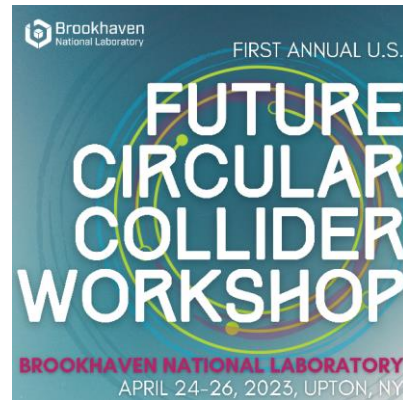




FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.



CHALLENGES OF FCC-EE MACHINE DETECTOR INTERFACE

Manuela Boscolo (INFN-LNF)

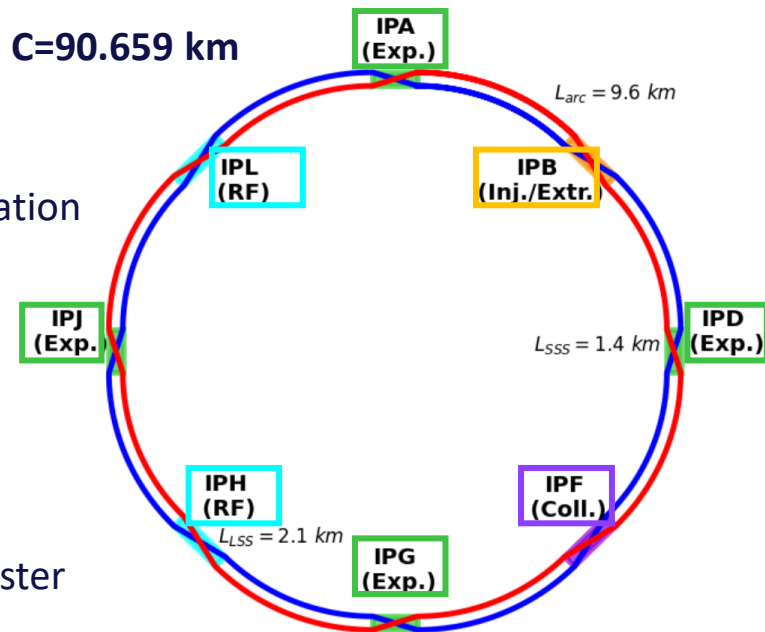
for the MDI group

* present US contributions underlined

First Annual US FCC Workshop
Brookhaven National Laboratory, 24-26 April 2023

FCC-ee collider

- **Double ring** e⁺ e⁻ collider
- Asymmetric IR layout and optics to limit synchrotron radiation towards the detector
- **crab-waist** collision optics
- Large Piwinski angle $\phi = \frac{\sigma_z}{\sigma_x} \frac{\theta}{2}$
- Synchrotron radiation power **50 MW/beam** at all beam energies
- **Top-up** injection scheme for high luminosity requires booster synchrotron in collider tunnel
- “**Tapering**” of magnets along the ring to compensate the sawtooth effect



8 surface sites

A-D-G-J Experiments

B Injection/Extraction

F Collimation section

H-L RF sections

FCC-ee Interaction Region

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 instantaneous overlap area, allowing for a lower β_y^*
- **crab-waist sextupoles**

Smaller beams at IP \rightarrow higher luminosity & potentially higher backgrounds
(due to the very high β -function in the final focus quads)

- Squeezed beams at IP, tens of nm in σ_y^* (vertical emittance $\varepsilon_y = 1$ pm at 45.6 GeV)
- This scheme, with the goal luminosity of $10^{36} \text{cm}^{-2} \text{s}^{-1}$ at 45.6 GeV sets the constraints to:
 - L^* (free distance between IP and first quad)
 - the **strength of the final focus doublet**
 - the solenoidal **detector field** ($\varepsilon_y \propto B_z^5$)



$L^* = 2.2$ m

$B(\text{detector}) = 2$ T

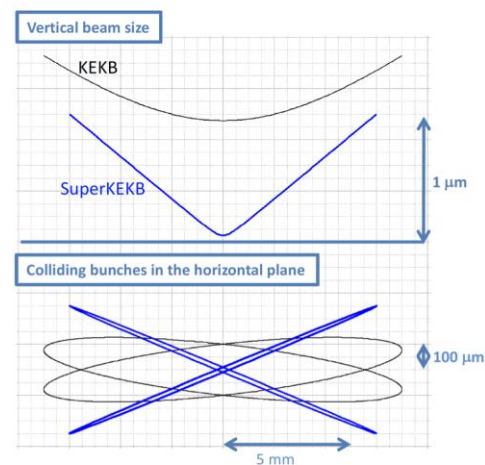


Figure 2: Schematic view of the nanobeam collision scheme.

<https://arxiv.org/pdf/1809.01958.pdf>

Compact interaction region with the first final focus quadrupole QC1 and two anti-solenoids inside the detector. The two beam pipes split at about 1 m, no common magnet between the two beams.

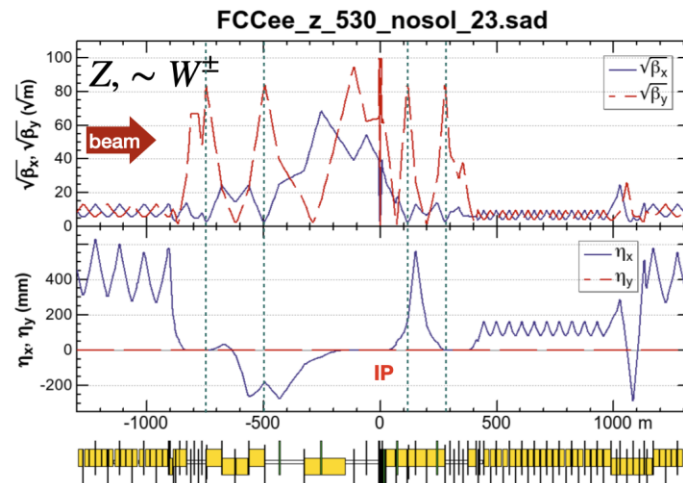
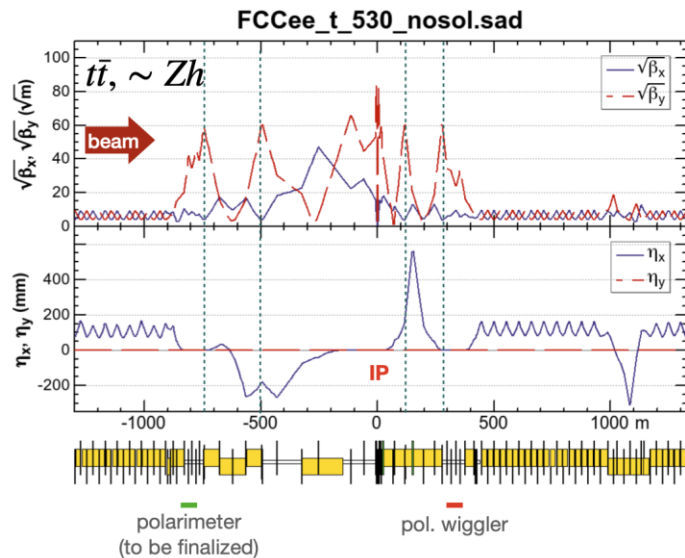
“Possible study on the detector solenoid compensation scheme” (à la DAFNE),

P. Raimondi (SLAC) recent proposal, 20/2/23 [link MDI meeting #44](#)

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 $\sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ 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
- **The cone angle of 100 mrad cone between accelerator and detector** seems tight,
 - it should be optimized considering constraints on both sides.
- **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

