FUTURE CIRCULAR COLLIDER

INFN Istituto Nazionale di Fisica Nucleare

A.D. 1308 unipg UNIVERSITÀ DEGLI STUDI DI PERUGIA

A Finite Volume Analysis for evaluating the thermal performance of an air-cooling system for the IDEA Vertex Detector at FCC-ee.

12th Forum on Tracking Detector Mechanics

Purdue CMSC, 29 - 31 May 2024

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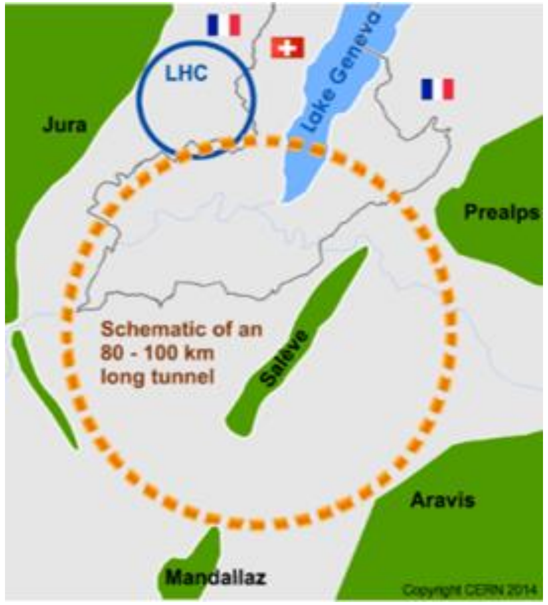
THE FUTURE CIRCULAR COLLIDER (FCC)

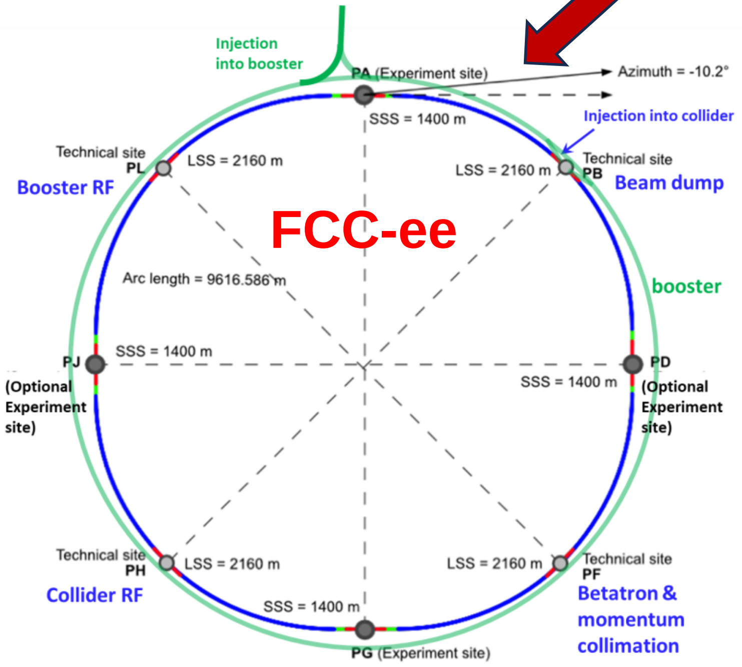
FUTURE CIRCULAR COLLIDER

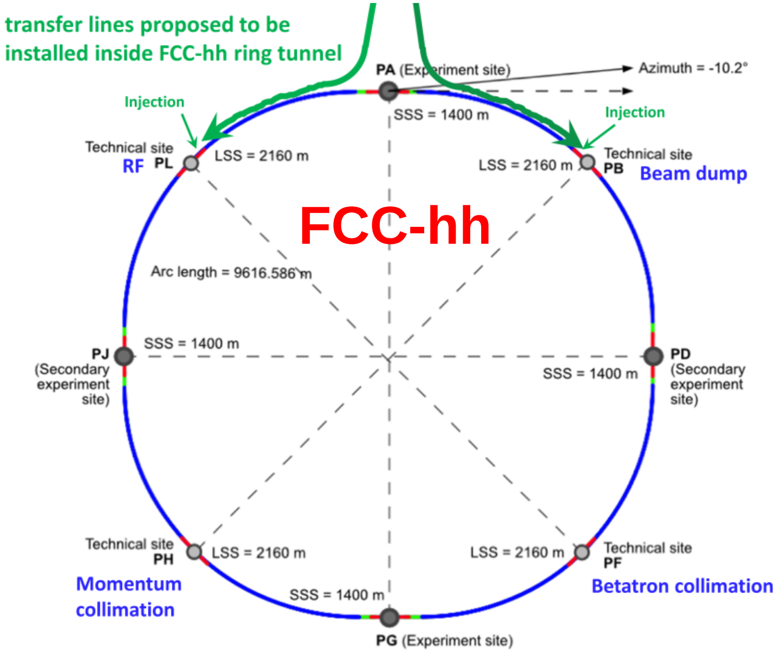
https://fcc.web.cern.ch/

- Feasibility study ongoing for a new research infrastructure at CERN to host the next generation of higher performance particle colliders.
- Will extend the research currently being conducted at LHC, once the High-Luminosity phase (HL-LHC) reaches its conclusion in around 2040.
- About 90.7 km circumference.

THE FUTURE CIRCULAR COLLIDER (FCC)







- 2040 | 2045 - 2060 | 2070 - 2095

A long-term program maximizing physics opportunities:

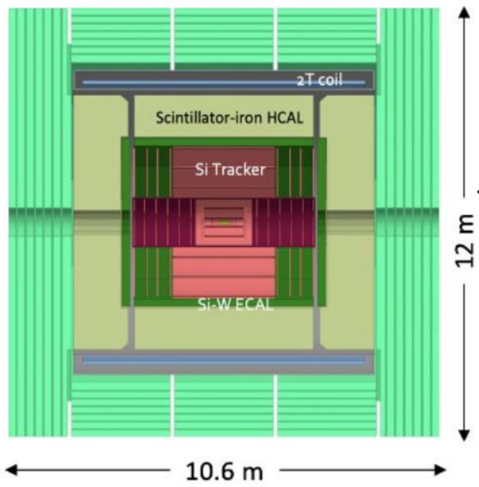
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- Highly synergetic and complementary programme boosting the physics reach of both colliders common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC

From F. Zimmermann & M. Benedikt - 7th FCC Physics Workshop

FCC-ee DETECTOR CONCEPTS

- Three detector concepts for FCC-ee:

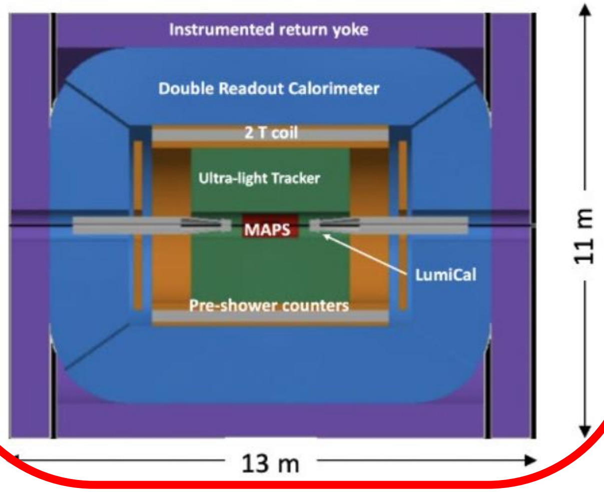
CLD



- Full Si vtx + tracker
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

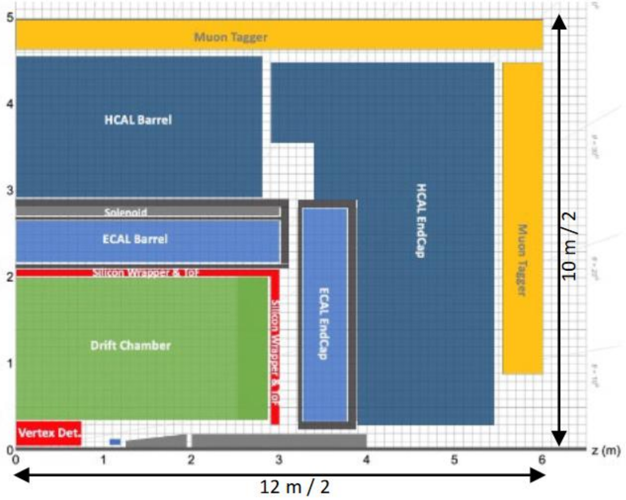
CDR

IDEA



- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO

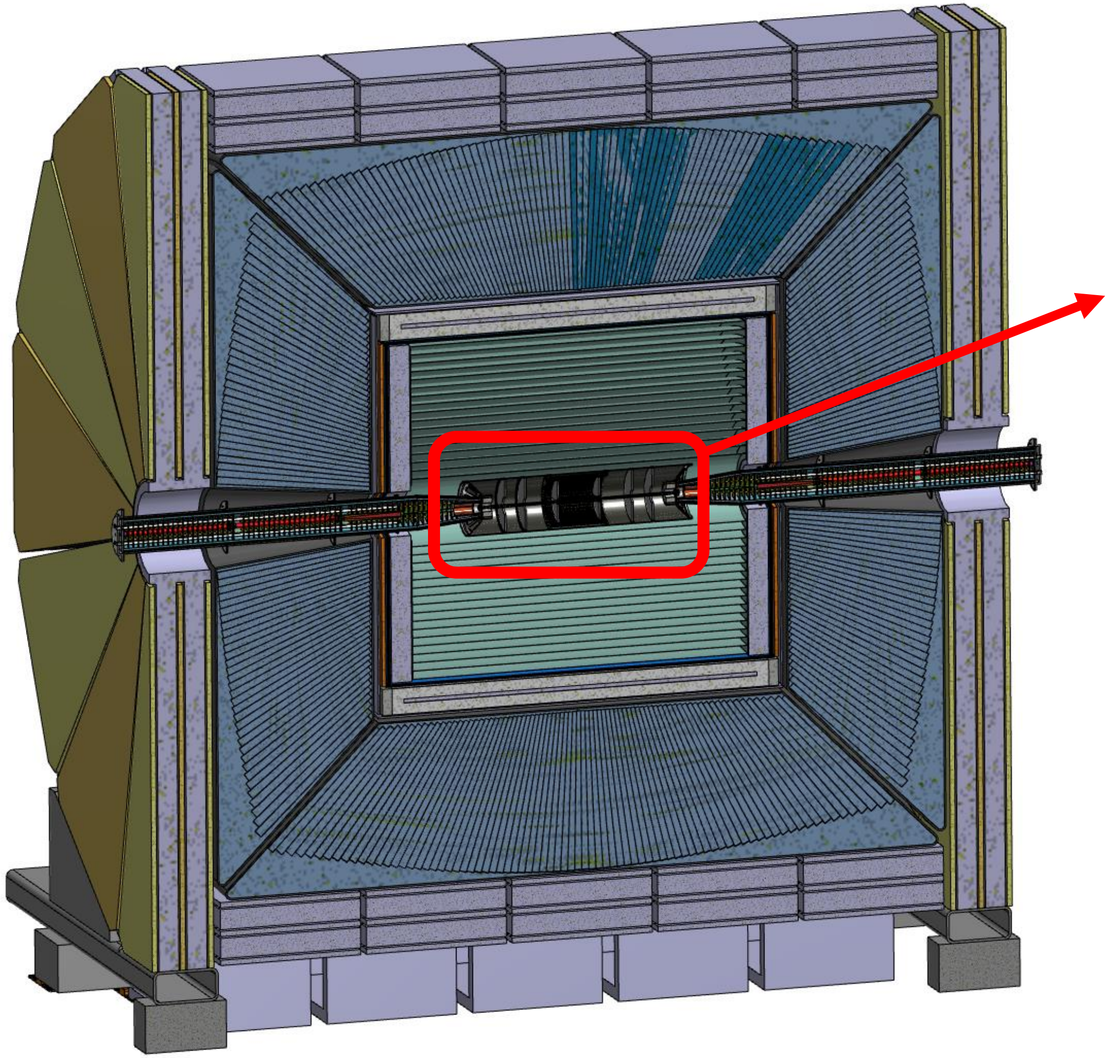


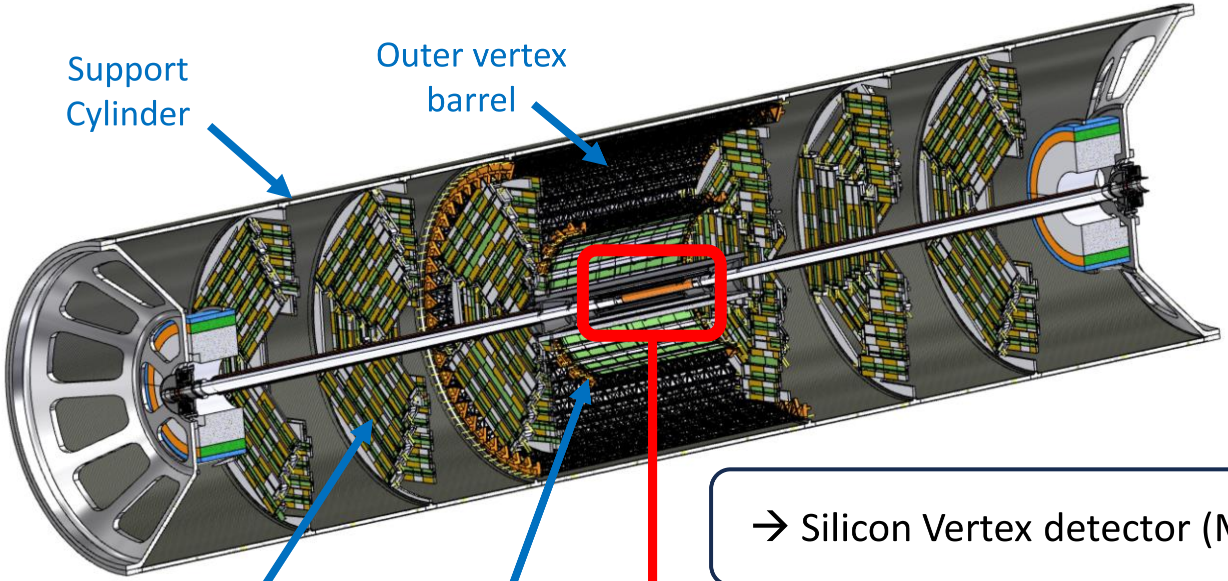
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

