VERTEX DETECTOR LAYOUT AND DETECTOR INTEGRATION

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INFN Pisa and CERN

2nd FCC Italy & France Workhsop
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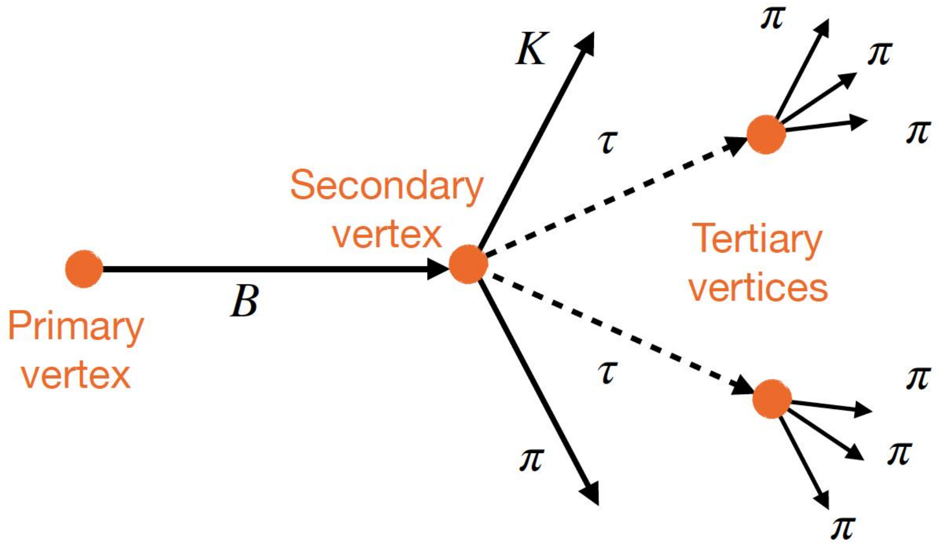
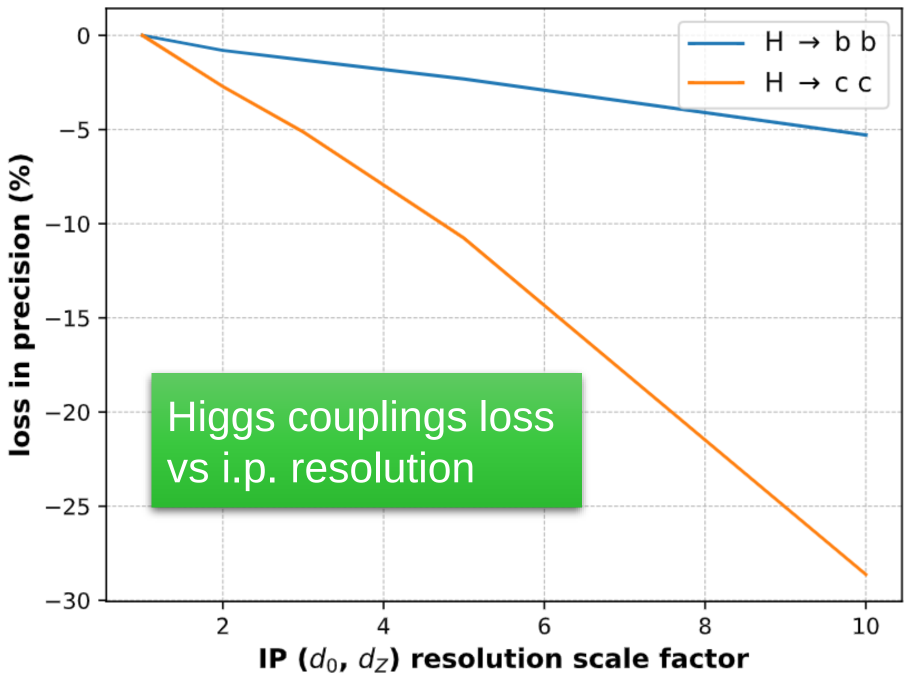
Vertex requirements

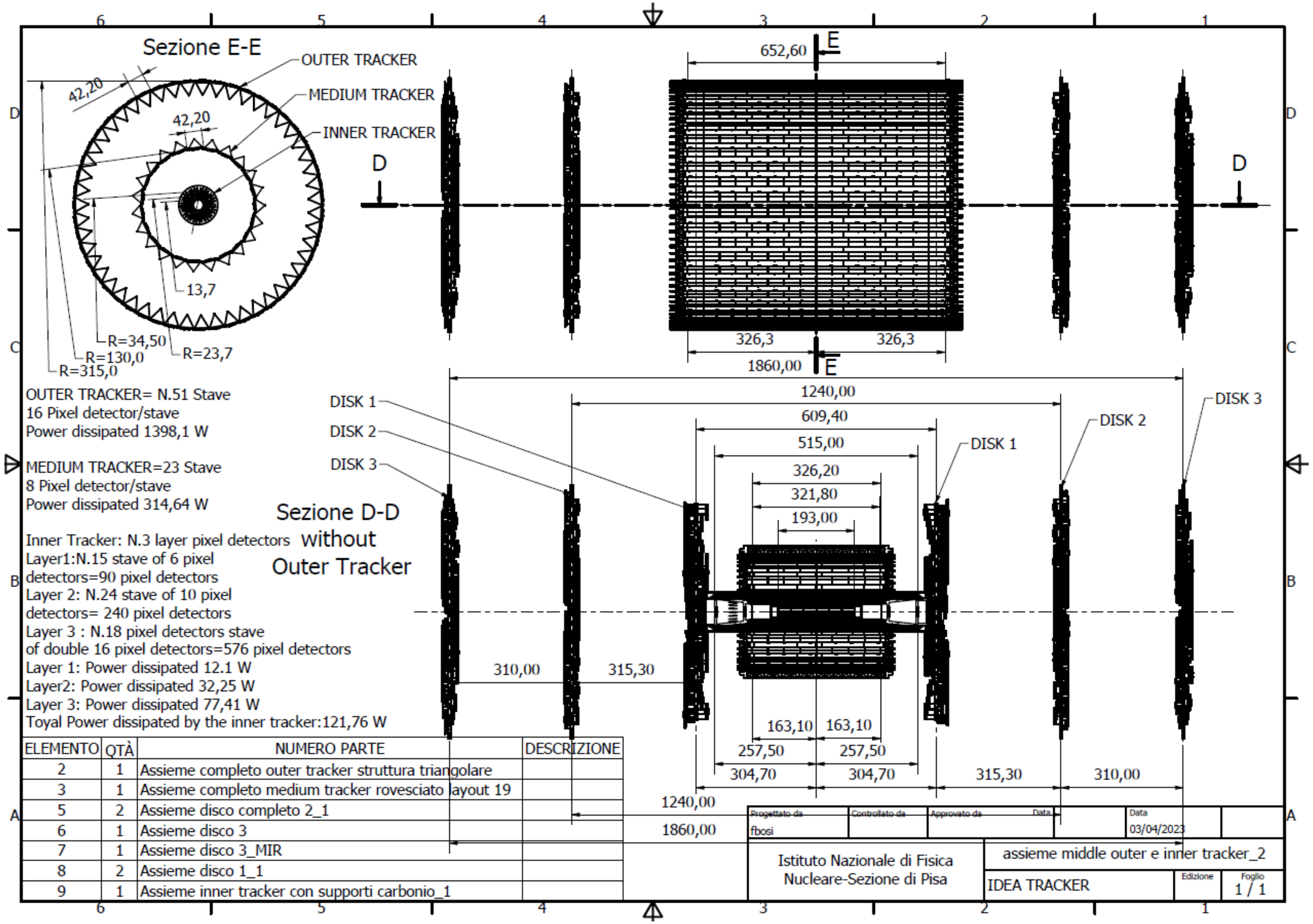
- **Performance: driven by Higgs and HF physics**
  - **Precise impact parameter resolutions**
    - $\boldsymbol{\sigma_{d_0}(\mu m) \approx 3 \oplus \frac{15}{p sin^{3/2}(\theta)}}$
    - Low mass and high granularity vertex detectors
    - **Air cooling**
- **Angular coverage constrained by LumiCal acceptance**
  - $\boldsymbol{110\, mrad \rightarrow |cos(\theta)| < 0.99}$
- NIEL ~ 10^{14} n_{eq}/cm^2
- Monolithic Active Pixel Sensors (MAPS) are the ideal candidate

$B^0 \rightarrow K^{*0}\tau^+\tau^-$





(IDEA and ALLEGRO) Vertex detector layout



Outer vertex tracker:
ATLASPix3 based

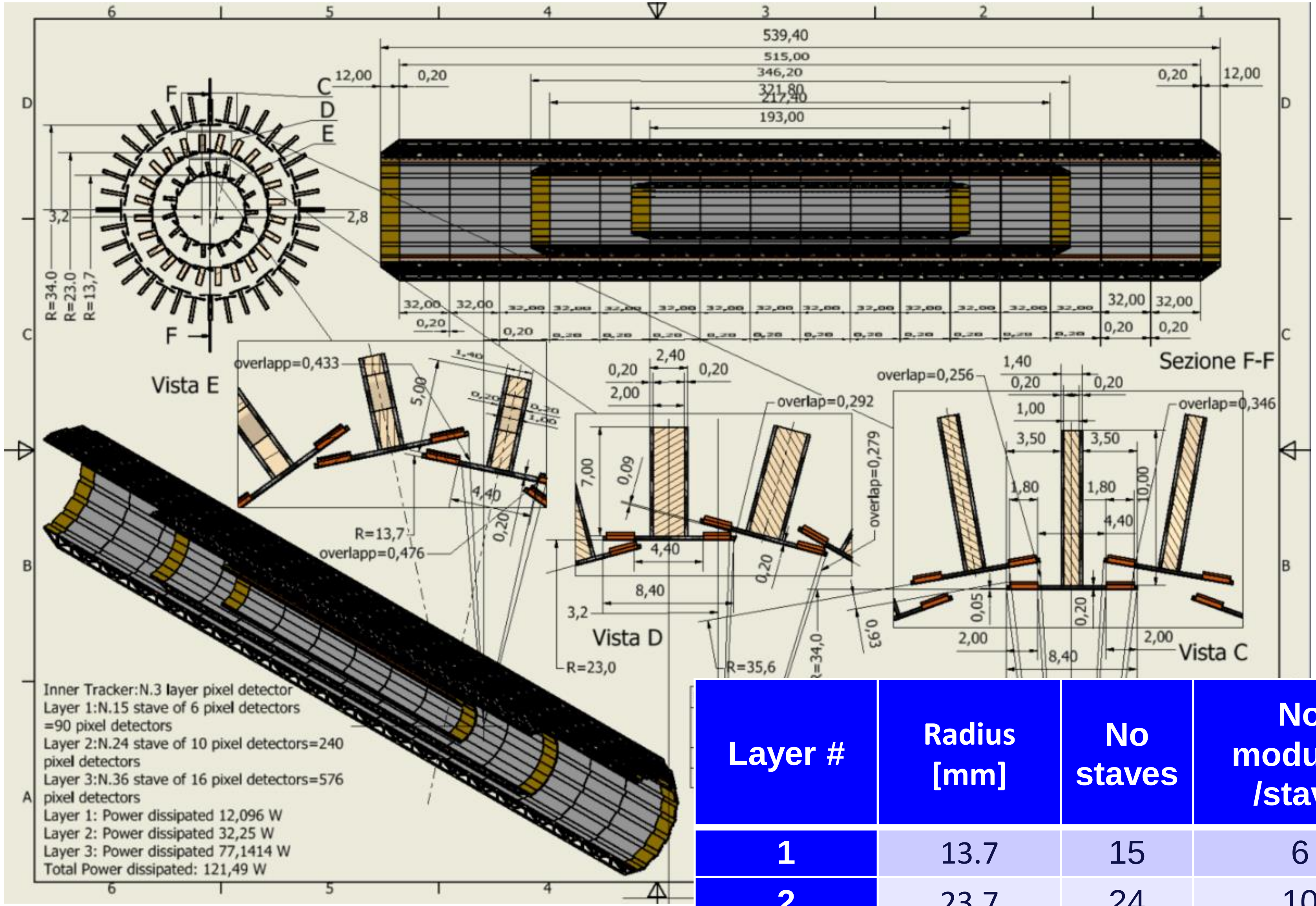
Modules of $50 \times 150\ \mu m^2$ pixel size
- Intermediate barrel at 13 cm radius
- Outer barrel at 34.5 cm radius
- 3 disks per side

Inner Vertex detector:
ARCADIA based

Modules of $25 \times 25\ \mu m^2$ pixel size

3 barrel layers at
- 13.7, 23.7 and 34/35.6 mm radius

Inner vertex



Total thickness per layer 0.25% X/X0

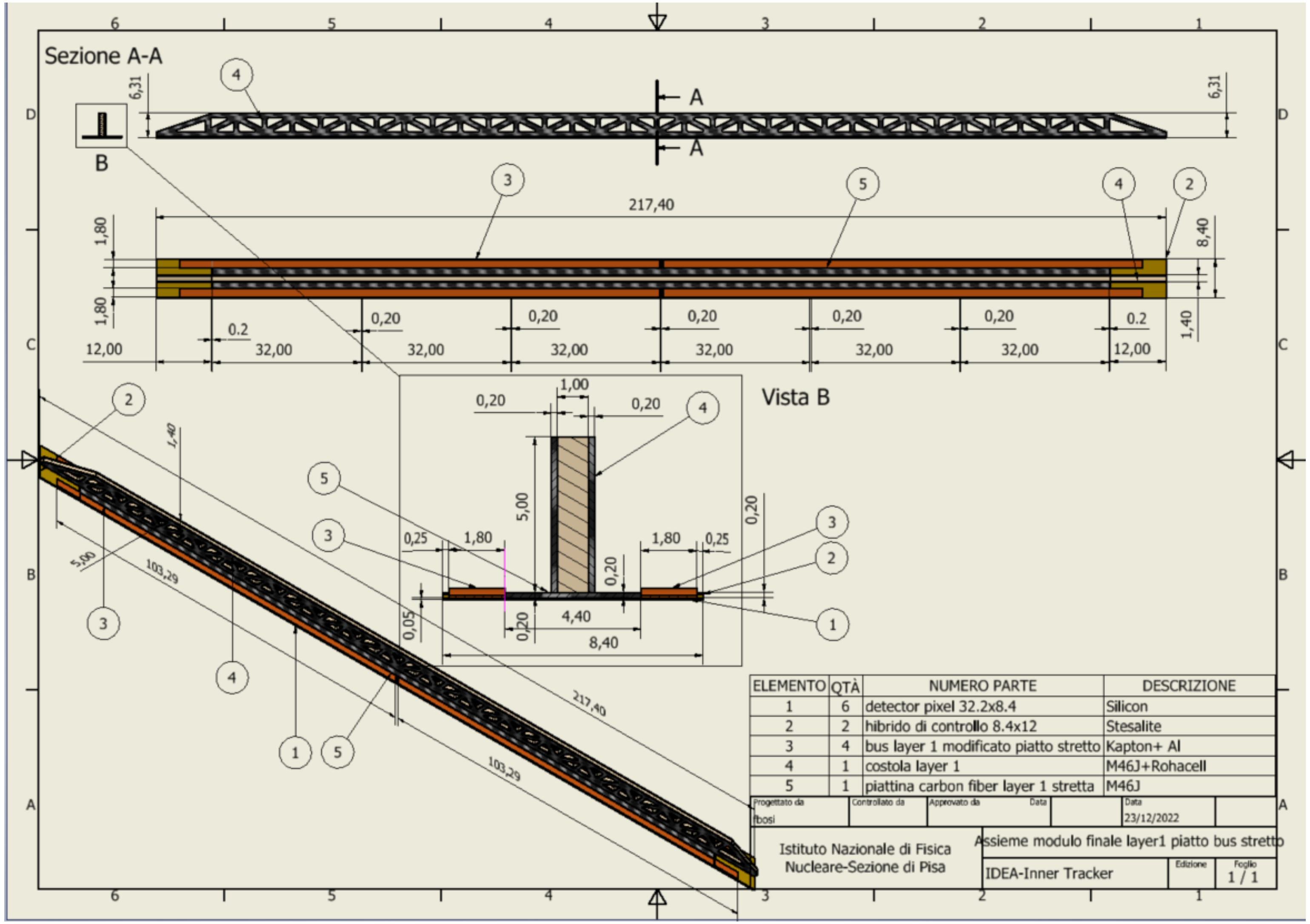
Carbon Fibre ~60 %

Silicon: ~20%

Power and readout bus: ~20%

Layer #	Radius [mm]	No staves	No modules /stave	Total Length [mm]	Active Area [cm²]	Power [W]
1	13.7	15	6	217.40	241.92	12
2	23.7	24	10	346.20	645.12	32
3	34 & 35.6	36	16	539.40	1548.29	77

Layer 1 stave detail



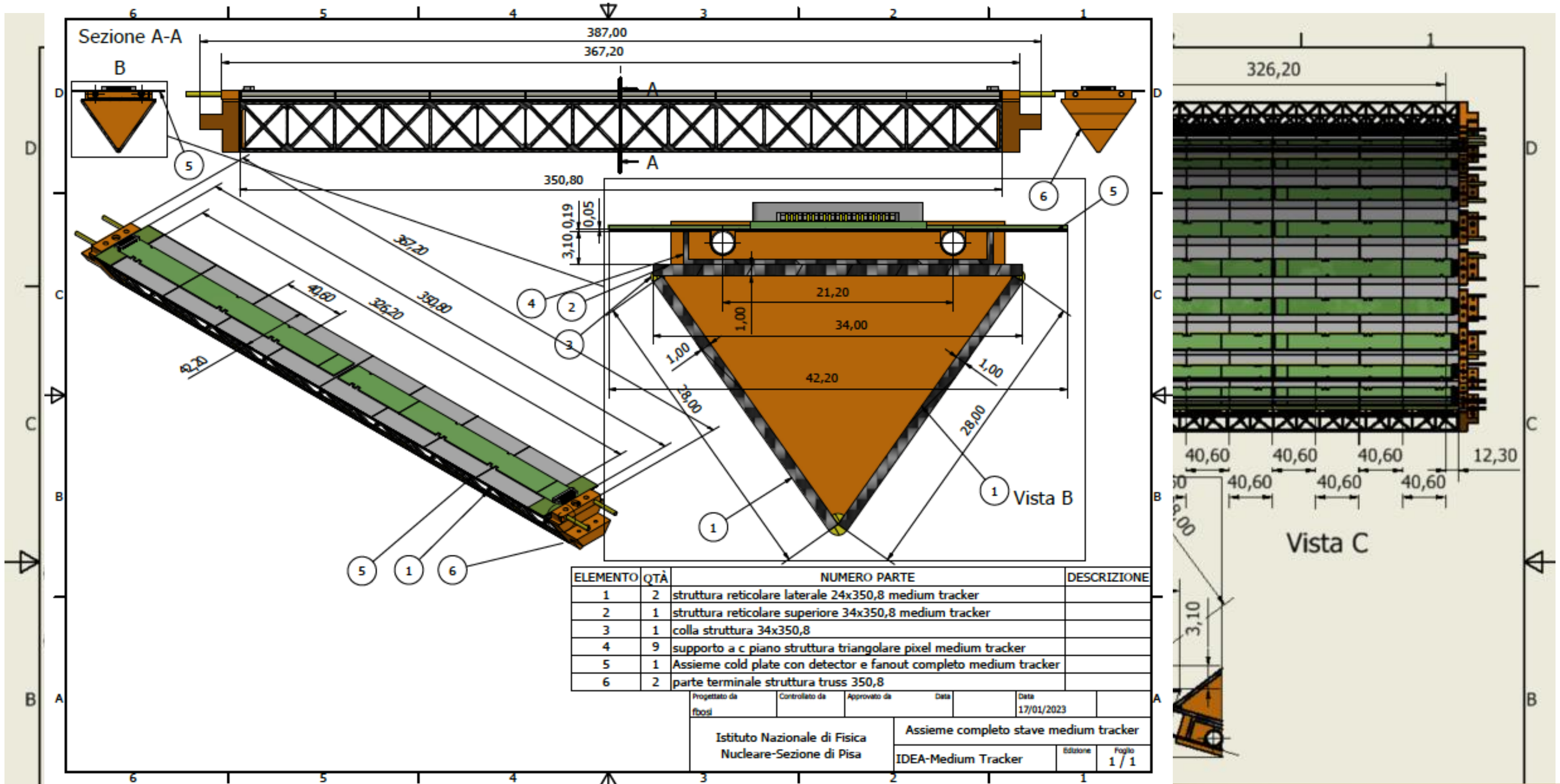
Reticular lightweight support to provide stiffness

- 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
  - Inspired to low mass hybrid R&D

Sensors facing interaction point w/o any other material in front

Readout chips either sides

Air cooled



ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
1	2	struttura reticolare laterale 24x350,8 medium tracker	
2	1	struttura reticolare superiore 34x350,8 medium tracker	
3	1	colla struttura 34x350,8	
4	9	supporto a c piano struttura triangolare pixel medium tracker	
5	1	Assieme cold plate con detector e fanout completo medium tracker	
6	2	parte terminale struttura truss 350,8	


Similar prototype built @ Pisa

Middle Barrel
At 13 cm radius

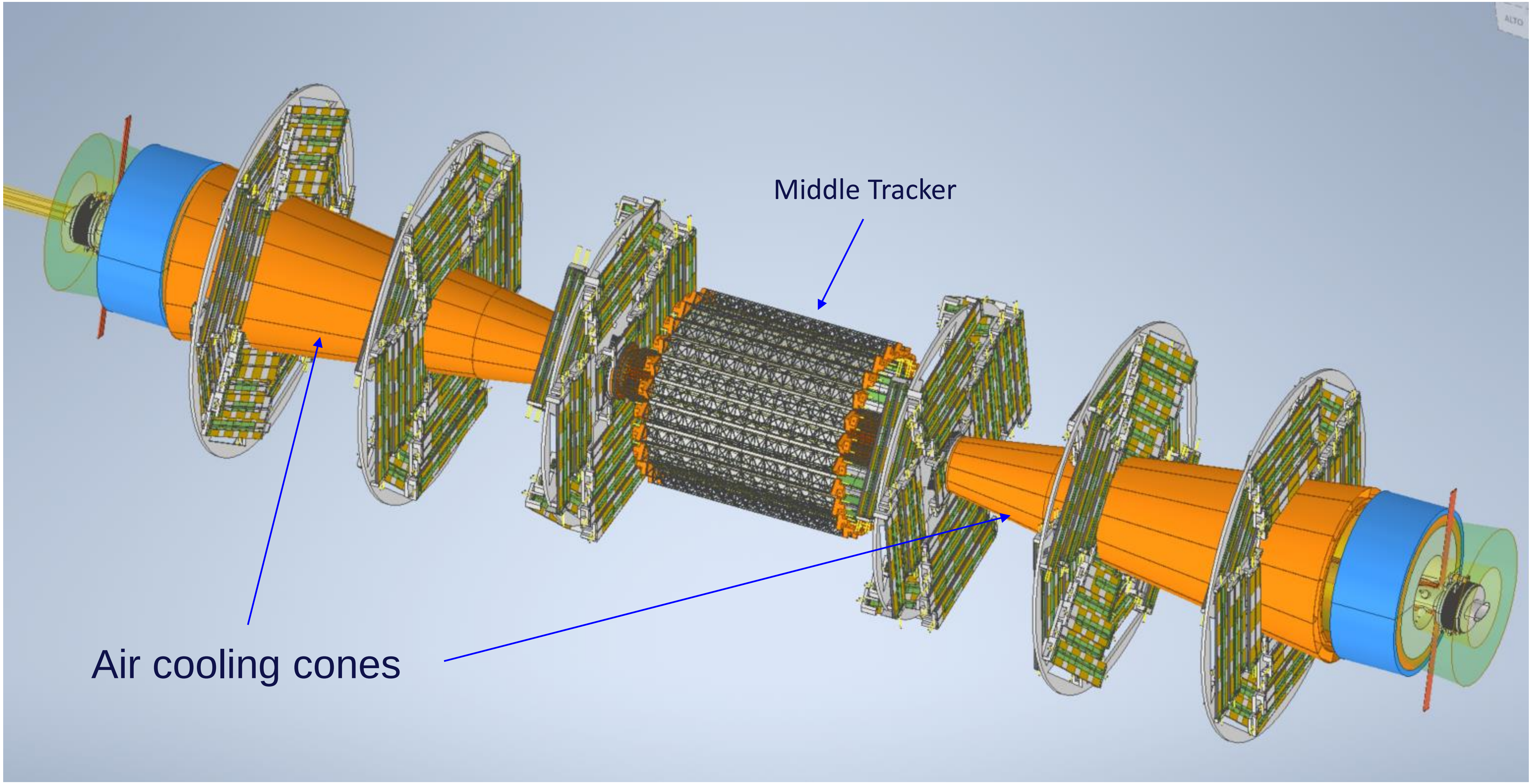
22 staves of 8 modules each.