IR optics



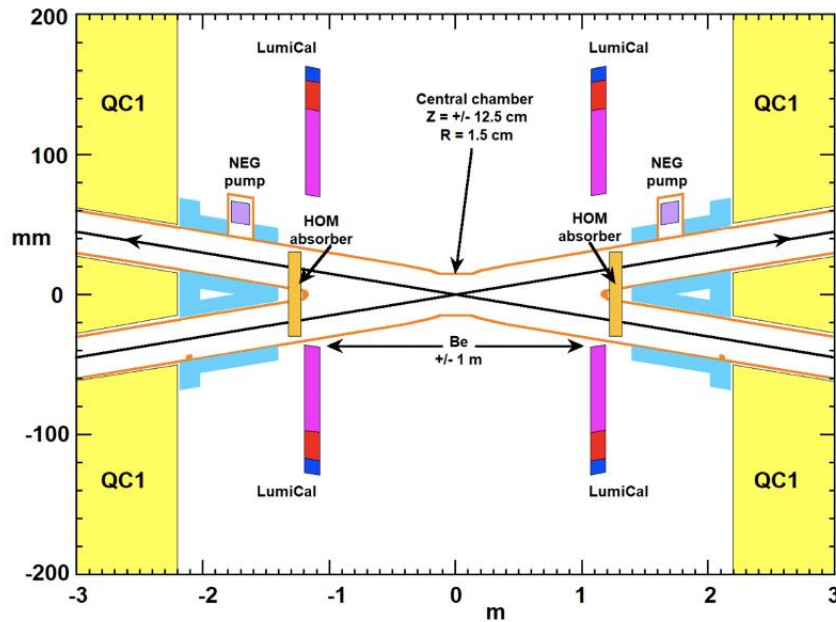
- The **beam optics** are highly asymmetric between upstream/downstream due to crossing angle & suppression of the SR below 100 keV from about 400 m upstream to the IP.
- Crab waist/vertical chromaticity correction sextupoles** are located at the dashed lines.

Interaction Region layout

2D-top view with expanded x-coordinate

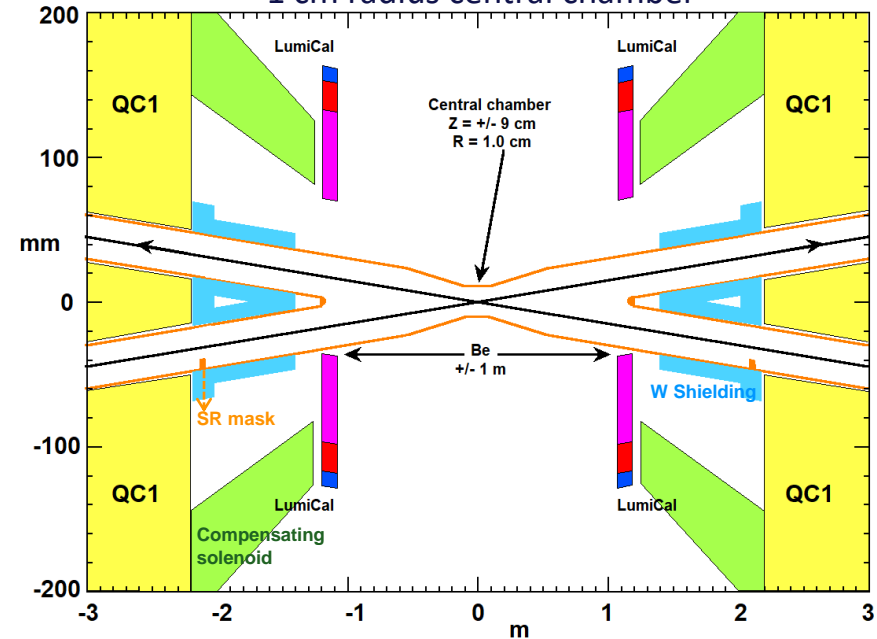
CDR

1.5 cm radius central chamber



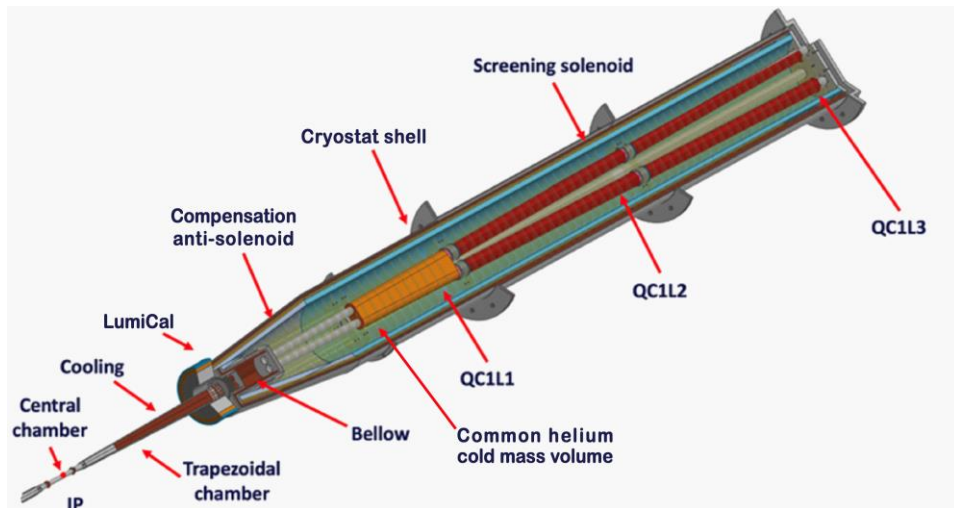
present low impedance beam pipe

1 cm radius central chamber



a smaller central vacuum chamber allows for a smaller radius of the innermost vertex detector layer

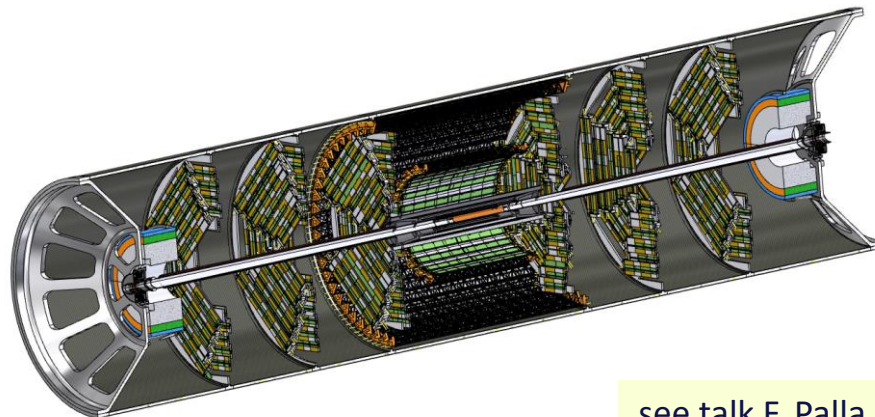
FCC-ee Interaction Region 3D view



Half-length of the detector ~ 5.2 m;
end face QC1 ~ 8.4 m.

