



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.

MDI OVERVIEW

Manuela Boscolo (INFN-LNF)
for the MDI group

FCC WEEK 2023
London, 5-9 June 2023



Outline

- Introduction to the IR MDI
- Highlights on the progress on some of the main key topics of the MDI design with perspectives toward the demonstration of MDI feasibility
- Summary

FCC WEEK 2023 – MDI sessions

<https://indico.cern.ch/event/1202105/>

3 sessions

Tue. 6 + Wed. 7
90 min. each

Mechanical model, vertex integration, vibration studies

Backgrounds, losses, SR, beamstrahlung

**IR magnets,
IR BPMs, alignment**

[illegible]

Agenda

MDI (I) Convener: John Seeman (SLAC)

M. Boscolo (INFN)	MDI overview
F. Palla (INFN)	Mechanical integration of the IDEA detector in the IR
A. Ing (Un. Zurich)	IDEA VXD implementation in full simulation
F. Franesini (INFN)	Mechanical model of the MDI
L. Brunetti (CNRS)	Towards mechanics and optics evaluation of the vibration effects for the MDI

MDI (II) Convener: Manuela Boscolo (INFN-LNF)

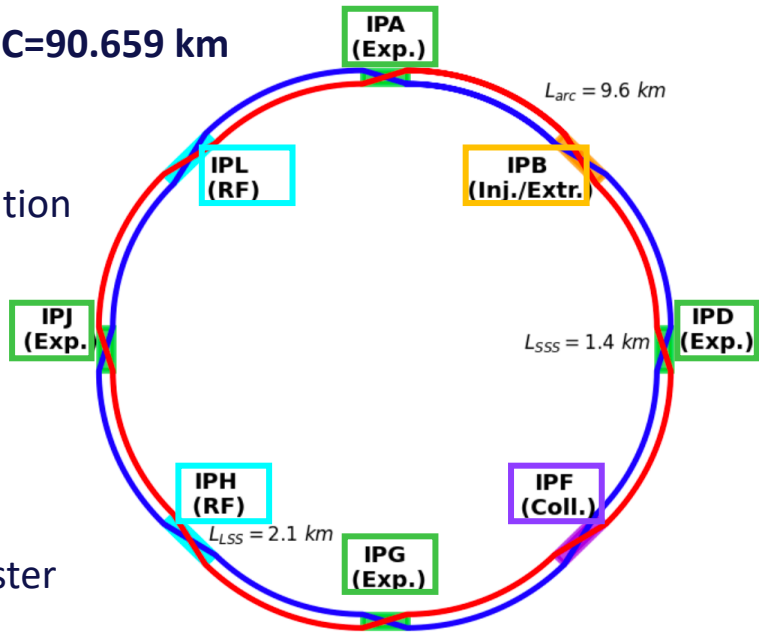
H. Nakayama (KEK)	SuperKEKB MDI lessons
G. Broggi (CERN&Sap.&INFN)	Beam Losses in the MDI
K. Andre (CERN)	Synchrotron radiation background studies
A. Ciarma (INFN)	Detector background simulations
G. Lerner (CERN)	Beamstrahlung dump and radiation levels in the experiment IRs

MDI (III) Convener: Kathleen Amm (BNL)

Brett Parker (BNL)	SC IR magnets system
Carl J Eriksson (CERN)	Magnet design for beamstrahlung photons extraction line
Arnaud Foussat (CERN)	Preliminary design study of interaction region crab sextupole for FCC-ee collider
Leonard Watrelot (CNAM)	Alignment systems propositions to face the FCC-ee MDI challenges
Manfred Wendt (CERN)	Challenges for the IR BPMs

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 rationale

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**

- This scheme, with the goal luminosity of $10^{36} \text{cm}^{-2} \text{s}^{-1}$ at 45.6 GeV sets constraints to the IR design, among which:

- L^* (free distance between IP and first quad)
- the **strength of the final focus doublet**
- the solenoid **detector field**

$L^* = 2.2 \text{ m}$
 $G \sim 100 \text{ T/m}$
 $B(\text{detector}) = 2 \text{ T}$

- Compact IR with the first final focus quadrupole (FFQ) QC1 and two anti-solenoids inside the detector.
- No common magnet between the two beams.
- The two beam pipes split at $\sim 1 \text{ m}$.

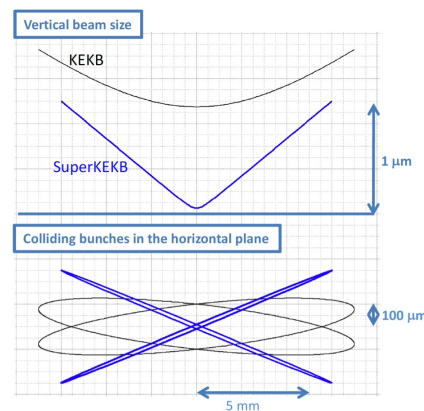


Figure 2: Schematic view of the nanobeam collision scheme.

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

High-level Requirements for the IR and MDI region

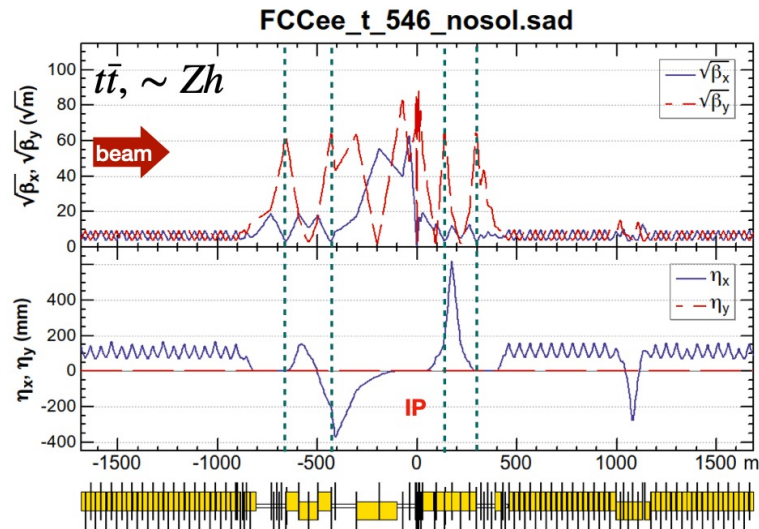
- **One common IR for all energies, flexible design** from 45.6 to 182.5 GeV with a constant detector field of **2 T**
 - At **Z pole**: Luminosity $\sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ requires crab-waist scheme, nano-beams & large crossing angle.
Top-up injection required with few percent of 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
- **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

