ATLAS Pixel detector

Outer Endcap of ITk Pixel Detector

Thermo-Mechanical FEA of the overall OEC model

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Introduction

The development of a simplified **overall OEC FEA model to perform thermo-mechanical simulations**, which can help giving results to the Pixel Collaboration towards the Global Mechanics & Integration FDR and beyond, is currently underway in Milan, since the beginning of January 2024.

The purpose is to build a sufficiently detailed FEA model, maintaining number of nodes/elements within the calculation capability currently available in Milan. So, the idea is to proceed step by step, starting from a basic model and adding more detail as possible.

The first attempt produced a preliminary model, called “version 0”, of about 5 million of nodes, which can converge to the solution in a reasonable time.

This model is currently being implemented into a more complete version1.

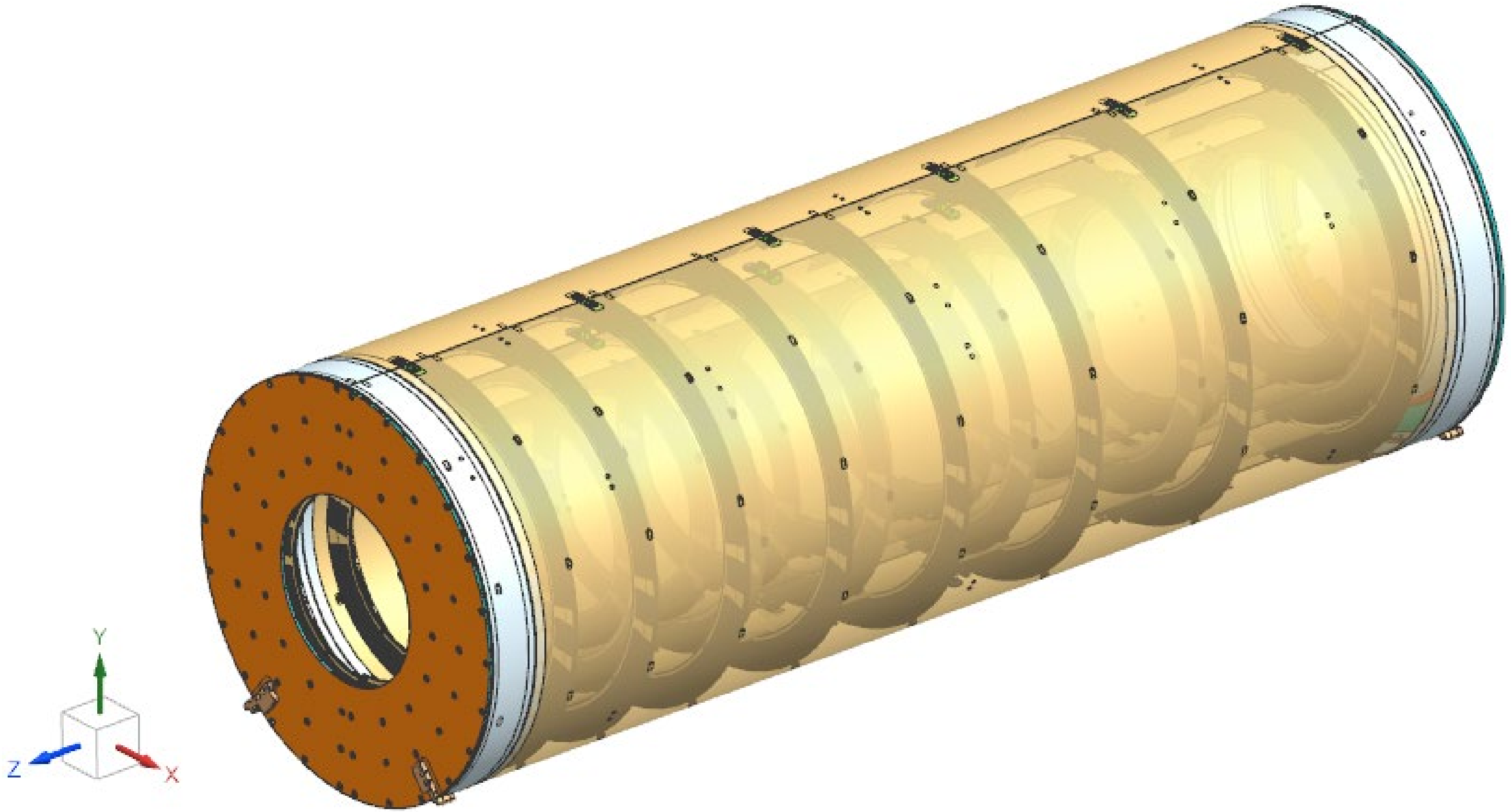
This presentation shows the progress in this business and the main aspects to be defined to proceed.

Overall OEC FEA model v.0

Starting point: simplified overall OEC FEA model which can converge to a solution, called "version 0".

Main reference: the last updated Peter Sutcliffe's OEC CAD model:

np49-04-100_issl.stp, **dated 2021-09-06** - **EDMS:** https://edms.cern.ch/document/2052151/2



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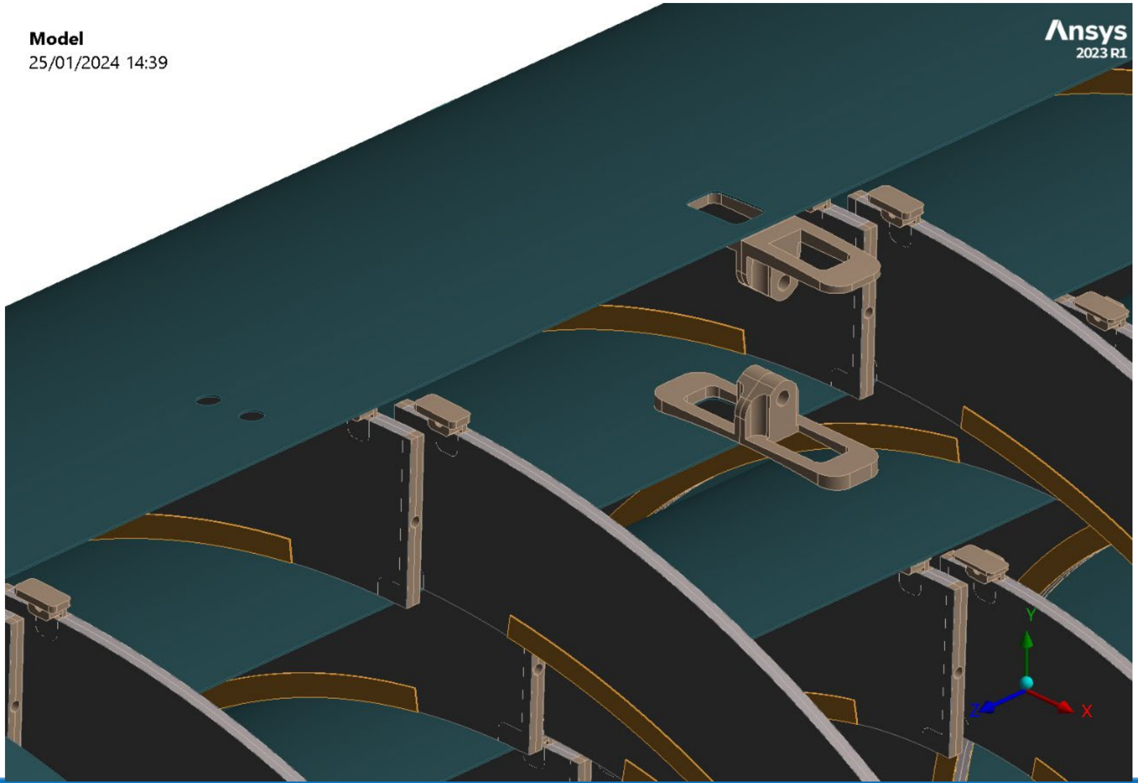
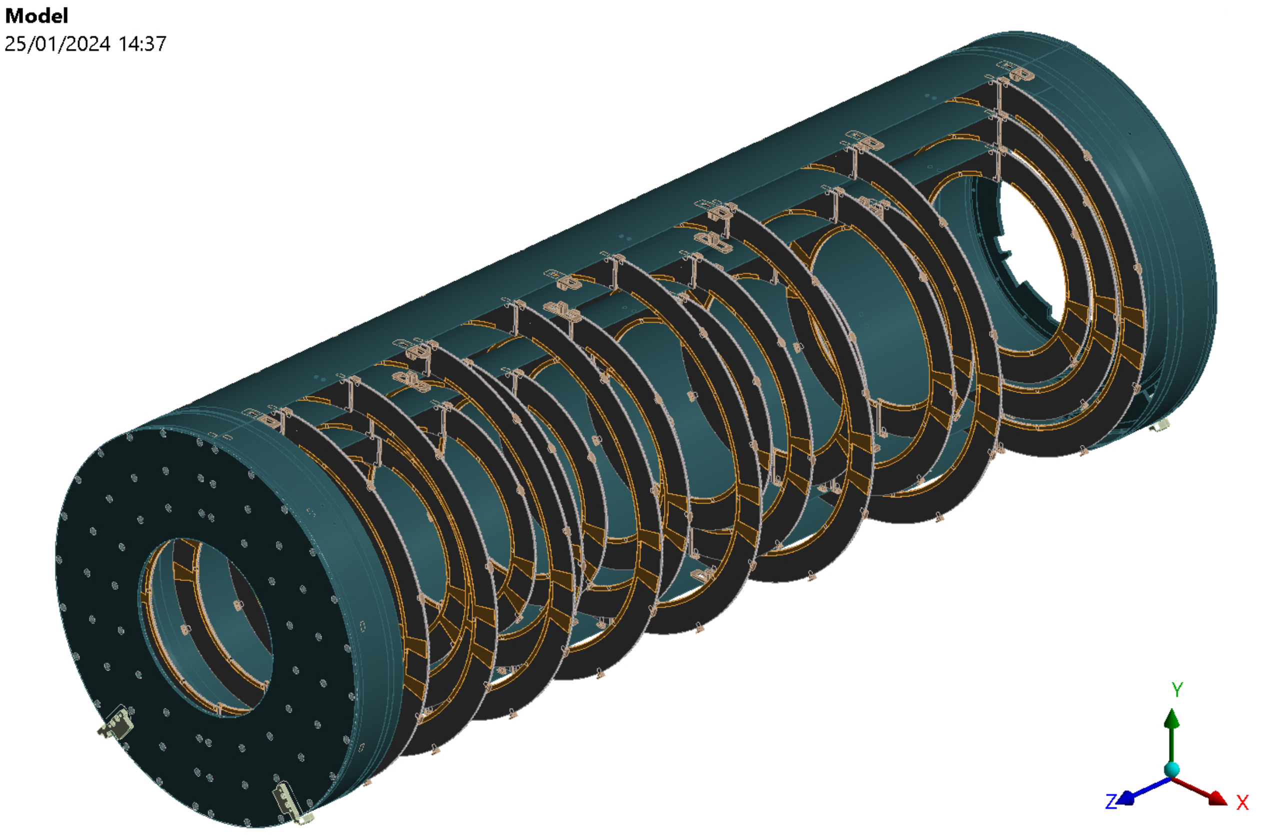
Overall OEC FEA model v.0

