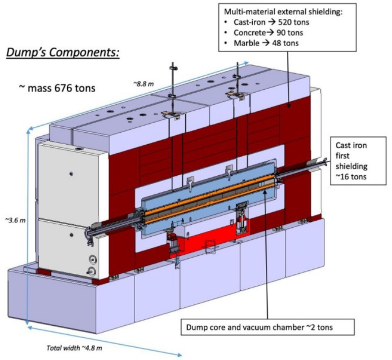
Dump placed 500 m from IP in order to have enough separation from booster / collider
(space for shielding)

First considerations on radiation fields/power deposition, but more studies and R&D needed to develop a conceptual dump design and shielding – liquid metal considered as core material



High-power beam dumps - example

SPS beam dump, designed for 300 kW in the most demanding scenario



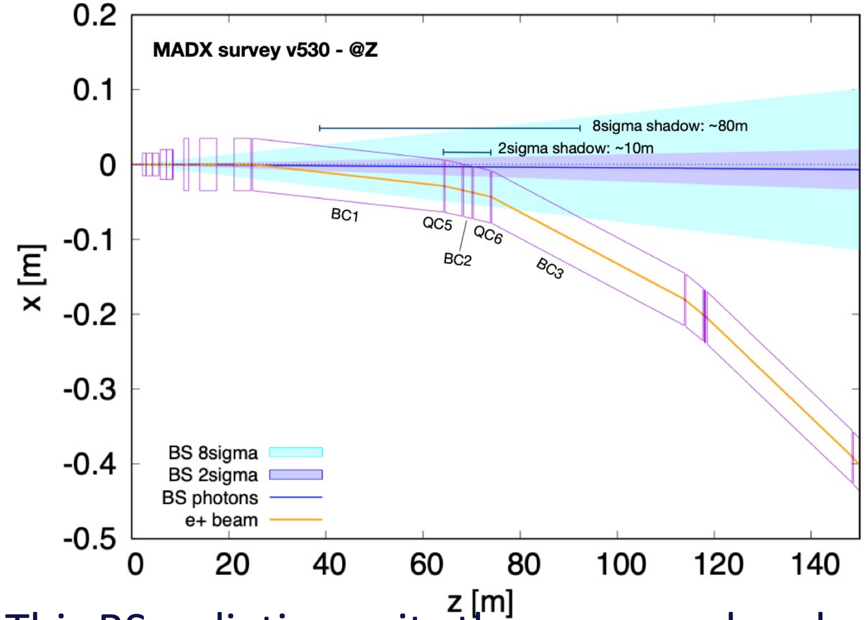
Beamstrahlung Photon Dump

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

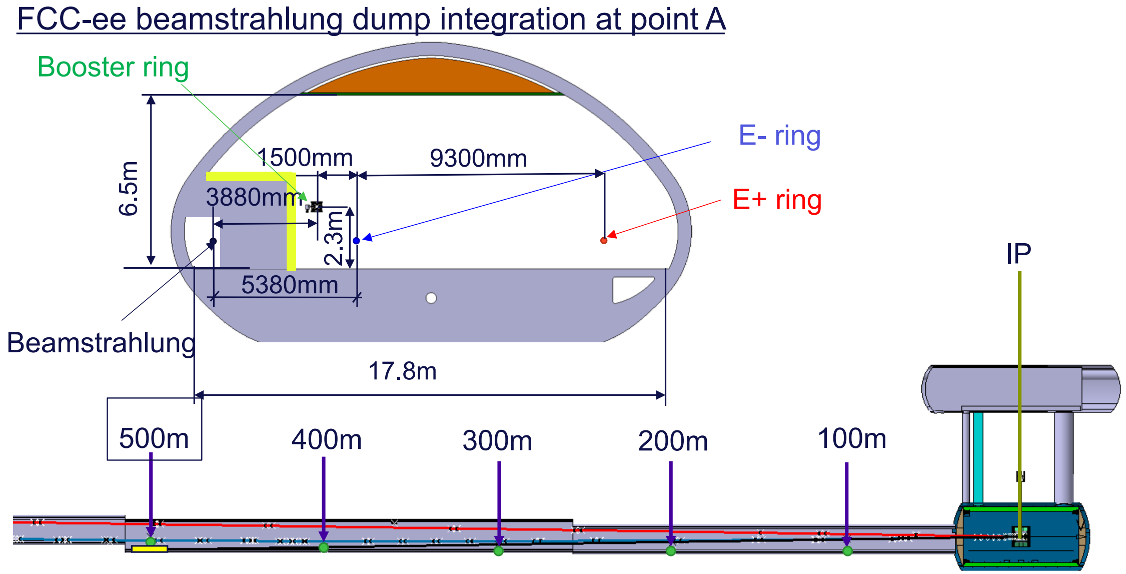
GuineaPig++

Radiation from the colliding beams is very intense 400 kW at Z

Synchrotron Radiation from the fringe solenoid and anti-solenoid is ~ 77 kW



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

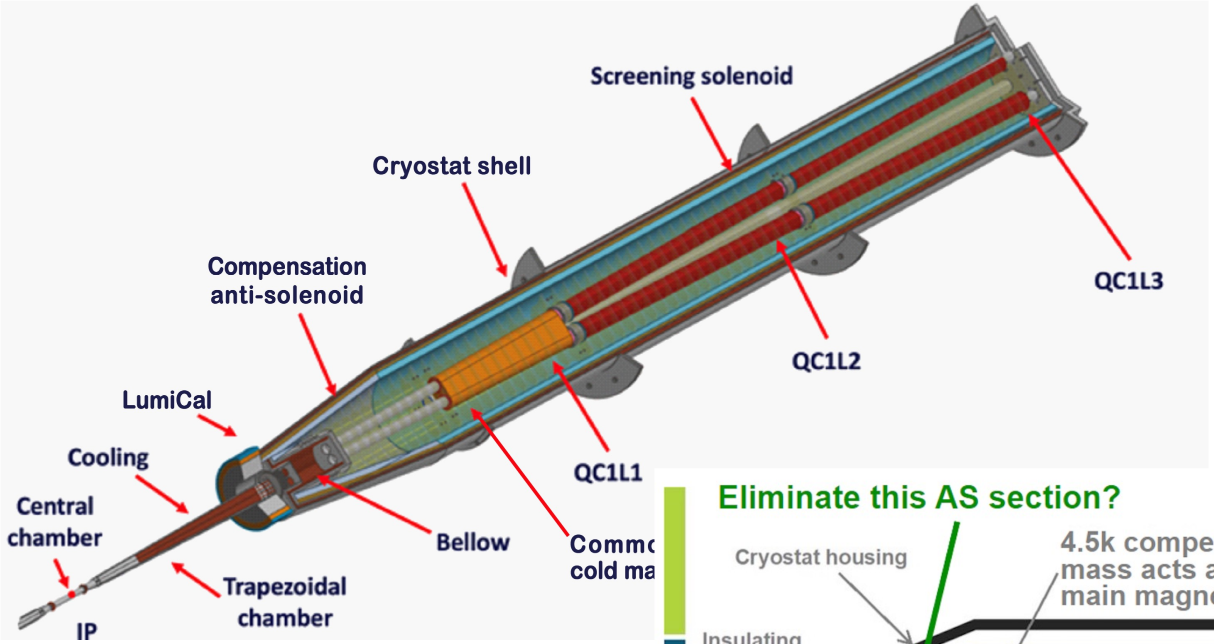


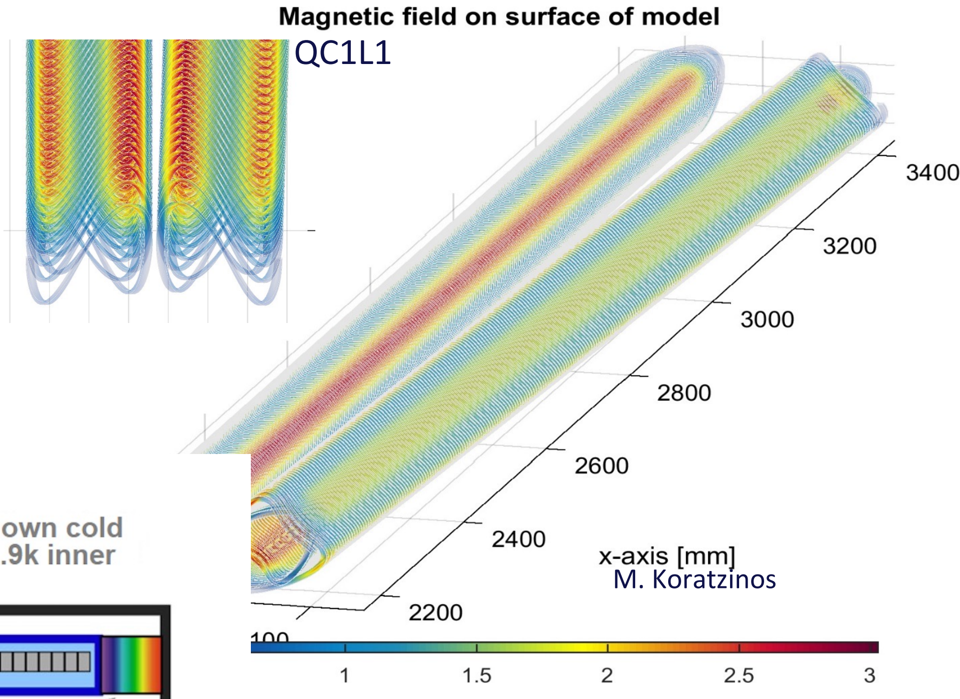