Since the last FCC WEEK 2022

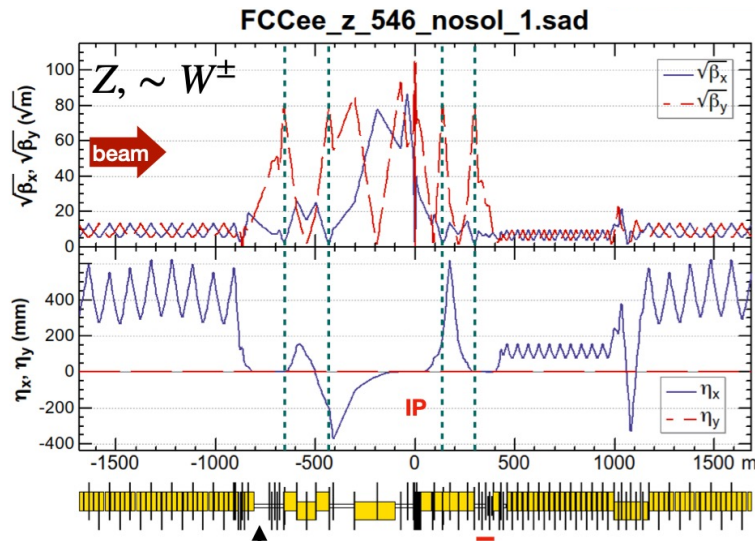
- New placement and layout → optics with smaller circumference and **4IPs**
- Progress on the **mechanical model**
 - engineered up to the IR magnets, beam pipe with cooling system, and its support
 - vertex detector designed, integrated in MDI, its software description implemented
 - integration of the lumical
 - assembly concept
- Progress on the **backgrounds** simulations:
 - **beam losses** in the MDI: halo collimation scheme and first loss maps in the MDI
 - **synchrotron radiation** in the MDI: SR collimators and masking, constraints to the top-up injection
 - **Detector backgrounds** simulations with refined and more realistic software model
- Progress on the **heat load** from wakefields, SR, and beam losses
- **Beamstrahlung** Photon dump:
 - optimal location at 500 m from IP, study on the magnet aperture yoke to allow an extraction line
 - radiation studies with Fluka started
- And also : **IR magnets, IR BPMs**, feedback
- **Alternative solenoid compensation** -with large impact on the MDI- has been proposed and pros&cons under evaluation

IR optics

K. Oide



6



- 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.

FCC-ee Interaction Region

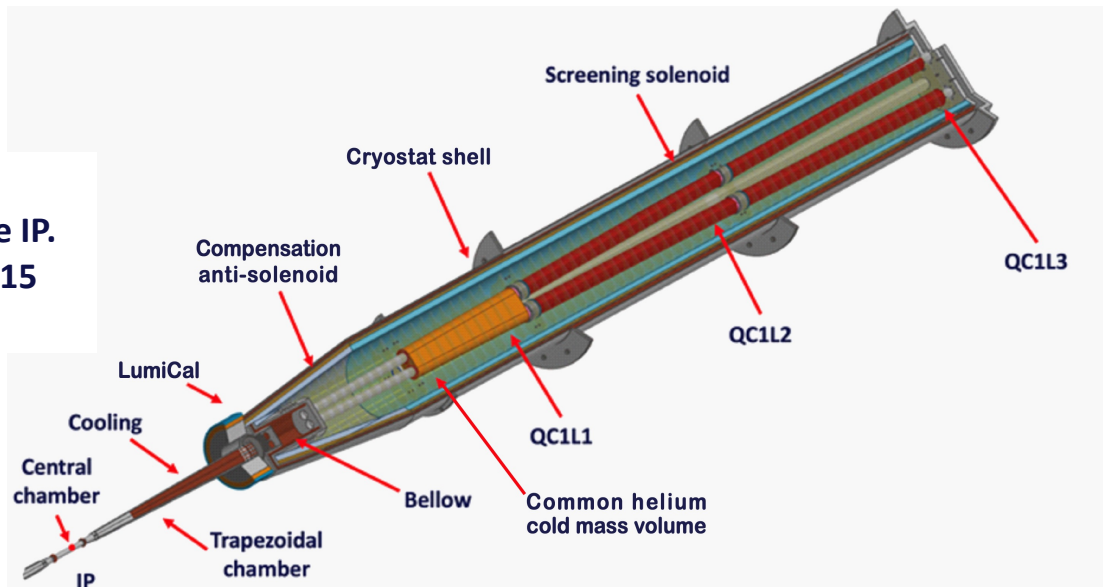
L^* is 2.2 m.

The 10 mm central radius is for ± 9 cm from the IP.

The two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP.

Half-length of the detector about 5 m

End face QC1L3 8.4 m.



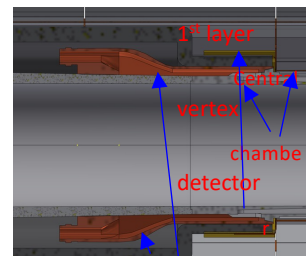
P. Raimondi proposed an alternative / evolved solenoid compensation scheme (à la DAFNE) It would largely simplify the present IR magnet system. Prons and cons under study. Excellent coupling correction seems possible.

