Design, performance and future prospects of vertex detectors at the FCC-ee

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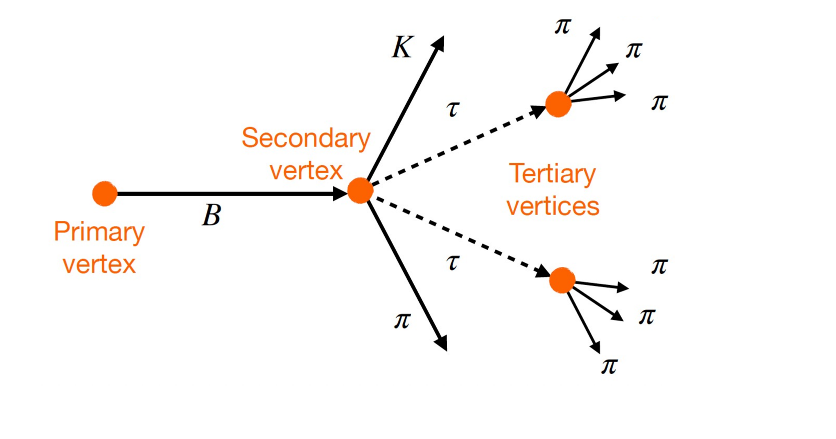
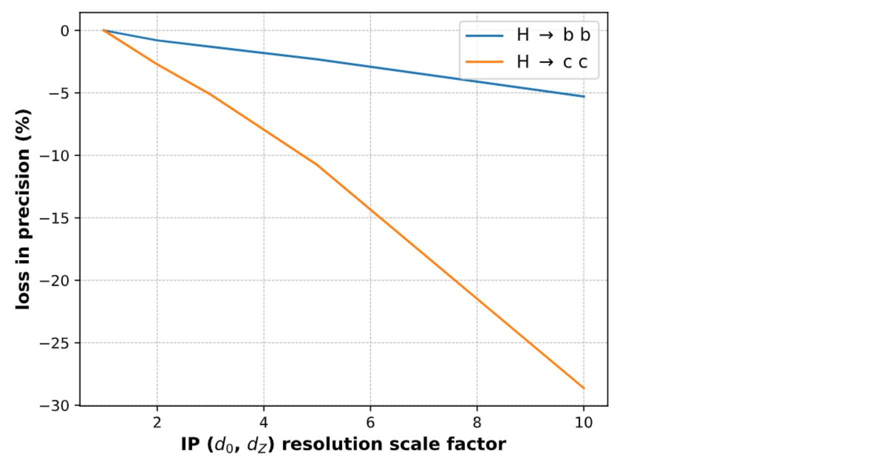
Abstract

The CERN proposed e⁺e⁻ Future Circular Collider (FCC-ee) is designed as an electroweak, flavour, Higgs and top factory with unprecedented luminosities. Many measurements at the FCC-ee will rely on the precise determination of the vertices, measured by dedicated vertex detectors. All vertex detector designs use Monolithic Active Pixel Sensors (MAPS) with a single-hit resolution of ≈3 µm and a material budget as low as 0.25% X_0 per detection layer, which is within specifications for most of the physics analyses. This contribution presents the status of the R&D on fully engineered vertex detector, together with the challenges due to its cooling and integration with the collider beam pipe. Discussions on an ultra-light vertex detector layout using curved wafer-scale MAPS are also presented, which allows reducing the material budget by about a factor of four, at the expenses of some losses in efficiency.