Central Support tube with endcaps
carbon-fibre lightweight rigid structure,
to be anchored to the detector

All elements in the interaction region (vertex, Tracker and LumiCal) are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment. Once the structure is assembled it is slid inside the rest of the detector



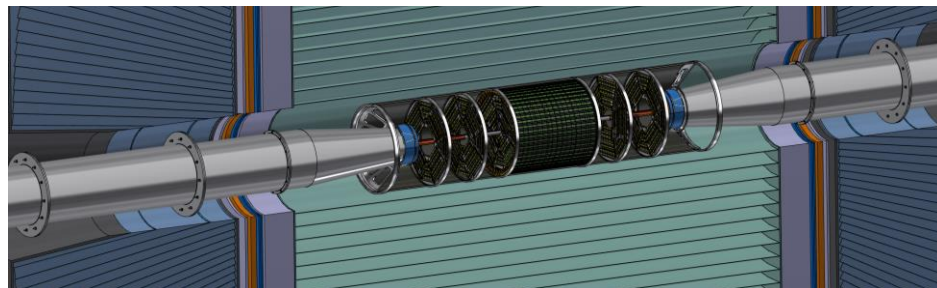
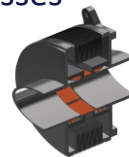
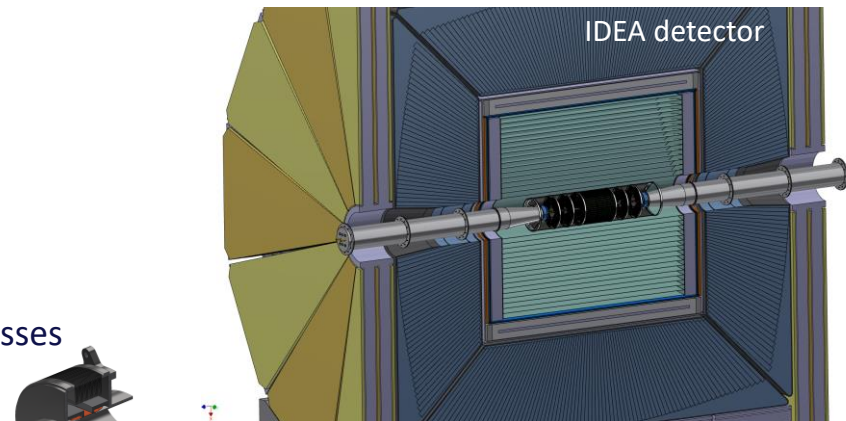
zoom

MDI central region ± 1.5 m from the IP

see talk F. Palla

Ongoing work on mechanical model of the FCC-ee MDI

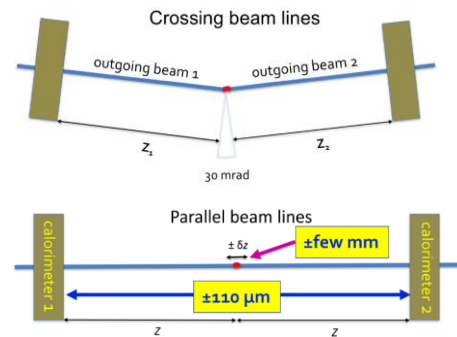
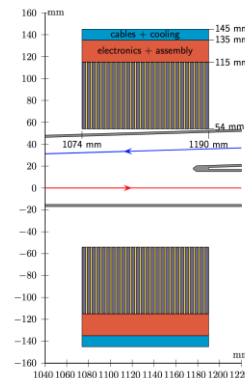
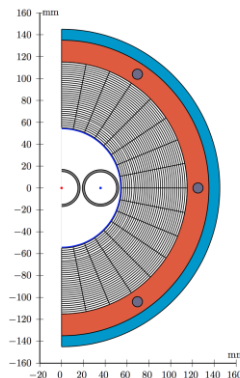
- **Integration of the support tube with the detector**
 - Anchoring points with the detector
 - Required space for services
- **Support and alignment of the LumiCal**
- **Cryostat-Support tube interface**
- Refine **FEA calculation with weights and thermal loads**
- Refine the **assembly procedure** while the MDI design progresses
- **Design of the Bellows** in progress, started from ESRF ones
 - Wakefields calculations in progress (A. Novokhatski, SLAC)
 - Engineered design of endcap-bellows & flange-bellows interface
- shape-memory-alloy (SMA) remote flange design
- IP diagnostics, especially BPMs
- Supports & vibration control
- Alignment system
- IR magnets design, key component for the MDI



LumiCal

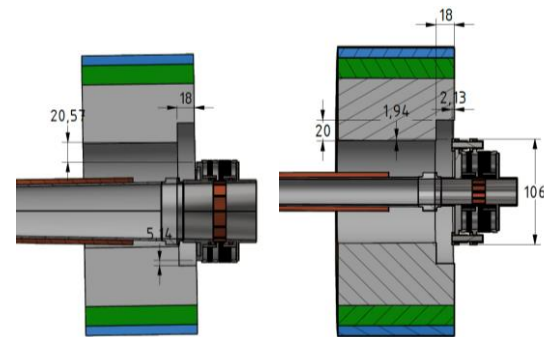
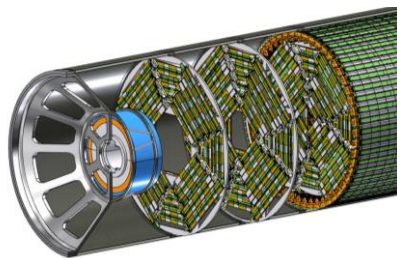
Goal: absolute luminosity measurement 10^{-4} at the Z
Standard process Bhabha scattering

- Bhabha cross section 12 nb at Z-pole with acceptance **62-88 mrad** wrt the outgoing pipe
- The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines



Integration of the lumical in the IR mechanical model has started:

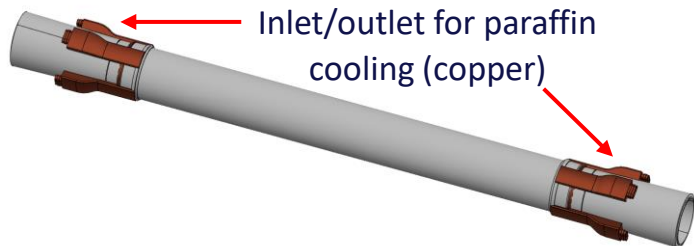
- asymmetrical cooling system provides required angular acceptance to lumical
- support tube includes the lumical (structural analysis with realistic weights)
- Requirements for alignment
 - few hundred microns in radial direction
 - few mm in longitudinal direction
- Engineering of the lumical required



slight modification to allow assembly

Low impedance vacuum chamber

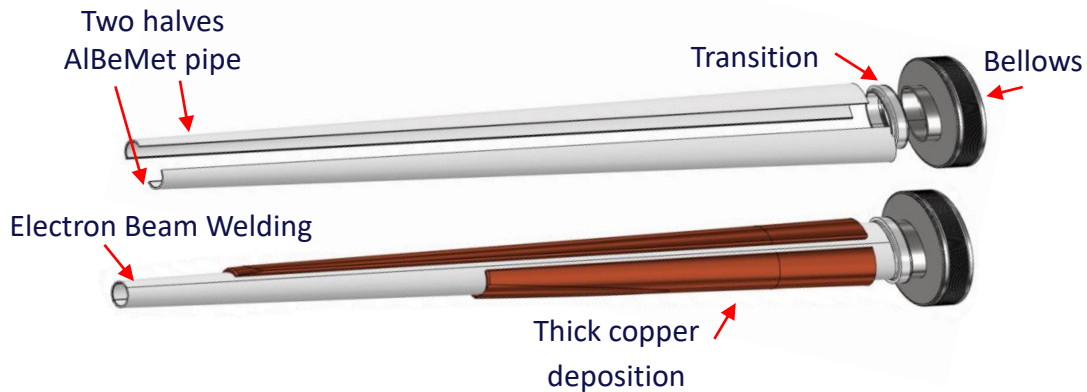
warm and cooled



Inner radius 10 mm
Outer radius 11.7 mm

Geometry studied to integrate the central chamber with the vertex detector

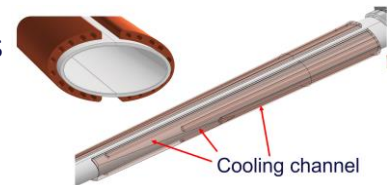
Material	thickness
AlBeMet162 (62% Be and 38% Al alloy)	0.35 mm
Paraffin (coolant)	1 mm
AlBeMet162	0.35 mm
Au	5 μ m



