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.

FUTURE CIRCULAR COLLIDER
Innovation Study

INFN LNF
Istituto Nazionale di Fisica Nucleare

MDI STATUS & PLANS

Manuela Boscolo (INFN-LNF)

FCCIS 2023 WP2 Workshop
13-15 November 2023,
Angelicum, Rome, Italy

Outline

- Introduction & MDI workshop in Frascati
- **Highlights on the progress of some of the main key topics of the MDI design with perspectives toward the demonstration of MDI feasibility**
  - Mechanical model of the IR and integration of detector
  - Background simulations

Introduction

- Today I will give an overview of the MDI with the status & plans
- Detailed discussion on MDI challenges and technical issues in the dedicated topical workshop in Frascati, Thursday and Friday this week (16-17 November)

FCCIS WP2 Task3 Workshop
16-17 November 2023 Frascati

https://agenda.infn.it/event/37720/

Workshop Goals

- Sign-off meeting for the IR mockup
- Discuss critical concepts for the MDI design & IR mockup, in particular
  - Accelerator and detector constraints in the IR
  - IR quads & cryostats
  - Synchrotron radiation
  - IR Beam losses
  - Heat loads
  - IR Radiation damage
  - IR optics
  - Alignment
  - Vacuum

FUTURE CIRCULAR COLLIDER

FCC-ee MDI & IR mockup Workshop

16–17 Nov 2023
Laboratori Nazionali di Frascati
Europe/Rome timezone

Enter your search term

Welcome to the FCCIS MDI and IR mockup workshop in Frascati!

The MDI and IR mockup workshop of FCC Innovation Study of WP2 and Task 3 will be held in Frascati, National Laboratories of INFN, from 16 to 17 November 2023.

This workshop will focus on Machine-Detector-Interface studies and on the IR mockup, covering topics such as:

- IR mockup critical concepts,
- Beam losses in the IR,
- Synchrotron radiation,
- IR HOM calculations,
- Vertex detector integration & cooling,
- Accelerator and detector constraints in the IR.

We are looking forward to seeing you in Frascati !

Overview
Timetable
Registration
Participant List
Committees
Hotel suggestions
Privacy Policies
Zoom Conference Room
Wifi Internet Access

Contacts
fcc.secretariat@cern.ch
fcc.logistics@lists.lnf.infn.it

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.

Starts 16 Nov 2023, 08:00
Ends 17 Nov 2023, 17:15
Europe/Rome

Laboratori Nazionali di Frascati
Aula Salvini
Via Enrico Fermi, 60, 00044 Frascati RM, Italie
Go to map

FRANK ZIMMERMANN
Manuela Boscolo

There are no materials yet.

Workshop Agenda

Discussions welcome in all sessions

Satellite meetings possible

Thursday, 16 November 2023

Time	Session
09:00	
09:25	MDI overview & IR mockup
11:00	Coffee break
11:20	Vertex detector mockup & cooling
13:05	Lunch
14:30	Vacuum & heat load
15:40	Coffee break
16:00	Lab Tour of DAFNE & SPARC
17:00	IR optics
18:30	Self-standing dinner at LNF

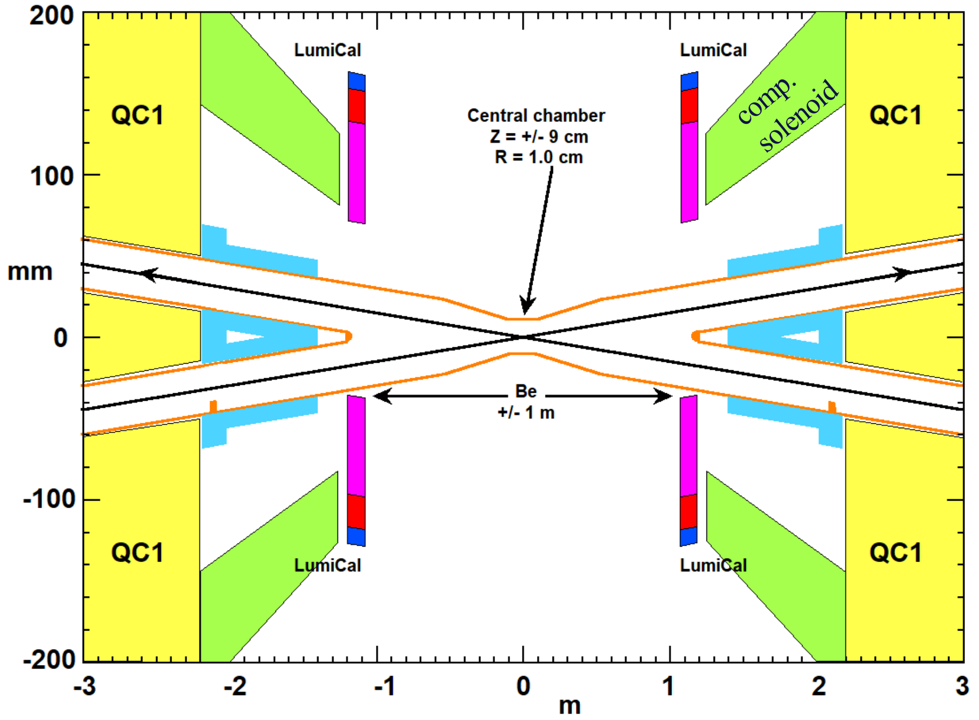
Friday, 17 November 2023

Time	Session
08:30	Machine & detector integration
10:20	Coffee break
10:40	IR quads & cryostat
12:10	Discussion
12:20	SR, beam losses, bkg
13:00	Lunch
14:30	SR, beam losses, bkg
15:10	Summaries & next steps
16:40	**Closing** - FRANK ZIMMERMANN (CERN)
16:55	Adjourn

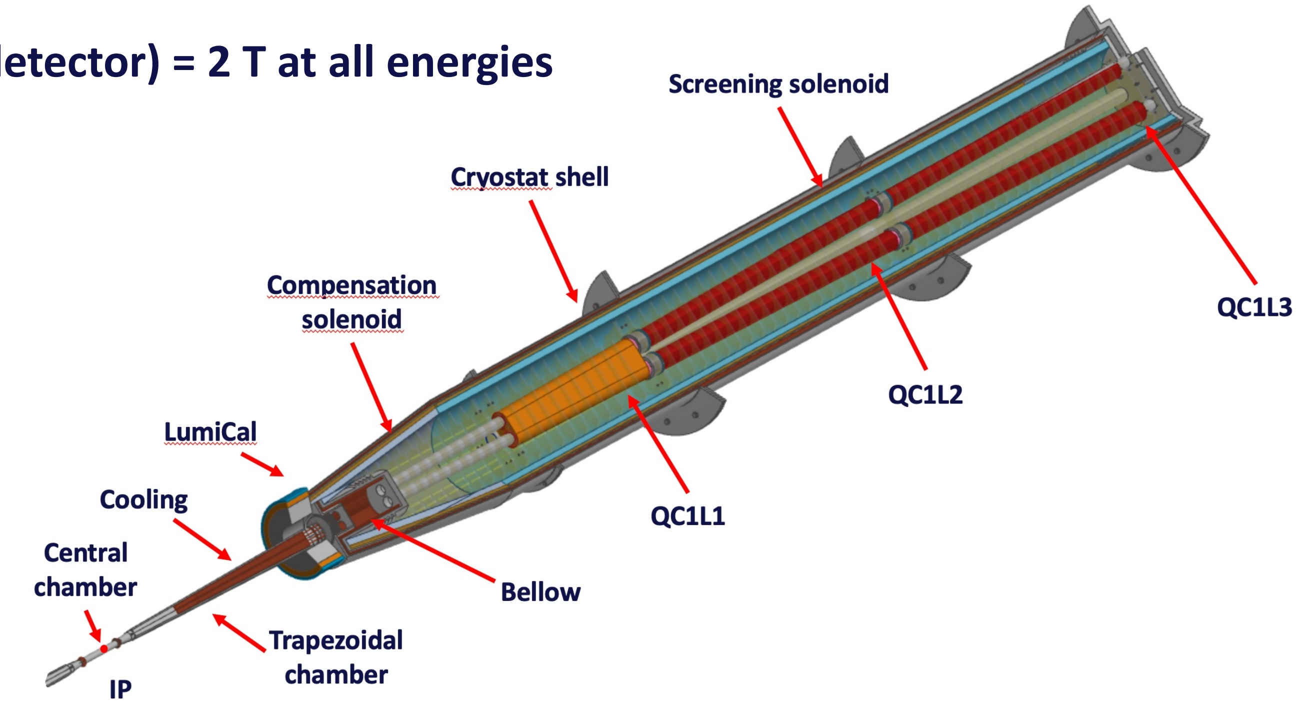
High-level Requirements for the IR and MDI region

- **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 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 Baseline 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.

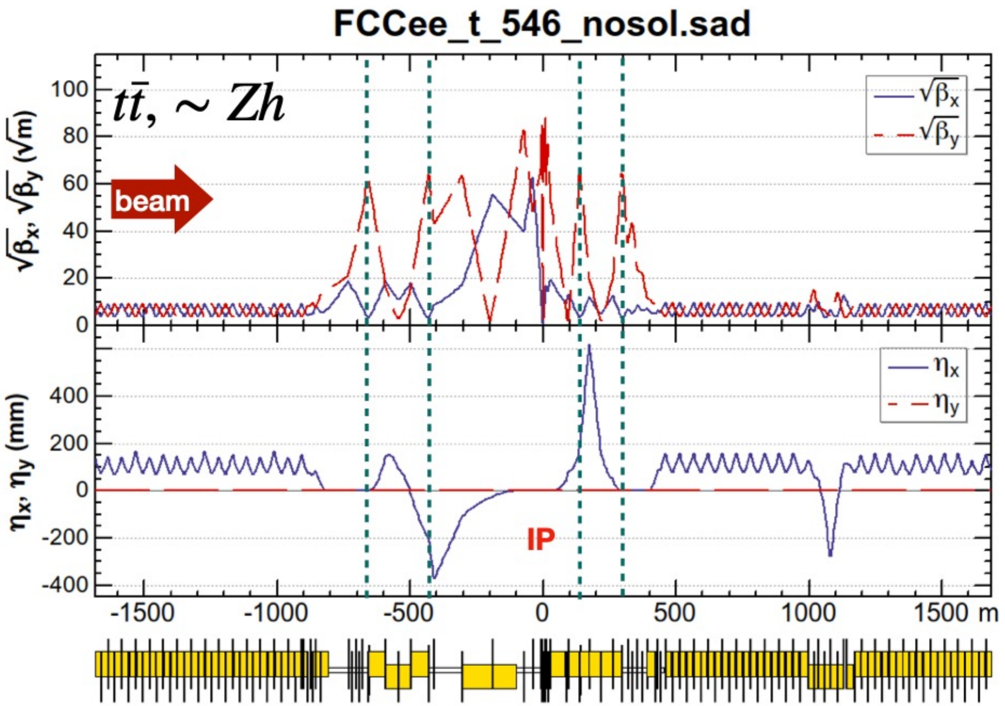
3D view of the FCC-ee IR until the end of the first final focus quadrupole

QC1 almost entirely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at 5.56 m.

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

Baseline IR optics

see talk by K. Oide, this workshop

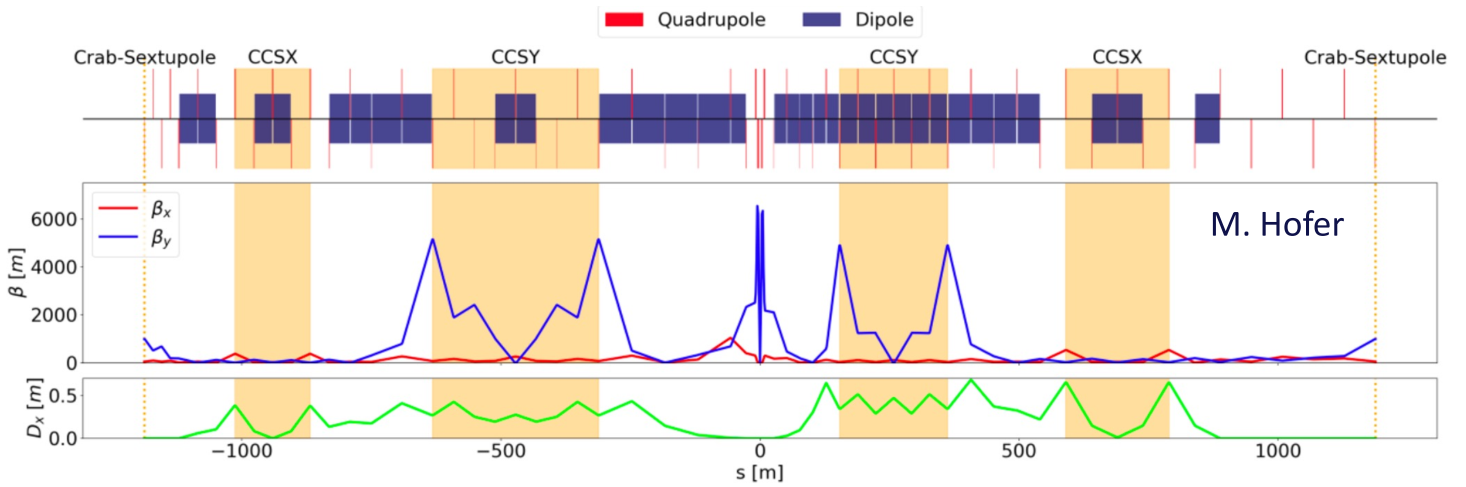


- Crab waist/vertical chromaticity correction sextupoles are located at the dashed lines, they are superconducting.

