FUTURE
CIRCULAR
COLLIDER
Innovation Study

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.

PROGRESS AND PROSPECTS ON THE MDI STUDY

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on behalf of the MDI group

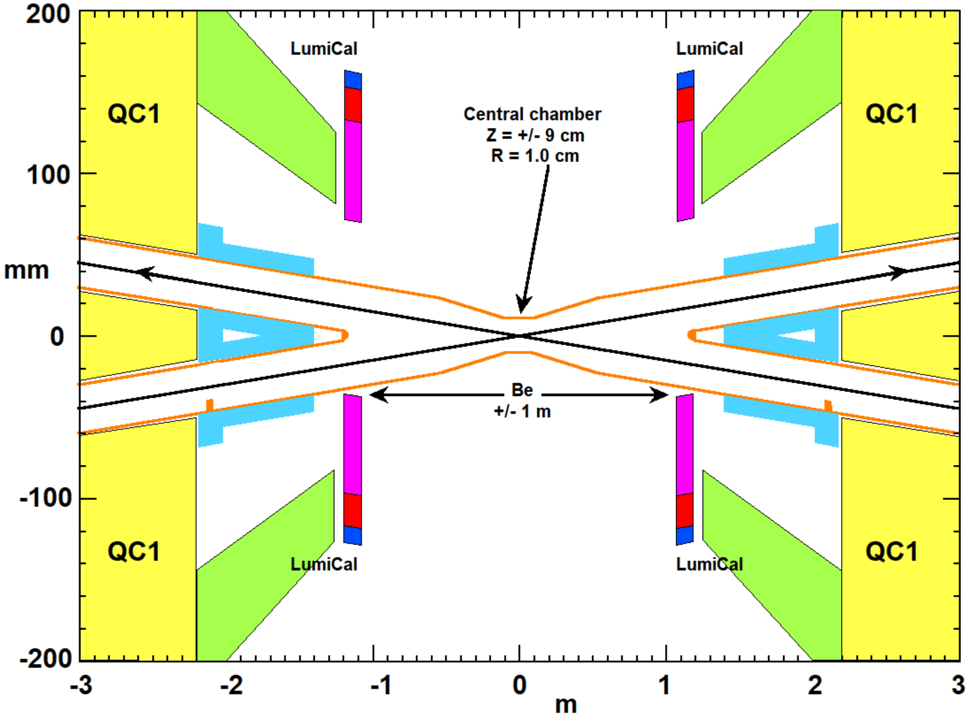
INFN
Istituto Nazionale di Fisica Nucleare

Second Annual US FCC Workshop 2024
25 - 27 March 2024
MIT, Boston

Outline

- Interaction region layout optimization
- Progress on the MDI engineering design
- Beam induced Backgrounds studies
- Outlook

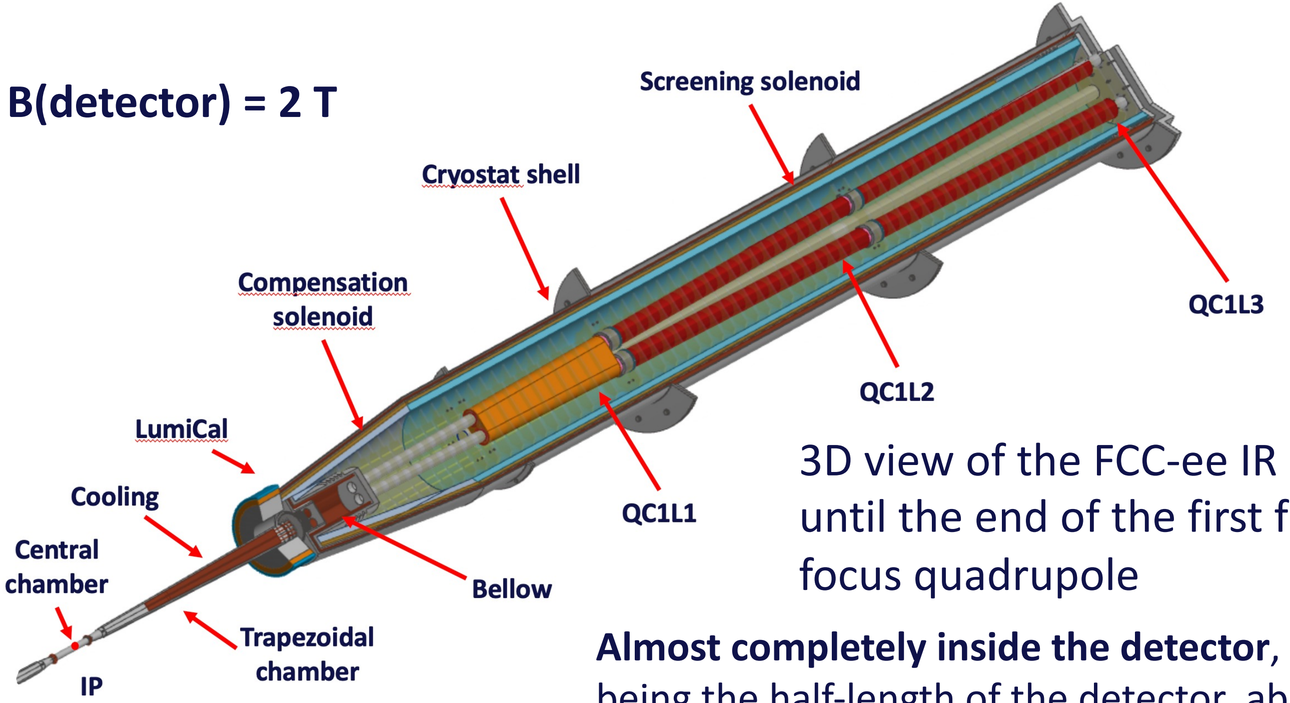
FCC-ee Interaction Region



FCC-ee IR layout.

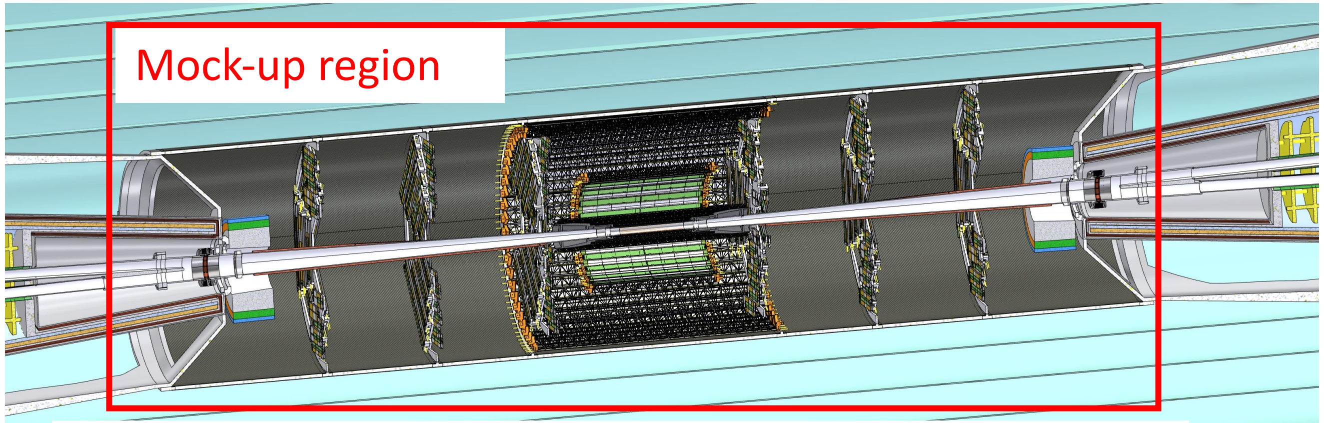
L*, is 2.2 m. The 10 mm central radius is foreseen for ± 9 cm from the IP, and the two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP.

B(detector) = 2 T



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

Almost completely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at about 5.6 m.

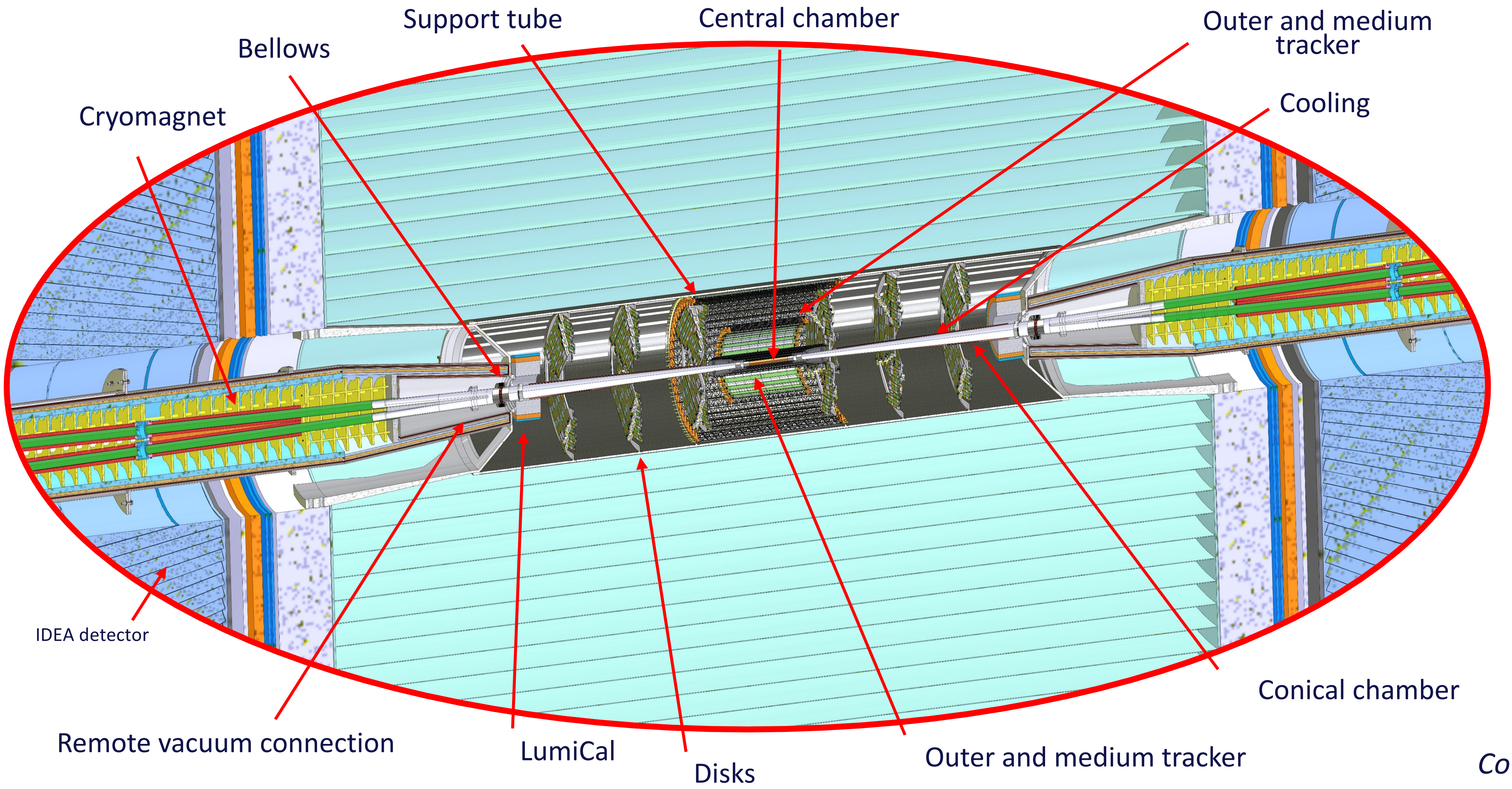


3D view of FCC-ee IR including the rigid support tube, vertex detector and outer trackers.