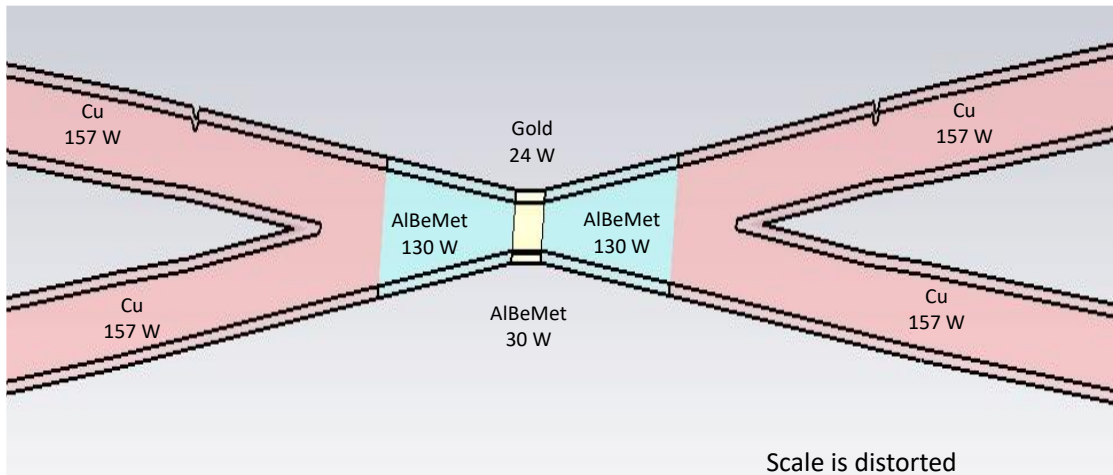
Starting from 90 mm to 1190 mm from IP

The cooling is based on an **asymmetric solution**, using the 50 mrad cone as the cutting profile, to assure the respect of the spatial constraint due to the **LumiCal requirement**.

To reduce the cooling material, the design provides **five channels** for each side; in this way is possible to use the needed quantity of coolant and reduce the material, creating a light structure.



Impedance-related heat load distribution



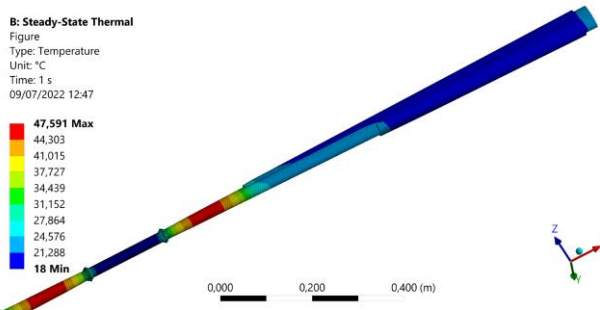
parameter	value
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

CST wakefields evaluations

A. Novokhatski *et al*, IPAC23



Estimations of heat load fed into ANSYS to develop the cooling system

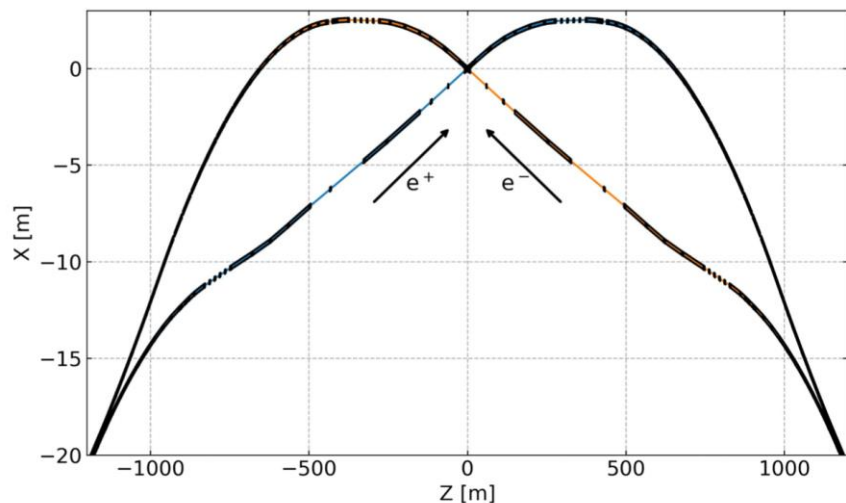


	trapezoidal chamber	central chamber
T_{\max}	48°C	33°C
T_{coolant}	20.5 °C (paraffin)	20 °C (water)

Synchrotron Radiation backgrounds

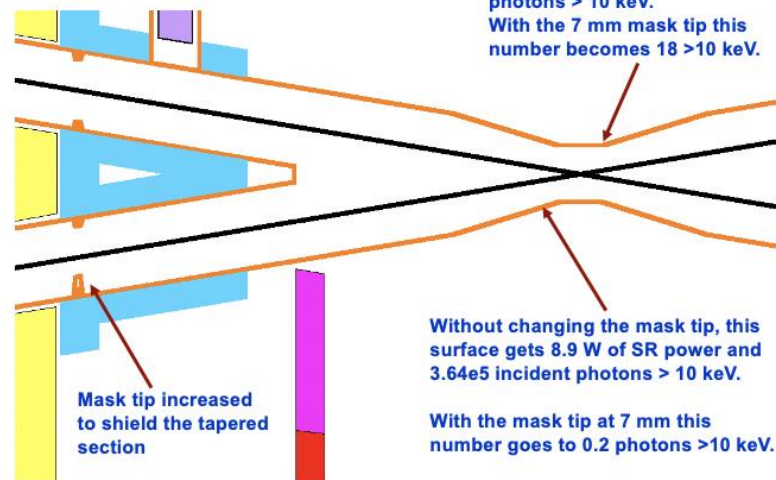
Simulation starts from about 1.2 km from the IP

On-axis beam, non-Gaussian beam tails to $20\sigma_x$ and $60\sigma_y$



M. Sullivan (SLAC)

New beam pipe – Z case

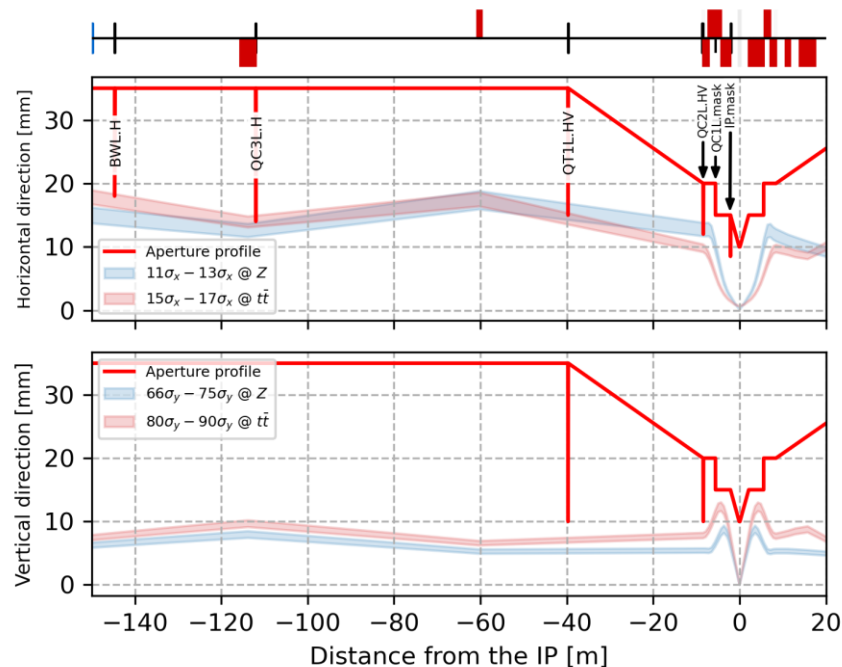
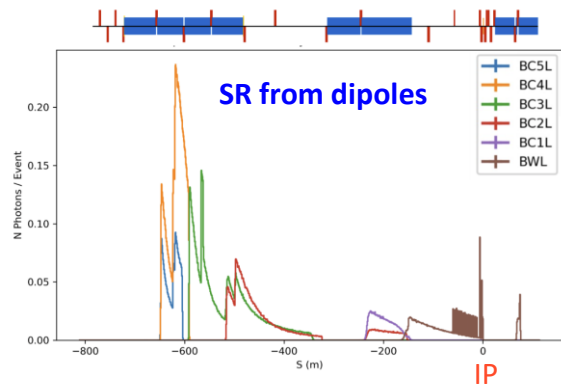


