FCC

Design of the FCC-ee IR, prototyping and MDI

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on behalf of the MDI group

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Outline

- MDI layout
- IR optics
- MDI prototyping
- Beam backgrounds
- Outlook

Few Challenges on FCC-ee MDI covered in this talk

Hardware

- **Small L* → QD0 inside detector**
  - trade-off between detector hermeticity and cryostat clearances
- **Integration**
  - Minimise impact of services on detector
- **Beam pipe**
  - material budget
  - Y-pipe very close to the IP and inside the detector
  - Active cooling for circular colliders
- **Alignment**
  - Stringent requirements of FFQs and LumiCal
- **Vibrations** suppression at the IR and vertex detector
- **Beamstrahlung and SR dump (~ hundreds of kW)**
  - dedicated alcove, radiation, target at dump

Performance

- **High Luminosity**
- Robustness against **beam-induced and IP backgrounds**
  - IPC dominant especially for LC
  - SR backgrounds
- **Collimation**
- **Radiation** environment, and occupancy and spurious hits

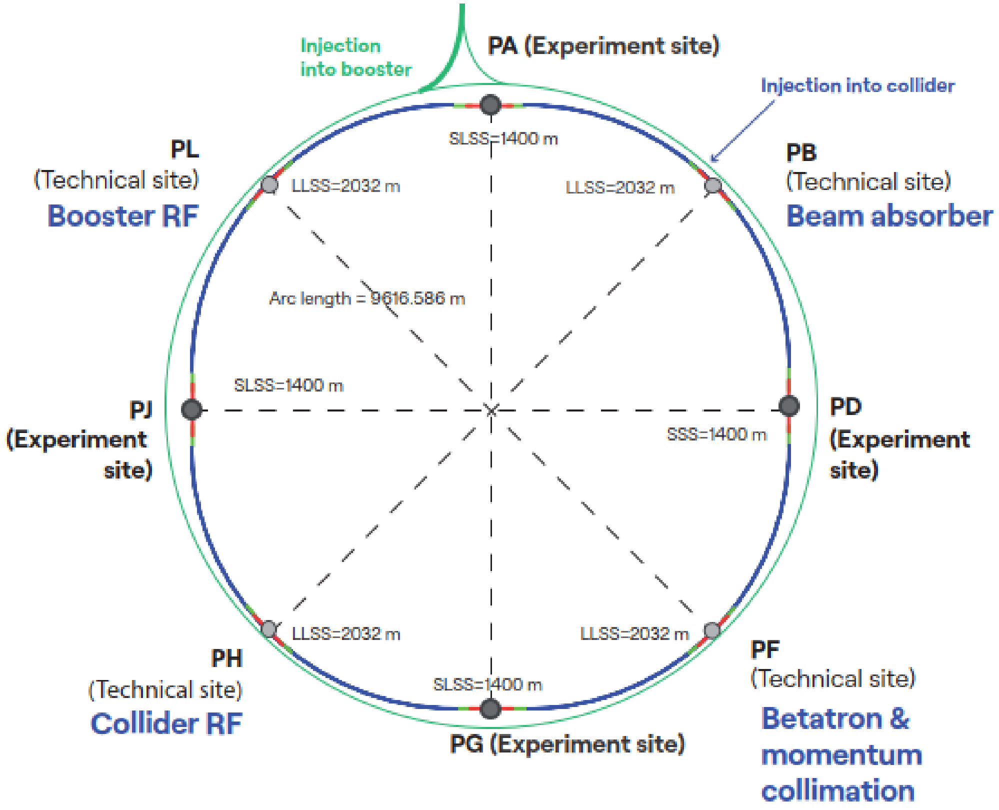
part of the ECFA-DRD8-WP1 Collaboration on Mechanics & Integration

MDI Overview and key parameters

- Beam crossing angle of 30 mrad in x-z
  - Allows to reach high luminosity
  - Determines the luminous region size in x and z
- Beam power limited to 50 MW (due to synchrotron radiation) by design
  - determines maximum beam current per each c.o.m. energy and therefore limits the available instantaneous luminosity
  - In turn determines the no. of bunches → interaction frequency
  - Also determines the size of the beam in z together with the beamstrahlung
- Final focus superconducting quadrupoles inside the detector (L*=2.2 m)
  - Determines the luminosity and the beam size in y
- Maximum detector B-field at 2 T at the Z not to decrease luminosity

[FSR] Table 12: Key parameters of FCC-ee IR for scenarios with 4 IPs.

	Z	W	H	ttbar
Beam energy (GeV)	45.6	80	120	182.5
Luminosity/IP ($10^{34}cm^{-2}s^{-1}$)	145	20	7.5	1.41
beam current (mA)	1294	135	26.8	5.1
bunch number /beam (#)	11200	1852	300	64
bunch spacing (ns)	27	163	1008	4725
σ_x^* (μm)	9.5	21.8	12.6	36.9
σ_y^* (nm)	40.1	44.7	31.6	43.6
bunch length by SR /BS (mm) σ_z	4.7/14.6	3.46/5.28	3.26/5.59	1.91/2.33
energy spread by SR /BS (%) σ_δ	0.039 / 0.121	0.069 / 0.105	0.102 / 0.176	0.151 / 0.184



FCC-ee Interaction Region rationale: crab-waist

Crab-waist scheme, based on two ingredients:

- concept of **nano-beam scheme:**
  - vertical squeeze of the beam at IP and large horizontal crossing angle
  - large ratio σ_z/σ_x reducing the instantanous overlap area, allowing for a lower β_y*
- concept of **crab-waist sextupoles:**
  - placed at a proper phase advance they suppress the hourglass effect by inducing a constant β_y along the larger coordinate of the beams overlap.

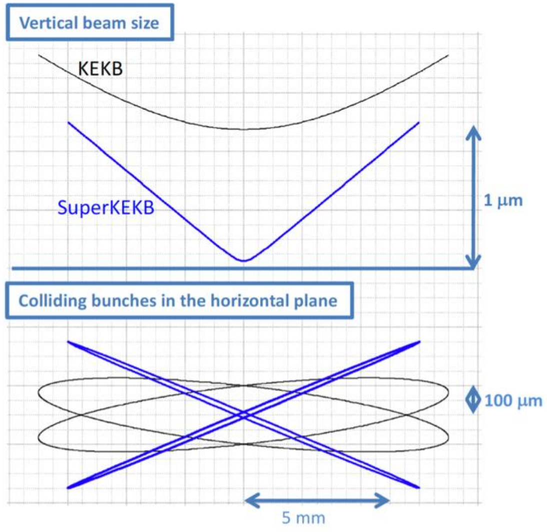
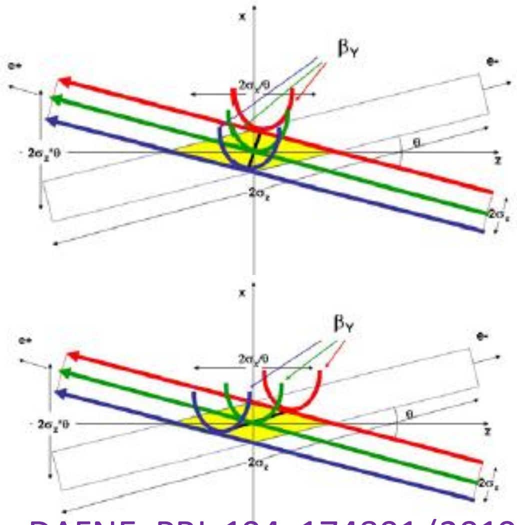
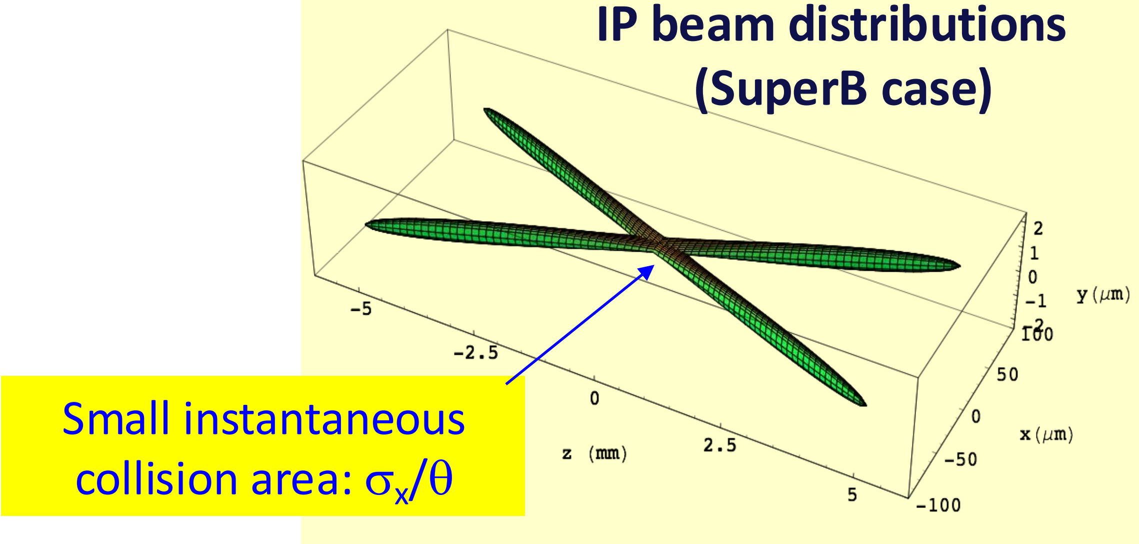


Figure 2: Schematic view of the nanobeam collision scheme.

SuperKEKB https://arxiv.org/pdf/1809.01958.pdf



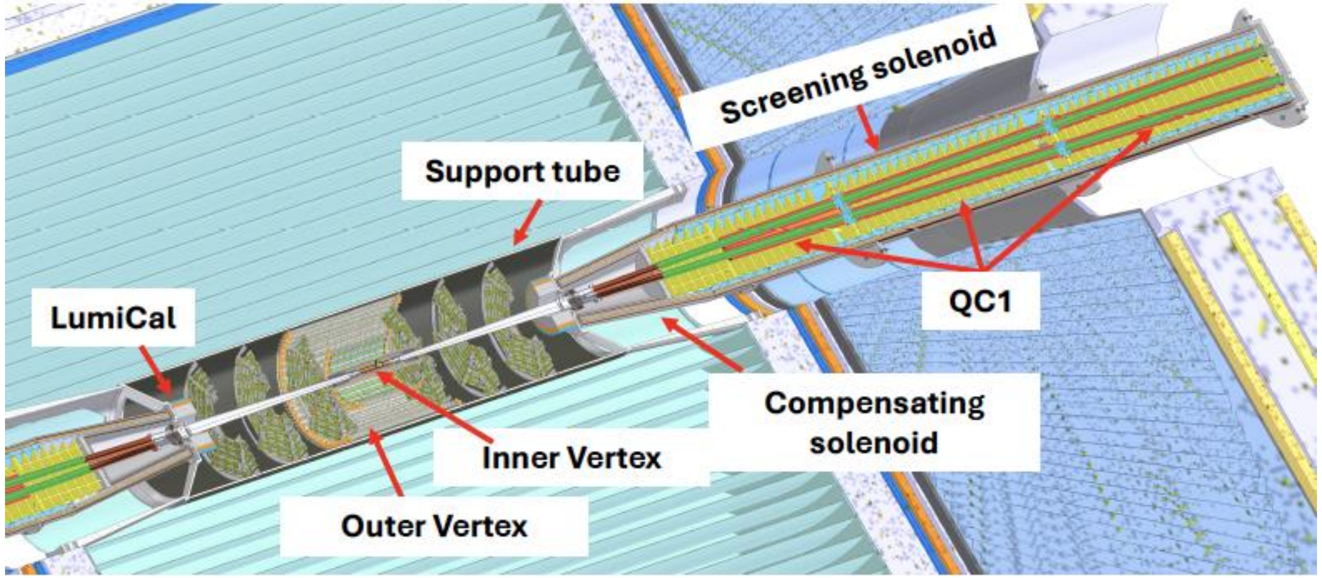
DAFNE, PRL 104, 174801 (2010)



Accelerator components inside the detector: IR magnet system

It is inside the detector and is all cryogenic

- Compensating solenoid
- Final focus quadrupole QC1
- Screening solenoid



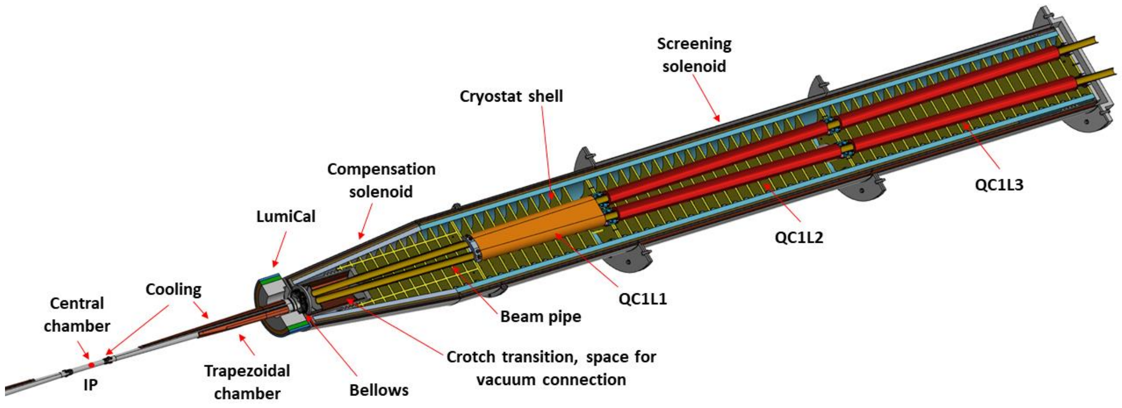
Challenges for first final quadrupole QC1:

- Small distance of coils at first segment of QC1L1
- Need space for skew correctors winding to be added around QC1
- Need to allow few per cents of different strength of the FFQ
- Cryostat has to fit in the crowded MDI region

IR Optics – Solenoid compensation scheme

Two schemes to compensate the coupling induced by the detector field.