FEA model v.0 includes:

- Assembly of the three layers (L2, L3, L4): half-shells with end flanges, interlinks, mounting lugs, Half-Rings (n.22x L2, n.16 x L3, n.18 x L4).
- Front and rear supports and high Z joints.
- VEE and FLAT sliders (front and rear)





ATLAS ITk

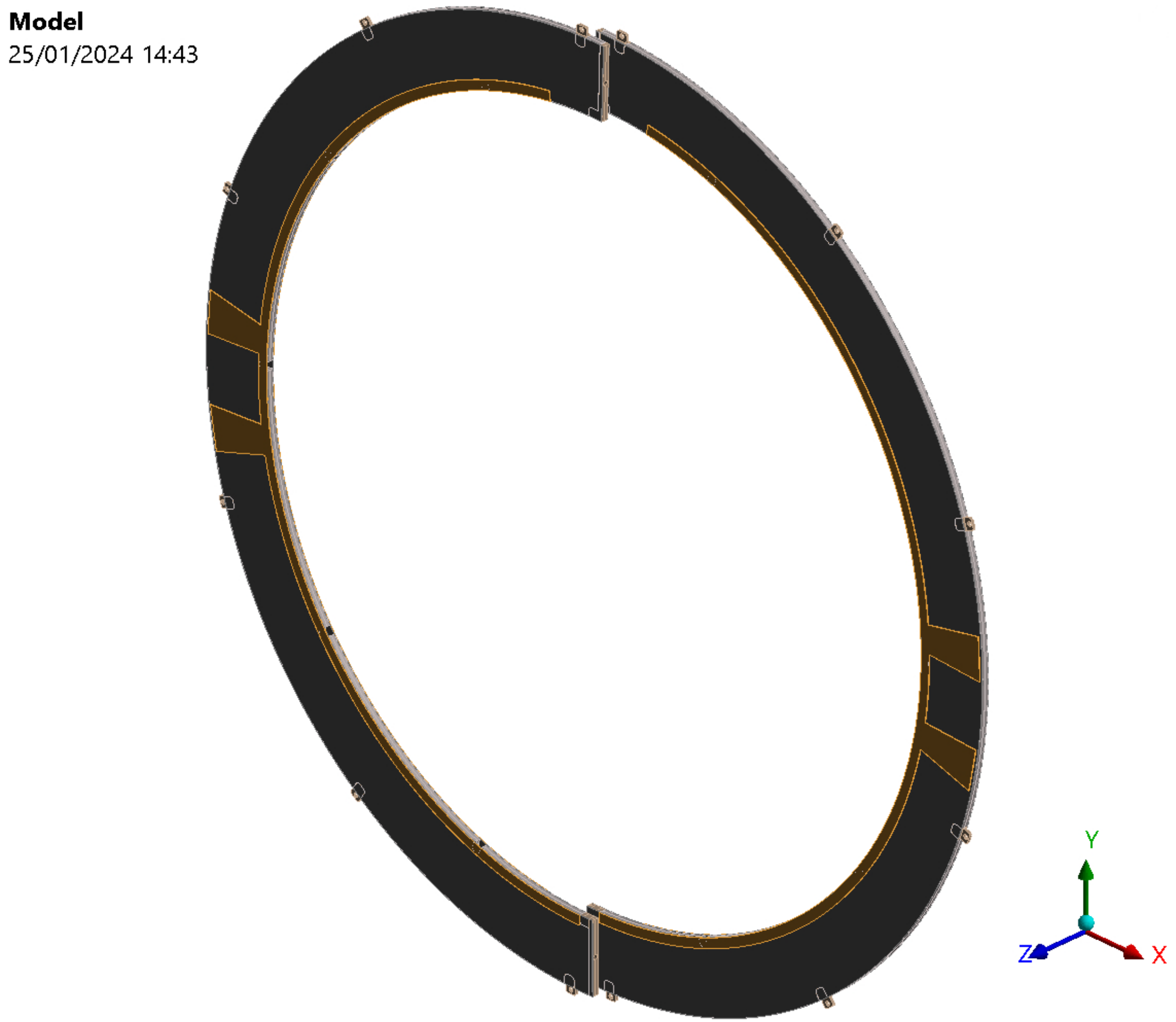
Overall OEC FEA model v.0

Half-ring assembly in the FEA model v.0 includes:

- CFRPs.
- Carbon foam.
- Lugs.
- Bus tape (necessary to obtain the right HRs deformation in thermo-mechanical simulations).

Intent: never include the geometries of the Pixel modules in the FEA model, defining their masses on their reference surfaces (possibly adding footprints on CFRPs).

Cooling pipe and fittings are too expensive to be modeled as geometries, so they could be considered as added mass.



Overall OEC FEA model v.0

Materials

defined as follow:

- **Half-ring facings**: CFRP **K13C2U/EX1515 [0/90/0] Vf 48.9%** – orthotropic properties calculated using EsaComp(R) software.
- **Half-ring carbon foam**: **LM K9 (0.40 g/cc).**
- **Half-ring lugs: ULTEM 1000**.
- **Half-ring bus tape v.6**: laminate orthotropic properties calculated using EsaComp(R) software.
- **Half-Shells with end flanges:** CFRP **M55J/EX1515 $[90/45/-45/0]_S$, Vf 46.5%, 620 µm thickness -** orthotropic properties calculated using EsaComp(R) software.
- **Interlinks/ mounting lugs: ULTEM 1000**.
- **OEC front and rear supports:** face sheets: CFRP **M55J/EX1515 [90/45/-45/0]S;** core: **honeycomb.**
- **VEE/FLAT support sliders: Titanium.**

***NOTE*:**

ANSYS ACP is too expensive in terms of nodes/elements to be used to model composites in this model, so we decided to proceed using their orthotropic properties.

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Half-shells material

properties of the HCS calculated by EsaComp software, as orthotropic solid.

UNIVERSITY OF LIVERPOOL

FEA Material properties

- *Data taken from LBNL Data sheet M55J EX1515 40% by mass*

				Imperial							Metric
1				Imperial							Metric
2	Material Properties of Test Sample										
3								Error Estimate			
4	FIBER	Fiber Modulus	E_{1f}	80,200,000	= Fiber Property	**Iterated to Match Test Data**	Reported Value =	79000000	Variance	1.52%	552,959,752,000
5	FIBER	Fiber Transverse Modulus	E_{2f}	1,000,000	$\sim x(E_m)$ where x =	2	(guess)				6,894,760,000
6	FIBER	Fiber Poisson Ratio	ν_{12f}	0.19	= Fiber Property	Occasionally Reported	(guess)				
7	FIBER	Fiber Shear Modulus	G_{12f}	33,697,479	$= E_{1f} / (2(1-\nu_{12f}))$						232,336,030,252
8	FIBER	Fiber Transverse Shear Modulus	G_{23f}	420,168	$= E_{2f} / (2(1-\nu_{12f}))$						2,896,957,983
9	FIBER	Fiber Transverse CTE	α_{ft}	2	=Fiber Property	Occasionally Reported	(guess)				
10	FIBER	Fiber CTE	α_f	-1.50	= Fiber Property	Reported Value	(guess)				
11	MATRIX	Matrix Modulus	E_m	500,000	= Matrix Property	Reported Value	(guess)				3,447,380,000
12	MATRIX	Matrix Poisson Ratio	ν_m	0.30	= Matrix Property	Occasionally Reported	(guess)				
13	MATRIX	Matrix Shear Modulus	G_m	192,308	$= E_m / (2(1-\nu_m))$						1,325,915,385
14	MATRIX	Matrix CTE	α_m	61	= Matrix Property	Reported Value					
15	LAMINA	Fiber Volume Fraction	V_f	46.5%	= Laminate Property	**Calculated From Test Data**					
16	LAMINA	Void Volume Fraction	V_v	0.0%	= Laminate Property	**TEST DATA**					
17	LAMINA	Matrix Volume fraction	V_m	53.5%	$= (1-(V_f + V_v)$						
18	LAMINA	Lamina Modulus 1 direction	E_{11}	**37,560,500**	$= E_{1f}V_f + E_mV_m$	**TEST DATA--iterate Fiber Modulus to Match**					258,970,632,980
19	LAMINA	Lamina Modulus 2 direction	E_{22}	651,466	$= E_m / (1- V_f (1- E_m / E_{2f})$						4,491,700,326
20	LAMINA	Lamina Shear Moduli	G_{12}	357,679	$= G_m / (1- V_f (1- G_m / G_{12f})$						2,466,114,116
21	LAMINA	Lamina Shear Moduli	G_{23}	257,155	$= G_m / (1- V_f (1- G_m / G_{23f})$						1,773,024,404
22	LAMINA	Lamina Shear Moduli	G_{13}	357,679	$= G_{12}$						2,466,114,116
23	LAMINA	Lamina Poisson Ratios	ν_{12}	0.25	$= \nu_{12f}V_f + \nu_mV_m$						0.25
24	LAMINA	Lamina Poisson Ratios	ν_{23}	0.27	$= (E_{22} / 2G_{23}) - 1$						0.27
25	LAMINA	Lamina Poisson Ratios	ν_{13}	0.25	$= \nu_{12}$						0.25
26	LAMINA	CTE Fiber Direction	α_{11}	-1.05	$=(\alpha_f E_{1f} V_f + \alpha_m E_m V_m) / E_{11}$						
27	LAMINA	CTE Transverse Direction	α_{22}	61.00	$\sim \alpha_m$						
28											