mask tips prevent FF quad radiation from striking nearby beam pipe elements

- Only the last dipole upstream the IP, and the quadrupoles QT1L, QC3L, QC1L produce SR that propagates until or traverses the IP.
- Various simulation codes used: **BDSIM**, **SYNC_BKG**, **SYNRAD+**, **MDISim** all in good agreement

Synchrotron Radiation backgrounds

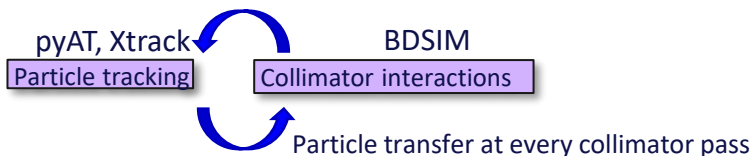
- Interaction region lattices for the 4 operation modes implemented in **BDSIM**
- Dipole, solenoid and quadrupole radiation evaluated
- Radiation from last bend reaches the IP
- SR photons from solenoid do not hit near the IP
- SR from FF quadrupoles leads to losses near the IP, in particular when beam tails are considered



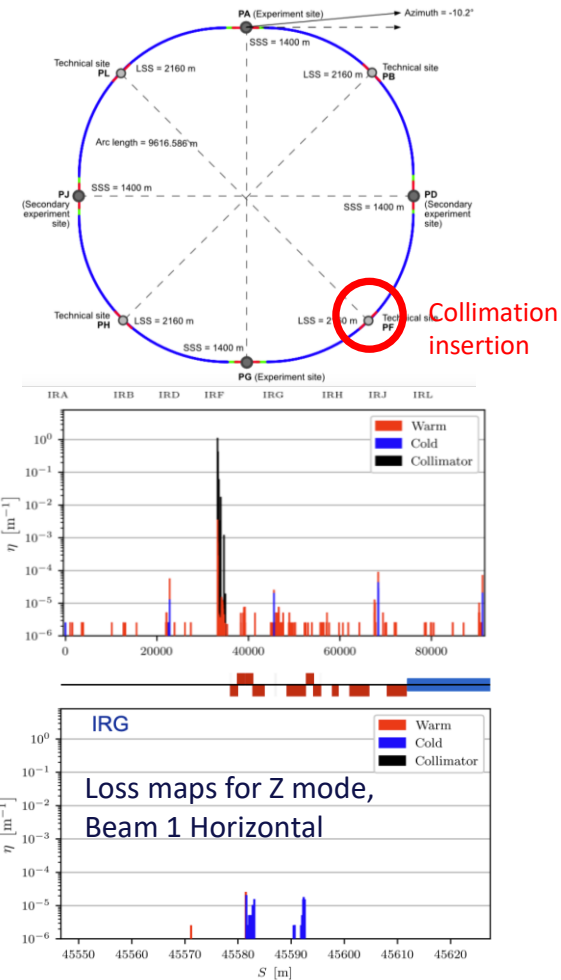
Photons tracks impacting the beam pipe need to be tracked with Key4HEP into the detector, to evaluate occupancy

Collimation studies & IR loss maps

- Using newly-developed simulation tools to study collimation for the FCC-ee

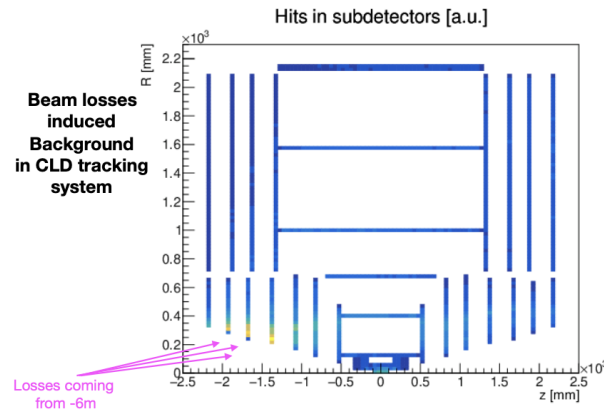


- First collimation scheme
- Currently focussing on beam halo losses with a workflow similar to LHC studies
- Various beam loss scenarios are being considered
- The beam loss maps need to be used to evaluate the impact to the detector using Key4HEP

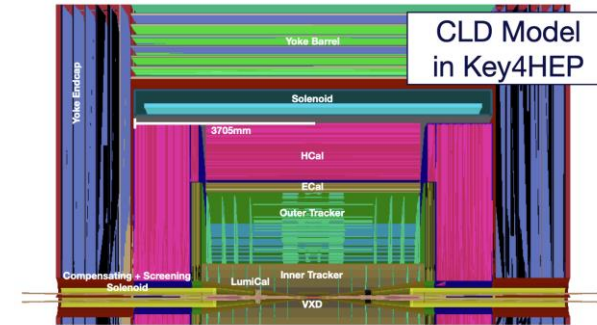


Detector Backgrounds

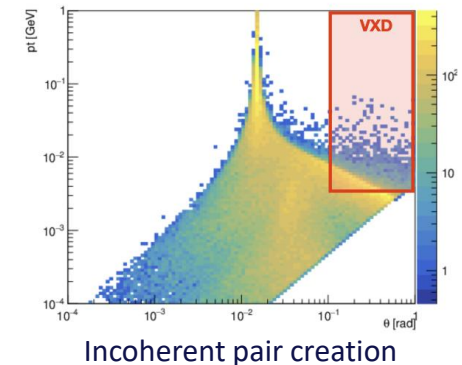
- CLD detector and MDI model in Geant4 adapted to 10 mm beampipe
- Solenoid field map imported in key4hep
- Collision products, beam, and photon losses are now studied
- Occupancy from incoherent pair production tolerable
- Occupancy from beam halo losses only concerning at ttbar, for beam loss scenarios considered until now



- Preliminary studies show little quench risk for the FF quads due to halo losses.
- Preliminary studies show photon losses absorbed or deflected by mask



	Z	WW	ZH	Top
Pairs/BX	1300	1800	2700	3300
Max occup. VXDB	70e-6	280e-6	410e-6	1150e-6
Max occup. VXDE	22.5e-6	95e-6	140e-6	220e-6
Max occup. TRKB	9e-6	20e-6	38e-6	40e-6
Max occup. TRKE	110e-6	150e-6	230e-6	290e-6