"Novel Coupling Correction Scheme for FCC-ee " A. Ciarma et al., poster session] Alternative optics session (Thursday)

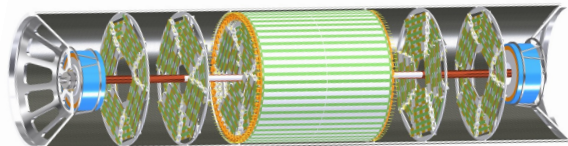
Additional links [MDI meeting #44](#) and [MDI meeting #46](#)

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



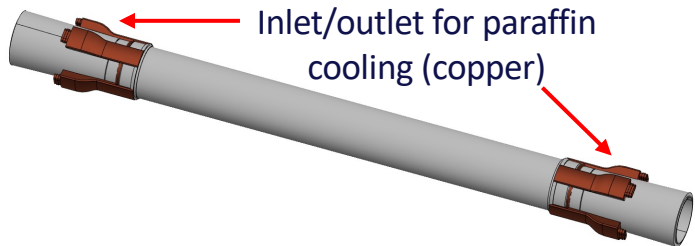
Inlet/outlet



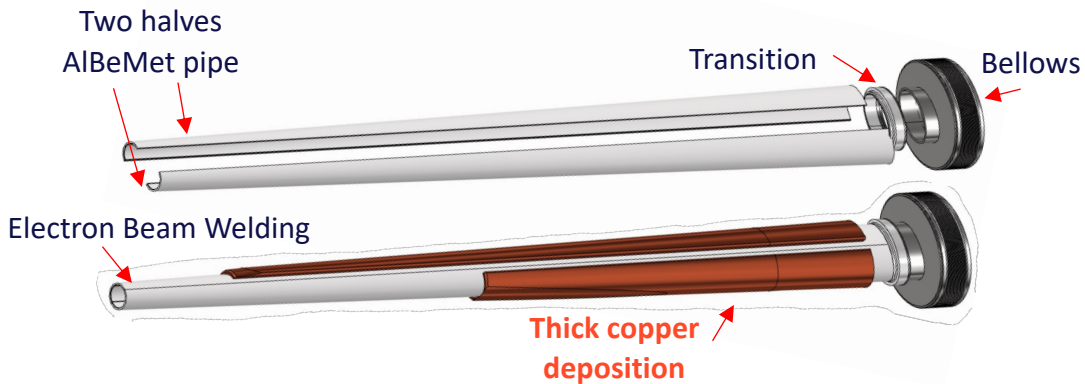
Low impedance vacuum chamber

warm and cooled

prototyping and mockup planned



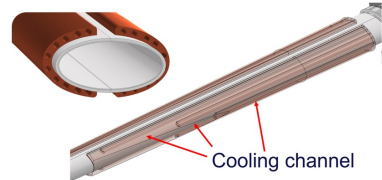
Inner radius 10 mm
Outer radius 11.7 mm



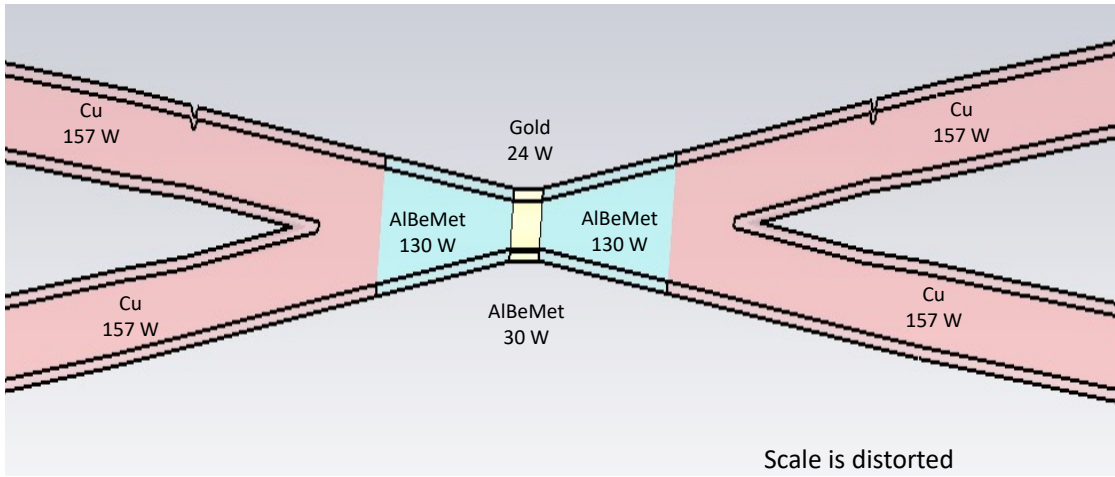
Starting from 90 mm to 1190 mm from IP
The cooling channels are **asymmetric** due to the **LumiCal acceptance requirements**.

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

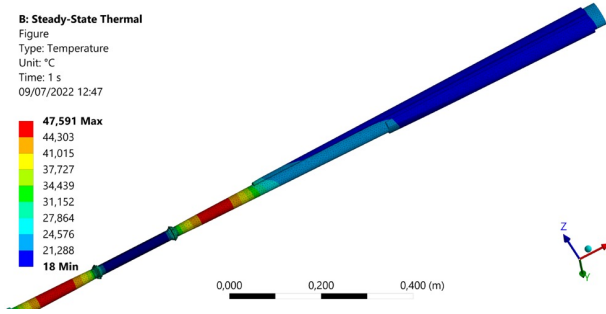
To reduce the cooling material, the design provides **five channels** for each side; in this way is possible to use the needed quantity of coolant and reduce the material, creating a light structure.