Lightweight reticular support structure (ALICE/Belle-II like)

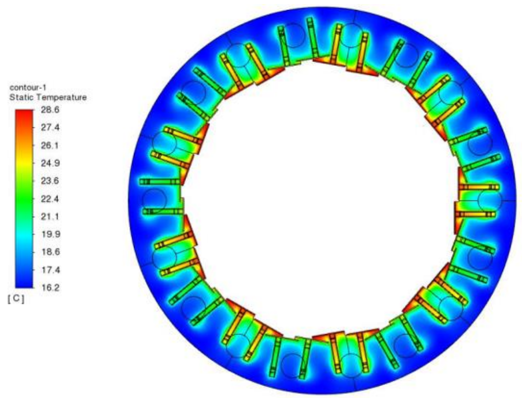
Readout chips either side
Power budget
~342 W

Total weight ~1 kg
Water cooled (2 pipes of 2 mm diameter)

Similar for outer barrel

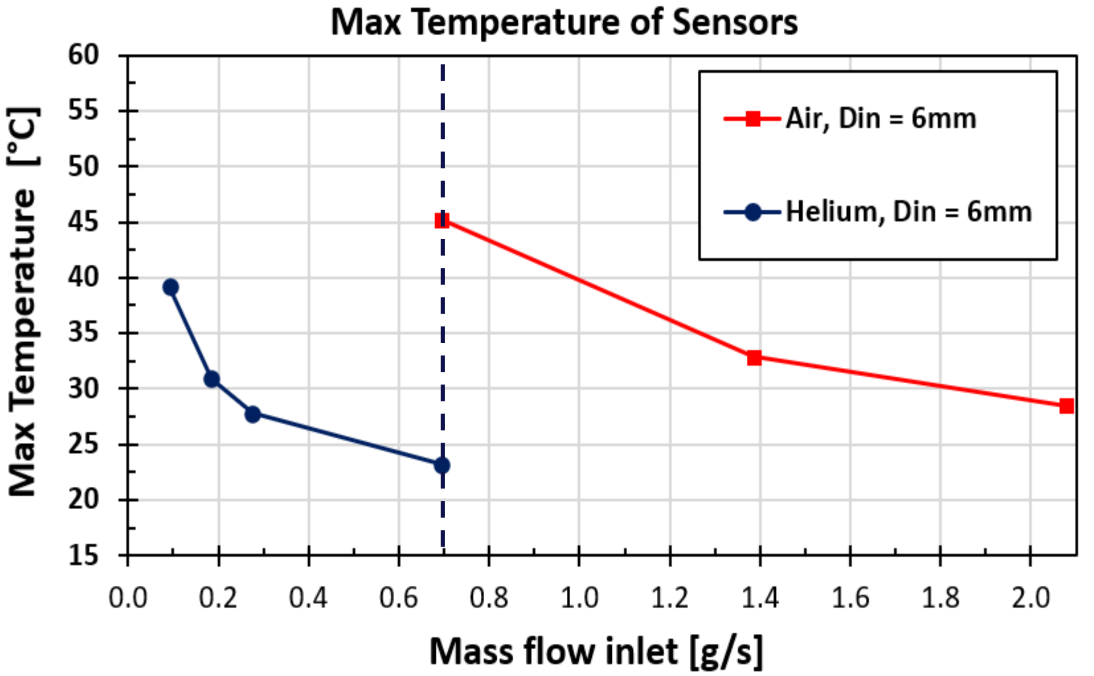

Middle Tracker
Air cooling cones

Air cooling simulations

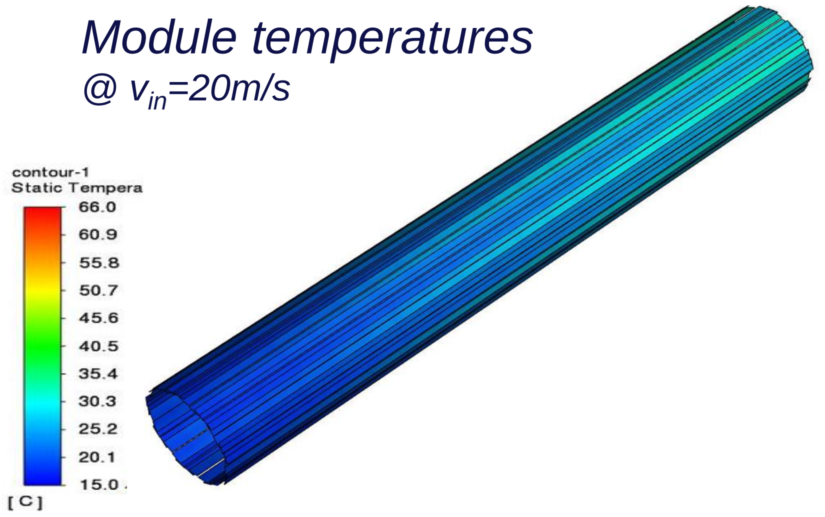


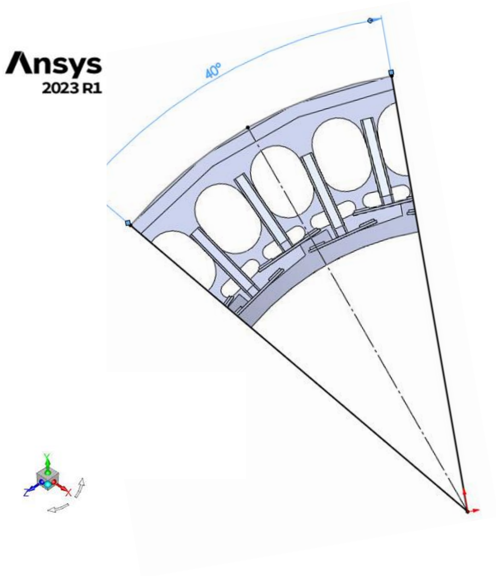
Layer 3 – largest power dissipation: 77 W

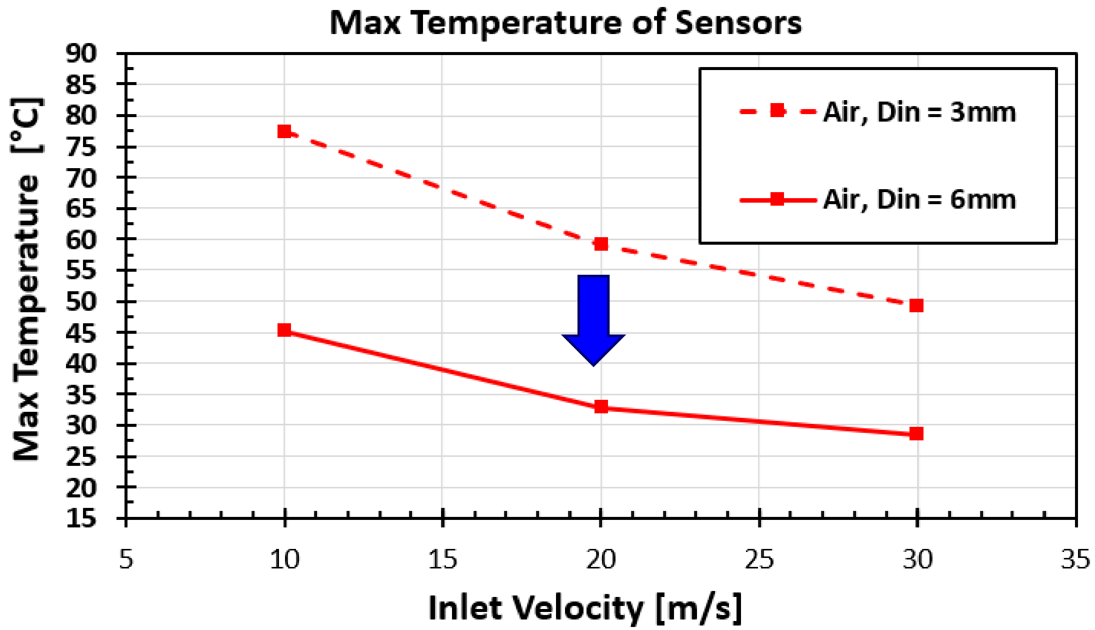
Optimization of flow rate
Compare Air with Helium
Max $\Delta T < 10ºC$ achievable



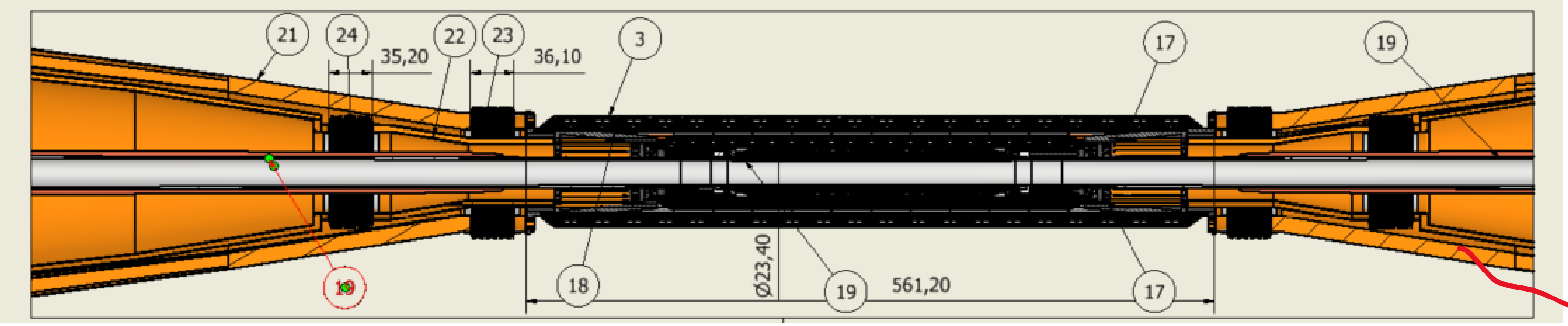
Module temperatures
@ v_{in}=20m/s



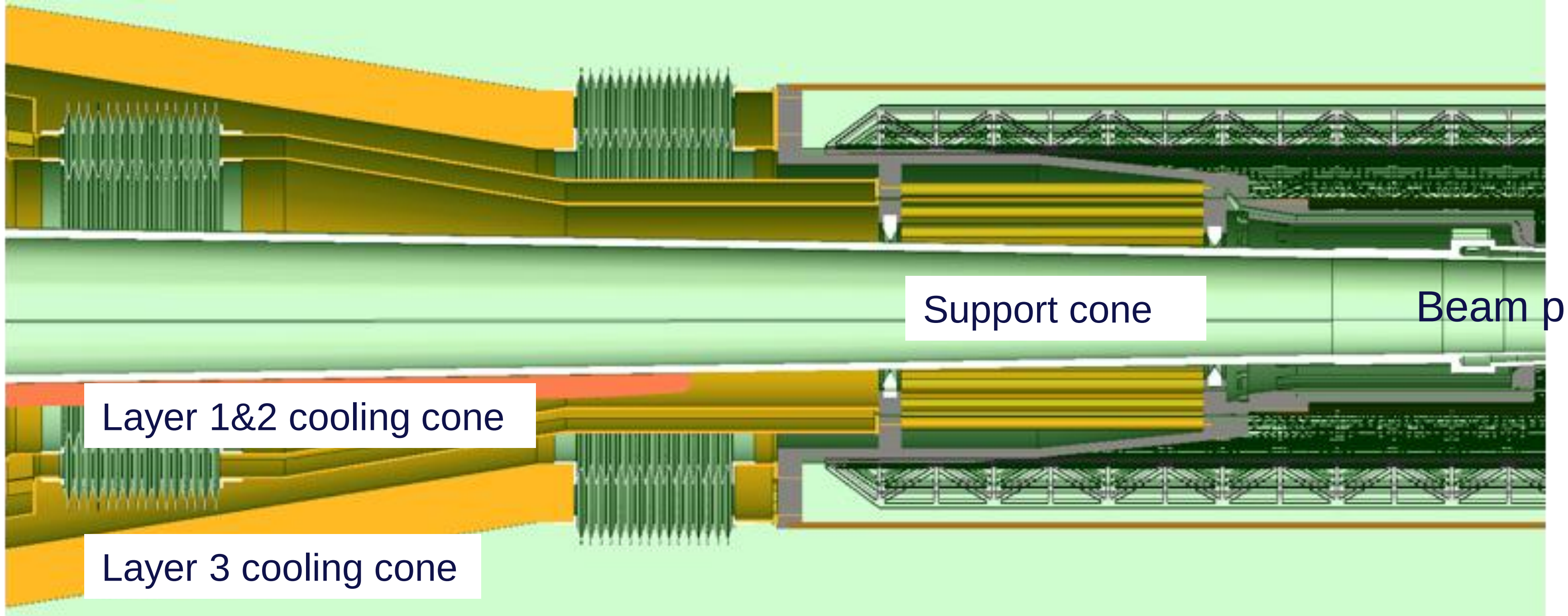




Inner vertex – beam pipe integration



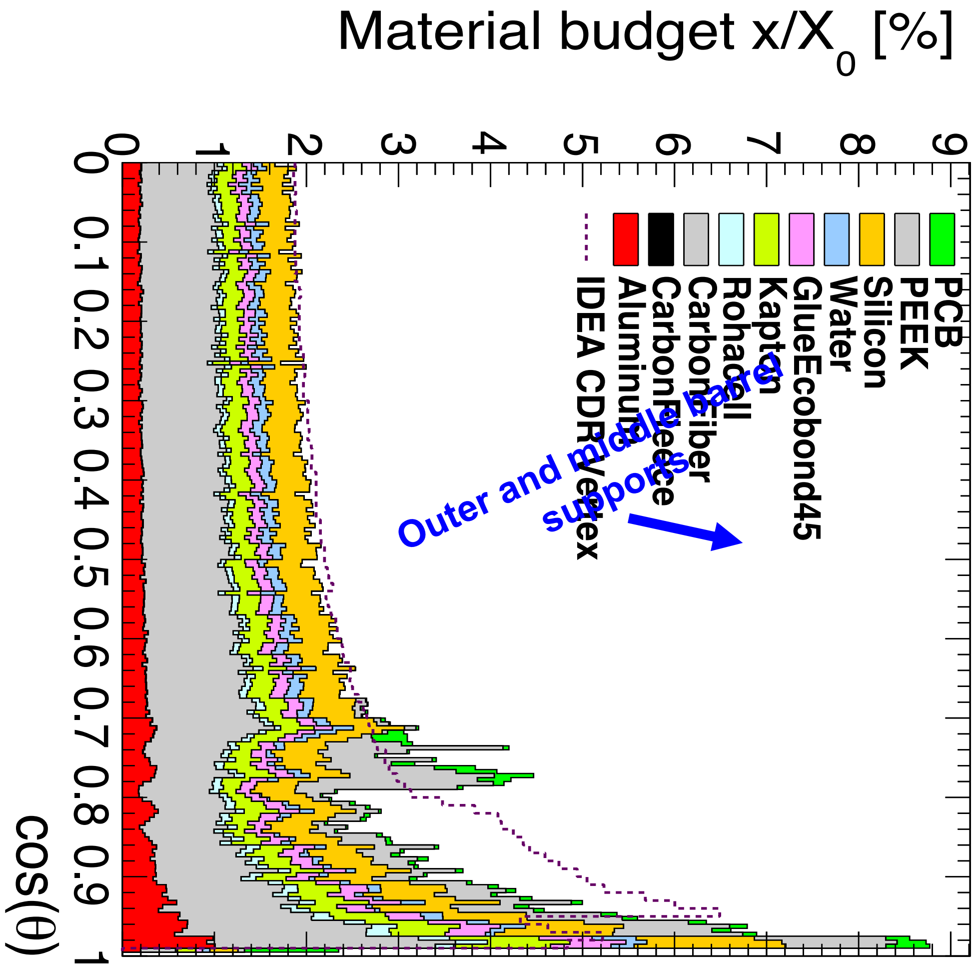
Air-cooling cones



Beam pipe cooling manifold

Courtesy F. Bosi

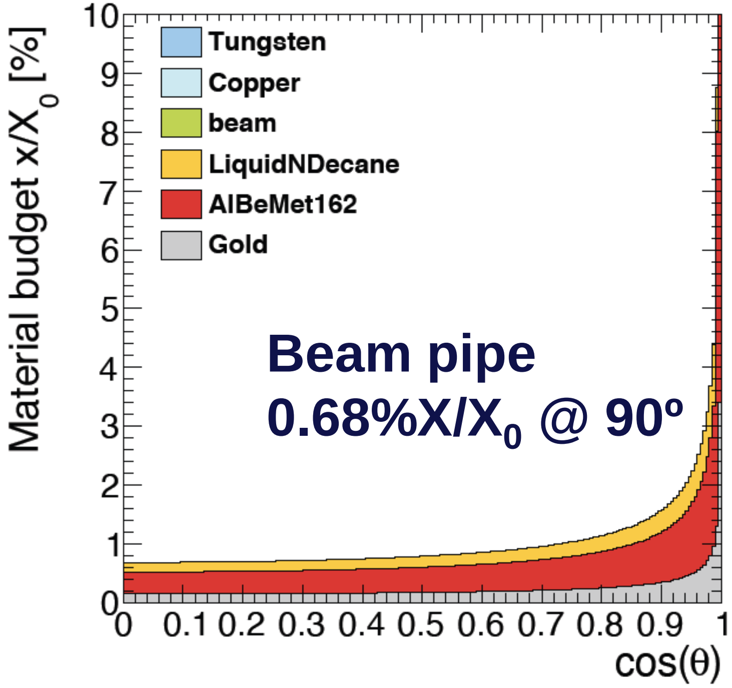
Simulated material budget

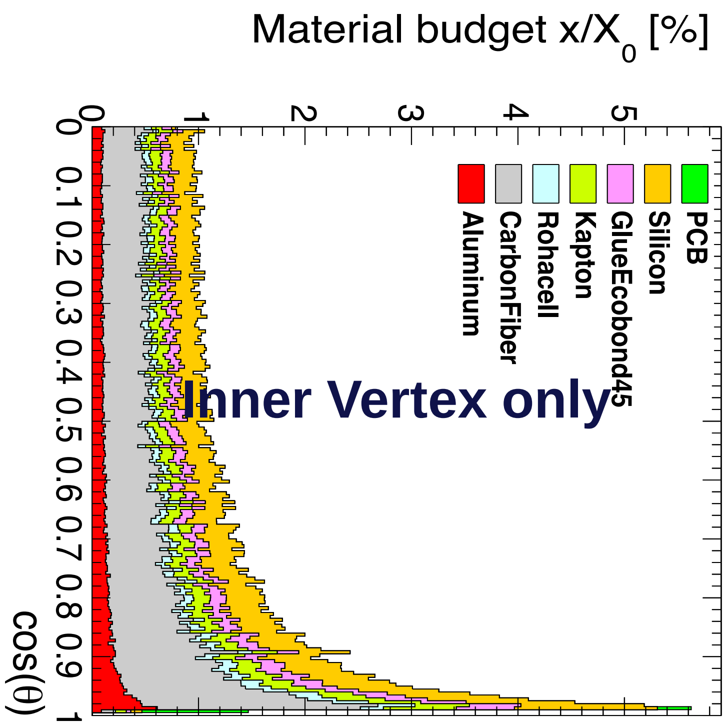


In agreement with CAD estimates

Smaller X/X_0 wrt IDEA CDR estimates even including power and readout cables in the sensitive region

Silicon only ~15% of the total





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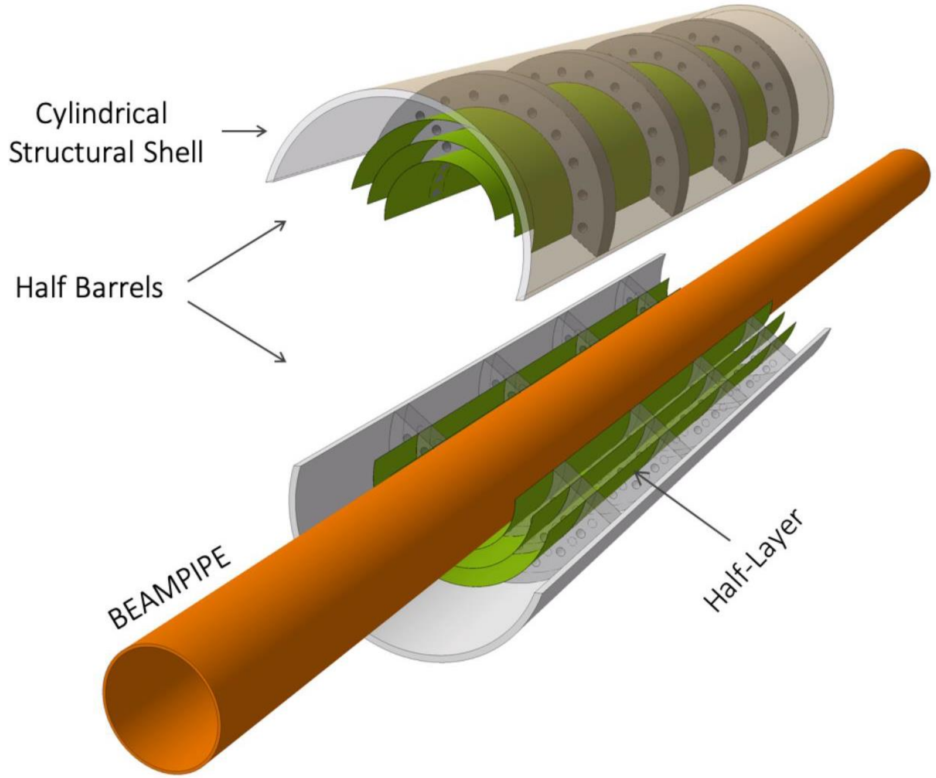
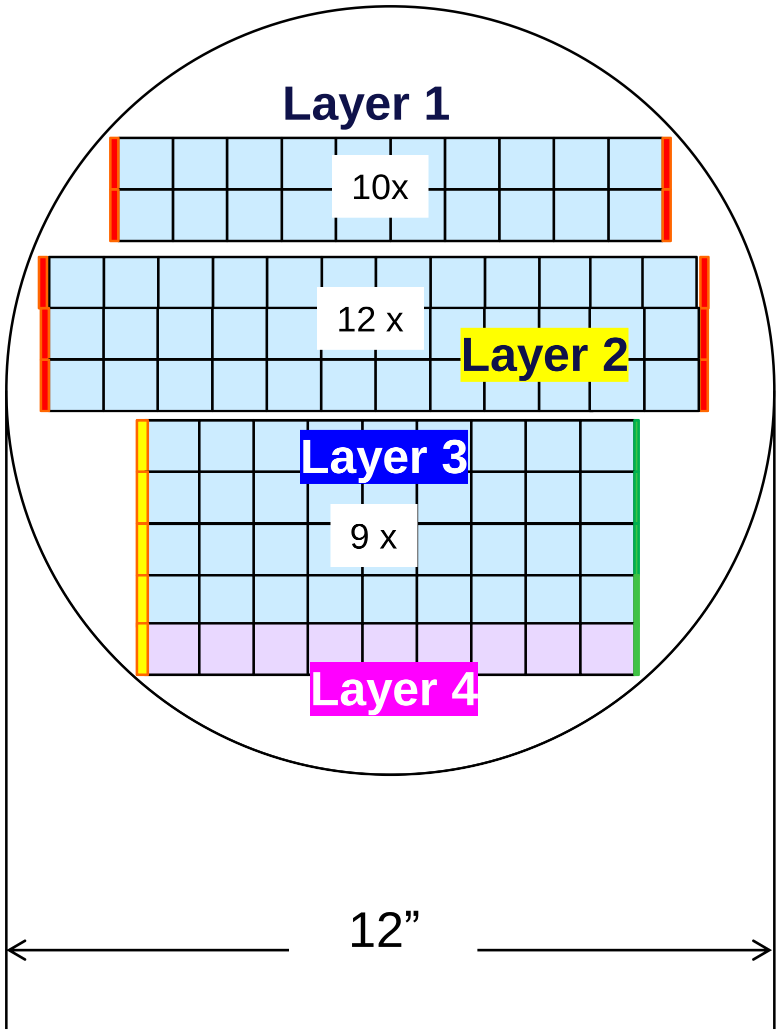
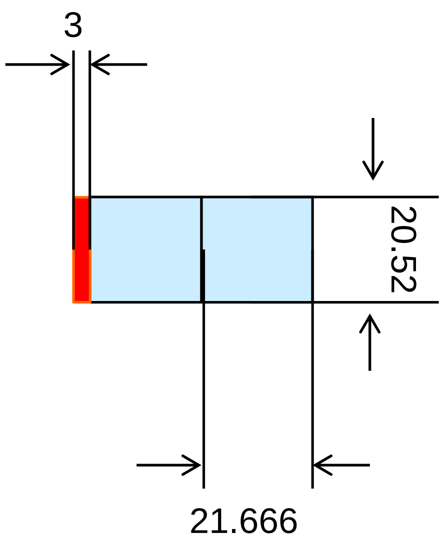