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 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

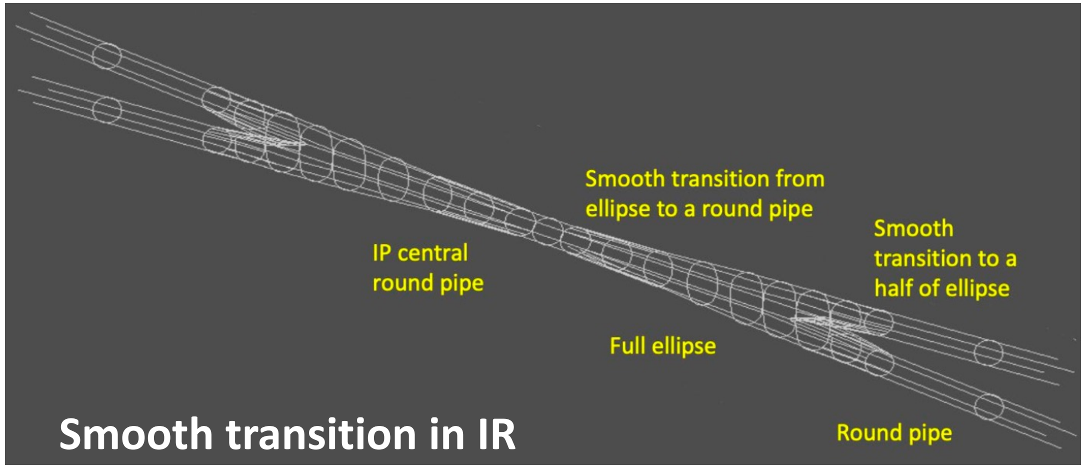
FCC-ee engineered Central Interaction Region



Courtesy by F. Fransesini

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

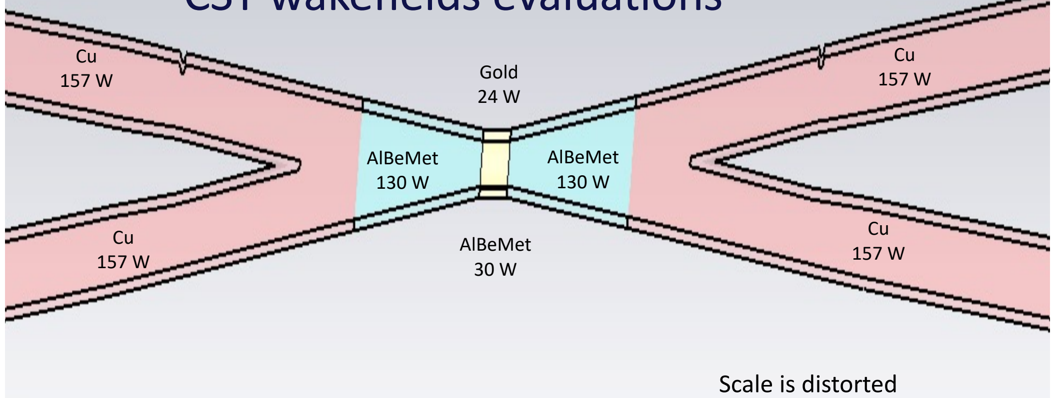
Low-impedance vacuum chamber and its cooling system



Smooth transition in IR

- warm and cooled vacuum chamber
  Beam heat load evaluated, cooling system made of paraffin in the central chamber and water elsewhere
- **Optimization of the overall design to integrate the luminosity calorimeter**

CST wakefields evaluations

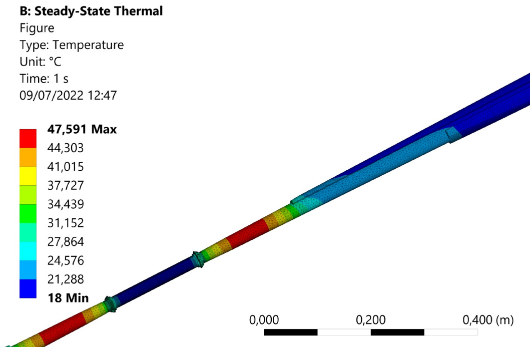


Scale is distorted

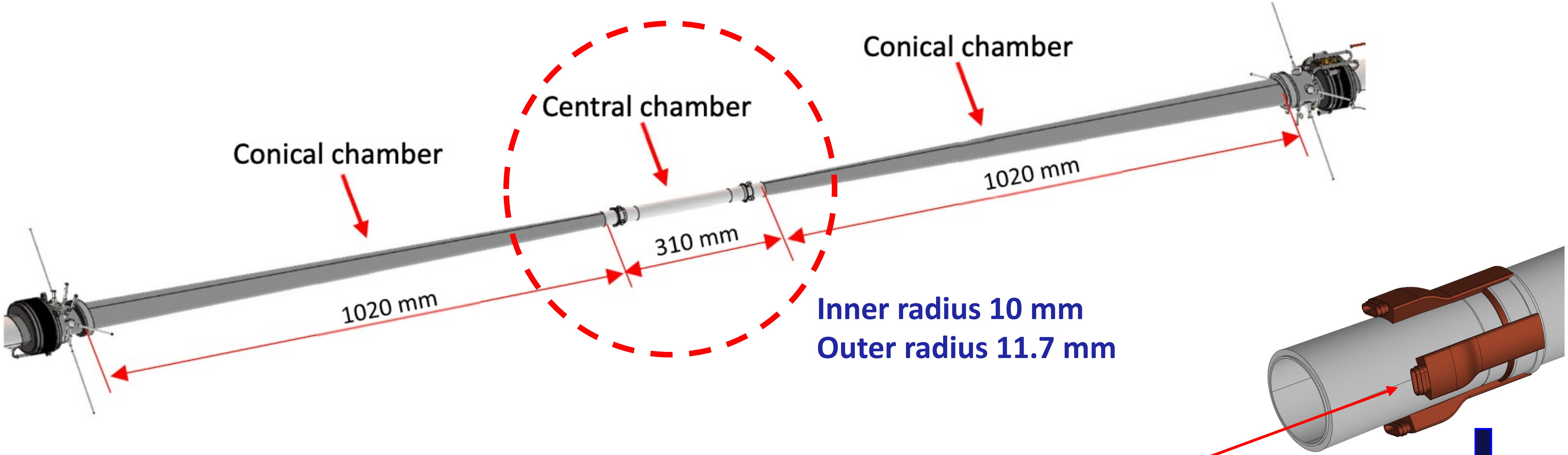
Courtesy by A. Novokhatski (SLAC)