Physics Requirements

Precise vertex reconstruction of rare $B^0 \to K^{*0}\tau^+\tau^-$ decays





Higgs couplings relative loss with respect to the degradation of the impact parameter resolution with respect to the nominal performance

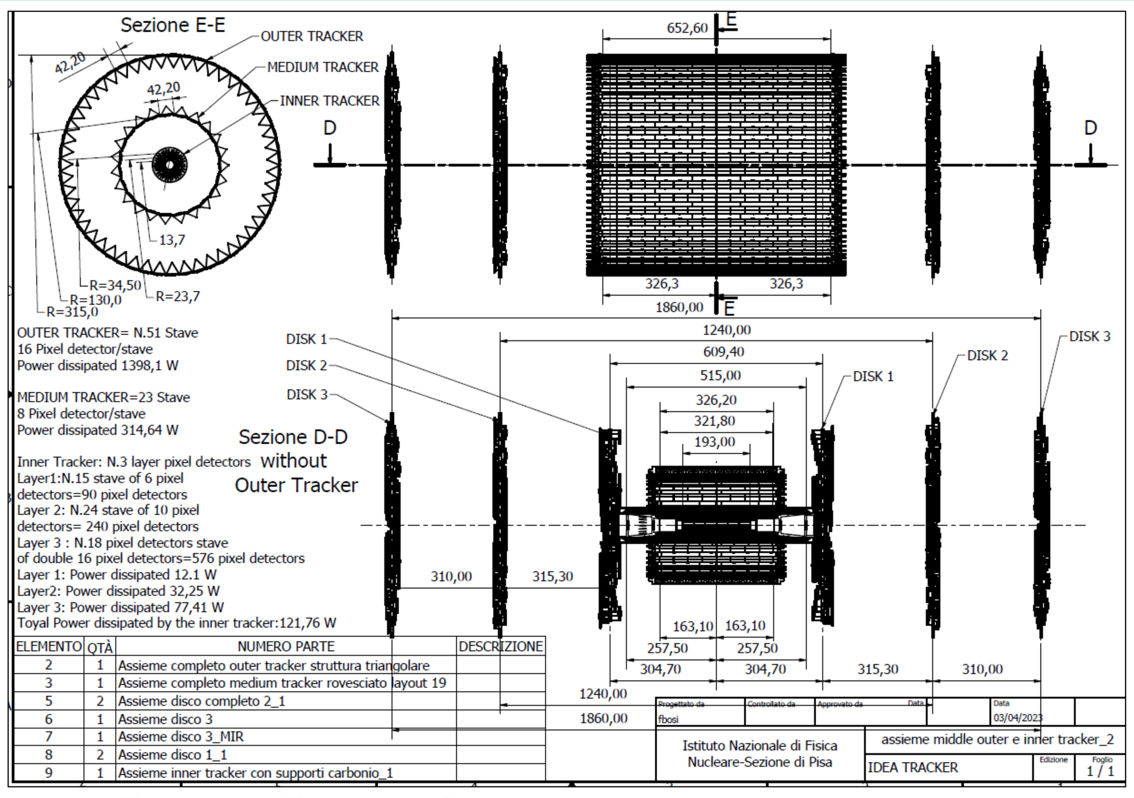
Precise impact parameter resolutions
- $\sigma_{d_0}(\mu m) \approx 3 \oplus \frac{15}{p\sin^{3/2}(\theta)}$
- Low mass and high granularity

Angular coverage
- $|cos(\theta)| < 0.99$

Radiation tolerance
- NIEL 10^{14} 1 MeV n_{eq}/cm²/year

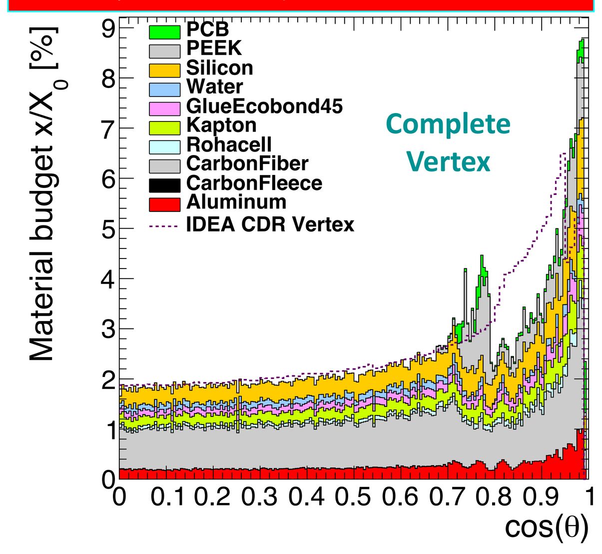
Monolithic Active Pixel Sensors is the natural technological choice