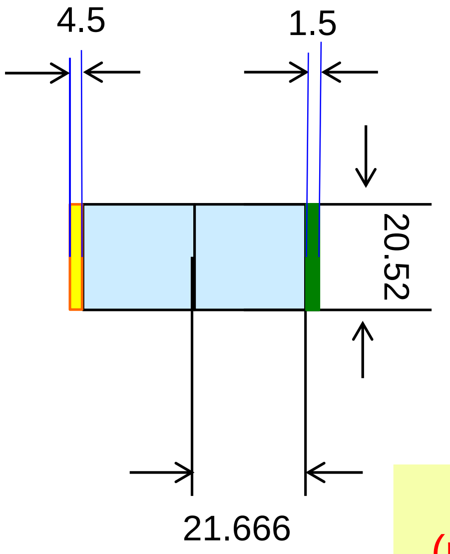
Lightweight layout using an ALICE ITS3 inspired design

Same reticle for all layers





Layer 1&2



Layer 3&4

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

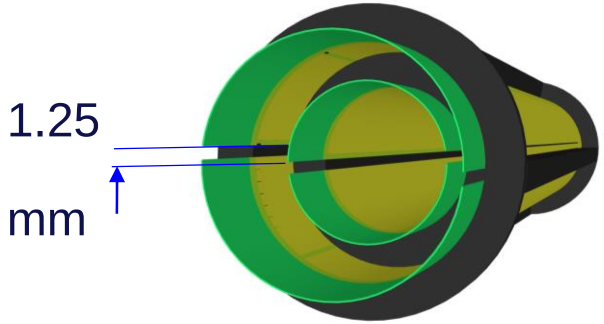
	Power density [mW cm^{-2}]		
	Expected 25 °C	Max 25 °C	Max 45 °C
Left End Cap (LEC)		791	
Active area (RSU)	28	44	62
Pixel matrix	15	32	51
Biasing	168	168	168
Readout peripheries	432	457	496
Data backbone	719	719	719

Power dissipation in ITS3
(not necessarily the same for FCC-ee)

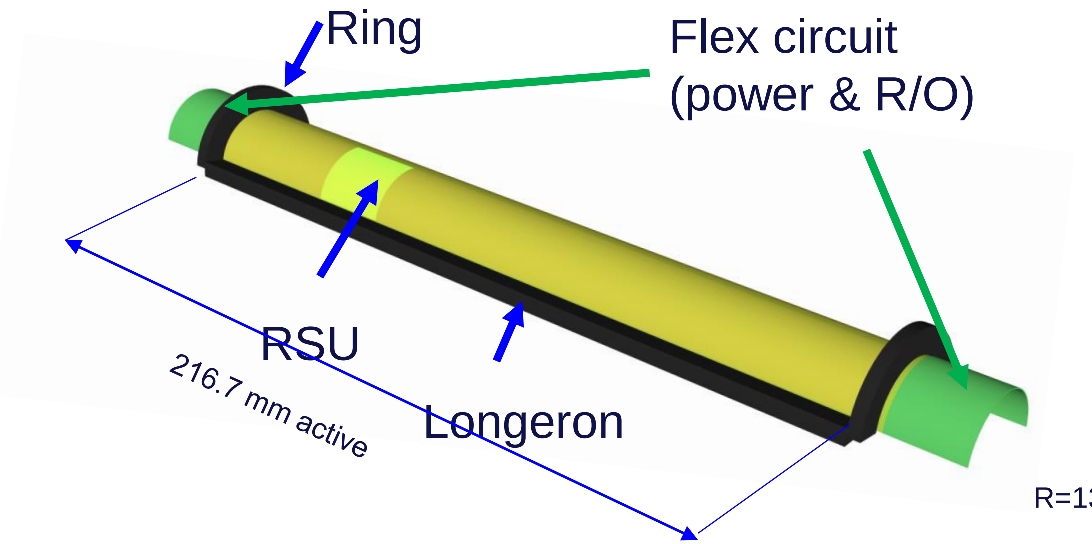
- RSU~ 50 mW/cm^2 (depends on Temp.)
- LEC ~ 700 mW/cm^2

Active pixels <95% of covered area

Layers 1 & 2



- Single stitched wafer
  - Readout and power from both sides (reduces transmission off-detector and limits power dissipation in the endcaps)
- Leaves ~1.25 mm* insensitive gap in R-phi, to account for assembly tolerances



R=20.35 mm

$|\cos(\theta)| < 0.99$

R=13.7 mm

$|\cos(\theta)| < 0.992$

Layer 1

Layer 2

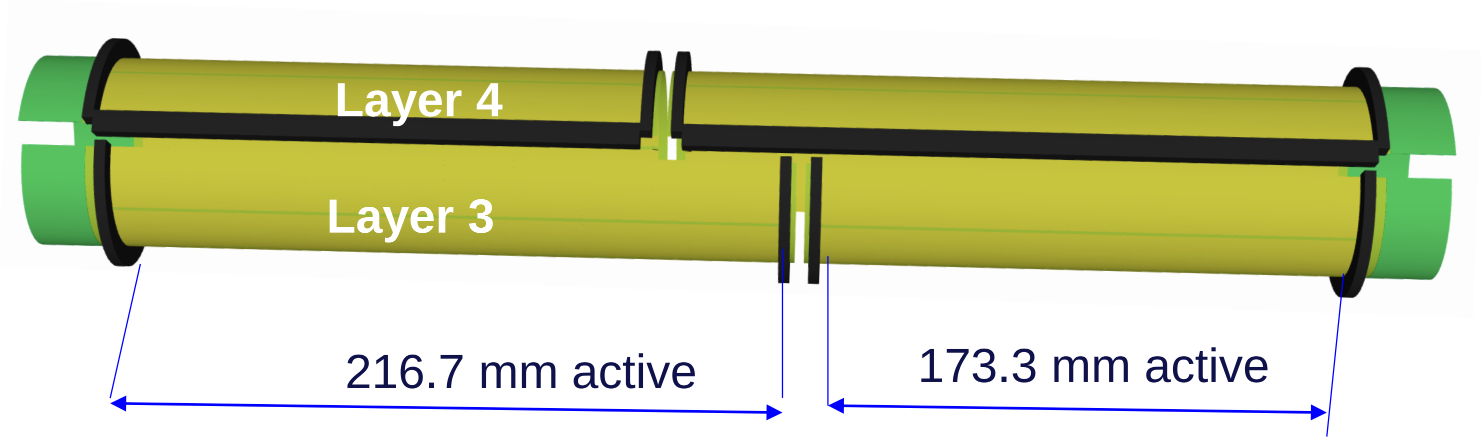
Layers 3 & 4

- Four “quarter” layers to allow ~same angular coverage for all layers and use 12” wafers
- Layer 4 has the same length of Layer 3 but higher radius
- Quarter readout only on one side, the other only for power (wire)
  - Gap of ~ 2xO(10 mm) at |z|~2.2 cm: **quarters with non-symmetric layout** (left quarter with 10 RSU and right one with 8 RSU, and swapped for L4)

Layer 3

R=27 mm

$|\cos(\theta)| < 0.991$



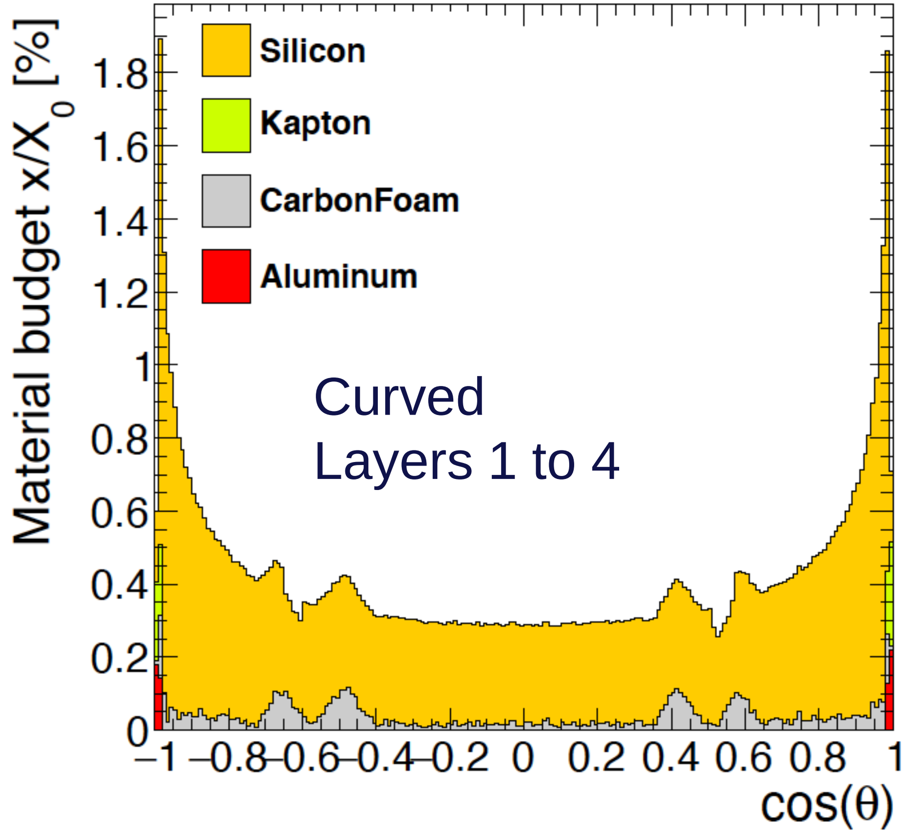
Layer 4

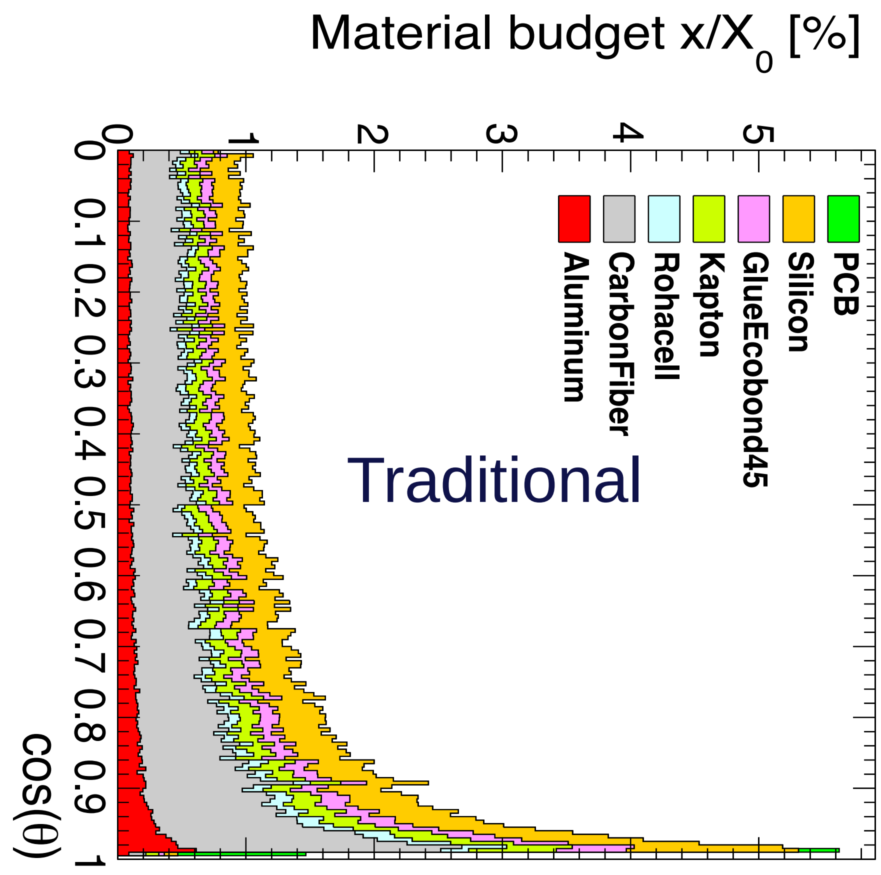
R=33.65 mm

$|\cos(\theta)| < 0.987$

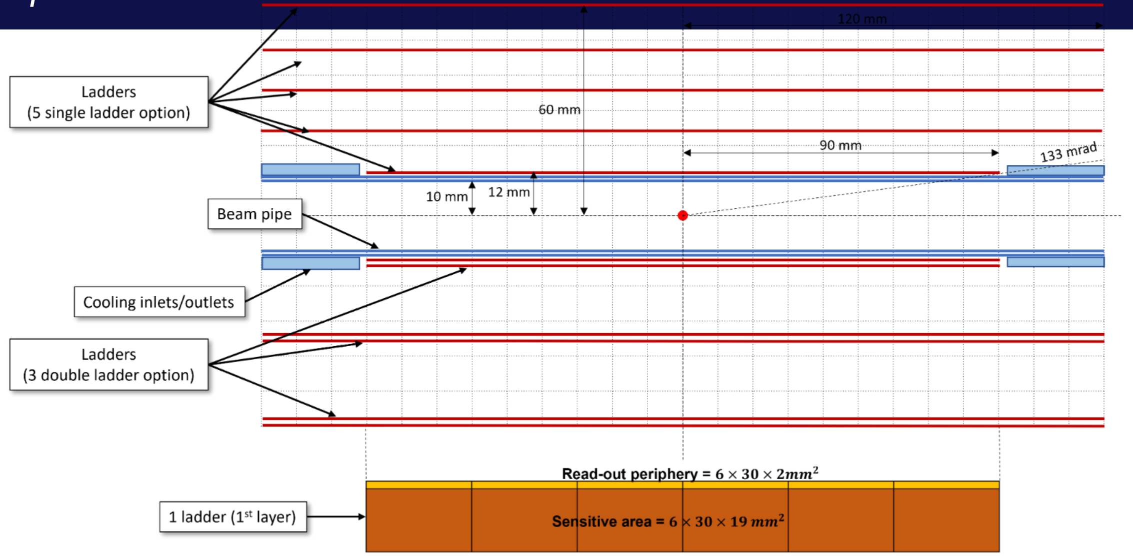
2x few mm (being optimised)

Material budget inner vertex





Schnecke: a vertex detector for FCCee



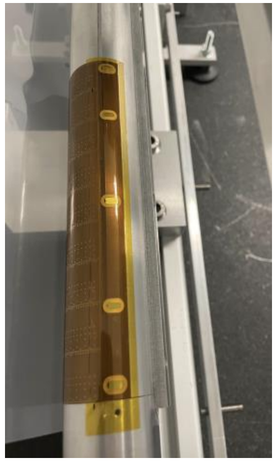
- Alternative Proposal: Schnecke concept = bent ladders
  - Stitching or not stitching
  - Radius approaching constant value
  - Full acceptance in φ
  - Double sided can be considered.
  - Number of layers = free parameter
  - Competitive for mat. Budget. AND full azimuthal acceptance

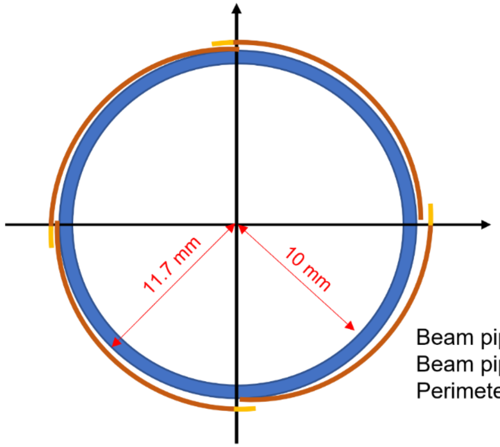
Table 3: Barrel dimensions (single and double sided option)

Layer	1	2	3	4	5
Radius (mm)	12-13	24	36	48	60
Zmax (mm)	90	120	120	120	120
Perimeter (mm)	75	151	226	302	377
# Chips per ladder	6	8	8	8	8
# ladders	4	8	12	16	20

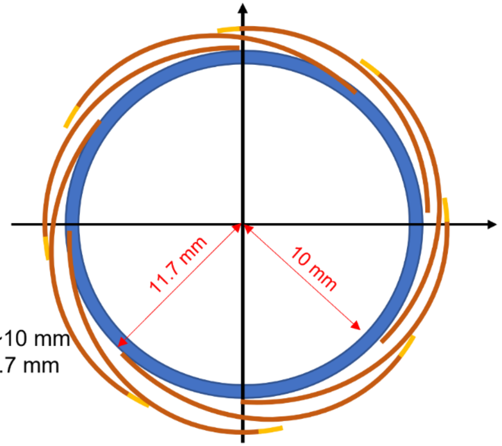
Layer	1-2	3-4	5-6
Radius (mm)	12-13	35-36	59-60
Zmax (mm)	90	120	120
Max perimeter (mm)	82	226	377
# Chips per ladder	6	8	8
# ladders	4	12	20
Single chip dimension			$30 \times 22.2\ mm^2$
Sensitive area chip dimension			$30 \times 19.2\ mm^2$

Bending setup @ IPHC





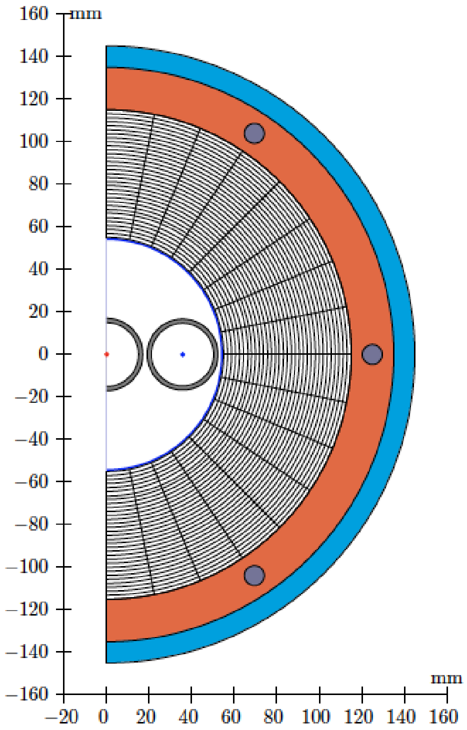
Beam pipe inner radius ~10 mm
Beam pipe thickness ~ 1.7 mm
Perimeter ~73.5 mm

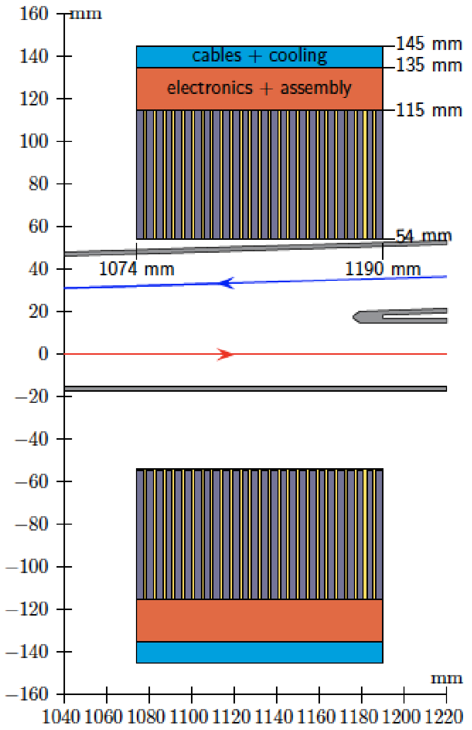


- Bent sensors pioneered by Alice ITS-3,
  - IPHC : working program dedicated to bent sensor with MIMOSIS
  - e.g. functional tests @ R = 12 mm

Luminosity monitor integration

- Luminosity measurement with low angle Bhabha scattering
  $64 < \theta[mrad] < 88\,; \sigma = 14\,nb$
- Silicon (active) + Tungsten (passive) sampling calorimeter with pointing resolution
- Aiming 10^{-4} precision
  - Tight construction and alignment tolerances
    - $\delta R_{min} = \pm 1.5\ \mu m$
    - $\delta R_{max} = \pm 3.5\ \mu m$
    - $\delta z = \pm 110\ \mu m$
  - Dictates the smallest angular acceptance of the vertex detector
  - Careful understanding of materials in front
  - Sensitive to thermal stability



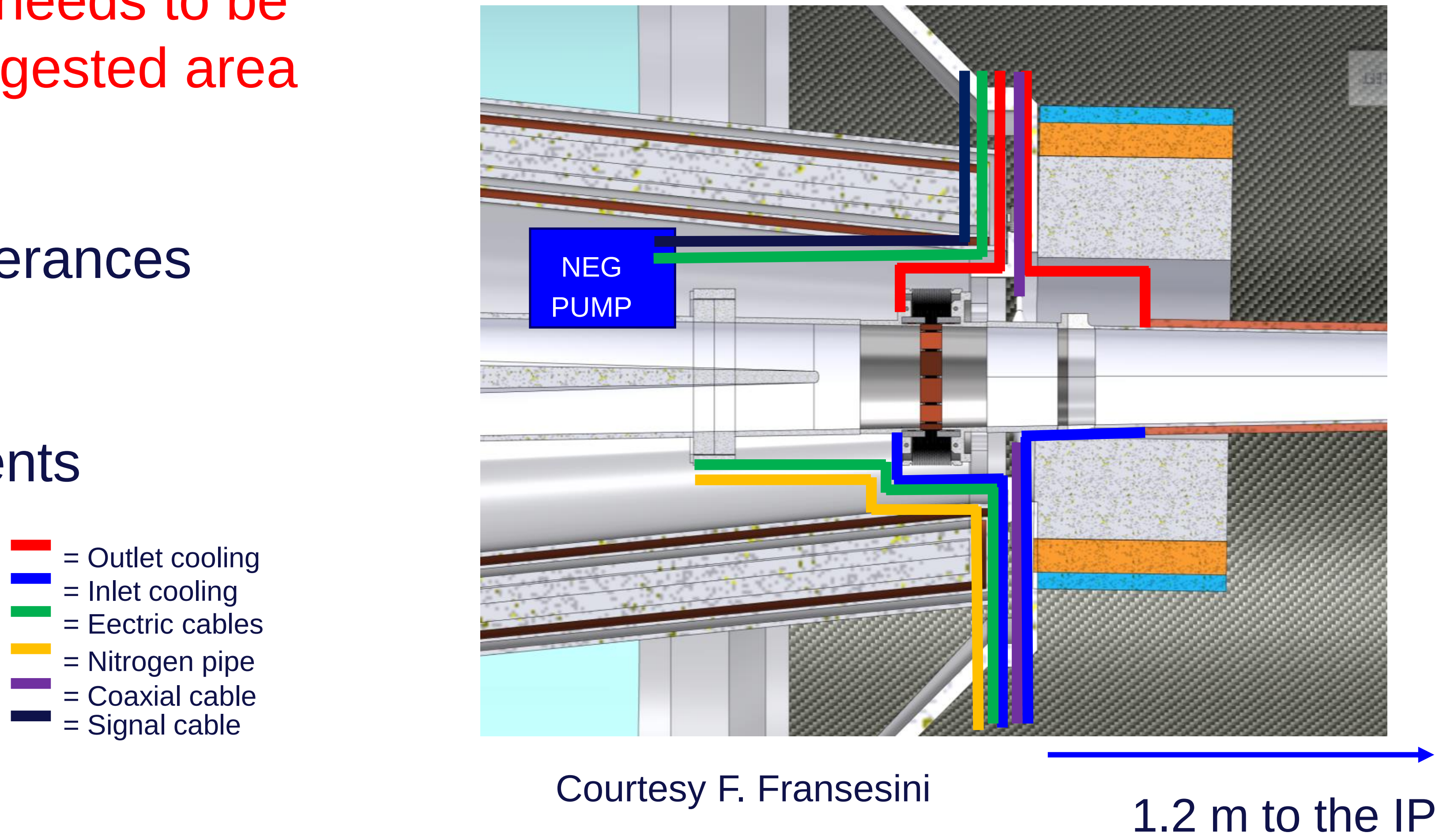


Courtesy M. Dam

Integration with cryo-magnet system

- Luminosity calorimeter needs to be integrated in a very congested area
  - Service routings
  - Tight construction tolerances
  - Alignment system
  - Accelerator components