LCCO (or HFD) Optics

see talk by P. Raimondi, this workshop

ttbar



LCCO: Local Chromatic Correction Optics
HFD: Hybrid FODO

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

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

LCCO Final Focus - Impact to IR design

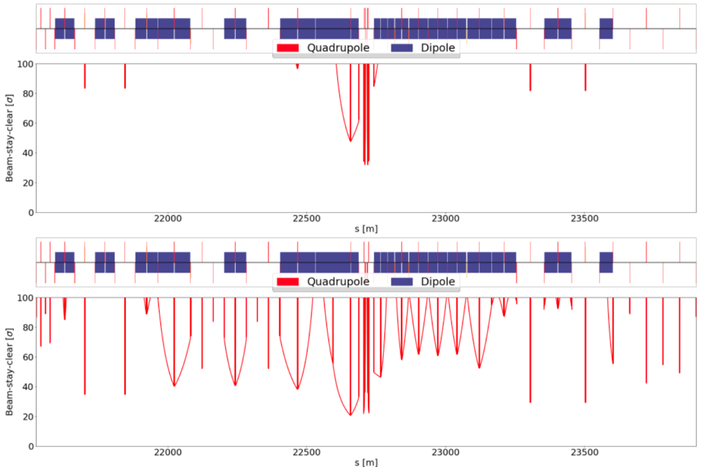
- The Final Focus is optimized to have the **largest possible beam stay clear (BSC) and minimum losses** in the final focus system and all the way through the IR
- The goal of the FF design is to have the **dynamic aperture larger than the physical aperture**

M. Hofer, link
173rd Optics meeting

Beam Stay Clear

Z-pole

ttbar



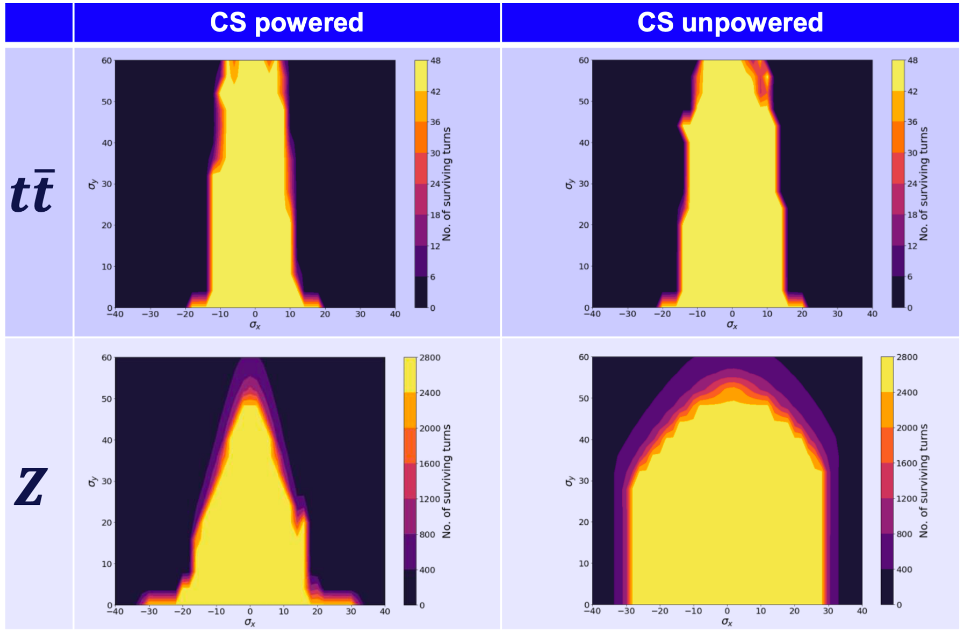
Preliminary aperture model same as baseline, r=35 mm everywhere, but: r=15 mm at QC1; r=20 mm at QC2

Bottlenecks:

- **baseline Z: 14.5 σ_x / tt$_{bar}$: 14.4 σ_x**
- **LCCO Z: 31 σ_x / tt$_{bar}$: 20 σ_x**

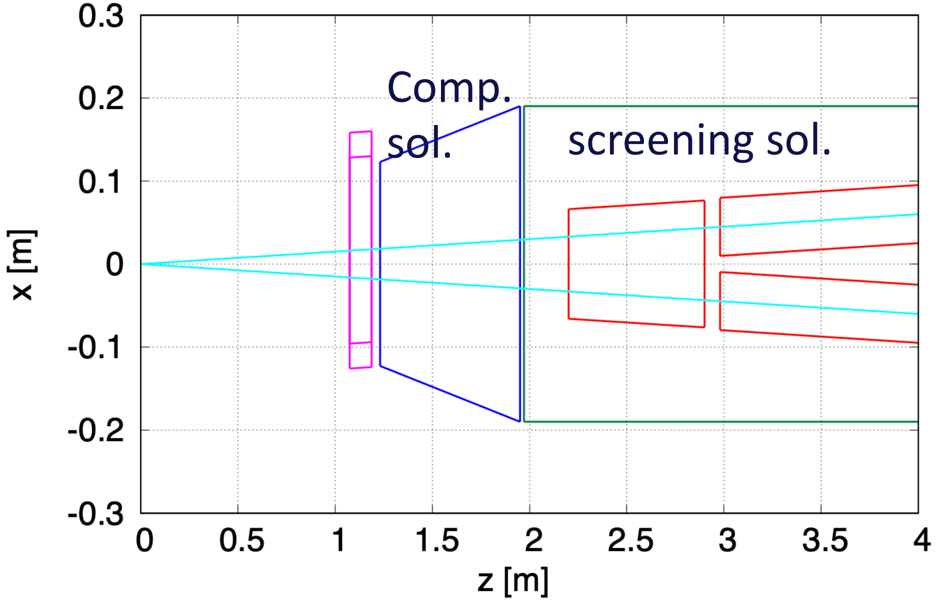
Dyn. Apert. with SR and Crab sextupoles (CS)

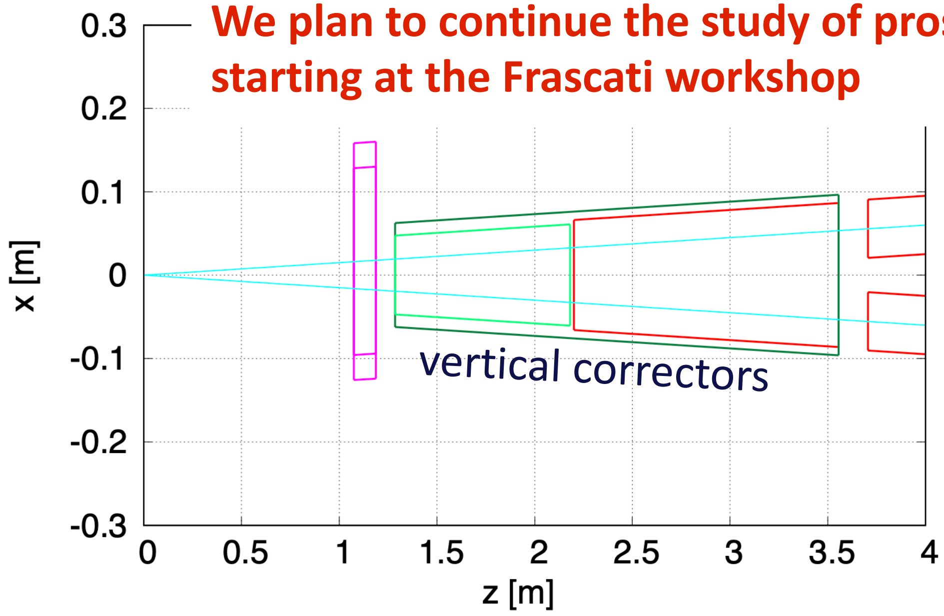
- DA tracking performed using Xsuite and Xdyna
- Crabsextupoles (CS) powered to 80% (Z)/ 40% (tt) of their geometric strength
- Tracking performed for ~ one damping time 2500 turns (Z)/ 45 turns (tt)
- CS have small impact on DA at Z,



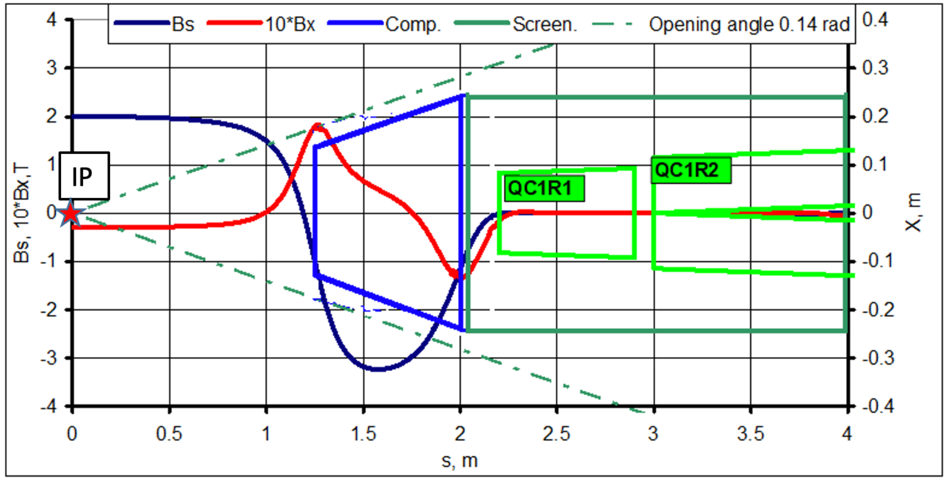
Solenoid Coupling Compensation Schemes

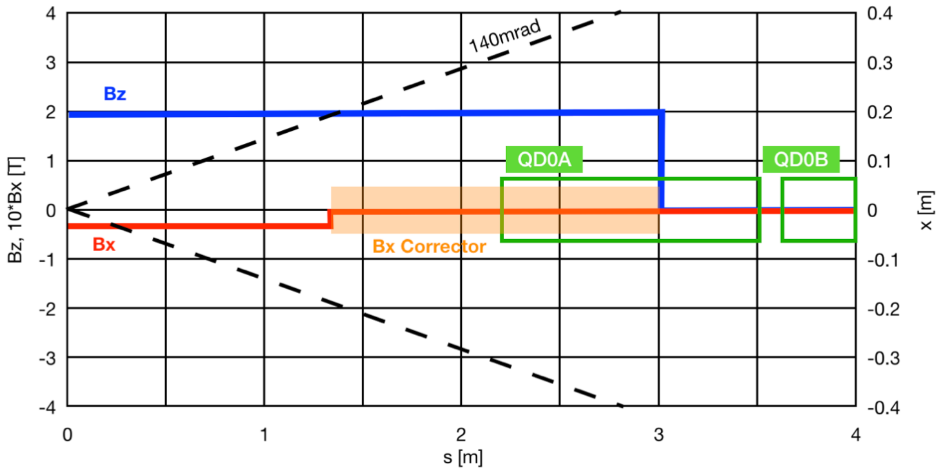
We plan to continue the study of pros & cons starting at the Frascati workshop





Field distribution along the reference trajectory





Standard Solenoid Compensation Scheme

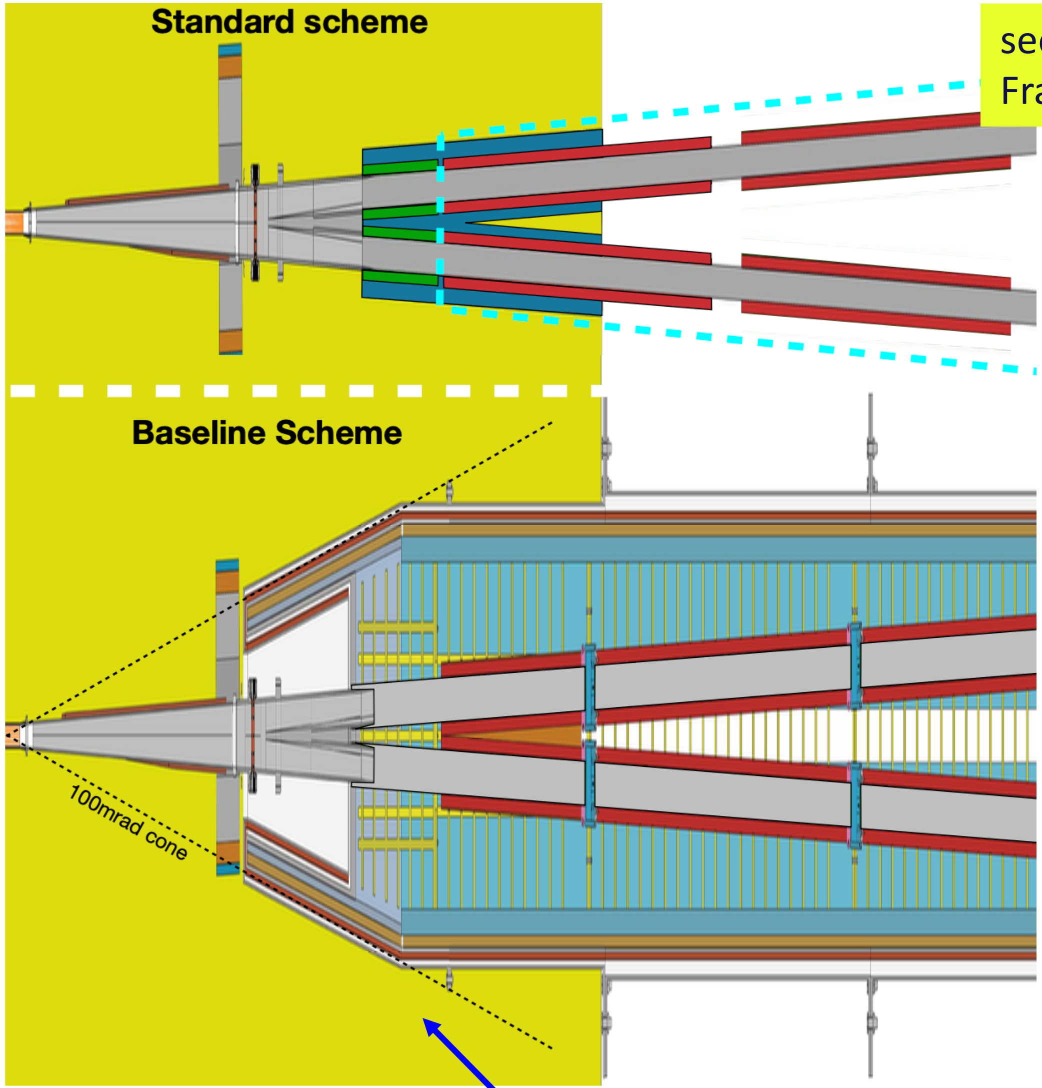
A compensation scheme similar to that used in DAΦNE would allow for the **removal of the IR anti-solenoids**, resulting in benefits such as **increased available space** in the MDI area.