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

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



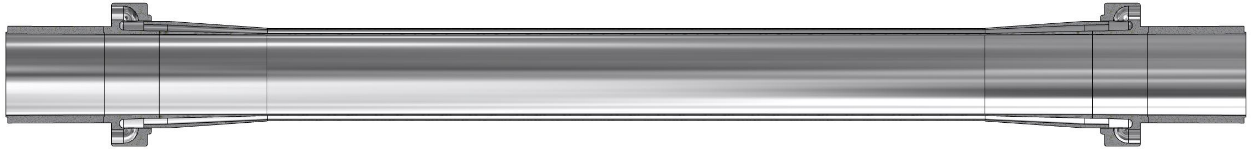
AlBemet Central Vacuum Chamber design



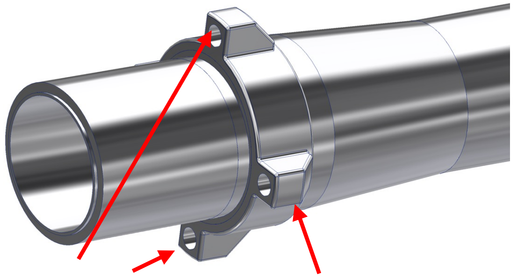
Inner radius 10 mm
Outer radius 11.7 mm

Inlet and outlet manifolds for the paraffin cooling system: copper removed

NOW



material budget is reduced especially in LumiCal

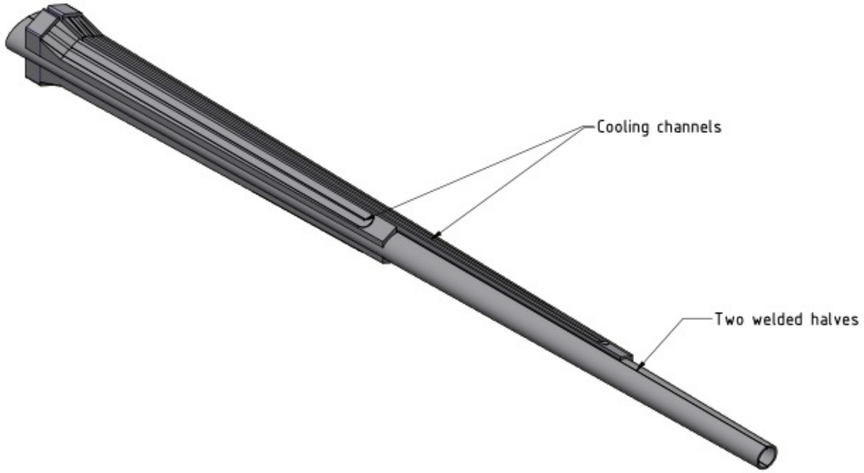


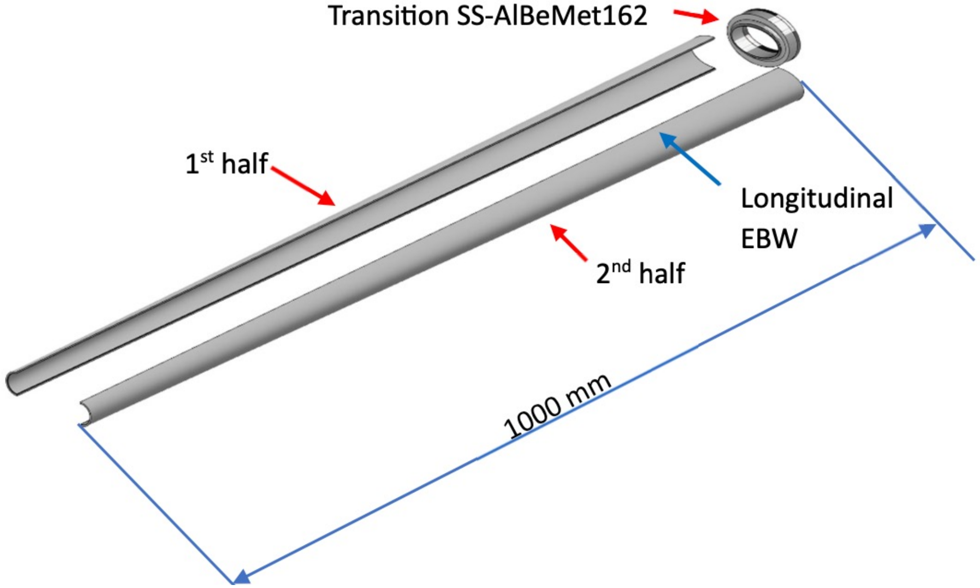
Inlet/outlet for paraffin cooling (AlBeMet)

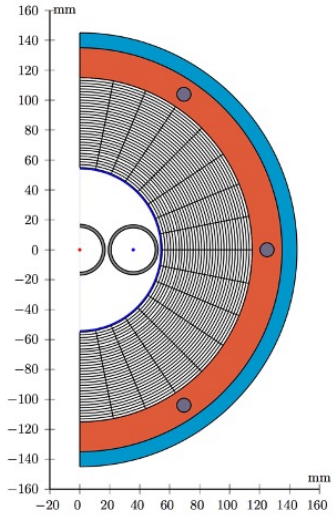
[AlBeMet: 62% Be and 38% Al alloy]

Conical vacuum chamber - progress

The cooling channels are **asymmetric** because the LumiCal is centered around the outgoing beam





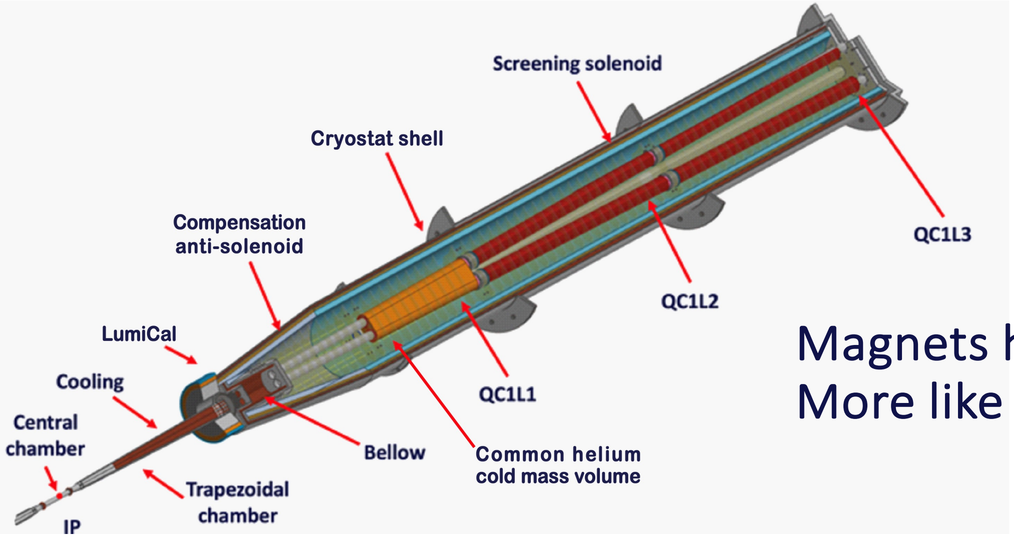


Courtesy by F. Fransesini

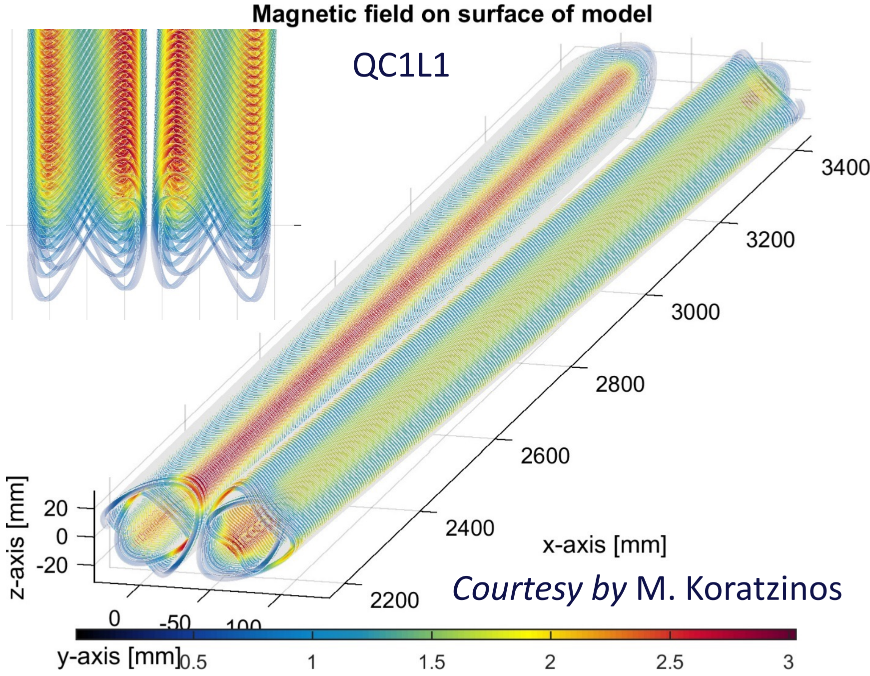
Water Cooling manifolds in copper are being replaced with **AlBeMet,**
following simulation studies indicating showers in the LumiCal (FCC Physics week, Annecy)

FCC-ee IR Magnets

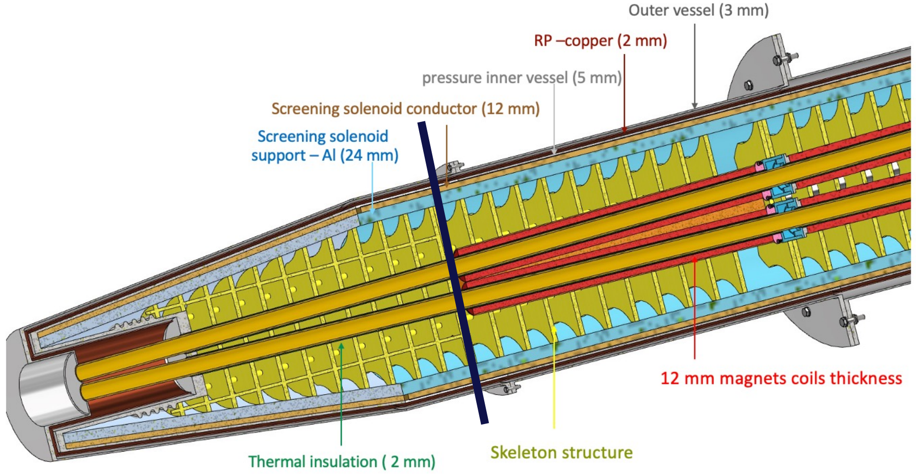
Ongoing work to develop IR quadrupoles with ~100 T/m



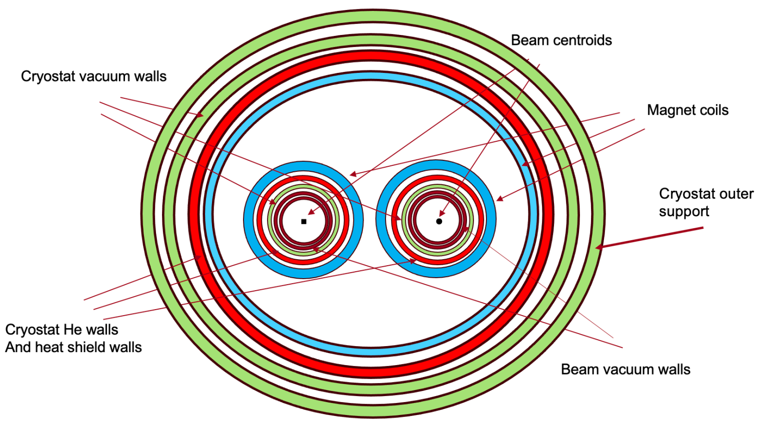
Magnets have 2cm radius.
More like LC final quads than LHC.



Courtesy by M. Koratzinos



IR Magnet Cross Section View (front and end of each magnet)



Courtesy by J. Seeman Nov 4, 2023

Option (Leading Candidate):
IR QC1 and QC2 in different cryostats but one integrated raft.

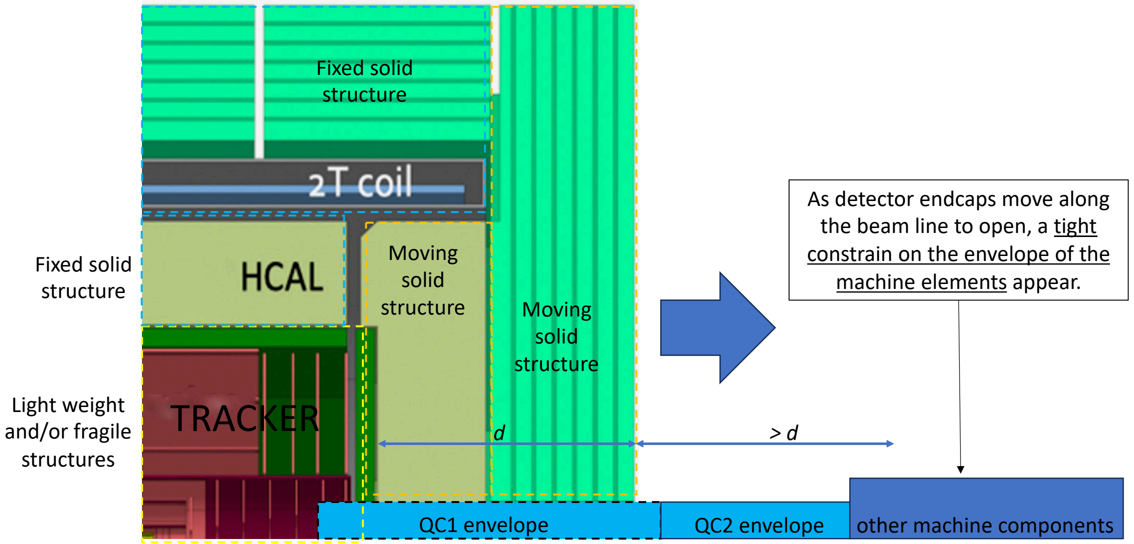
Integration of complete cryostat with magnets, correctors, and diagnostics is required.