From M.A. Pleier - 7th FCC Physics Workshop

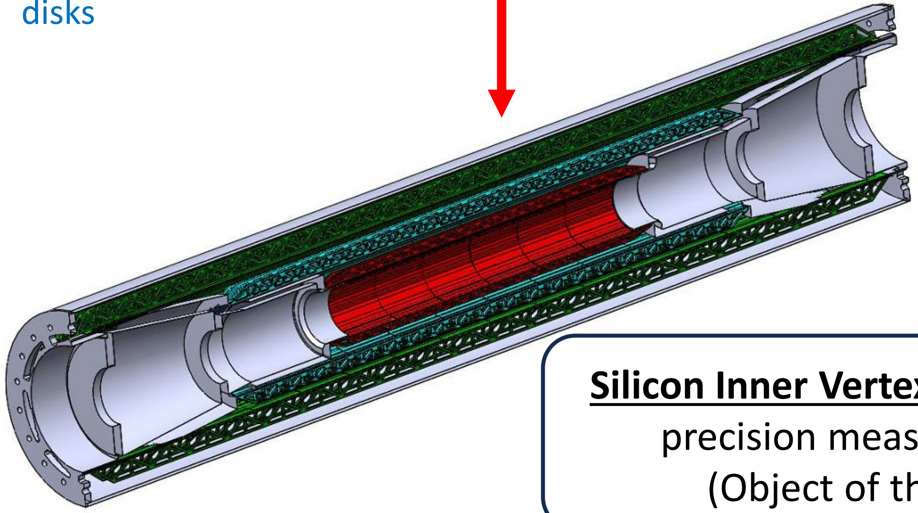
FCC-ee Conceptual Design Report: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

THE IDEA DETECTOR CONCEPT





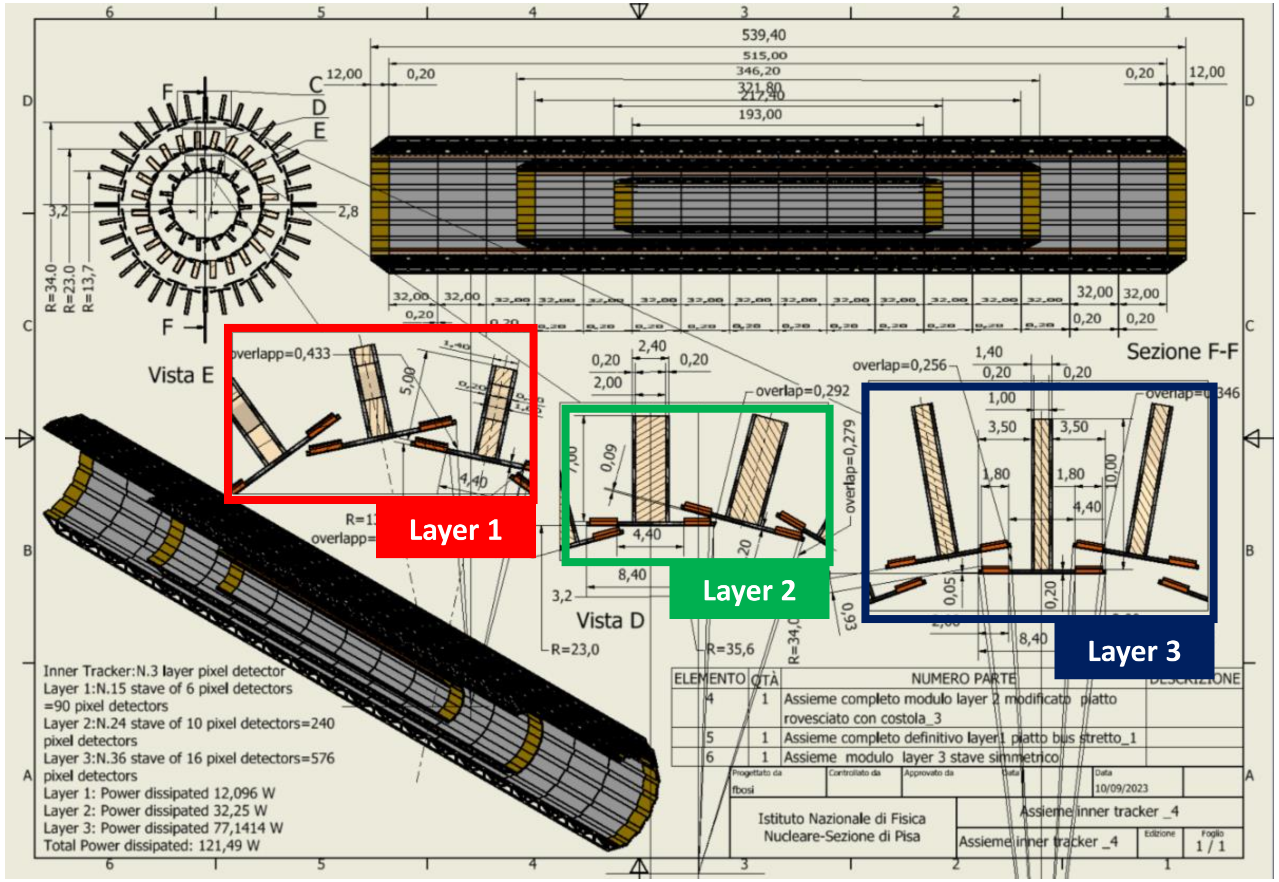
→ Silicon Vertex detector (MAPS)

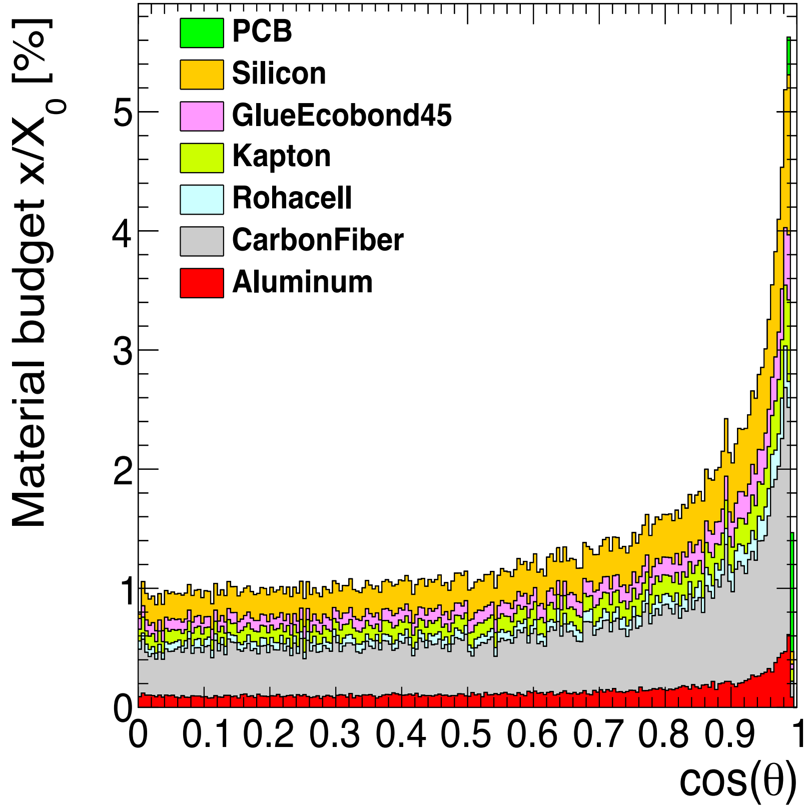


<u>Silicon Inner Vertex Detector</u> for precision measurements (Object of this talk)

For more info: *Boscolo, M., Palla, F., Bosi, F. et al. Mechanical model for the FCC-ee interaction region. EPJ Techn Instrum 10, 16 (2023).* https://doi.org/10.1140/epjti/s40485-023-00103-7

INNER VERTEX DETECTOR LAYOUT





The vertex detector innermost radius should profit of the reduced beam pipe diameter (2 cm) and should cover $|cos\theta| < 0.99$.

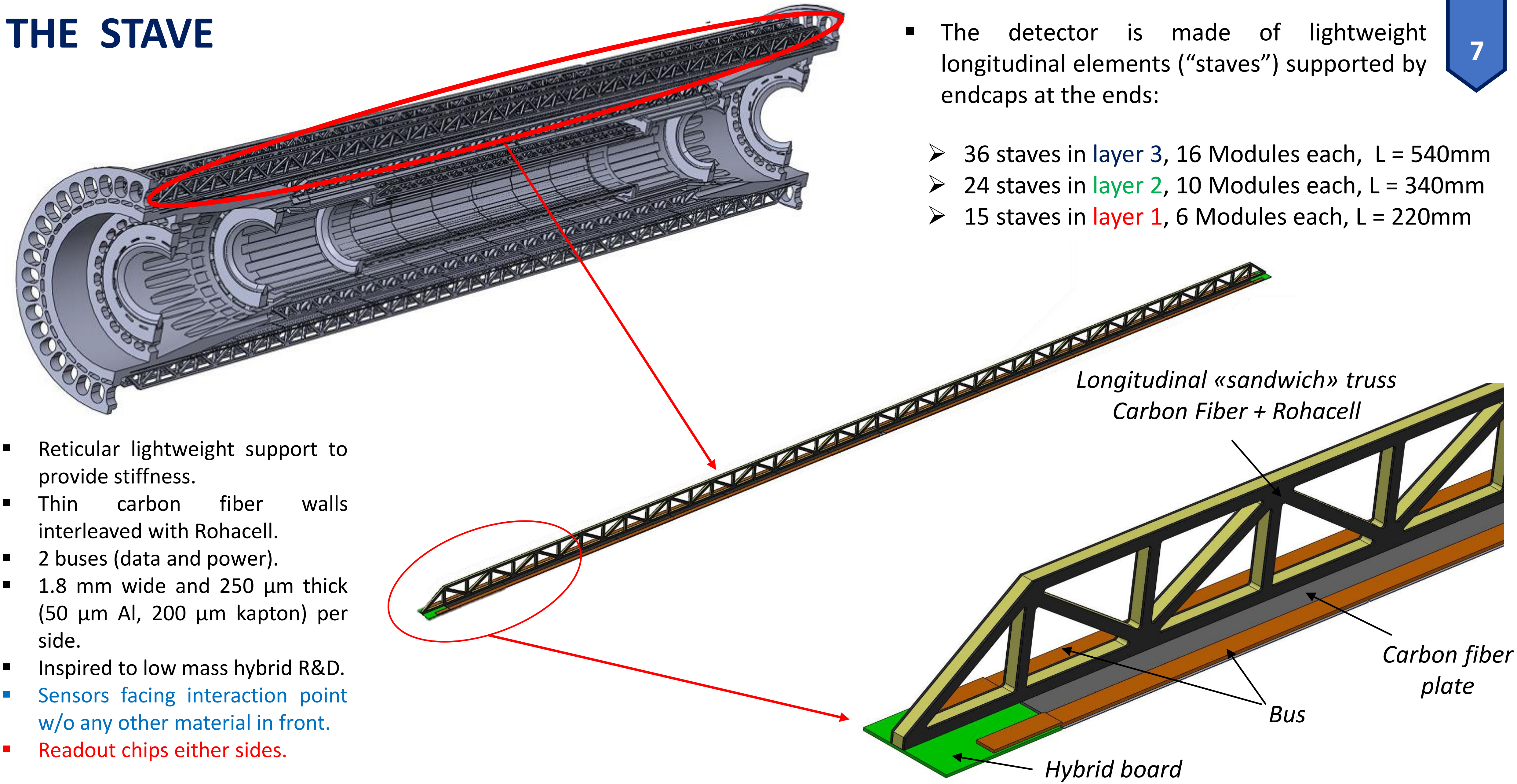
Layer 1
- Total weight ~22 grams
- Overlap to allow alignment ~500 µm
- Geometry: all modules at the same (smallest) radius
- Total thickness 0.25% X_0
  (Silicon: 0.053% X_0, Power and readout bus: 0.056% X_0)

Layer 2
- Total weight ~63 grams
- Pinwheel geometry
- Counter-rotated wrt layer 1 to mitigate charge-asymmetry effects in track reconstruction
- Total thickness 0.25% X_0

Layer 3
- Total weight ~150 grams
- Lampshade geometry.
- Charge symmetric track reconstruction.
- Total thickness 0.25% X_0

THE STAVE

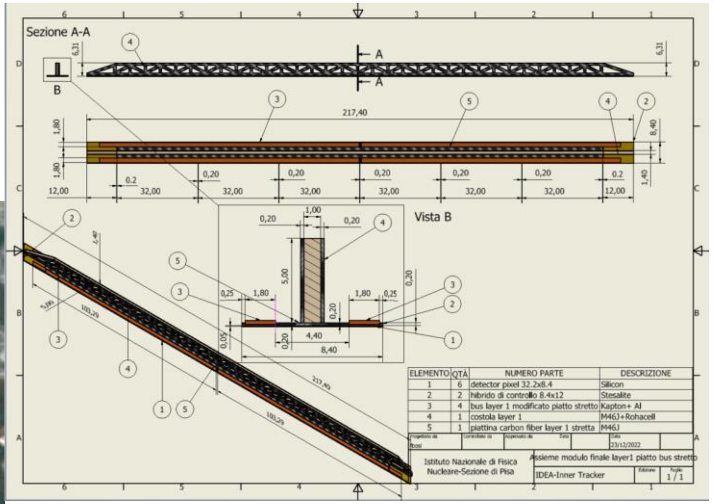
- The detector is made of lightweight longitudinal elements ("staves") supported by endcaps at the ends:
  - 36 staves in layer 3, 16 Modules each, L = 540mm
  - 24 staves in layer 2, 10 Modules each, L = 340mm
  - 15 staves in layer 1, 6 Modules each, L = 220mm



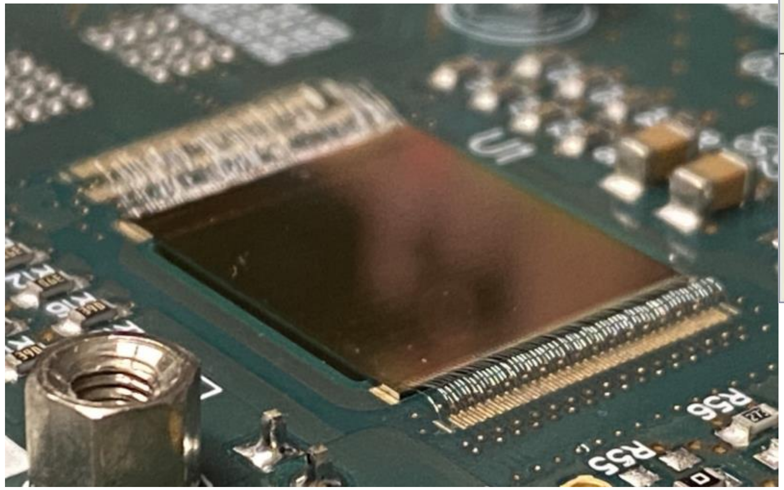
- Reticular lightweight support to provide stiffness.
- Thin carbon fiber walls interleaved with Rohacell.
- 2 buses (data and power).
- 1.8 mm wide and 250 µm thick (50 µm Al, 200 µm kapton) per side.
- Inspired to low mass hybrid R&D.
- Sensors facing interaction point w/o any other material in front.
- Readout chips either sides.

SENSORS

- Sensors are in the bottom face of each stave.