EX	258.970	GPa
EY	4.49	GPa
EZ	0.1	MPa
GXY	2.466	GPa
GYZ	1.773	GPa
GXZ	2.466	GPa
vXY	0.25	
vYZ	0.27	
vXZ	0.25	

Thickness per sheet 7.75 e-5m (80gsm)

Fiber Volume Fraction	V_f	46.5%
Void Volume Fraction	V_v	0.0%
Matrix Volume fraction	V_m	53.5%

ATLAS EXPERIMENT 18/03/2020 Endcap Global Supports Mechanical Prototyping 25

Half-cylinder

- Material: M55J/EX-1515
- Laminate $[90,+/-45,0]_s$

Shell thickness: 620 µm

Laminate engineering constants and expansion coefficients

Laminate : **M55J-EX1515 [90,45,-45,0]s**
Modified : Fri Sep 03 15:45:11 2021

Lay-up : (90a/+45a/-45a/0a)SE h = 0.62 mm

Ply
a M55J-EX1515

Moduli (GPa)

In-plane			Flexural		
E_x	=	89.85	E^f_x	=	26.88
E_y	=	89.85	E^f_y	=	157.12
G_xy	=	33.92	G^f_xy	=	23.86

Poisson's ratios

nu_xy	=	0.324	nu_yx	=	0.324

Thermal expansion coefficients

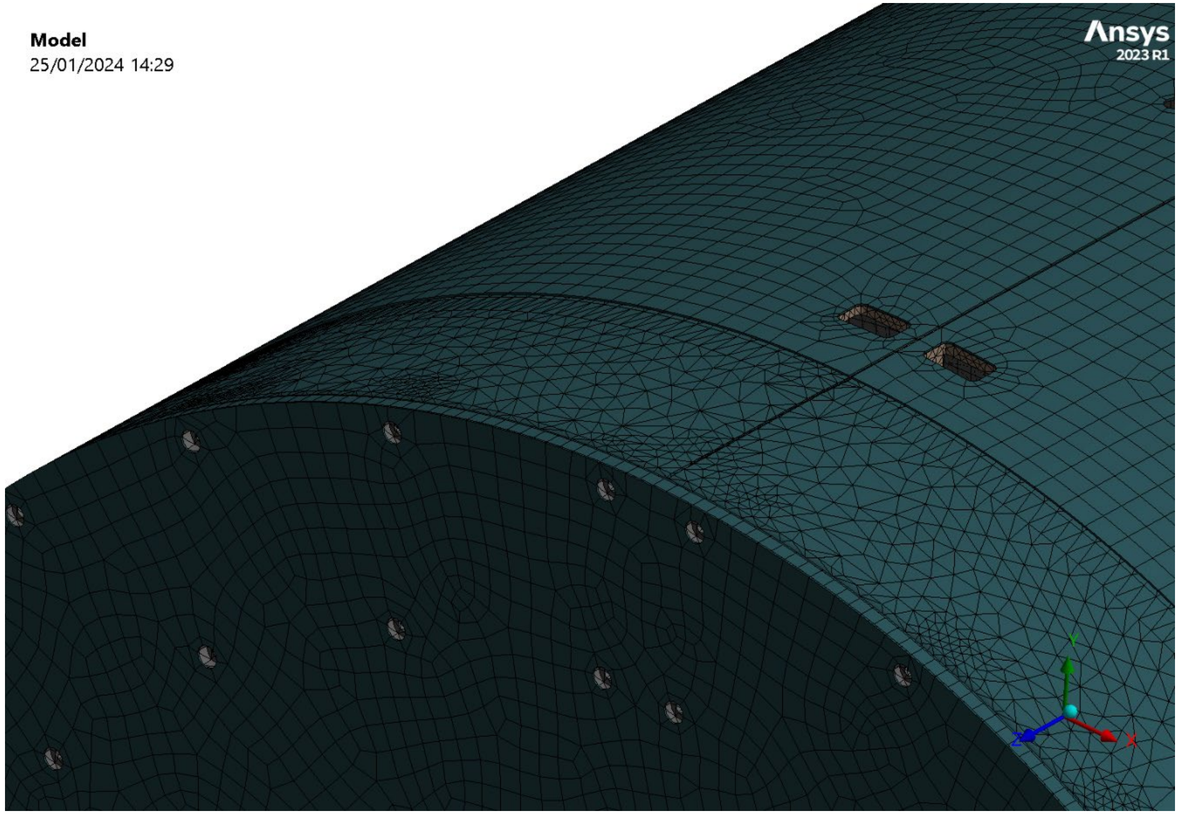
In-plane		e-6/°C	Curvat.		(1/m)/°C
alpha_x	=	0.261	delta_x	=	0
alpha_y	=	0.261	delta_y	=	0
alpha_xy	=	0	delta_xy	=	0

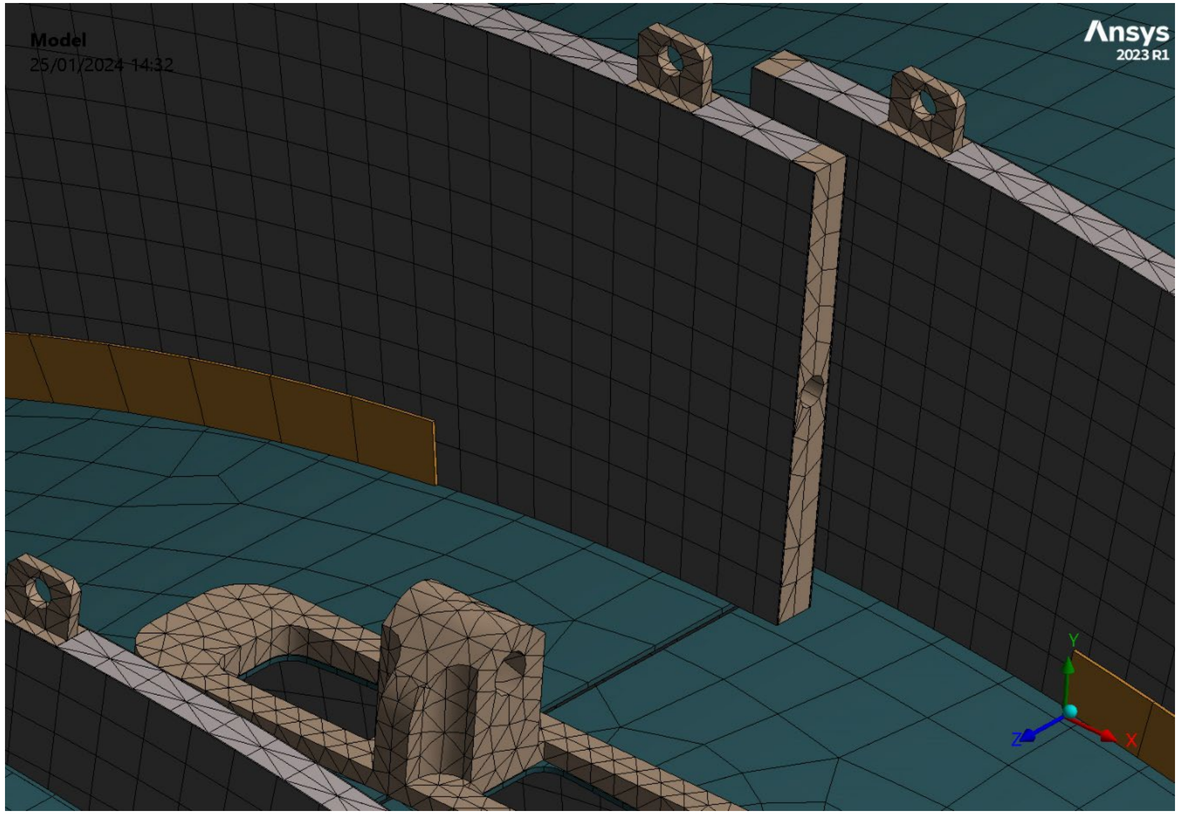
Overall OEC FEA model v.0

FEA Mesh

Nodes: ≈ 5 million. Elements: ≈ 1.5 million of 3D quadratic bricks, average aspect ratio: 10.

This model takes about half of the current calculation capability…further improvements are still possible.