Screening solenoid around portion of QC1 inside the detector

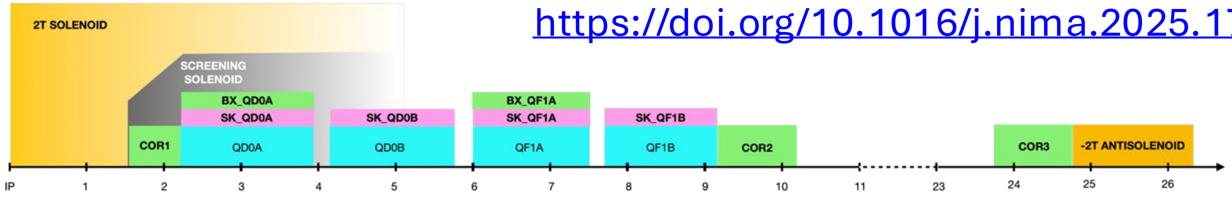


Local solenoid compensation scheme (Baseline design)

- Strong anti-solenoid (-5 T) in front of QC1

Non-Local solenoid compensation scheme

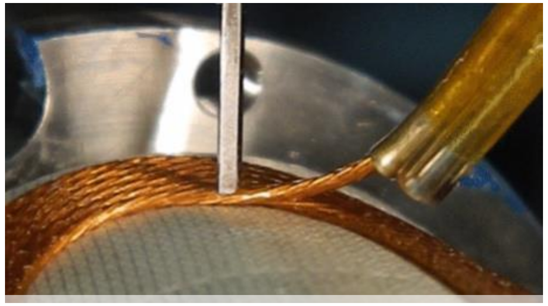
- Anti-solenoid outside detector (~ 10 m from the IP)
- Weak corrector dipoles
- Skew quads windings around FFQs



https://doi.org/10.1016/j.nima.2025.171135

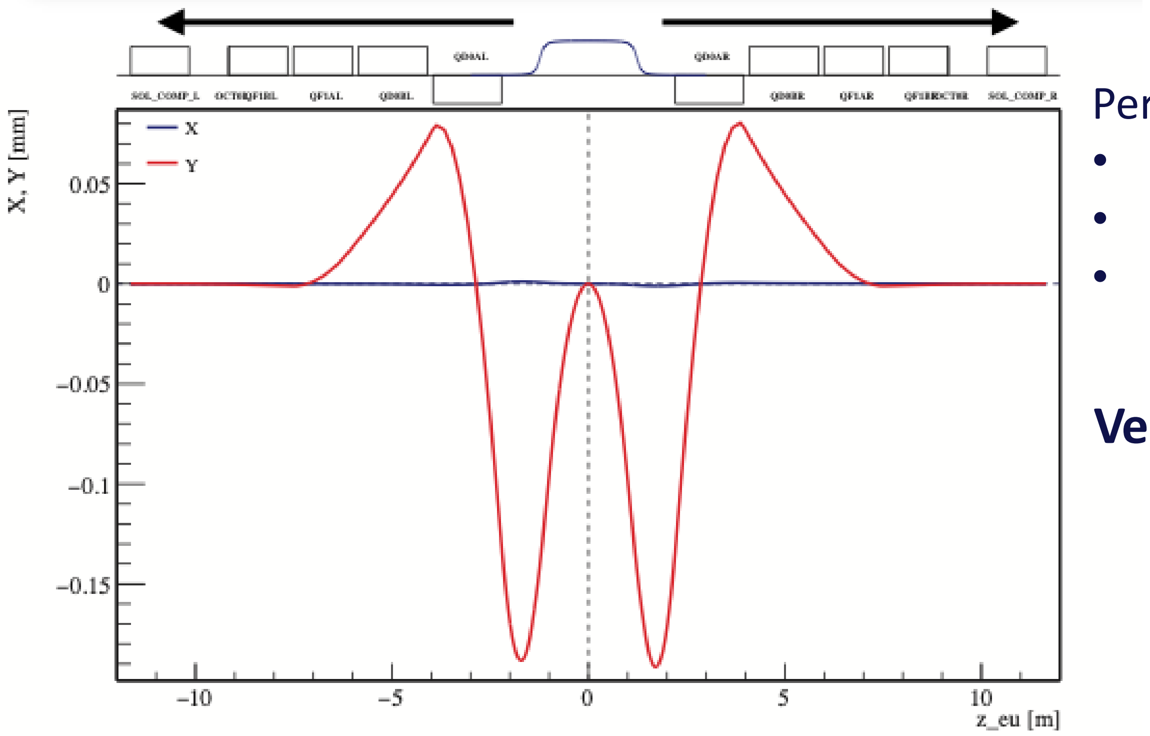
- This solution is optics independent (in terms of final focus quads)
- The tuning knobs -correctors and skews- are needed for orbit and coupling correction for all optics.

BNL Direct Wind



“3D Printing” Superconductor

Non-local Solenoid Compensation Scheme



Courtesy H. Burkhardt

Perfect compensation of orbit, dispersion coupling with

- 3 rather weak orbit corrections each side of the IP
- small skew components to the FFQs (equivalent to 10 mrad rotation)
- anti-solenoid at 11m from the IP.

Vertical emittance increase is very small ($\leq$ 100 fm at Z pole)

- Allows to **increase detector B field up to 2.5 T** contrary the local scheme (due to a better coupling compensation)
- **Lower SR produced at the IR**
- **Polarisation under study**. **Anyway, solvable with e+e- polarised injector**.

Interaction region layout: beam pipe

- **Beam pipes in AlBeMet (62% Be, 38% Al)**
- **Central beam pipe 1 cm internal radius**
  - Internally 5 µm gold coated to reduce impedance and shield of sync. rad. photons.
- **Actively cooled**
  - Liquid paraffin for the central one (~60 W) and water for the lateral ones (~130 W).
- **Minimised material budget**
  - Central beam pipe double wall AlBeMet, paraffin and Au (0.68% X_0)
  - Lateral beam pipes minimised within LumiCal acceptance: (mostly 7% X_0, few regions up to 50% of X_0). Shaped to minimise showers off manifolds

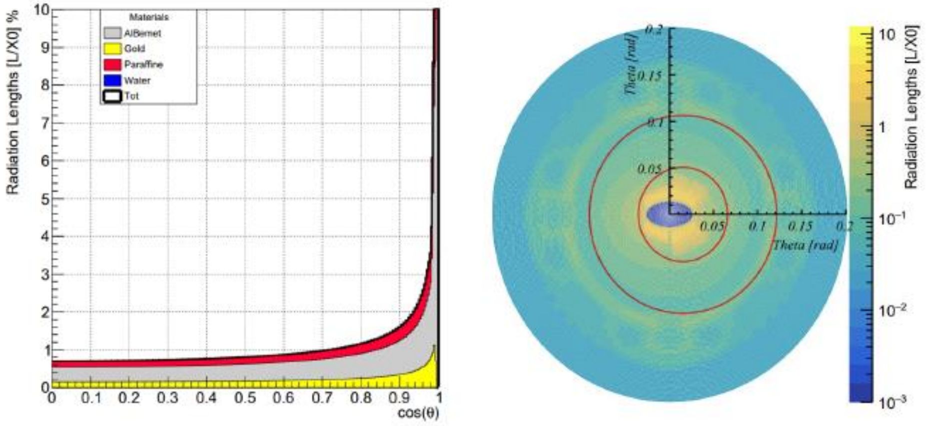
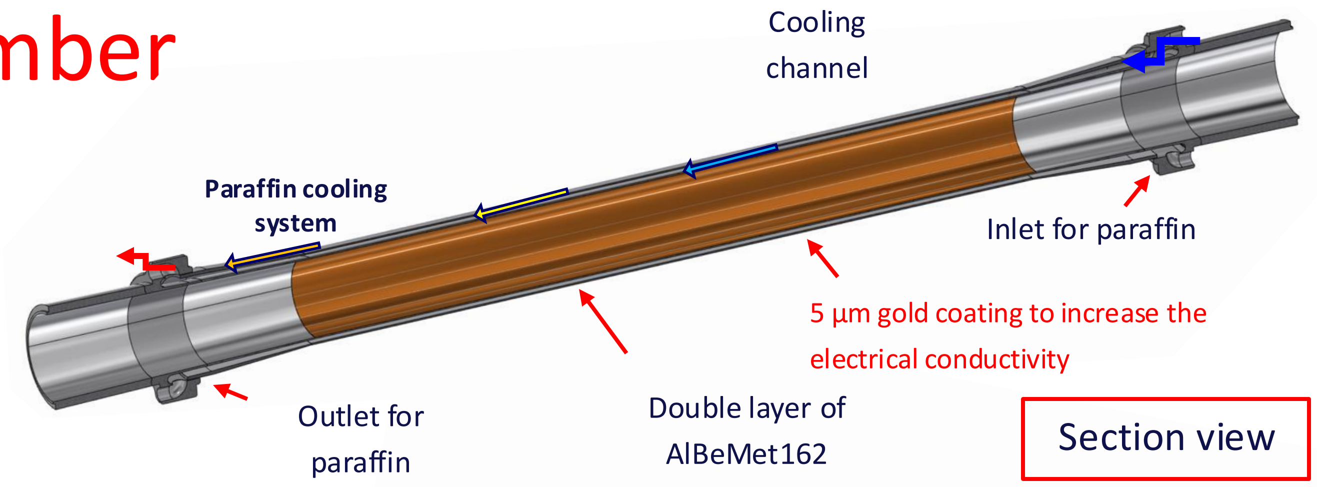


Fig. 50: Material budget of the beam pipe as a function of the polar angle (left) and in front of the LumiCal (right) in the region $\theta \in [0, 0.2]$ rad. The red lines represent the LumiCal acceptance, i.e. the 50 mrad and 105 mrad cones.

FCC-ee IR central chamber

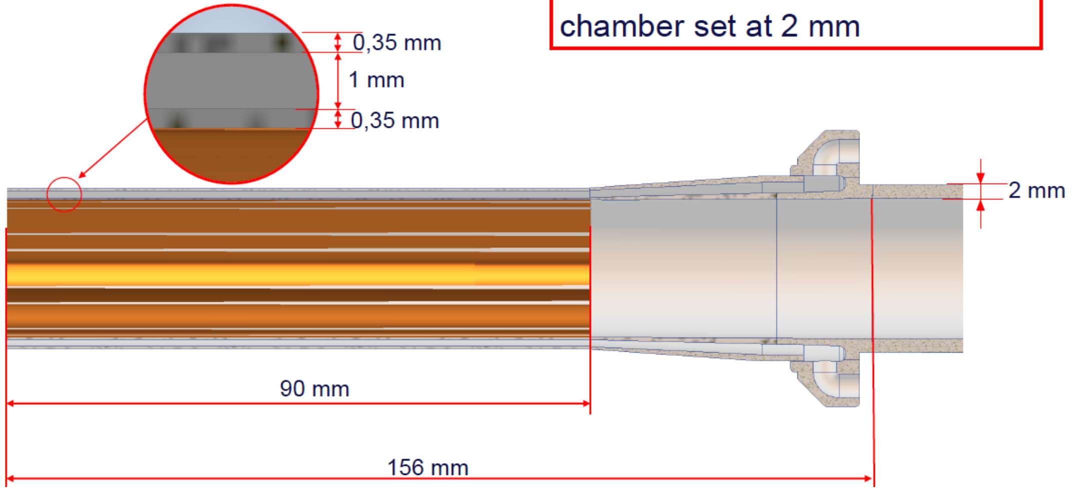
- AlBeMet 162 (62% Be, 38% Al)
- 180 mm long centered at the IP

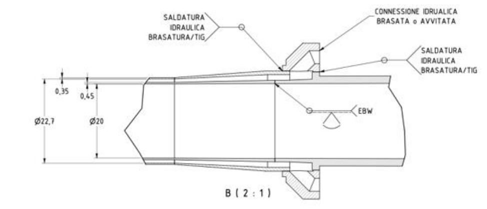
- **0.35 mm** outer radius AlBeMet162
- **1 mm gap** for paraffin
- **0.35 mm** inner radius AlBeMet162



Thickness of the chamber

Uniform thickness of the conical chamber set at 2 mm





The prototype is in aluminium:

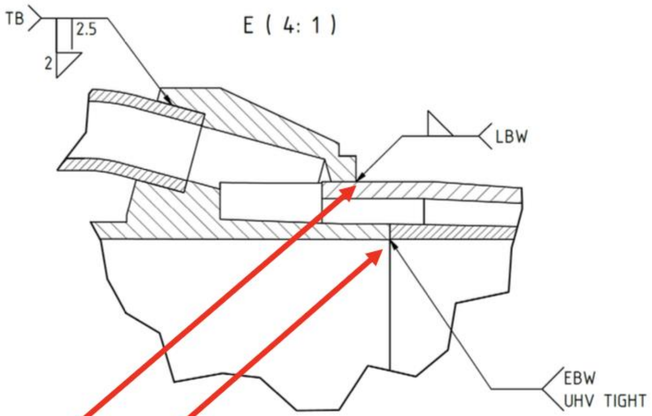
- **0.35 mm** outer radius
- **0.9 mm gap** for paraffin
- **0.45 mm** inner radius