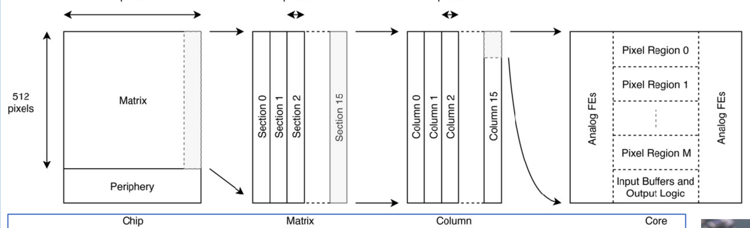
Flat Layout



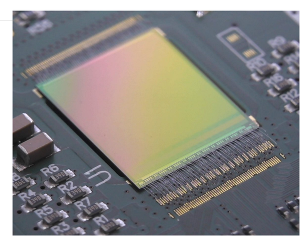
Outer Vertex tracker:
ATLASPix3 based
Modules of 50 ×150 µm² pixel size
- Intermediate barrel at 13 cm radius
- Outer barrel at 34.5 cm radius
- 3 disks per side

Inner Vertex detector:
ARCADIA based
Modules of 25 ×25 µm² pixel size
3 barrel layers at
- 13.7, 23.7 and 34/35.6 mm radius

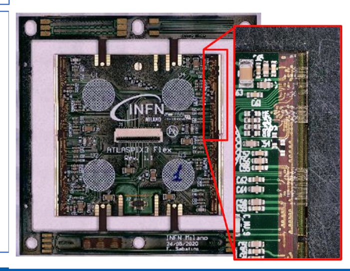


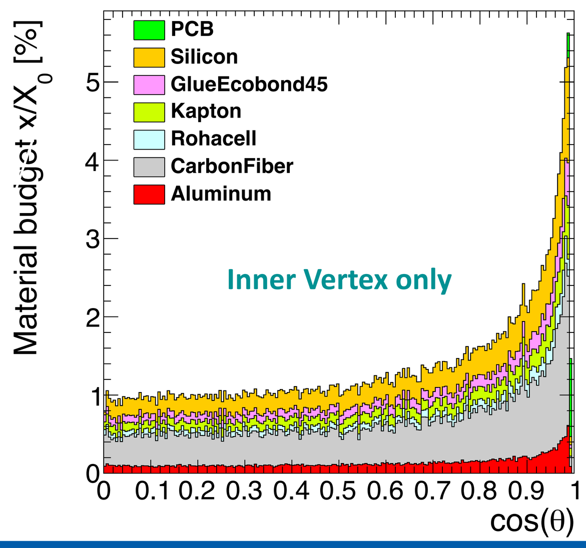


ARCADIA:
LFoundry 110 nm process
50 µm thick, 25 µm x 25 µm pitch
Module dimensions: 8.4×32 mm^2
Power density 50 mW/cm^2 (core 30 mW/cm^2)
Capable of hit rates up to 100 MHz/cm²