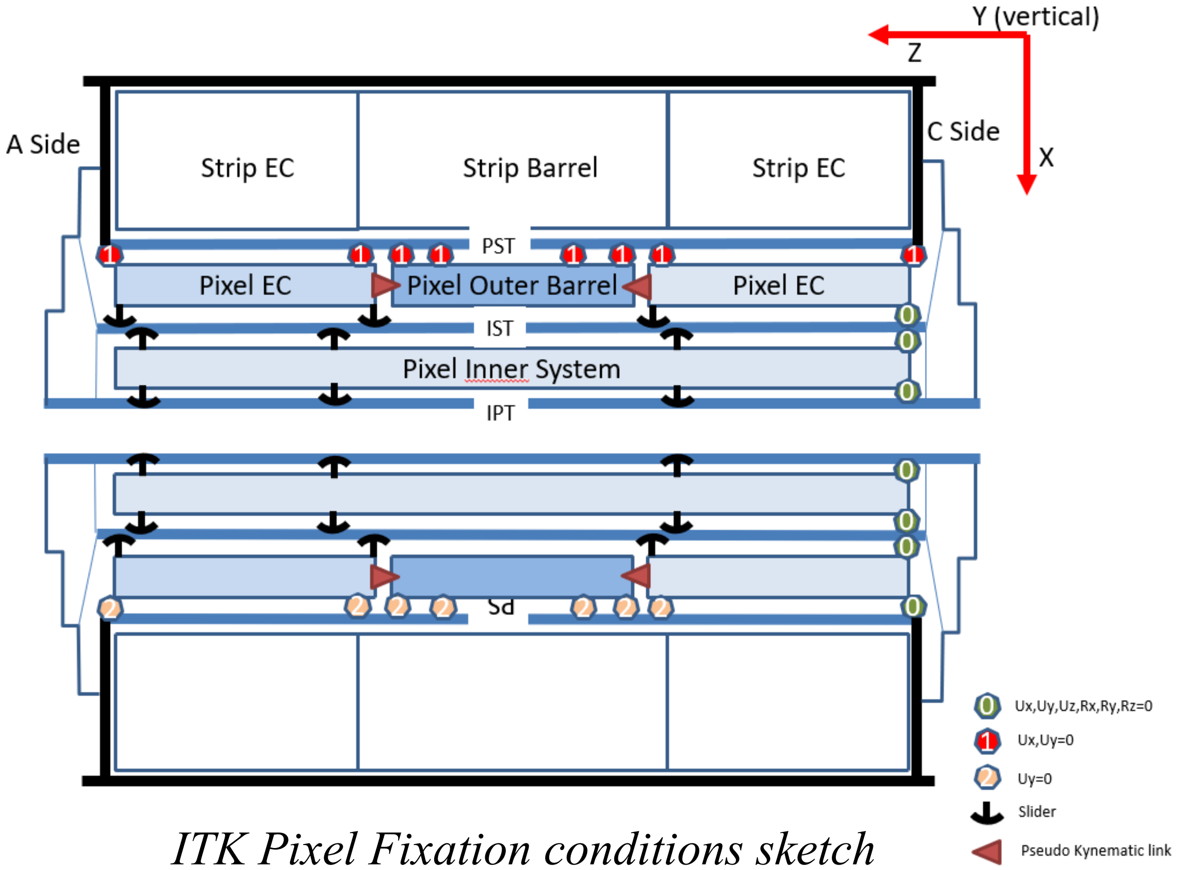




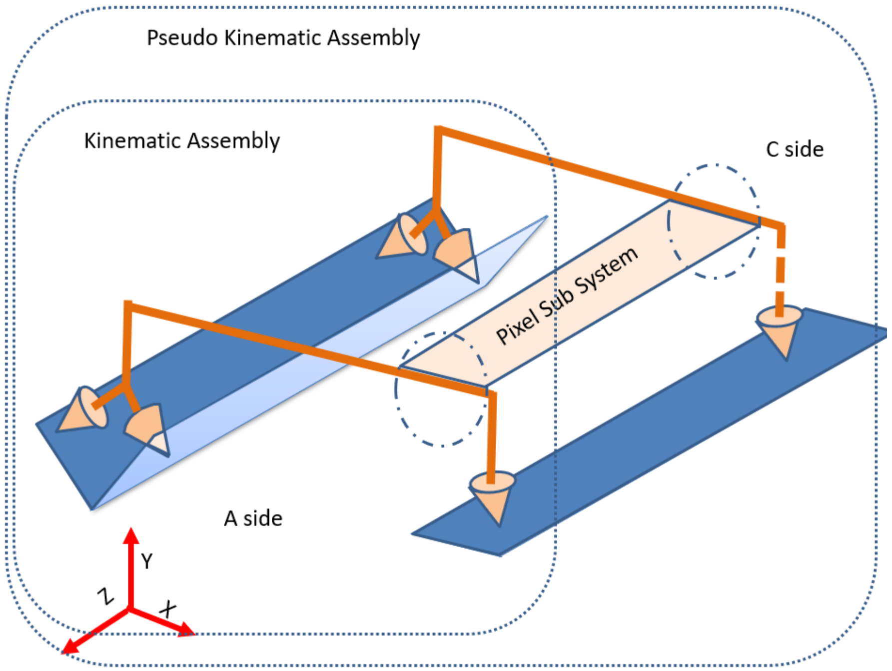
Overall OEC FEA model v.0

Pixel detector fixation conditions

Ref.: Global supports specifications for ITK Pixel - AT2-IP-ES-0007_V4.docx
EDMS: https://edms.cern.ch/file/2016196/4/AT2-IP-ES-0007_V4.docx



ITK Pixel Fixation conditions sketch



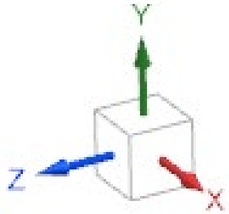
Kinematic assembly sketch

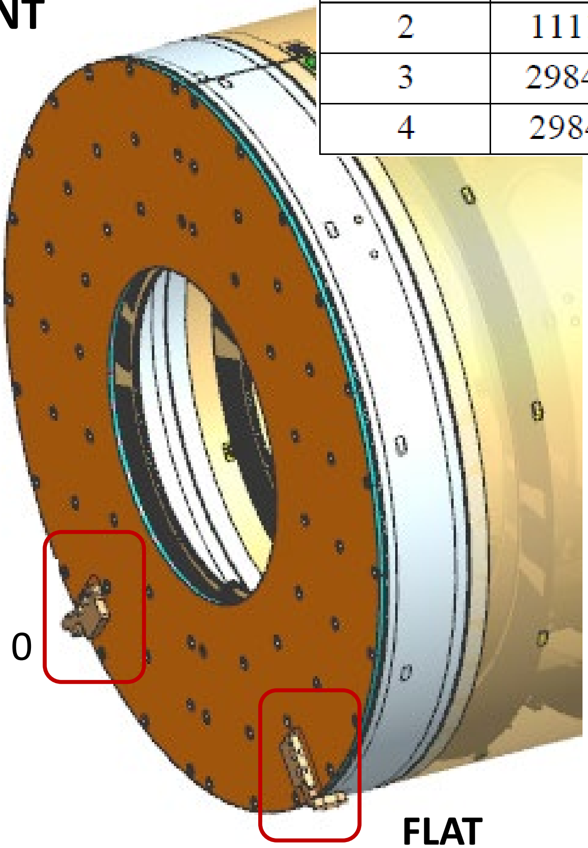
Overall OEC FEA model v.0

FEA Constraints on support sliders

Support	Location Z/phi	Ux	Uy	Uz
1	1111.5mm / +39°	Free	0	Free
2	1111.5mm / -39°	0	0	Free
3	2984.5mm / +39°	Free	0	Free
4	2984.5mm / -39°	0	0	0