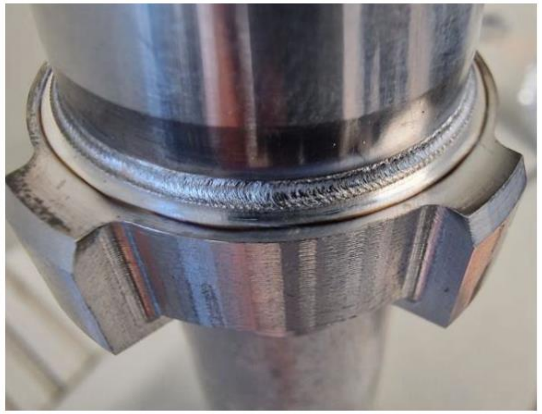
Leveraging Belle-II beam pipe design (0.4 mm Be +0.6 mm Be + 1mm paraffin)

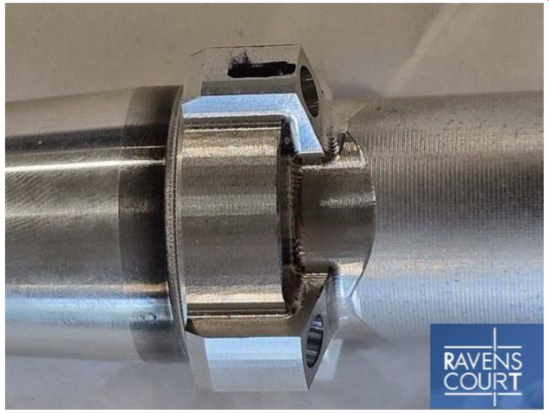
IR Mockup project in Frascati INFN-CERN

Central chamber – manufacturing

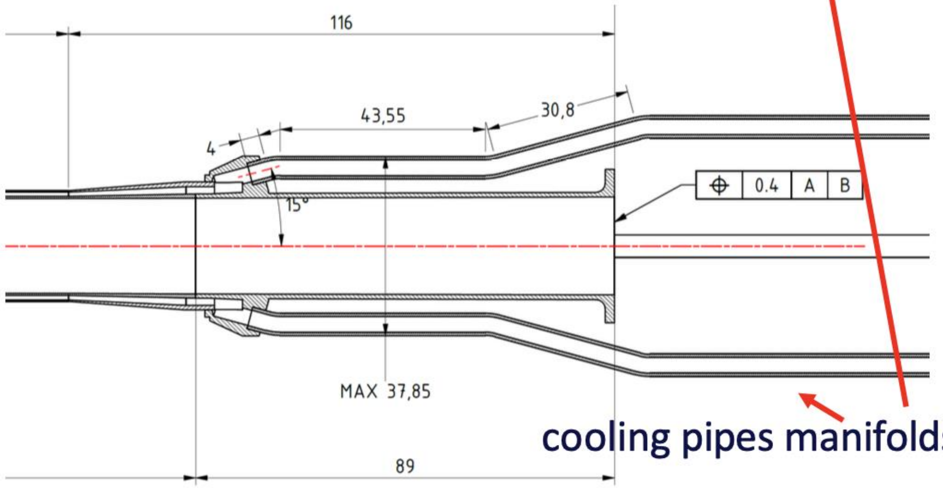
Vacuum chambers manufactured by COMEB s.r.l. (Italy)







Electron Beam Welding (EBW) by Ravenscourt Eng. Limited (UK)



cooling pipes manifolds

IR Mockup project in Frascati INFN-CERN

Detector beam pipes

Courtesy F. Fransesini

Paraffin flow (central chamber)

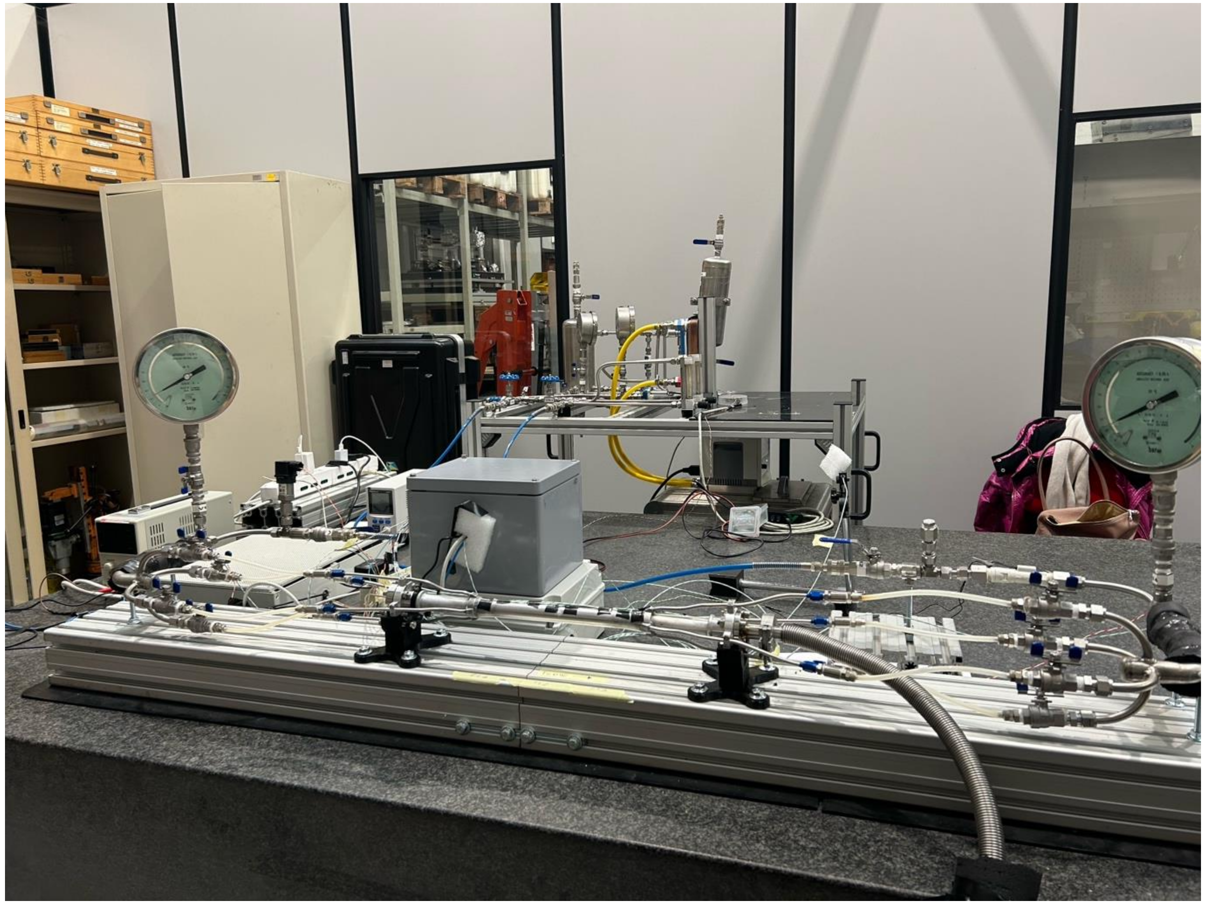
- Flow rate: 0,015 kg/s
- Section:68,17 mm^2
- Velocity: 0,3 m/s
- Inlet temperature: 18°C
- Convective coefficient: 900 W/m^{2}K

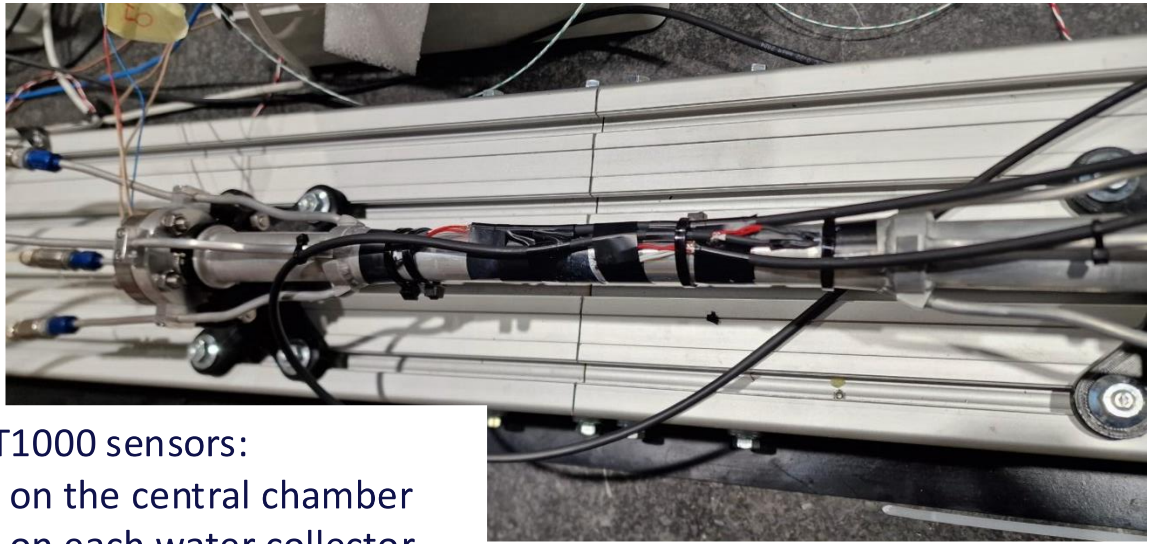
Water flow (Ellipto-Conical chamber)

- Flow rate: 0,01 kg/s (4 channels per side)
- Total flow rate per side: 0,04 kg/s
- Section: 12,25 mm^2
- Velocity: 1 m/s
- Inlet temperature: 16°C
- Convective coefficient: 1200 W/m^{2}K

Active cooling of the central chamber: measurement set-up

IR Mockup project in Frascati

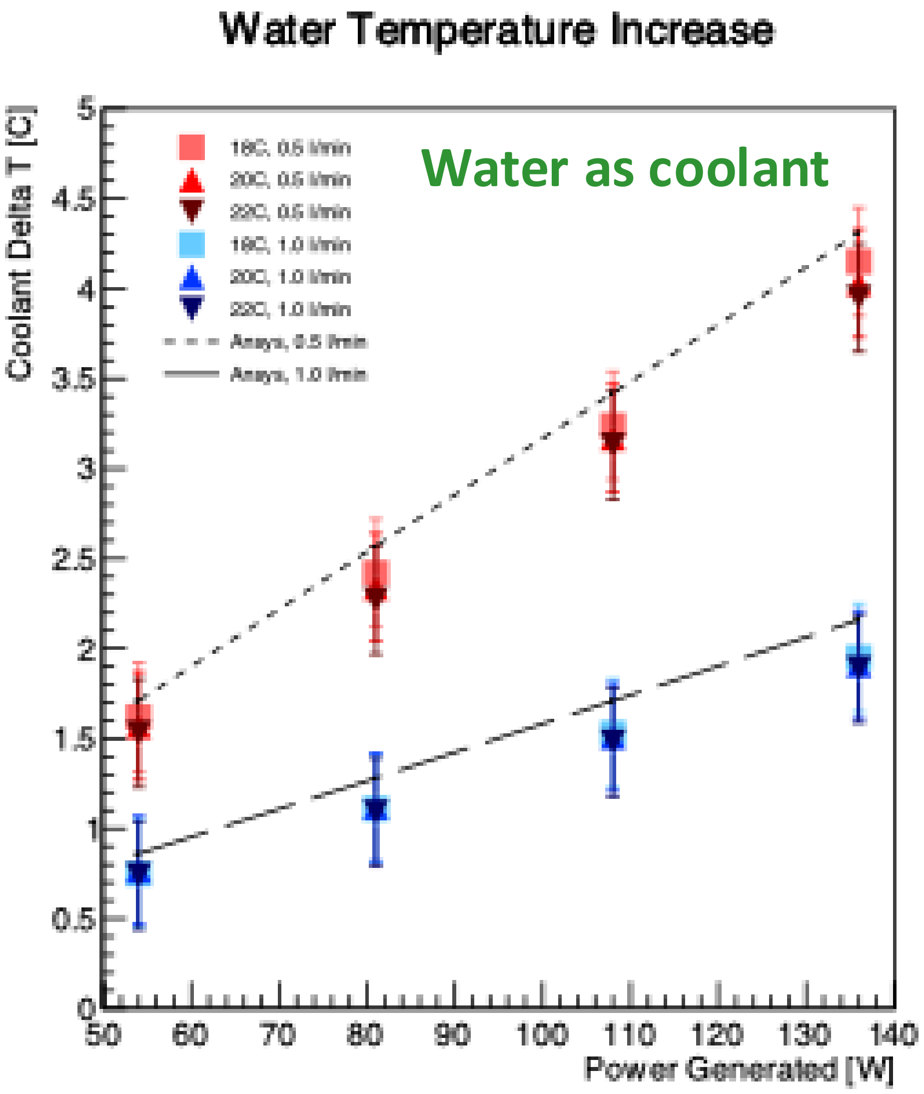




PT1000 sensors:
- 3 on the central chamber
- 1 on each water collector
- 1 environment

An internal ohmic heater inside the vacuum chamber simulates the beam heat load on the pipe during the beam passage.
A variable power supply controls the power deposited on the chamber.