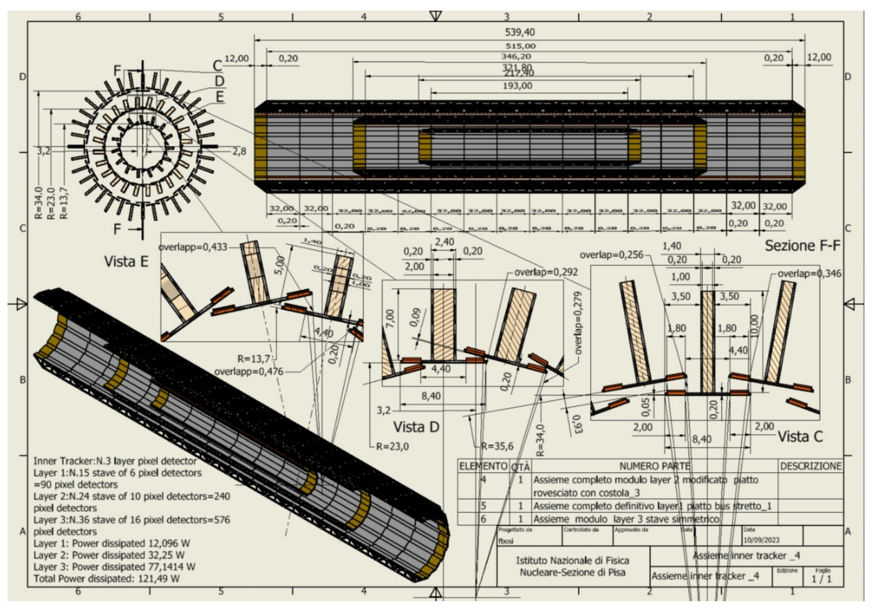


ATLASPIX3 :
TSI 180 nm process
50 µm thick, 50 µm x 150 µm pitch
Module dimensions: 42.2×40.6 mm^2
Power density: assume 100 mW/cm^2
Up to 1.28 Gb/s downlink