Impedance-related heat load distribution



B: Steady-State Thermal
Figure
Type: Temperature
Unit: °C
Time: 1 s
09/07/2022 12:47



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

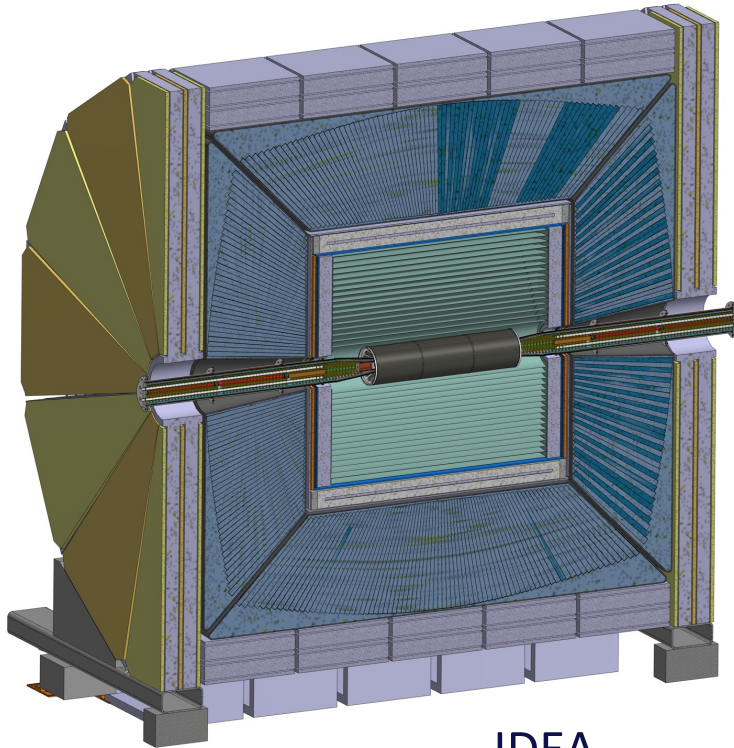
A. Novokhatski, SLAC



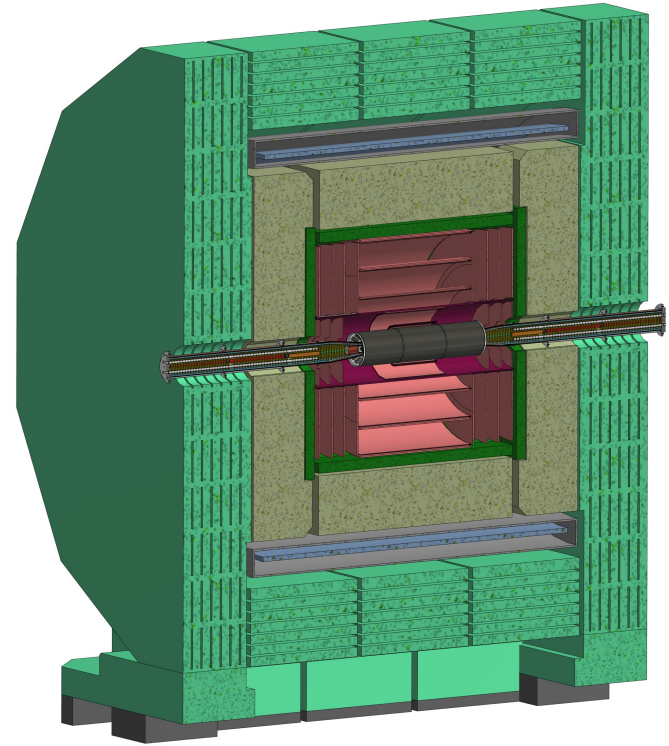
Fed into ANSYS to dimension the cooling system