- Rotation of FFQs to fit beam orientation
- Skew quadrupoles
- Vertical correctors in the IR

Antisolenoids far from the IP to cancel $\int B_z ds$

Vertical emittance blowup with this scheme:

$$\epsilon_y = 0.040 \ [\pi \ pm \ rad]$$



see talk by A. Ciarma, Frascati workshop

Inner cryostat design between the lumical and QC1a to be looked at, P. Borges Sousa, Frascati workshop

We plan to continue the study of pros & cons for this solution.

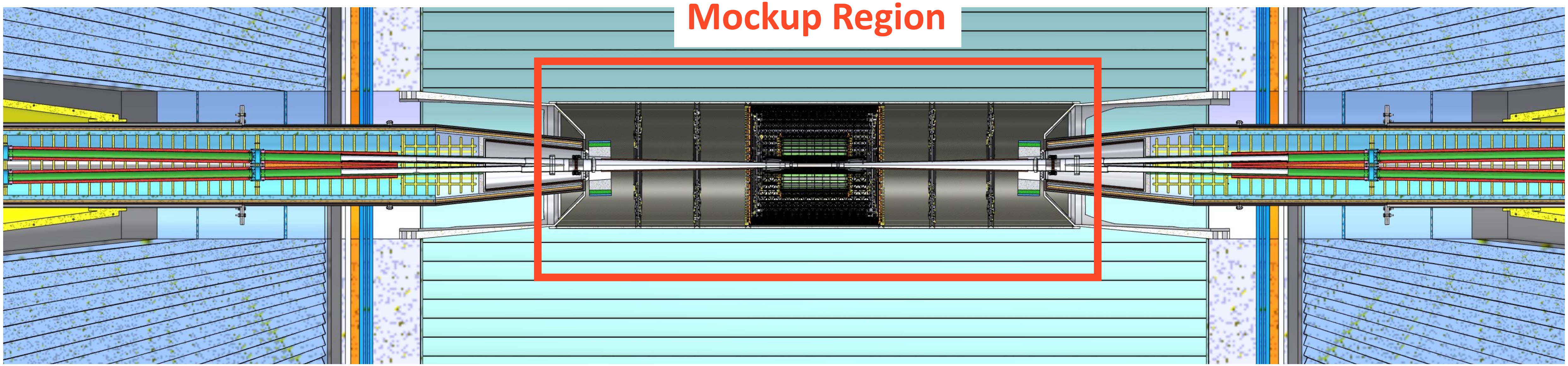
Solenoid coupling compensation scheme – *Conventional* scheme

- The detector solenoid field is compensated with **two anti-solenoids at about +/- 20 m from the IP and skew quads around the FF quads** with a relative gradient of about 2×10^{-3} at Z and 0.5×10^{-3} at ttbar.
  [This is equivalent to rotate the FF quads on the solenoid-rotated reference system].
- The horizontal crossing angle in the detector field generates vertical orbit, i.e. vertical emittance growth.
- This is coped with **weak vertical correctors** (kick of the order of **10^{-4} μrad**) placed after the crotch and next to FF quads, one per beam. This way the smooth correction generates a very small **vertical emittance growth** (about **0.04 pm**, ~4% term, about ten times less wrt the present baseline scheme) .
- *Additionally:* machine global coupling due to residual compensating errors & chromatic coupling is four times lower if the **sign of the 2T detector solenoidal field is alternated between one IP and the next**. **Four times lower systematic errors**.
- In addition, as it will be done for the baseline scheme:
  - vert & hor correctors are needed next to QC1 and QC2 for IP orbit bumps, to correct the orbit.
  - Skew correctors next to final focus sextupoles (SDY1 and SDY2) at 200 and 400 m from the IP are needed to correct IP dispersion.

Comments:
- The detector integral field is set to zero with the antisolenoid, but this is required only to preserve the longitudinal polarization. (Quads+skew quads are enough to control the solenoid induced coupling.)
- The anti-solenoid will be much cheaper and simpler of the comp. solenoid because the section beampipe in that location is about 70 mm diameter instead of 500 mm.
- SLC, LEP, DAFNE, PEP-II, … adopted this scheme, proven to be extremely effective.

FCC-ee Central Interaction Region

zoom at the central region about ± 1.2 m

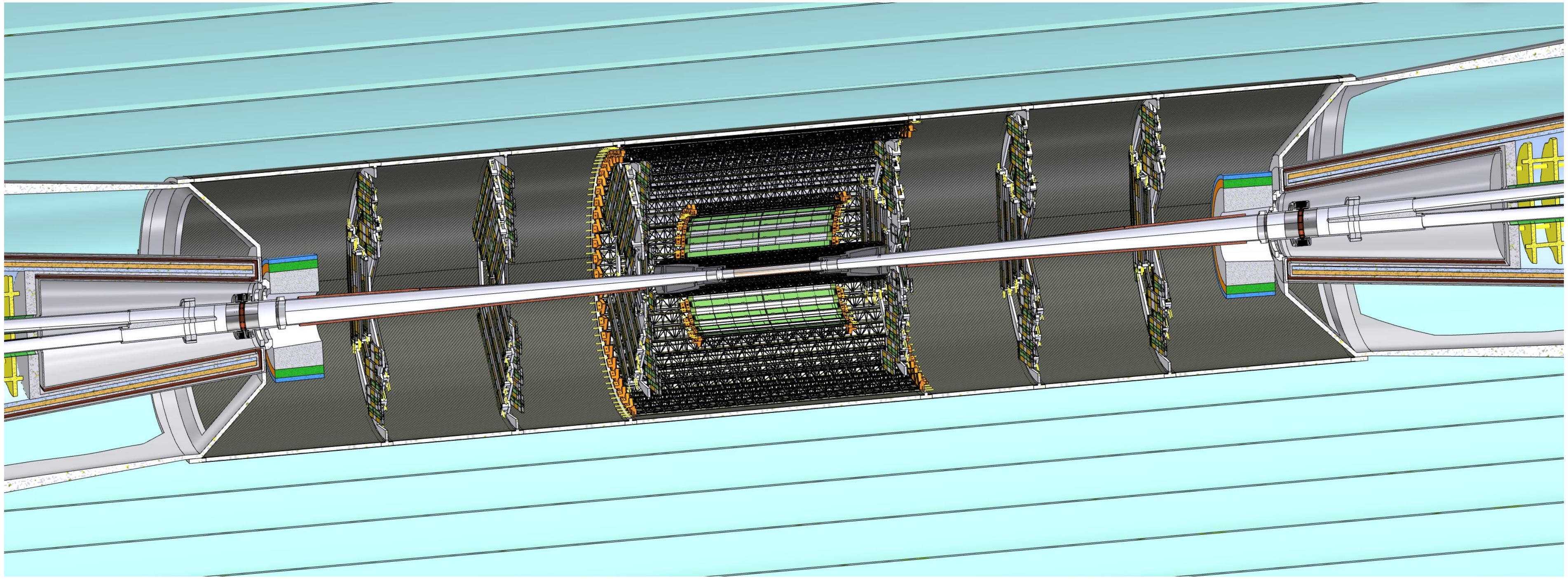


View including the rigid support tube, vertex detector and outer trackers

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

FCC-ee Central Interaction Region

zoom at the central region about ± 1.2 m



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

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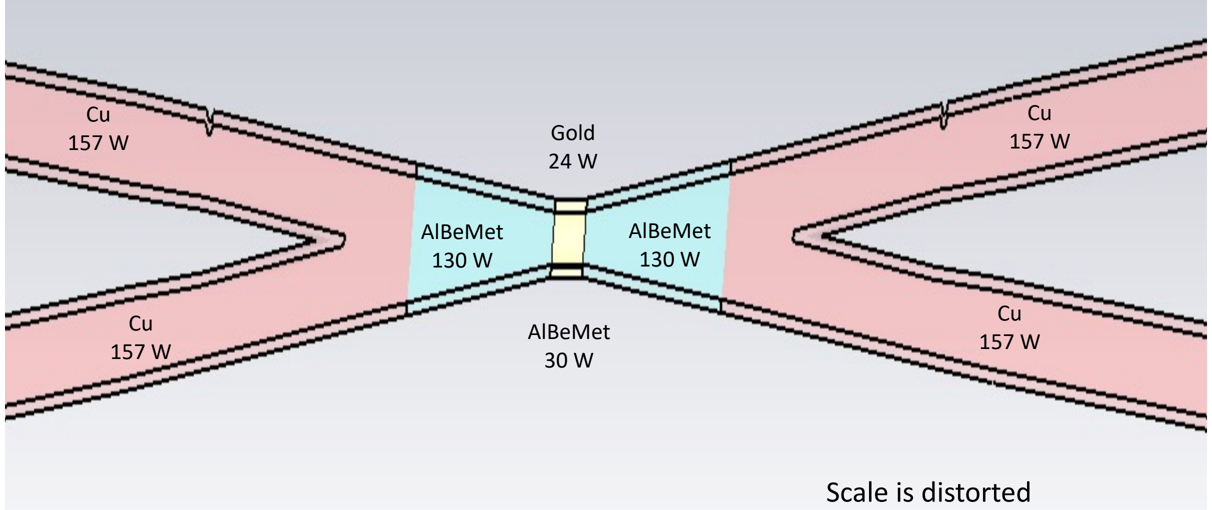
Impedance-related heat load distribution

see talk by A. Novokhatski, Frascati workshop



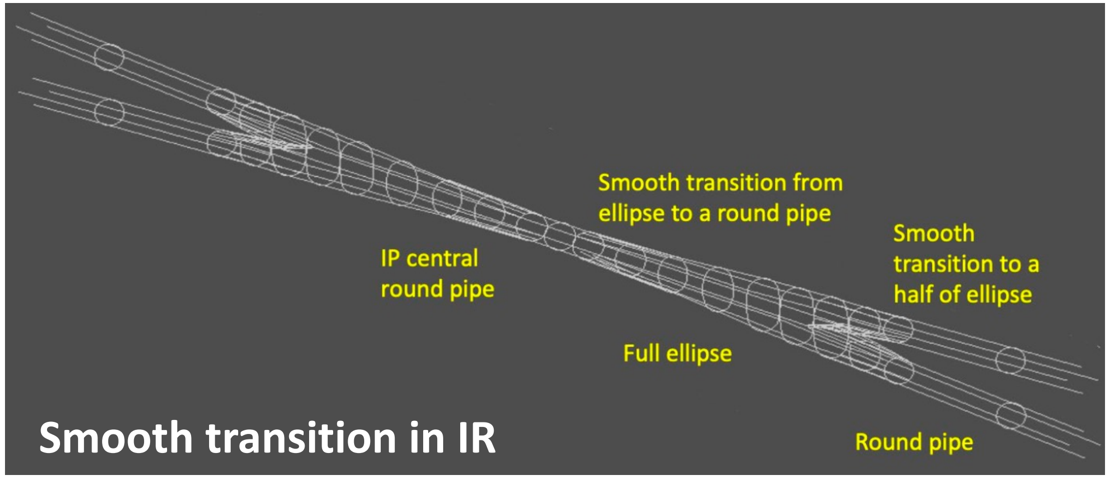
parameter	value
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

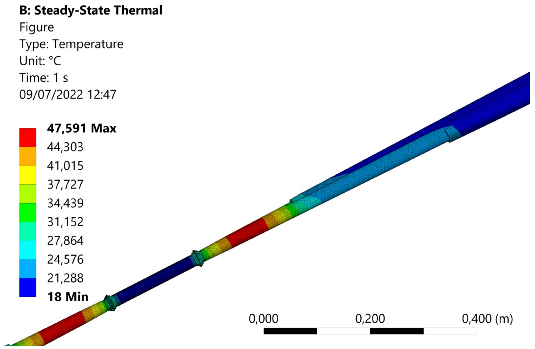
CST wakefields evaluations

Estimate heat load

↓

Fed into ANSYS to dimension the cooling system





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

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

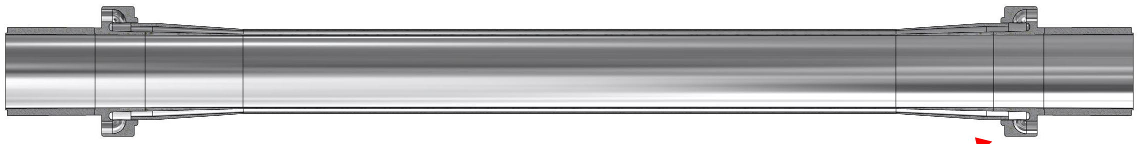
Ref. A. Novokhatski, F. Fransesini, *et al.* "*Estimated heat load and proposed cooling system in the FCC-ee IR beam pipe*", MOPA092, IPAC23