Measurements with the prototype of the central beam pipe



- **Each measurement corresponds to the water temperature increase for a given power on the beam pipe for a flow rate of 0.5 l/min and 1 l/min.**

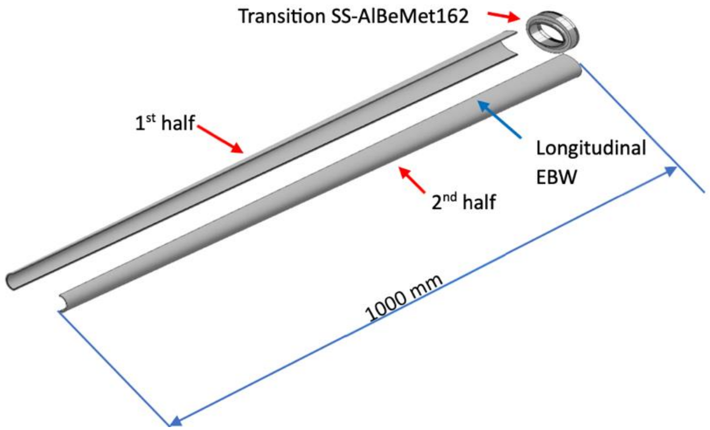
- 54 W is the nominal beam heat load on the beam pipe.
- Measurements in good agreement with expectations.
- Linear behaviour as expected.

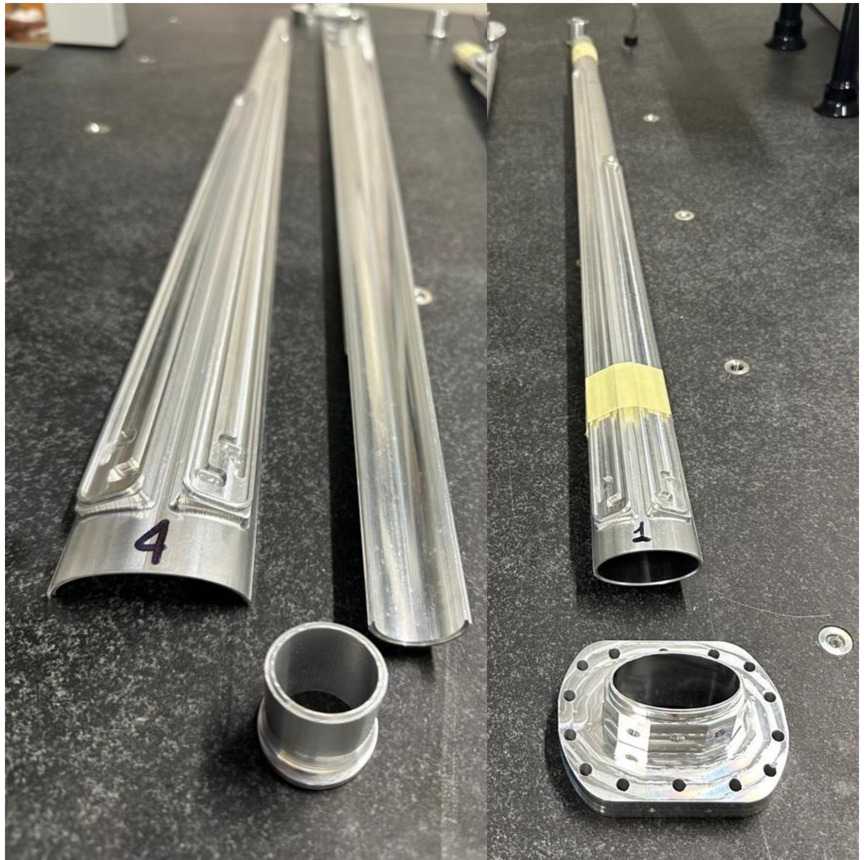
- Measurements also with **paraffin** as coolant have been performed. Analysis of data are ongoing.

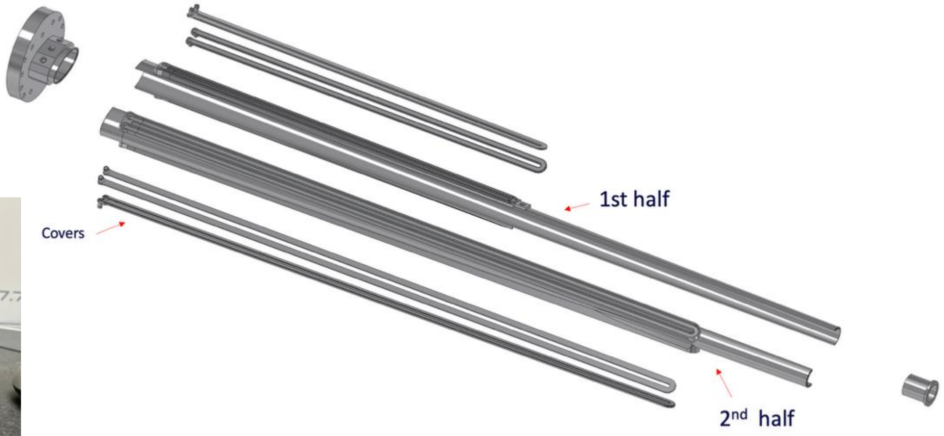
Conical Vacuum Chambers

Presently in UK for EBW

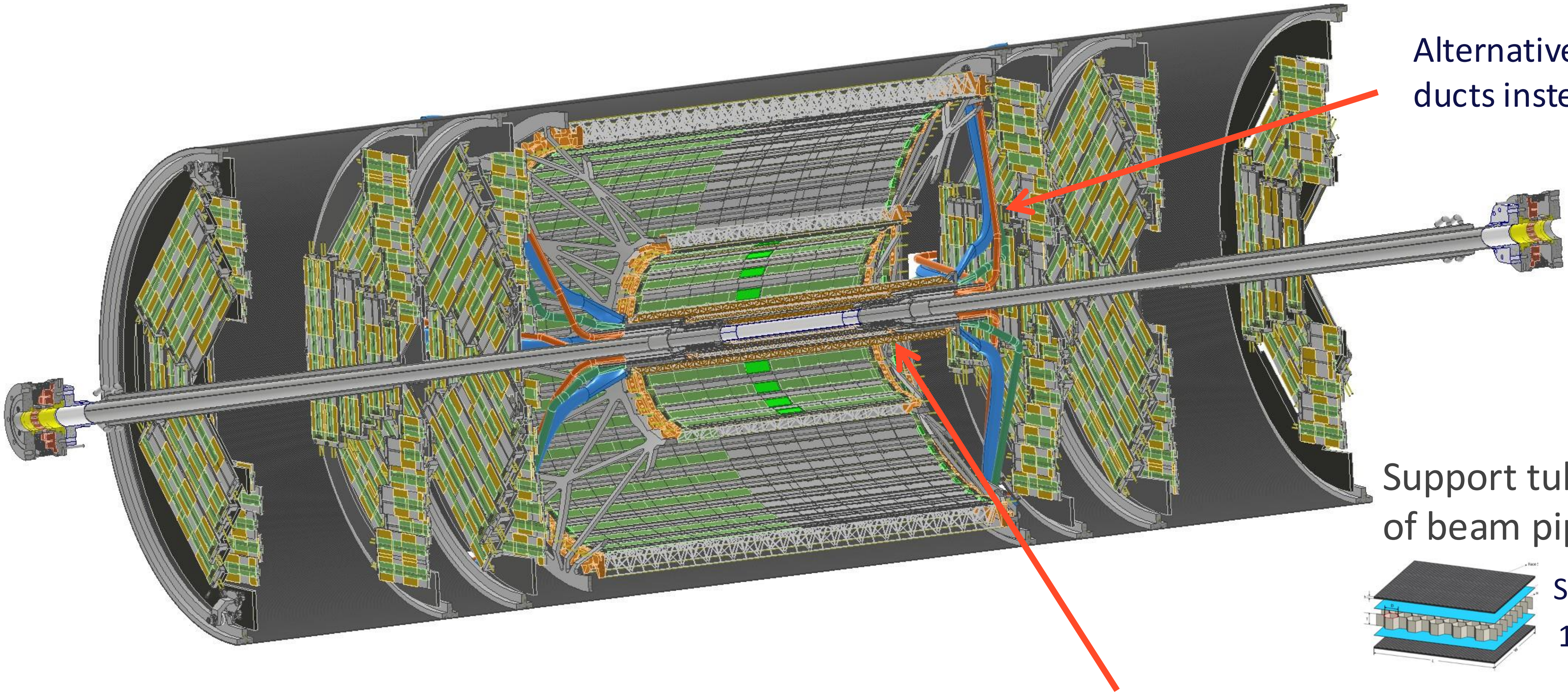
Prototype in aluminium.
Conical chambers are fabricated in two halves that need to be welded with EBW.
The cover part of the water cooling channels will be brazed on top.







FCC-ee engineered Interaction Region

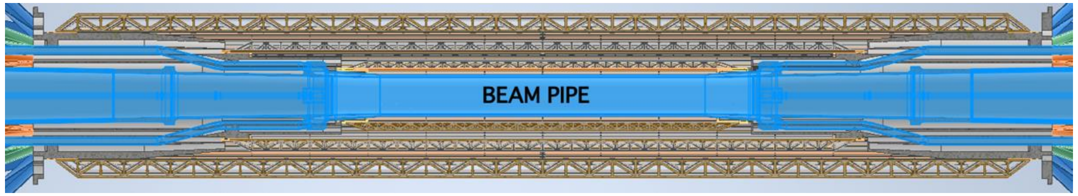


Alternative (better) option for air ducts instead of air-cooling cones

Support tube provides integration of beam pipes, vertex and LumiCal

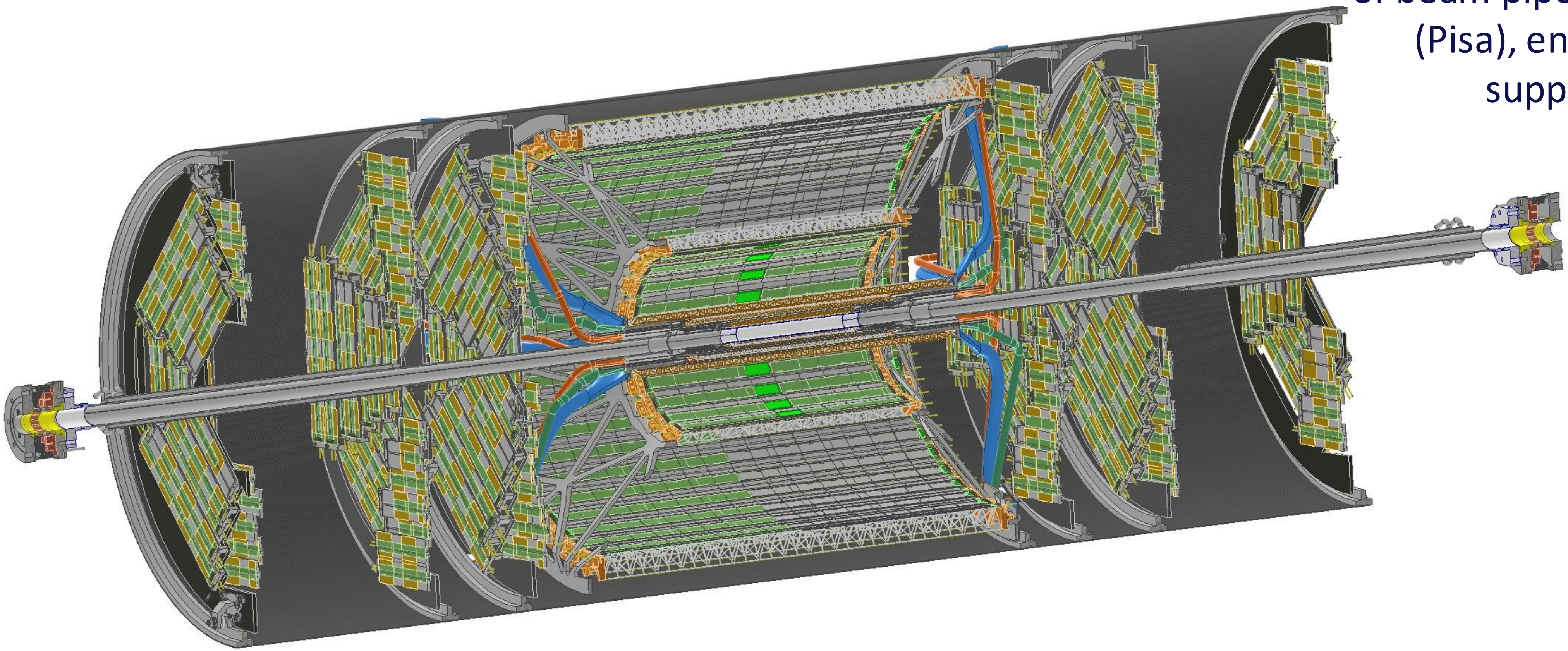
Support tube material
1mm CF + 4mm HC + 1mm CF

Beam pipe cooling services and innermost vertex detector layer ones need to be carefully integrated



FCC-ee engineered Interaction Region

Support tube provides integration of beam pipes, vertex and LumiCal (Pisa), endcaps and lumical supports (Frascati)