General detector integration issues

Considering how to access the detector elements taking care of the final focus superconducting quads

There is enough clearance to envisage the scenario to move the detector aside the beamline and get full access to the detector’s inner parts

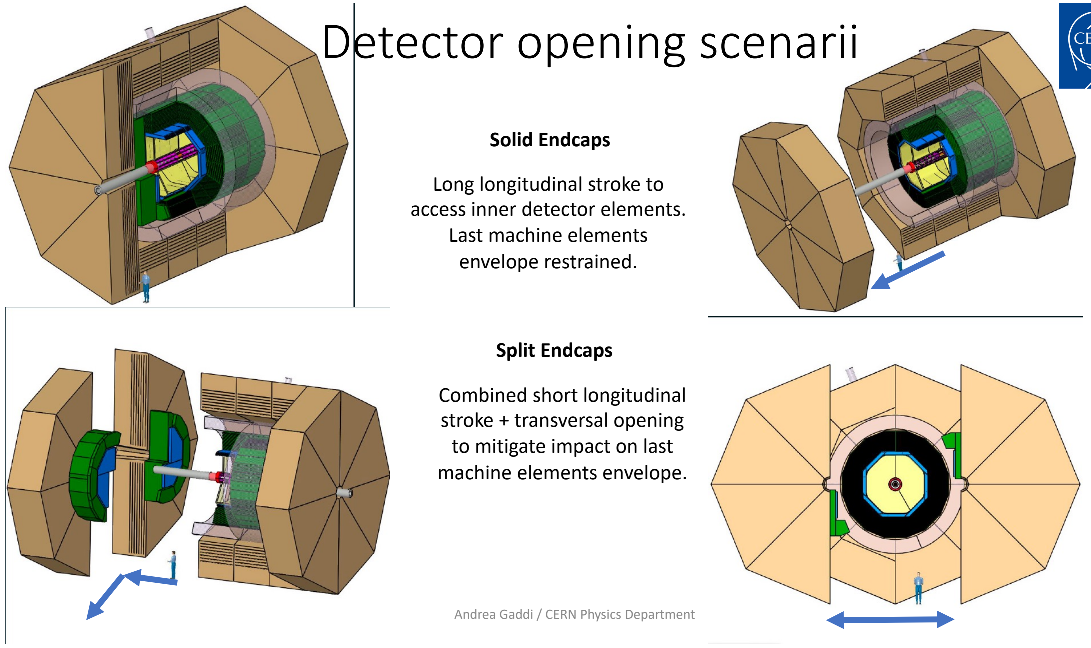
Typical detector structure.



As detector endcaps move along the beam line to open, a tight constrain on the envelope of the machine elements appear.

Andrea Gaddi / CERN Physics Department 3

Detector opening scenarii



Solid Endcaps

Long longitudinal stroke to access inner detector elements. Last machine elements envelope restrained.

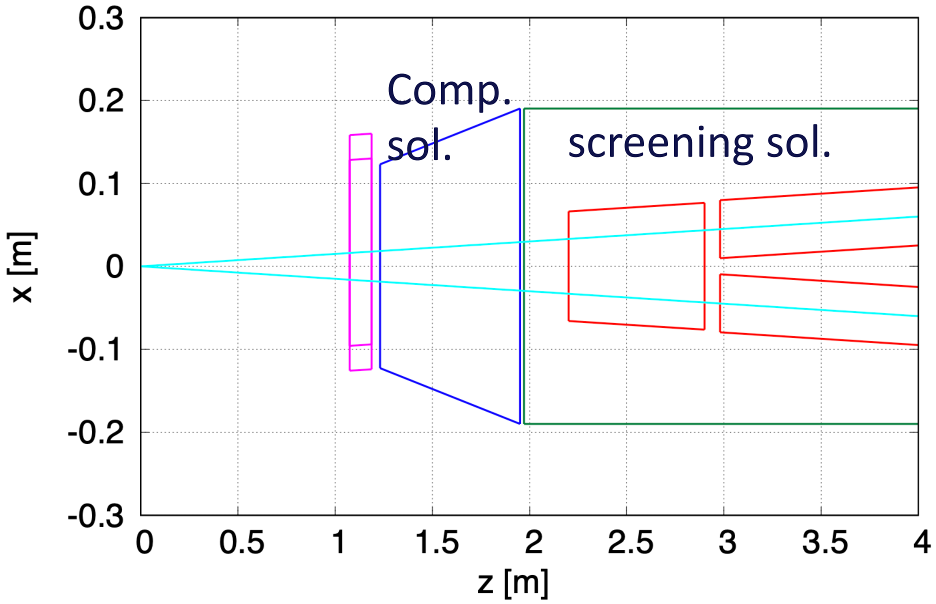
Split Endcaps

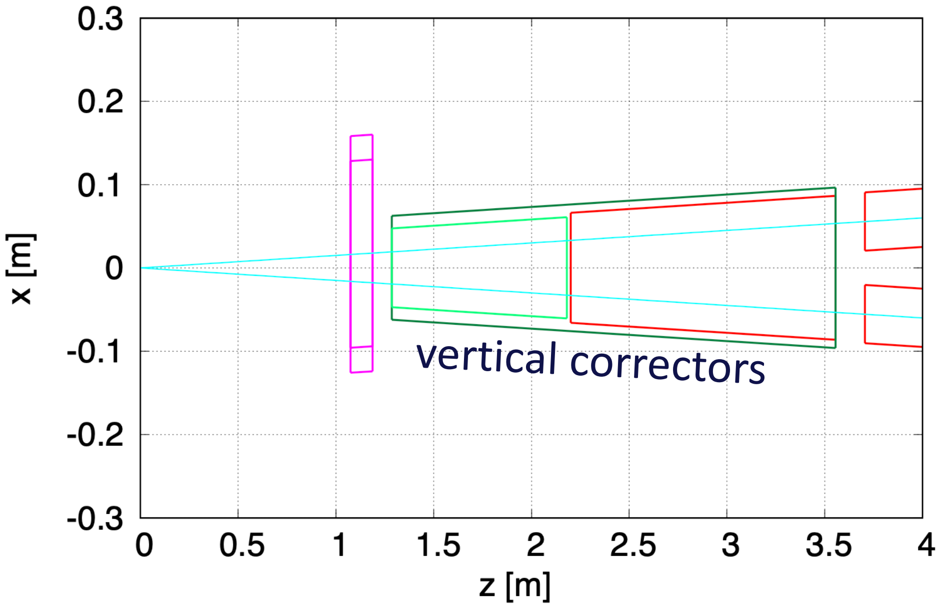
Combined short longitudinal stroke + transversal opening to mitigate impact on last machine elements envelope.

Andrea Gaddi / CERN Physics Department

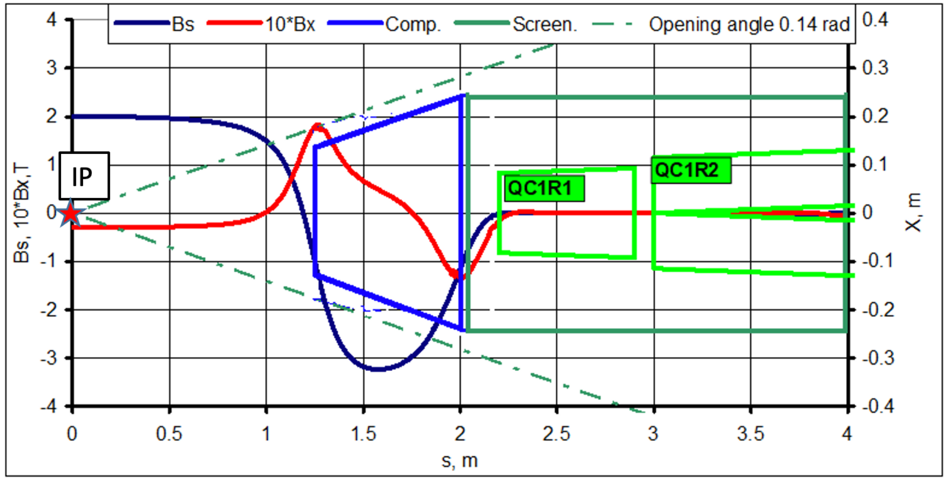
A. Gaddi, FCC Physics Week , Annecy

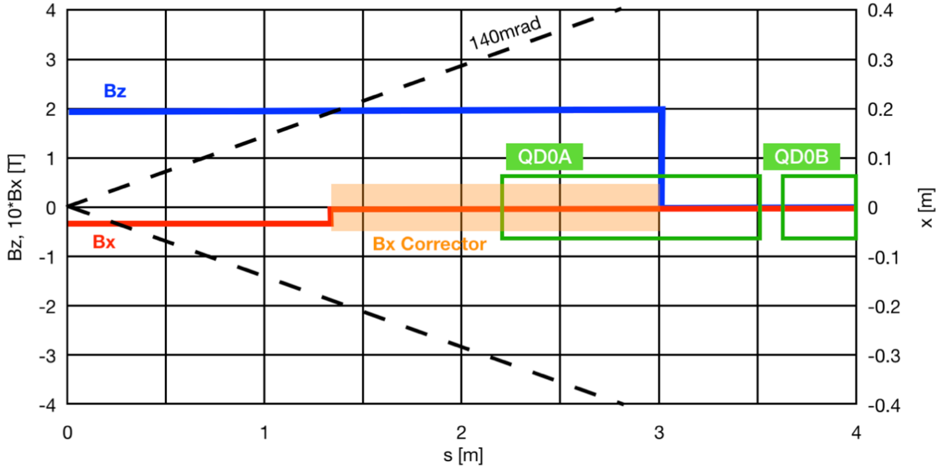
Solenoid Coupling Compensation Scheme





Field distribution along the reference trajectory





“Standard” Solenoid compensation (P. Raimondi)