Low impedance central vacuum chamber

F. Fransesini, Frascati workshop

warm and cooled

Prototyping planned with the IR mockup



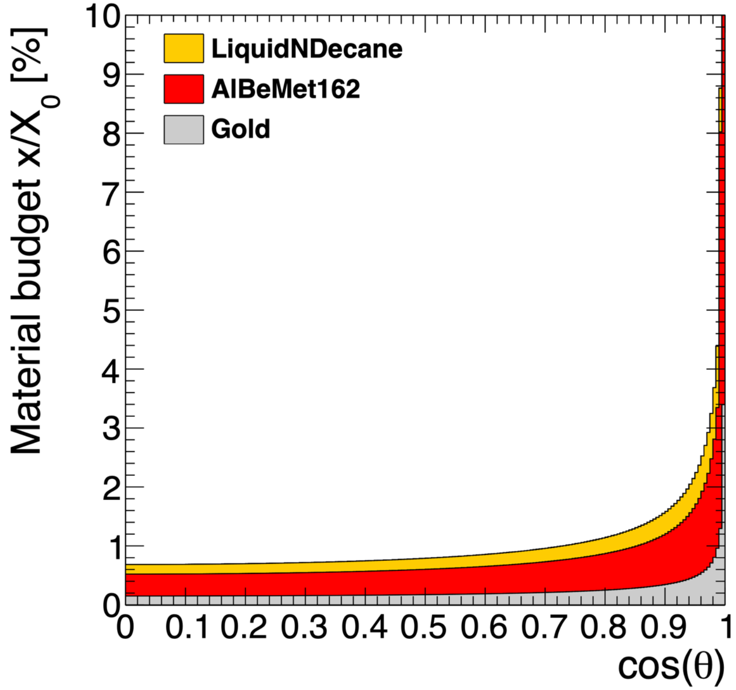
Inlet/outlet for paraffin cooling , all AlBemet, 180 mm long

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

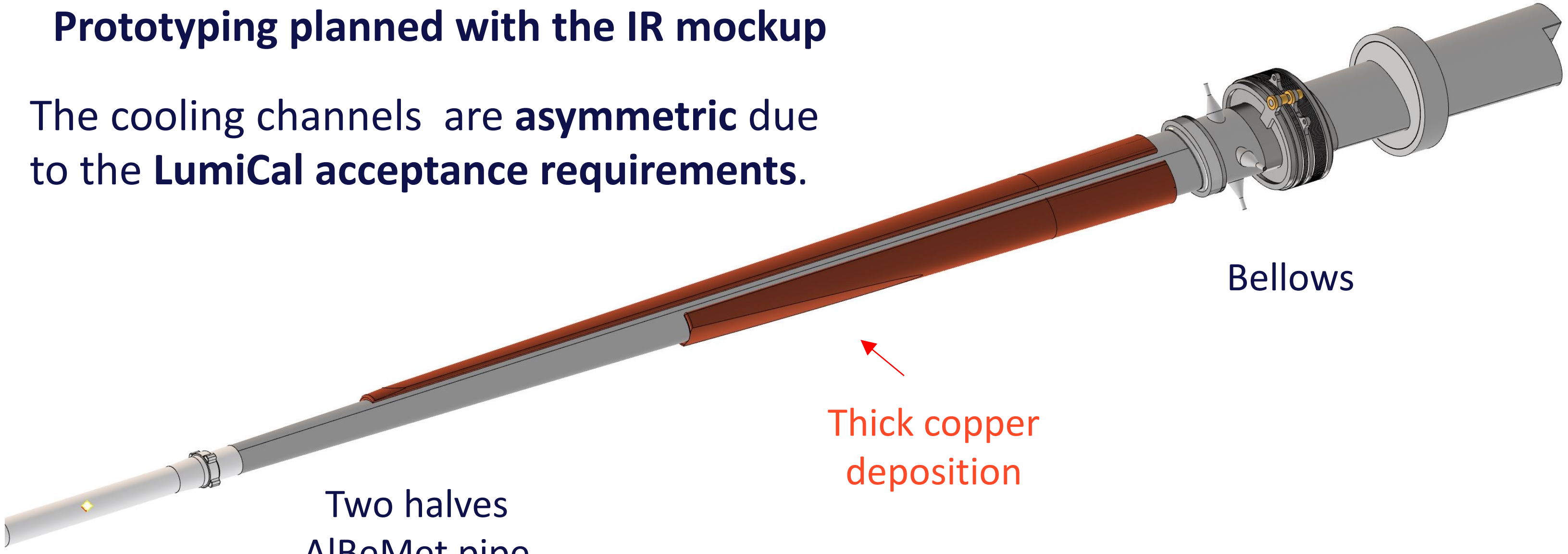


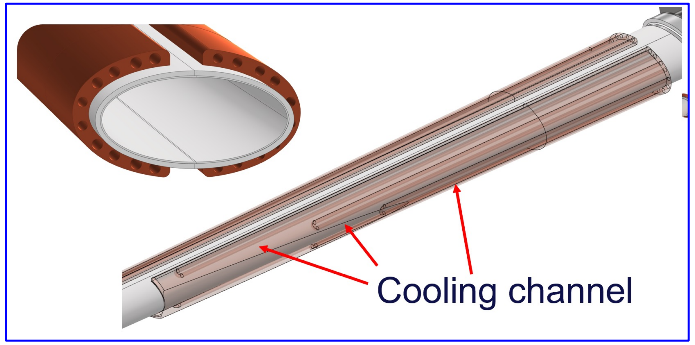
This modification to all AlBeMet recently implemented during the vertex detector integration and due to the constraints from the lumical acceptance.

Low impedance Conical vacuum chamber warm and cooled

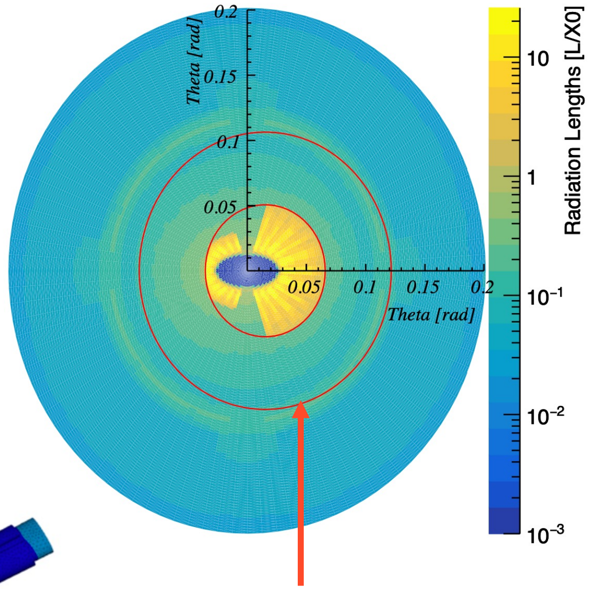
Prototyping planned with the IR mockup

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



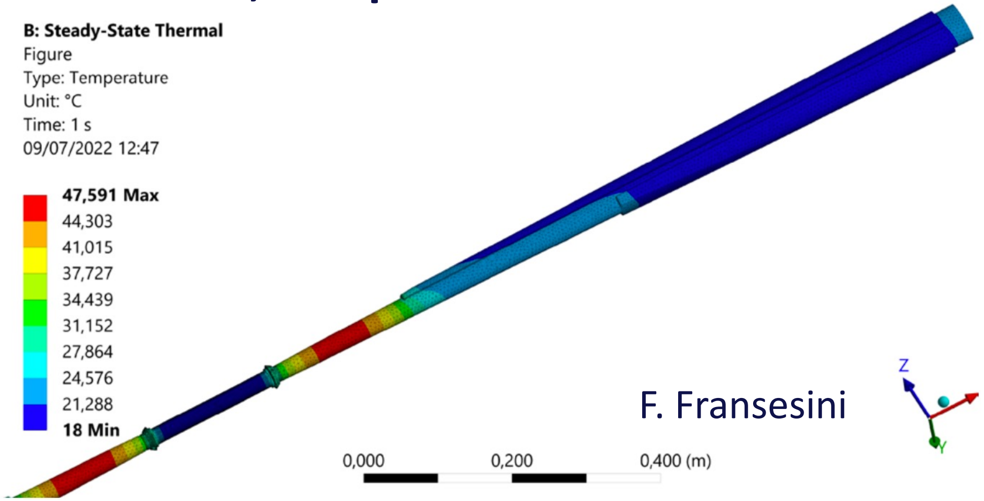


Beam pipe material budget as seen from lumical



Geant4, A. Ciarma

ANSYS, Temperature distribution



F. Fransesini

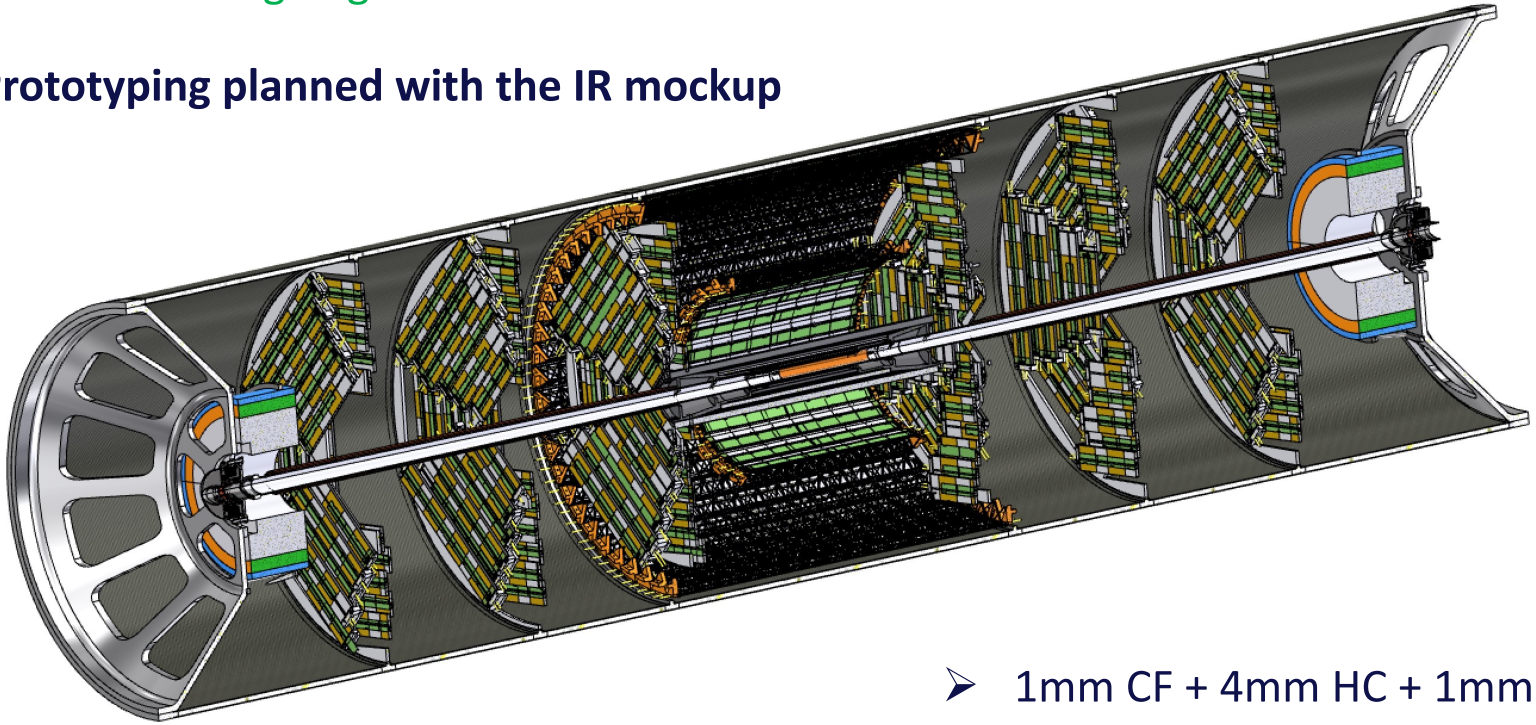
Support cylinder

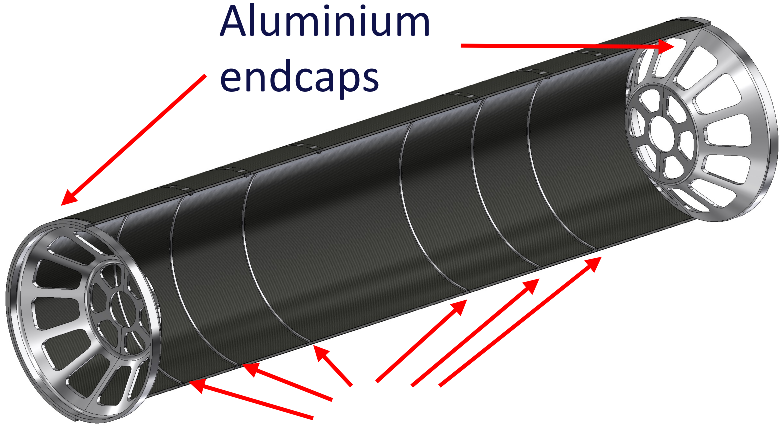
All elements in the interaction region (Vertex and LumiCal) are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment

- Provides a cantilevered support for the pipe
- Avoids loads on thin-walled central chamber during assembly or due to its own weight

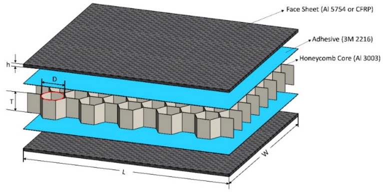
- Once the structure is assembled it is slided inside the rest of the detector
- Studies on-going where to anchor it