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

Interaction Region in two detectors



IDEA



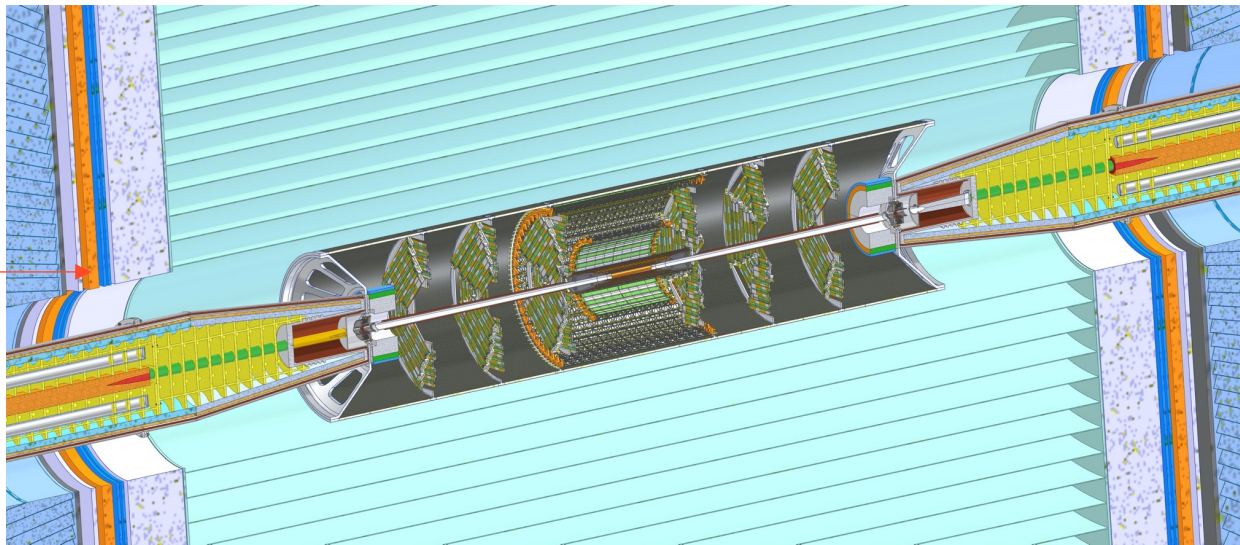
CLD

Central Support tube with endcaps

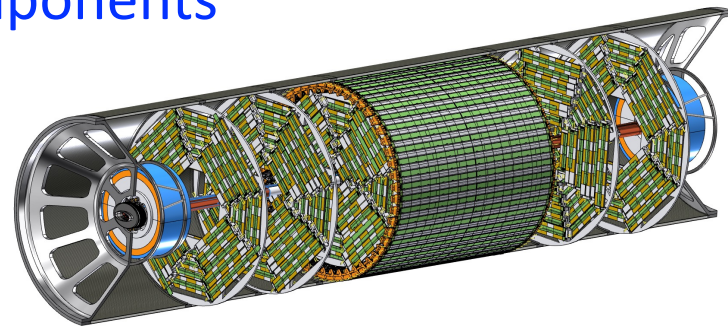
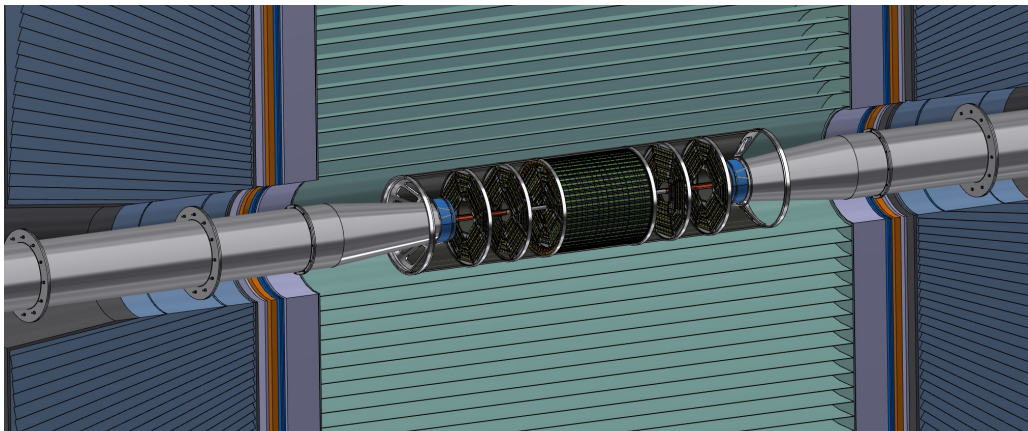
- All elements in the interaction region -beam pipe, vertex, tracker disks, LumiCal- are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment.
- The support tube is a **carbon-fiber lightweight rigid structure**.
- This study has been performed for the **IDEA** detector.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

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



Vertex integration with accelerator components

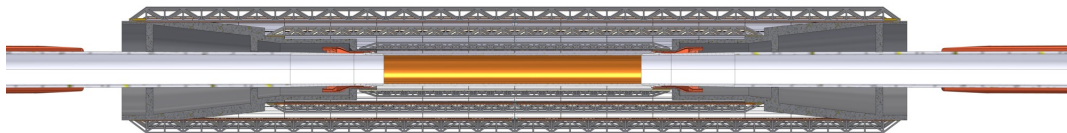


Vertex (MAPS) with 3 inner layers supported by the conical chamber and mounted with the beam pipe and LumiCal to the support tube

Vertex outer layers and 6 disks (MAPS) mounted directly on the support tube.

Imported full CAD designs in Key4HEP

Study of the services and cooling ongoing

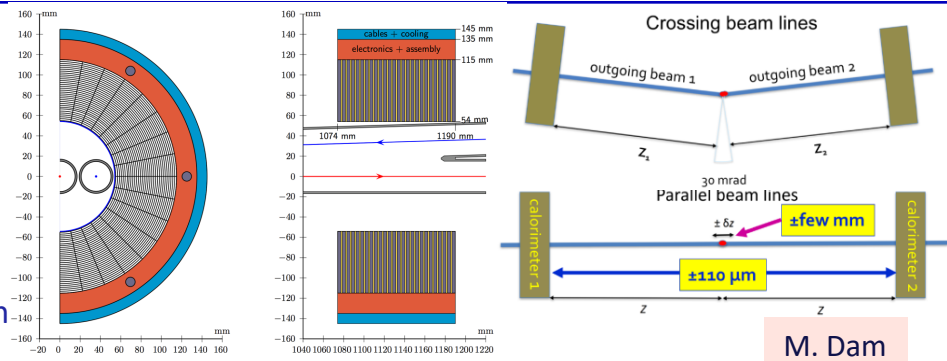


mockup planned for the support tube and detector components

LumiCal Integration

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

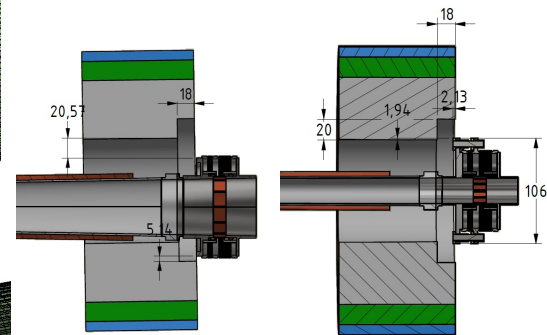
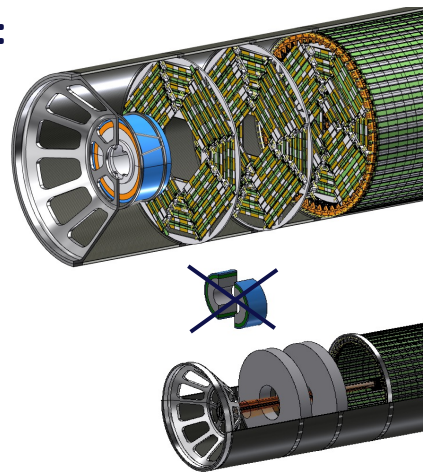
- Bhabha cross section 12 nb at Z-pole with acceptance **62-88 mrad** wrt the outgoing pipe
- The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines
- Requirements for alignment **few hundred μm** in radial direction
few mm in longitudinal direction



M. Dam

Study on the integration of the lumical performed:

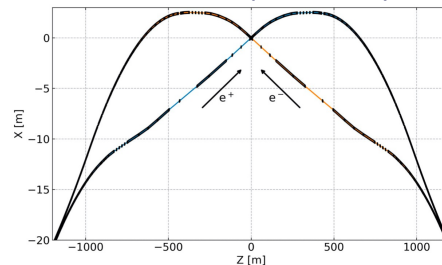
- Asymmetrical cooling system** in conical pipe to provide angular acceptance to lumical
- Support tube includes the lumical** (structural analysis with realistic weights performed)
- We avoid the splitting of the lumical in two halves for the assembly
- Engineering of the lumical required



slight modification to allow assembly

Synchrotron Radiation backgrounds

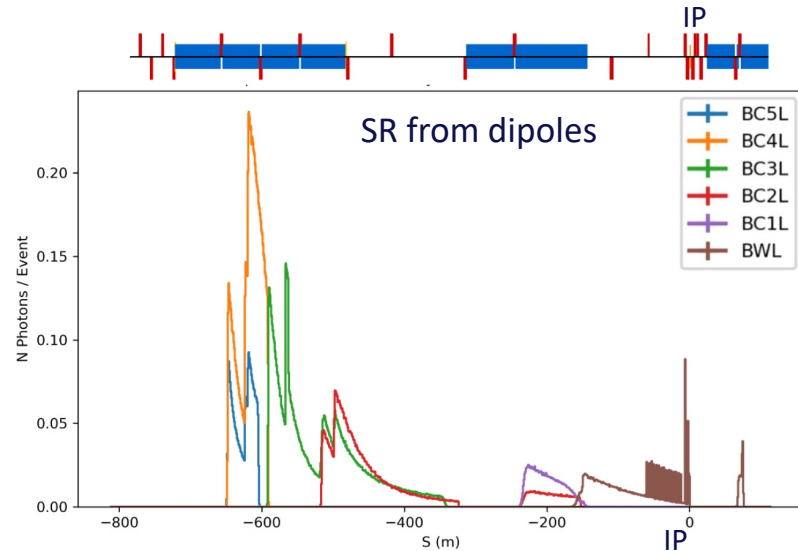
- Simulation of the synchrotron radiation (SR) starts **from 1.2 km upstream the IP**, simulation code: **BDSIM (GEANT4)**
- We evaluate the SR produced
 - by the **last dipoles and quadrupoles upstream the IR** -> can be a background source
 - by the **IR quads and solenoids** -> collinear with the beam and will hit the beam pipe at the first dipole after the IP.
- Simulation with **on-axis beam**
 - Gaussian **core** beam (98% of the beam)
 - Non-Gaussian beam tails** to $10 \sigma_x$ and $50 \sigma_y$ (2%)
- Characterisation of the SR for **all beam energies**
- SR collimators (W, movable) and masks (W, 2 cm long) implemented**
- SR power deposition on the IR evaluated, acceptable values**
- Study of the **impact of SR** in the IR with **off-axis top-up injection** -> constraints to the injection scheme
- Study of the **impact of SR** in the IR for the **alternative HFD** lattice (dedicated talk on Thursday, alternat. optics session)
- Also other simulation codes are used, e.g. SYNC_BKG, SYNRAD+, MDISim, all in good agreement. Each has slightly different features and adds additional and useful informations.



Photon tracks are being tracked with key4hep to evaluate beam induced detector backgrounds in the detectors

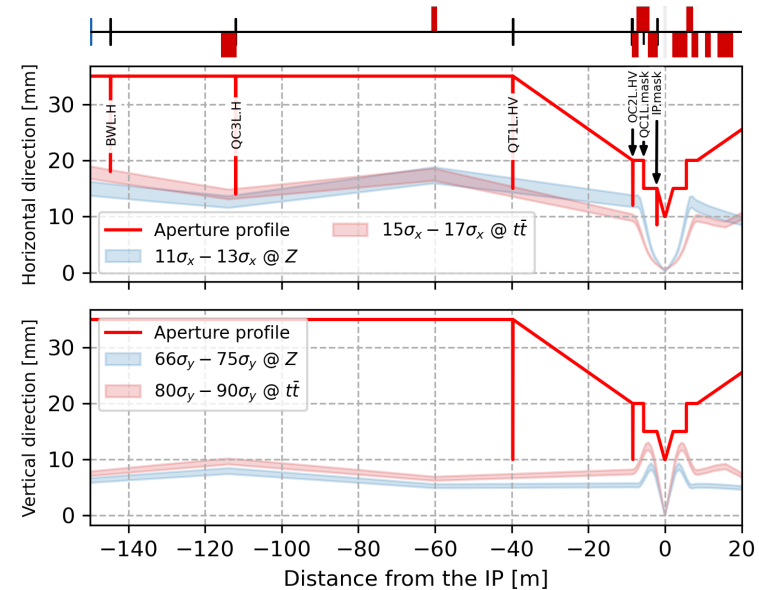
A. Ciarma

Synchrotron Radiation backgrounds



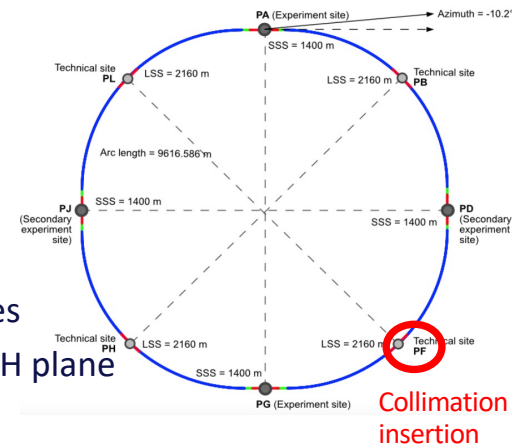
- Radiation from last bend reaches the IP
- SR photons from solenoid do not hit near the IP
- SR from FF quadrupoles leads to losses near the IP when beam tails are considered

SR collimation scheme



FCC-ee Collimation system & Beam losses in the IR

- **New Xtrack-BDSIM** simulation framework
combines particle tracking and particle-matter interactions in the collimators
- **Collimation scheme for beam halo losses** with a workflow similar to LHC
 - Betatron collimators (upstream PF): 1 primary (MoGr) + 2 secondary (Mo), H+V planes
 - Off-momentum collimators (downstream PF): 1 primary (MoGr) + 2 secondary (Mo), H plane
- Collimators set to protect the aperture bottlenecks in the IR and safely dissipate the loss power away from the physics detectors and equipments.
- Also the SC IR magnet system need to be protected from loss power, to avoid the risk of quenches.
- The collimator system need to be robust and do not have to produce backgrounds.
- **IR beam loss maps** found for various beam loss scenarios.
- **Beam power loss evaluated for +/- 100 m from the IP** → safe values found



Primary losses are being tracked with key4hep to evaluate beam induced detector backgrounds in the detectors