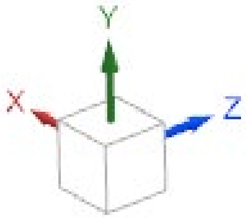
FRONT



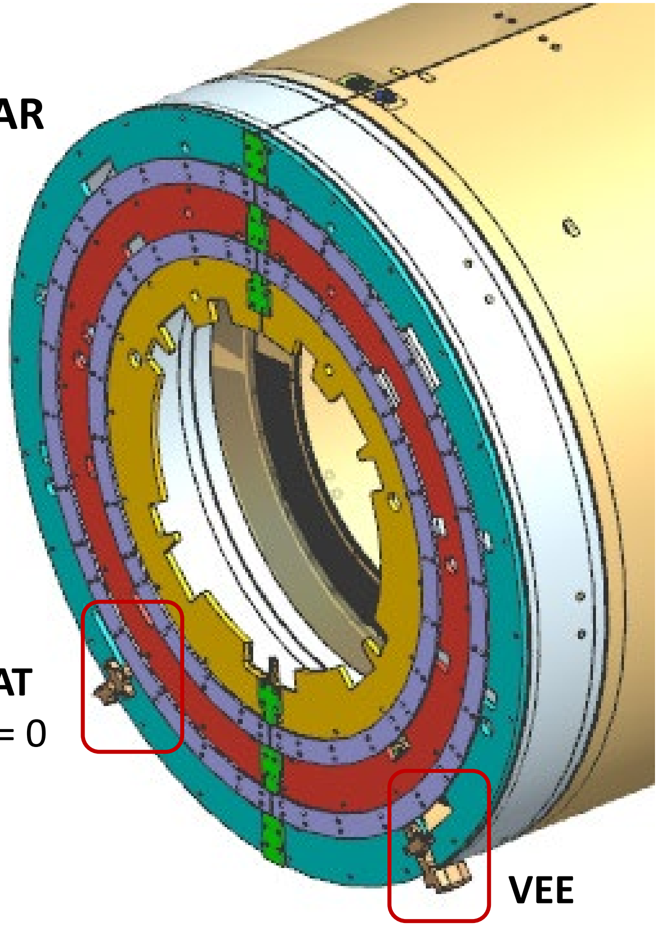


VEE
UX = UY = 0

FLAT
UY = 0



REAR



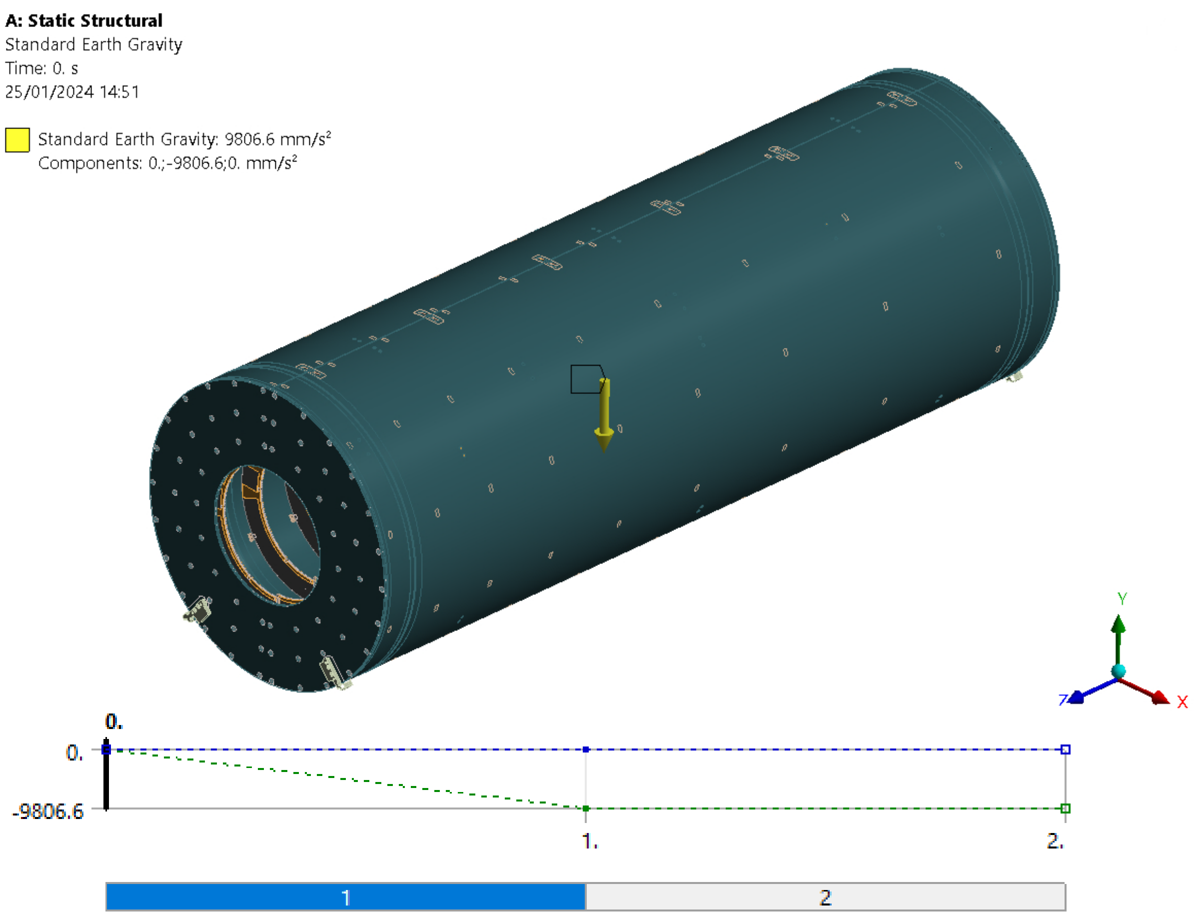
FLAT
UY = 0

VEE
UX = UY = 0
UZ = 0

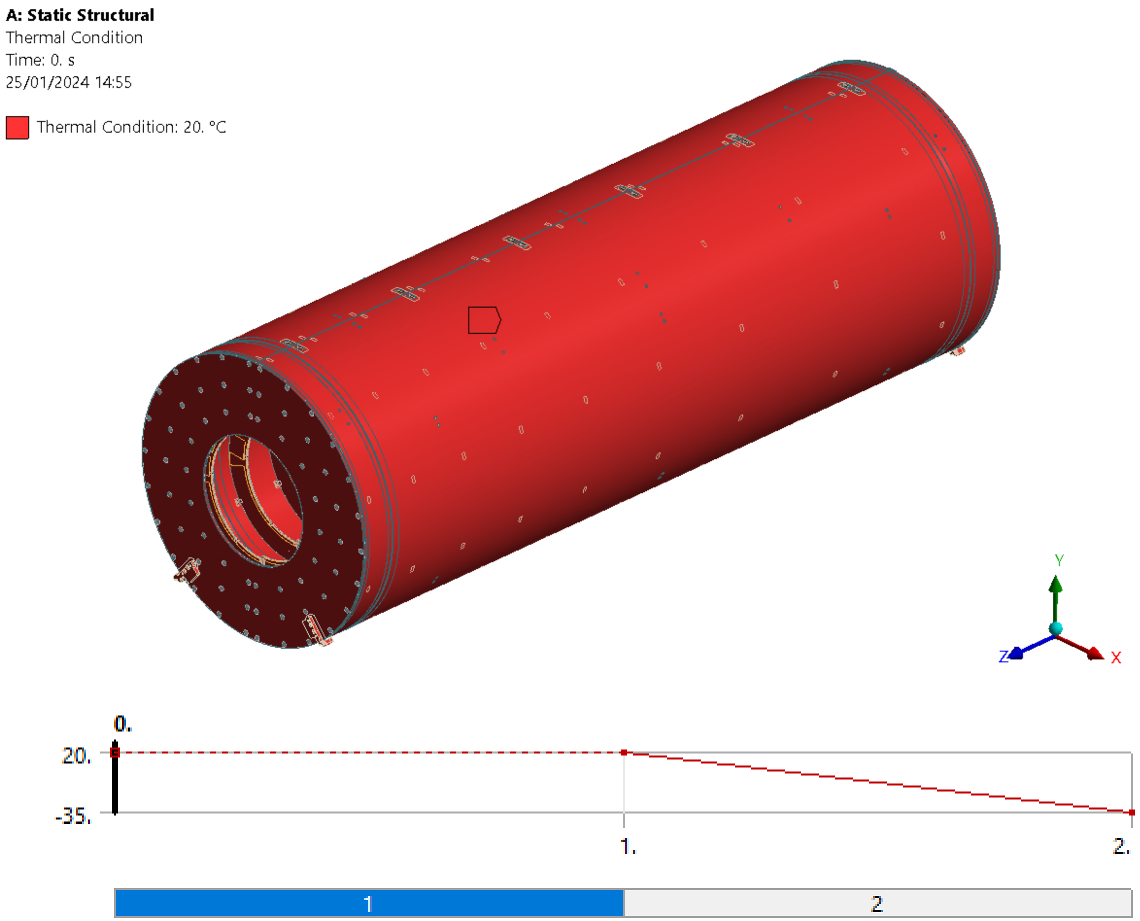
Thermo-Mechanical FEA of the OEC model v.0

Loads

Load step 1 : Gravity

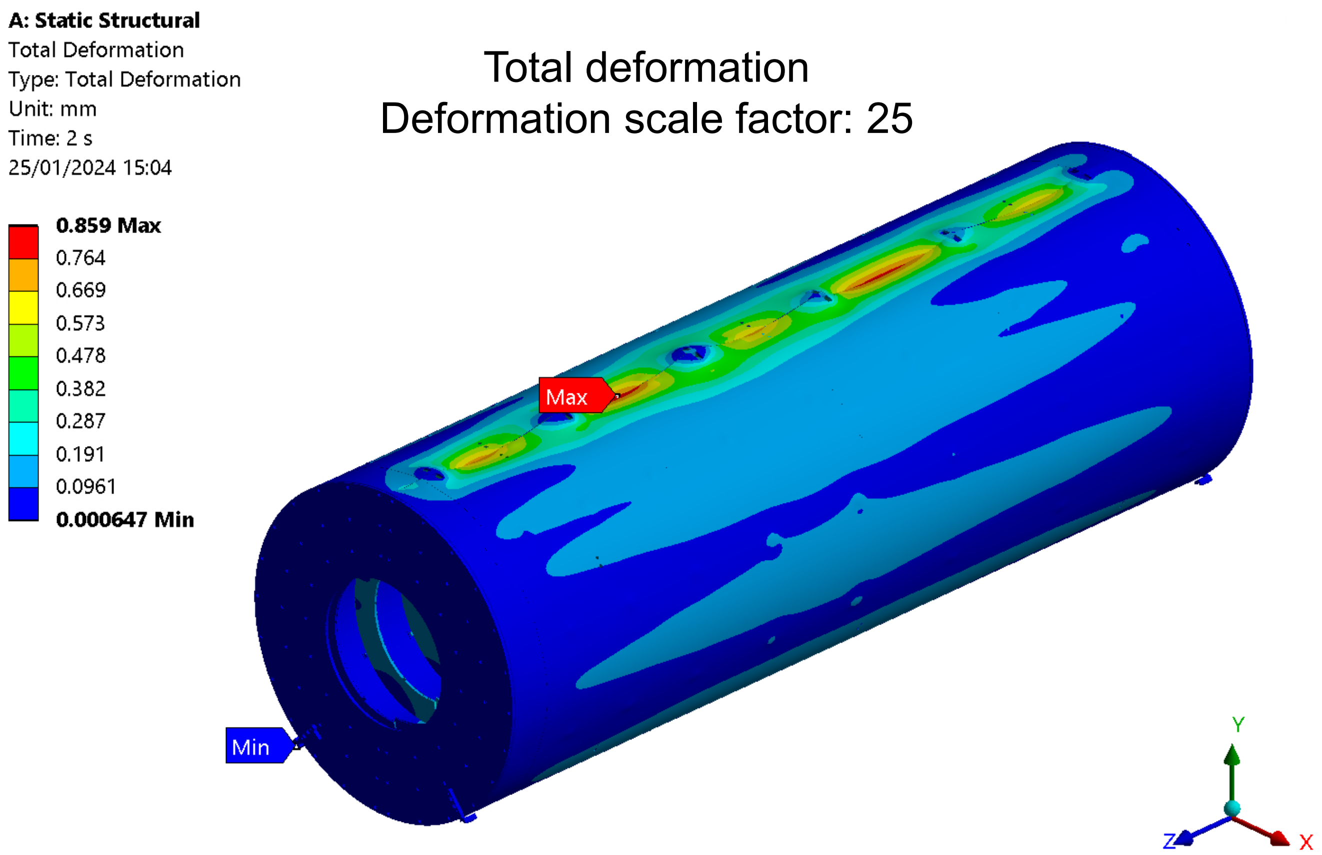


Load step 2 : Cooling down



Thermo-Mechanical FEA of the OEC model v.0

Thermo-mechanical Simulation of FEA model v.0 converges to solution



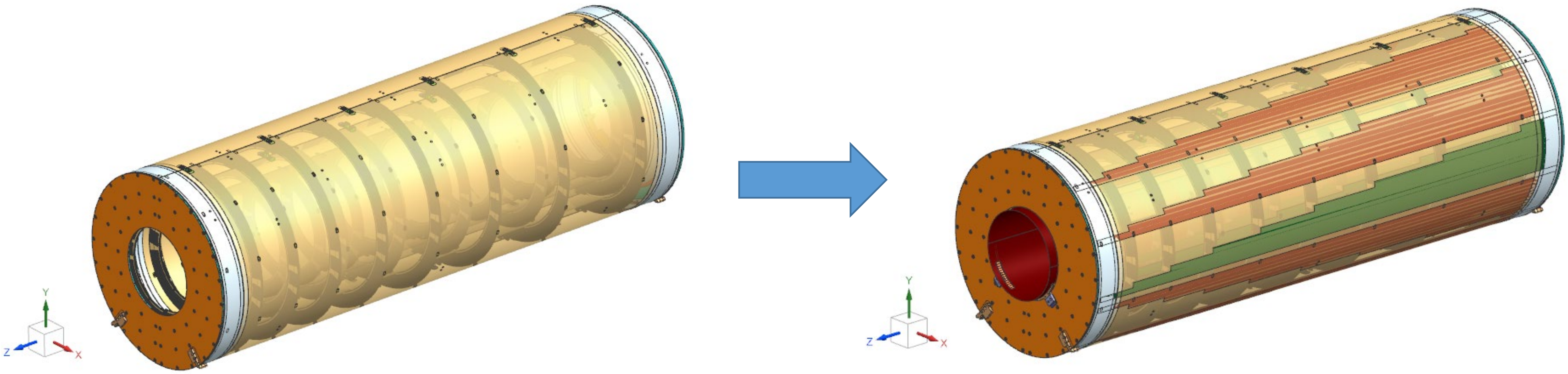
FEA model v.0 proves the capability to manage a thermo-mechanical simulation of the overall OEC within the current calculation limits in Milan.