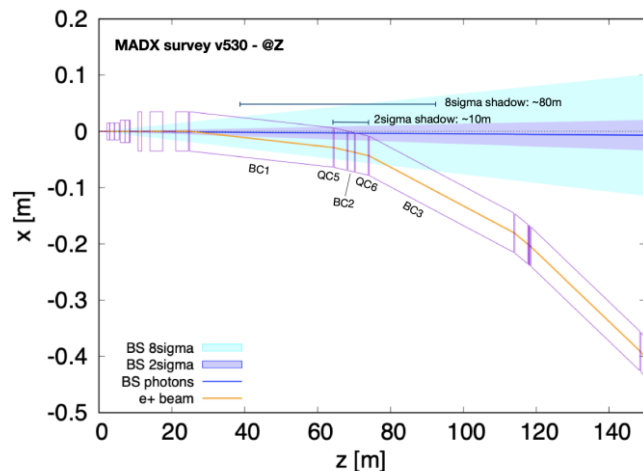
Beamstrahlung Photon Dump

Radiation from the colliding beams is very intense 370 kW at Z

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

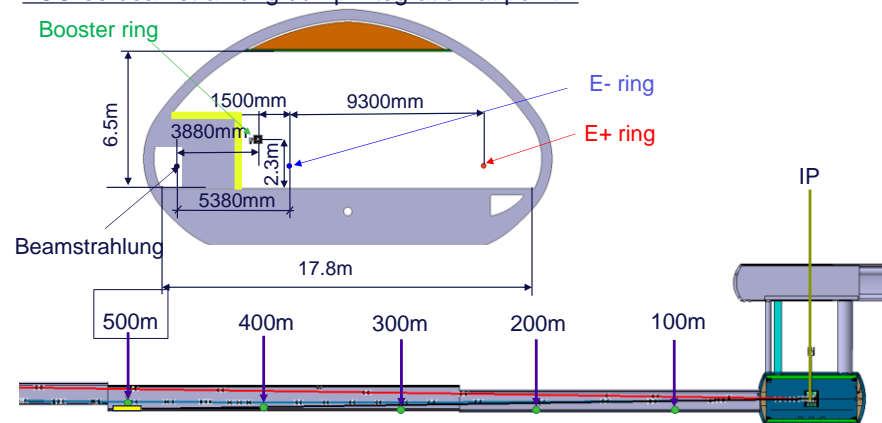
	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

GuineaPig++



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

FCC-ee beamstrahlung dump integration at point A

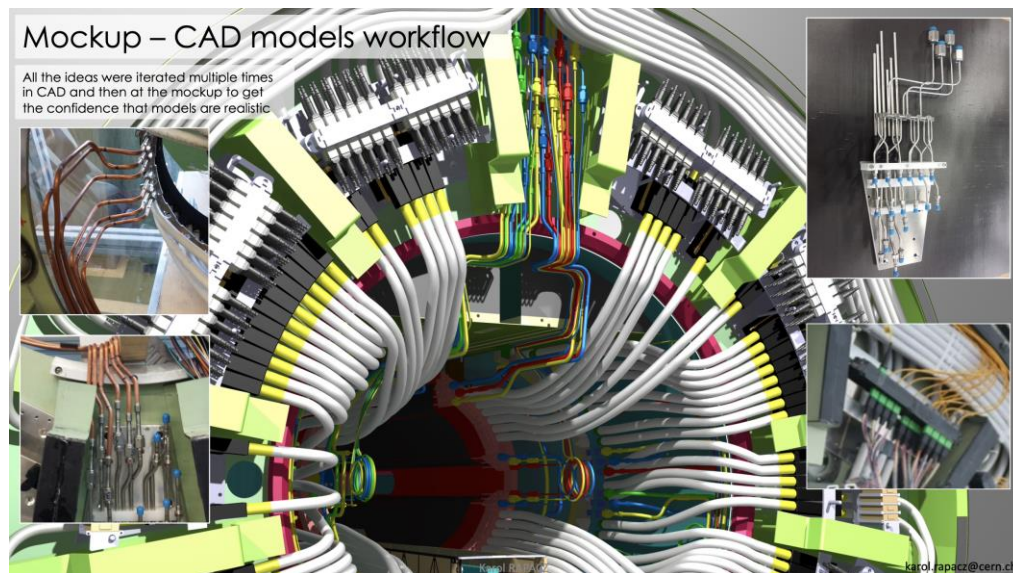


High-power beam dump needed to dispose of these BS photons + all the radiation from IP

- Dump absorber material non defined yet, liquid lead is a possibility
- Shielding needed for equipment and personnel protection

IR Mock-up

- We propose to add to the CAD model of the MDI a **complementary R&D activity consisting in a full-scale IR mock-up to be realised at Frascati**. We need to conclude with FCC addendum.
- It will allow to test technological solutions with prototypes and to address the main issues related to the assembly.
- The IR mock-up will eventually be available for further studies on stability, alignment and vibrations, to be conducted by other interested international partners.
- An independent IR in-cryostat mock-up including integrated magnets would be a complementary R&D important to assess the whole IR feasibility.



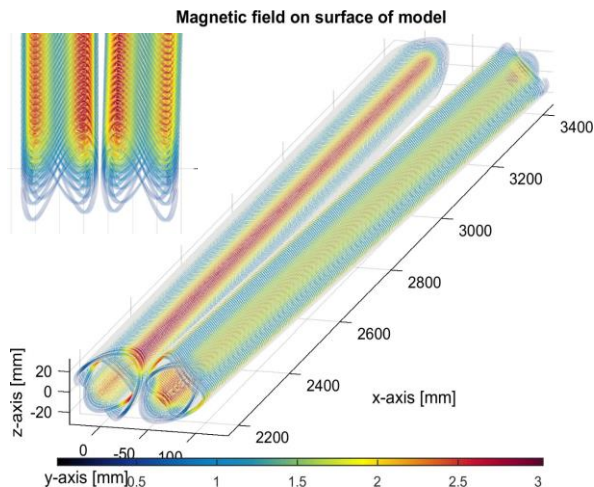
Example of CMS IR mock-up

IR magnet system

- Progress on the overall IR magnets design including solenoids and correctors is essential to progress with the overall mechanical design, integration and assembly of the MDI.
- Review April 2022 on IR magnets design with cryostat, challenges identified - tapering, corrector design, accessibility and serviceability- **we need to move to the next level of the design.** There are pending details on the mechanical support, cryogenics, thermal heat loads, alignment, services which need resourcing to move forward.
- TE Magnet group identified two main work packages as potential collaboration to be discussed with FCC.
 - **IR final focus magnets with solenoids, interest of BNL and other US magnet groups to collaborate, collaboration CERN-BNL under discussion.**
 - Crab high field sextupole on FCC-ee are under evaluation for conduction cooled options, optics sensitivity requested and magnetic design. Resourcing subject to pending collaboration with TE.

Magnets of the Interaction Region

- **Two superconducting compensating solenoids** inside the detector
- **Final Focus superconducting Canted Cos theta (CCT) quadrupole QC1** at 2.2 m from the IP, inside detector and embedded in one of the two compensating solenoids.
- Max gradient 100 T/m, NbTi, 4.2 K.
- It provides an excellent field quality and allows for embedded correctors.



