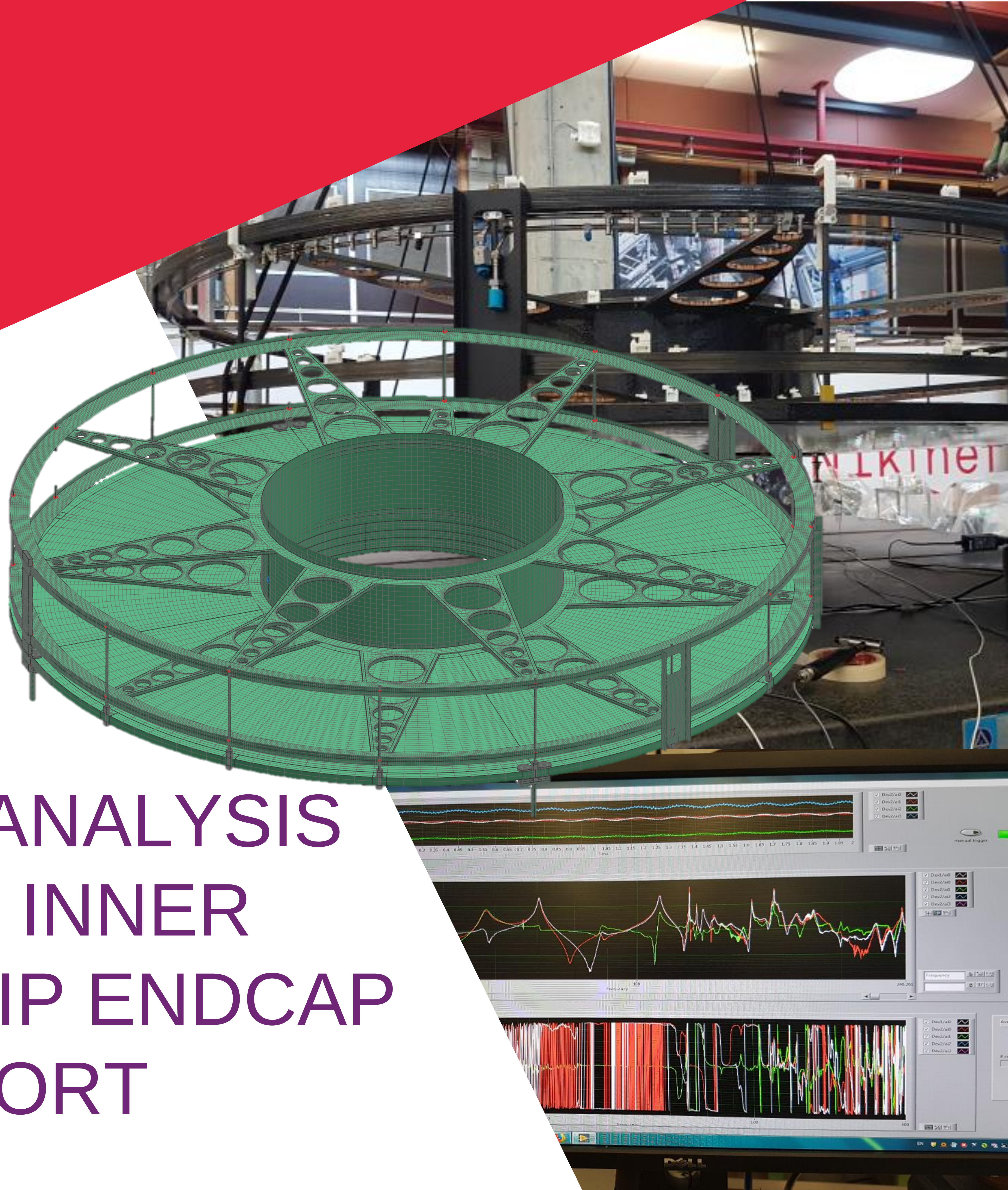
Nikhef



MECHANICAL ANALYSIS OF THE ATLAS INNER TRACKER STRIP ENDCAP GLOBAL SUPPORT

CONTENTS

- **Introduction**
- Requirements