Warning: results shown in this slide are qualitative only, due to the lack of modules/services masses in the FEA model.

Overall OEC FEA – towards the v.1 model

Implementation of the FEA model

The version 0 of the overall OEC FEA model is currently being implemented in a more “complete” version1.



Overall OEC FEA – towards the v.1 model

Masses to add

A complete FEA model requires a **precise definition of the masses not directly modelled** via CAD geometries/densities, to be added as distributed masses over reference surfaces. The masses of interest are listed in the table below (see highlighted cells), **all should be referred to one OEC**.

Ref.: ***AT2-IP-EN-0024 (rev.1.0) Description of the Global Mechanics and Integration Sequence for the Endcaps.***

Load Case	Component Mass in model (kg)						
	Struct.	Type1 Elec	Type1 CO2	Half-rings	OB Serv.	Inner Pixels	Mass
1	12.8						12.8
2	12.8	24.3					37.1
3	12.8	24.3	4.7				41.8
4	12.8	24.3	4.7	13.8			55.6
5	12.8	24.3	4.7	13.8	53.6		109.2
6	12.8	24.3 (1)	4.7 (1)	13.8	53.6 (2)	~~76.8~~ **41.875** tbc!	186.0

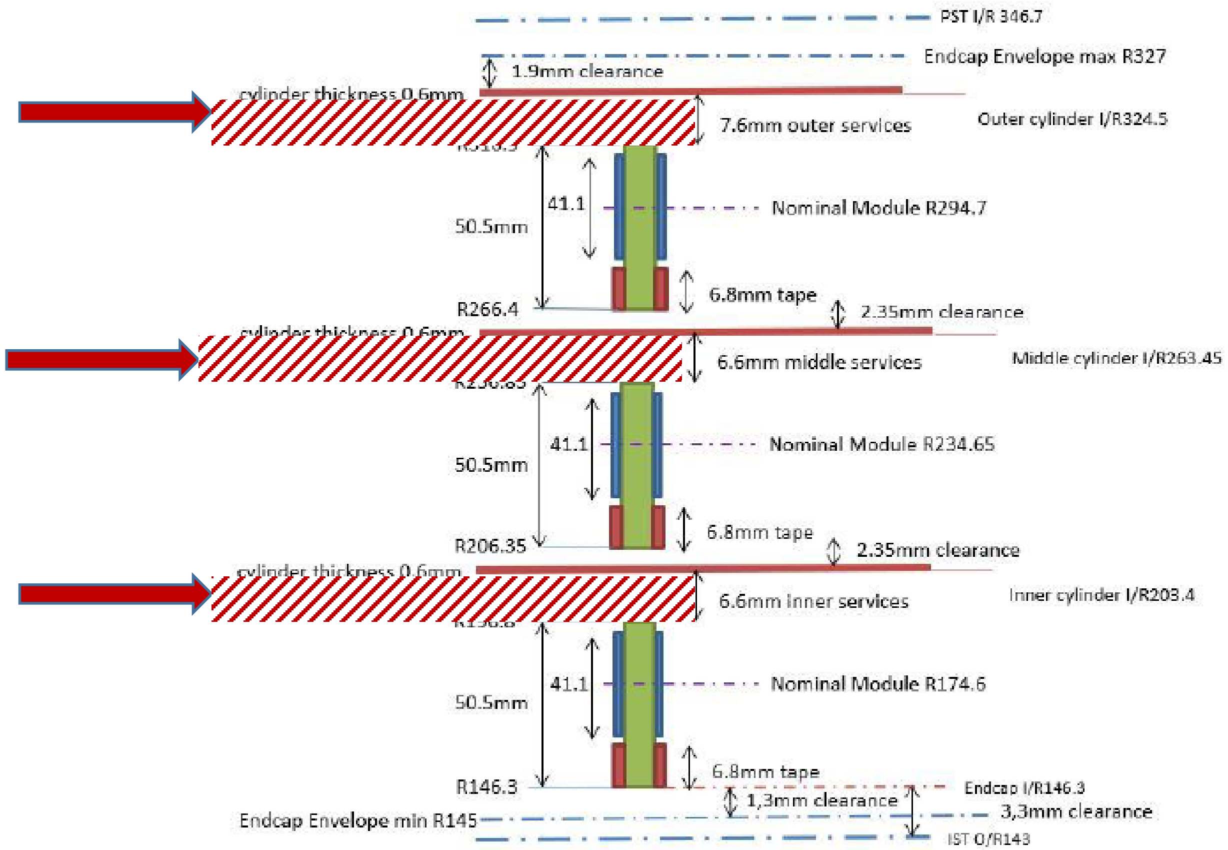
(1) Masses actually applied to one OEC in Tim's FEA (ref.*EndcapShellModelStaticDeflection.wbpj)*

(2) Mass applied to one OEC in Tim's FEA: 44 Kg (?)

Overall OEC FEA – towards the v.1 model

Masses of OEC Type-1 Services

Type-1 services (CO_2 cooling lines and electrical services) will be implemented in the FEA model as distributed masses, without their specific 3D geometries. Type-1 services, for each layer, are allocated to a dedicated annular volume, between the inner surface of the half-shells and the outer circumference of the half-rings, as shown below.

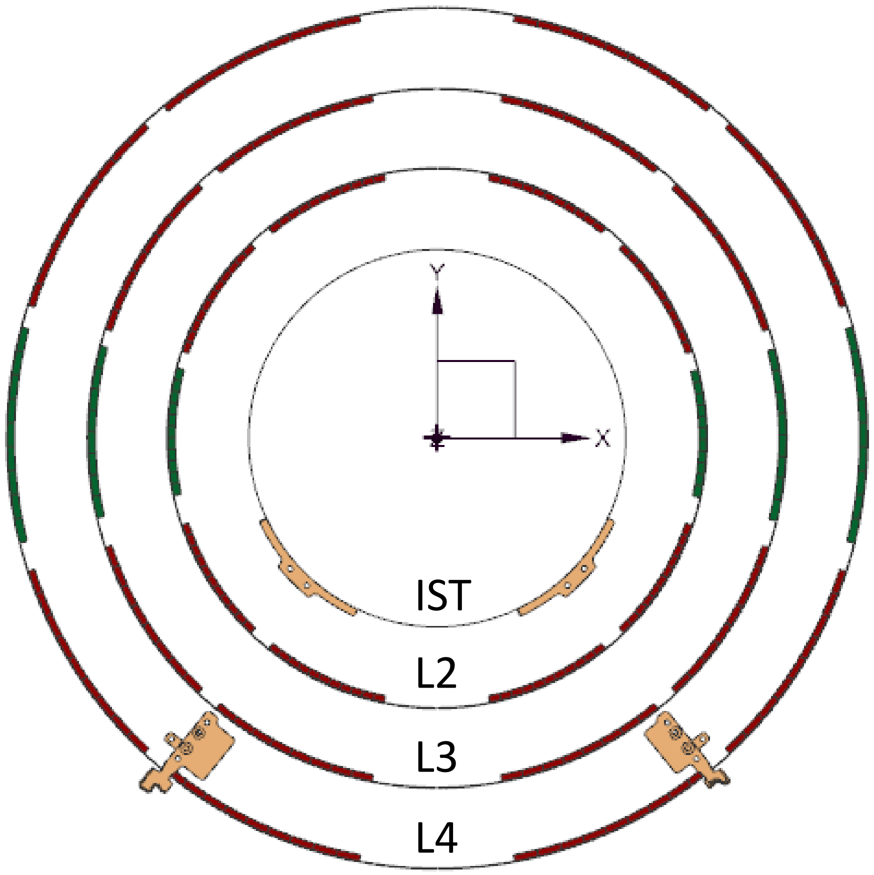


Reference for dimensions:
Peter Sutcliffe's envelope drawing (2019)

Overall OEC FEA – towards the v.1 model

Masses of OEC Type-1 Services

In **previous simulations** (Tim),for each half-shell, the Type-1 electrical services were bundled into four identical (red) annular volumes whilst the Type-1 cooling structures were grouped together into a (green) fifth annular volume.

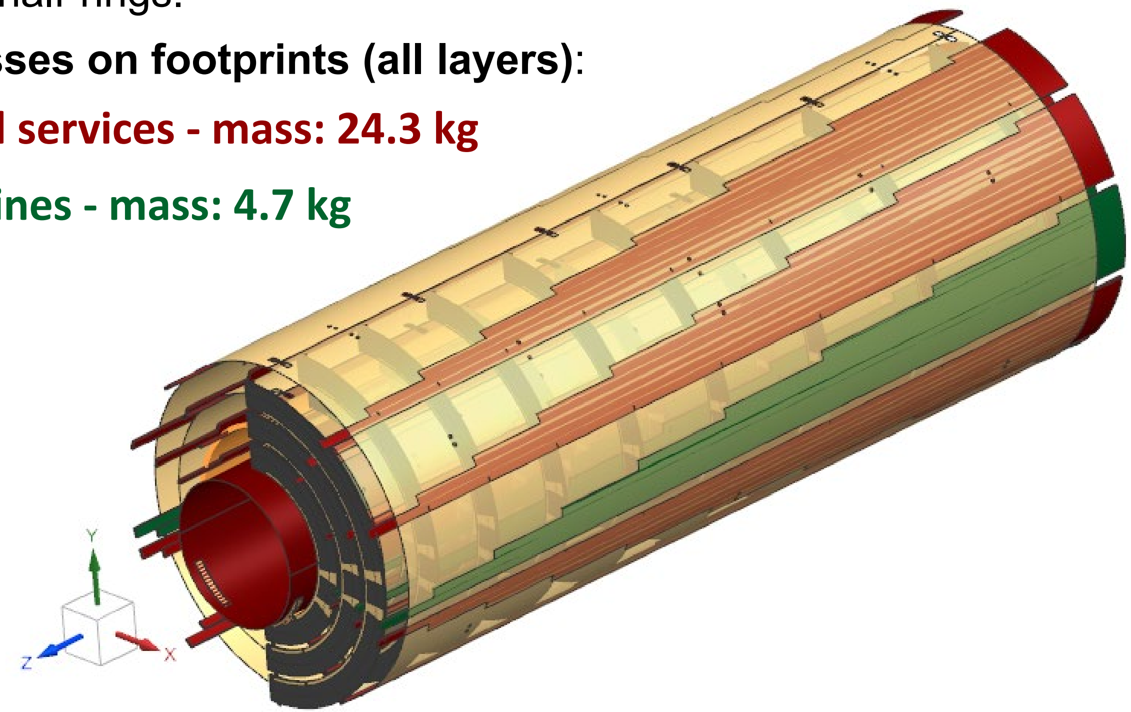


Now: relevant bundle surfaces must be imprinted on the inner wall of the half-shells and divided up into as many sections as the half-rings. The length of each section varies according to the Z position of the half-rings.