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

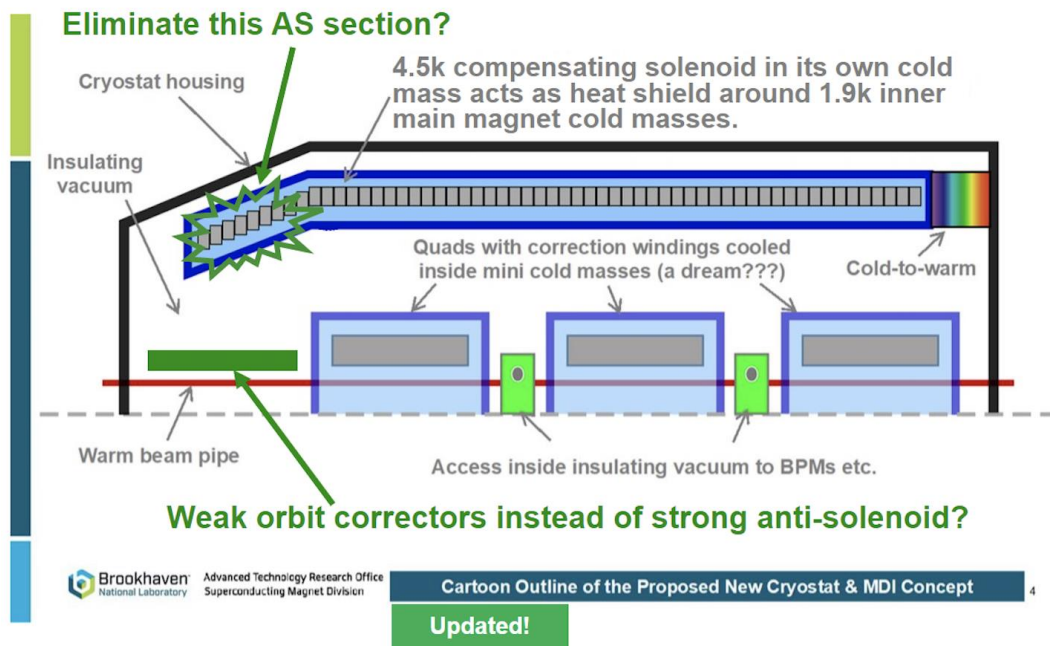


QC1 prototype during construction, tested at warm at CERN

Next step: cold tests on this prototype for quench analysis

FCC-ee MDI: Can we partially decouple the anti-solenoid and IR quadrupole designs?

see talk B. Parker



At the present time the anti-solenoid and IR quads share helium cooling in a common cold mass and this brings many complications for inner access (BPM etc) and magnetic force management with acceptable heat leak without going into the detector acceptance.

What could we do instead if the anti-solenoid was in its own semi-independent cold mass volume so as to somewhat decouple anti-solenoid (AS) cooling and support issues from those of the Final Focus?

HTS coil at 40k is not practical here, but even a 4.5k NbTi solenoid could be a useful heat shield for 1.9k cooled inner quadrupoles coils.

Maybe eliminate the first anti-solenoid section and instead use weak orbit correctors, i.e. only shielding solenoid remains (avoids high AS fields and large longitudinal forces); optics then need correctors.

IR magnet design with cryostat. Challenges identified - tapering, corrector design, accessibility and serviceability, may require substantial changes to the current design

FCC-EIC Joint & MDI Workshop

- 2 week workshop: 17-28 October 2022

FIRST WEEK: FCC-EIC Joint

Common challenges and collaborative opportunities

SECOND WEEK: FCC-EE MDI

MDI and IR topics

Indico page: <https://indico.cern.ch/event/1186798/>

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Rogelio Tomas (CERN)

Frank Zimmermann (CERN)



FCC-EIC Joint & MDI Workshop 2022

17–28 Oct 2022

CERN

Europe/Zurich timezone

This extended two week working meeting combines the 1st FCC-EIC Joint Workshop and the 4th FCC-ee MDI Workshop. The event will take place at CERN, from 17 to 28 October 2022 in a hybrid in-person and online participation format. The working meeting will start on Monday 17 October after lunch and will end on Friday 28 October. It will be organized with presentations in the afternoon, followed by discussions on various topics.

The first week of the event will include joint sessions on topics of common interest to FCC-ee and EIC, while the second week will focus more on FCC-ee MDI topics. This will be an opportunity to share knowledge and experience from the diverse and complementary research related to the FCC and EIC. Experience from SuperKEKB will also be presented.

The goal of the second week is to make progress on the mechanical design and integration of the interaction region layout, including the FCC-ee MDI region. Here, the constraints are tight, and the intent is to improve the current design through close interaction with engineering proposals as to how to manufacture, integrate and assemble the various components that make up the heart of the collider and detector. The aim is to develop a list of requirements for each subsystem as well as for the integration of the sub-assemblies.

During the event the following topics will be addressed:

- IR optics, beam dynamics, collective effects
- IR magnet design, mechanical integration
- Beam losses and SR in the MDI, collimation, detector backgrounds
- Tuning, mechanical stabilization, and alignment
- Impedance, heat load evaluation
- MDI assembly concept, beam pipe model, and IR mock-up
- Vertex detector & Luminical integration study

During the workshop we came out with topics of common interest for a collaboration between FCC and EIC

- MDI design, Interaction Region design, IR magnet design, Backgrounds modeling
- SR and IR beam losses
- Collimation simulation tool and collimator design
- Beam-beam, lifetime and dynamic aperture modeling
- Non-linear optics optimization
- Beam Instrumentation
- Impedance
- Optics tuning
- Simulation and modeling tools

Summary – MDI focus topics

- New placement and layout → optics with smaller circumference ($C=90.6$ km) and 4 IPs
- Progress on the **mechanical model** of the MDI area, with a focus on the central region ± 1.5 m from IP
 - beam pipe with the cooling system and its support
 - IR bellows + assembly
 - integration of the lumical
 - integration of the vertex and outer tracker detectors
- Progress on the **backgrounds** studies:
 - **beam losses** in the MDI: collimation scheme and first loss maps
 - **synchrotron radiation** in the MDI: SR collimators and SR source on the MDI
 - **Detector backgrounds**: primary beam losses and photons tracked with Key4HEP on CLD
- **Beamstrahlung** Photons dump:
 - optimal location at around 400-500 m from IP, impact on the civil engineering addressed
 - characterization of the BS & radiation studies

Conclusion

- Relevant contributions to the MDI design study from US
- Synergies with FCC/EIC
- Common tools
- Plenty of areas for collaborations to the MDI design.
- **Success of FCC relies on strong global participation in all domains.**

Regular FCC-ee MDI meetings, second Monday of each month at 16H00-18H00: <https://indico.cern.ch/category/5665/>

MDI mailing list : self-subscription to the e-group **fcc-ee-mdi**

from this page: <https://e-groups.cern.ch/e-groups/EgroupsSearchForm.do>

Backup

Parameters (19 Jan 2023)



Table 1: FCC-ee collider parameters as of Jan. 19, 2023

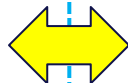
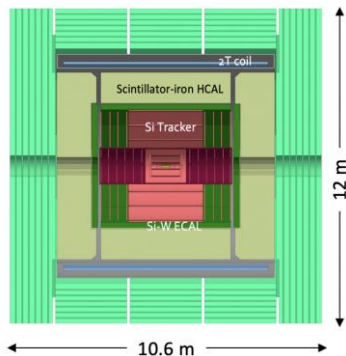
Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bending radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.370	1.89	10.1
SR power / beam	[MW]	50			
Beam current	[mA]	1270	134	26.7	4.94
Bunches / beam		9200	688	260	40
Bunch population	[10 ¹¹]	2.60	3.68	2.04	2.33
Horizontal emittance ε_x	[nm]	0.71	2.16	0.67	1.55
Vertical emittance ε_y	[pm]	1.42	4.32	1.34	3.10
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10 ⁻⁶]	28.6		7.34	
Arc sextupole families		75		146	
$\beta_{x/y}^*$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.565 / 53.595		100.556 / 98.590	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.143	0.069 / 0.176	0.103 / 0.179	0.157 / 0.220
Bunch length (SR/BS) σ_z	[mm]	4.37 / 15.9	3.55 / 9.09	3.34 / 5.78	1.89 / 2.66
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.1 / 0	2.1 / 9.4
Harmonic number for 400 MHz		121200			
RF frequency (400 MHz)	[MHz]	400.786684			
Synchrotron tune Q_s		0.0370	0.0800	0.0327	0.0881
Long. damping time	[turns]	1158	215	63.8	18.3
RF acceptance	[%]	1.6	3.3	1.9	3.1
Energy acceptance (DA)	[%]	±0.8	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y^a		0.0023 / 0.139	0.011 / 0.139	0.014 / 0.126	0.093 / 0.136
Luminosity / IP	[10 ³⁴ /cm ² s]	186	21.4	6.94	1.20
Lifetime (q + BS + lattice)	[sec]	1120	–	< 1660	< 4170
Lifetime (lum) ^b	[sec]	980	960	620	750

^aincl. hourglass.