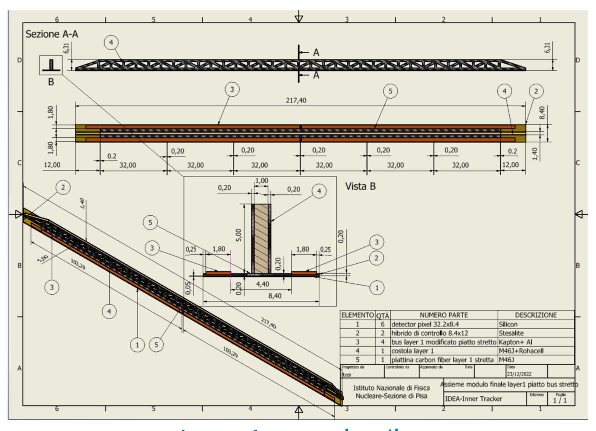




Mechanical integration

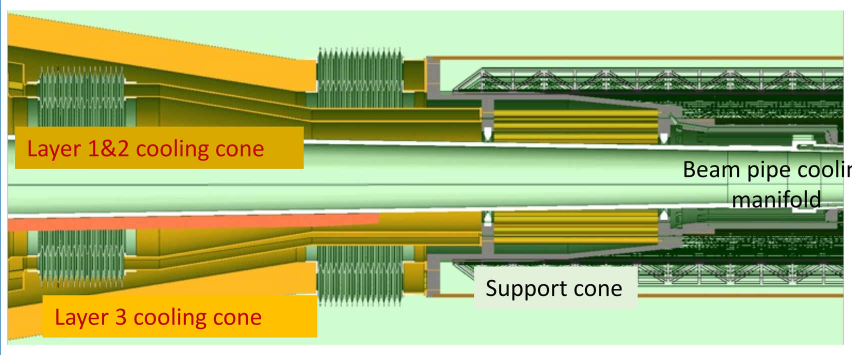


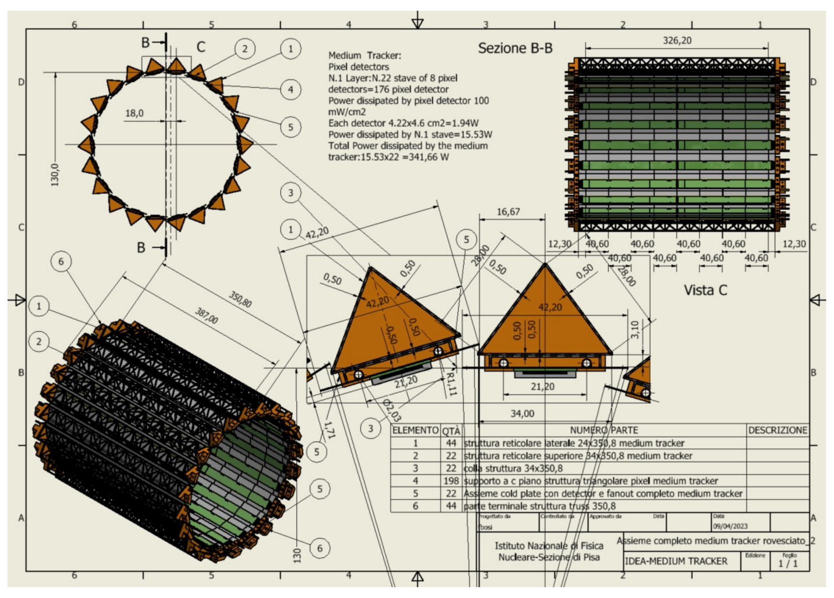
Lightweight reticular support structure – Air cooled



Layer 1 stave detail

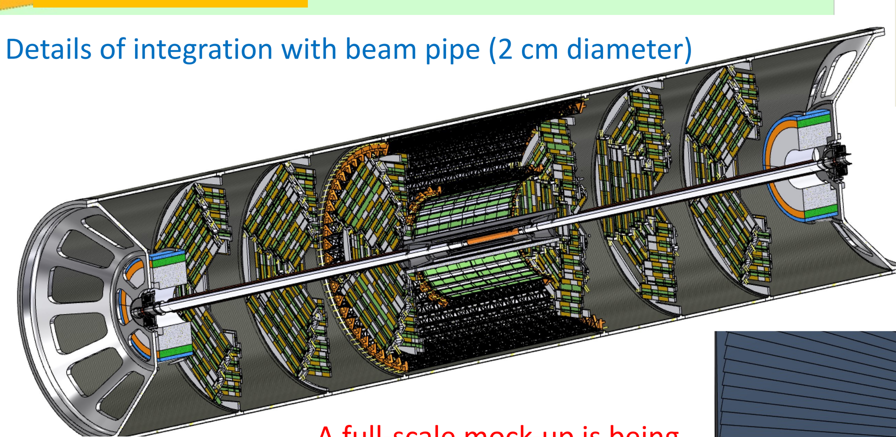
- Thin carbon fiber walls interleaved with Rohacell
- 2 buses (data and power) 1.8 mm wide and 250 µm thick (50 µm Al, 200 µm kapton) per side

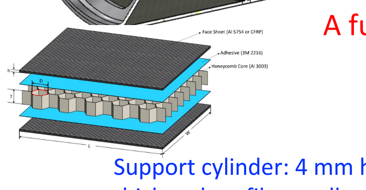




Lightweight reticular support structure (ALICE/Belle-II like)
Outer/Middle/Disk vertex detector
Water cooled

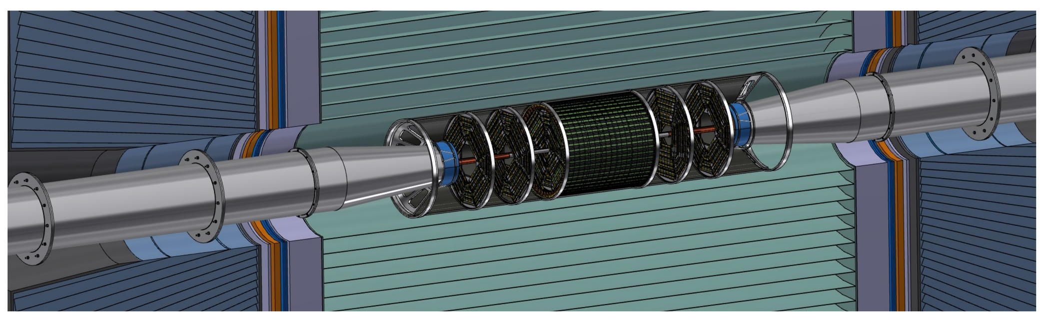
Details of integration with beam pipe (2 cm diameter)