Distributed masses on footprints (all layers):

Type-1 electrical services - mass: 24.3 kg

Type-1 cooling lines - mass: 4.7 kg



Overall OEC FEA – towards the v.1 model

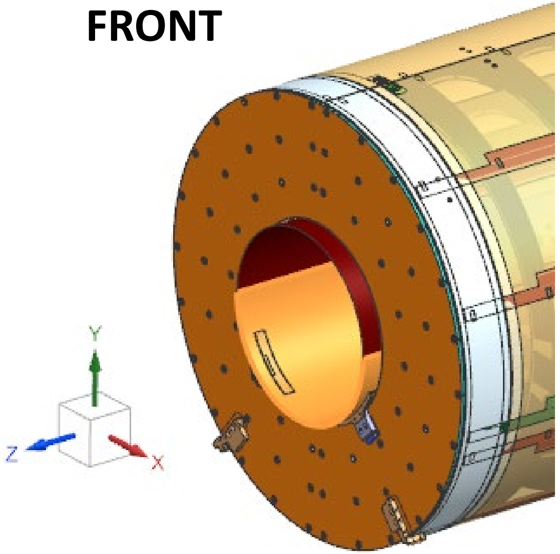
Masses of IS, IST, beam pipe

The overall load due to the Inner System is calculated by summing the mass of the **IS (73.70 kg)**, the **IST (6.40 kg)**, and the **beam pipe (3.65 Kg)** [3]**.** The **assumption** is that **this total mass (83.75 Kg) is shared equally by the two OECs.**

IST will be added to the FEA model as a continuous shell passing through the entire endcap, to account its stiffness, with assigned thickness = 0.6 mm and the same material properties of the half-shells. In the FEA model IST will be connected to the front/rear supports of the OEC by simplified supports. A**ssuming the mass of IST comes via geometry/calculated density in the FEA model (3.20 Kg),** in conclusion **the distributed mass to be applied on the lower half of the IST** should be:

[73.70 Kg (IS) + 3.65 kg (b.p.)]/2 = **38.675 g** (**to be confirmed**).

FRONT



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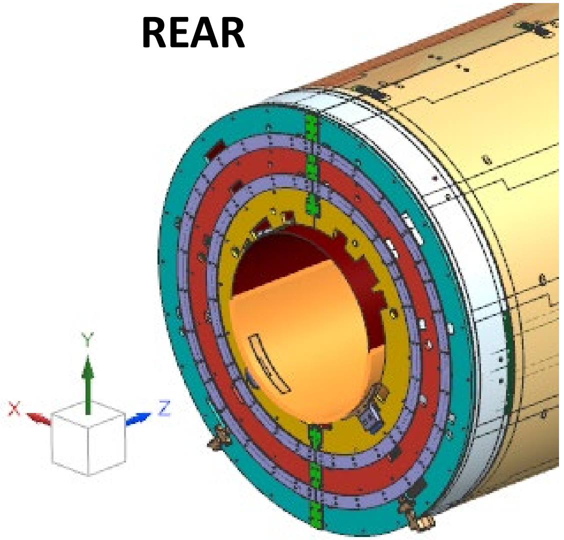
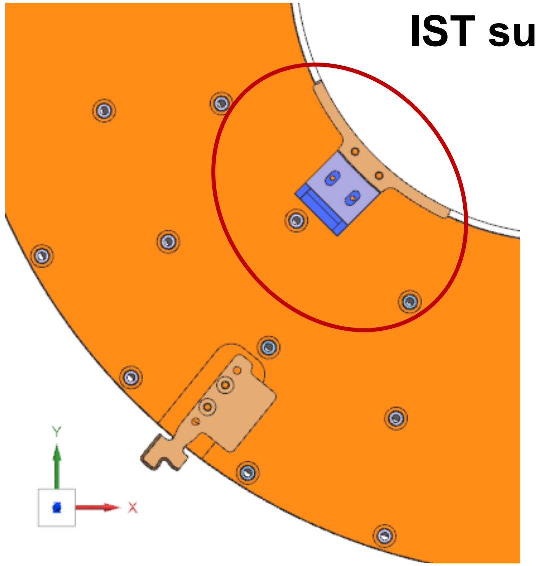


IST support

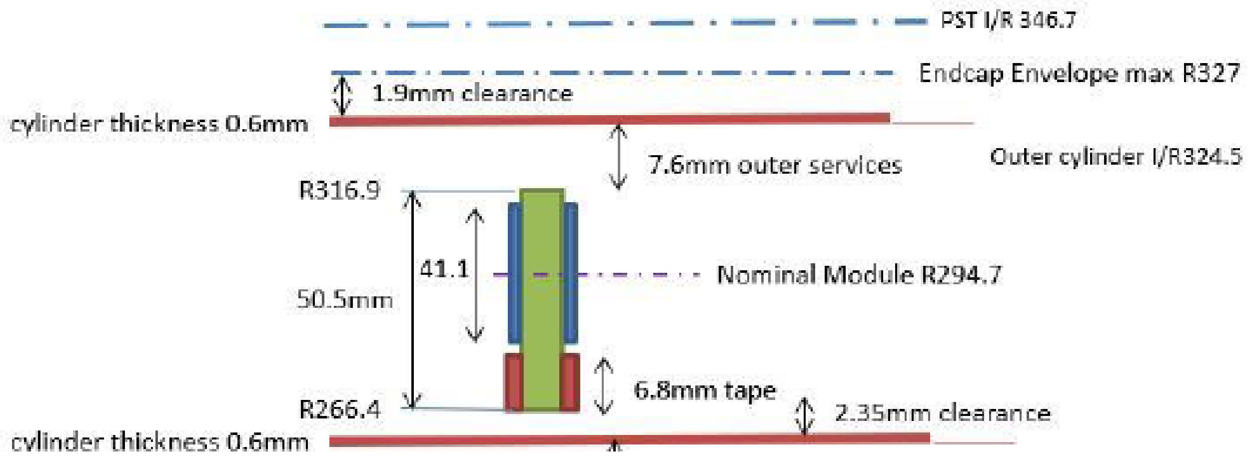


[3] Ref.: *AT2-IP-EN-0024 (rev.1.0) Description of the Global Mechanics and Integration Sequence for the Endcaps.*

Overall OEC FEA – towards the v.1 model

Mass of the OB Type-1 services

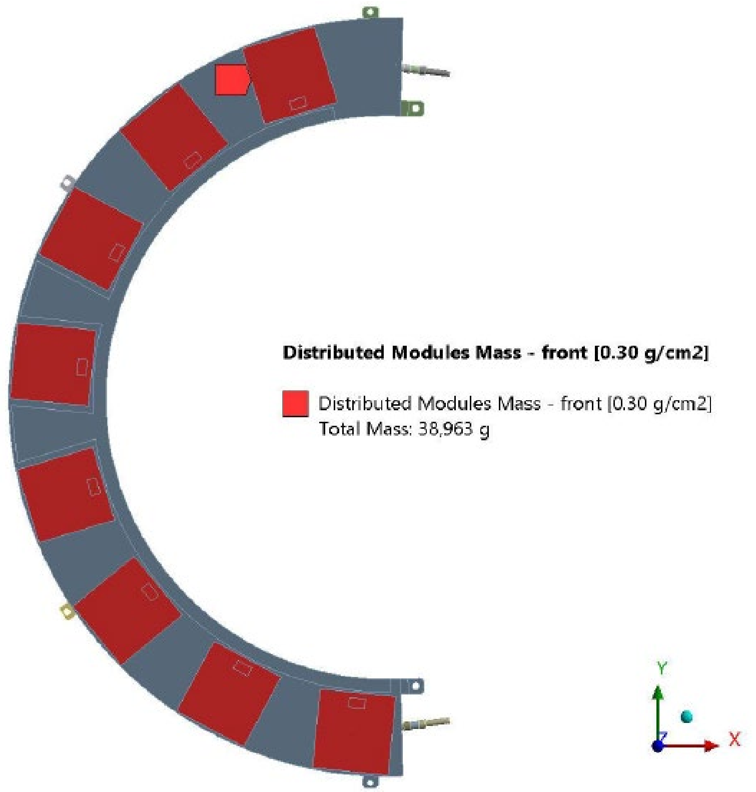
The OB Type-1 services run in a cylindrical corridor supported by half-shells at inner radius 327 mm, while the outer radius of the L4 half-shells is 325.1 mm. Not known, for now, engineering details of the connection between them through the gap of 1.9 mm, so the mass of the OB Type-1 services has been applied on to the outer surface of L4 half-shells at radius **325.1 mm**.
The **mass of the OB Type-1 services**, to be applied as uniformly distributed mass on to the two Layer 4 half-shells in the FEA model, **should be 53.6 Kg** (see note (2) in slide #13).



Overall OEC FEA – towards the v.1 model

Masses of the Pixel Modules

The masses of the Pixel modules loaded on each half-ring flavour were calculated for the step1 of the thermo-mechanical simulations carried out for the bare LS FDR (Oct. 2021). Below the results of this calculation.



To perform the **Step 1** of the thermo-mechanical FEA the modules are not modelled explicitly, but they are added as distributed masses, corresponding to **0.3 g/cm²** per unit of active area.
In the FEA model the footprint of the Module Assembly, imprinted on the CFRP, is identical to that of the corresponding sensor: 39.5 mm x 41.1 mm (**Figure 6.2**). Below the calculation of EMM (Estimated Module Mass) for the three different Half Ring flavours:

- **Inner Half Ring** – total number of modules: 16 (8 per side)
  Total mass per Half Ring side: 8 x (3.95 x 4.11) x 0.3 = **38.963 g**.
- **Middle Half Ring** – total number of modules: 22 (11 per side)
  Total mass per Half Ring side: 11 x (3.95 x 4.11) x 0.3 = **53.574 g**.
- **Outer Half Ring** – total number of modules: 26 (13 per side)
  Total mass per Half Ring side: 13 x (3.95 x 4.11) x 0.3 = **63.315 g**.