- Envisioned Design

- Simulation Goal
- Simulating the Endcap
- Endcap Simulation History & Software

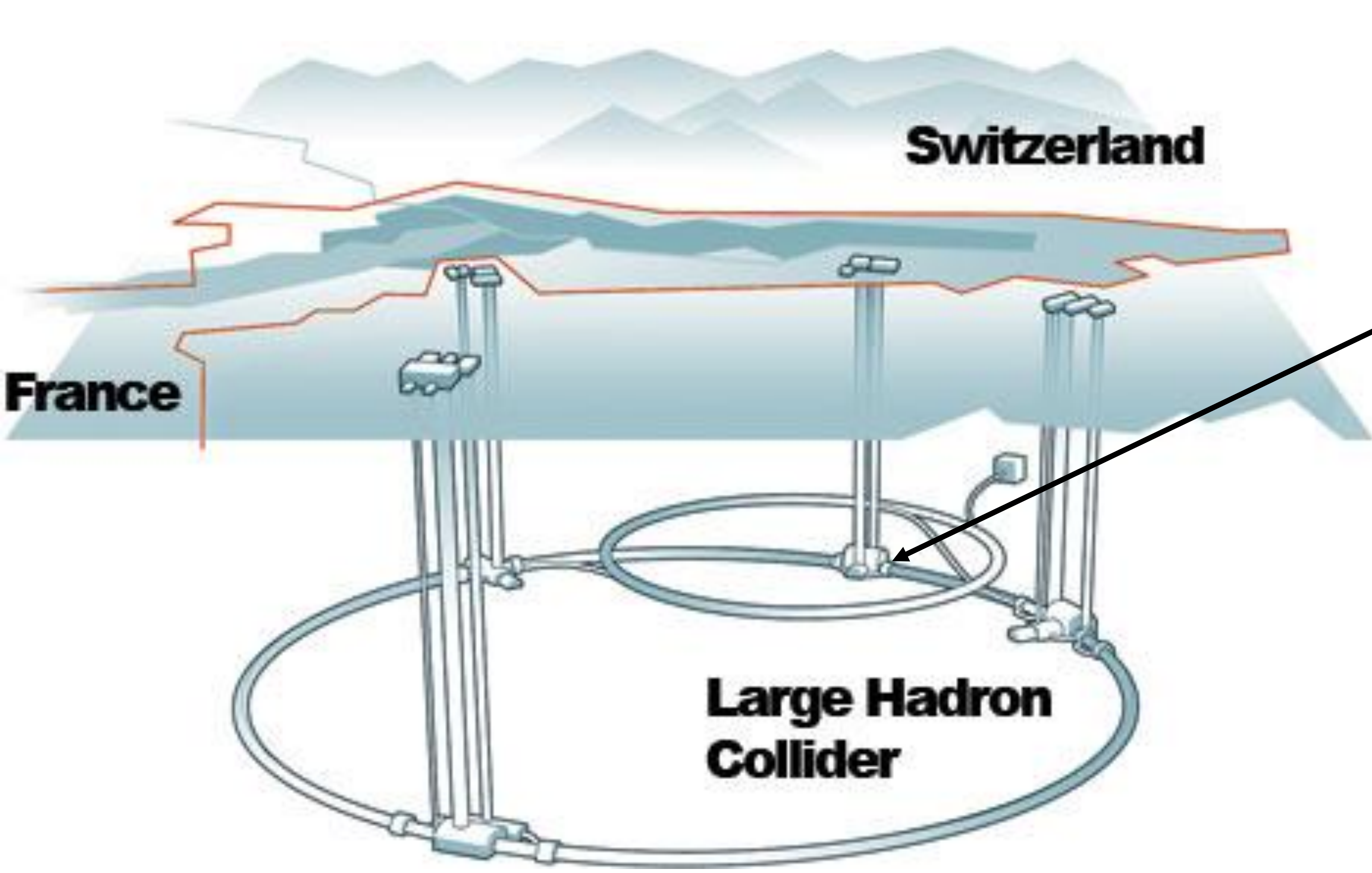
- Physical prototype
- Comparing Results