Support cylinder: 4 mm honeycomb with two 1 mm thick carbon fibre walls

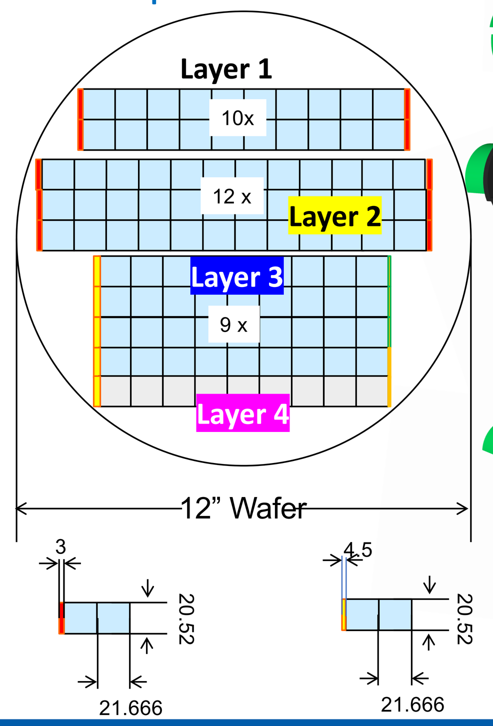
A full-scale mock-up is being built in Frascati

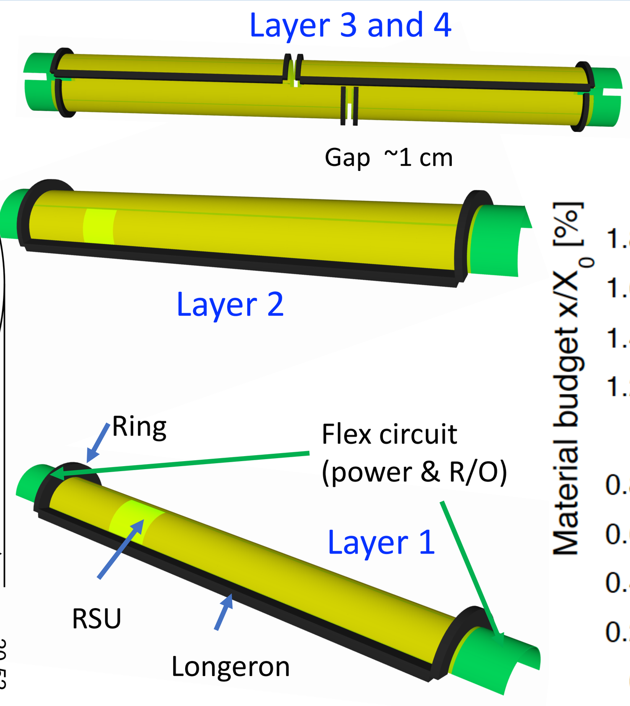


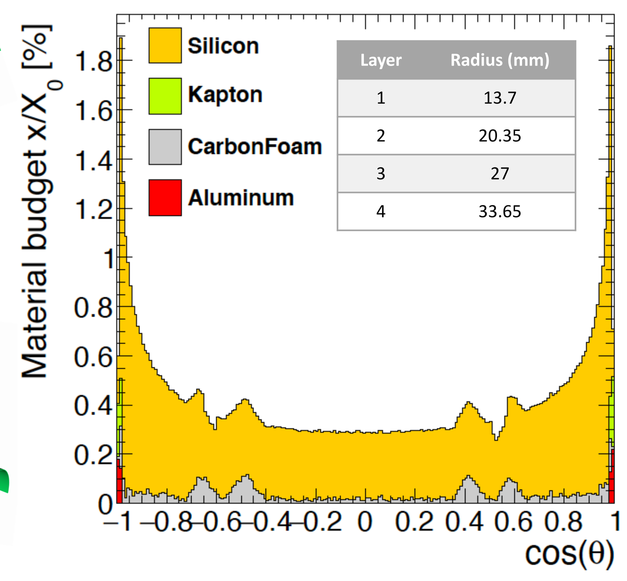
All elements in the interaction region (Vertex, LumiCal, beampipes) are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment
Once the structure is assembled it is slided inside the rest of the detector