High-power beam dump needed to dispose of these BS photons + all the radiation from IP

- liquid lead target as dump absorber material is under investigation
- Shielding needed for equipment and personnel protection for radiation environment

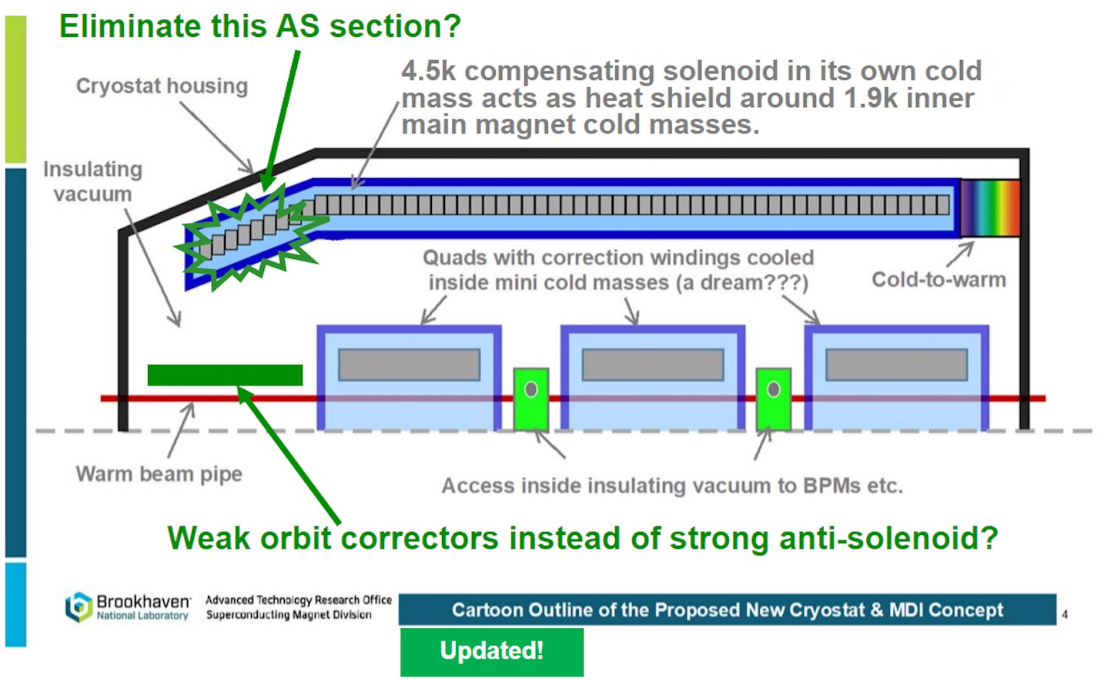
FCC-ee IR Magnets

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





Magnets have 2cm radius. More like LC final quads than LHC. Ongoing collaboration with BNL on direct-wind tech.