^bonly the energy acceptance is taken into account for the cross section

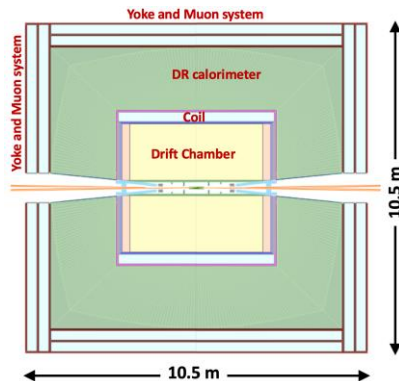
FCC-ee Detector Concepts

CLD



CDR

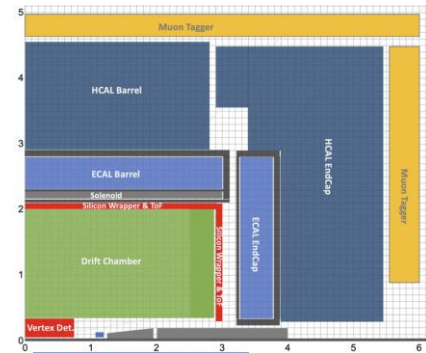
IDEA



- 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. powerful PID;
- Monolithic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;
- Possibly augmented by crystal ECAL in front of coil;

Noble Liquid ECAL based



new

- 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.

Layout in the Interaction Region

Both IPs of FCC-ee and FCC-hh now completely overlap.

- The IP transversely deviates from the layout line by about 10.5 m outward.
Beams always enter the IP from inside of the ring.
- The **placement of the booster** has not been perfectly determined yet.
The booster must be at least 8 m from the IP, to bypass the detector

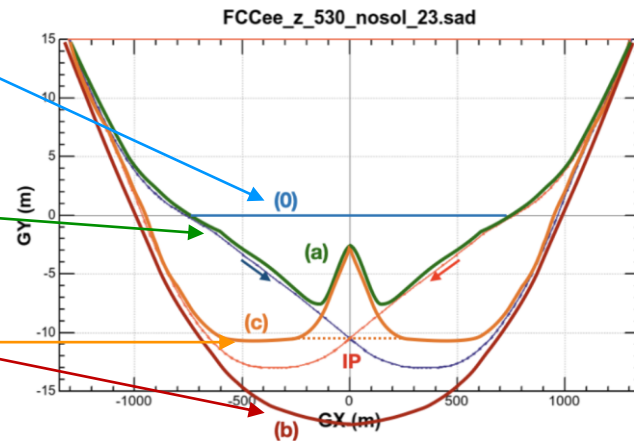
Possibilities for location of booster

(a) stay inside of the inner collider ring with a bypass chicane within about ± 200 m of the IP.

(b) going outside of the detector

(c) follow the FCC-hh beam line with a bypass chicane.

(0) Layout line



The choice depends on the size of the tunnel, synchrotron radiation toward the detector

Assembly procedure



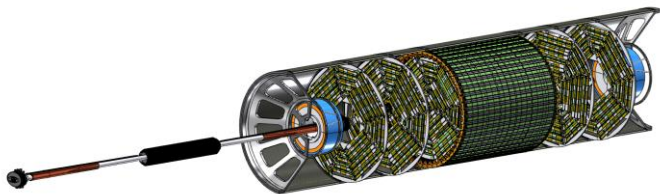
Section view

1) Outer tracker, Medium tracker and disks 1 are installed as a rigid structure inside the support tube

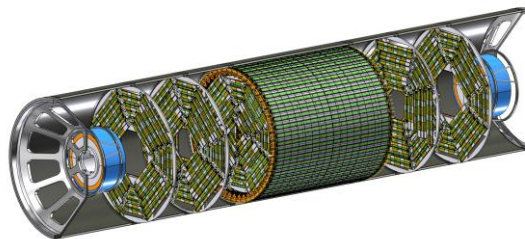


2) Disks 2 and 3 are installed inside the support tube

Assembly procedure (2)



3) LumiCal is installed in centered position, then beam pipe with vertex detector is inserted with a dedicated tool inside disks and outer tracker, then fixed to both endcaps



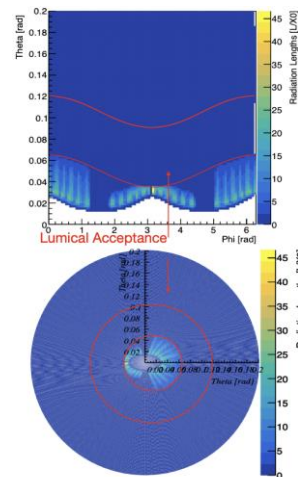
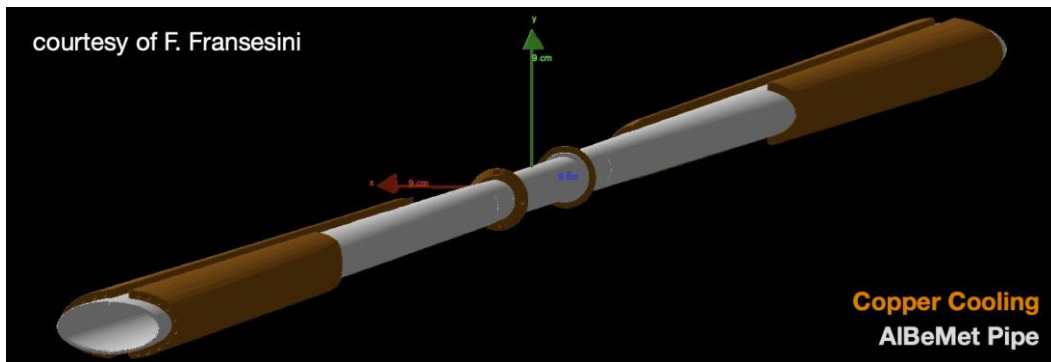
4) LumiCal can be aligned in the correct position on the outgoing beams



5) Support tube can be closed

Luminosity Monitor acceptance and the vacuum chamber

- The central chamber has double layer with Paraffin cooling
- The vacuum chamber (2 mm AlBeMet162) before the luminosity monitor (LM) has cooling channels, copper thermal exchangers with water channels.
- The requirement coming from the LM is an acceptance of a 50 mrad cone with a low material budget.



The design has a radiation length between $0.2-0.5 X_0$ in front of the LM, due to AlBeMet162

GEANT4

The chamber thickness and shape and dimension of the cooling channel fits the requirements. Studied its technological feasibility.

F Palla, F Bosi, INFN-Pisa

Study the integration of the vertex detectors

The design of the vertex detector region has started
Presently we are studying the insertion of vertex detectors inside the cylindrical rigid structure supporting the LumiCal and the beam pipe

- Innermost structures supported by the beampipe
- Outermost layers (and endcaps) supported by the rigid structure - Mechanical structure still under study
- IDEA barrel vertex detector almost defined, wrapper and endcap will soon be finished
- The integration of the CLD vertex detector will follow