Prototyping planned with the IR mockup





➢ 1mm CF + 4mm HC + 1mm CF

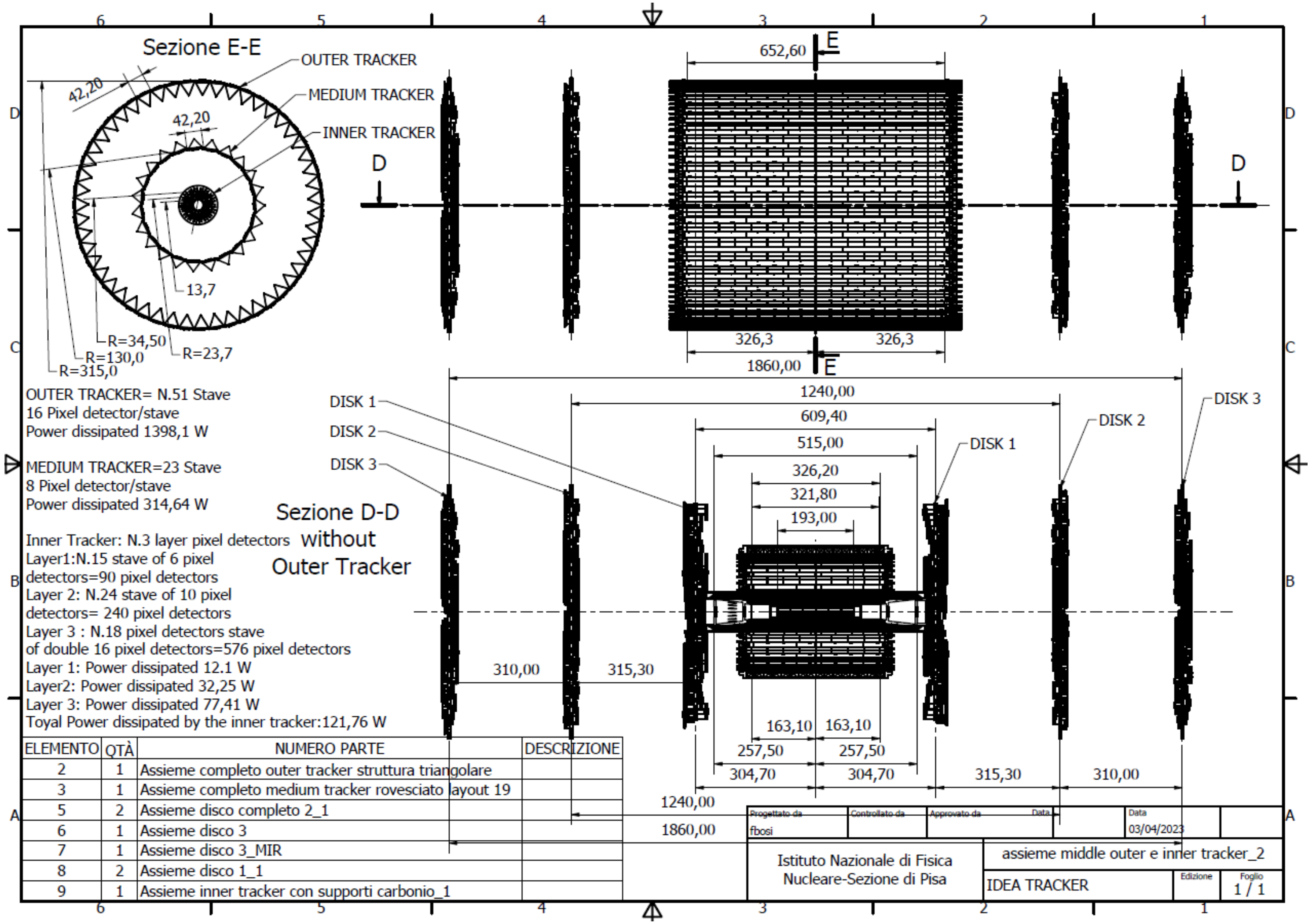


Overall Vertex detector layout and dimensions

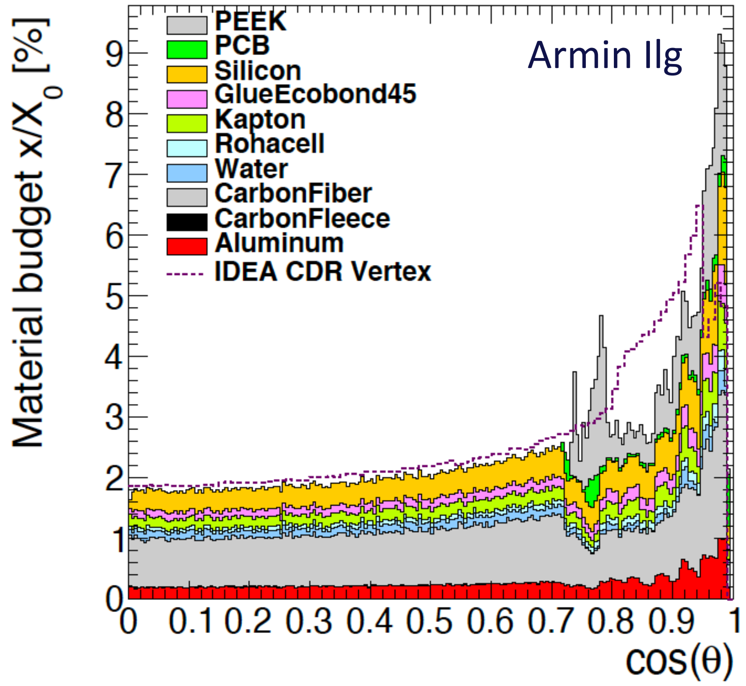
see talk by F. Palla, Frascati workshop

Vertex detector engineered

Mockup planned



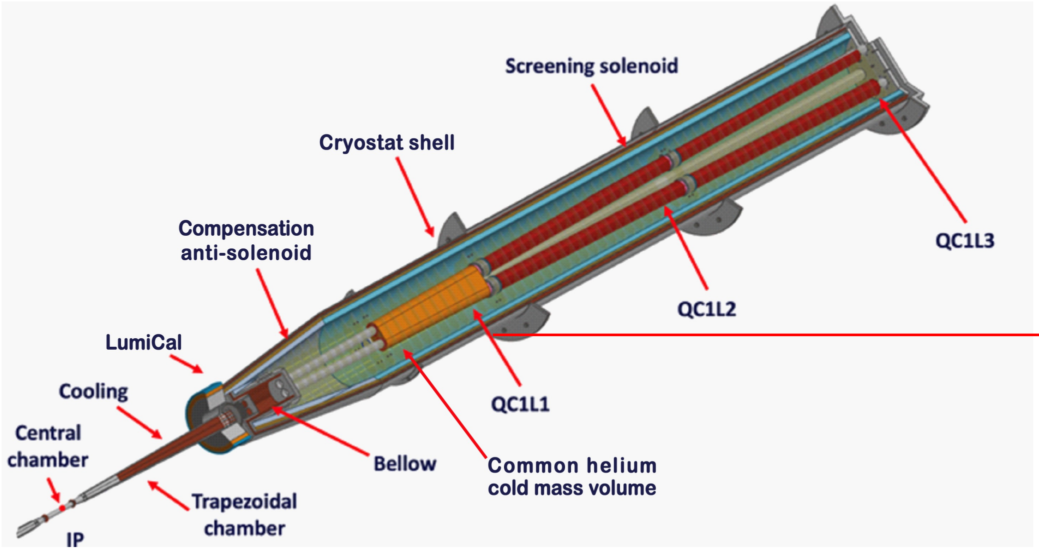
Simulated material budget



- In agreement with CAD estimates
- Smaller X/X_0 wrt IDEA CDR estimates even including power and readout cables in the sensitive region
- Silicon only ~15% of the total

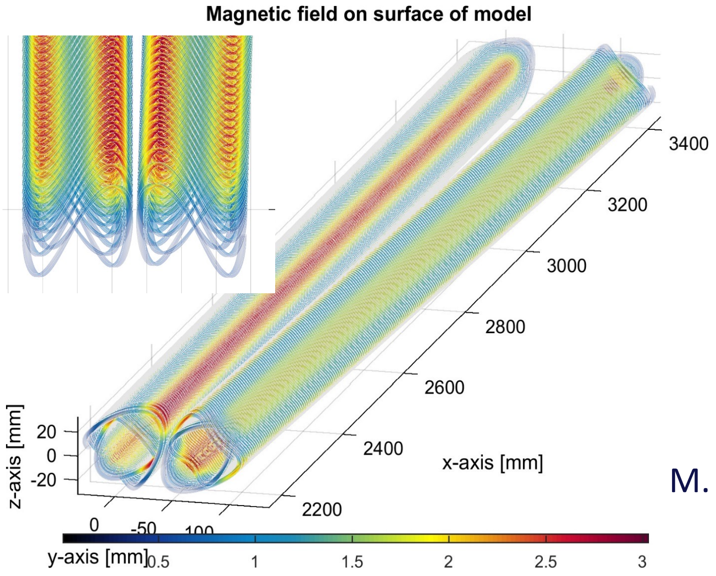
see talk by J. Seeman and dedicated session, Frascati workshop

FCC-ee IR magnet system



IR FF Quad QC1L1

QC1L1



M. Koratzinos

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

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.

see talk by M. Koratzinos, Frascati workshop

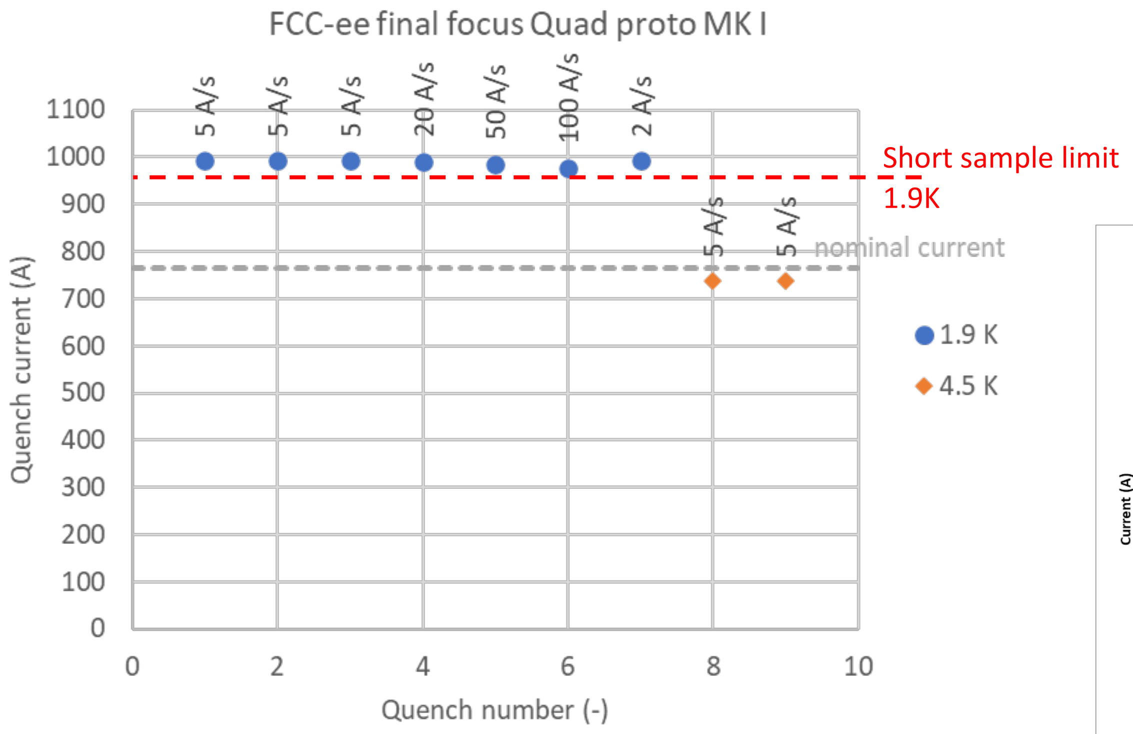
SM18 Test results Oct 27-31 - Training of the first FCC-ee FF Quad prototype

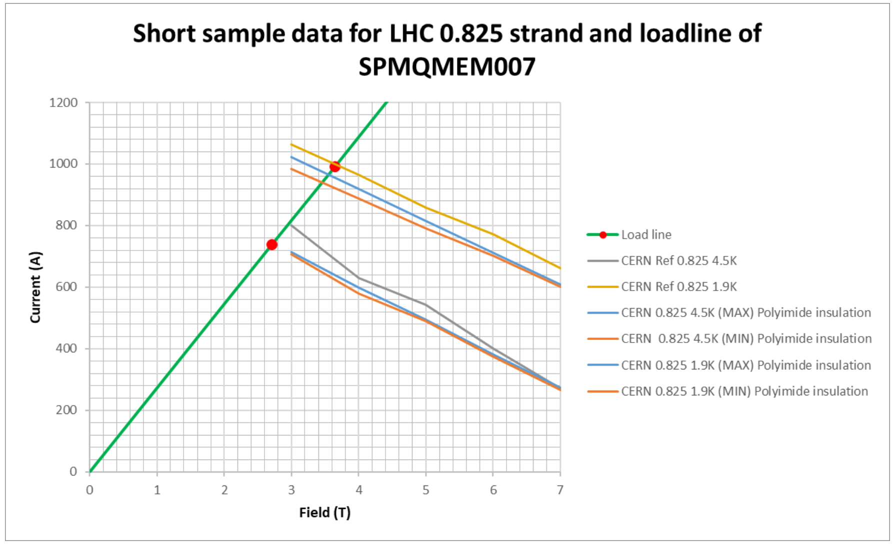
NEW!