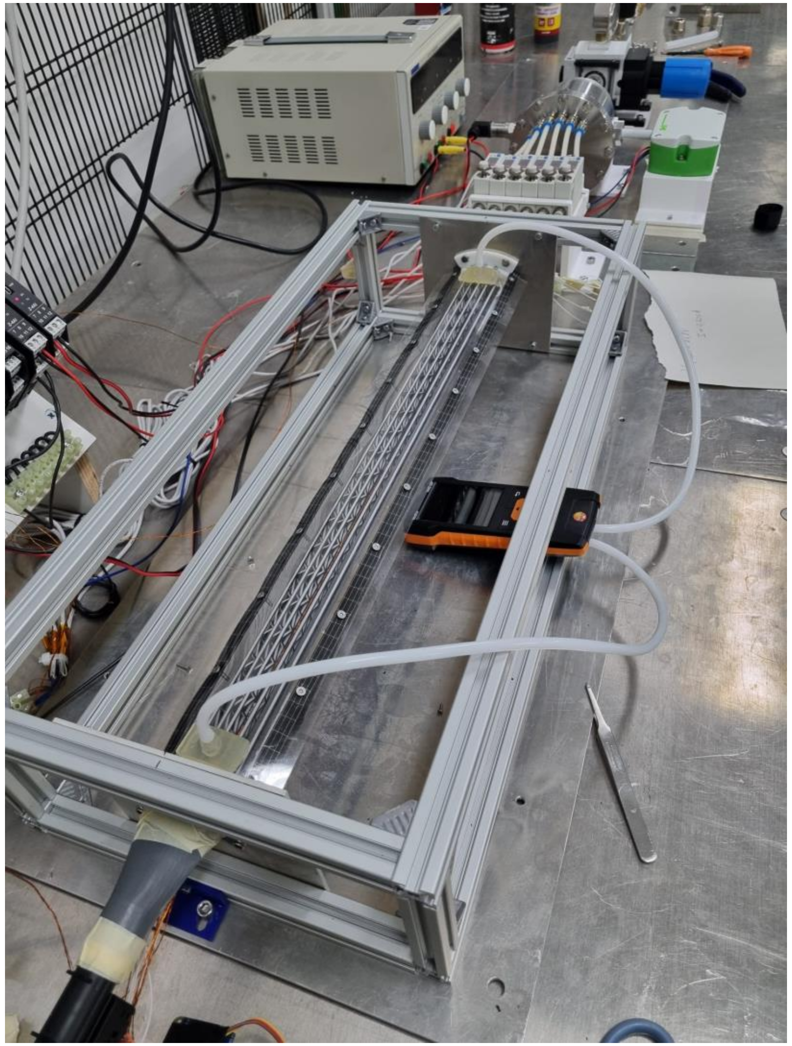
Funded project INFN & CERN to realise in Frascati a full-scale mockup of this layout

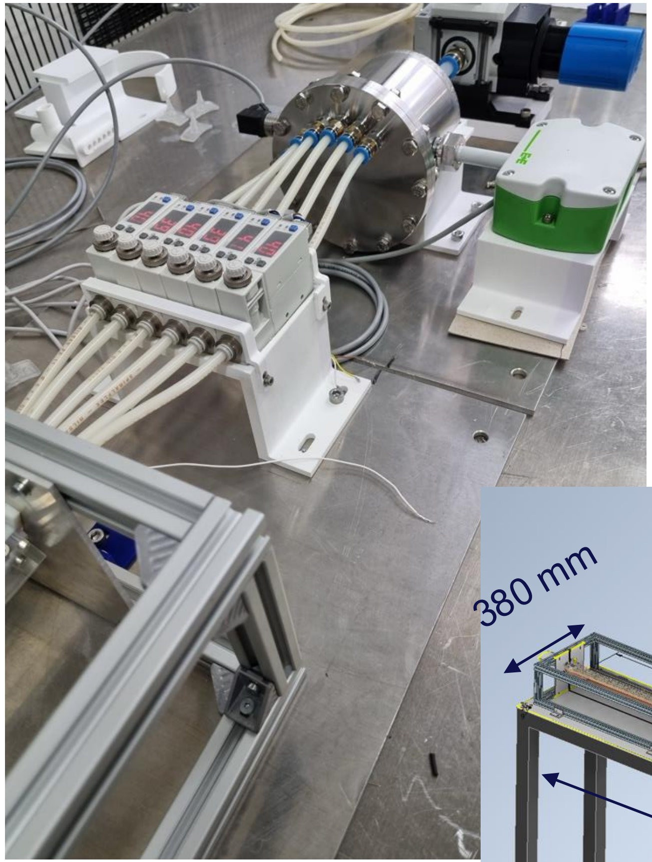
Linked to the DRD8 WP1

Goal: design validation, buckling test, assembly and cooling/services test

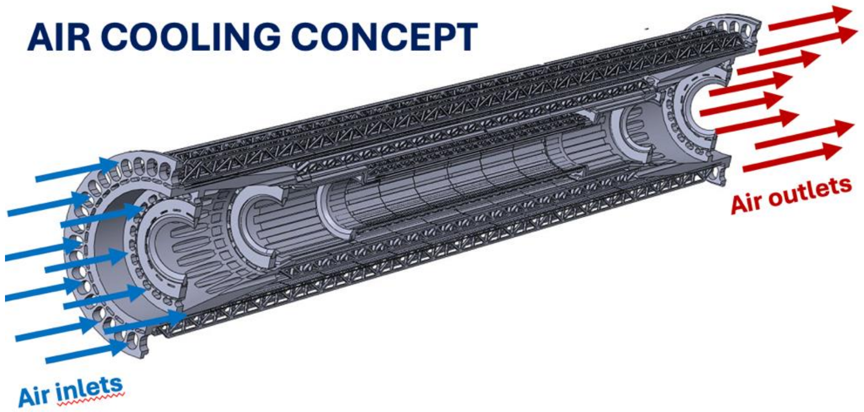
IR Mockup project: activity in Pisa

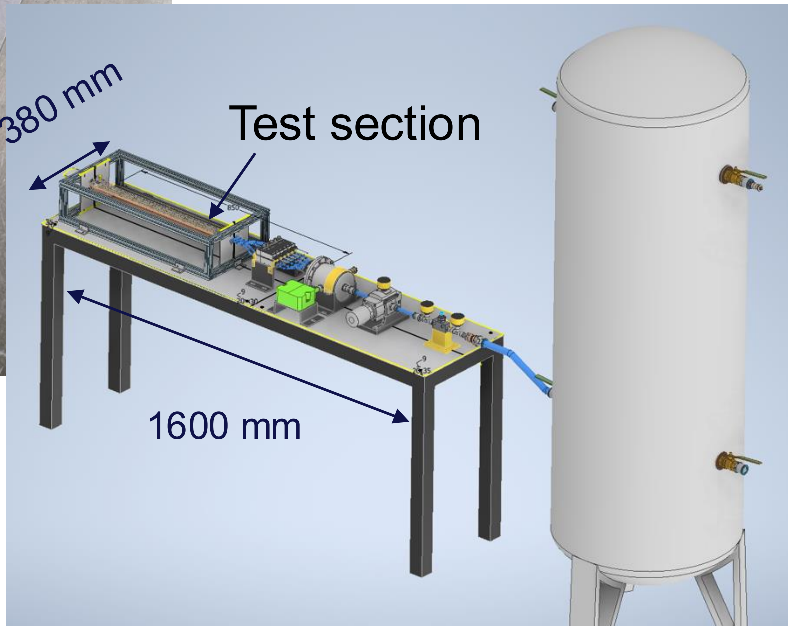
Wind tunnel for the air-cooling vertex demonstration



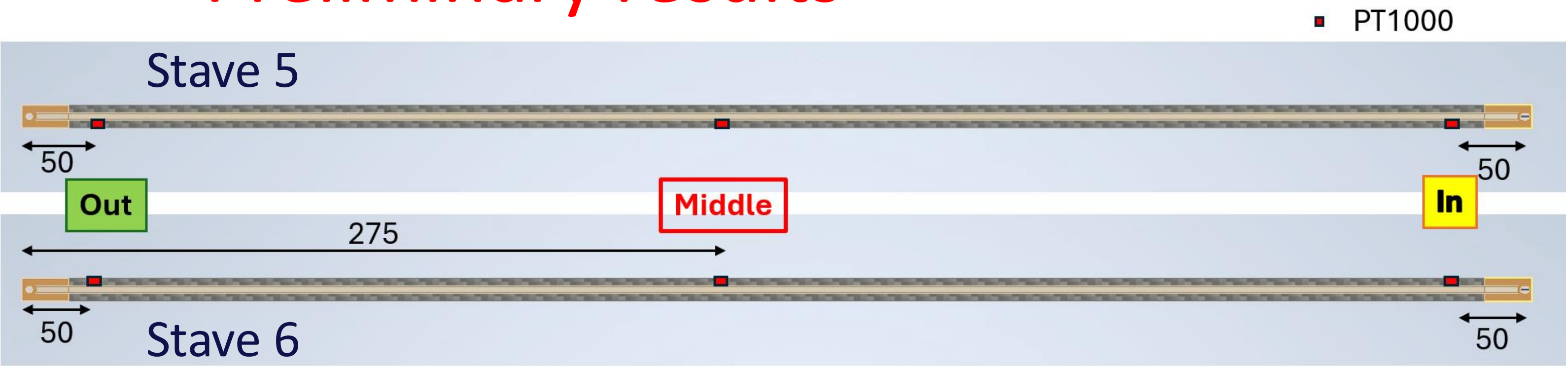


Compressed air system

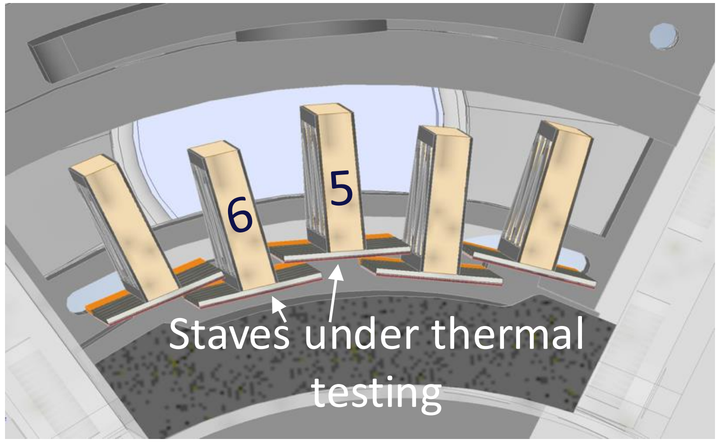


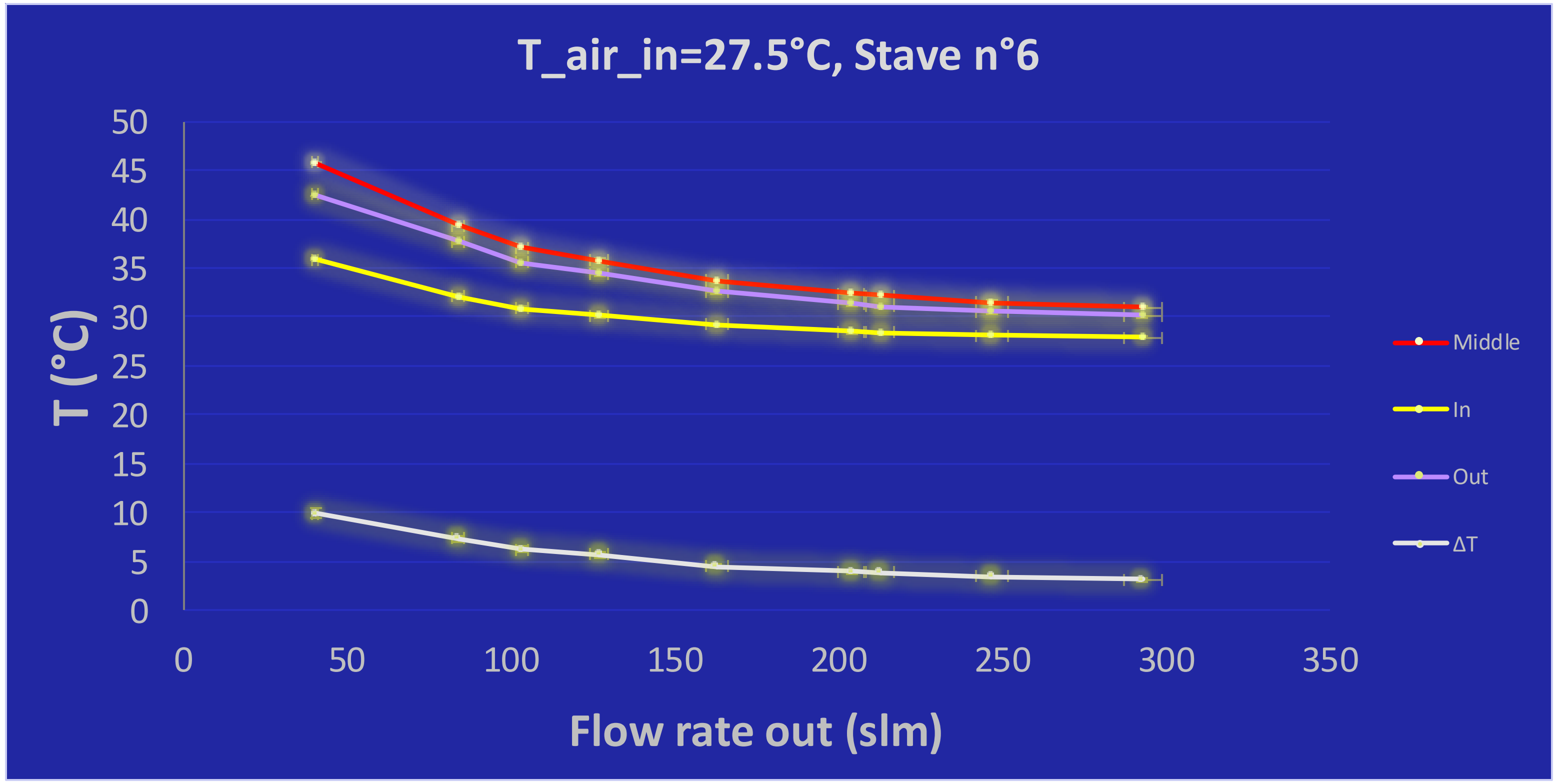


Preliminary results



Top view





Power density (sensor) = ***50 mW/cm²***
Total power (each stave) = ***2.2 W***

Results for Layer 3

Average stave temperature ~7ºC above air inlet temperature for flow rates>100 litres/min