Coupling compensation

The best compromise between performances and feasibility seems to be:

- **no compensating solenoid**
- **zero the Bs (solenoid) field with starting from 2m** from the IP until the end of the detector solenoid
- **zero the Sum(Bs*l) with antisolenoids (2 per beam) outside the IR quads.**
- corrects residual coupling with weak **skew quads** wrapped around the IR quads.
- correct orbit with weak **correctors** in several locations around the IR
- correct dispersion with standard tuning knobs

Courtesy H. Burkhardt

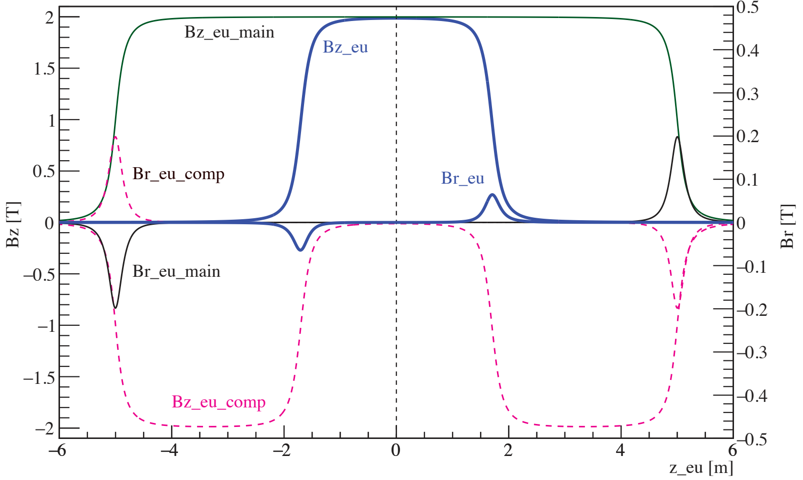


Figure 123: Analytical B_z and radial B_r solenoid fields as seen on a straight line with 15 mrad horizontal angle in detector (eu) coordinates.

Correctors and skews are no matter what needed for orbit and coupling correction (tuning knobs)

This solution is “optics independent”, could be applied to the baseline or the LCCO optic

Beam induced Backgrounds

Luminosity backgrounds

Radiative Bhabha

Beamstrahlung: photons and spent beam

- Incoherent/ Coherent e^+e^- Pair Creation
- $\gamma\gamma$ to hadrons

**Synchronous with the interaction,
can be discriminated at trigger level**

Single Beam effects

Synchrotron Radiation

Beam-gas,

Thermal photons,

Touschek

Injection backgrounds

**Mostly can be mitigated with collimators & shieldings,
except for those produced just in the IR**

**A collimation region has been implemented for halo beam.
Additional tertiary collimators upstream MDI area being studied.**

Luminosity backgrounds

Radiative Bhabha *BBBrem/GuineaPig & SAD/MADX & Fluka*

- multiturn tracking of spent beam
- characterisation of photons produced at IP

First studied with SAD (CDR), ongoing effort to implement it in Xsuite.

Recent simulations with Fluka indicate the need of additional shielding of QC1

Beamstrahlung *GuineaPig /BBWS & SAD/MADX*

- multiturn tracking of **spent beam**
- characterization of **photons**
  - **collinear** with the core beam → not a source of detector backgrounds, but need to handle the intense radiation power produced (order of 400 kW) → BS photon dump under study, at 500 m after the IP

Ongoing effort to implement it in Xsuite

Studied with baseline lattice

- **e^+e^- pairs** *GuineaPig, G4 into detector*
  - **Coherent** Pairs Creation: **Negligible**

    Photon interaction with the collective field of the opposite bunch, strongly focused on the forward direction
  - **Incoherent** Pairs Creation (**IPC**): **Dominant** (real or virtual photon scattering)
- **γγ to hadrons** combination of *GuineaPig and Phythia, G4*

  Small effect (Direct production of hadrons, or indirect, where one or both photons interact hadronically)

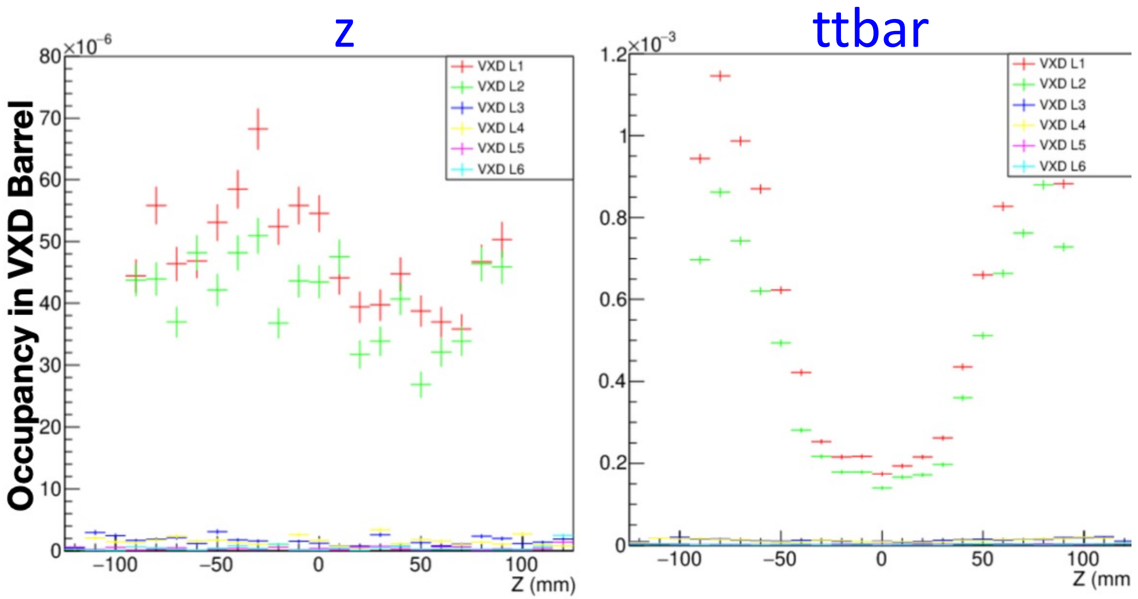
Study performed for the CDR and for baseline lattice

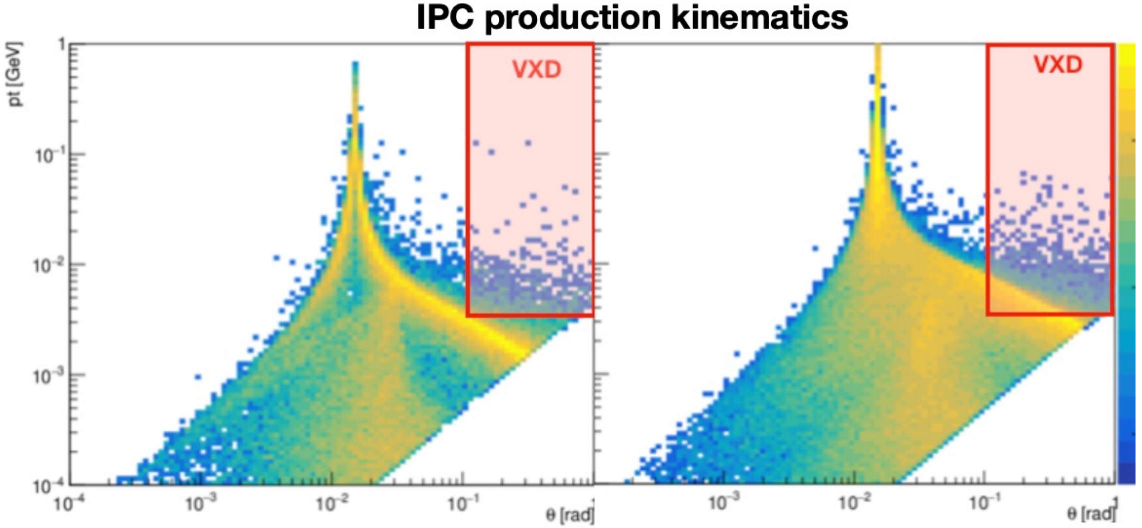
A. Ciarma

Background from IPC

Considering a (very conservative) $10\mu s$ window, the occupancies will remain below the 1% everywhere **except for the VXD barrel** at the **Z**. While the pile-up of the detectors has not been defined yet, it is important to **overlay this background** to physics event to verify the **reconstruction efficiency.**

	Z	WW	ZH	Top
Bunch spacing [ns]	30	345	1225	7598
Max VXD occ. 1us	2.33e-3	0.81e-3	0.047e-3	0.18e-3
Max VXD occ.10us	23.3e-3	8.12e-3	3.34e-3	1.51e-3
Max TRK occ. 1us	3.66e-3	0.43e-3	0.12e-3	0.13e-3
Max TRK occ.10us	36.6e-3	4.35e-3	1.88e-3	0.38e-6





Beam induced backgrounds impact on detectors

- Machine backgrounds were evaluated during FS with **limited impact** on detector design, **except for IPC backgrounds** revealing constraints on vertex detector.
- The main limitation for completing these studies is twofold:
  - **lack of digitizers** (describing the readout electronics) for some sub-detectors
  - not all single beam induced backgrounds simulations, such as beam-gas, were ready. Complication is that these backgrounds build up with time or originate far from the IP and necessitate an interface plane with the detector.
- Efforts underway to standardize simulation of machine-induced backgrounds, akin to LHC methods, aiming to provide detector experts with background events for estimating occupancy, data rates, to evaluate the effects on reconstruction.