LumiCal

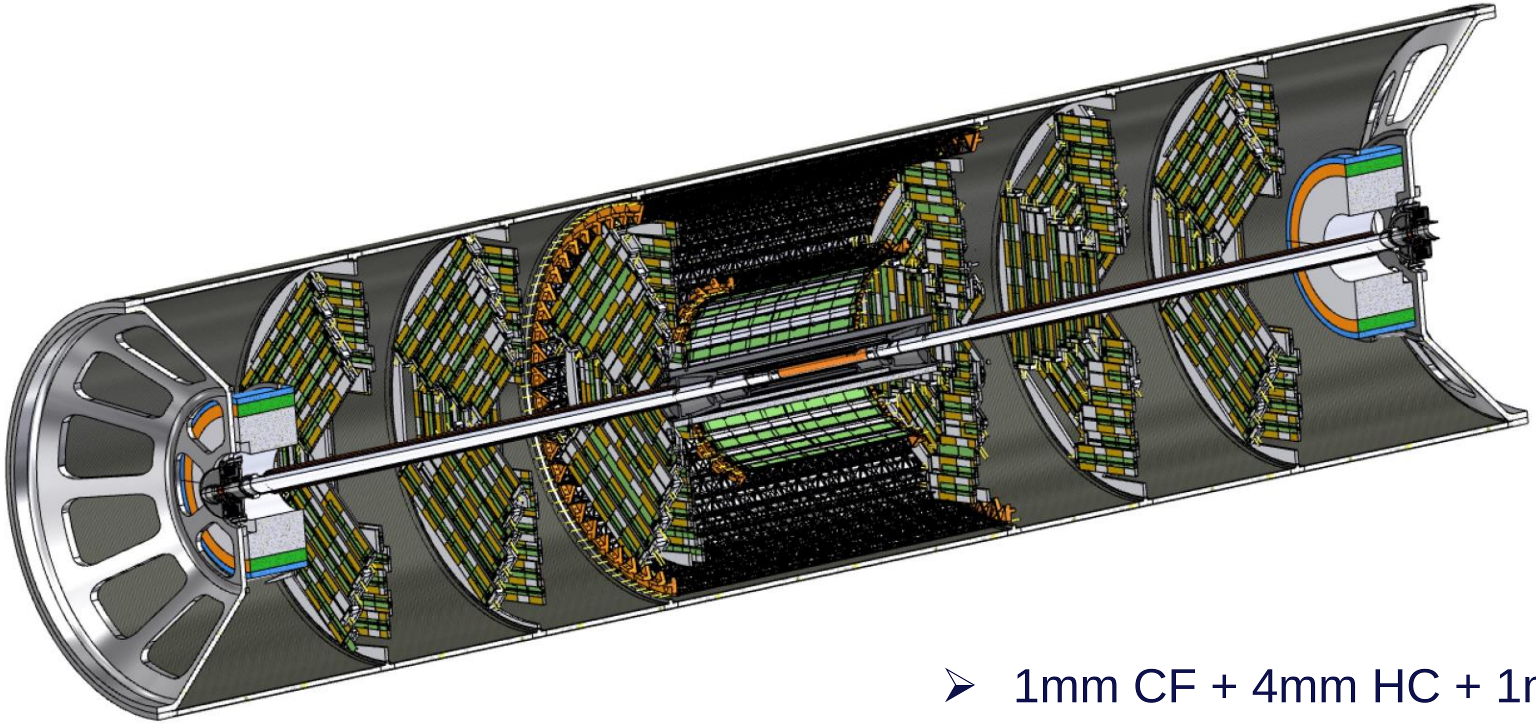


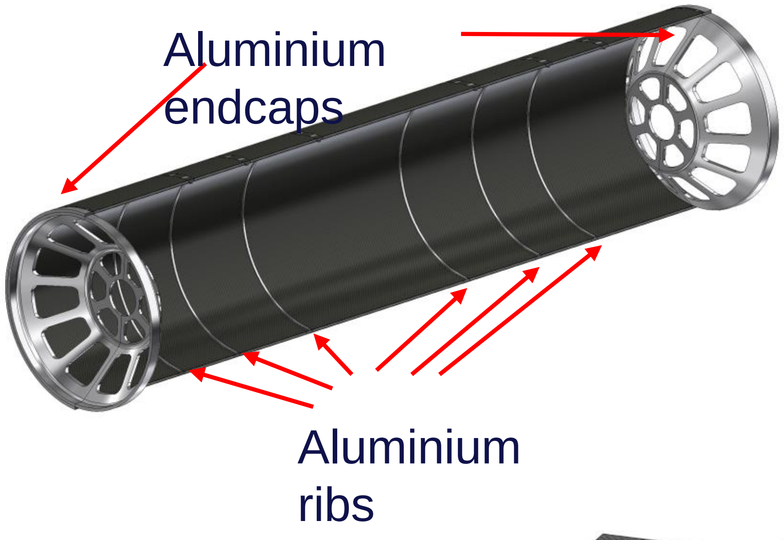
Courtesy F. Fransesini

Support cylinder

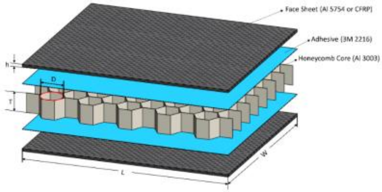
All elements in the interaction region (Vertex and LumiCal) are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment

- Once the structure is assembled it is slided inside the rest of the detector





➢ 1mm CF + 4mm HC + 1mm CF



R&D Full scale IR mockup at LNF in collaboration with Pisa and CERN

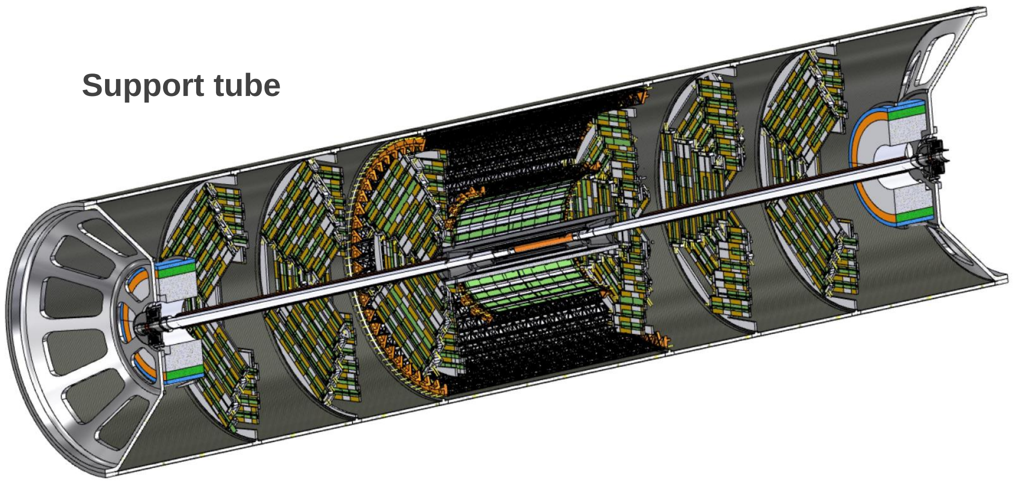
Goal: design validation, buckling test, assembly and cooling/services test

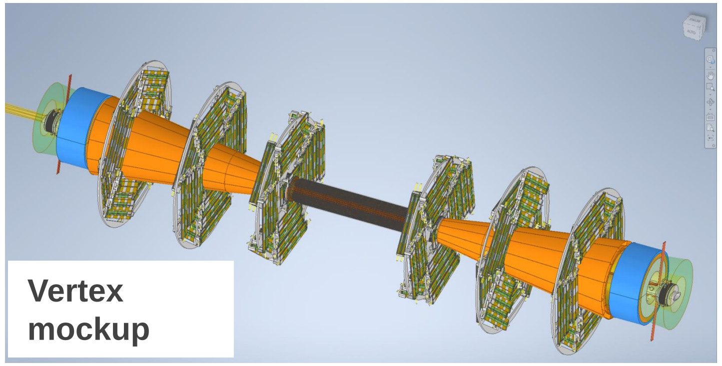
Central chamber: double layer with paraffin cooling

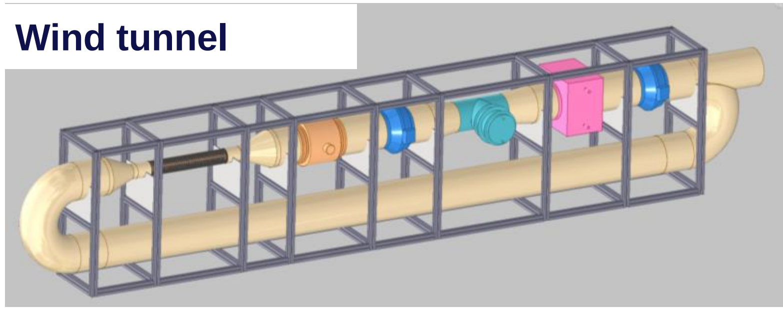
Bellows

Ellipto-conical chamber with water cooling manifolds

Support tube







Integration and overall assembly targeting Q4-2025

General integration

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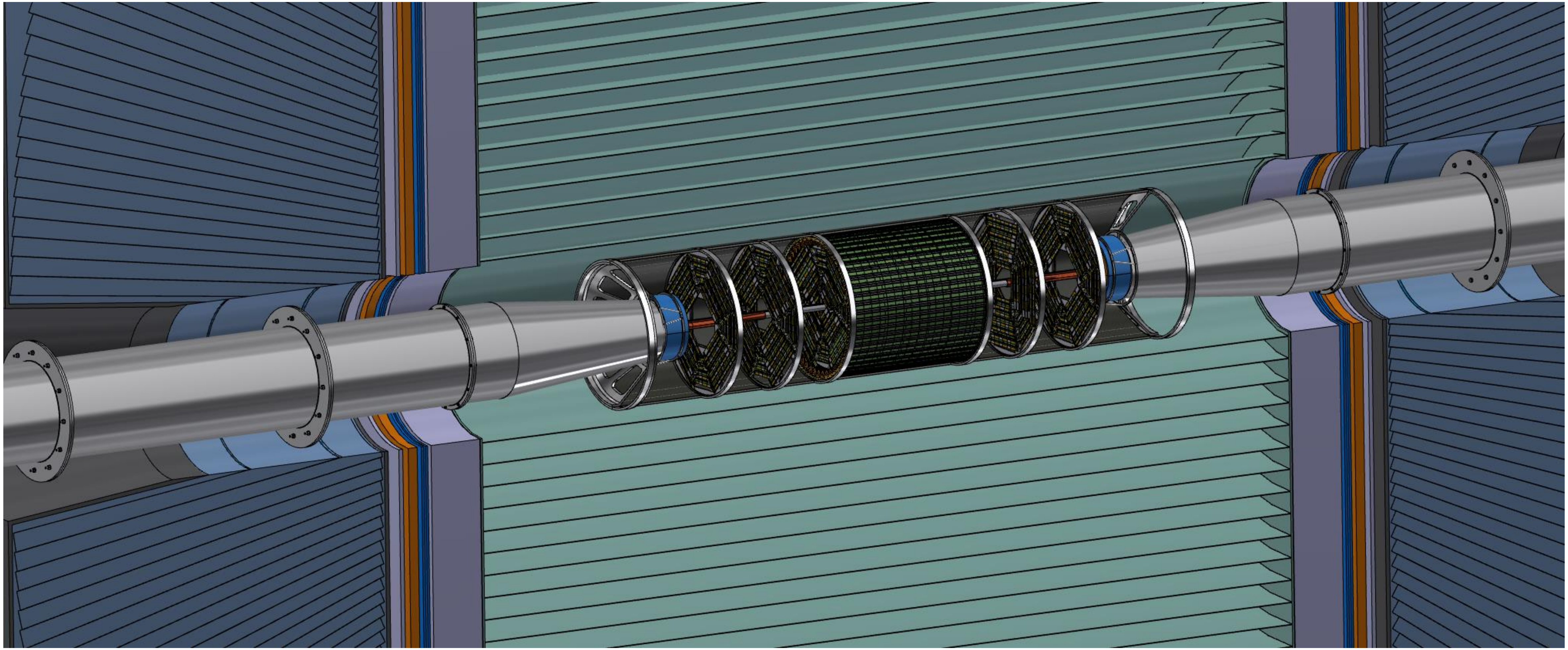
M. Boscolo, F. Palla, F. Fransesini, F. Bosi and S. Lauciani, Mechanical model for the FCC-ee MDI, EPJ Techn Instrum **10**, 16 (2023).
https://doi.org/10.1140/epjti/s40485-023-00103-7

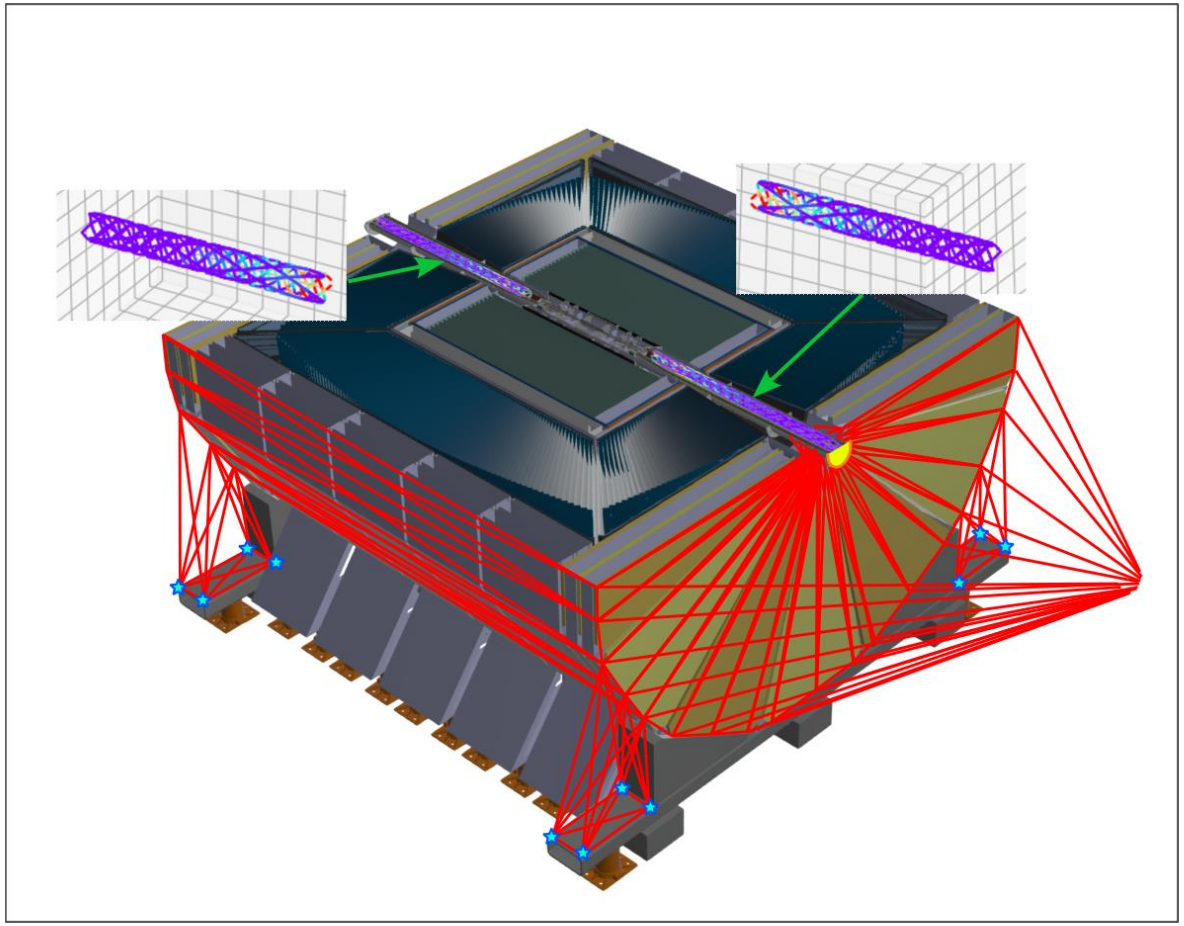


Alignment system

Using 3 subsystems with Frequency Scanning Interferometry:

- Deformation monitoring of the QC1 as reference system
- Short distance between the QC1 end and the LumiCal, BPM, + other elements
- A Long distance monitoring

- Work ongoing on the technical side



Courtesy L. Watrelot

Detector opening scenarios

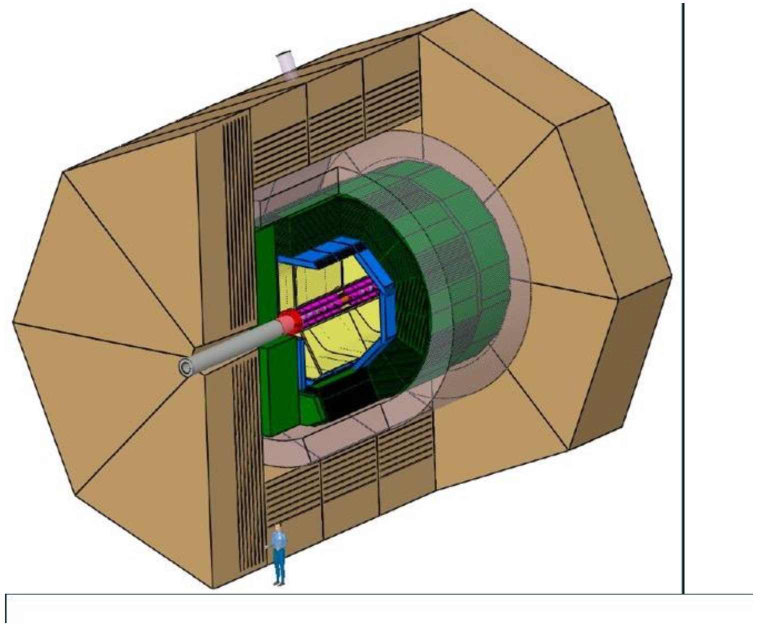
Detector vs machine requirements:

Detector side:

- Detector acceptance and hermeticity
- Simple opening sequence – minimal services disconnection & handling
- Accessibility to detector inner parts in reasonable time during shut-downs

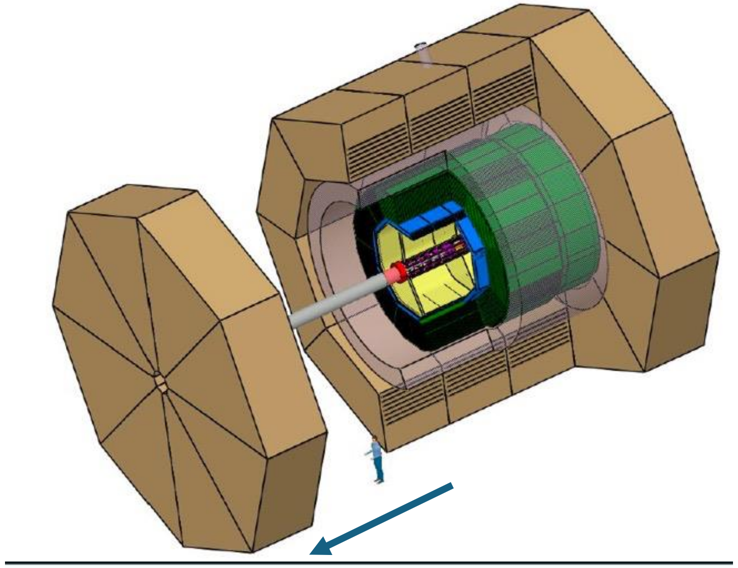
Machine side:

- Stability of the FFQ supports
- Quick and reliable alignment procedure
- Beampipe vacuum preserved



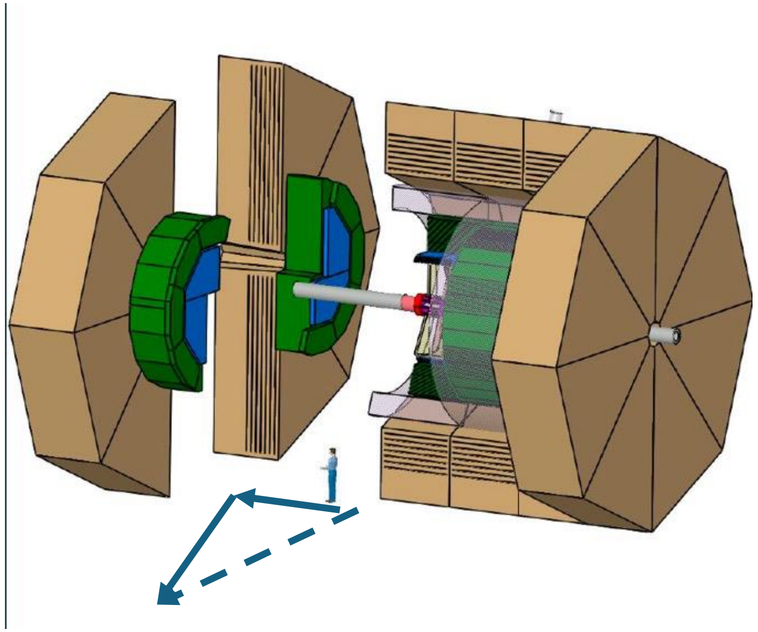
Scenario #1

Long (7m) longitudinal stroke to access inner detector elements. Last machine elements cantilevered & removed for opening.



#1. Full longitudinal opening of the two endcaps.

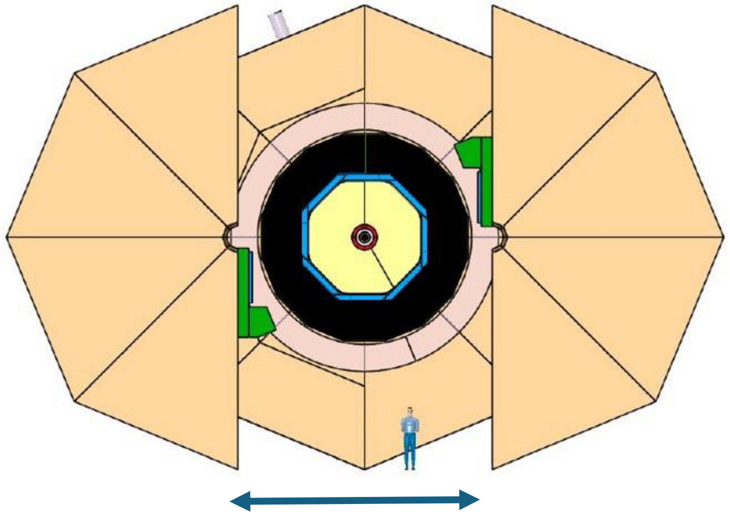
- Detector acceptance in the forward region depends on machine layout
- FFQ and other machine elements beyond detector endcaps shall be removed (with their supports).
- BP vacuum broken also in cold pipes.
- Realignment of the machine needed.



Scenario #2

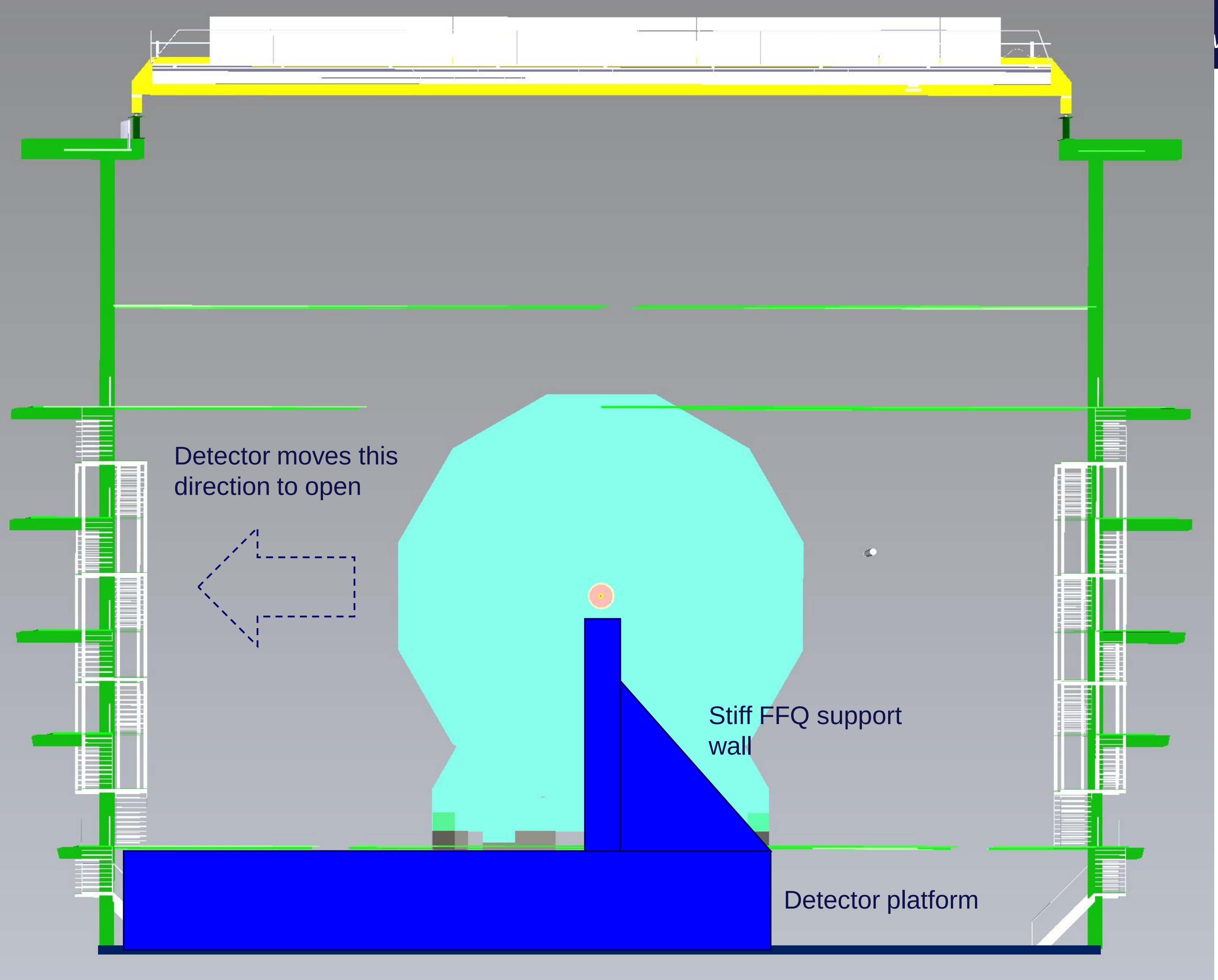
Combined short (2m) longitudinal stroke + transversal opening.