Test report EDMS https://edms.cern.ch/document/2976492/1
Gerard Willering, Jerome Feuvrier for TE-MSC-TM

No training quenches were seen up to short sample limit
No degradation was seen for quenches at short sample limit

1.9 K: reached 991 A, peak field on conductor is 3.65 T
4.5 K: reached 738 A, peak field on conductor is 2.71 T



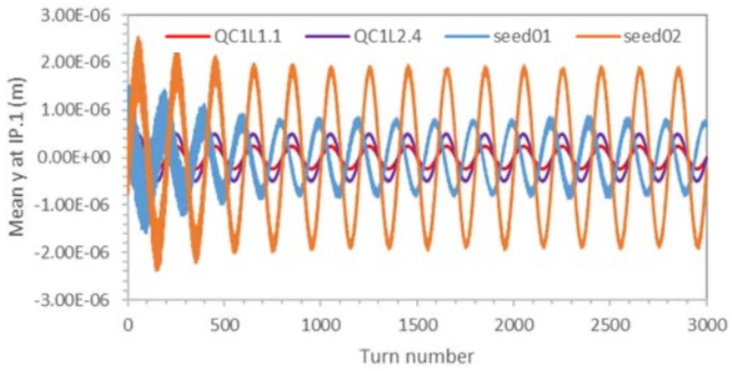


Testing at cold at SM18 (CERN)

Field quality: work ongoing but less than one unit in 10^{-4} of multipole errors (Carlo Petrone, Melvin Liebsch TE/MSC/TM)

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

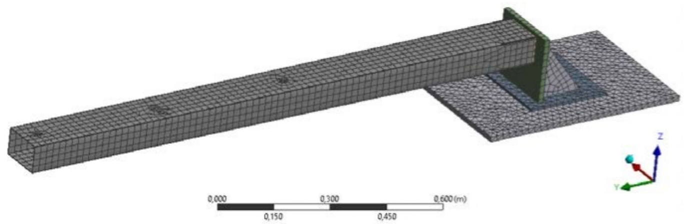
Optics: beam tracking studies



Setup tracking simulation:

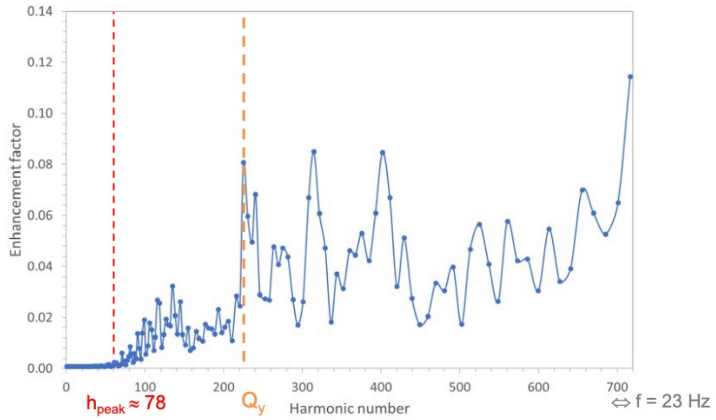
- sinusoidal vibration of all FFQs at 15 Hz with 1 µm of amplitude (first mode of vibration for SuperKEKB)
- Each FFQ contributes to the mean vertical offset at the IP.

Mechanics



validation of the method on a cantilever beam prototype

Effect of plane ground waves on the closed orbit

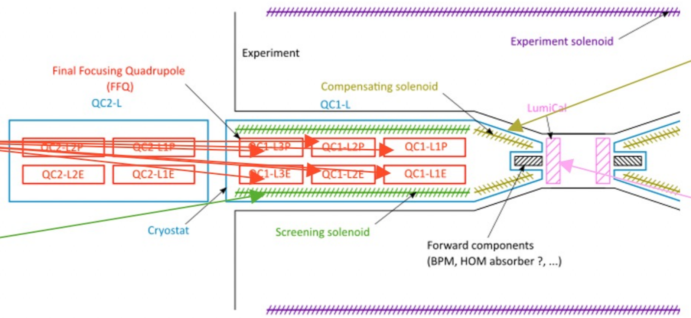


study performed with MADX, each quad of the ring is assumed with a vertical misalignment

MDI Alignment and monitoring system

see L. Watrelot, Frascati workshop

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

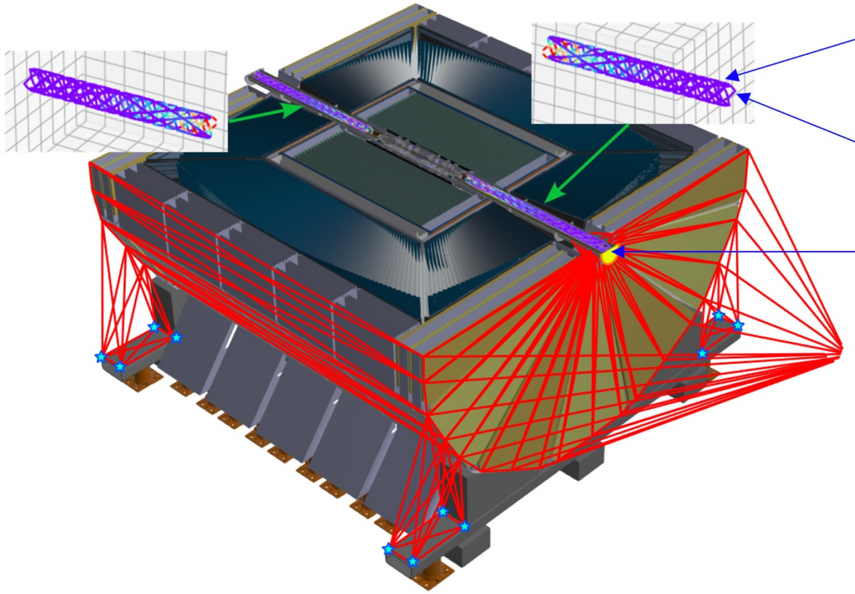


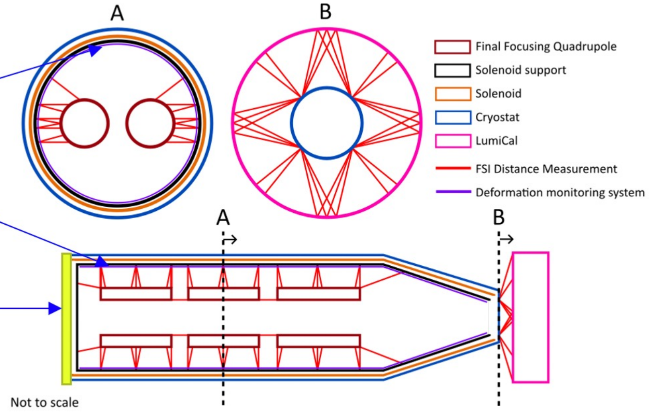
Permanent network of interferometric distance measurements based on Frequency Scanning Interferometry (FSI).

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

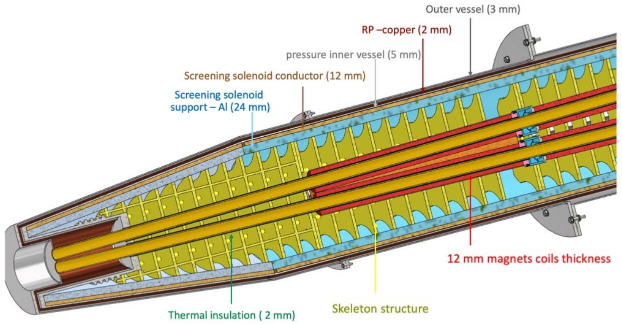
Internal alignment using optical fibers and deformation monitoring.

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



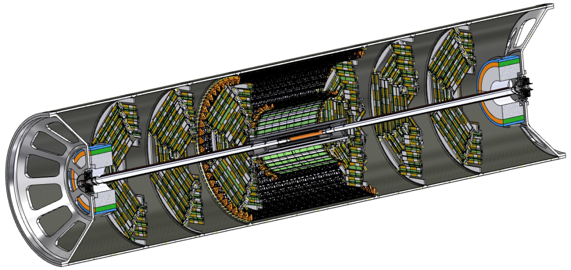


Plans for Engineering MDI design & integration



- **IR magnet system & cryostat design and interfaces (critical)**
  - Proposal of IR magnet design and final focus demonstrator (prototype) including correction coils to be pursued between CERN and BNL under discussion.

- Central IR
  - Services (i.e. air & water cooling for vertex and vacuum chambers) and cables
  - Anchoring to the detector
  - Accessibility & Maintenance



- Vacuum connection
- IR BPMs
- Integrate in the design an alignment system

- Beamstrahlung dumps

- **Build an assembly of the central IR in Frascati (IR mockup)**

Plans & Beam induced Background

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

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

Luminosity induced background (e^+e^-)

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

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

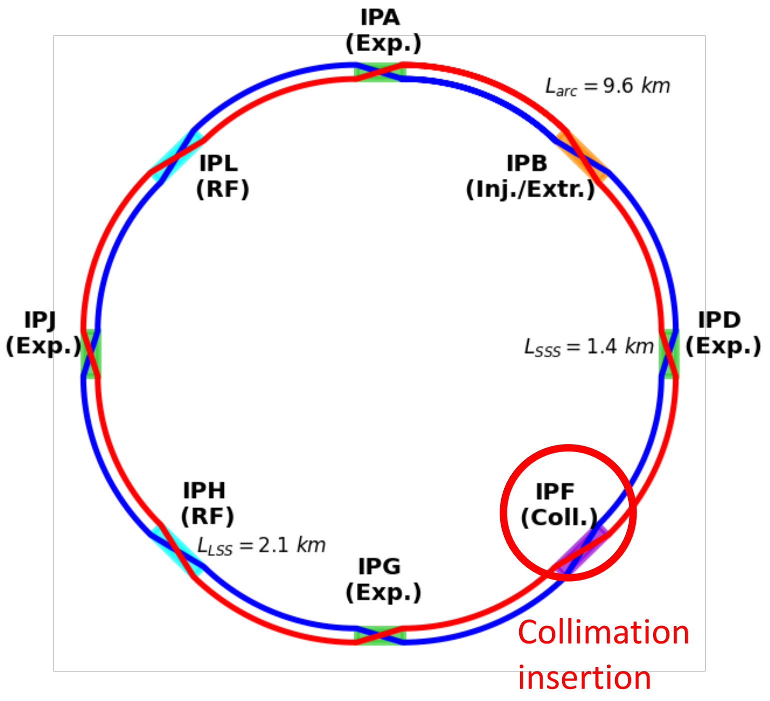
We have performed first evaluations of these effects for the CDR.

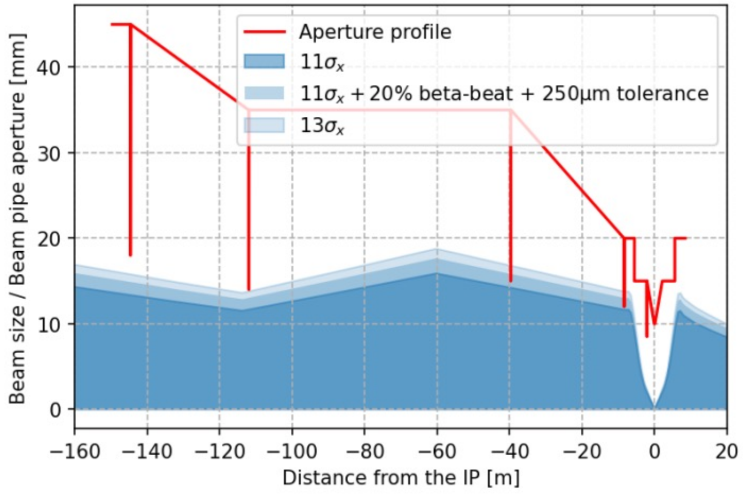
For the feasibility study the topic was tackled starting from developing a new code for particle tracking and study the **halo beam**, with an LHC-like approach. **A collimation region was implemented for halo beam.**

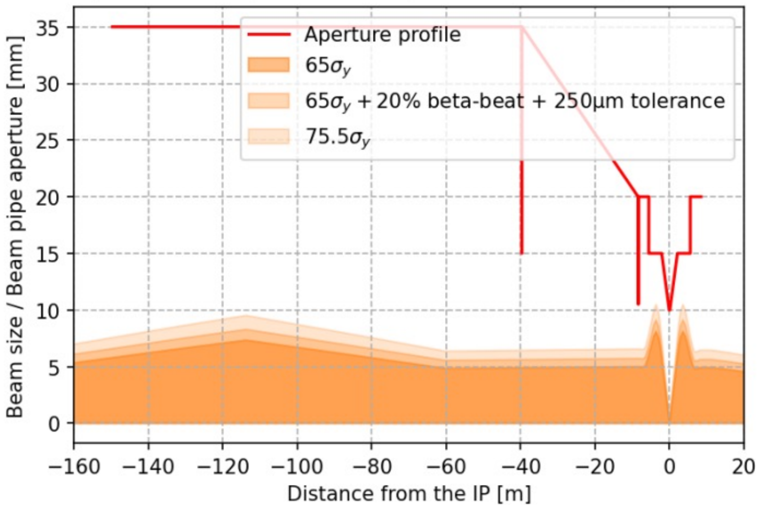
The MDI region is now improved as more realistic, and software model developed.
We need to update and complete those studies .

Main Ring Collimation

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







see K. Andrè, Frascati workshop

Synchrotron Radiation backgrounds

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

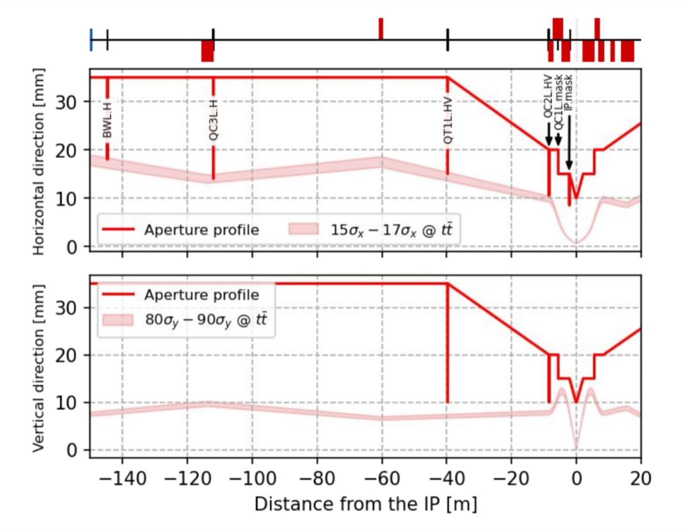
Characterisation of the SR produced for **all beam energies**.