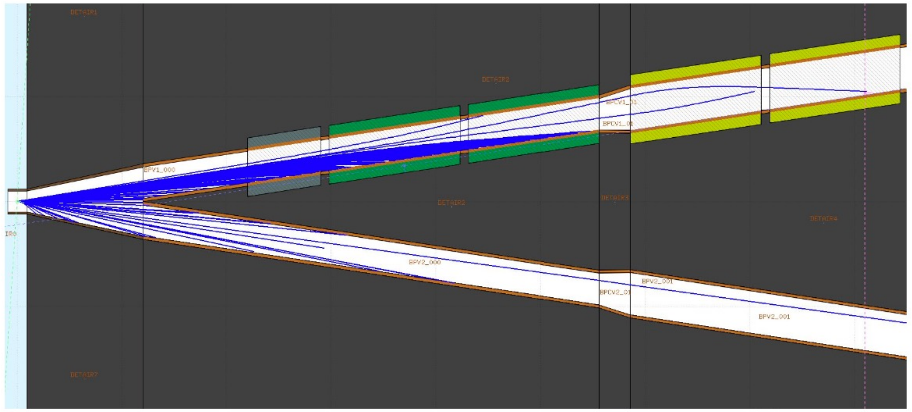
A. Frasca, FLUKA, MDI meeting #52, 11/3/24

Fluka studies of Radiative Bhabhas

Fluka model of the MDI under development for the evaluation of the IR radiation levels and fluence

Power deposition in FFQs

- simulated distributions
  - **50% energy cut, 1 σ$_y$ cut** (σ=18.315 mb)
  - **50% energy cut, no cut** (σ=33 mb)
- normalized with nominal luminosity foreseen at Zpole: 1.82e36 cm^{-2}s^{-1}



		1 σ$_y$ cut	**no cut**
TOTAL POWER DEPOSITED	-QC1R1	0.24 W	0.43 W
	-QC1R2	1.28 W	2.24 W
	-QC1R3	1.46 W	2.66 W
	-QC2R1	0.14 W	0.25 W
	-QC2R2	0.03 W	0.06 W

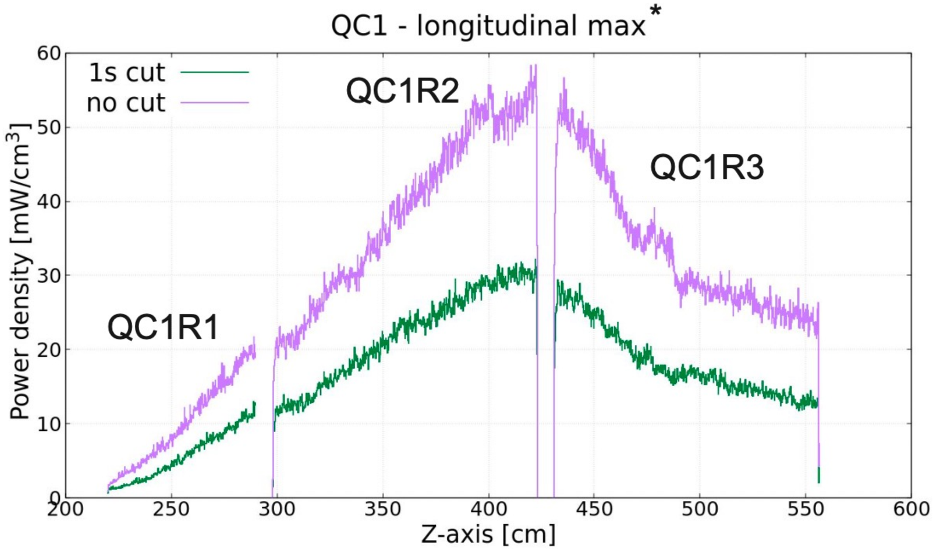
Estimated power deposition

~10 mW/cm³

Estimated dose

~10 MGy/y inside

ıe superconductive FFQs



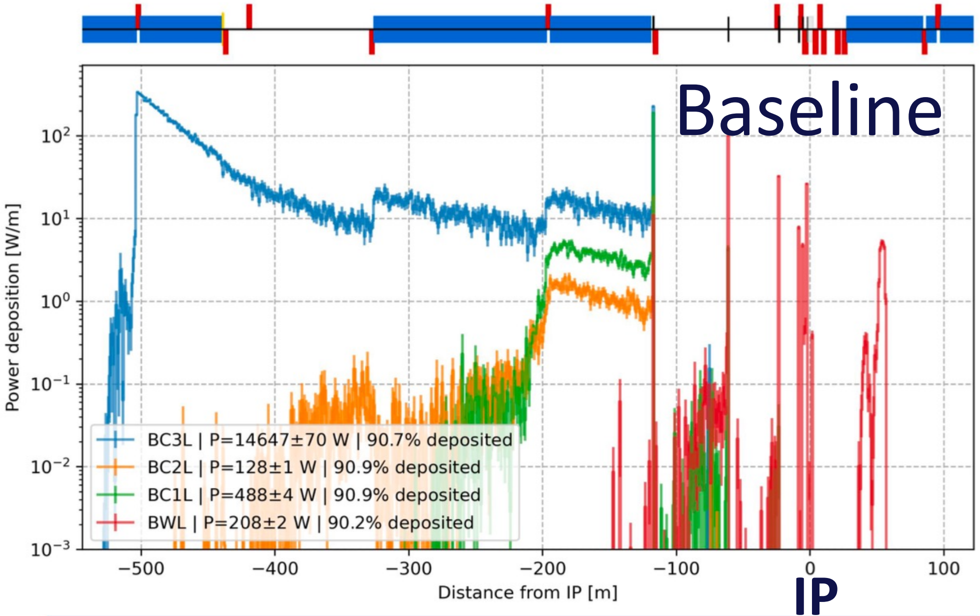
*rφz mesh: bins 0.5mm*2°*2mm

Investigating whether internal shieldings need to be developed to avoid quench and protect the magnets

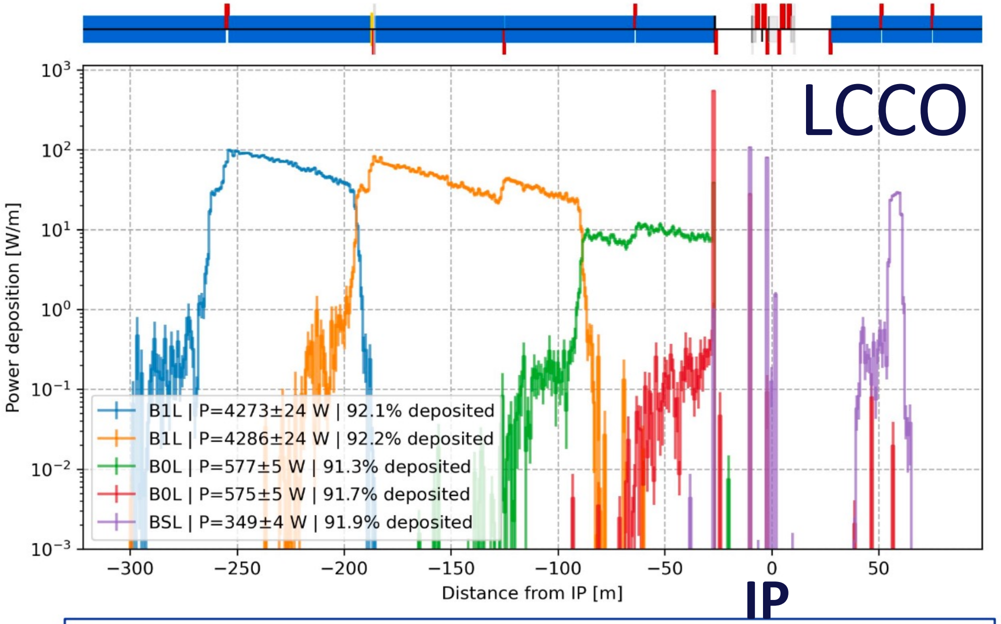
K. Andrè

Synchrotron Radiation Backgrounds Studies

- BDSIM simulation to handle and evaluate the impact in the IR
- SR collimators and masks have been designed, optimization in progress with the optics improvement, and including top-up injection. Example of power deposition for two optics below.



Synchrotron radiation from BC3L do not propagate further than the 2nd SR collimator. Only radiation from BWL reach the IP and hit BC1R. This conclusion may change once **x-ray reflection will be implemented**.



Synchrotron radiation from B1L do not propagate further than 75m from the IP. Radiation from B0L reach the first SR collimator. BSL emits photons that go beyond the IP.

Conclusion – Progress & plans on key aspects of the MDI design

❑ IR magnet system & Cryostats

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

❑ Beam induced backgrounds

- The MDI region is now improved as more realistic, and software model developed.
- Single beam effects being implemented in Xsuite, and additional collimators might be needed. Halo beam collimators have been added.
- SR backgrounds studied in different conditions and baseline/LCCO optics compare
- Study of IR radiation level & fluences started (Fluka)
- Optimization of shielding will follow
- Beamstrahlung dump with radiation levels

❑ Heat Loads from wakefields in IR region

- In progress

If you are interested, please join our MDI monthly meetings: https://indico.cern.ch/category/5665/ and *subscribe* to the MDI e-group

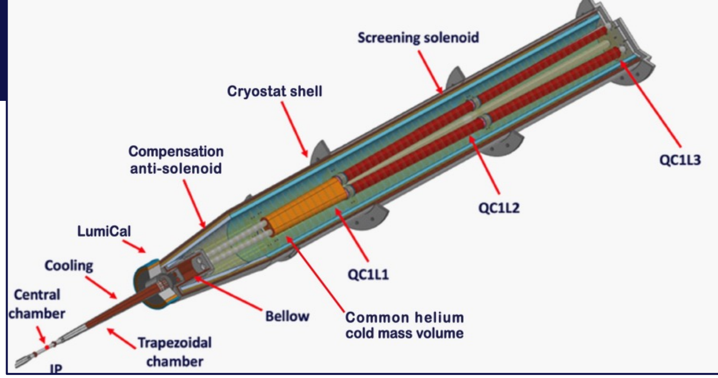
And thanks to many people for inputs!