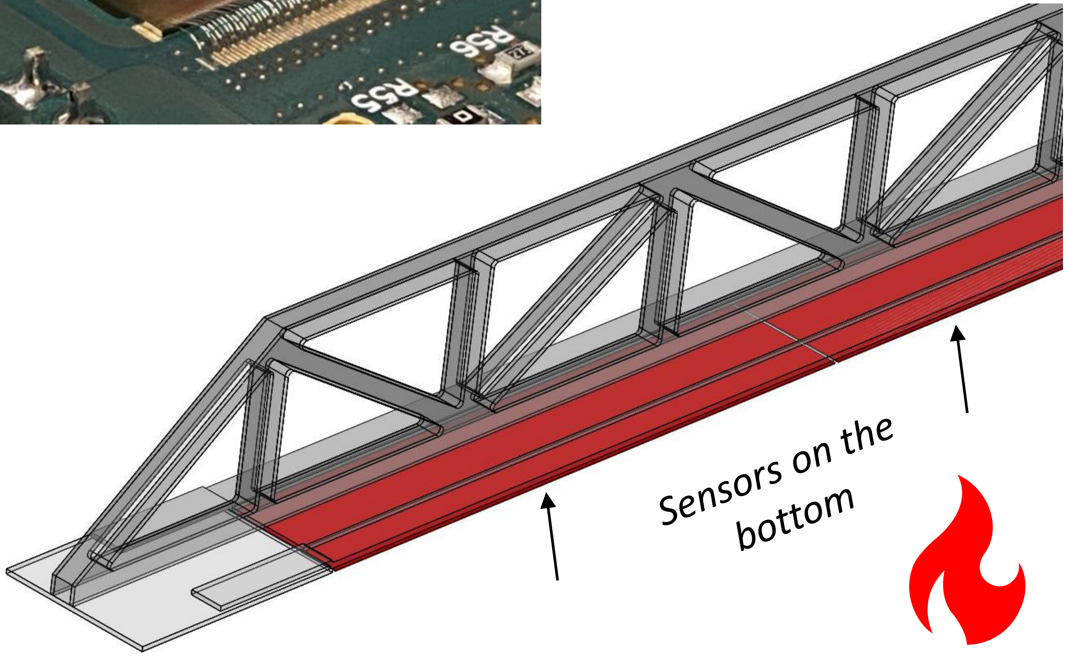


Modules of 25 $\times$ 25 μm^2 pixel size

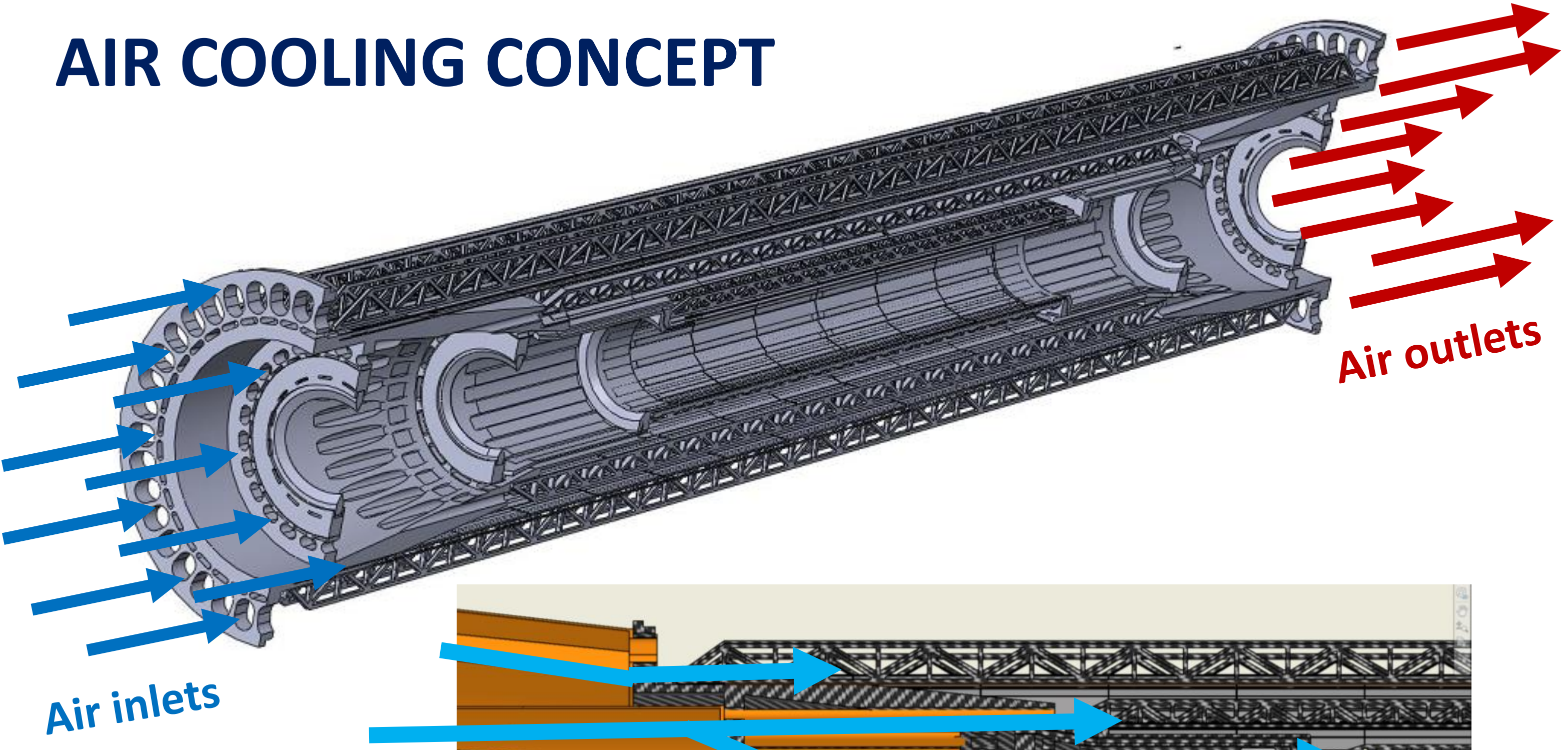


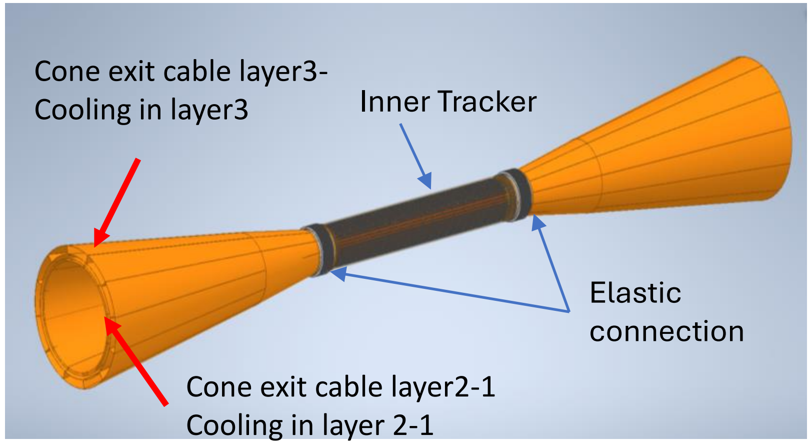
- **Inner Vertex (ARCADIA based):**
  - Lfoundry 110 nm process
  - *50 μm thick*
  - Module Dimensions: $8.4 \times 32\ mm^2$
  - Power density $50\ mW/cm^2$
  - **100 MHz/cm²**

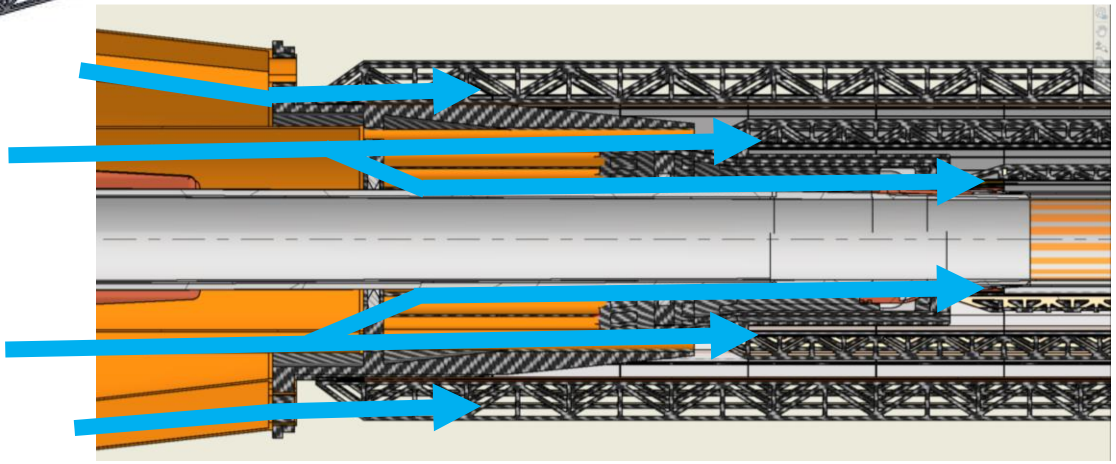
- Estimation for sensors power dissipation:
  - Layer 3: $\dot{Q}$ **~ 77 W** (total)
  - Layer 2: $\dot{Q}$ **~ 32 W** (total)
  - Layer 1: $\dot{Q}$ **~ 12 W** (total)

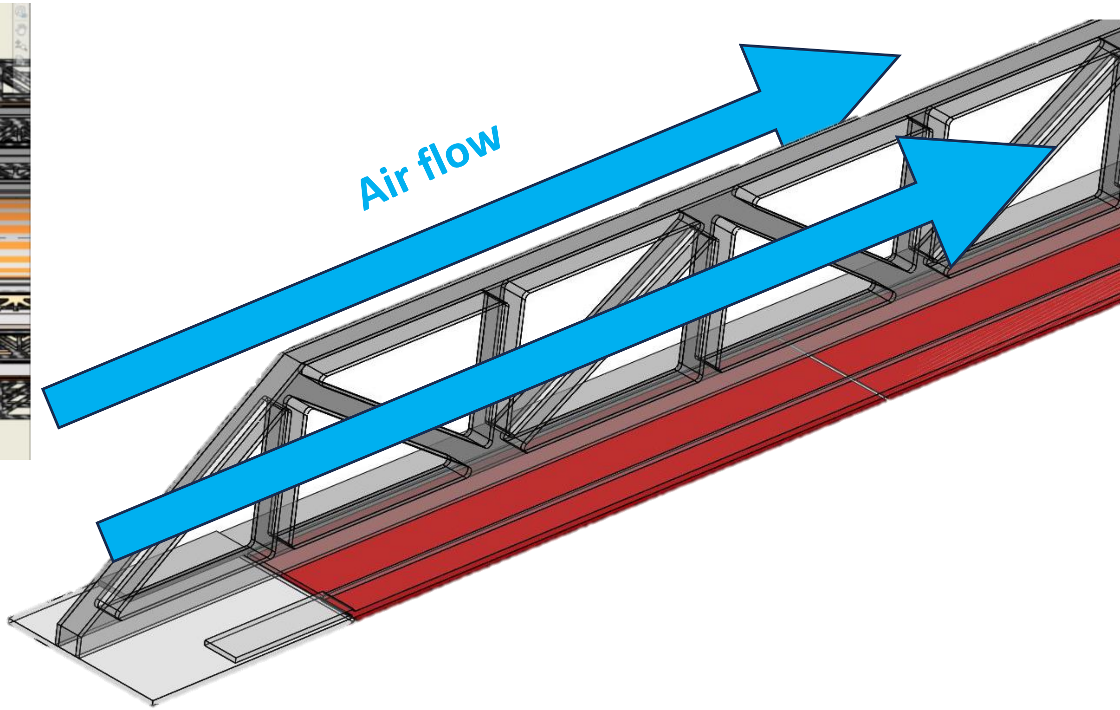


AIR COOLING CONCEPT







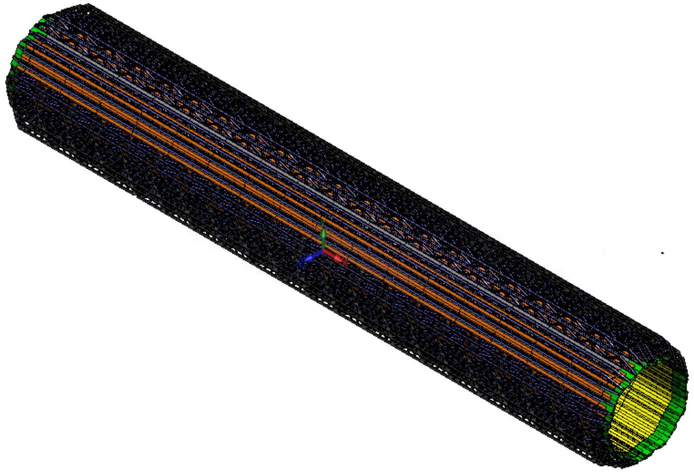


- Cooling method: longitudinal air flow along the the detector.
  - Temperature of air at inlet: T_{air} = 15°C
  - Air flow has the same direction for all the layers

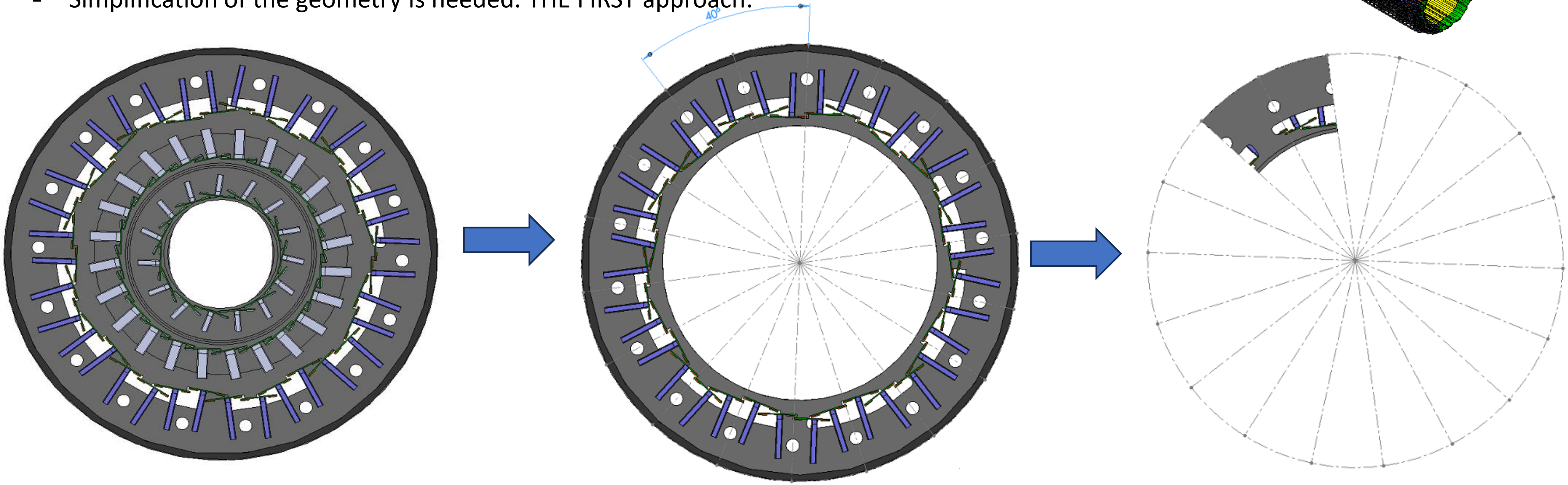
EVALUATING THERMAL PERFORMANCE

By Finite-Volume-Method (FVM) simulations
Software: Ansys Fluent

EVALUATING THERMAL PERFORMANCE



- Challange: create the calculation grid for such a complex geometry.
  - Overall lenght about 540mm
  - Level of details of the order of sensor thickness = 50 μm
- Simplification of the geometry is needed. THE FIRST approach:



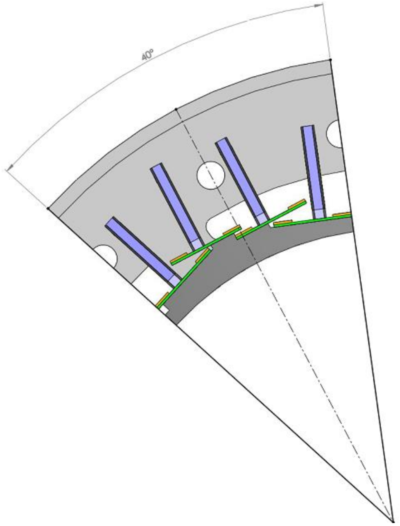
Starting from the full geometry

Removing
layer 1 and 2

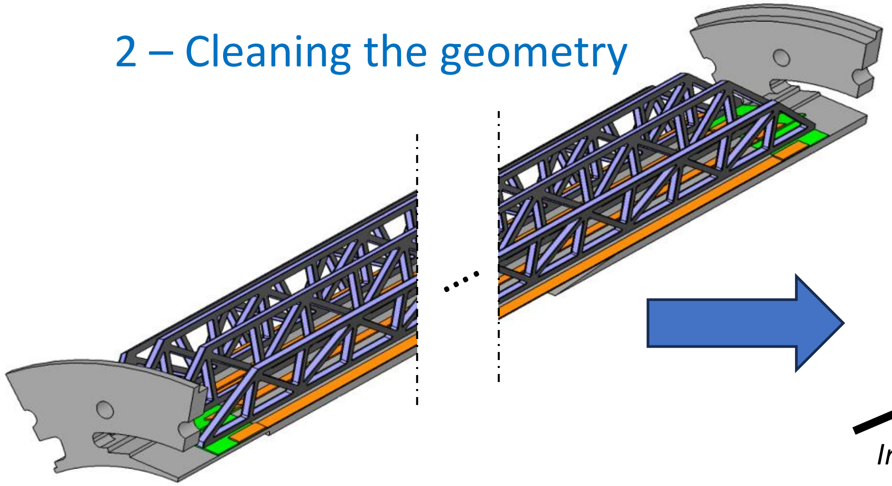
Focus on one sector of Layer 3
(40° circular symmetry)

STEPS FOR THERMAL SIMULATIONS

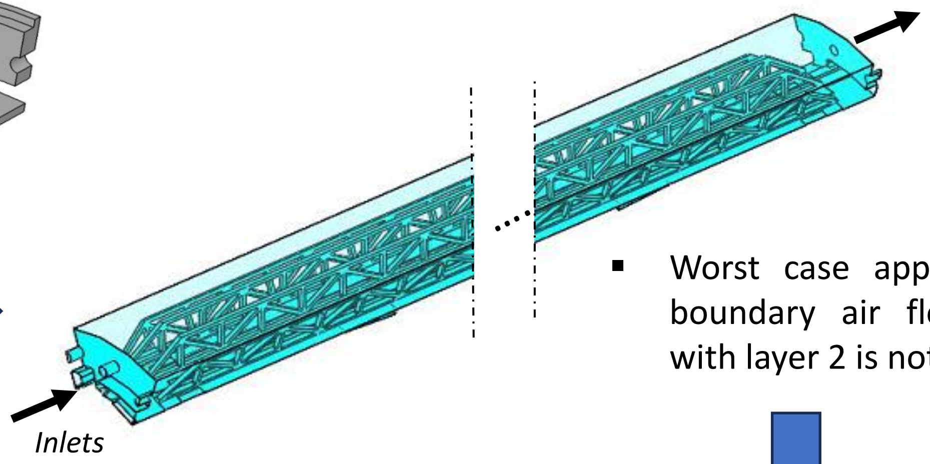
1 - Definition of the domain



2 – Cleaning the geometry

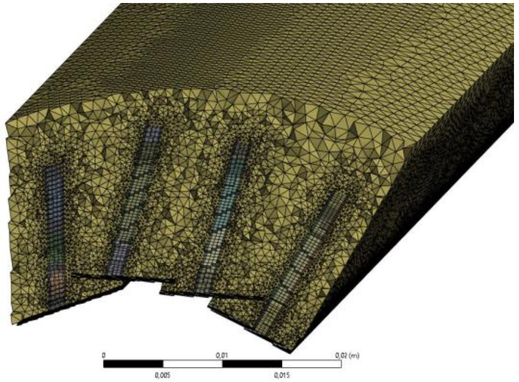


3 - Adding the volume of fluid



- Worst case approach: the boundary air flow shared with layer 2 is not included.

4 – Creating the grid

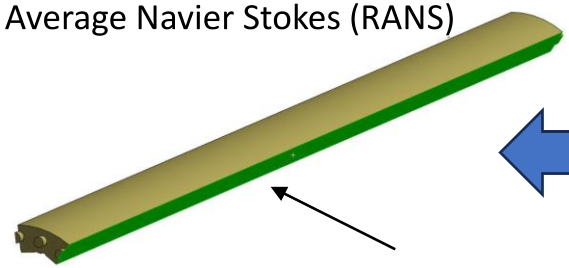


- Both the solid and fluid domains are simulated at the same time (***Conjugate heat transfer***)

10’500’000 Elements
17’000’000 Nodes

5 – Setting up the model

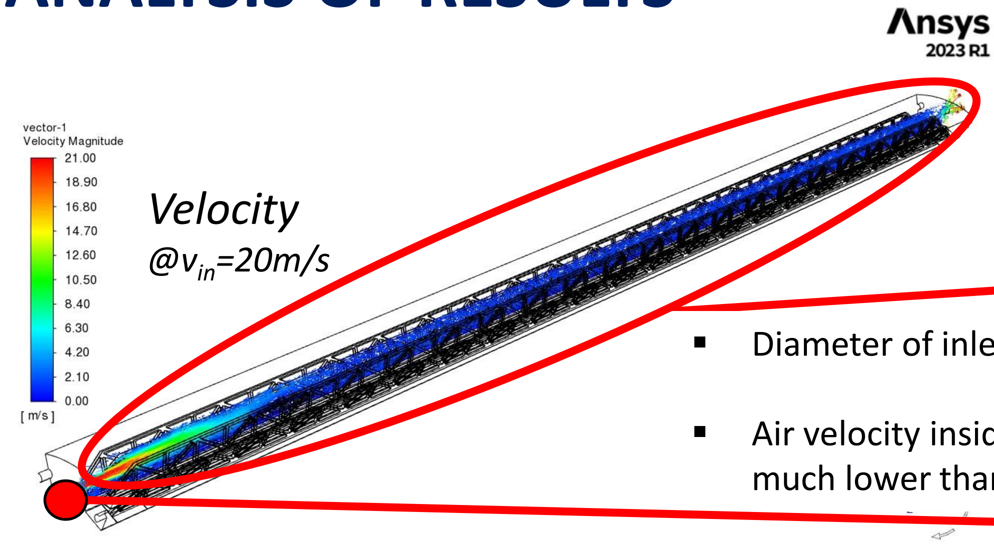
- ✓ Steady state conditions
- ✓ Turbulent flow: Reynolds Average Navier Stokes (RANS)
- ✓ Viscous model k-ω SST
- ✓ Pressure based solver
- ✓ No radiation heat exchange
- ✓ Volumetric constant power source on sensors volume

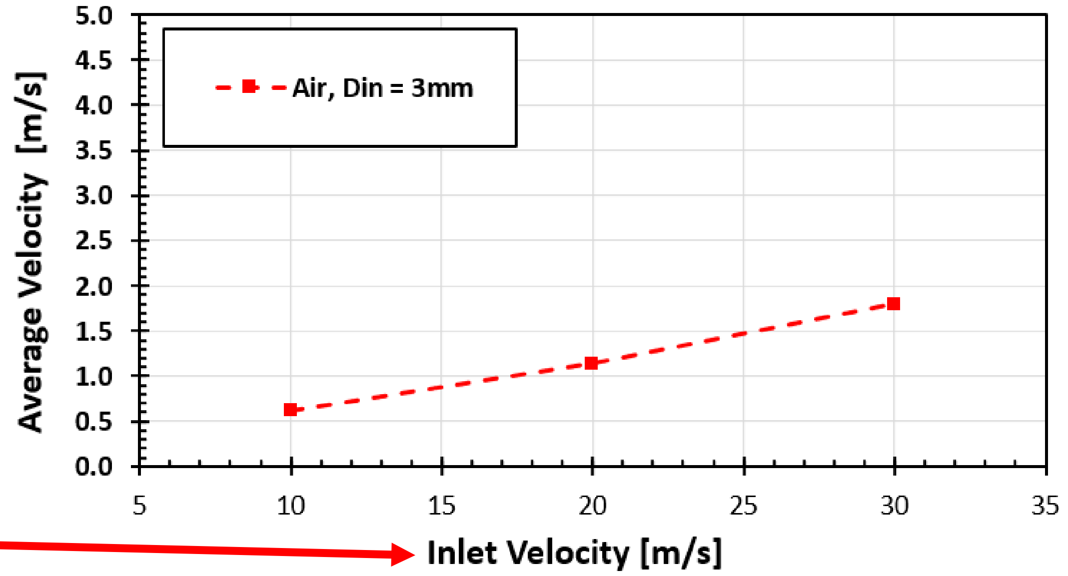


6 – Run calculations

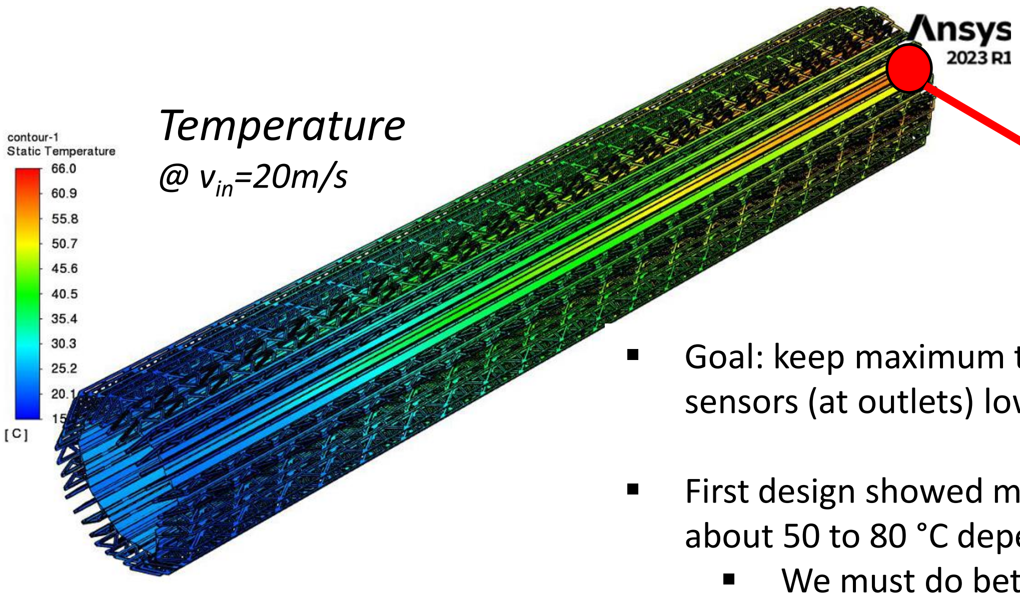
We used: i9-10900X CPU, 20 threads, RAM 128 GB, 2 TB SSD

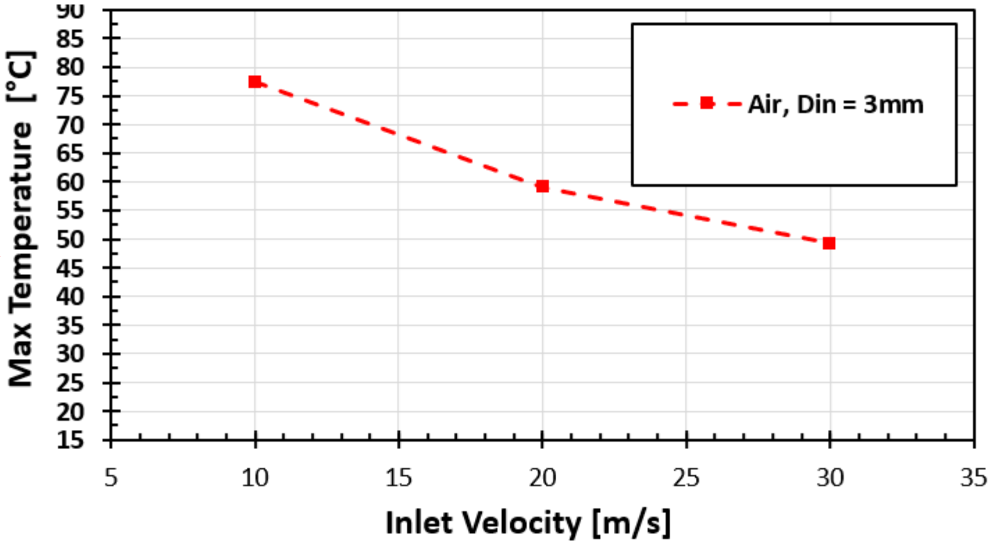
ANALYSIS OF RESULTS





- Diameter of inlet holes D_{in} = 3mm
- Air velocity inside the cylinder much lower than inlets.