Inner Vertex Curved Layout

ALICE ITS3 inspired





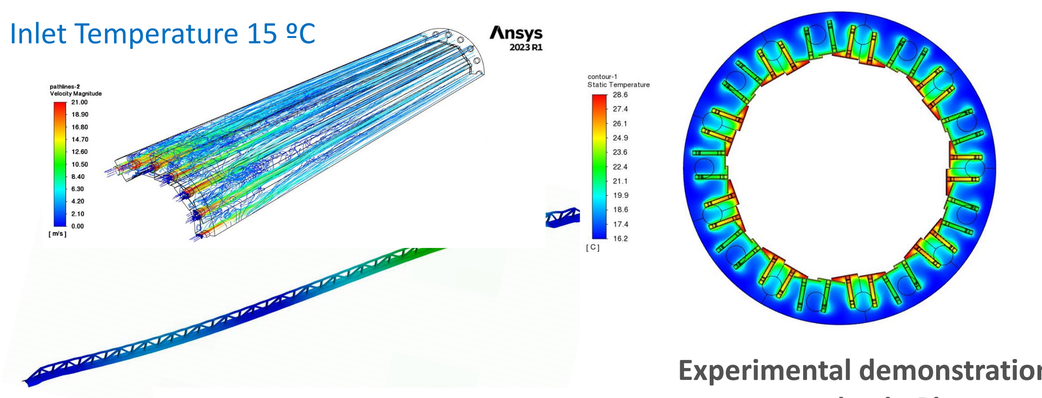


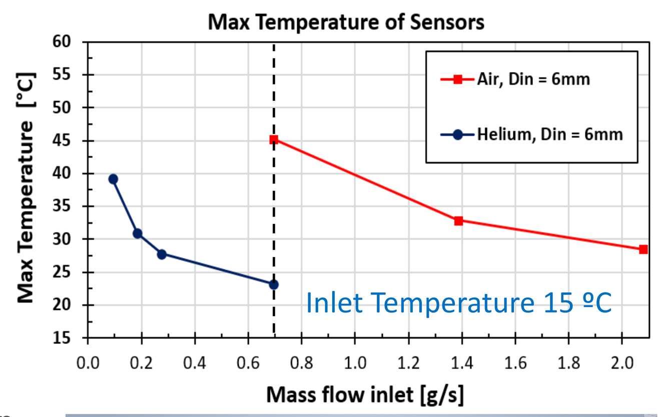
Layer	Radius (mm)
1	13.7
2	20.35
3	27
4	33.65

Air/He – Cooling

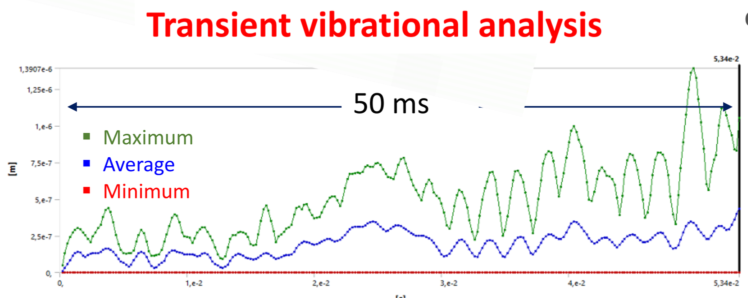
CFD Simulation for Layer 3 (largest power dissipation of 77 W)