SR produced upstream the IP:

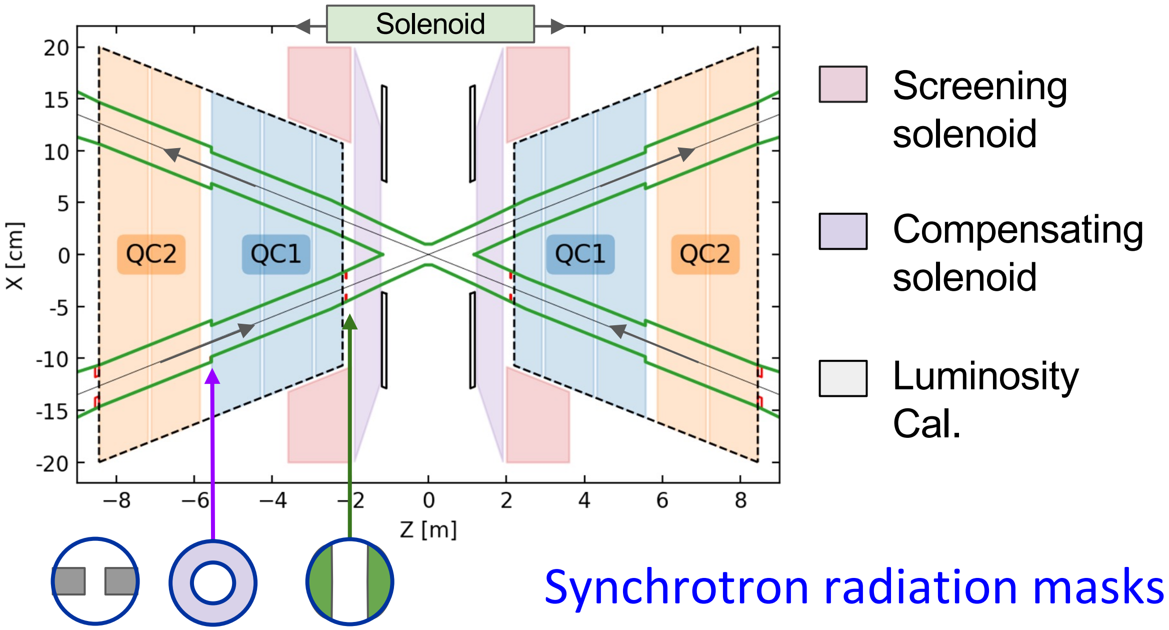
- by the **last dipoles and quadrupoles upstream the IR** can be a background source, to be collimated and masked
- by the **IR quads and solenoids** collinear with the beam and will hit the beam pipe at the first dipole after the IP.

Name	s [m]	half-gap [m]	plane
BWL.H	-144.69	0.018	H
QC3L.H	-112.05	0.014	H
QT1L.H	-39.75	0.015	H
PQC2LE.H	-8.64	0.011	H
MSK.QC2L	-5.56	R = 0.015	H&V
MSK.QC1L	-2.12	0.007	H

15 σ_x corresponds to the aperture of the **primary** collimators, **17 σ_x** corresponds to the aperture of the **secondary** collimators.

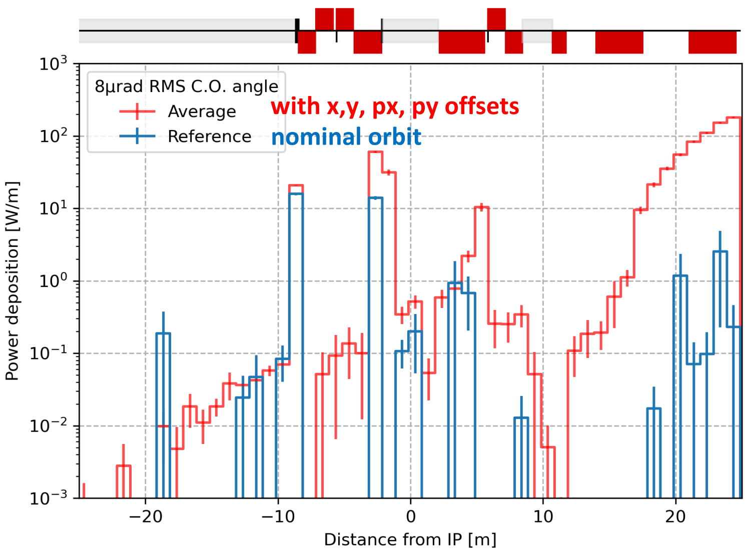


Synchrotron radiation collimators



Synchrotron radiation masks

Synchrotron Radiation backgrounds

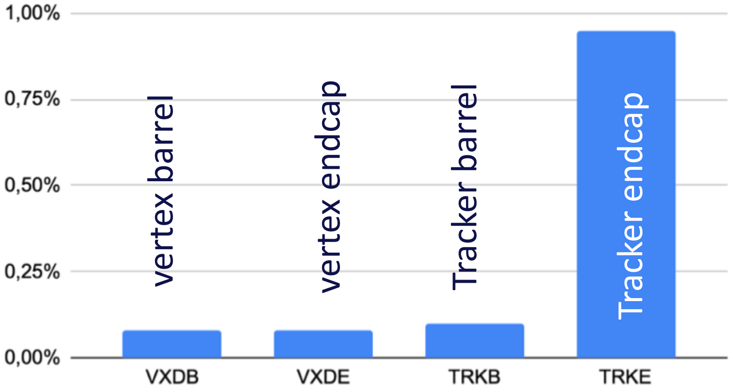


Power deposition from beam core for Z-mode (v22)

Blue is the reference closed orbit

Red is the average with possible soffsets due to misalignments

Maximum occupancy in subdetector/BX

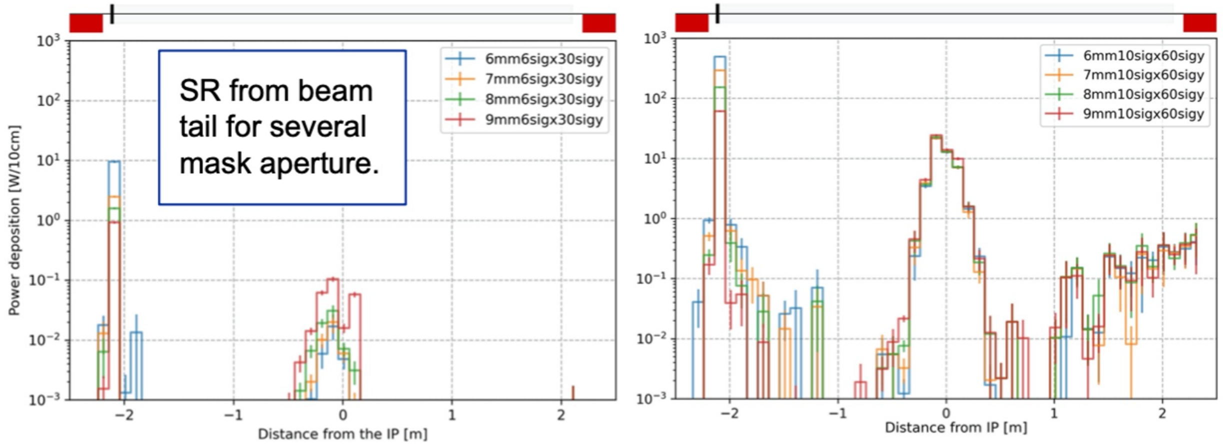


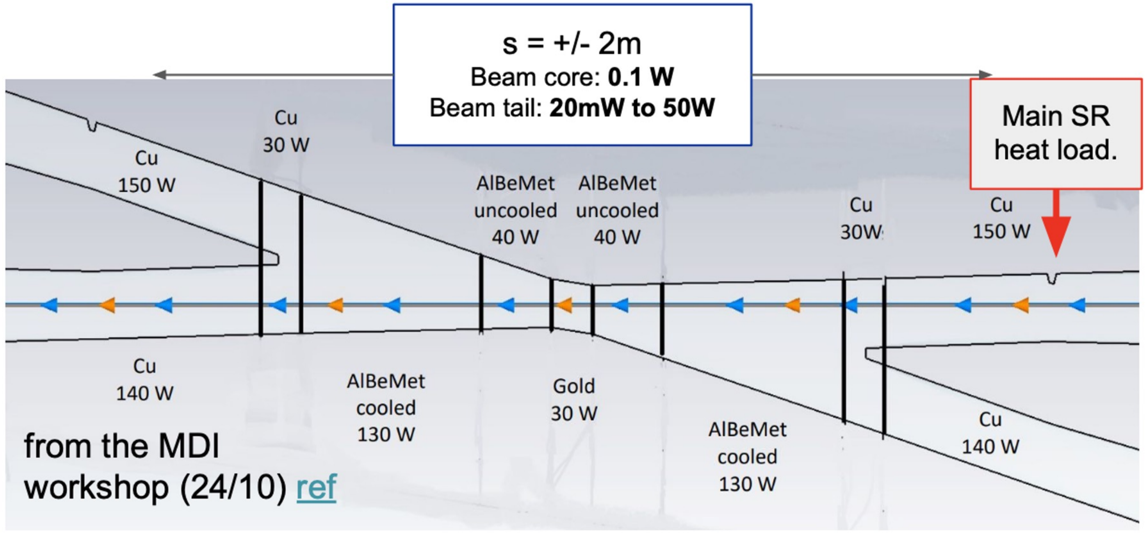
($t\bar{t}$ threshold - CDR beam parameters
CLD detector - NO shieldings)

A. Ciarma

from beam tails hitting SR mask tips

Heat load from beam halo synchrotron radiation





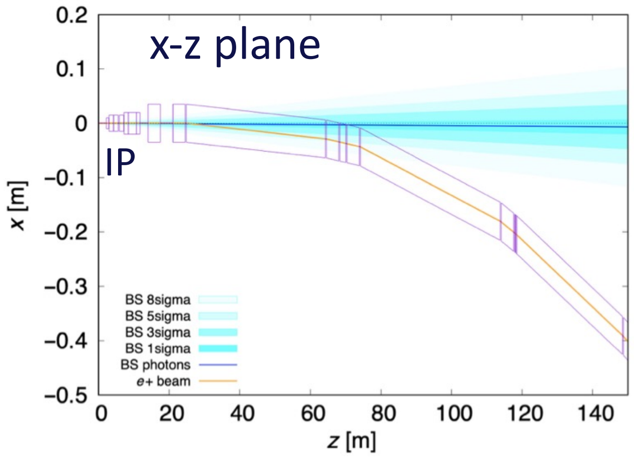
Heat Load from wakefields

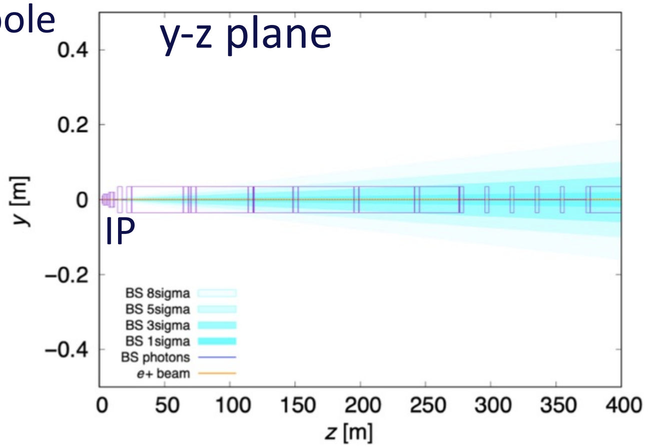
Beamstrahlung Radiation

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

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

Z-pole





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

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

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

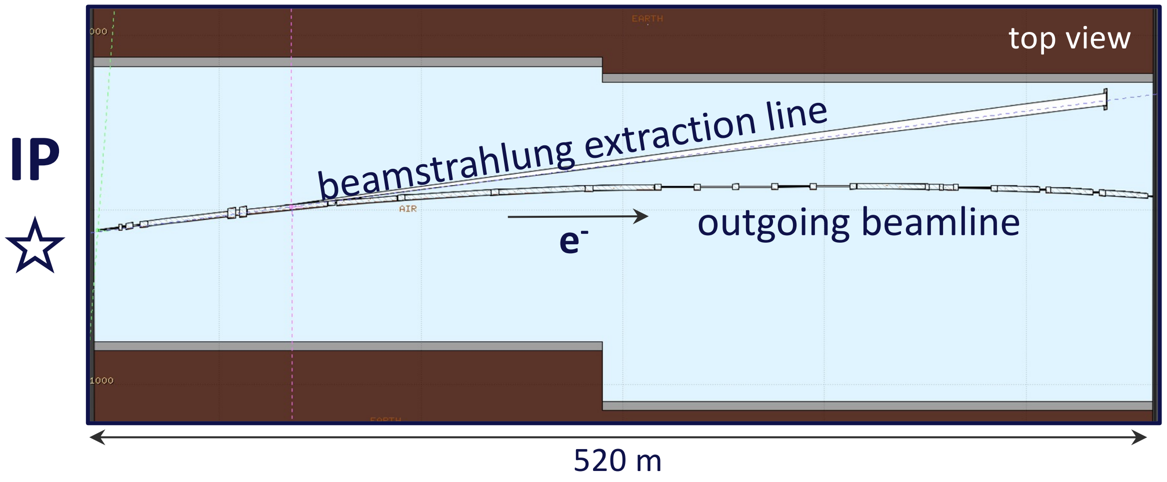
- Different targets as dump absorber material are under investigation
- Shielding needed for equipment and personnel protection for radiation environment