A. Ciarma

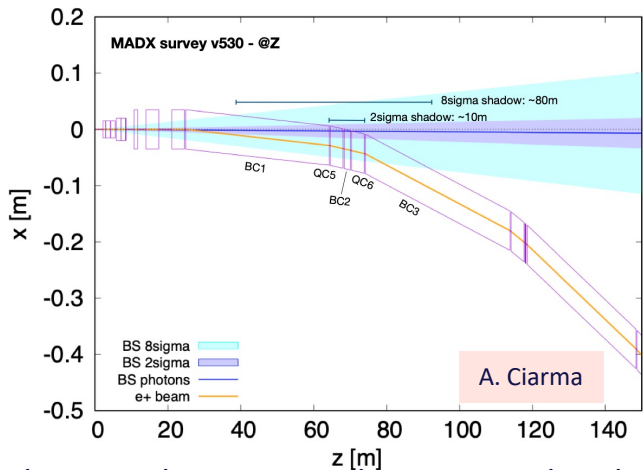
Beamstrahlung Photon Dump

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

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

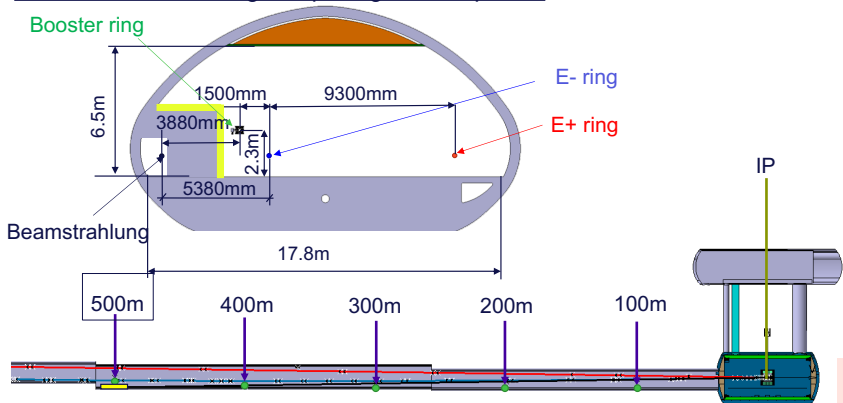
	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

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

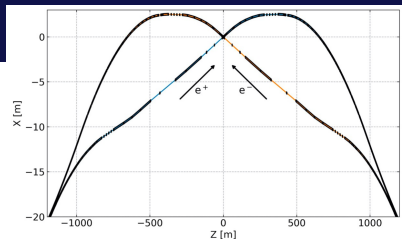


High-power beam dump needed to dispose of these BS photons + all the radiation from IP

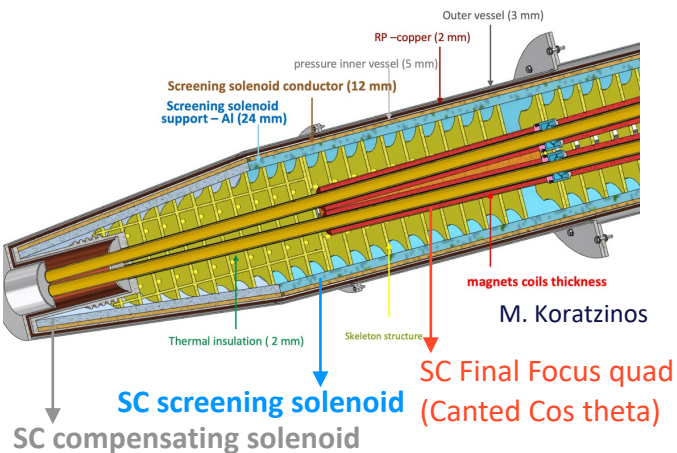
- liquid lead target as dump absorber material is under investigation
- Shielding needed for equipment and personnel protection for radiation environment

IR Magnets

IR goes +/- 1.2 km around the IP



B. Parker

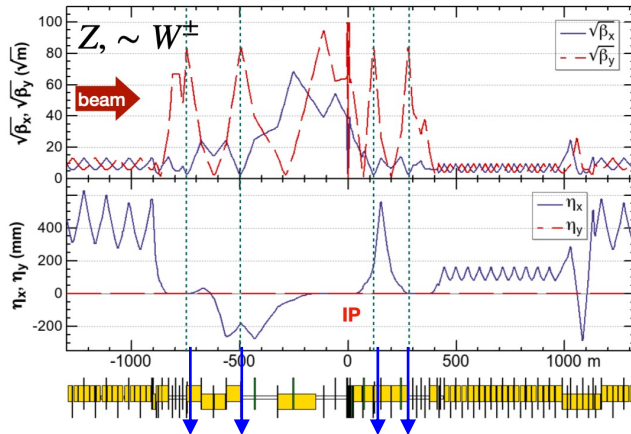


A. Foussat

IR Optics

FCCee_z_530_nosol_23.sad

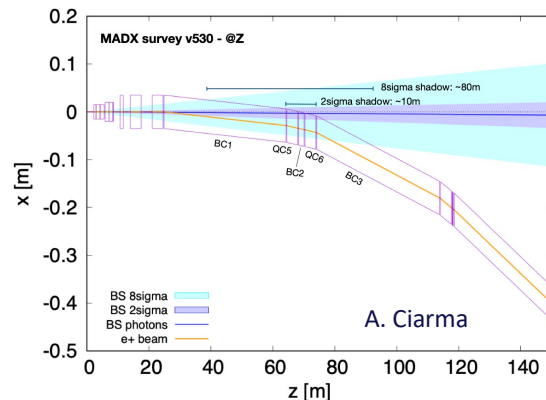
K. Oide



SC IR sextupoles for

crab-waist and chromaticity correction

Carl J Eriksson



A. Ciarma

large yoke aperture radius required for the (normal conducting) magnets after the IP to handle the beamstrahlung radiation

- Canted Cost theta FF quad
- Compensating and screening solenoid
- Corrector windings