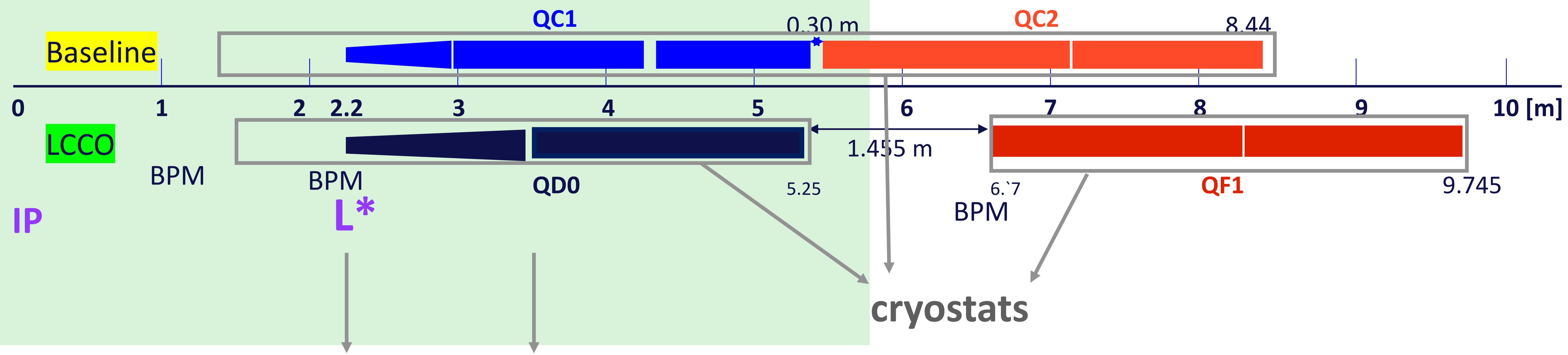
Backup

Single Beam particles effects

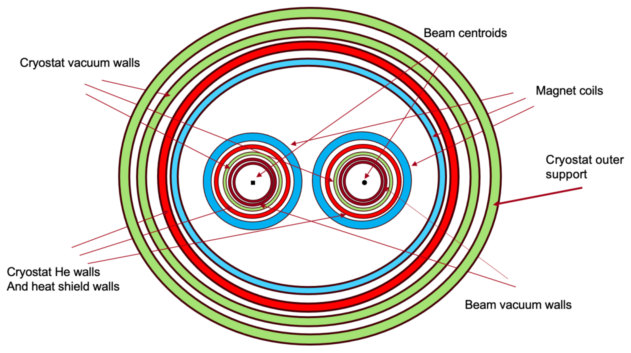
- Synchrotron Radiation
  - main driver of the IR design, studied with various tools, approaches, for all the optics
  - SR collimators and masks implemented, effect of non-Gaussian tails on the mask tip & effect during top-up injection studied
- Inelastic/ Elastic beam-gas scattering
  - Only first studies done for the CDR.
  - Pressure maps (all ring and MDI region) now available for the baseline lattice.
  - Ongoing effort to implement it in Xsuite for multiturn tracking and loss maps, and eventually determine collimators in the upstream MDI regions.
  - Beam-gas background produced in the IR and its impact to detector: planned with Fluka, now working on the MDI model
- Thermal photons
  - Only first studies done for the CDR
  - Ongoing effort to implement it in Xsuite for multiturn tracking and loss maps, and determine collimators in the upstream MDI regions.
- Touschek
  - Expected not to be relevant due to high beam energy, but to be studied, especially at the Z-pole, due to the dense beam (high bunch current and low emittance)

Final Focus quadrupoles layout





IR Magnet Cross Section View (front and end of each magnet)



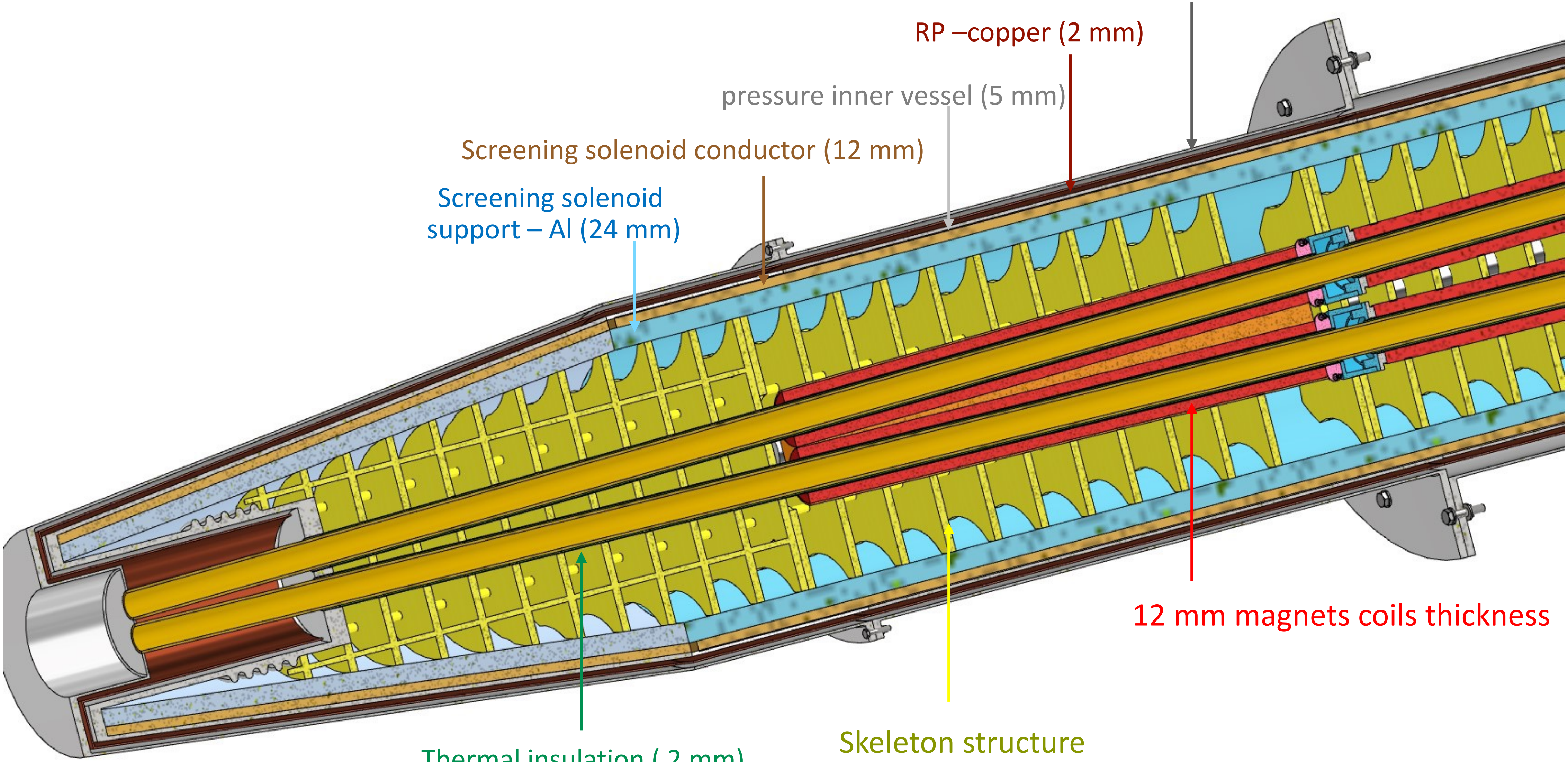
J. Seeman Nov 4, 2023

Option (Leading Candidate): IR QC1 and QC2 in different cryostats but one integrated raft

Design by cryogenic/mechanical engineer(s) required

Courtesy of J. Seeman (SLAC)

Courtesy M. Koratzinos



Outer vessel (3 mm)

RP –copper (2 mm)

pressure inner vessel (5 mm)

Screening solenoid conductor (12 mm)

Screening solenoid support – Al (24 mm)

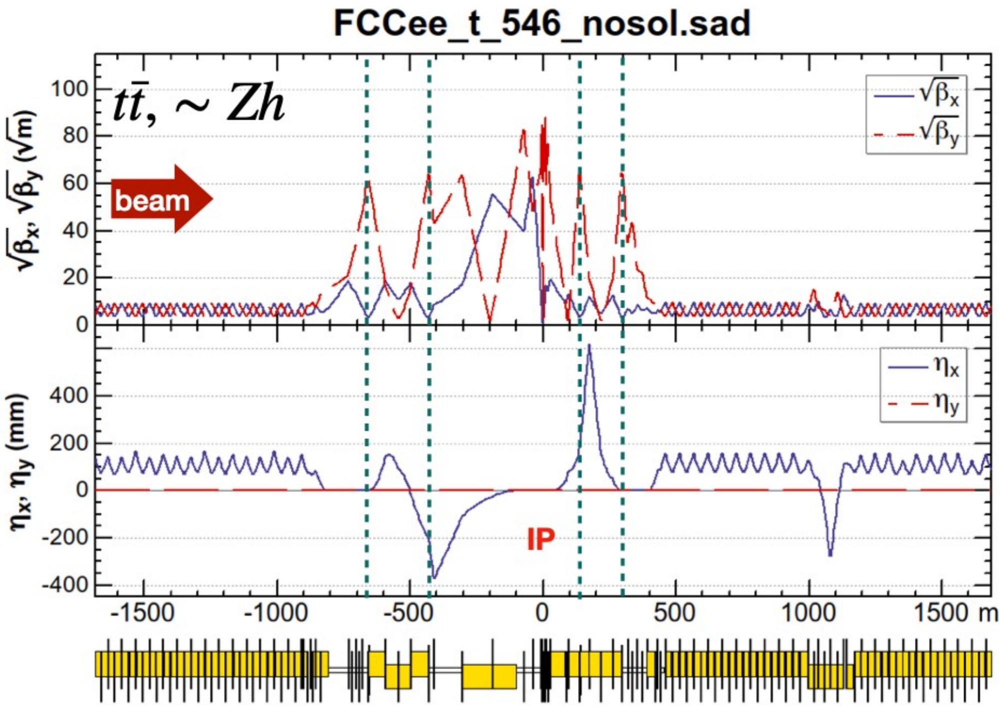
12 mm magnets coils thickness

Thermal insulation (2 mm)

Skeleton structure

Baseline IR optics

K. Oide

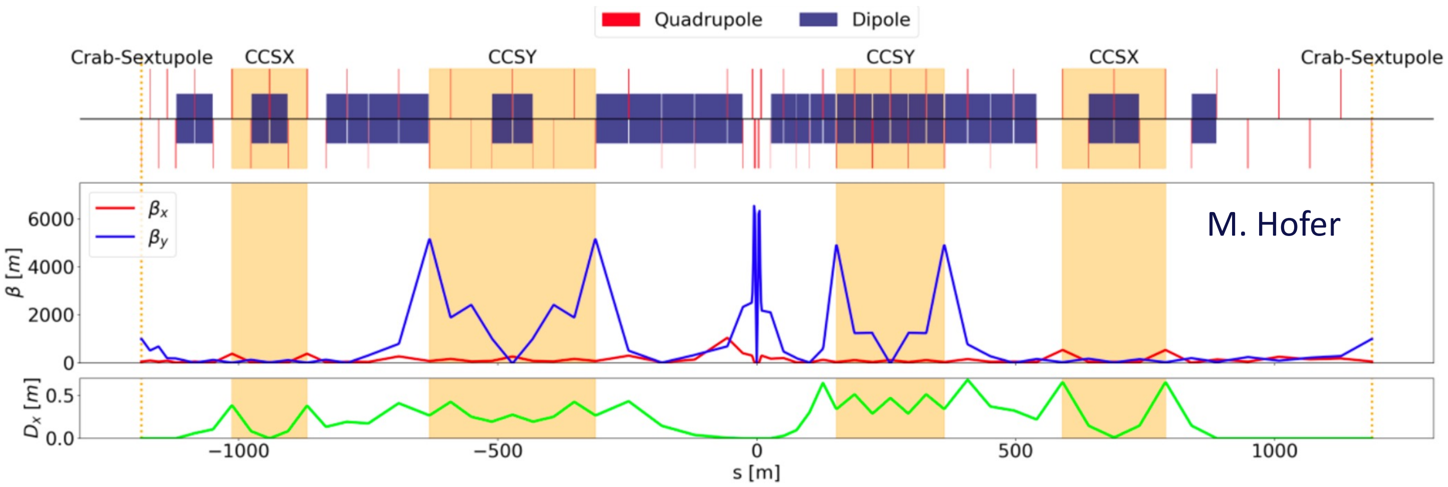


- Crab waist/vertical chromaticity correction sextupoles are located at the dashed lines, they are superconducting.