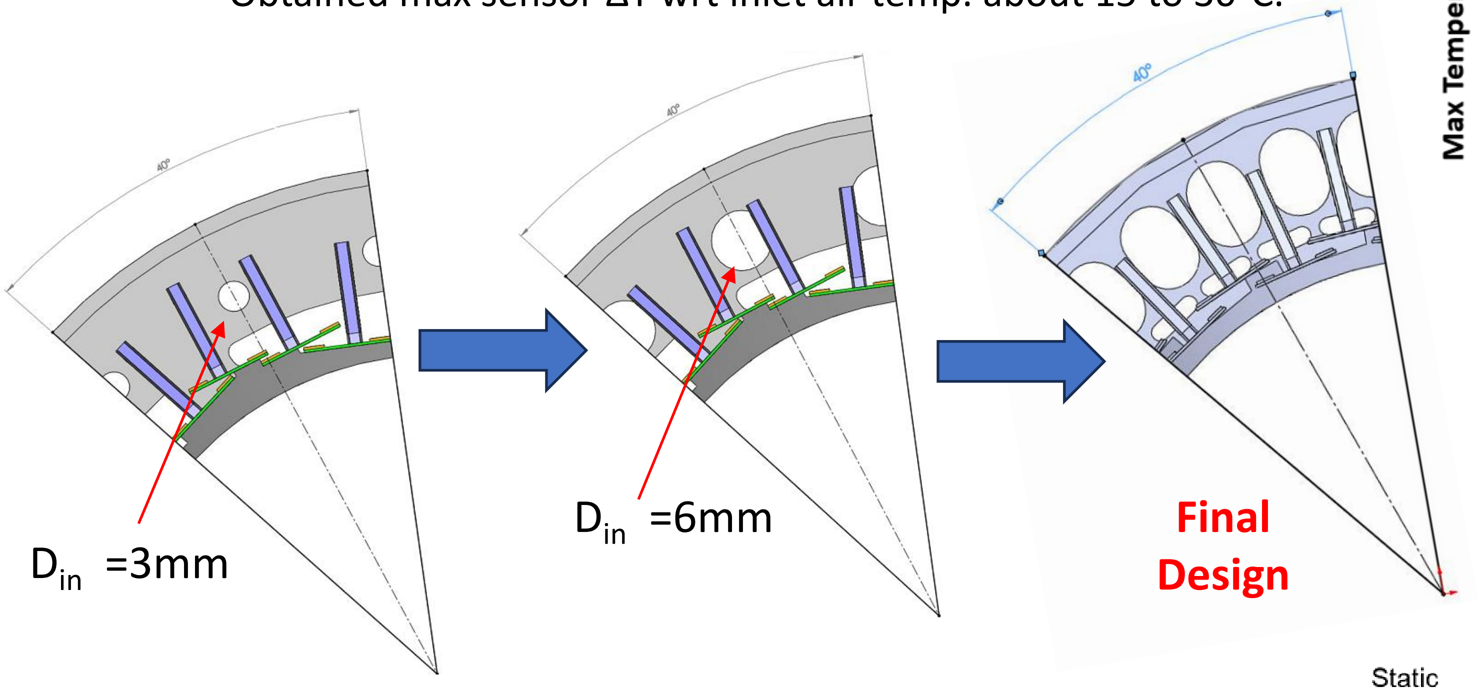


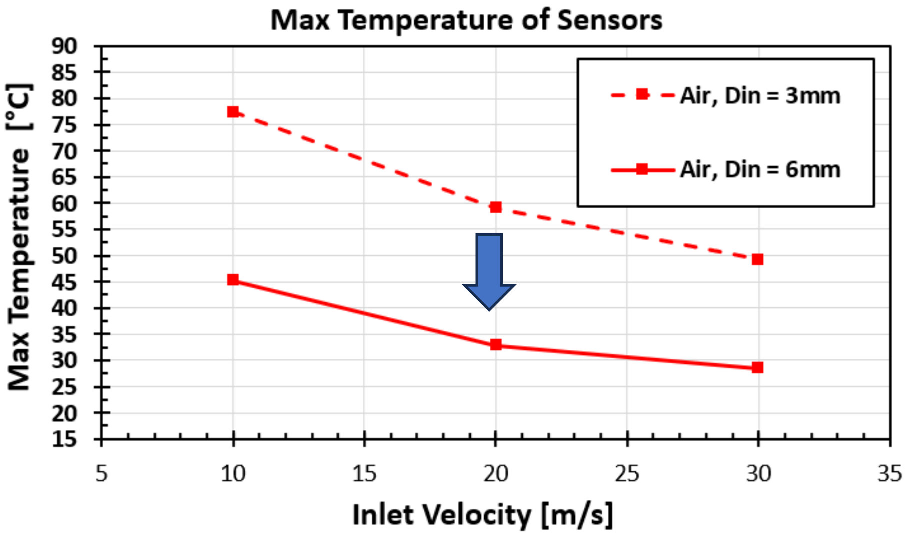


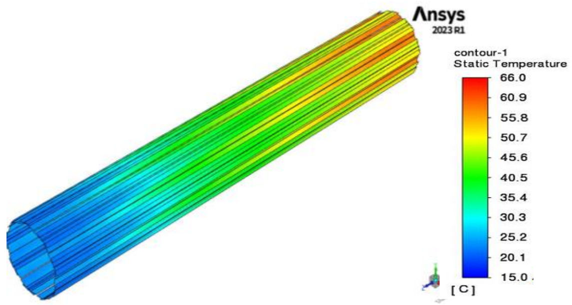
- Goal: keep maximum temperature of sensors (at outlets) low.
- First design showed max temperature about 50 to 80 °C depending on air flow.
  - We must do better!

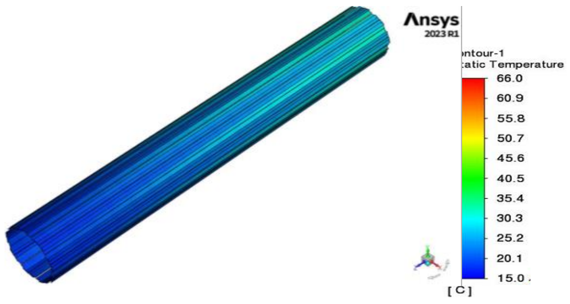
DESIGN OPTIMIZATION

- Increase the diameter for inlets holes.
  - Mass flow rate increase as well (for same v_{in}).
  - Obtained max sensor ΔT wrt inlet air temp. about 15 to 30°C.

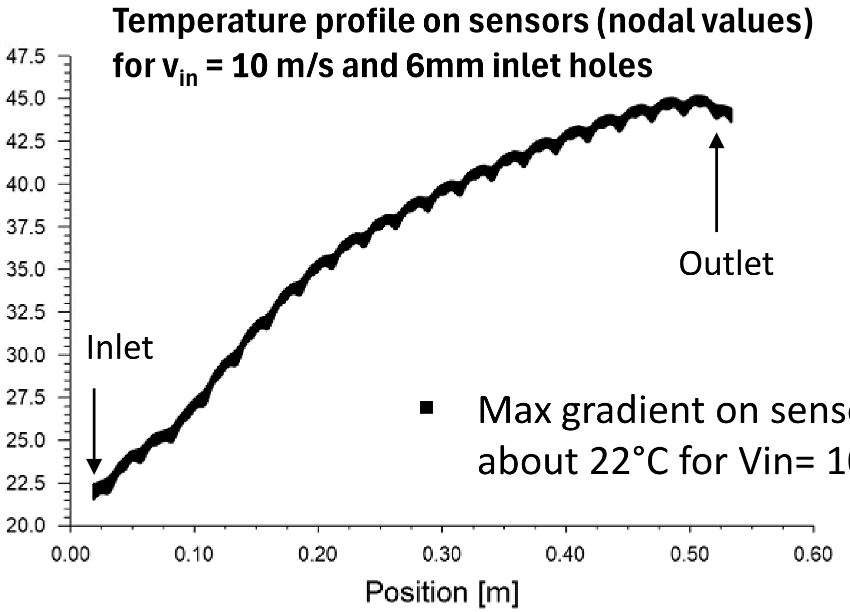








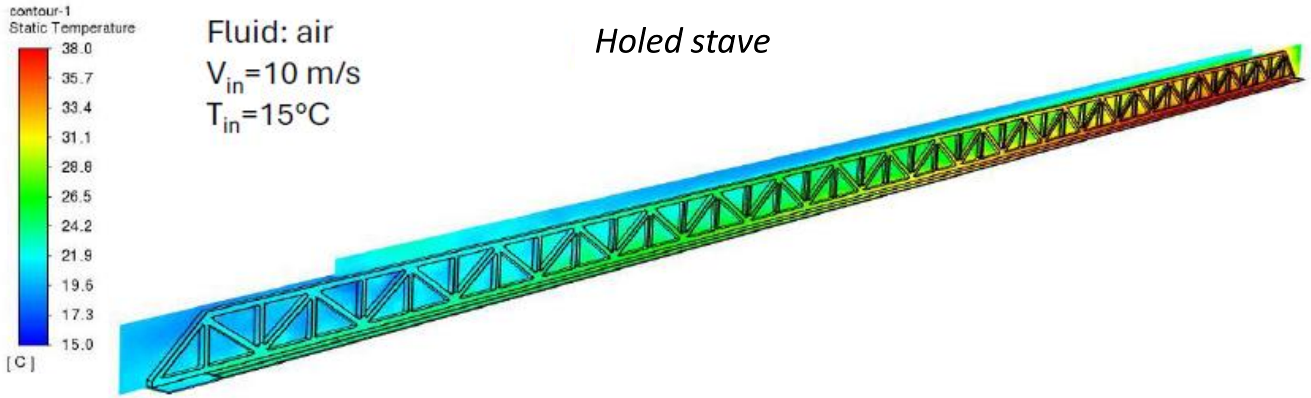
Static Temperature [C]



- Max gradient on sensors about 22°C for Vin= 10m/s

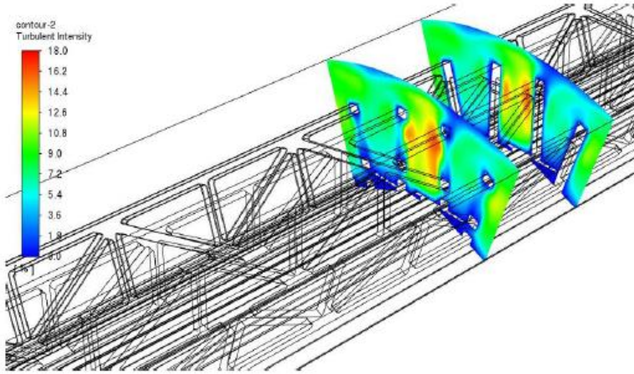
DESIGN OPTIMIZATION

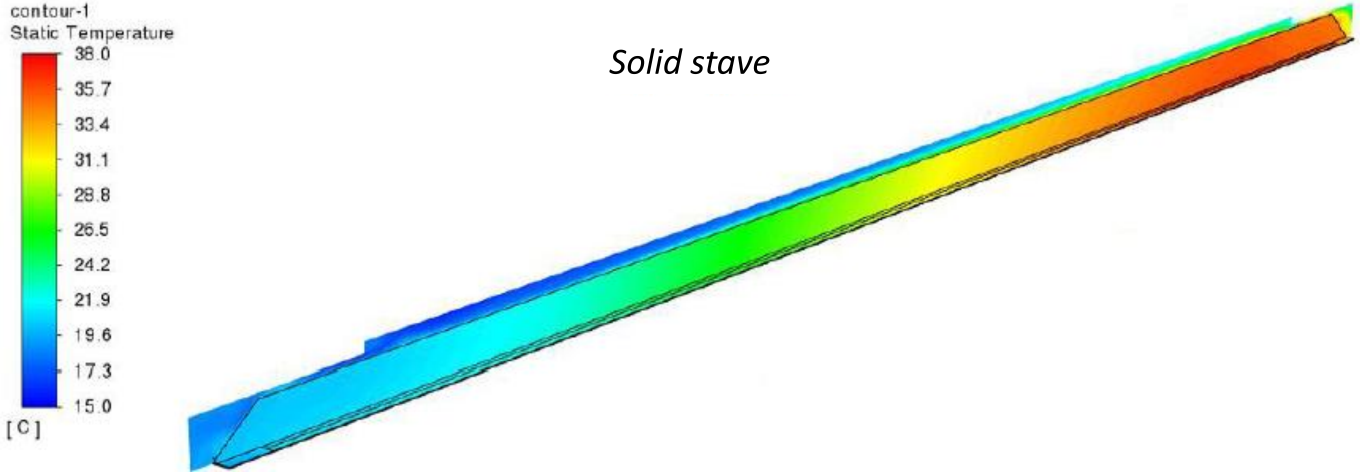
- Evaluated different performance between «holed stave» and «solid stave».
  - Thermal performance very similar (Solid stave 1.7°C colder)
  - More turbulence in case of holed stave.



Holed stave

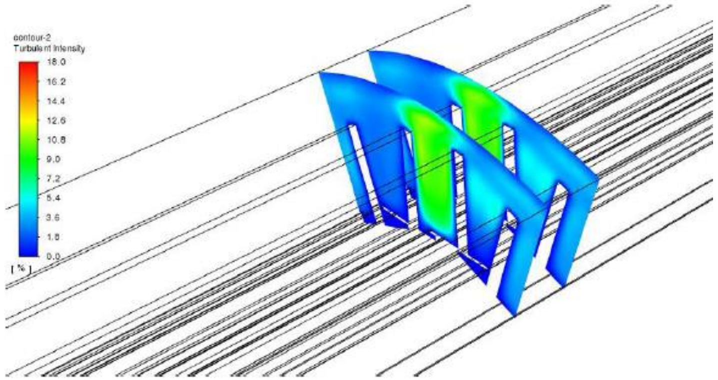
V_{media_aria}=1.5 m/s
Turbulent Intensity=12.6%
T_{max_sensor}=37.9°C
Mass_flow=0.17 g/s





Solid stave

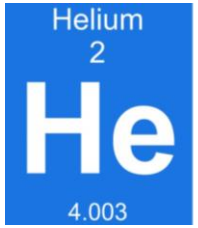
V_{media_aria}=1.5 m/s
Turbulent Intensity=10.5%
T_{max_sensor}=36.2°C
Mass_flow=0.17 g/s



ANOTHER POSSIBILITY: CHANGING THE FLUID PROPERTIES

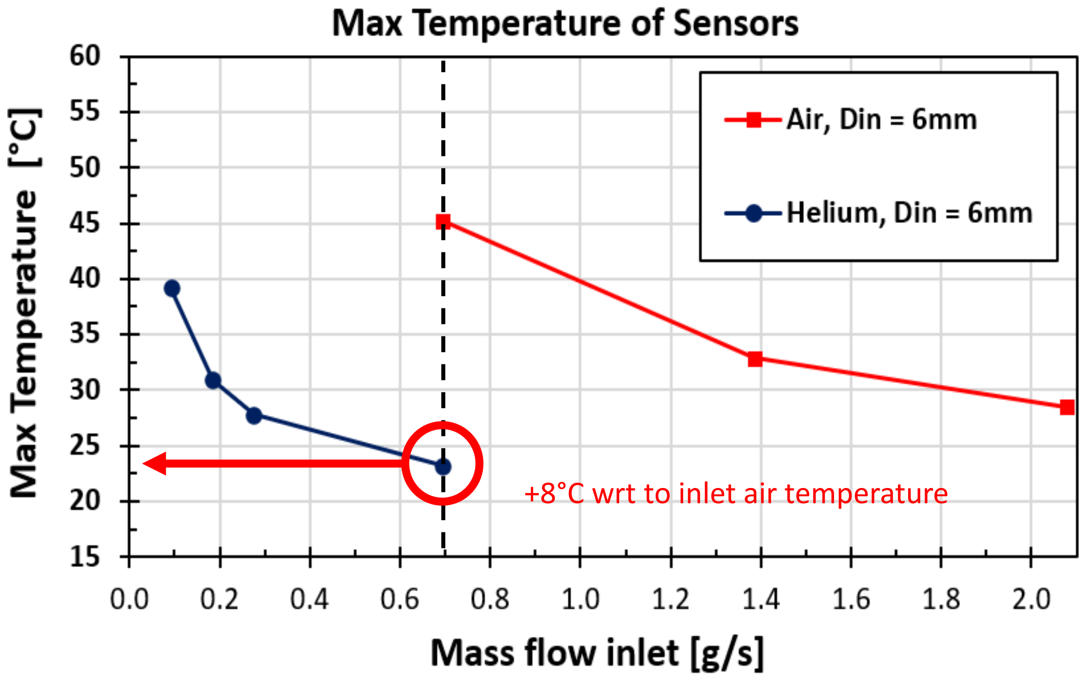
- The use of helium as a fluid instead of air was investigated.

- Properties of helium taken from Ansys libraries:
  - Lower density than air.
  - Higher thermal conductivity than air.