Andrea Gaddi / CERN Physics Department



#2. Limited longitudinal opening to disengage the detector endcaps plus transversal opening (split endcaps) or diagonal opening of the split endcaps.

- Split endcaps significantly deteriorate detector precision measurements
- The cross section of the FFQ cryostat determines the envelope into which the machine elements just behind the detector endcap shall ideally stay. This constraint refers specifically to the cryo-services of the FFQ assembly.
- BP vacuum stay (or Ne flushing), no realignment needed.



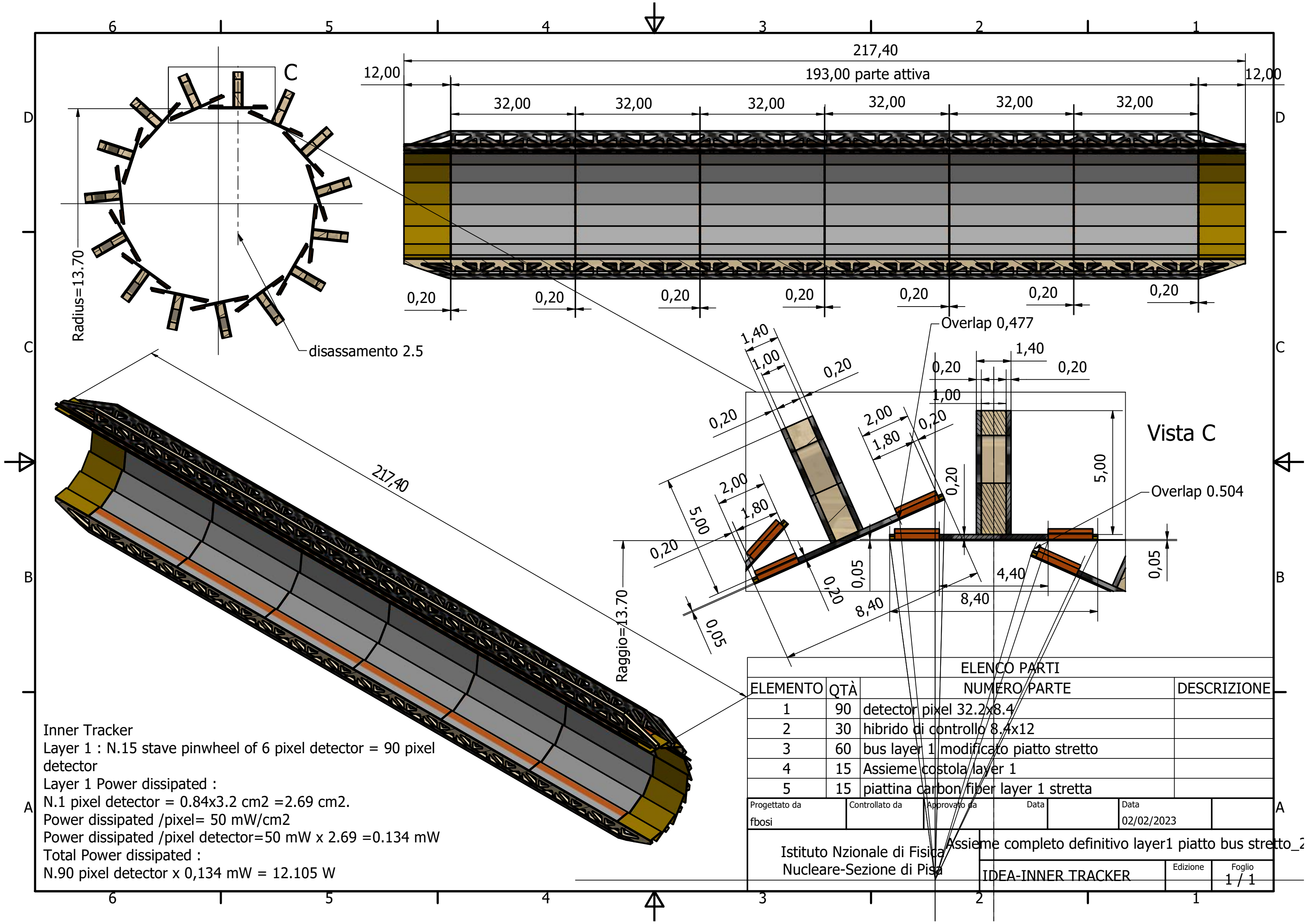
Scenario #3

In the large experimental sites A & G 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.
The FFQ can either be removed before the translation or move with the detector and be removed from the garage position.

Conclusions and next steps

- **A few options for Vertex Detector with MAPS are being studied**
  - A fully engineered version with staves overlaps has been fully engineered
    - 0.25% X0 per layer
    - Integration with beam pipe and Lumical has been fully studied
    - Air/He cooling studies on-going
  - Two variants of curved layouts under study
    - Can reach 0.075% X0 per layer
    - Need to address technical feasibility
- **Integration studies of Vertex and Lumical with the machine elements is on-going**
  - A mockup is being built in Frascati
- **Assembly in the cavern and access/maintenance scenarios are addressed**

Thank you for your attention.



Layer 1

15 overlapping staves of 6 modules each

Overlap to allow alignment ~500 µm

Pinwheel geometry: all modules at the same (smallest) radius

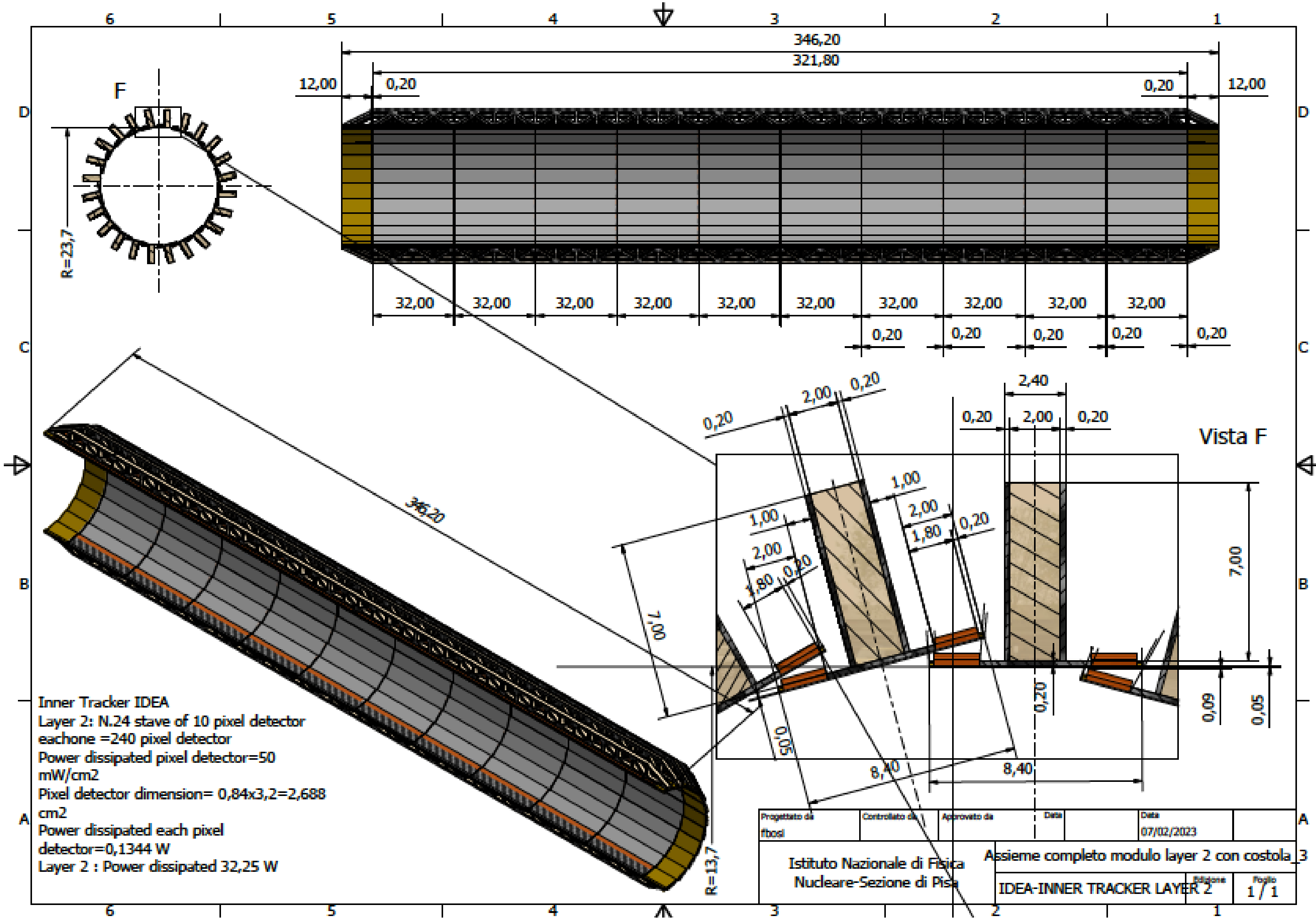
Power budget ~12 W

Total weight ~22 grams

Total thickness 0.25% X_0

Silicon: 0.053% X_0

Power and readout bus: 0.056% X_0



Layer 2

24 overlapping staves of 10 modules each

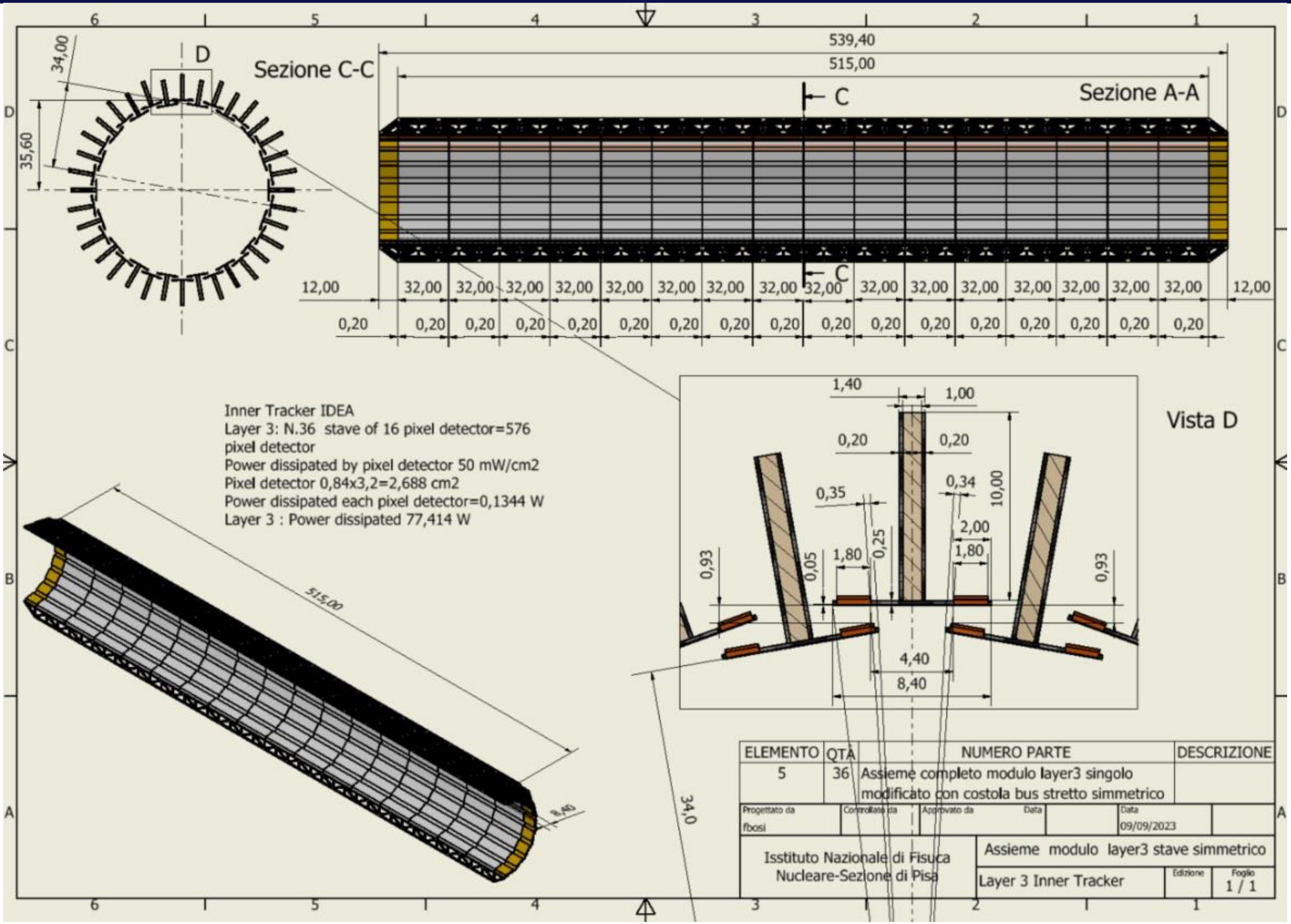
Pinwheel geometry

Counter-rotated wrt layer 1 to mitigate charge-asymmetry effects in track reconstruction

Power budget
~32 W

Total weight ~63 grams

Total thickness 0.25% X_0



Layer 3

36 staves of 16 modules each

Lampshade geometry.

Charge symmetric track reconstruction

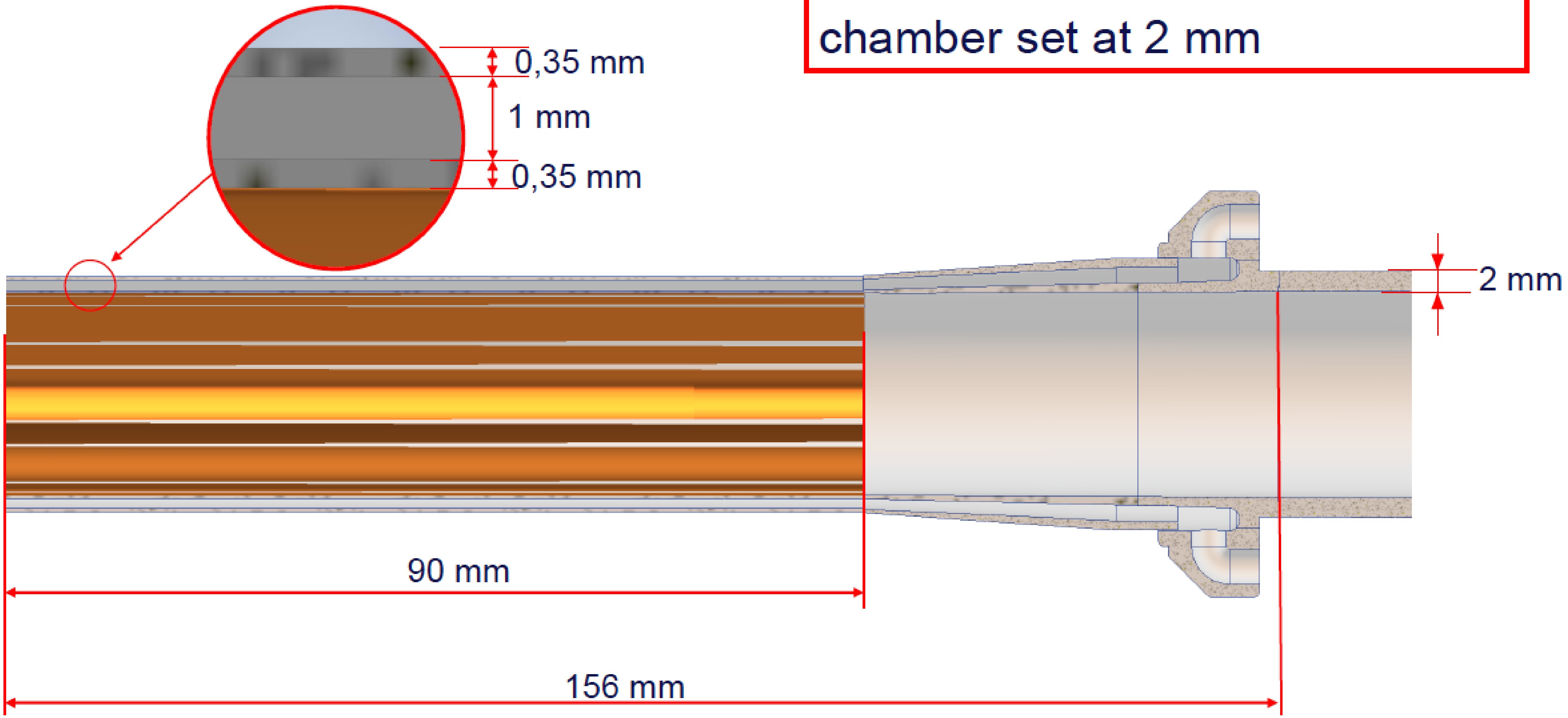
Total weight ~150 grams

Total thickness 0.25% X_0

Power budget ~77 W

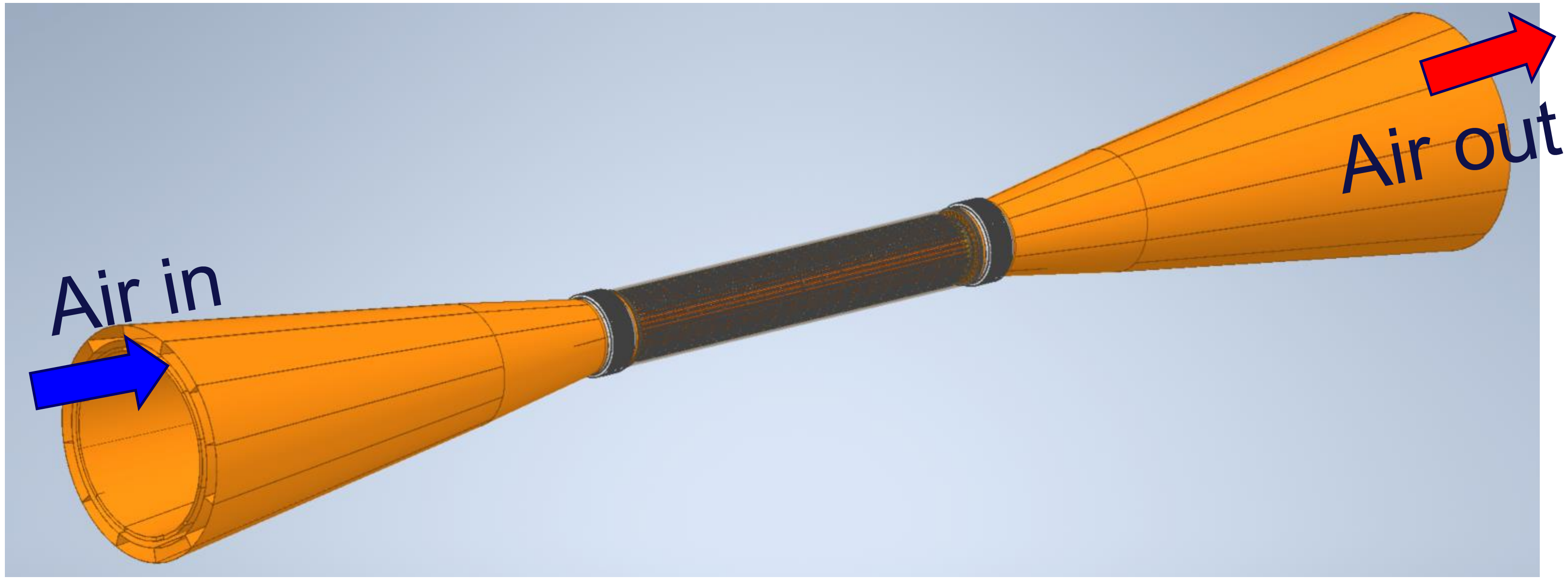
Thickness of the chamber

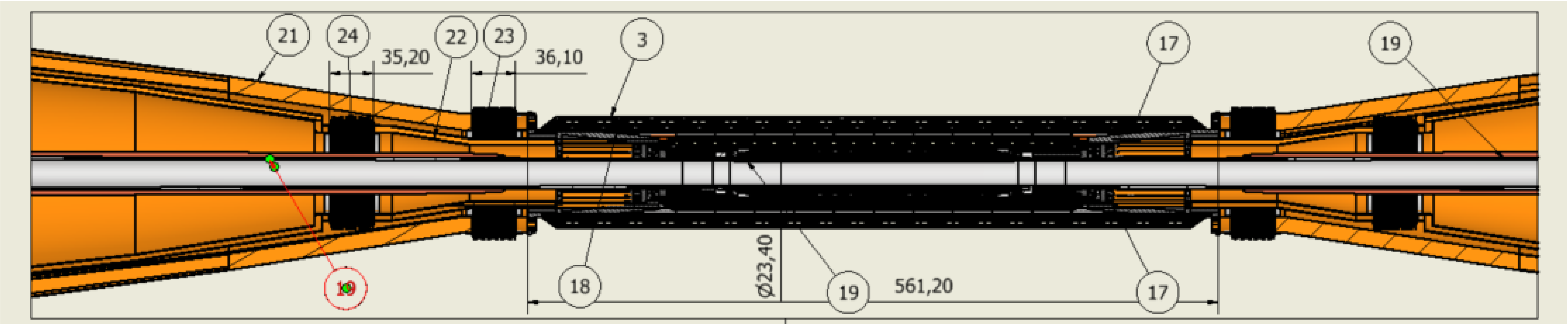
Uniform thickness of the conical chamber set at 2 mm



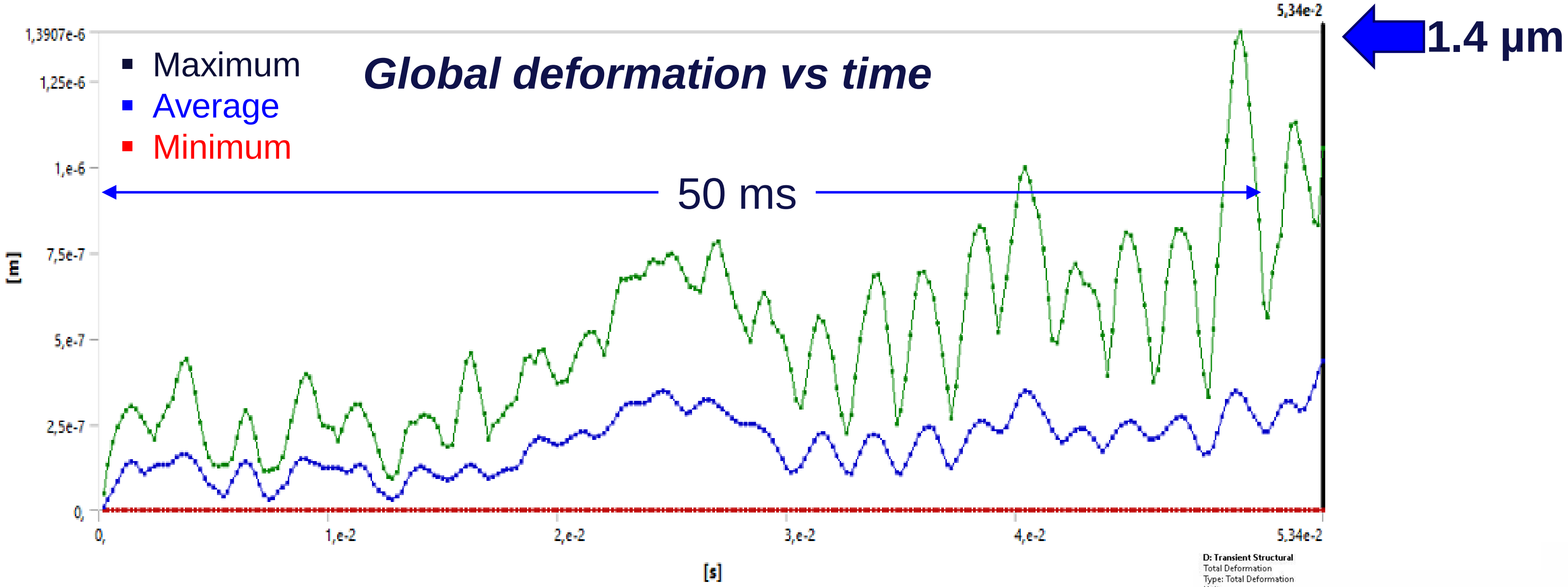
Air cooling + Cables cones

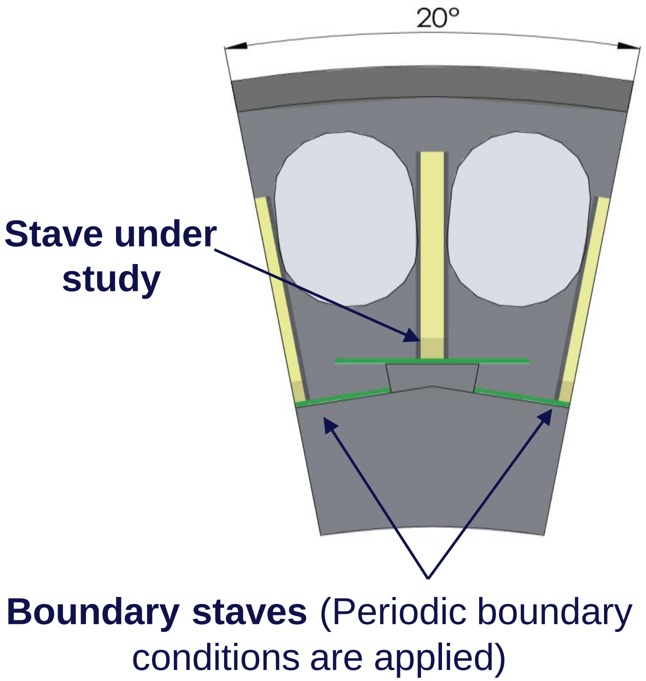
Elastically joined with bellows to the inner vertex to avoid stress.