ΔT between sensors in the stave ~5ºC (affordable for sensors operation)

Tests for Layer 1 and 2 ongoing (but expected lower ΔT

Beam-induced backgrounds in detectors

Simulation tools being validated with SuperKEKB data

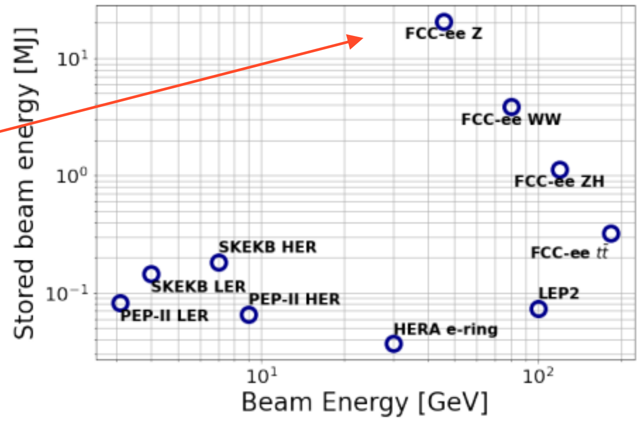
A lot of effort to build a workflow for detector BIB evaluation, feedback is starting, necessary to optimize masking, shielding, collimator settings

Single beam:

- ✓ Beam halo losses datasets ready to be tracked in detectors
- ✓ Beam-gas: Coulomb and Bremsstrahlung datasets ready to be tracked in detectors
- ✓ Synchrotron radiation caused by deviation to the zero-orbit and beam tails being tracked in detectors
- ✓ Touschek scattering losses
- ✓ Injection background first datasets ready to be tracked in detectors
- ✓ Fast instability – first datasets ready to be tracked in detectors
- Thermal photons planned

- **Colliding beams:**
  - ✓ Incoherent Pair Creation (IPC) dominant – datasets ready and being tracked in detectors
  - ✓ Radiative Bhabha $e^+e^- \rightarrow e^+e^-\gamma$ BBREM+GUINEAPIG +FLUKA
  - ✓ Beam-beam losses with multiturn tracking
- Fluences and Ionization doses studies extending at larger radii

FCC-ee collimation overview



FCC-ee presents unique challenges:

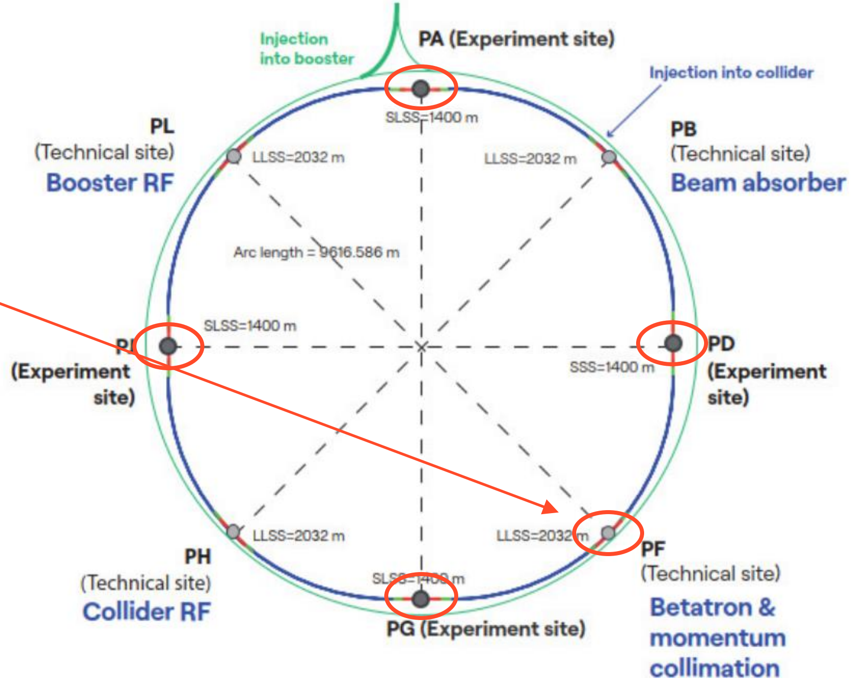
- At Z pole 17.5 MJ of stored beam energy (two orders of magnitude bigger than any other lepton collider)
- Beams are highly destructive

Collimation system must:

- Protect the machine and the detectors from unavoidable beam losses
- **Minimize background for the experiments**

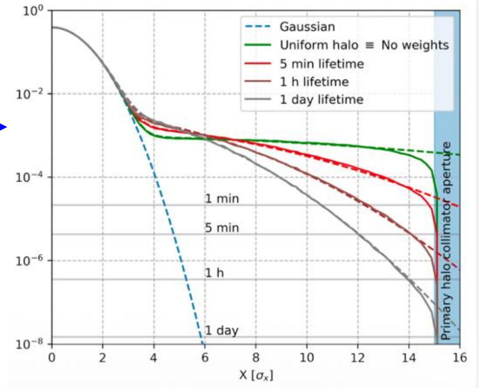
Collimation set-up:

- Global system in **PF**: 2 stage betatron + momentum
- **Experimental IRs**: SR collimators and mask + robust tertiary collimator
- Local protection for injection, extraction
- **Secondary particle shower absorber**

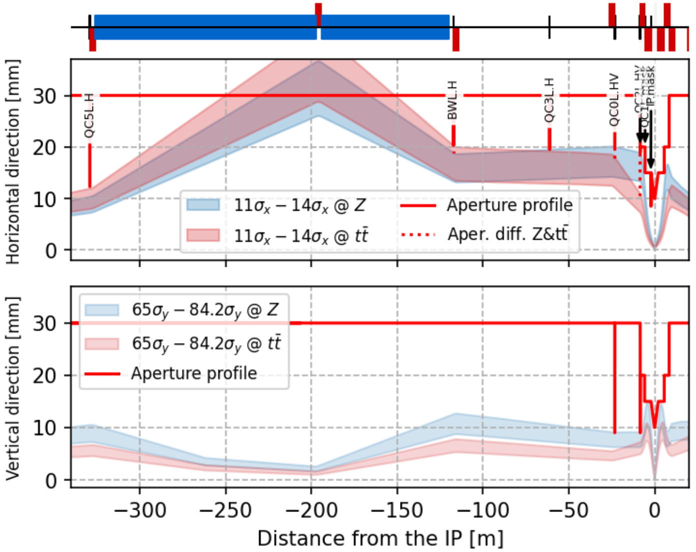


Synchrotron Radiation (SR) backgrounds

- Simulations with BDSIM (GEANT4 toolkit)
- SR evaluated for
  - **beam core** with non-zero closed orbits for considering optics imperfections
  - **transverse beam tails,** pessimistic weighted halo model used:

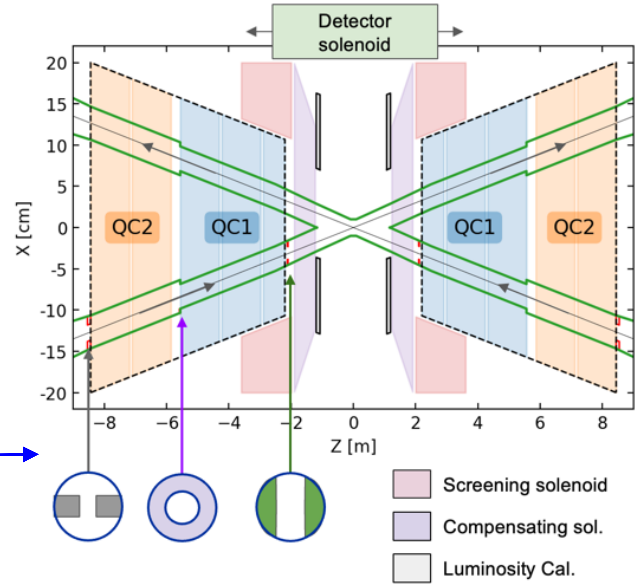


bulk of SR produced upstream the IR is stopped by collimators



Courtesy Kevin Andrè

- **SR produced in the IR** by **IR quads and solenoids:**
  - bulk of SR is collinear with the beam and will hit the beam pipe at the first dipole after the IP → no direct hits in the detectors
  - Transverse tails in the fringing field of the final quads produce SR that may hit the detector: **masks at the exit of QC1 and QC2**



Beam-gas interaction contribution to detector

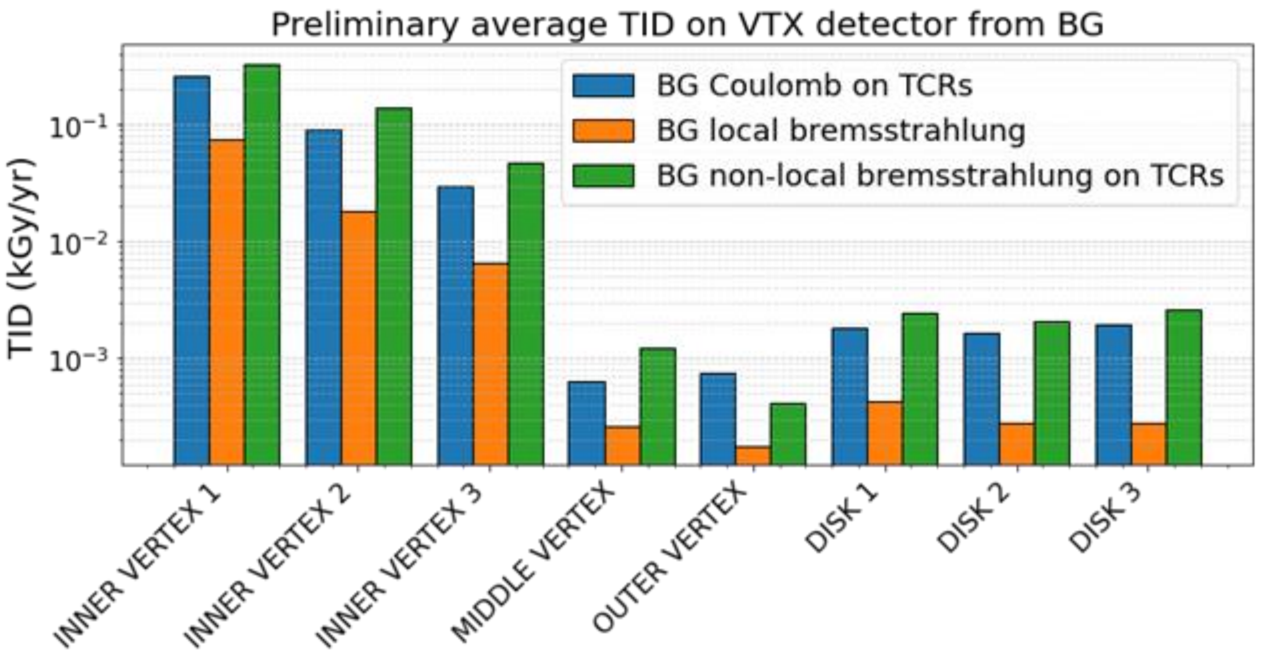
local: upstream the MDI, single pass
non-local: generated far from IP and multiturn

Beam-gas bremsstrahlung

- contribution from TCTs negligible
- contribution from hits on TCRs non-local, higher than local BG bremsstrahlung

Beam-gas Coulomb scattering

- contribution from TCTH negligible
- contribution from hits on TCRs comparable to BG bremsstrahlung hits
- contribution from TCTV difficult to estimate



Doses are proportional to backgrounds, subleading wrt IPC

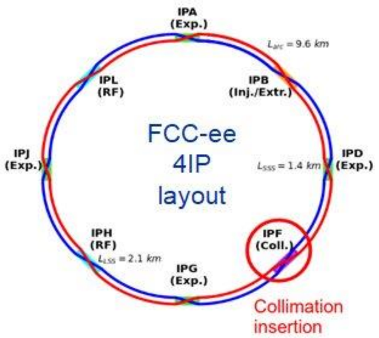
Detector backgrounds

- workflow established to evaluate detector background from FLUKA simulations

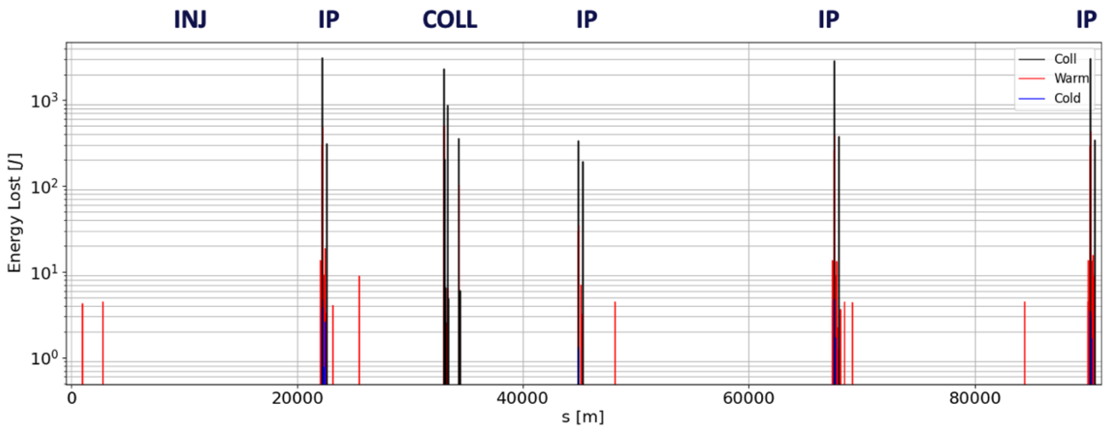
Courtesy Alessandro Frasca and Giacomo Broggi

Injection backgrounds

Top-up injection required, on-axis & off-energy injector is being studied
Injection efficiency is assed at 88% for lattice V25.1_GHC.