	Air	Helium
Density [kg/m³]	1.225	0.1625
Specific Heat [J/(kg K)]	1006	5193
Thermal Conductivity [W/(m K)]	0.024	0.152
Viscosity [kg/(m s)]	1.79e-05	1.99e-05

$$\dot{m} = \rho \cdot \boldsymbol{v} \cdot \boldsymbol{A}$$



- Comparison is interestesting considering the same mass flow rate instead of same inlet velocity.

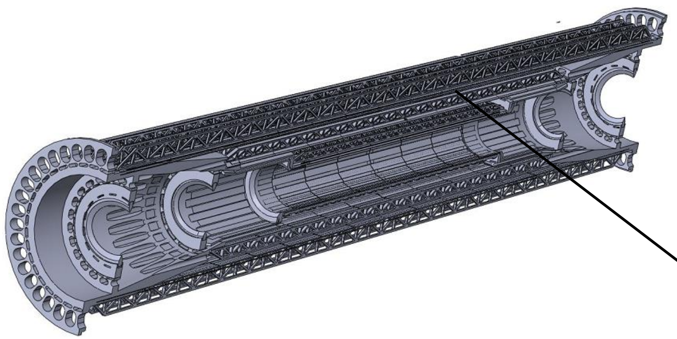
- Helium offers much better cooling than air for the same mass flow rate.

A METHOD FOR EVALUATING MECHANICAL PERFORMANCE

Computational Fluid Dynamics (CFD) + Finite element analysis (FEA)
Software: Ansys Fluent + Ansys Mechanical

A MULTIPHYSICS MODEL FOR THE EVALUATION OF MECHANICAL STRESS

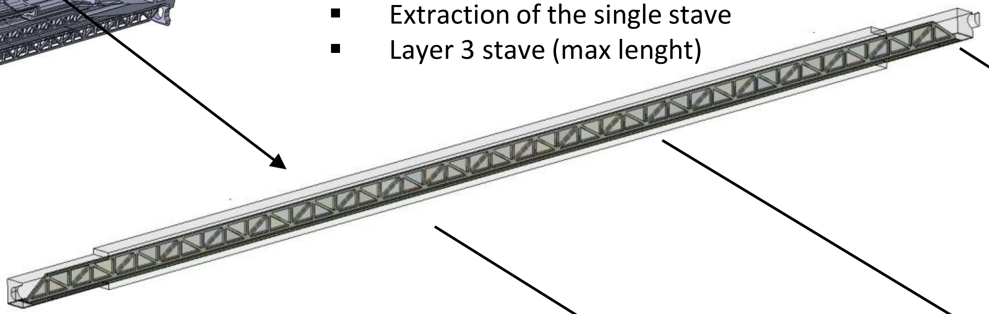
- Define a tool to evaluate whether the air flow necessary to remove the heat generates excessive vibrations on the stave.

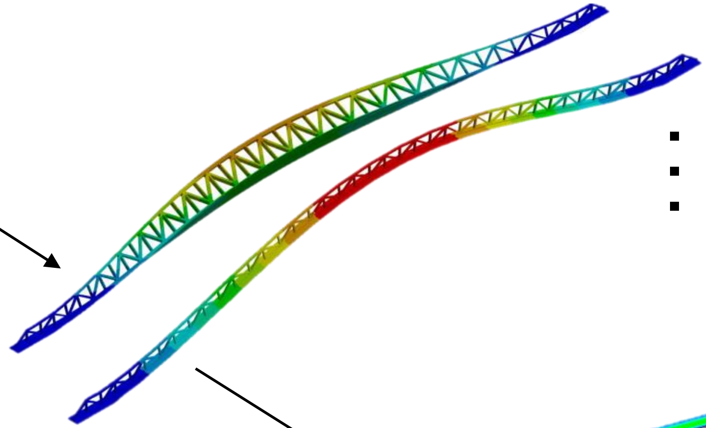


CAD Model

Geometry simplification

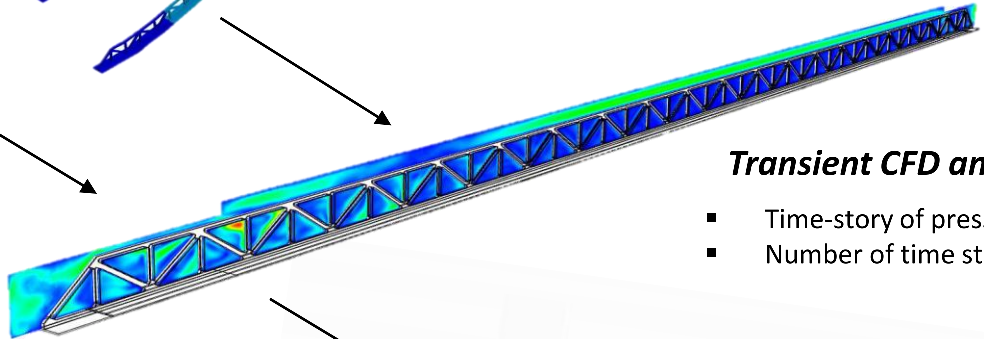
- Extraction of the single stave
- Layer 3 stave (max lenght)





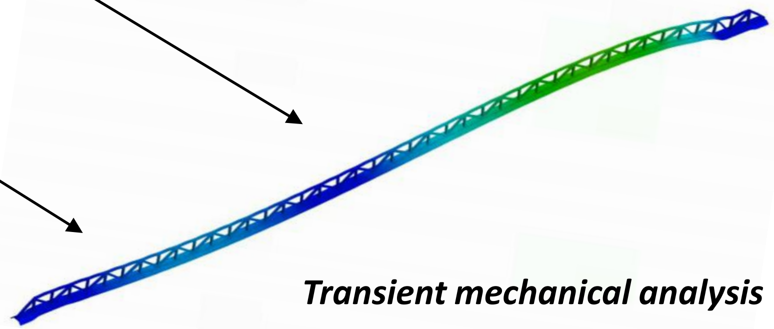
Modal analysis

- Natural frequencies.
- Participation factors.
- Define time step for transient analisys.



Transient CFD analysis

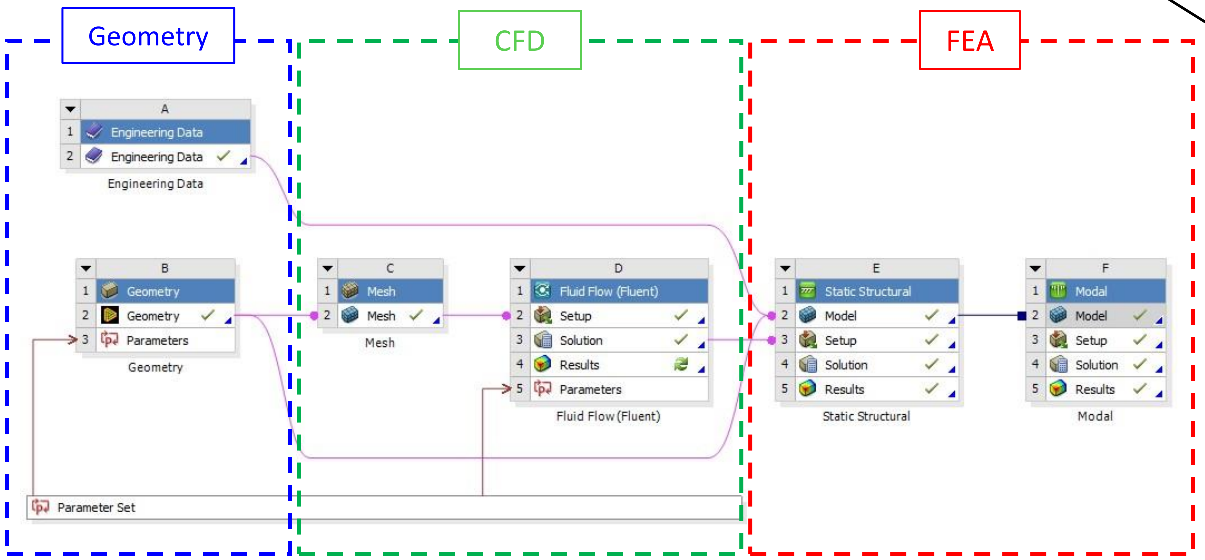
- Time-story of pressure load.
- Number of time steps.



Transient mechanical analysis

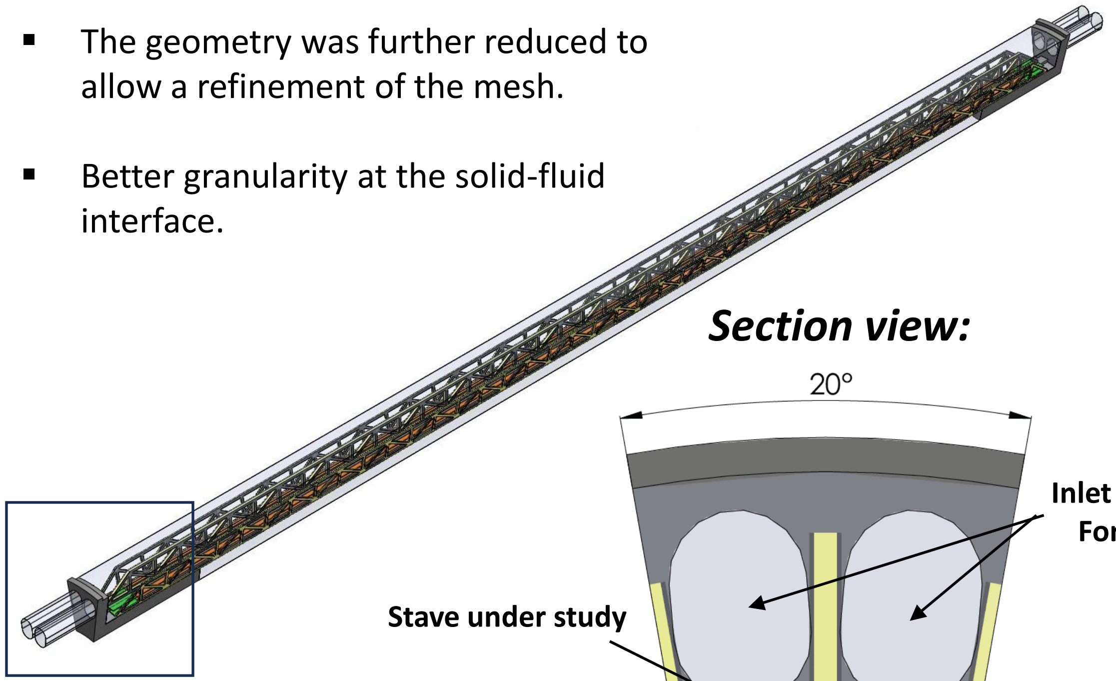
- Dynamic displacement

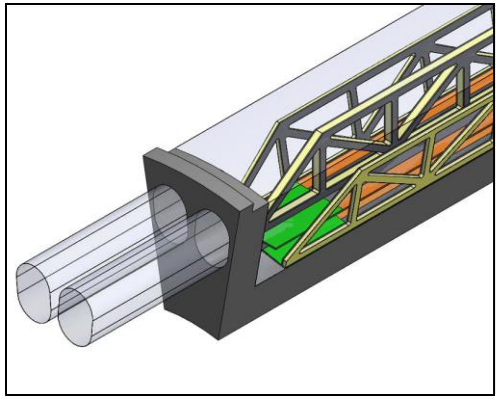
- Flow of data managed by Ansys Workbech



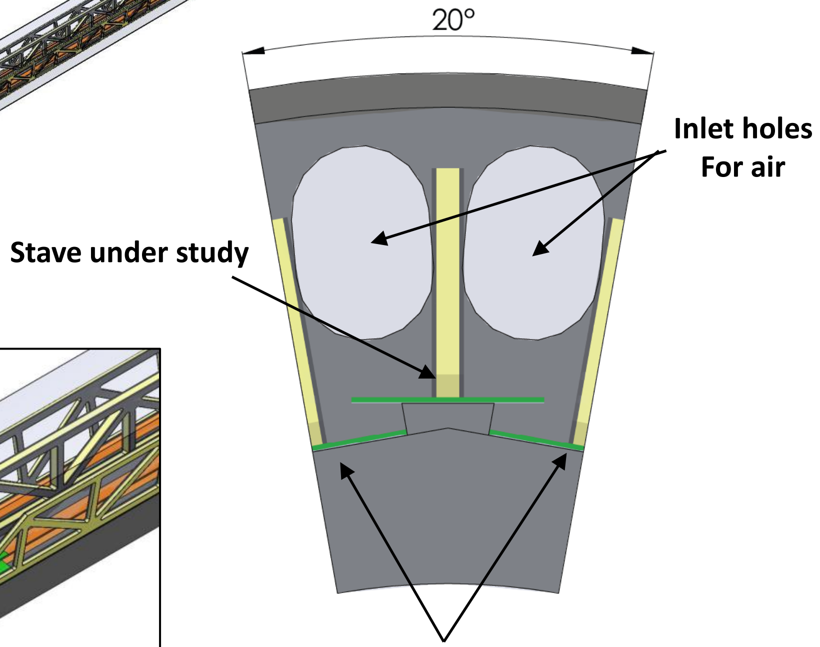
GEOMETRY

- The geometry was further reduced to allow a refinement of the mesh.
- Better granularity at the solid-fluid interface.