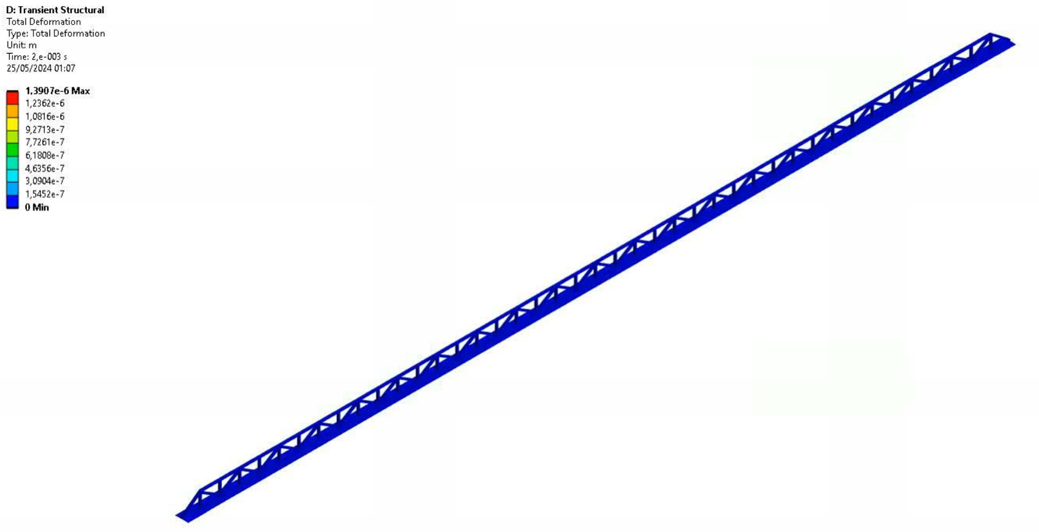




Transient mechanical analysis



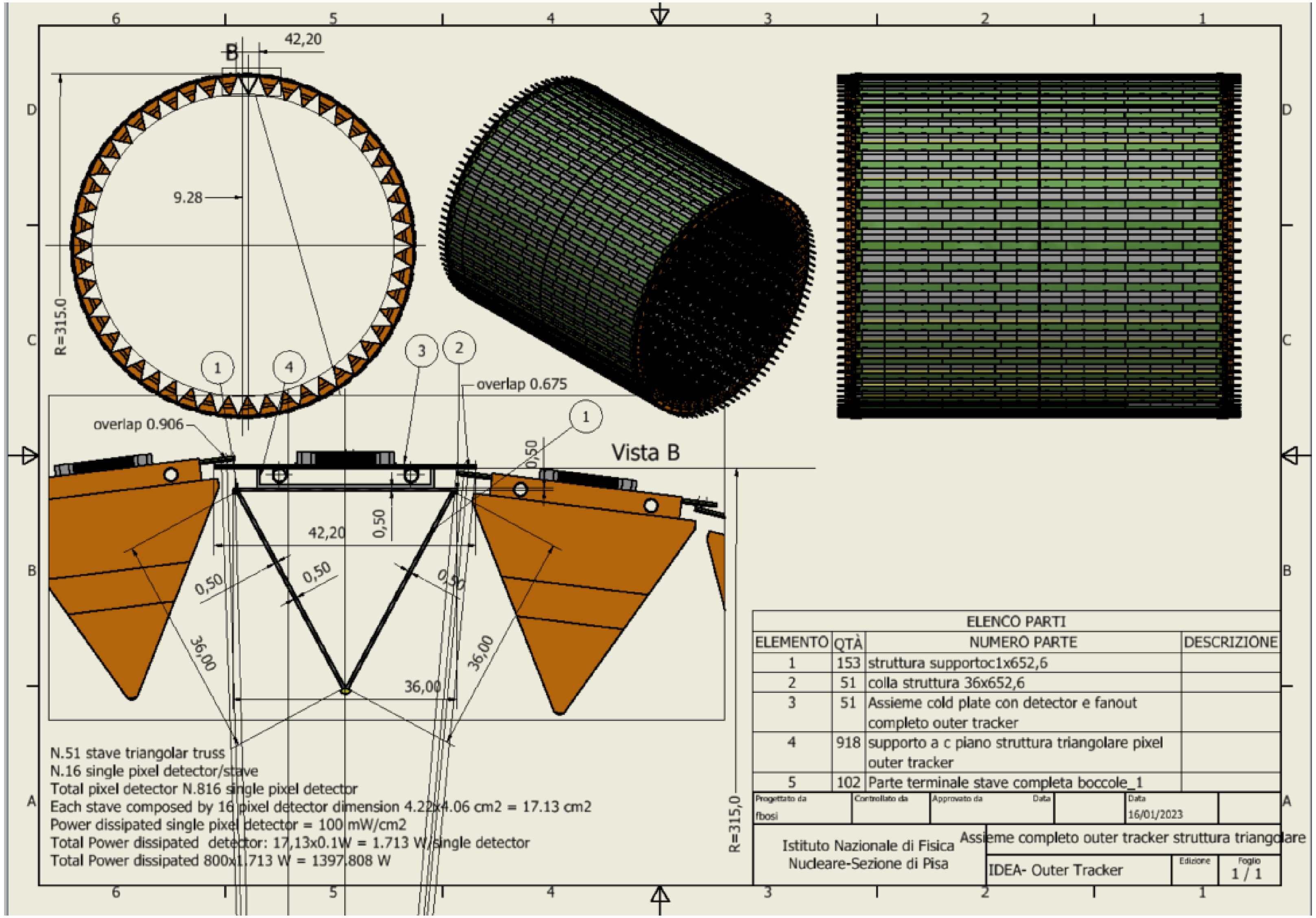




Maximum displacement ~ 1.5 μm @ v_{in} = 10 m/s due to first flapping mode – can be easily mitigated by redesign the supporting cone envelope.

More simulations ongoing changing boundary conditions.

A test setup will be made in Pisa and Perugia to validate the simulation



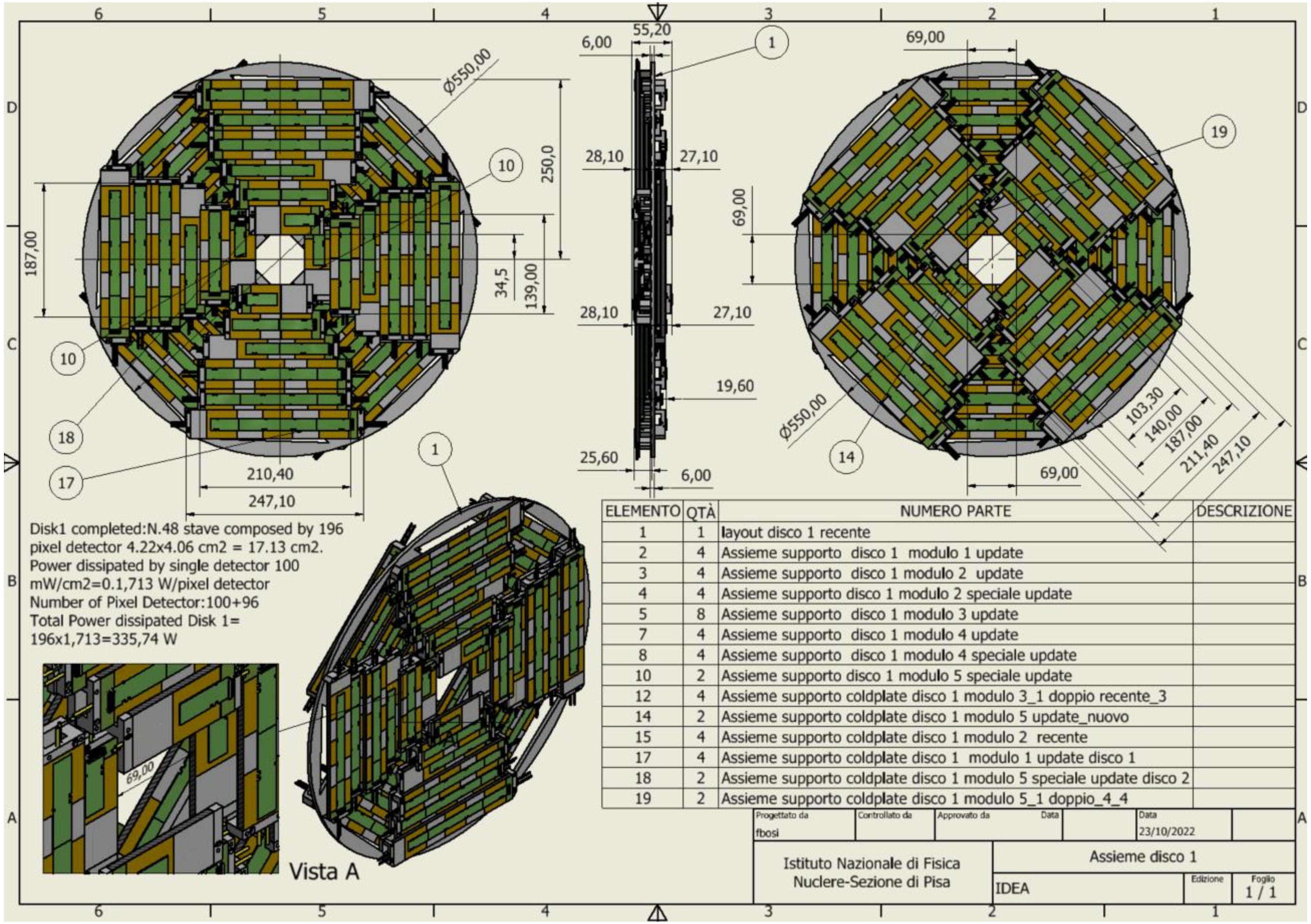
Outer Vertex Tracker Barrel
At 31.5 cm radius

51 staves of 16 modules each

Lightweight reticular support structure (ALICE/Belle-II like)

Total weight ~3.7 kg
Readout chips either side
Power budget ~1400 W

Water cooled (2 pipes of 2 mm diameter)



Outer Vertex Tracker Disk 1

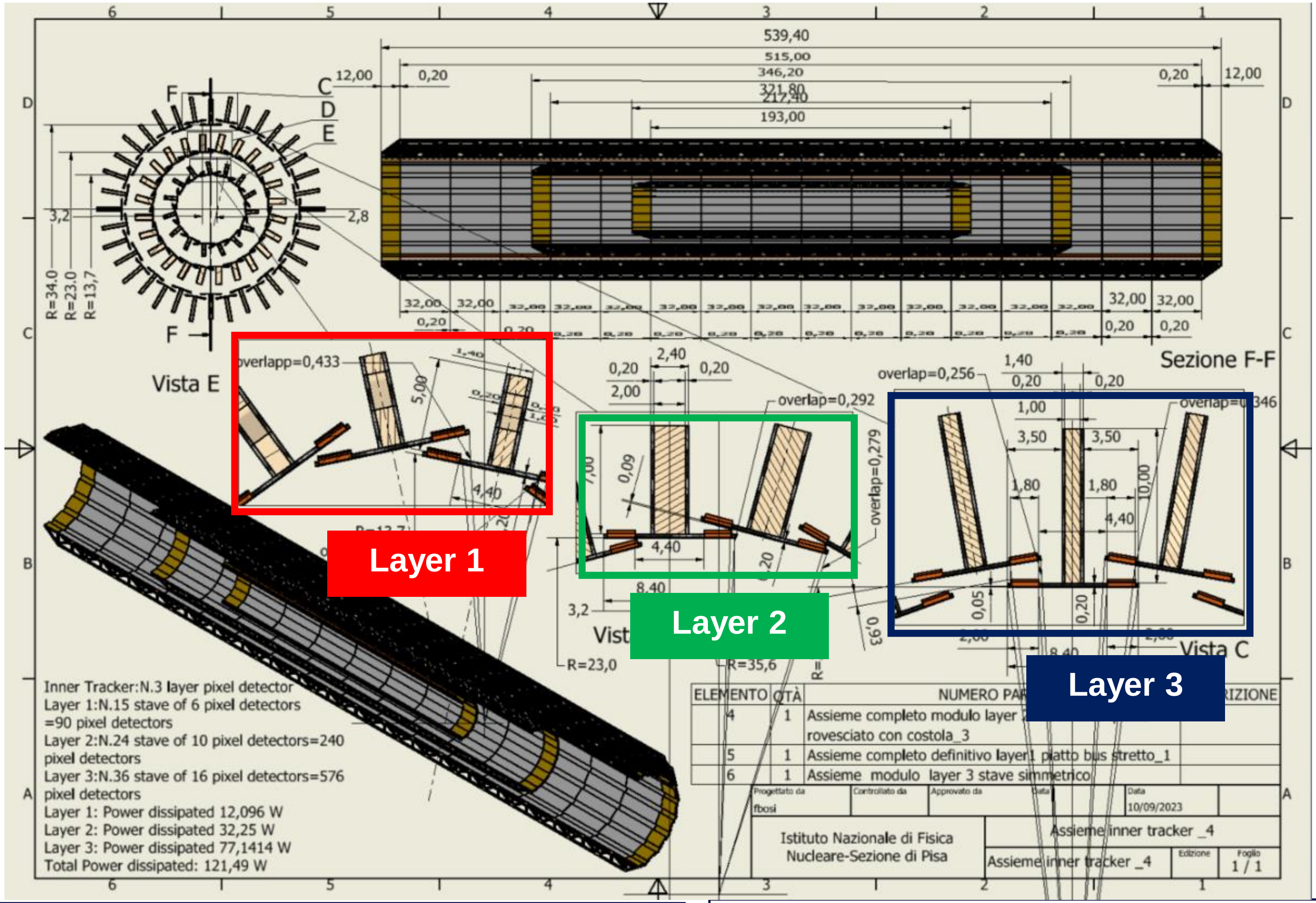
2 sides (front and back) each with 4 petals.

One petal is made of different staves of overlapping modules

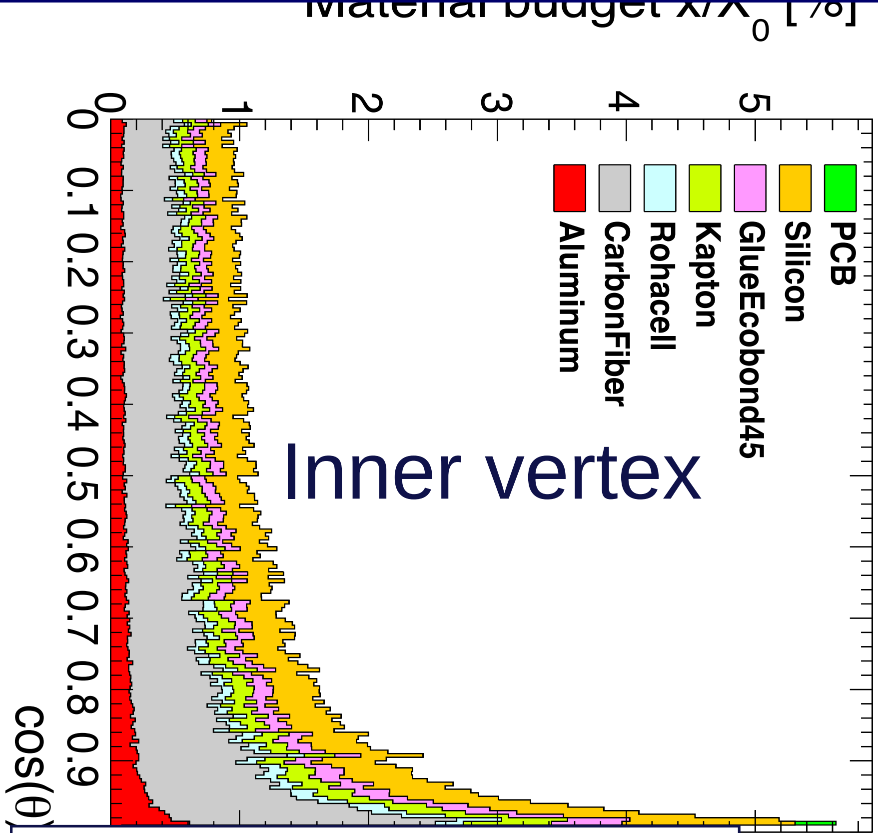
Total modules per disk: 196
Total weight ~850 grams
Power budget ~ 336 W

Cooling using 1 water pipe (2 mm diameter)

Similar geometry for the other two disks



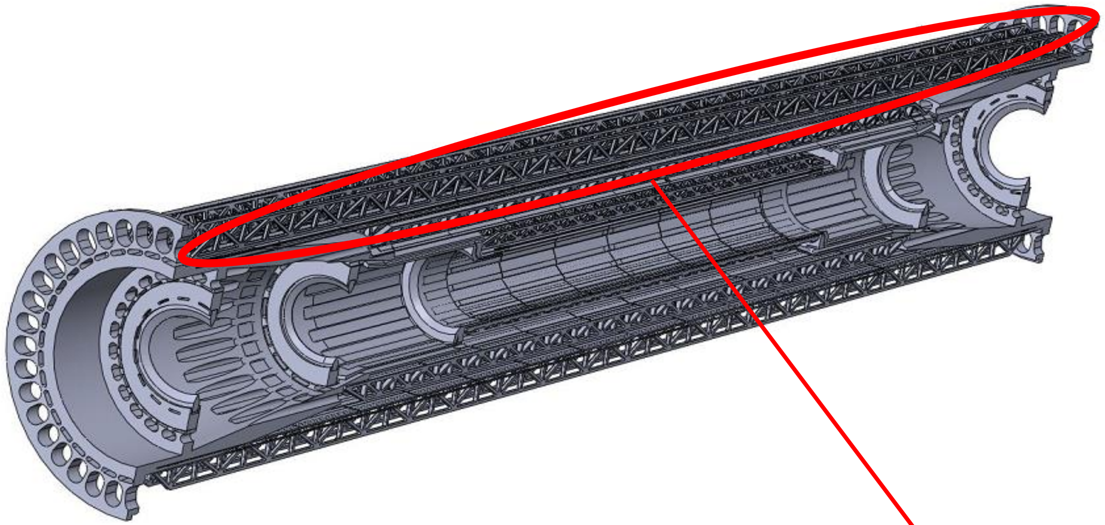
Total thickness 0.25% X_0 *per layer*
- *Silicon: 0.053% X_0,*
- *Power and readout bus: 0.056% X_0*



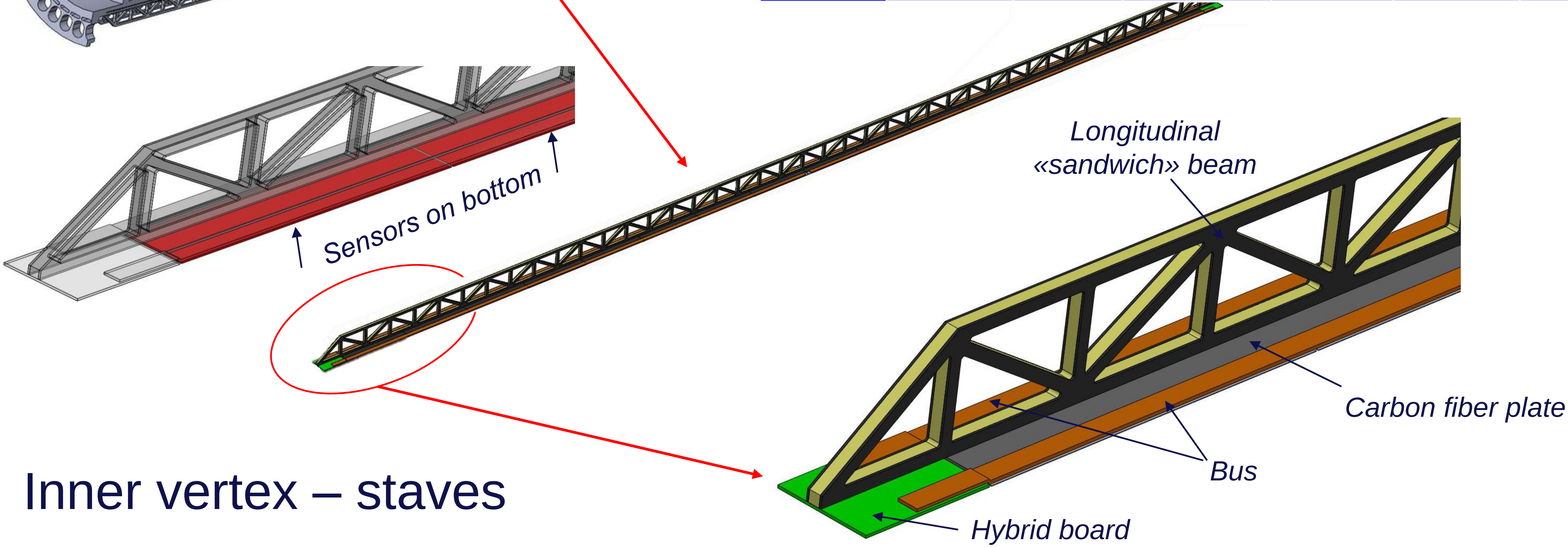
Layer 1
- Overlap to allow alignment ~500 µm
- Pinwheel geometry
- Total weight ~22 grams
- *Power 12 Watt*

Layer 2
- Pinwheel geometry
- Counter-rotated wrt layer 1
- Total weight ~63 grams
- *Power 32 Watt*

Layer 3
- Lampshade geometry.
- Total weight ~150 grams
- *Power 77 Watt*



Layer #	Radius [mm]	No staves	No modules /stave	Total Length [mm]	Active Area [cm^2]	Power [W]
1	**13.7**	**15**	**6**	**217.40**	**241.92**	**12**
2	**23.7**	**24**	**10**	**346.20**	**645.12**	**32**
3	**34 & 35.60**	**36**	**16**	**539.40**	**1548.29**	**77**