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

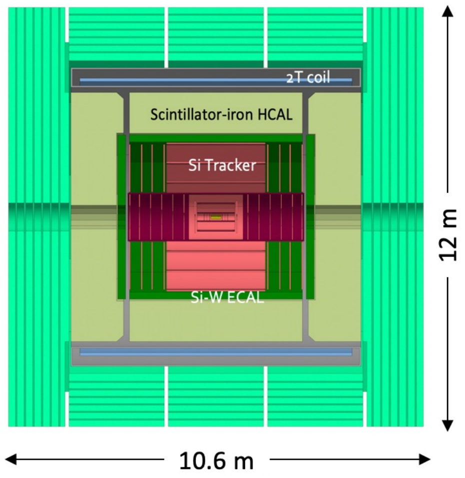
Summary

- **FCC-ee has highest luminosity at Z, W and H@240 GeV of all proposed factories**
- **Feasibility Study is under the Mid-Term review with a ‘complete’ design**
  - Beam optics and beam physics, inc. collective effects, addressing major challenges
  - Describe high-cost technical systems, e.g. SRF, arc magnets, vacuum, …
  - Layout identified to ensure complete civil / infrastructure cost estimates
  - Alternative options and R&D identified to further improve performance / cost
- **Based on 60 years of experience with circular e^+e^- colliders, some of which currently in operation, hence no need for a large demonstrator facility**
  - Super KEKB and EIC will provide important information
  - R&D on components focused on improved performance, increased efficiency, industrialization, cost aspects, sustainability and minimizing environmental impact
  - R&D timelines are consistent with construction in 2030’s
- **Very significant progress over the last two years!**

Backup

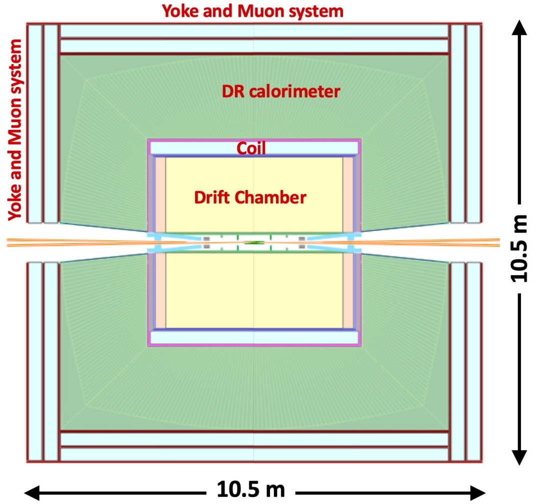
FCC-ee Detector Concepts

CLD

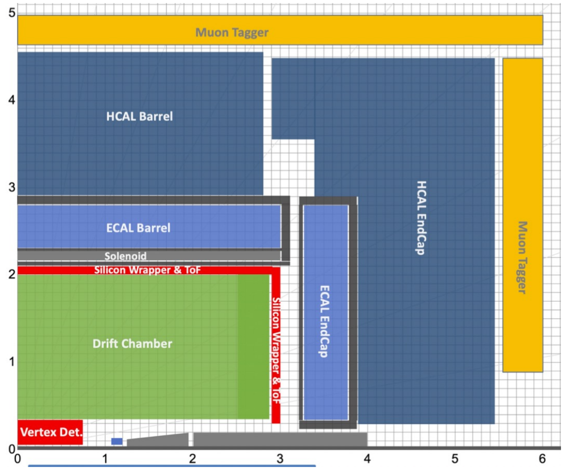


CDR

IDEA



Noble Liquid ECAL based



new

CLD

- 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.