MDI- IR Magnet system

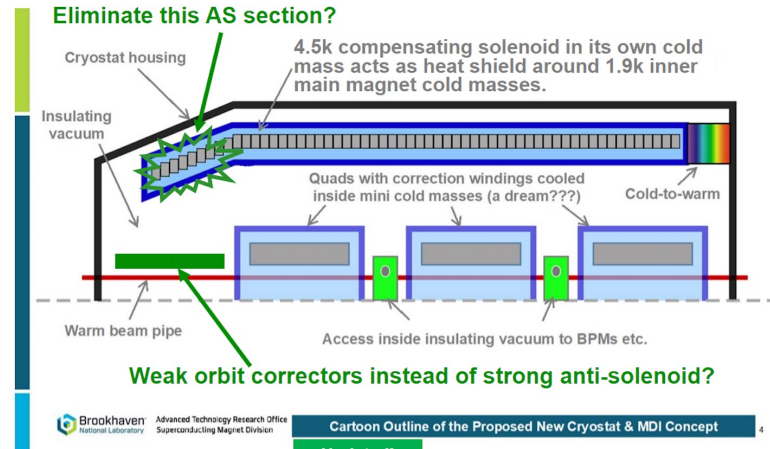
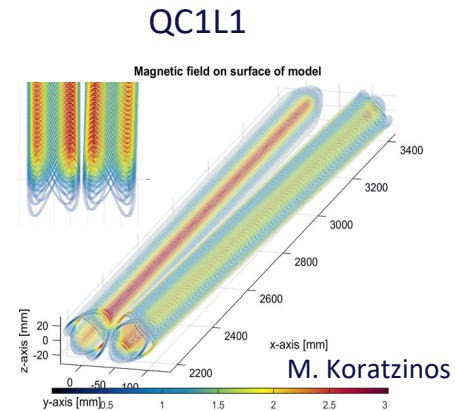
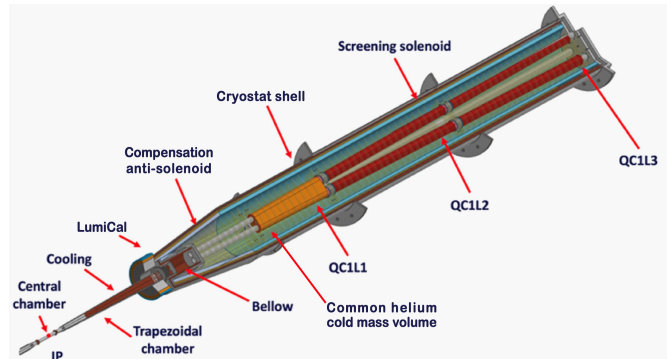
SC magnets inside the detector

BNL -and potentially other US labs- are interested to collaborate with CERN on the SC IR magnet system design

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

IR magnet system development flow:

- Functional specification
- Preliminary design
- Detailed design and manufacture
→ final design layouts



Summary

- Significant progress on all 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
- IR magnets, ongoing work to progress on a complete design of magnets, cryostat, correctors, and diagnostics
- Alternative solenoid compensation under evaluation, even if not for the midterm review

Backup

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 $\varepsilon_{y,lattice}$	[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 frequency (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 $(\theta_x\sigma_z,BS)/\sigma_x^*$		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

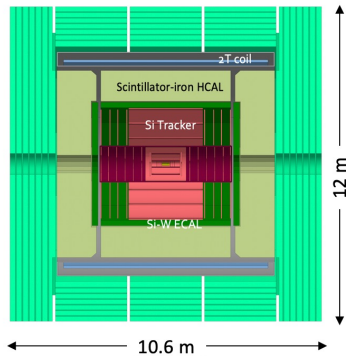
^aincl. hourglass.

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

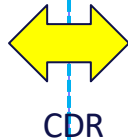
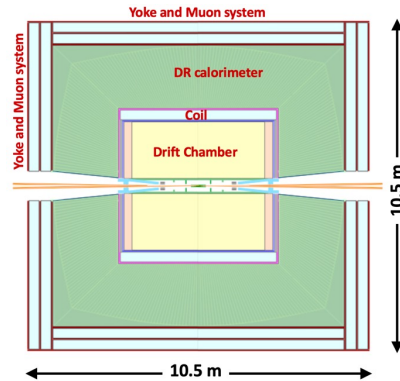

- Parameters such as tunes, β^* , crab waist ratio are chosen to maximize the luminosity keeping the lifetime longer than 4000 sec without machine errors.
- The choice of the parameters including the sextupole settings still has a room for further optimization.
- Including injection/extraction/ collimation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

FCC-ee Detector Concepts

CLD

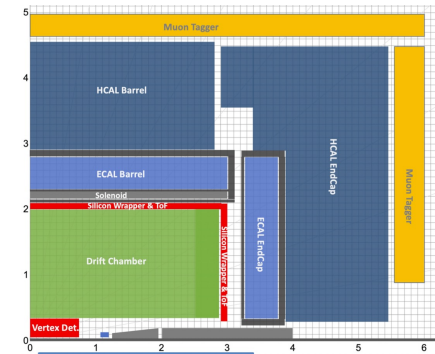


IDEA



CDR

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. powerful PID;
- Monolithic 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.

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

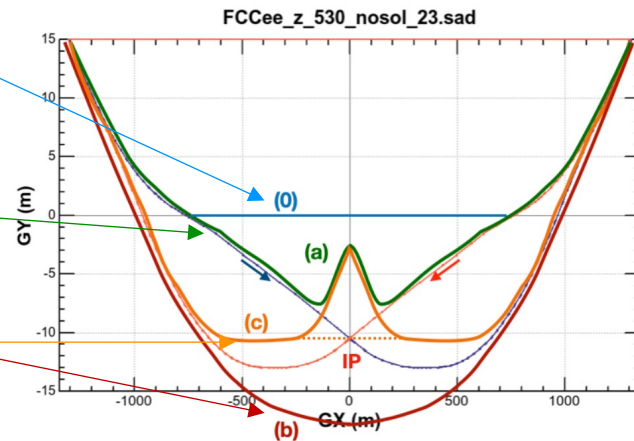
Possibilities for location of booster

(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

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>