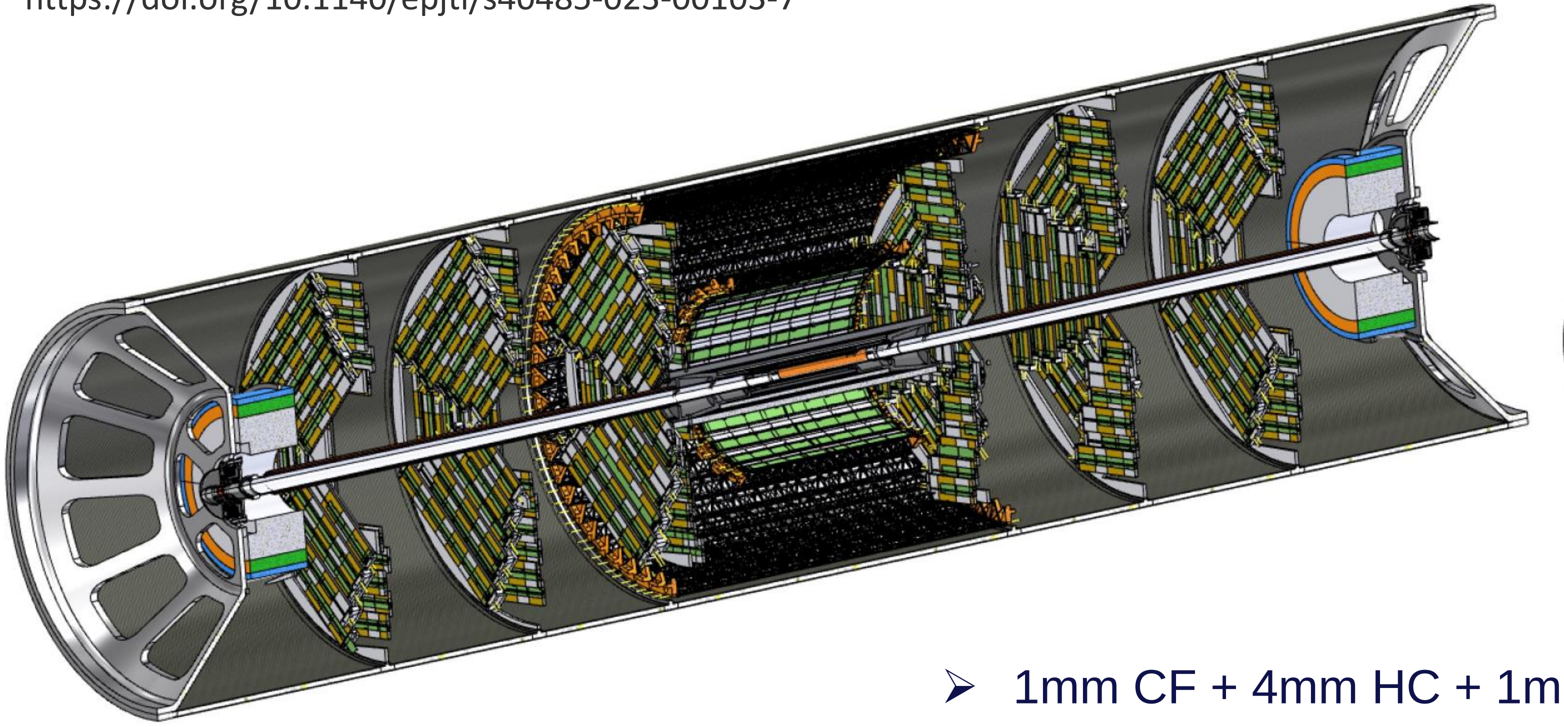
Inner vertex – staves

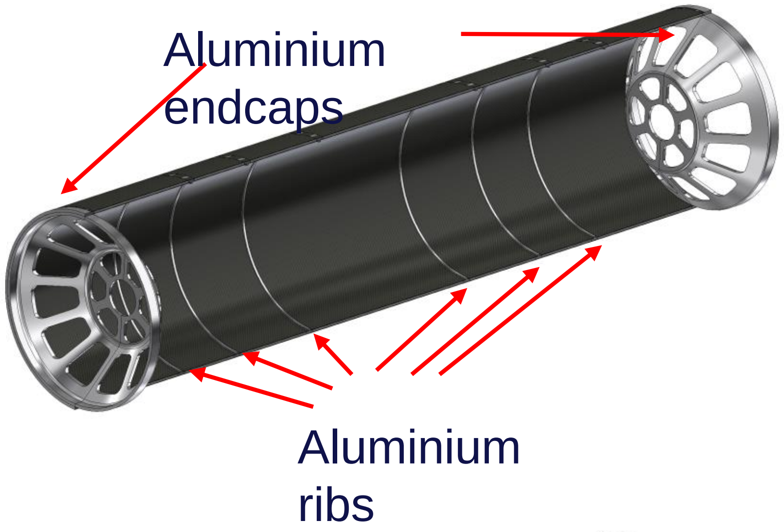
Support cylinder

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

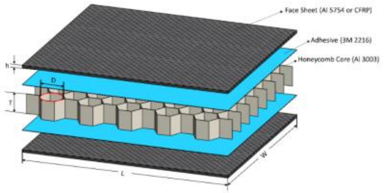
- Once the structure is assembled it is slided inside the rest of the detector

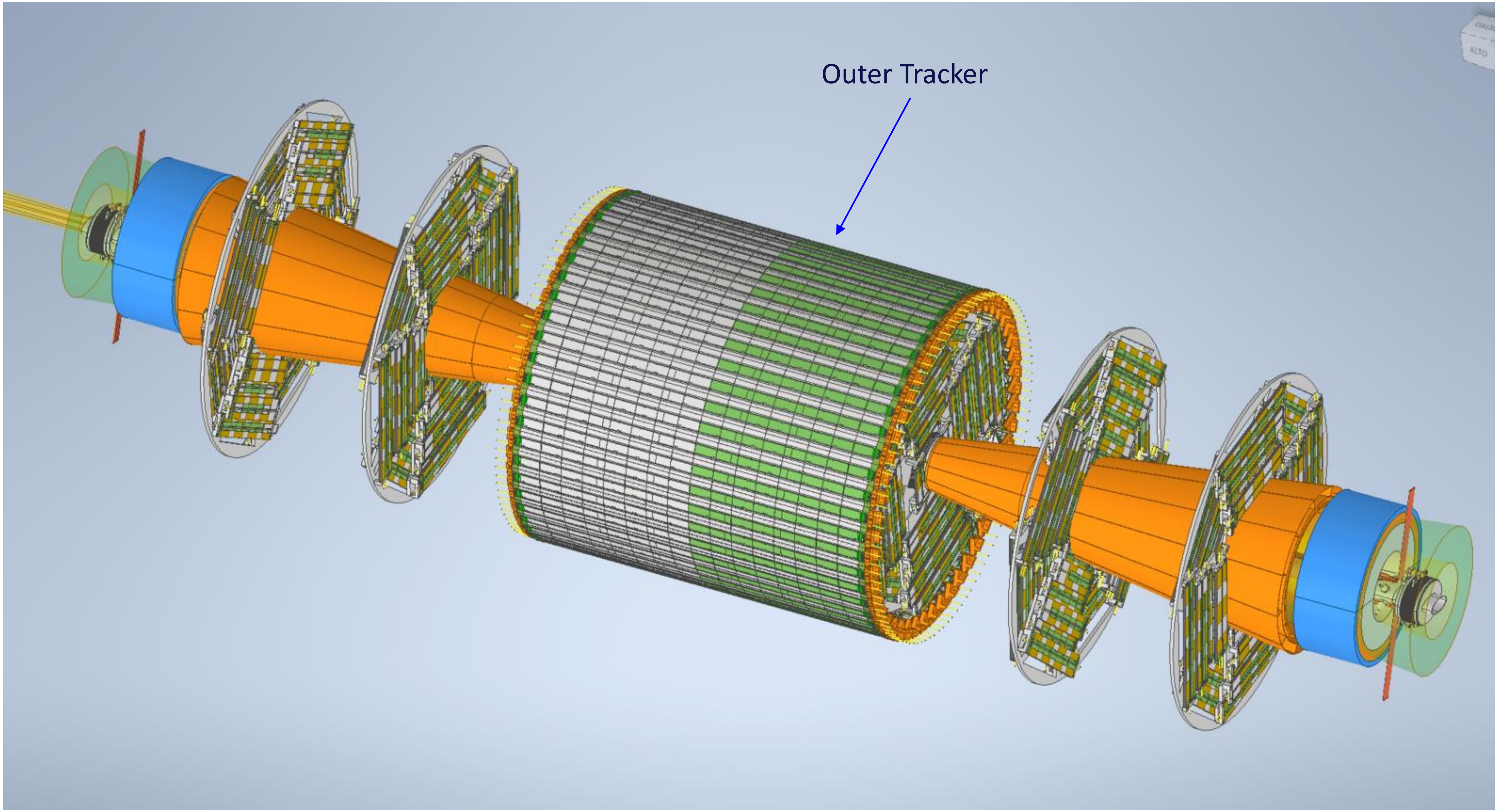
M. Boscolo, F. Palla, F. Fransesini, F. Bosi and S. Lauciani, Mechanical model for the FCC-ee MDI, *EPJ Techn Instrum* **10**, 16 (2023). https://doi.org/10.1140/epjti/s40485-023-00103-7

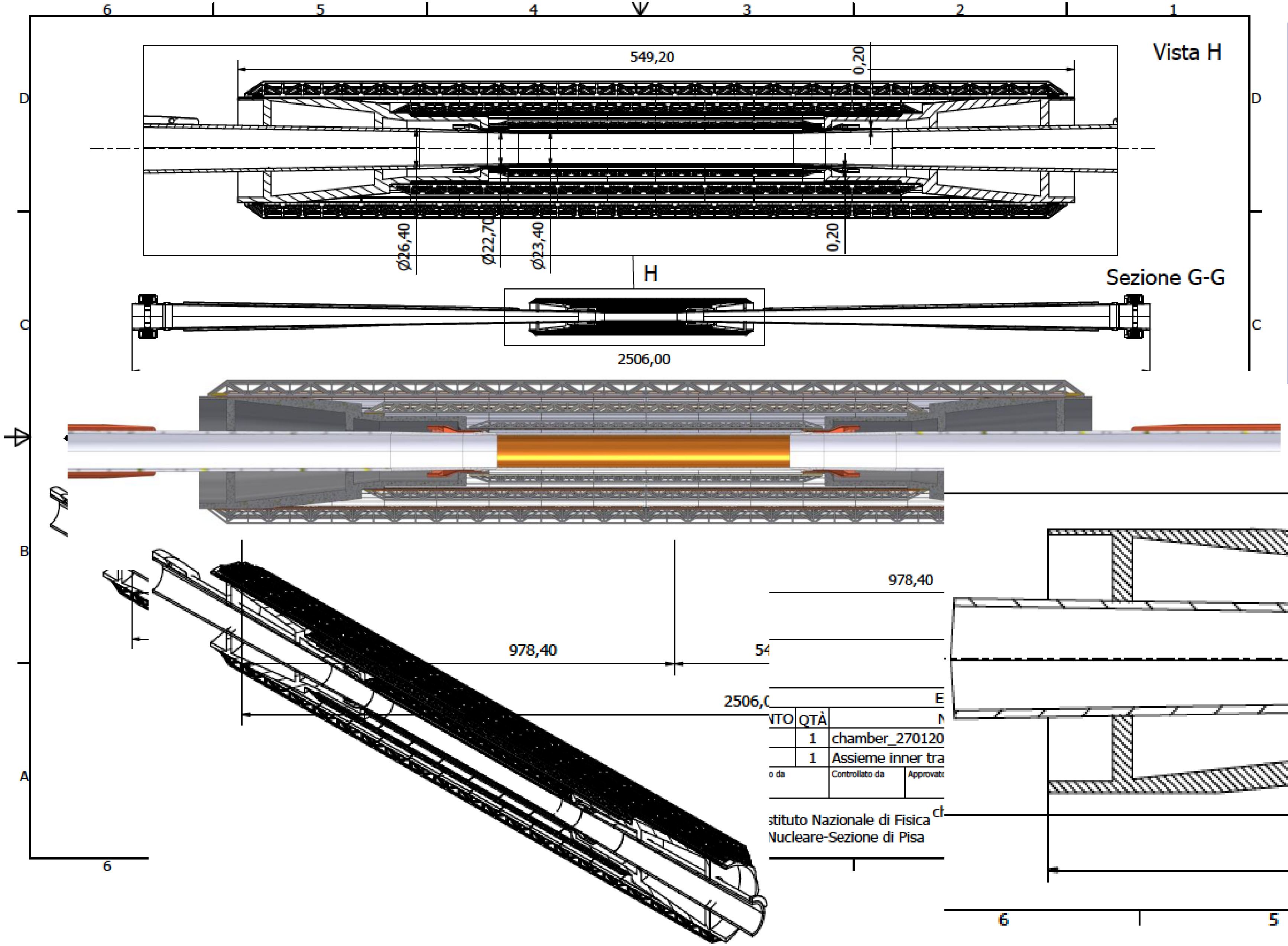




- 1mm CF + 4mm HC + 1mm CF

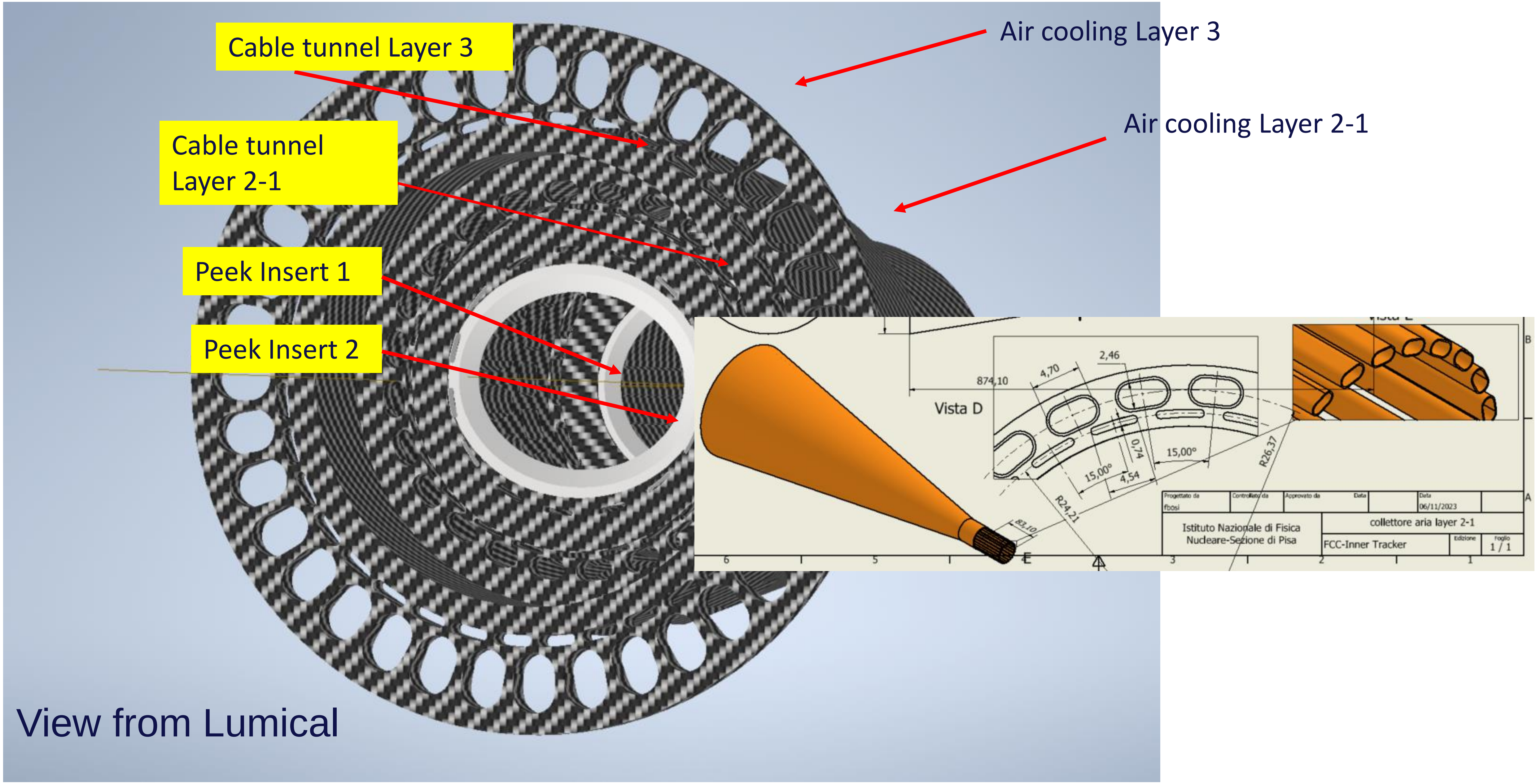



Outer Tracker

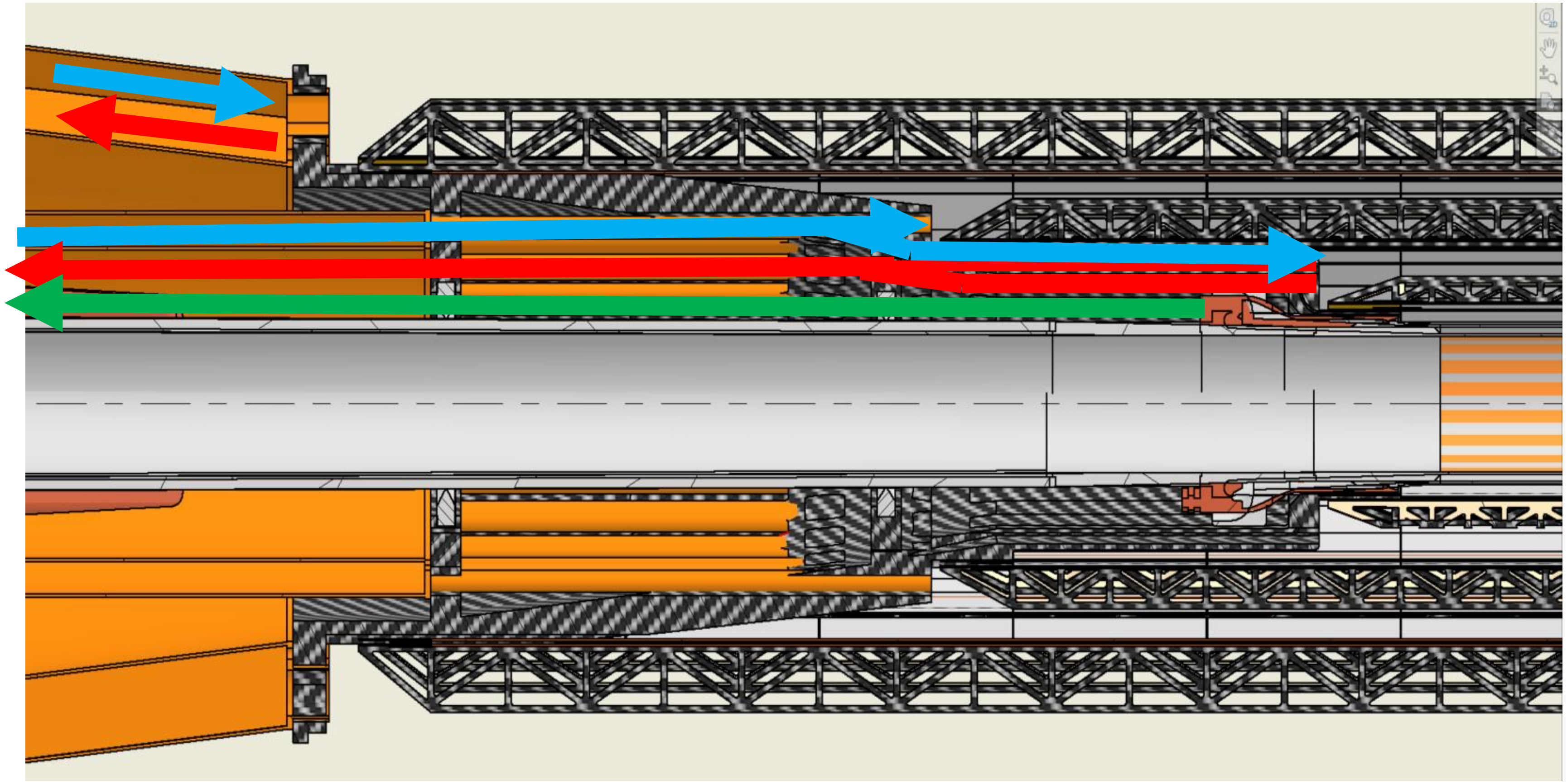


Inner vertex detector supporting conical structures on elliptical chamber
~450 grams

Engineered for air ducts and thermal isolation from the beam pipe during bakeout


Cable tunnel Layer 3
Cable tunnel Layer 2-1
Peek Insert 1
Peek Insert 2
Air cooling Layer 3
Air cooling Layer 2-1
View from Lumical
Vista D
874,10
4,70
2,46
0,74
15,00°
15,00°
4,54
R26,37
R24,21
06/11/2023
Istituto Nazionale di Fisica Nucleare-Sezione di Pisa
collettore aria layer 2-1
FCC-Inner Tracker

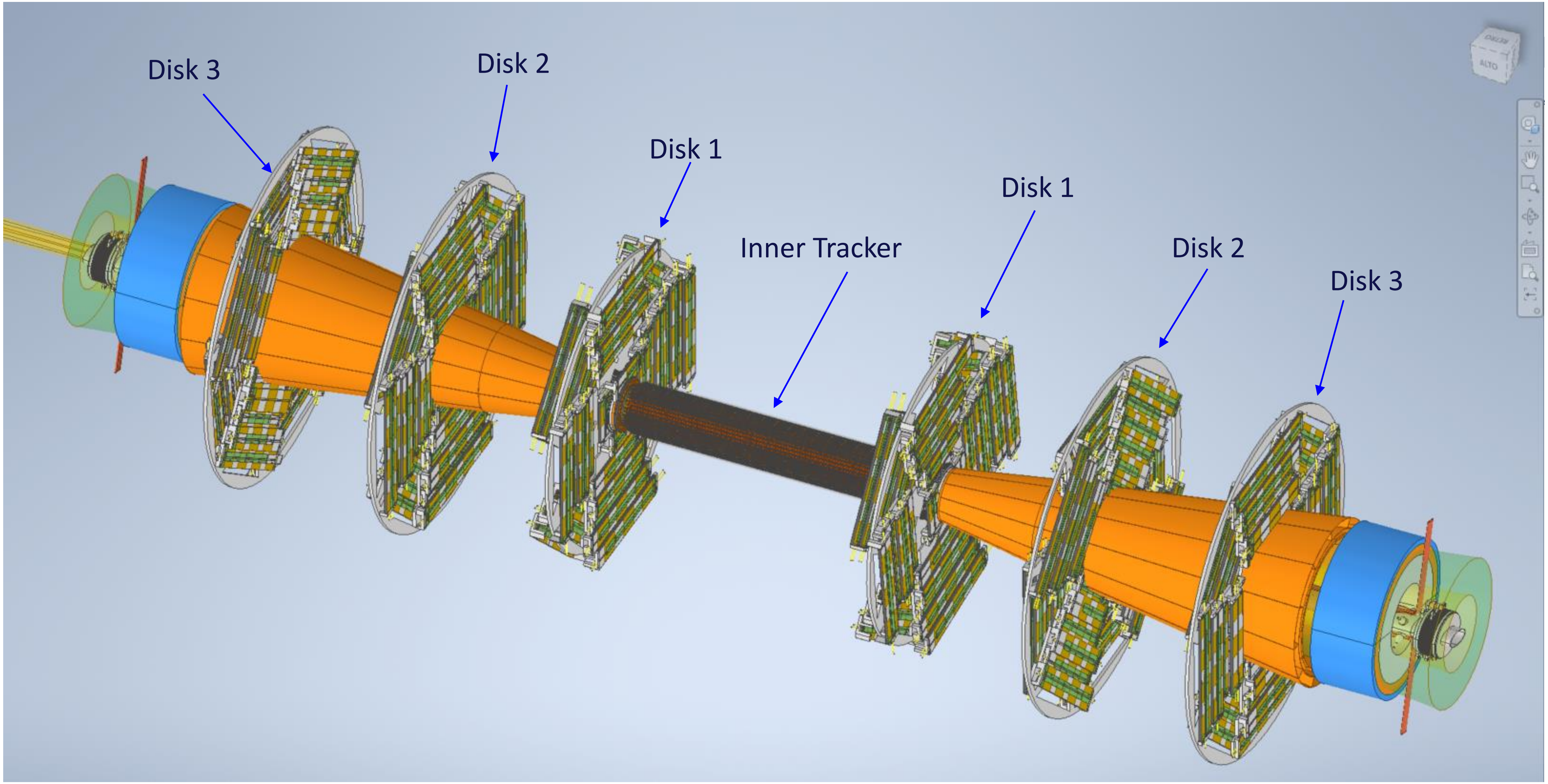
Integration with beam pipe cooling manifold

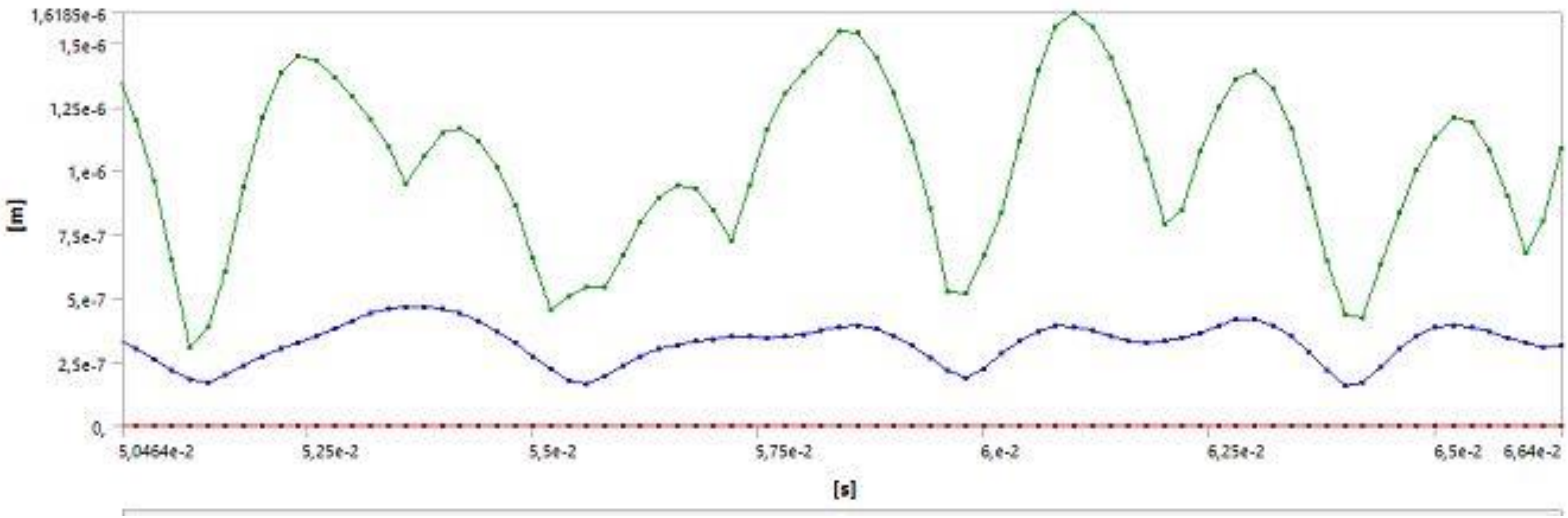


Air Cooling

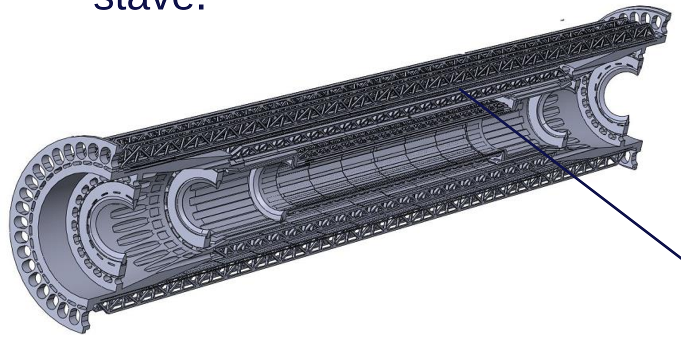
Cooling pipe paraffin

Cables


Disk 3
Disk 2
Disk 1
Inner Tracker
Disk 1
Disk 2
Disk 3


1,6185e-6
1,5e-6
1,25e-6
1,e-6
7,5e-7
5,e-7
2,5e-7
0,
[m]
5,0464e-2
5,25e-2
5,5e-2
5,75e-2
6,e-2
6,25e-2
6,5e-2
6,64e-2
[s]

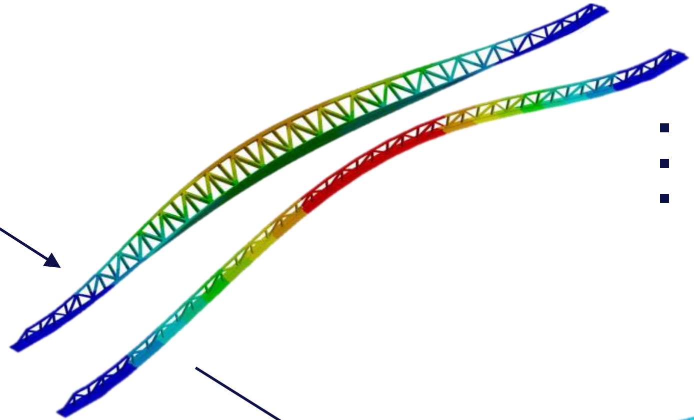
- Define a tool to evaluate whether the air flow necessary to remove the heat generates excessive vibrations on the stave.