Parameters

FCC-ee collider parameters as of June 3, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum) [b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

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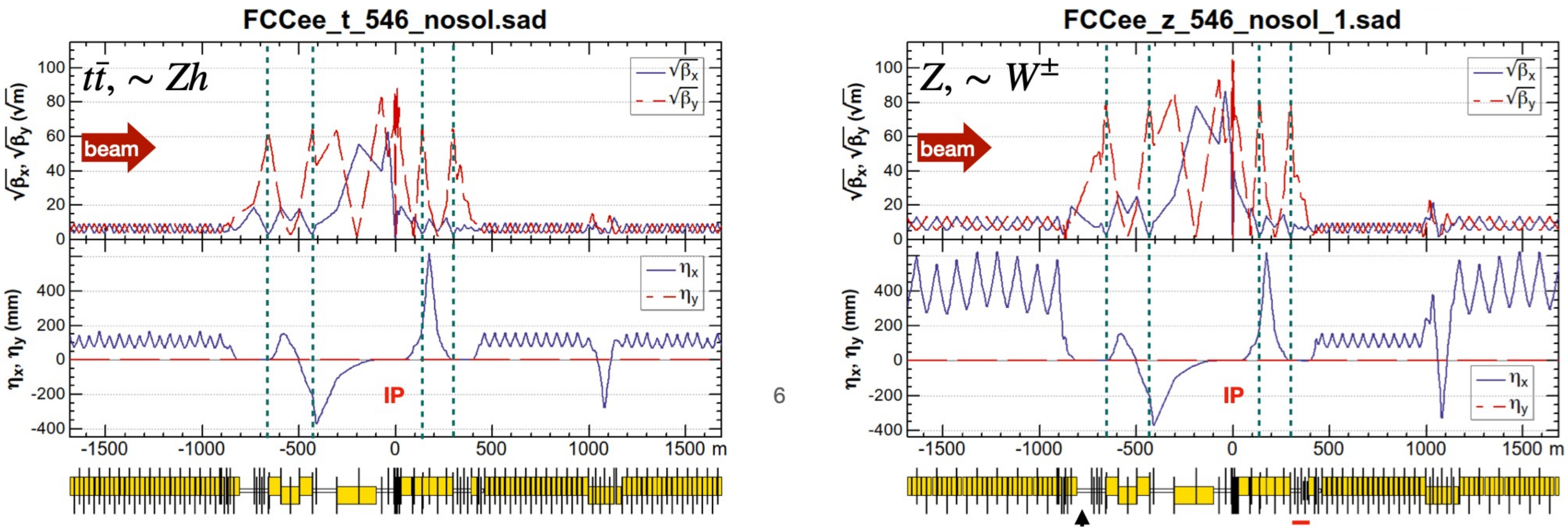
- Parameters such as tunes, β^*, crab waist ratio are chosen to maximize the luminosity keeping the lifetime longer than 4000 sec without machine errors.
- The choice of the parameters including the sextupole settings still has a room for further optimization.
- Including injection/extraction/ collimation optics will need additional optimization.

05 - 09 June FCC WEEK 2023

June 6, 2023, K. Oide

IR optics

K. Oide



- The **beam optics** are highly asymmetric between upstream/downstream due to crossing angle & suppression of the SR below 100 keV from about 400 m upstream to the IP.
- **Crab waist/vertical chromaticity correction sextupoles** are located at the dashed lines, they are superconducting.

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

MDI alignment and monitoring

- Tight alignment requirements on IR magnets, Lumical, and BPMs especially
- Cryostats surround the FF quads, the BPMs.
- External / internal (to the cryostat) alignment and monitoring system

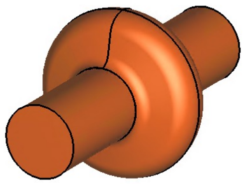
- Progress in the deformation monitoring system design with optical fibers placed in a helix shape. Two technologies are available:
  - SOFO (Surveillance d’Ouvrage par Fibre Optique)
  - In-line multiplexed and distributed FSI measurement (in development at CERN)