FLUKA studies of the FCC-ee IR

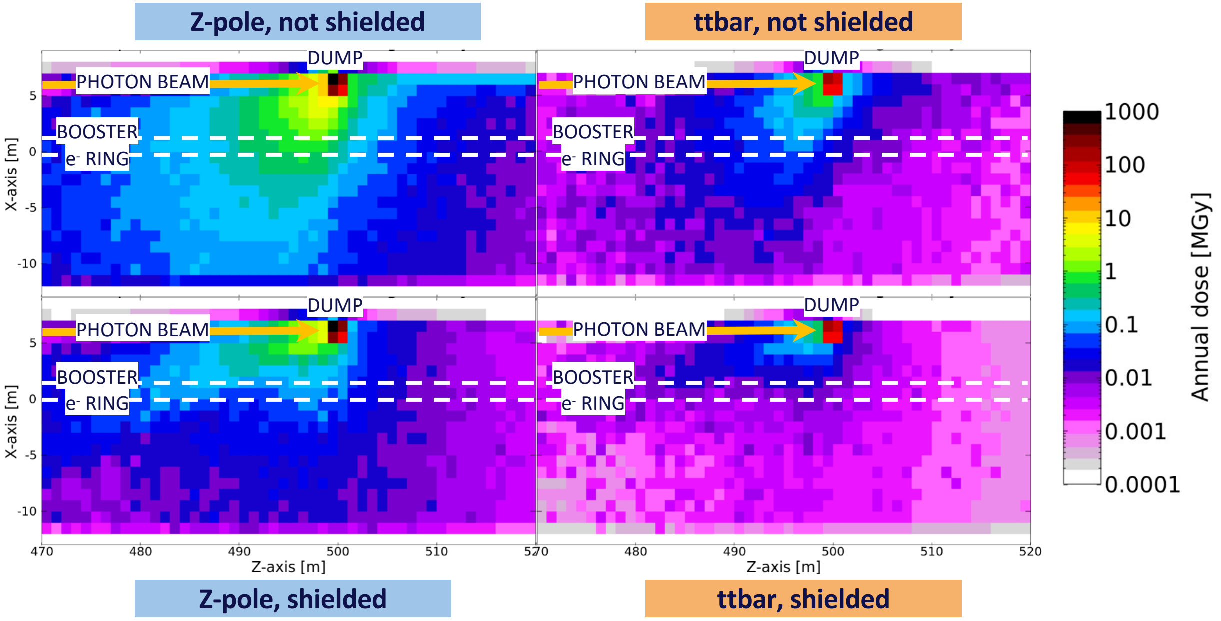
FLUKA model to estimate the radiation levels in the FCC-ee tunnel in the experimental IR

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

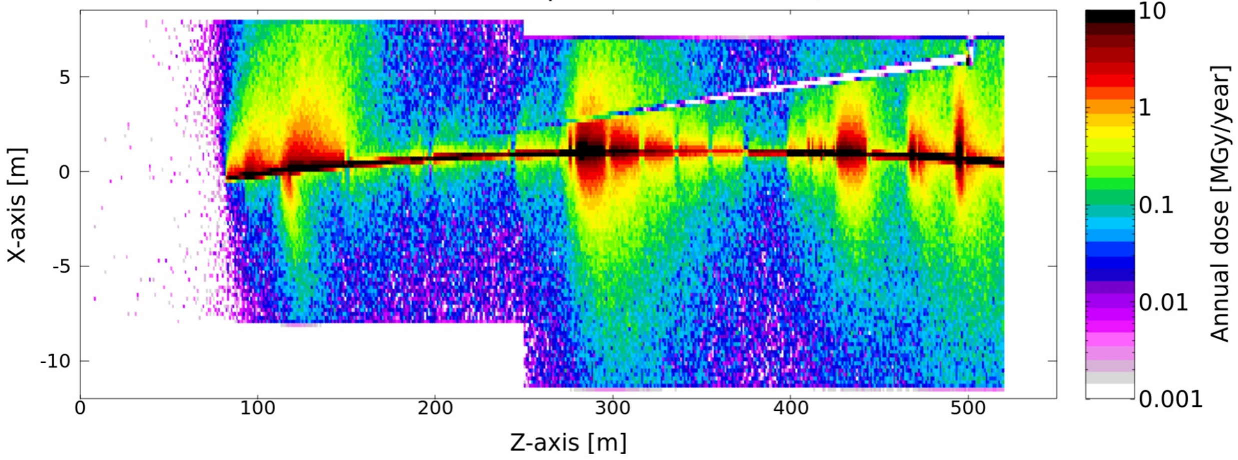
FLUKA MODEL



ANNUAL DOSE FROM BEAMSTRAHLUNG DUMP



ANNUAL DOSE FROM SR @ttbar



Conclusion
Progress & plans on key aspects of the MDI design

❑ IR Mechanical model, including vertex and lumical integration, and assembly concept

- Services (i.e. air & water cooling for vertex and vacuum chambers) and cables
- Anchoring to the detector
- Accessibility & Maintenance
- Vacuum connection
- IR BPMs
- Integrate in the design an alignment system

❑ IR magnet system & Cryostats

- FF Quads & Correctors
- Solenoid comp. scheme & anti-solenoid design

❑ Beam induced backgrounds

- The MDI region is now improved as more realistic, and software model developed.
  Need to update and complete those studies .
- Backgrounds, halo beam collimators, IR beam losses, SR, IR radiation level & fluences
- Beamstrahlung dumps with radiation levels

❑ Heat Loads from wakefields in IR region

- In progress

And thanks to many people for inputs!

Backup

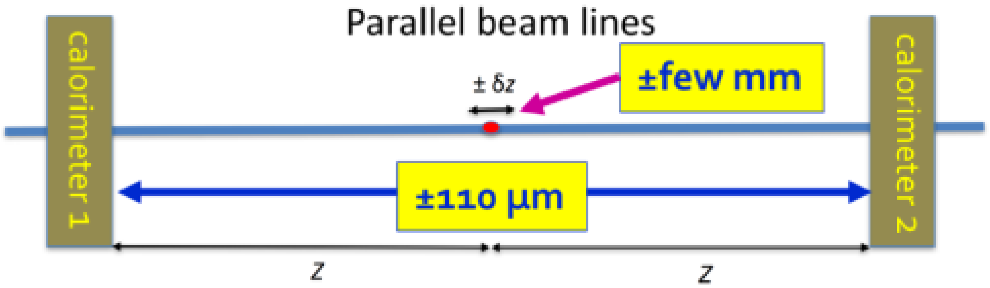
LumiCal constraints & requirements

see talk by M. Dam, MDI workshop, Frascati

Goal: absolute luminosity measurement 10^{-4} at the Z

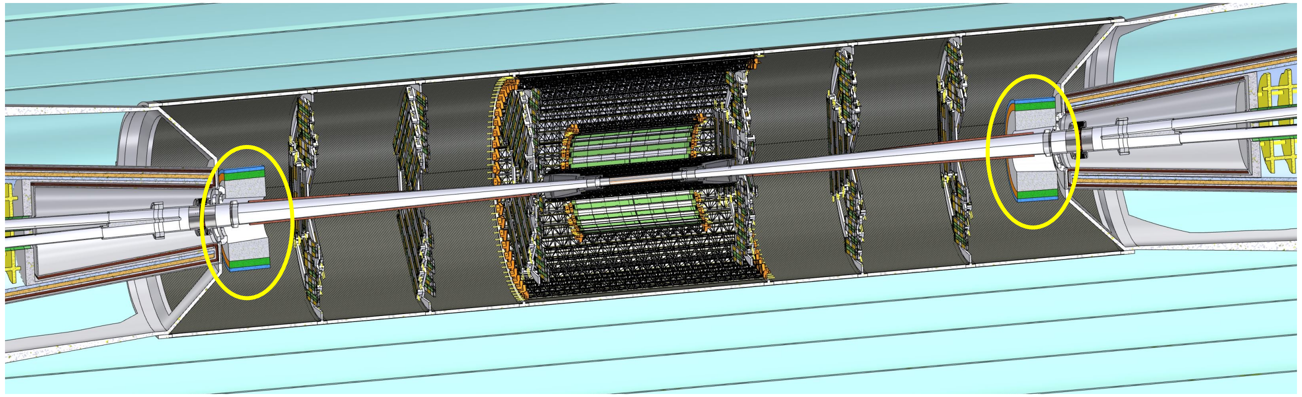
Standard process Bhabha scattering

- 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



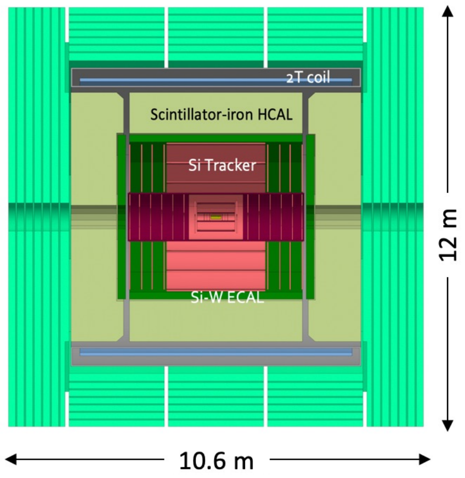
Lumical integration:

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



FCC-ee Detector Concepts

CLD

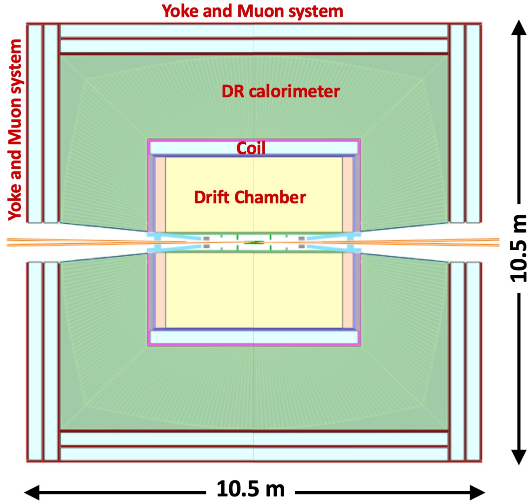


- Full Silicon vertex detector + tracker;
- Very high granularity, CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system;

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

CDR

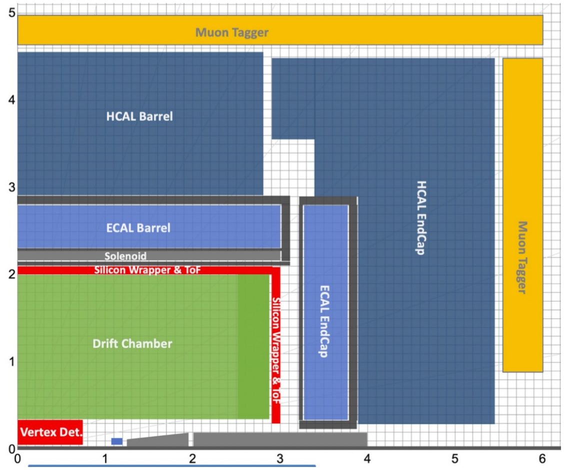
IDEA



- 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;

ALLEGRO

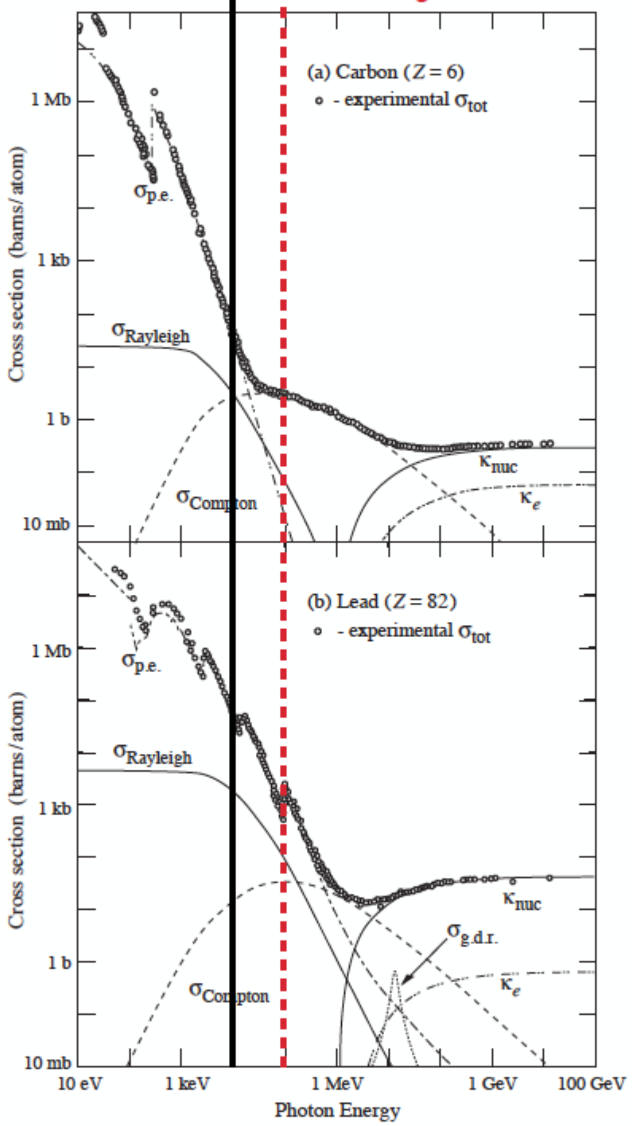


new

- 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.

Spectrum and absorption

✓ < 10 keV | very difficult above 100 keV



Typical mean (0.3 E_c) photon energies

B-factories (and **FCC-hh**) mostly below 10 keV

LEP1 : 21 keV
LEP2 : 320 keV (arc, last bend 10× lower)

TLEP : ~ 350 keV (arc, 175 GeV)
-> very similar to LEP2
difficult to collimate

Enormous photon flux, MWs of power
can get kW locally, melt equipment, detectors..

Aim as for LEP2 :
do not generate hard synchrotron radiation anywhere close to the IR

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
$>2 \times 10^8$ WW
LEP x 10^4

3 years
2×10^6 H

5 years
2×10^6 tt pairs

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