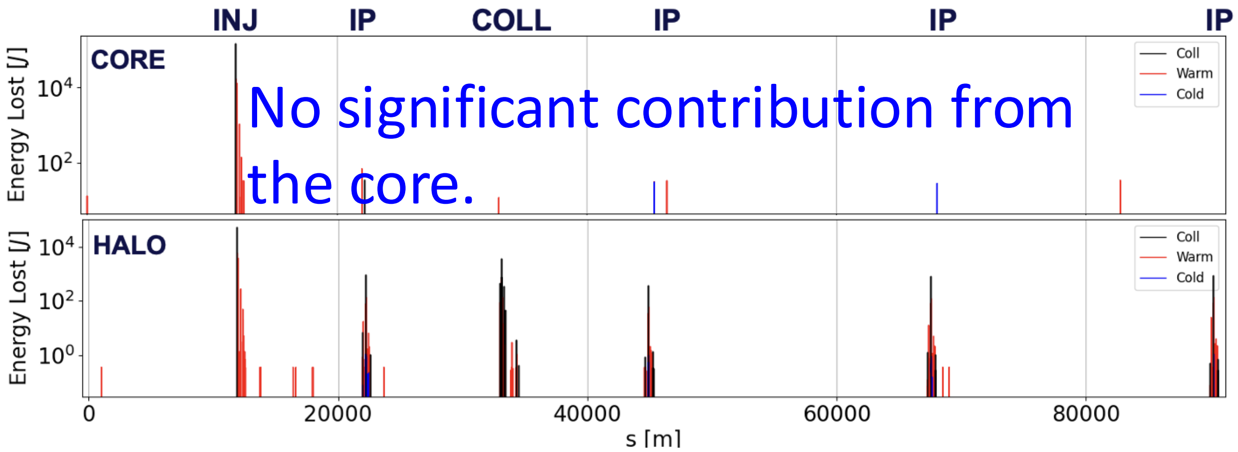


injected beam



The 12% of the injected beam is lost, and losses are distributed along the whole ring.

circulating beam



No significant contribution from the core.

The study on the leakage to experiments is starting.

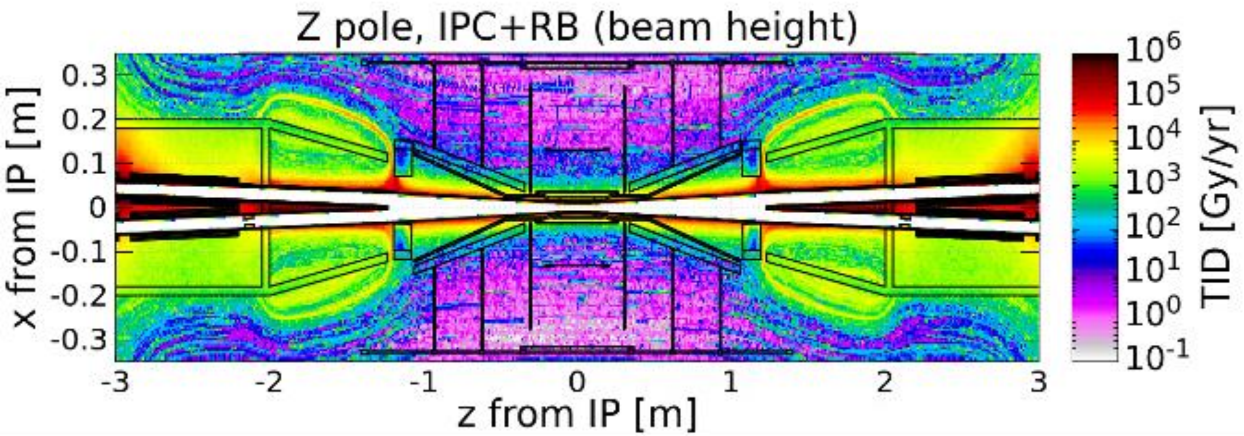
Courtesy Giulia Nigrelli

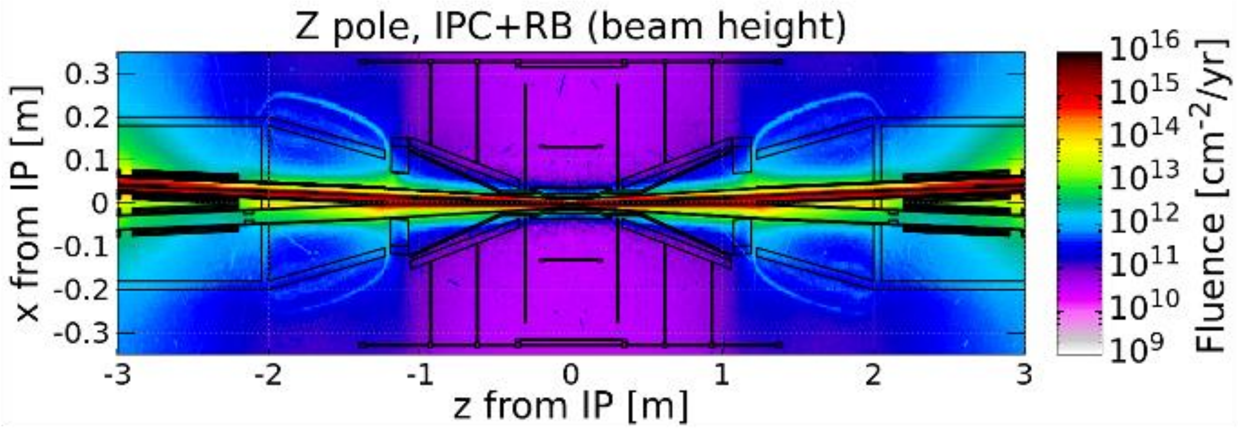
Beam losses due to injection that may impact the detector are tracked up to the MDI interface surface. Next step is to evaluate occupancy and data rate.

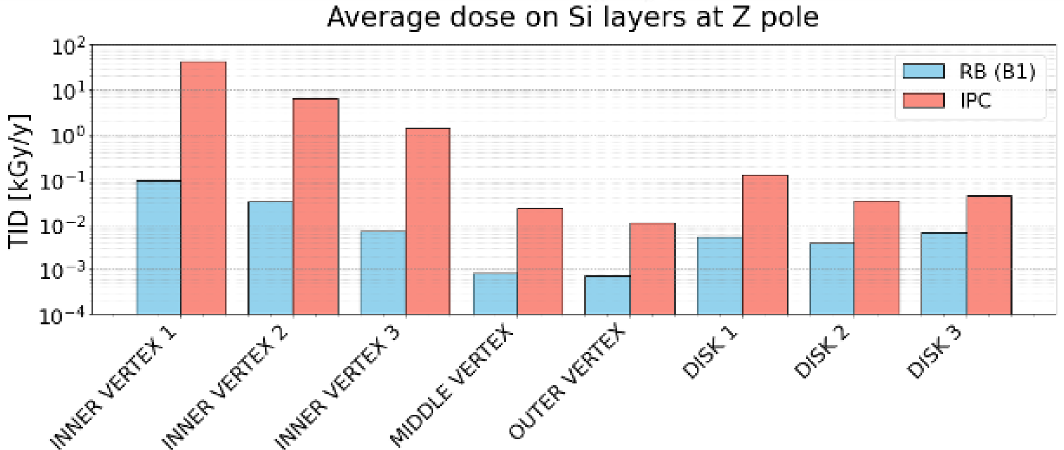
Vertex detector radiation levels

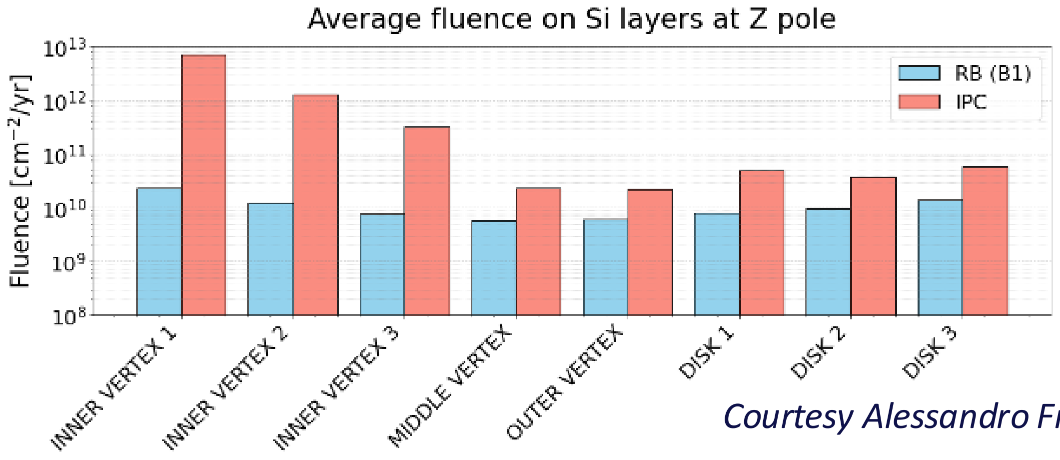
IPC dominant source

- Innermost layer (at ~1.3 cm) TID and fluence are one order of magnitude higher than second layer.
- Current MAPS technologies are OK
  - At 15 cm distance, dose and fluence are about 3 orders of magnitude smaller than innermost layer









Courtesy Alessandro Frasca

Outlook

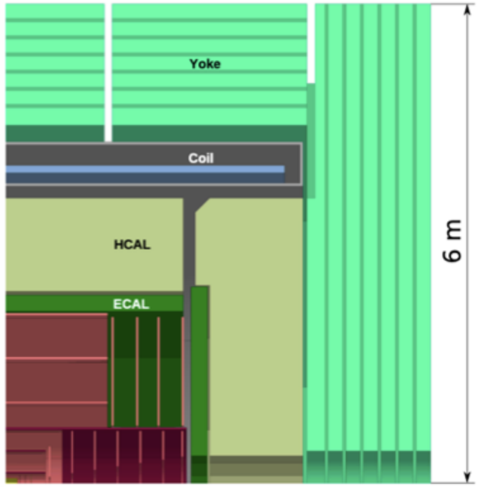
- Interaction region layout mainly engineered and its validation with the experimental mockup
  - Beam pipes, bellows, support tube, vertex detector designed and prototyping in progress
  - Integration of vertex and LumiCal detectors in accelerator in progress
- IR optics with Solenoid coupling compensation scheme
- Main beam backgrounds studied and workflow in place to evaluate effect in sub-detectors
  - Beam losses and synchrotron radiation evaluated for baseline optics
- Outstanding MDI design optimisations:
  - IR magnet system design and prototyping
  - QC1 cryostat design
  - Remote vacuum connection
  - IR diagnostics

FCC

Thank you
for your attention.

FCC-ee Detector Concepts

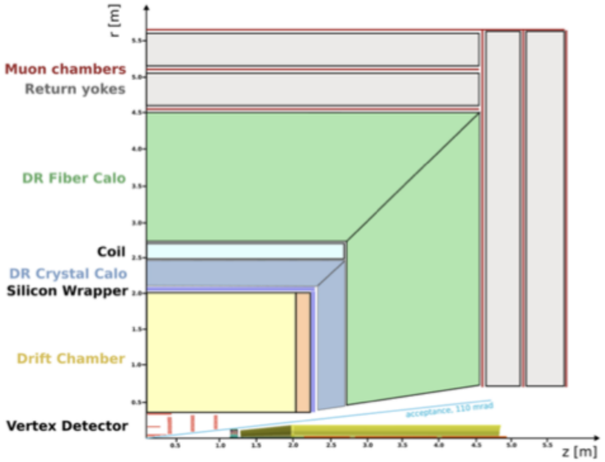
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

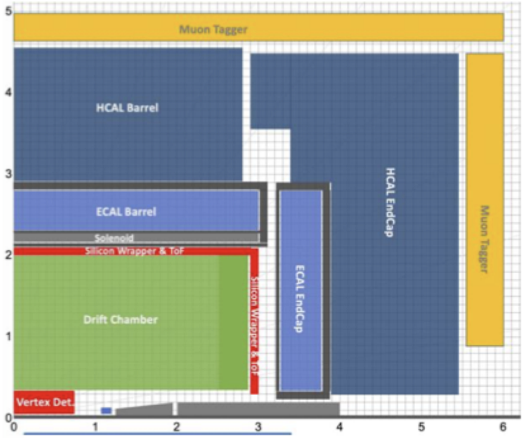
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

https://doi.org/10.48550/arXiv.2502.21223

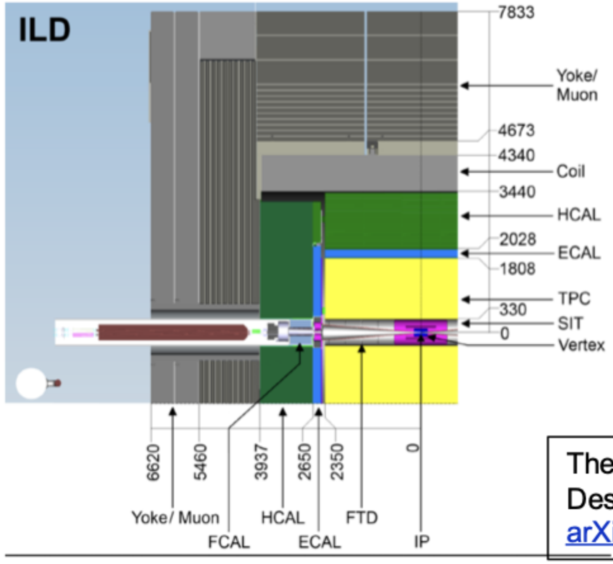
Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391