LCCO (or HFD) Optics

P. Raimondi

ttbar



LCCO: Local Chromatic Correction Optics
HFD: Hybrid FODO

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

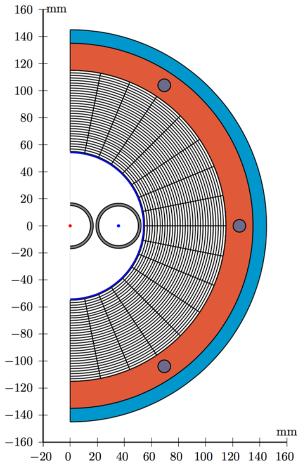
The beam optics are asymmetric between upstream/downstream due to crossing angle & suppression of the SR upstream to the IP

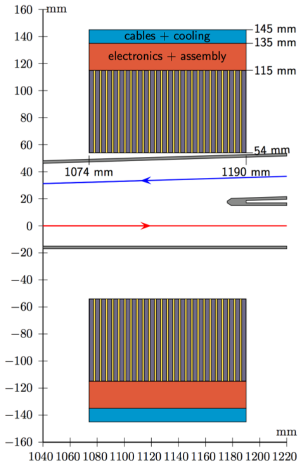
LumiCal constraints & requirements

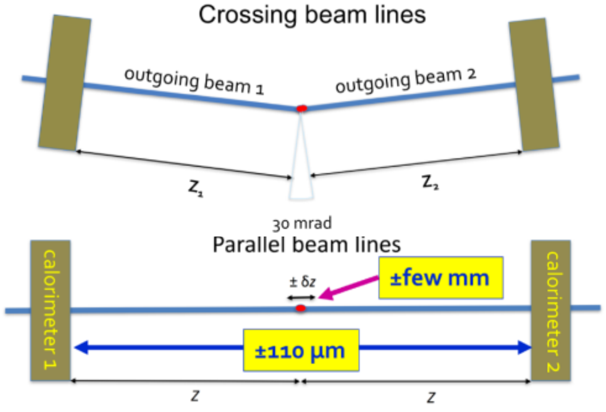
Goal: absolute luminosity measurement 10^{-4} at the Z

Standard process Bhabha scattering

- Bhabha cross section 12 nb at Z-pole with acceptance **62-88 mrad** wrt the outgoing pipe
- Requires **50-120 mrad clearance to avoid spoiling the measurement**
- The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines
- Requirements for alignment
  - few hundred μm in radial direction
  - few mm in longitudinal direction

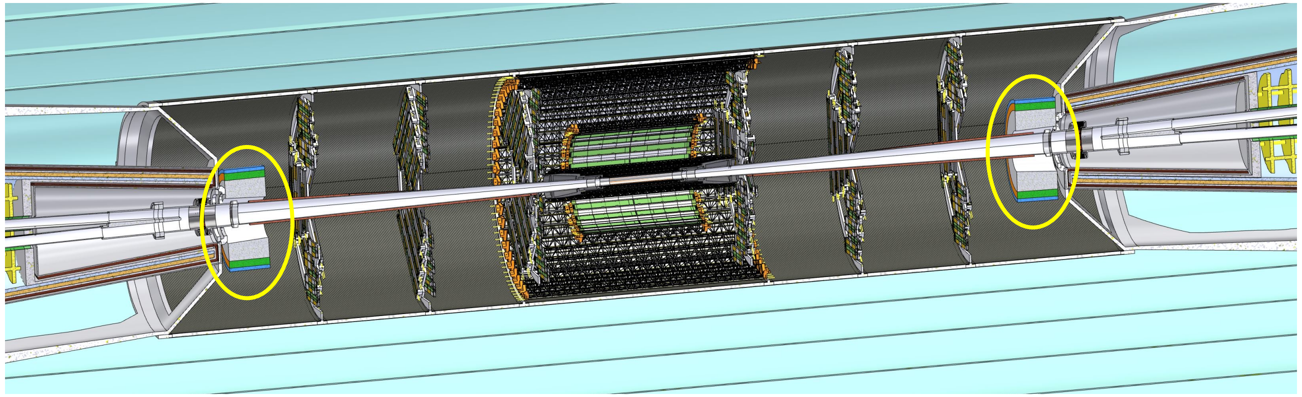






Lumical integration:

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

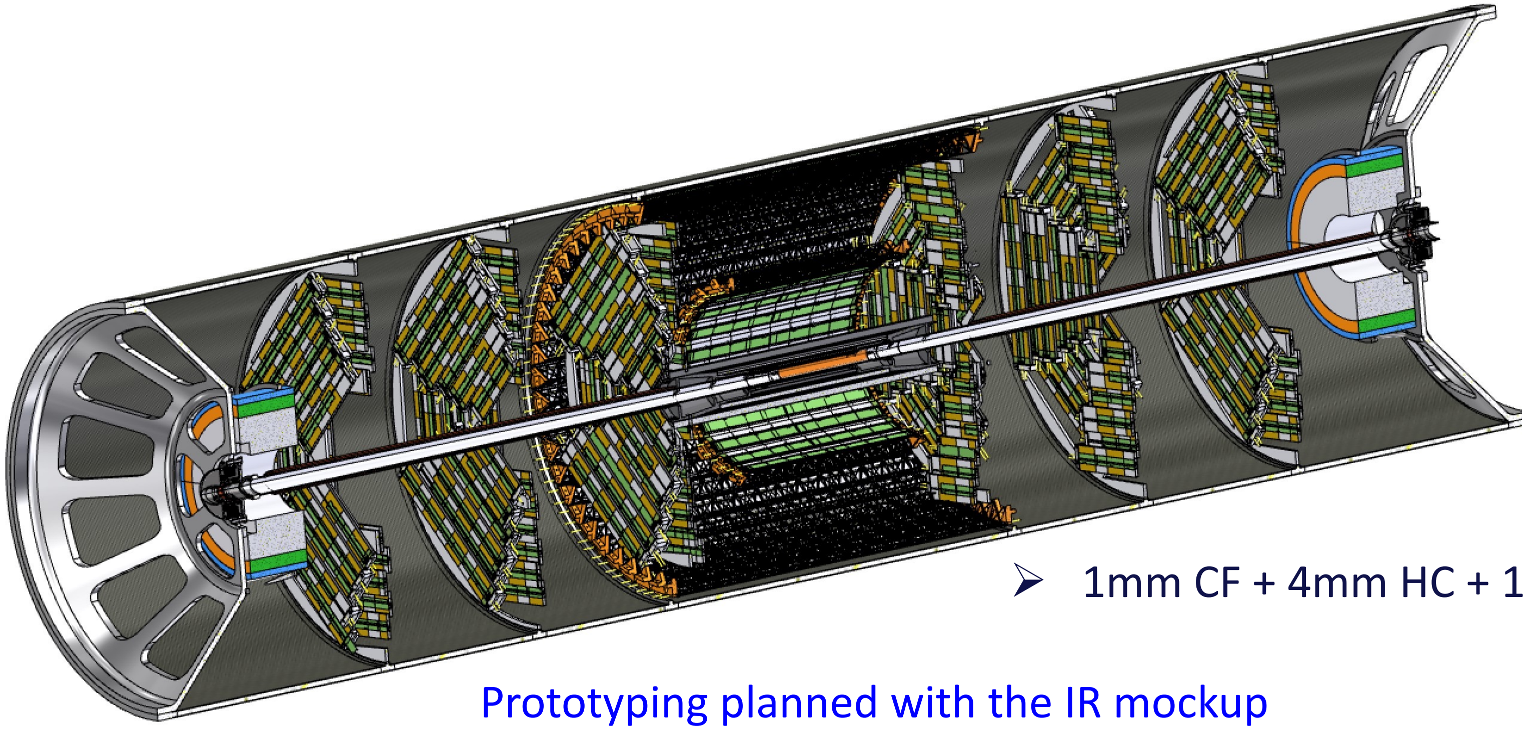


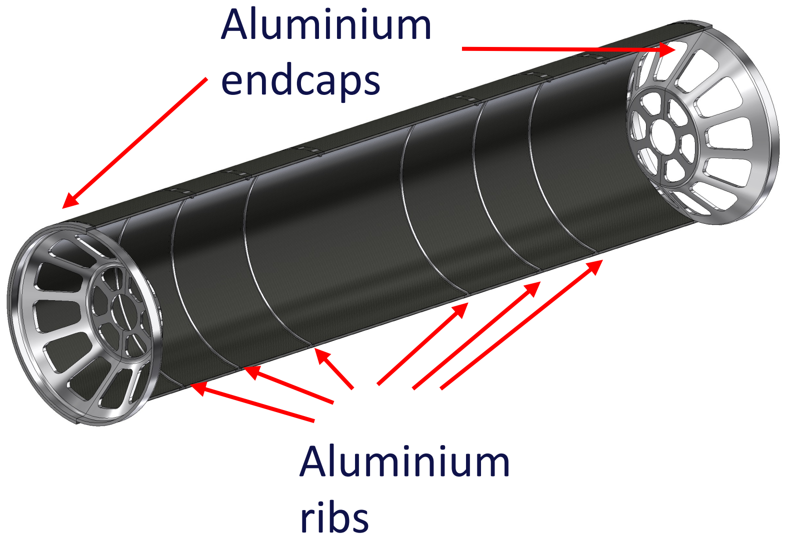
Support cylinder

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

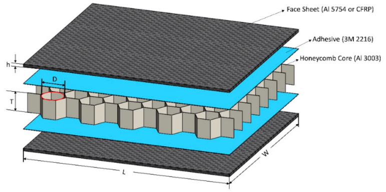
- Provides a cantilevered support for the pipe
- Avoids loads on thin-walled central chamber during assembly or due to its own weight

- Once the structure is assembled it is slided inside the rest of the detector
- Studies on-going where to anchor it (see A. Gaddi, Joint Det.-MDI session)





- 1mm CF + 4mm HC + 1mm CF



Prototyping planned with the IR mockup