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

FCC-ee SRF Technology

Z

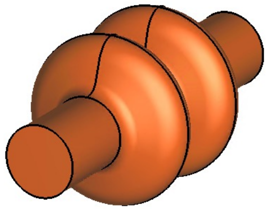
1-cell
400 MHz,
Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

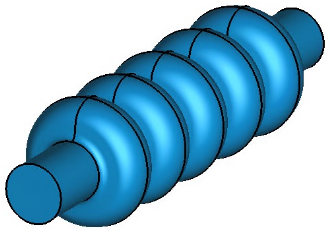
2-cell
400 MHz,
Nb/Cu



moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

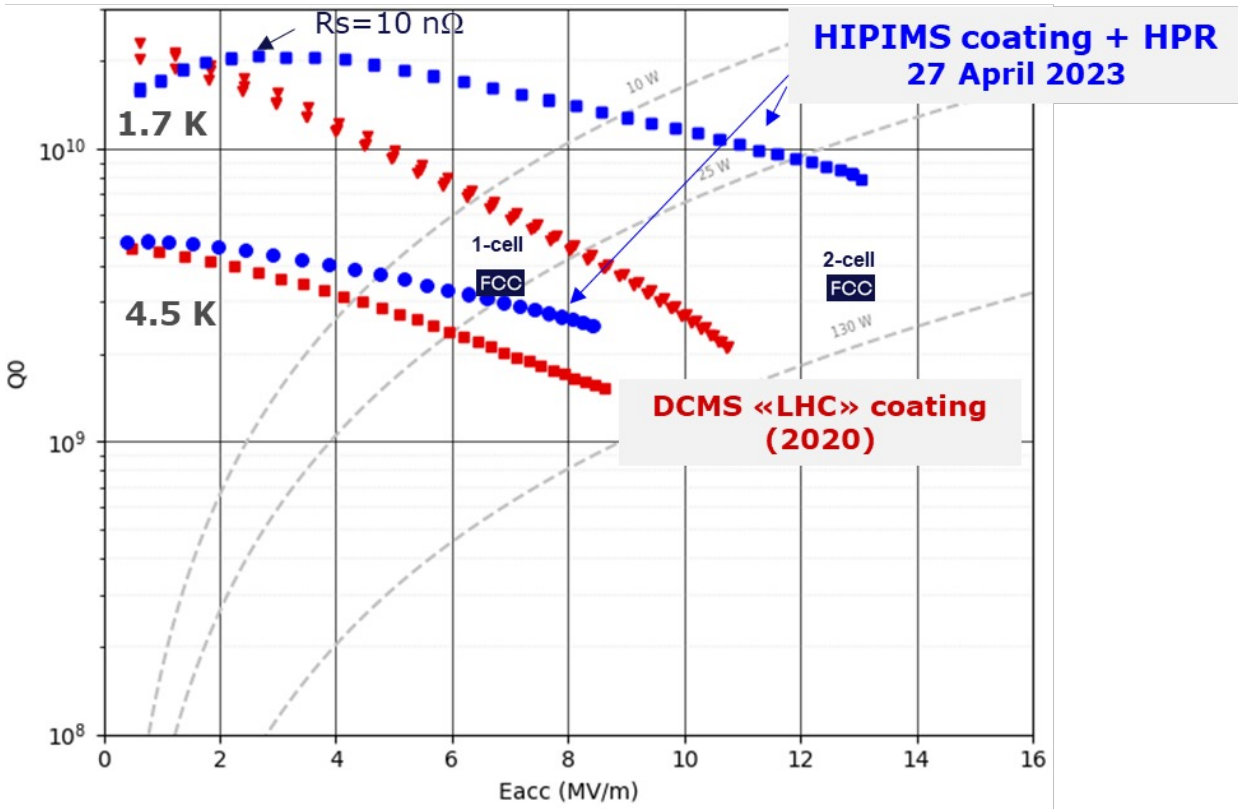
ttbar, booster

5-cell
800 MHz,
bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

Broad R&D collaborations on SRF



First attempt of HiPIMS* niobium coating on a 400 MHz Cu cavity

*High-power impulse magnetron sputtering

F. Peauger, O. Brunner