CAD Model

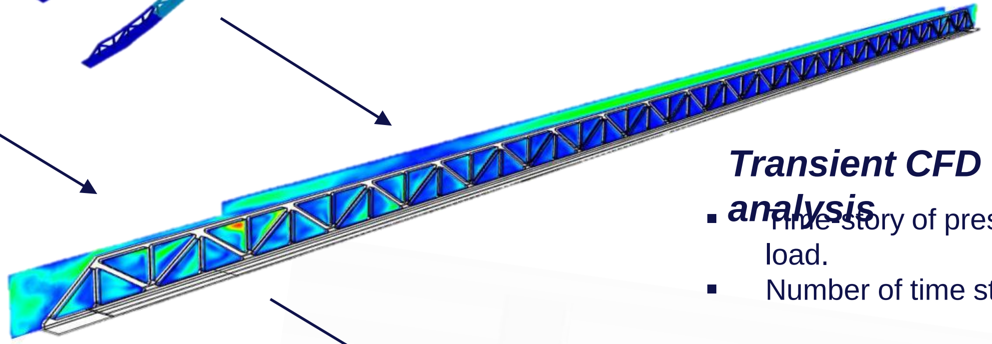
Geometry simplification

- Extraction of the single stave
- Layer 3 stave (max lenght)



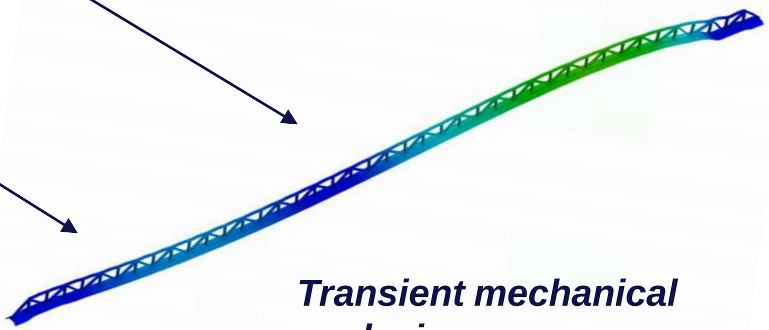
Modal analysis

- Participation factors.
- Natural frequencies.
- Duration of time step.



Transient CFD analysis

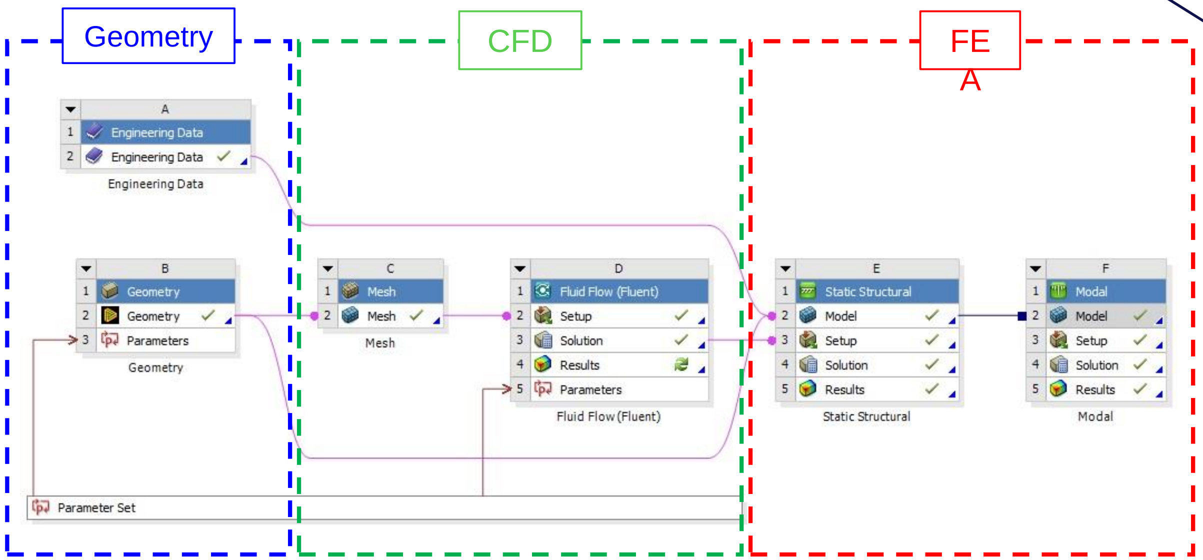
- Time-story of pressure load.
- Number of time steps.



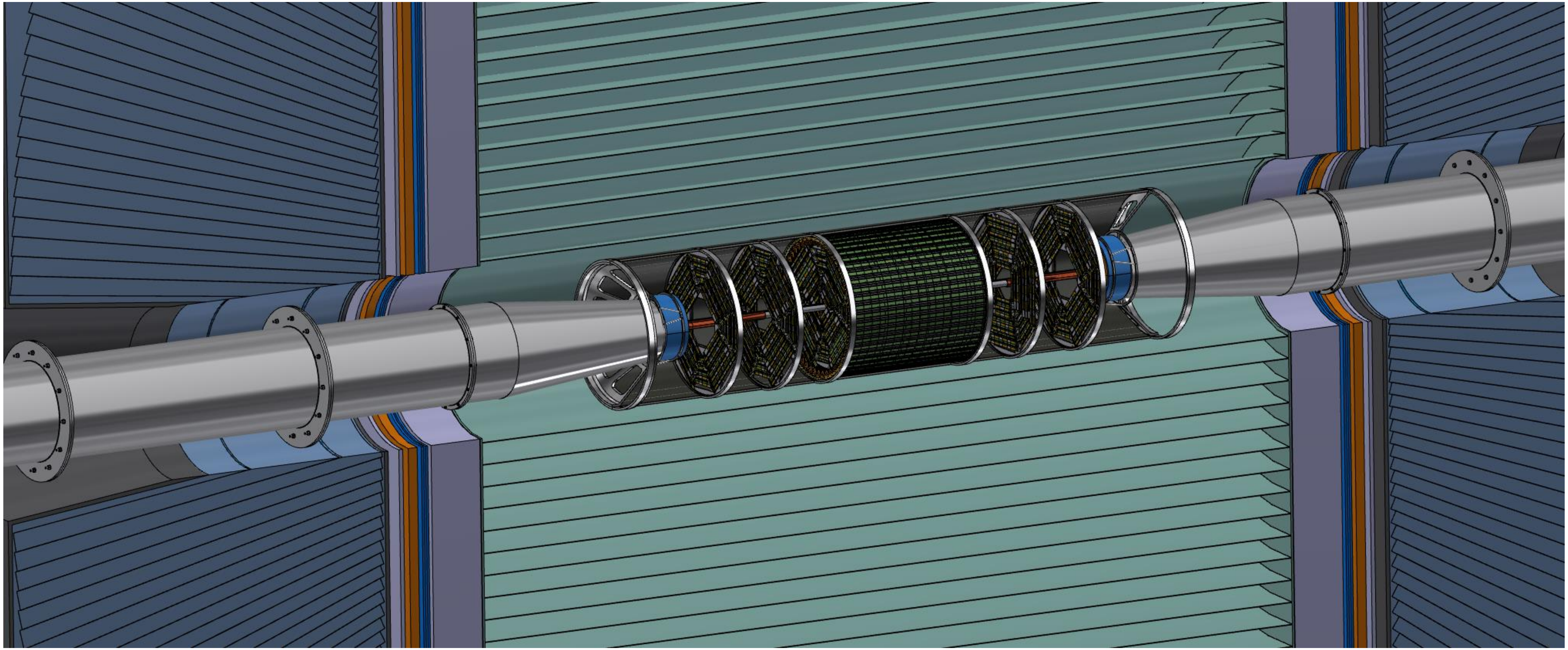
Transient mechanical analysis

- Dynamic displacement

- Flow of data managed by Ansys Workbech



General integration



ELECTRICAL UNITS

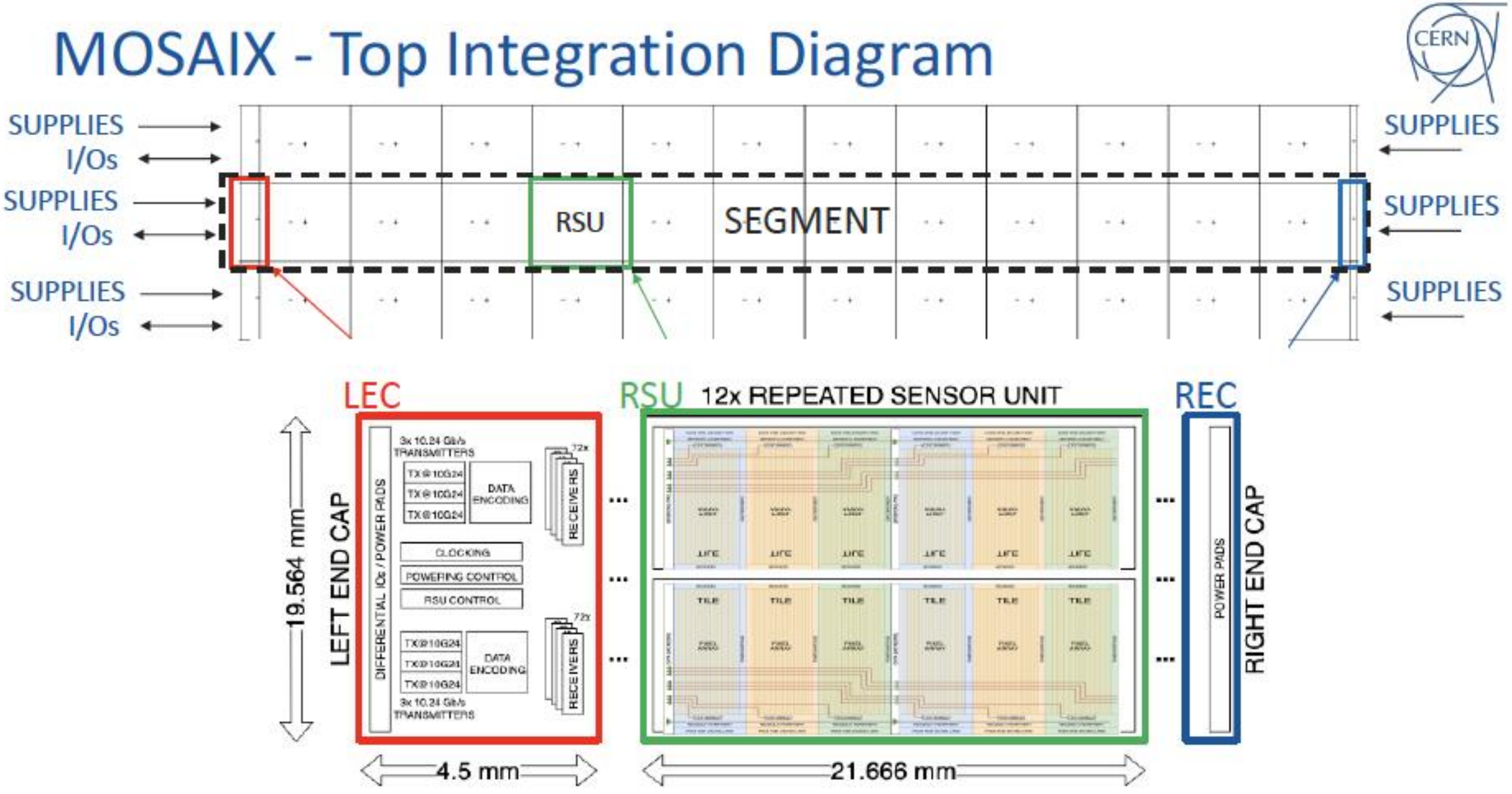
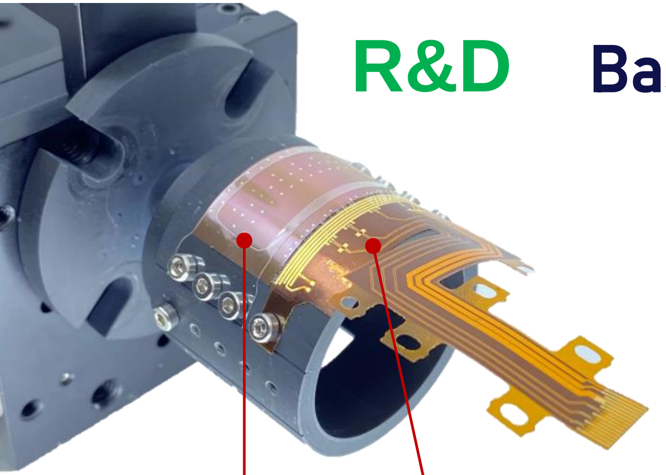


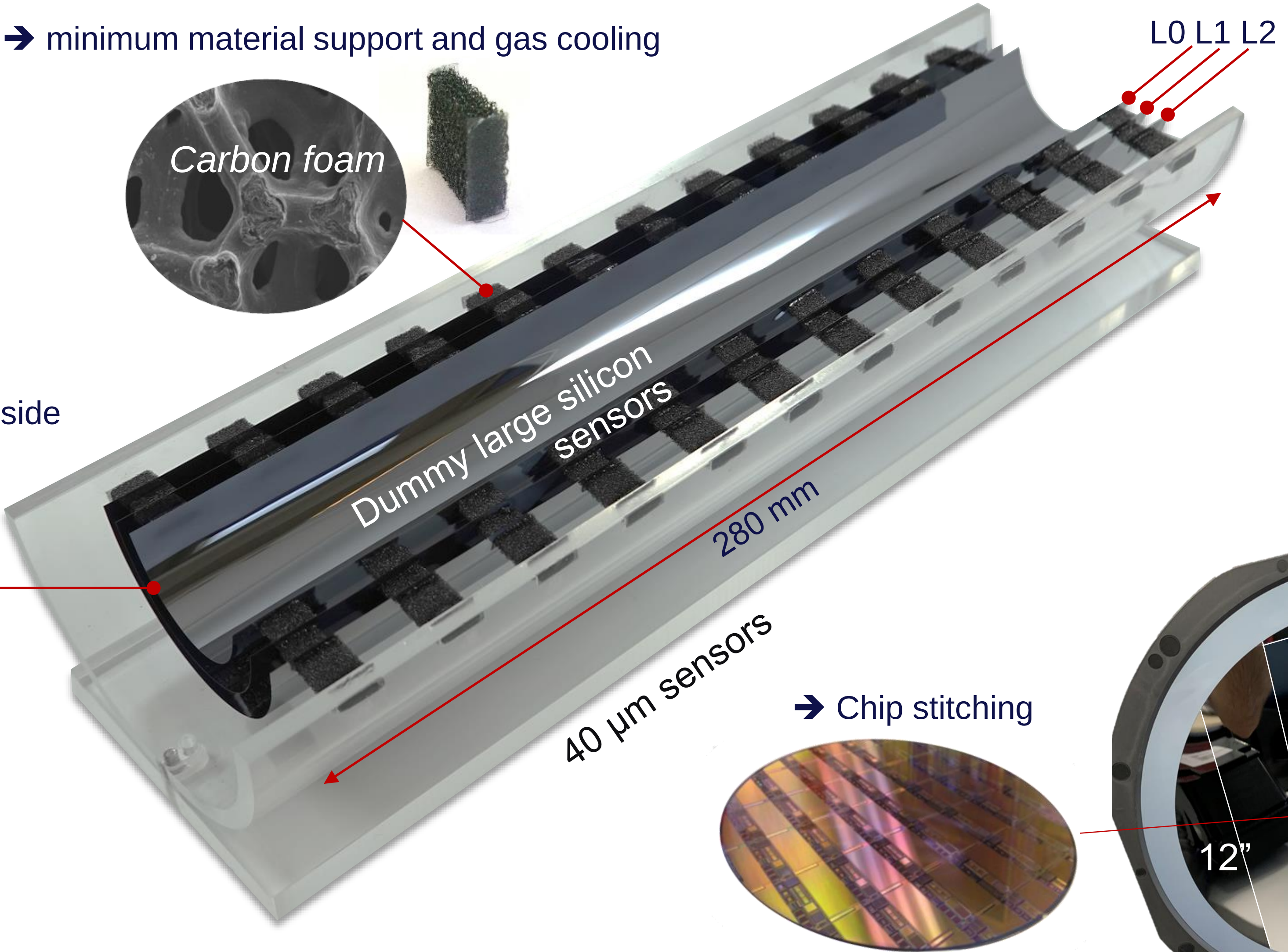
Figure 3.34: Block diagram of the sensor segment.

A column driven approach reaches higher bandwidth, but needs low power consumption

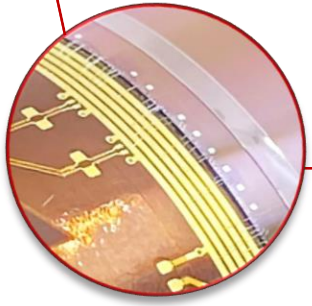
R&D Based on present effort in the design of the ITS3 (RUN4 –LS3)



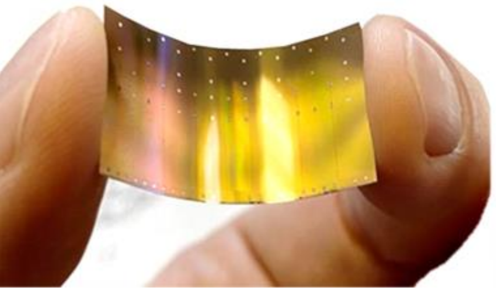
➔ minimum material support and gas cooling



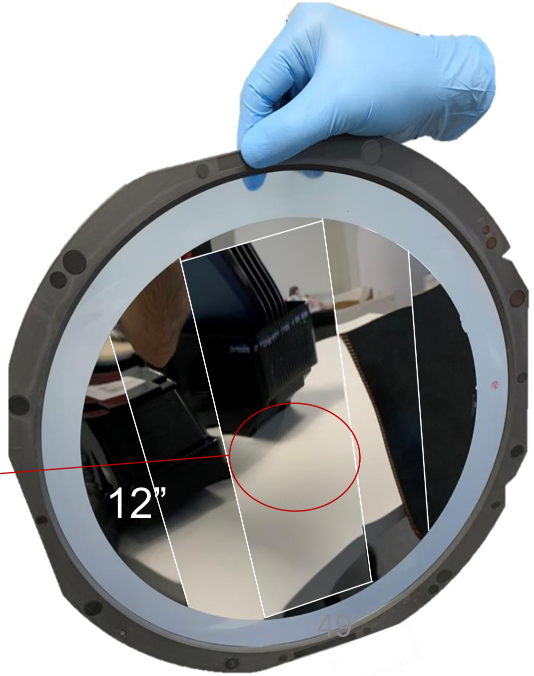
➔ Wire bonding at the edge side



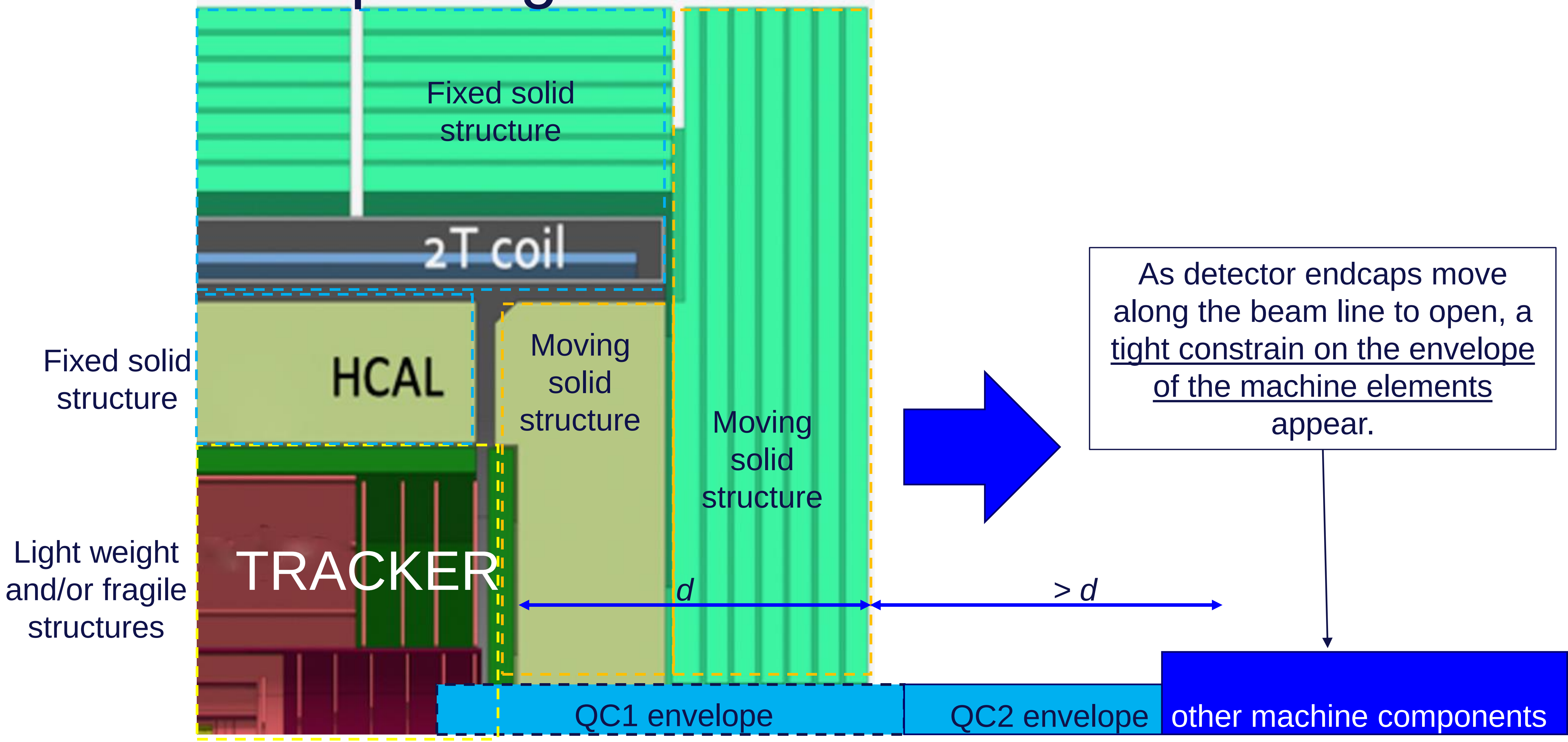
➔Curved Silicon sensors



➔ Chip stitching



Detector opening and maintenance



Courtesy A. Gaddi