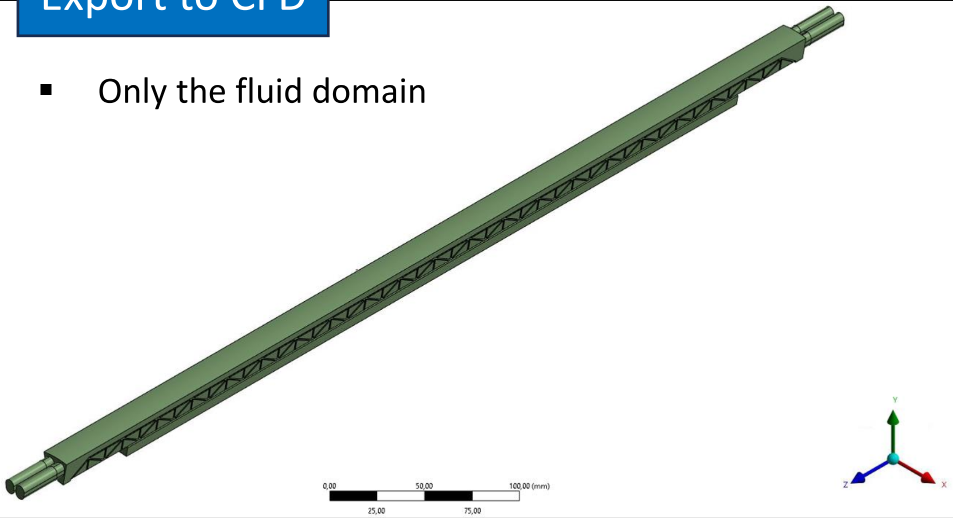


Section view:



Export to CFD

- Only the fluid domain



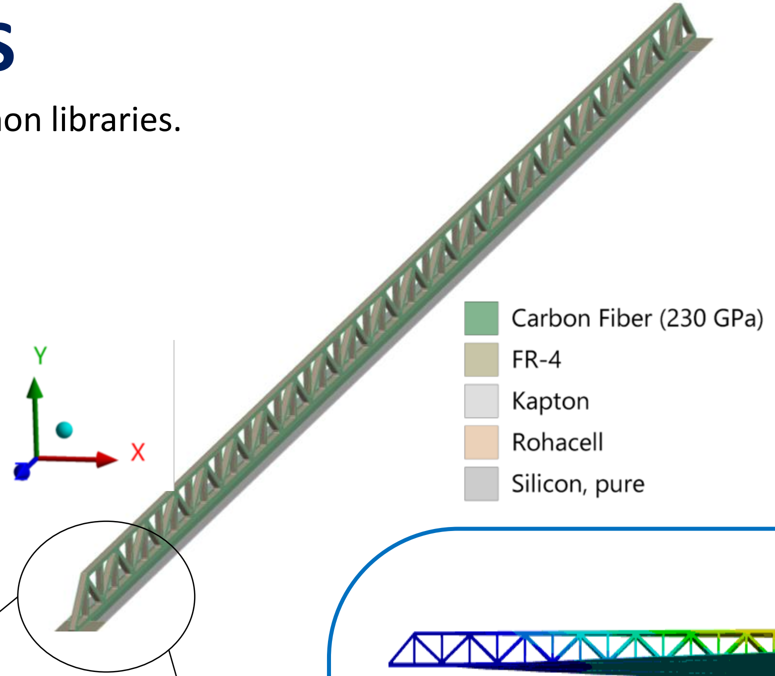
Export to FEA

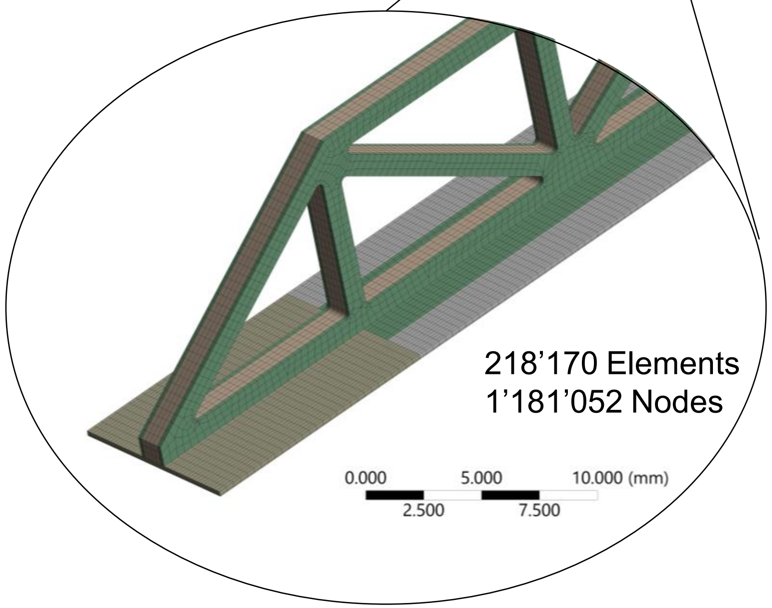
- Only the central stave

MODAL ANALYSIS

- Material data taken from common libraries.
- Frequencies > 100 Hz
- 1° Mode torsional
- Natural frequencies are used to define the time step for next transient analysis:

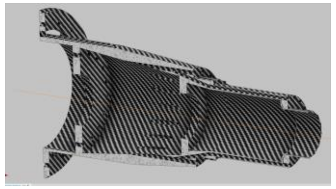
$$\Delta t < \frac{1}{f_{max} \cdot 10}$$

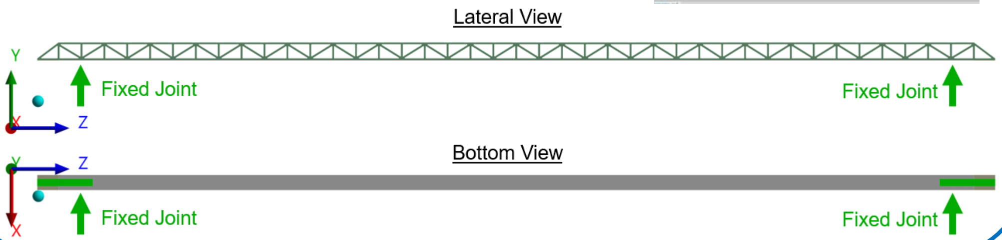




Constraints

- Hypothesis: support cone (anchoring of each stave) not deforming with time.





Results

(video)

Mode	Frequency [Hz]
1	118.8

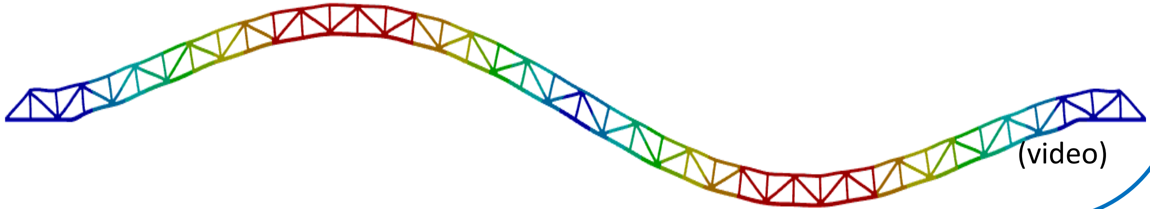
Mode	Frequency [Hz]
2	147.1

(video)

(video)

Mode	Frequency [Hz]
4	292.1

Mode	Frequency [Hz]
5	394.4



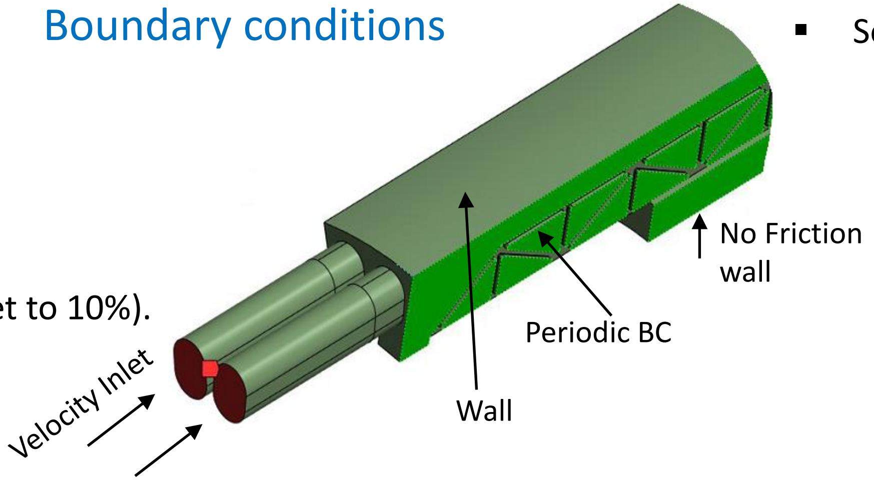
(video)

CFD TRANSIENT ANALYSIS

- Re > 4’000 – Turbulent flow $Re = \frac{F_{inertia}}{F_{viscous}} = \frac{\rho V D_H}{\mu}$
- Viscous model: Large Eddy Simulation (LES) Model
- Average velocity at inlet: V_{in_avg} = 10 m/s
- Turbulence generator at inlet (turbulence intensity set to 10%).
  - ➢ Spectral Synthesizer Algorithm [Link]

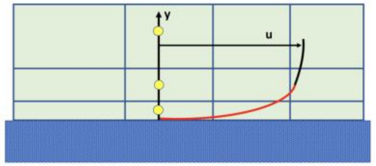
$$\mathbf{u}'(\mathbf{r},t)=2K_t\sum_{n=1}^{N}\sqrt{q^n}\left[\boldsymbol{\sigma}^n\cos\left(k^n\mathbf{d}^n\cdot\mathbf{r}+\phi^n+s^n\frac{t}{\tau}\right)\right]$$

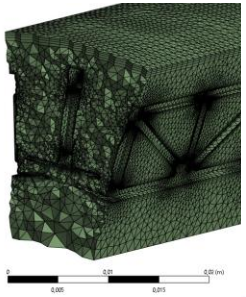
Boundary conditions



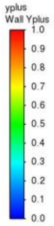
- Solver parameters:
  - Time step = 6.8e-4 s
  - N° of time steps (Total simulated time) defined by the time a flow particle takes to cross the entire beam, given the RMS velocity of the flow along the axis.
  - NOTE: this involve long calculation time !

Mesh

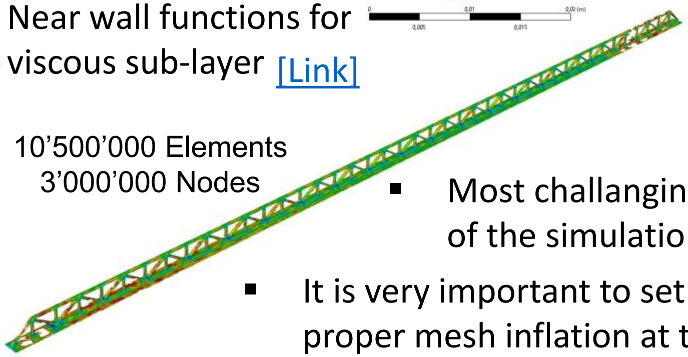




- Near wall functions for viscous sub-layer [Link]

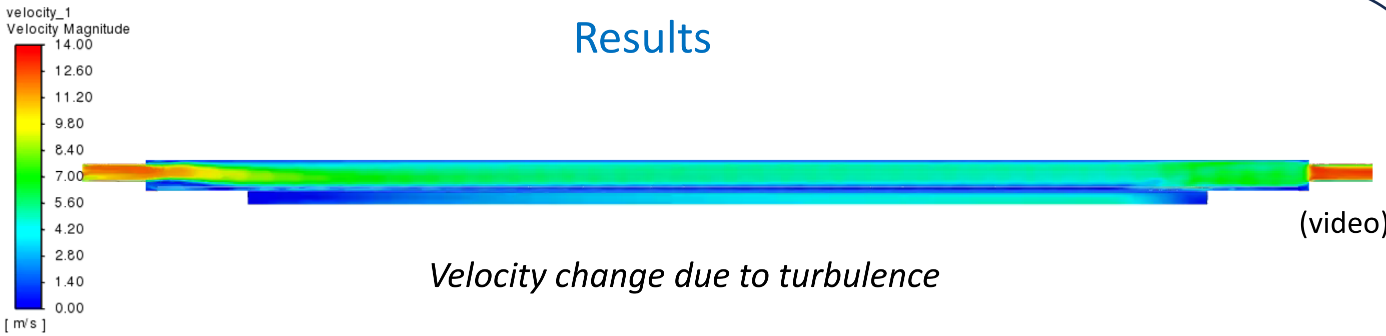


10’500’000 Elements
3’000’000 Nodes



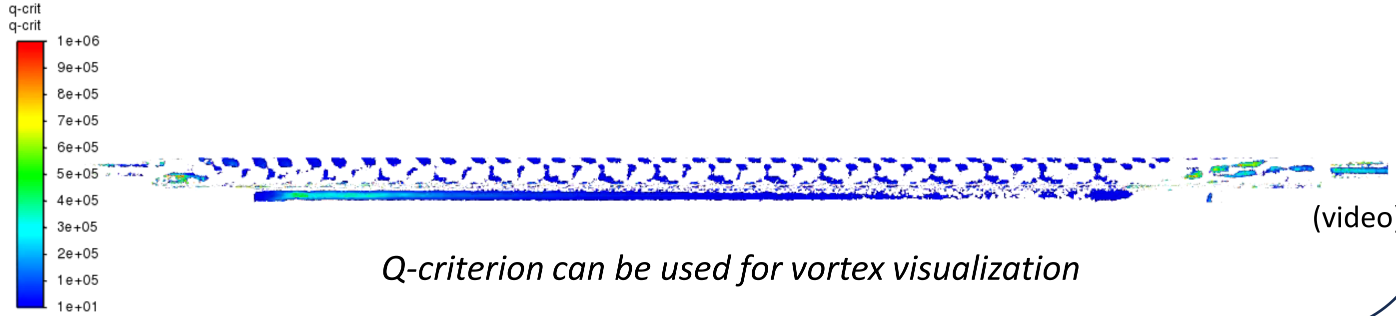
- Most challanging part of the simulation.
- It is very important to set a proper mesh inflation at the boundary layers.

Results



(video)

Velocity change due to turbulence



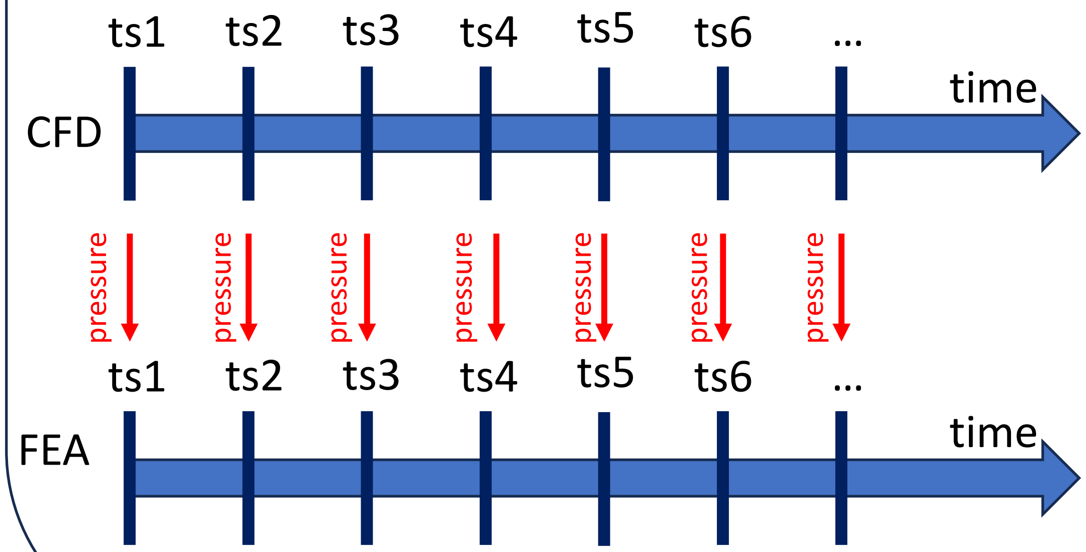
(video)

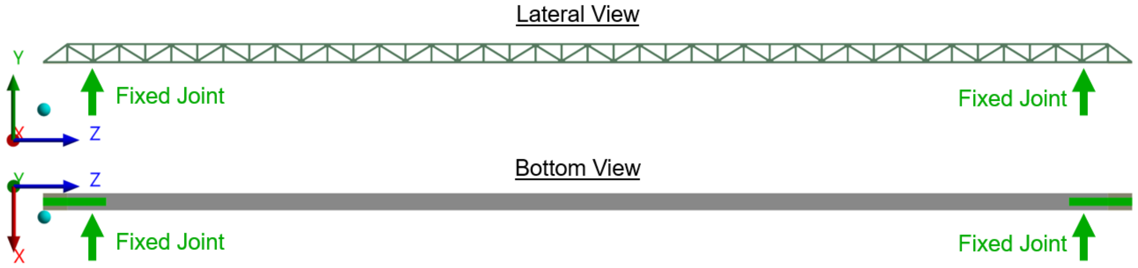
Q-criterion can be used for vortex visualization