Inlet Temperature 15 ºC



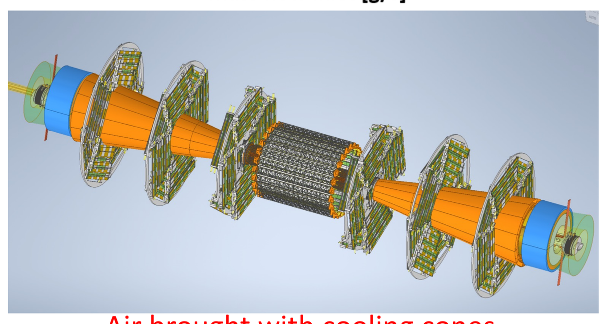


Transient vibrational analysis



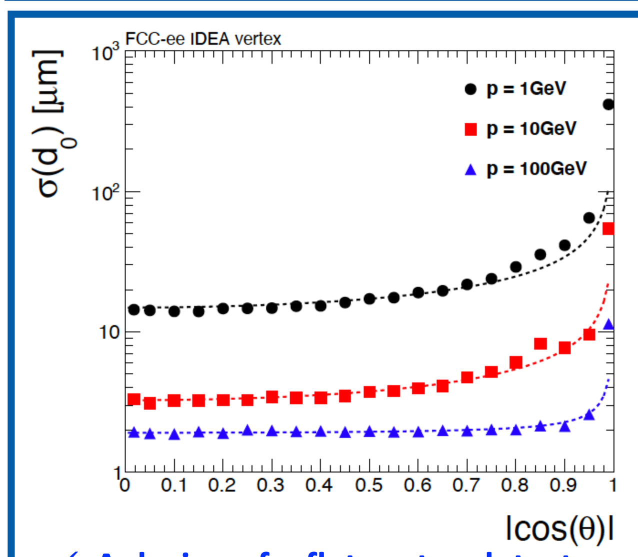
±1.5 µm

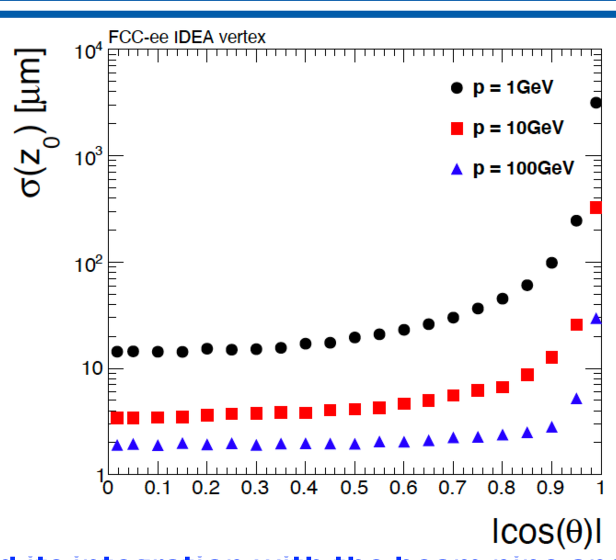
Experimental demonstration on-going in Pisa



Air brought with cooling cones

Performance and Prospects





Impact parameter resolution for the flat layout.

The resolution is limited by multiple scattering

✓ **A design of a flat vertex detector and its integration with the beam pipe and services has been engineered and is being constructed. A curved inner vertex detector solution could achieve 0.3% X_0 with four layers.**

- Some optimisation and further studies are being finalised:
  - Optimisation of the geometry and material budget:
    - Radius and number of measurement points
  - Stability and alignment challenges (ultimate precision):
    - Air-cooling induced vibrations and thermal stress
- Optimisation of the curved layout is in progress, to overcome problems in hermeticity:
  - Overlapping curved sensors?
  - Forward disks ?
- Readout challenge
  - Machine induced backgrounds, mainly from **incoherent pair creation** (*real or virtual photon scattering* e^+e^-) yields **~200 MHz/cm²** hit rate in the first layer, or **10 Gb/s** per module (flat) or **~200 Gb/s** per ¼ layer (curved) – higher but close to ALICE3 (100 MHz/cm²).

Reference: *M. Boscolo, F. Palla, F. Fransesini, F. Bosi and S. Lauciani, Mechanical model for the FCC-ee MDI, EPJ Techn Instrum* **10**, 16 (2023). https://doi.org/10.1140/epjti/s40485-023-00103-7

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