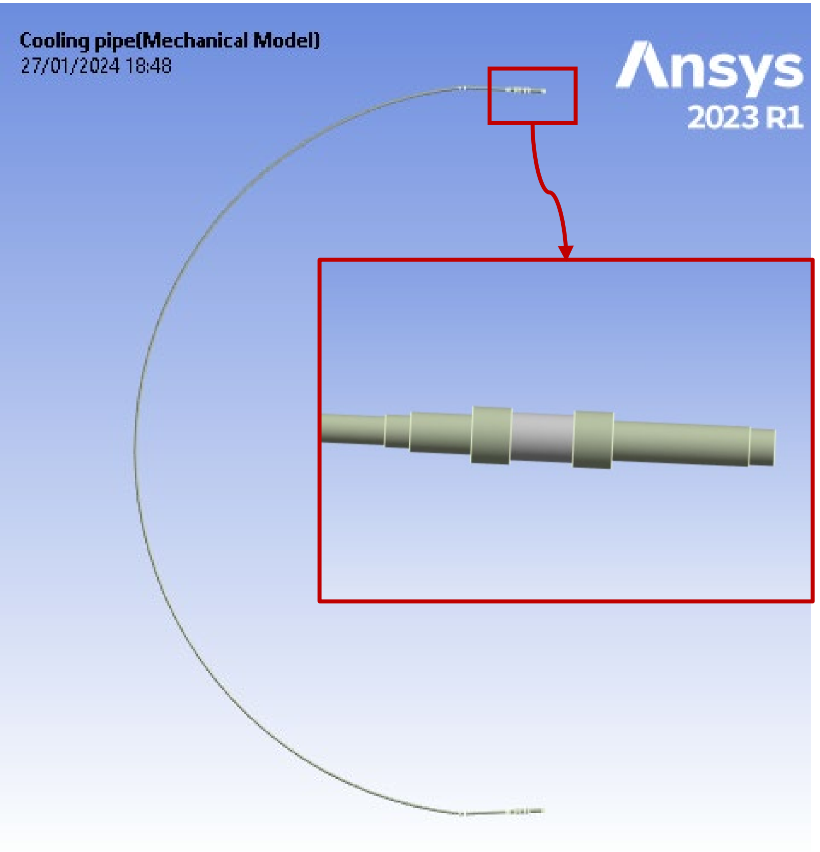
Ref.: AT2-IP-ER-0010-1_v.0-Inputs_for_the_Thermo-mechanical_Finite_Elements_Analysis_of_the_HalfRings

EDMS: https://edms.cern.ch/document/2474998/3

Overall OEC FEA – towards the v.1 model

Masses of the half-rings evaporators

The masses of the evaporators of the half-rings, each one composed by cooling pipe (titanium grade 2), electrical breakers (alumina ceramic of 97.6% content) and fittings (titanium grade 2), have been calculated by ANSYS via geometries/ materials density defined in the half-rings FEA models.



- **L4 half-ring evaporator: m = 5.100 g**
- **L3 half-ring evaporator: m = 4.578 g**
- **L2 half-ring evaporator: m = 4.406 g**

L2

Entity	Volume (cm³)	Mass (g)
7 Bodies, Summary	1.0065	4.406

L3

Entity	Volume (cm³)	Mass (g)
7 Bodies, Summary	1.0448	4.5781

L4

Entity	Volume (cm³)	Mass (g)
7 Bodies, Summary	1.1607	5.0998

Overall OEC FEA – towards the v.1 model

Missing data for a complete definition of the v.1 FEA model

What is **still missing** for a complete definition of the model v1?

- **C-rings supporting the Type-1 Services** could provide significant stiffness to the half-shells: if available in a reasonable time, these geometries could be added in the FEA model (Tim).
- **Reaction forces due to the thermal contraction and internal pressurization of the Type-1 cooling lines**, calculated by dedicated FEA simulations (Liam).
- The **total mass of 83.75 Kg** due to the IS, weighing on the two OECs, must be confirmed (Danilo?).

Thermo-Mechanical FEA of the overall OEC model

Simulations list

As soon as the version 1 of the FEA model will be ready, simulations can start.
To define a list of simulations to do, is useful to have a look at the **Global Mechanics Specifications.**
Table below shows the **loads relevant to the OEC global supports** and is a summary of *section 4* of *AT2-IP-ES-007 Rev 2.*
Highlighted in yellow the relevant for this study.

Load Id	Title	Load Range
1	Operational Temperature Range (OTR) Design Temperature Range	-45°C < T < 40°C -55°C < T < 60°C
2	Maximum Design Pressure (MDP)	162 bar
3	Heat Load (Type 1 services = 10% FE)	T < OTR (H)
4	Moisture Absorption	(20°C / 50%RH) to (OTR(L) / N_2)
5	Mass (all quoted for one side and excluding 1.5 safety factor)	Endcap (Z<2850) = 56kg Barrel Type 1 Services = 54kg Inner System = 38kg
6	Radiation Environment	NIEL: 4 x 10^{15} 1MeV neq cm^{-2} TID: 3.5MGy
7	Transport	DC-18 Power Spectral Density
8	Insertion (Slider/rail friction coefficient = 0.23 x SF=1.5)	Mass on EC sliders = 148kg

Ref.: *AT2-IP-EN-0024 (rev.1.0) Description of the Global Mechanics and Integration Sequence for the Endcaps.*

Thermo-Mechanical FEA of the overall OEC model

Simulations list

Table below is a compilation of specifications from *section 6* of *AT2-IP-ES-007 Rev. 4* and summarizes the performance specifications the endcap global supports must meet.

Spec. ID	Title	Specification Range
0	General Design Parameters (PST rails)	Abs. pos.: +/- 0.25mm over 2.4m Straightness: +/-0.25mm over 2.4m
1	Envelope with all loads applied (use design temperature range and mass SF = 1.5)	No violation of envelope with gravitational and thermal loads applied
2	Assembly Precision (hermeticity)	Half-ring mounting points within +/- 0.4 mm of nominal OB/EC coaxial alignment < 0.8mm EC/IS coaxial alignment < 0.4mm
3	Geometric Stability 3.1 (Gravitational sag) & 3.2 (first vertical mode) 3.3 (Short Term Stability: Power=10%, T_{evap}=1°C) 3.4 (Long Term Stability: RH=10%, T_{evap}=3°C)	Sag <0.5mm / f_0(V) > 25Hz δR<14µm, δRphi<3µm, δZ<30µm δR<14µm, δRphi<7µm, δZ<30µm
4	Cooling manifold leak tightness	< 1×10^{-9} atm.cc.s^{-1} (at 100% He. conc.)
5	Operating environment	See AT2-I-ES-0001

Ref.: *AT2-IP-EN-0024 (rev.1.0) Description of the Global Mechanics and Integration Sequence for the Endcaps.*

Thermo-Mechanical FEA of the overall OEC model

Simulations list

It's fairly clear that **the first steps should be**:

1. **Simulation of the gravitational deflection** of the OEC @+20°C (Spec. ID 3), applying g = 9.806 m/s^2.
   Requirement: Sag < 0.5 mm.
2. **Modal analysis of the first vertical vibration mode** (Spec. ID 3).
   Requirement: f_0 > 25 Hz.
3. **Thermo-mechanical simulation of the OEC in nominal operating condition**: iso-thermal temperature @ -45°C (OTR) applied to all the structures and gravity g multiplied for safety factor 1.5 (Spec. ID 1).
   Requirement: no violation of the envelope.

Is all this in time for G&I FDR scheduled in march 2024?
Not possible to say now, every possible effort will be made, but it depends on a good response of the model.

Following:

4. **Failure condition:** one layer @ -55°C, two other layers @ -45°C, gravity g multiplied for safety factor 1.5?
5. **Stability FEA studies** (Short term and Long term).

Conclusions

- The **development of an overall OEC FEA model to perform thermo-mechanical simulations is currently underway** in Milan, since the beginning of January 2024.
- A **preliminary simplified FEA model**, called "version 0", works well and **can converge to the solution of a thermo-mechanical analysis** in a reasonable time.
- **The preliminary FEA model is currently being implemented to a more complete version 1**, which include all the masses and the relevant geometries, with the purpose to perform significant simulations for the OEC Pixel Collaboration, towards the G&I FDR and beyond.
- **Some data from the Pixel OEC Collaboration are necessary to proceed,** they are listed in this presentation.
- A **list of the priorities regarding the FEA simulations has been established** and presented today.
- The management of INFN and ATLAS group in Milan approved our proposal to implement the FEA calculation capability two weeks ago. The timing is unpredictable for now but, reasonably, **within few months we should be able to manage and solve more complex FEA simulations.**

Back-up slides

Masses of IS, IST, beam pipe

Ref.: *AT2-IP-EN-0024 (rev.1.0) Description of the Global Mechanics and Integration Sequence for the Endcaps.*

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4.3.1.8 OB services and IS masses

The mass of the OB Type 1 services for the 4MHz readout option (old baseline) is applied as a uniformly distributed mass of 26.8kg on to the two Layer 4 half-shells (DAF – 14/4/20). The load imparted by the Inner System is found by summing the mass of the IS (73.7kg), the IST (6.4kg), the beam pipe (26.8kg) = 107.7kg. Assuming this mass is shared equally by the four OE support points corresponding to a mass of 26.9kg bearing on the lower half of each IST support ring. Unfortunately, an un-intended safety factor of 1.5 was applied to this mass in the solutions presented below making the mass at each point equal to 38.4kg. In addition, the mass of the beam pipe used here came from a previous version of AT2-IP-ES-0007 which has subsequently found to be in error. The actual mass is 3.65kg. The FEA will be repeated with up-to-date loads as soon as possible in early 2021.

Routing of Type-1 services

Ref.: F. Gannaway model file: *DISC_ARRAY_INNER_LH_ASM_29-6-22.stp*