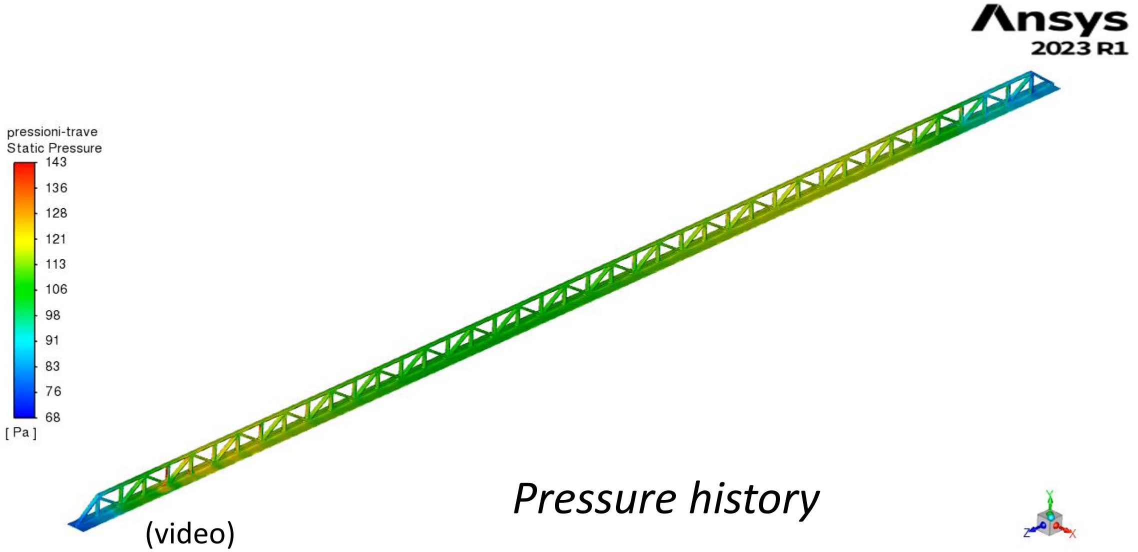
SETTING THE MECHANICAL TRANSIENT ANALYSIS

Boundary conditions

- Same constrains and materials used for Modal analysis.
- Pressure history is imported from CFD as external load on all the boundary surfaces of the beam.
- Set time step (ts) for FEA simulations the same as for CFD (pressure load is updated each time step).



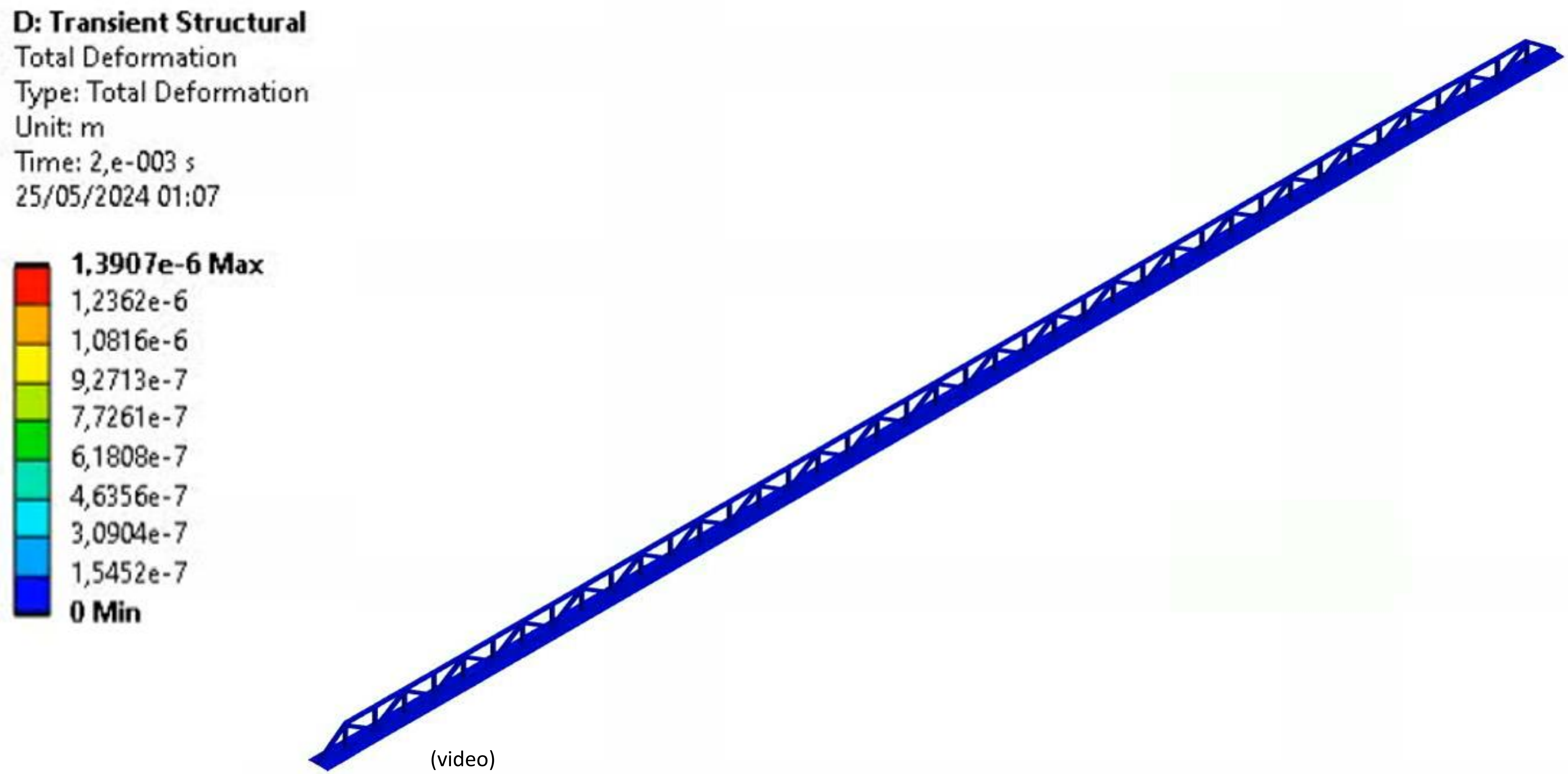




(video)

Pressure history

RESULTS

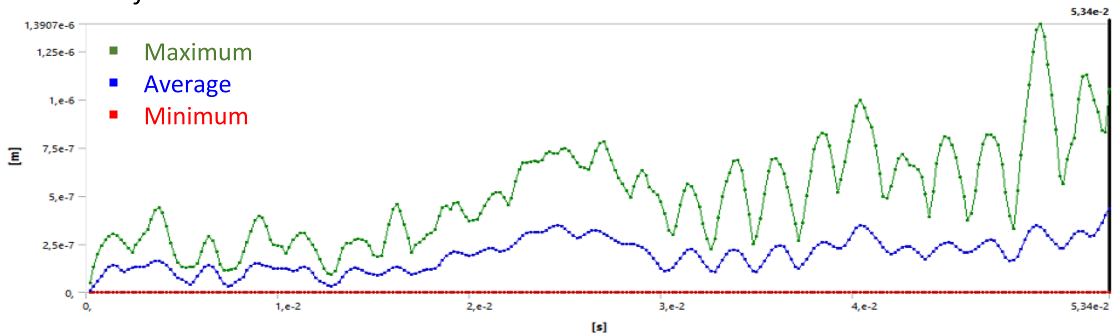


(video)

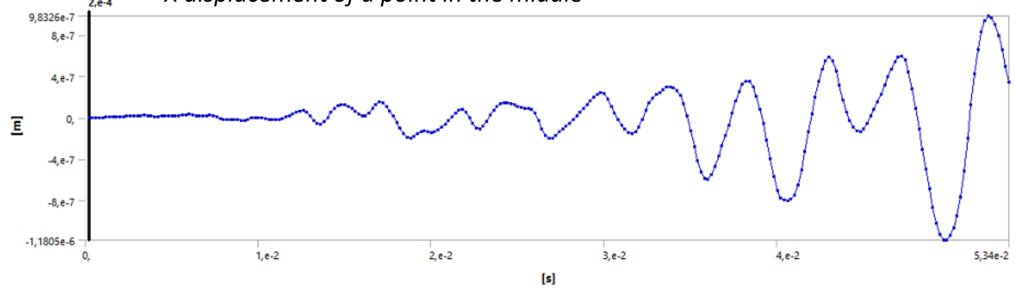
RESULTS

- Simulation takes some time steps before first modes are fully triggered.

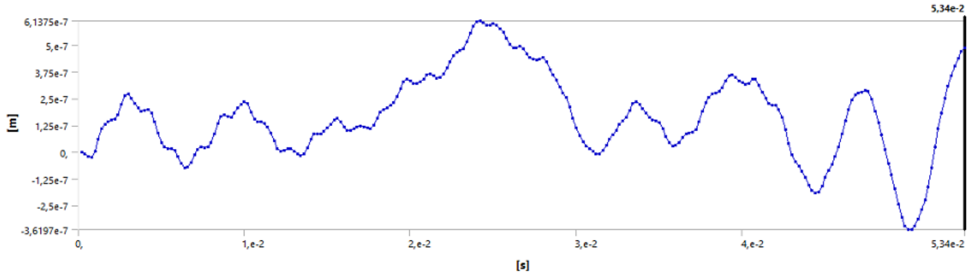
Global deformation:

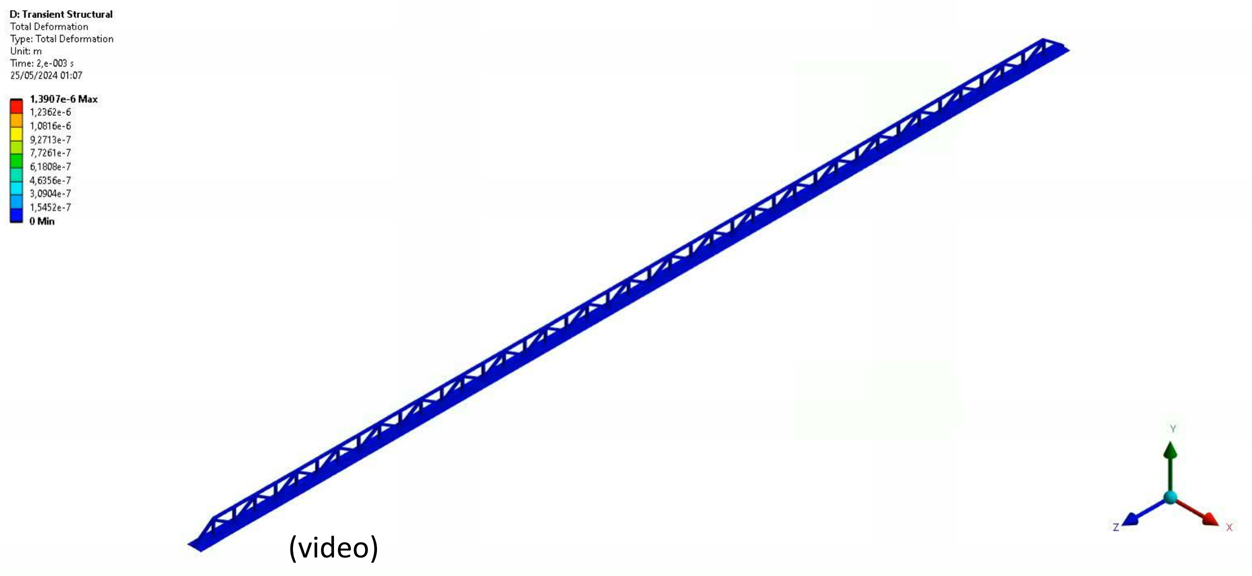


X displacement of a point in the middle

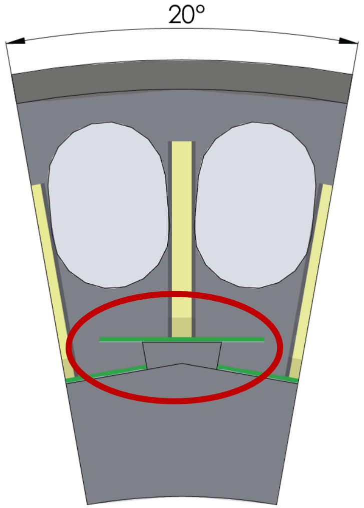


Y displacement of a point in the middle

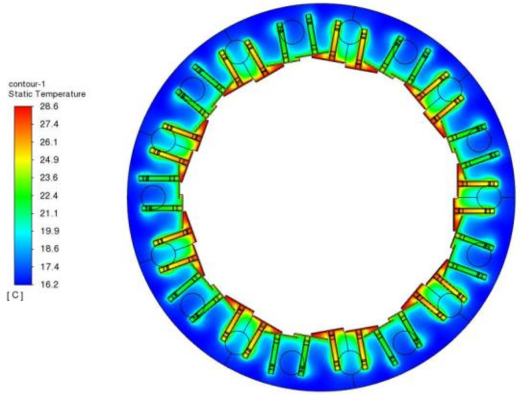




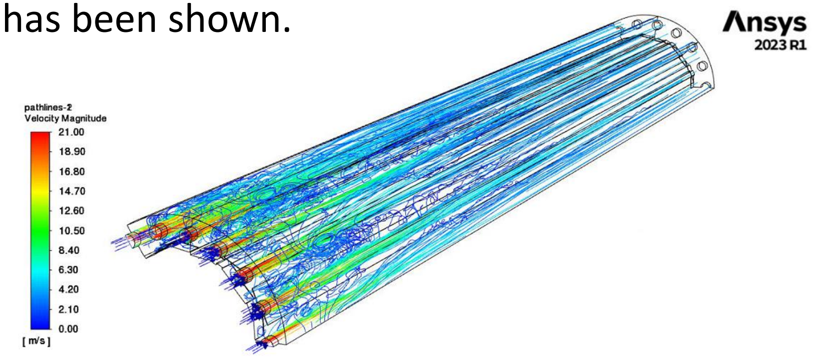
- Maximum displacement magnitude about 1.5 µm @ v_{in} = 10m/s
  - Mainly due to first-mode
  - This give hint to improve stiffness in the fixation region to the support cone.
- Model must be tuned with experimental data



SUMMARY & FINAL REMARKS



- The silicon vertex detector for the IDEA concept at FCC-ee has a well defined design.
- A FVM model for evaluating the thermal performance for air cooling solution has been shown.
  - Conjugate heat transfer: solid and fluid simulated at same time.
  - Steady simulation with RANS modeling of turbulence.
- A multiphysics model joining CFD and FEA is proposed for the study of the dynamic behavior has been shown.
  - Separated geometry for the solid and the fluid part.
  - One-way-coupling of the pressure at the interfaces.
  - Transient simulation with LES modeling of turbulence.



- Both the models provide useful hints for geometry optimization and design of experiments for lab tests.
- An experimental validation is crucial to tune the model (expecially for the turbulence model to be used) !
- Given the model complexity, the resources needed for this kind of analysis are not a negligible point.

Thanks for your attention

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FUTURE CIRCULAR COLLIDER

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