ILD



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

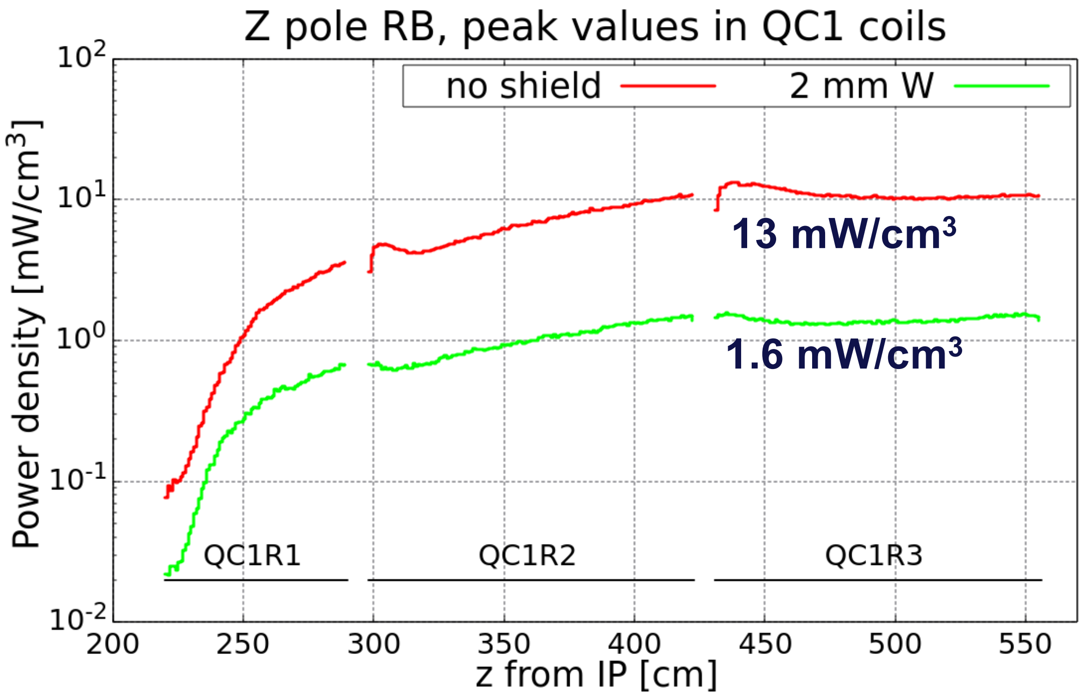
The International Linear Collider Technical Design Report - Volume 4: Detectors arXiv:1306.6329

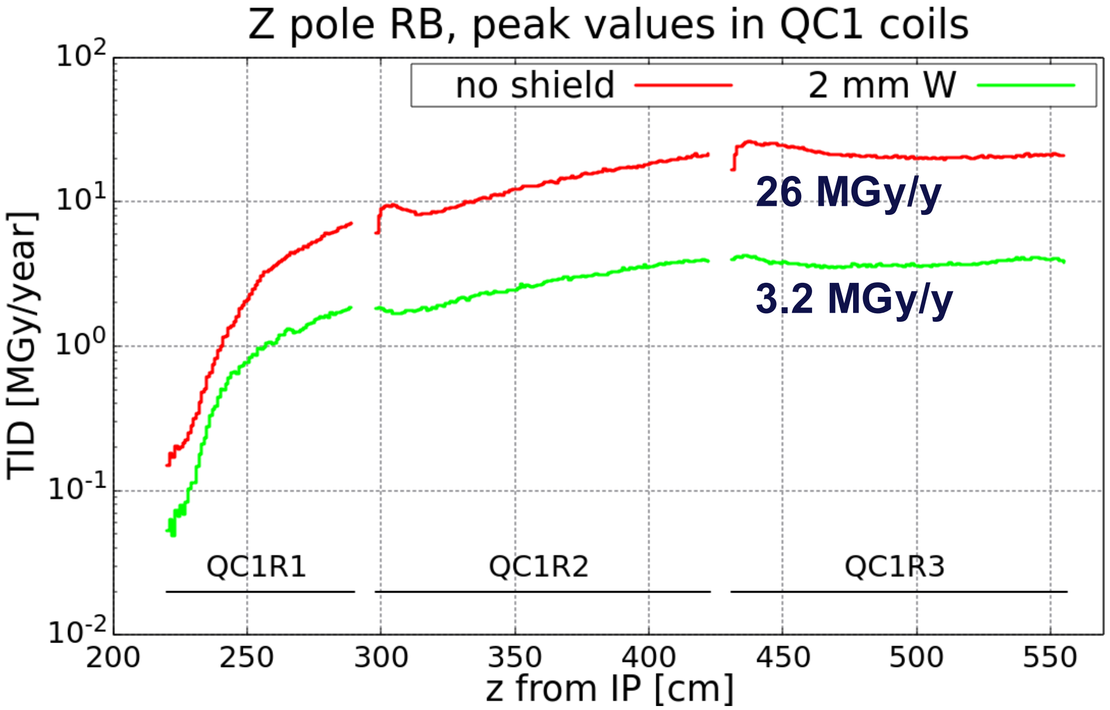
Radiative Bhabha impact on FFQs

Simulated a realistic FFQ geometry

- water-cooled beam pipe in SS
- magnets modelled as layers of Al and coils (NbTi+Al+Cu mixture)

Estimates based on BBBrem+GuineaPig





Courtesy of Alessandro Frasca

Maintenance and accessibility of the detectors

Three options for opening the detector in the caverns

1. longitudinal shift
   - FFQ and other machine elements beyond detector endcaps shall be removed (with their supports). BP vacuum broken also in cold pipes. Realignment of the machine needed.
2. longitudinal + transverse shift
   - Split endcaps significantly deteriorate detector precision measurements. BP vacuum stay (or Ne flushing), no realignment needed.
3. Transversal shift of the full detector and the FFQ assembly (parking position), then extraction of the FFQ and full longitudinal opening of the detector endcaps
   - Optimal detector acceptance. FFQ assembly stays inside the detector, temporarily supported by the detector's endcaps. Machine elements beyond detector endcaps also stay in place. BP vacuum broken for detector beampipe. Realignment needed
   - Can only be done for large caverns

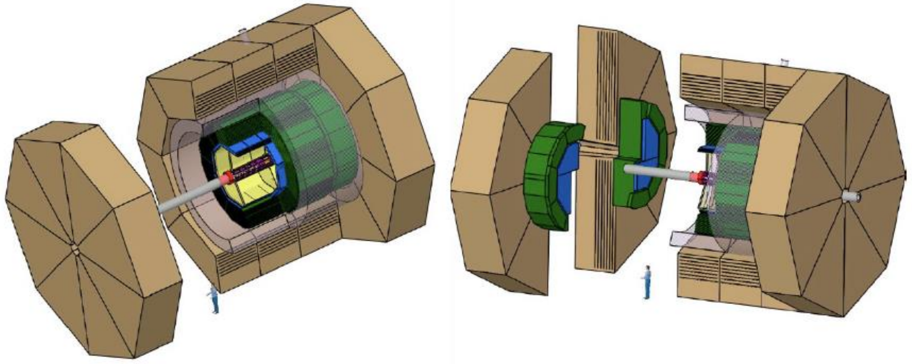
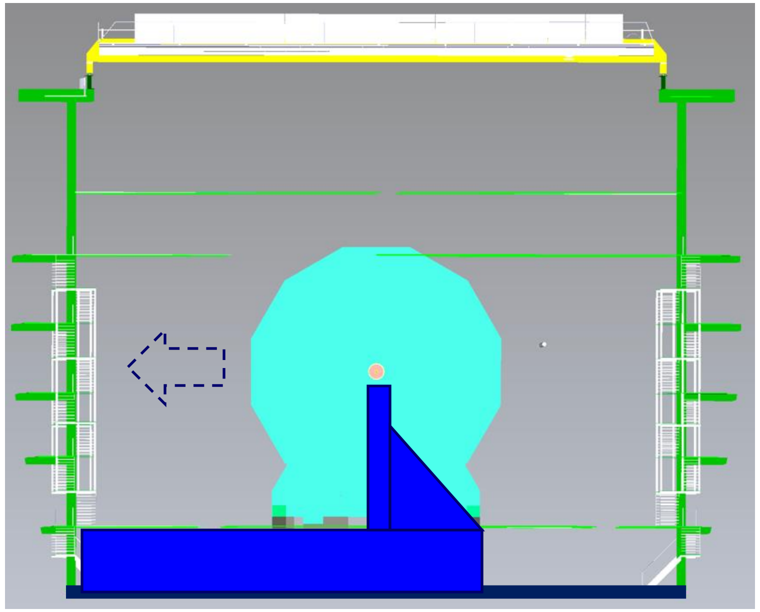
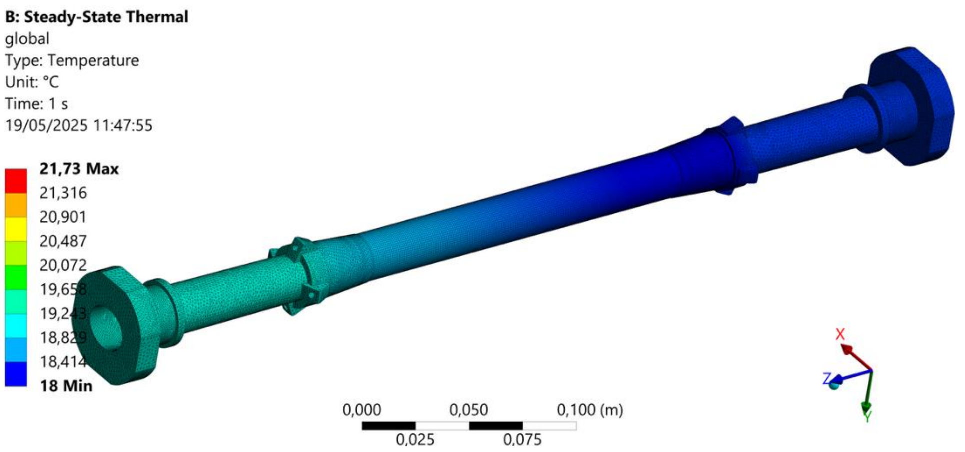


Fig. 54: Longitudinal (left) and short longitudinal plus transversal endcap (right) detector opening

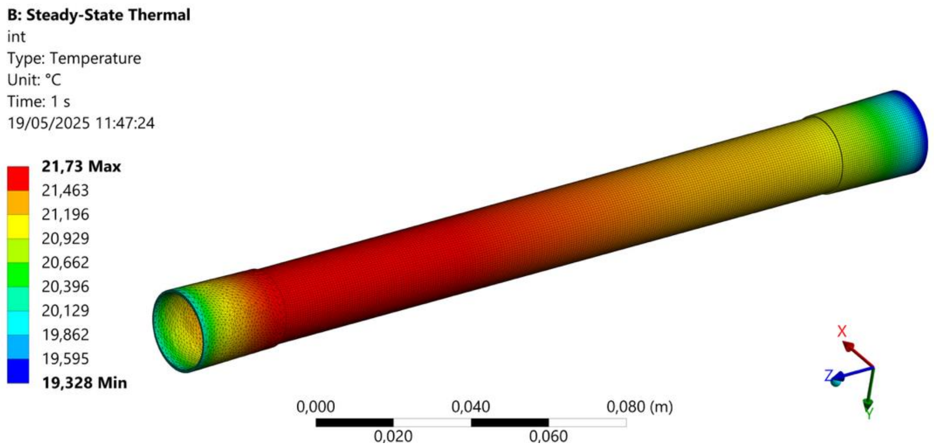


Ansys simulation with the prototype of the central beam pipe

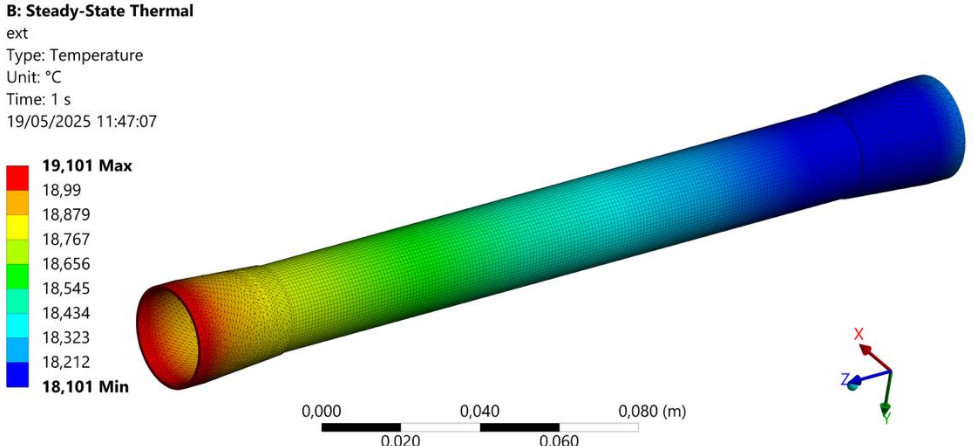
Water at 18 ºC, flow rate 1 l/min, and beam pipe at 54 W



Temperature of the external side of the the beam pipe



Temperature of the internal side of the the beam pipe



water temperature

Courtesy F. Fransesini