- Conclusion

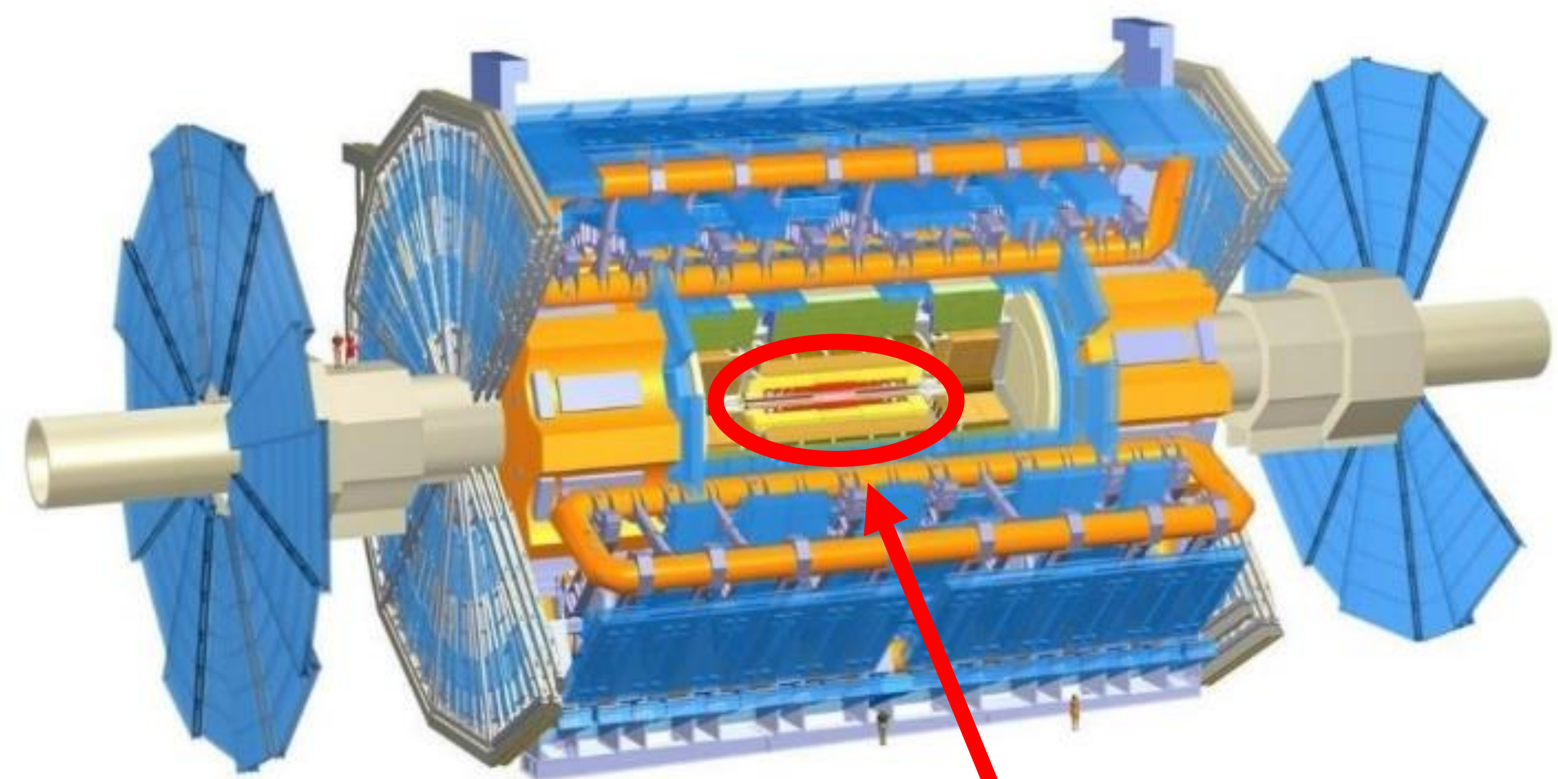
Work by:

Presentation by: Jesse van Dongen
Contact: jvdongen@nikhef.nl

INTRODUCTION

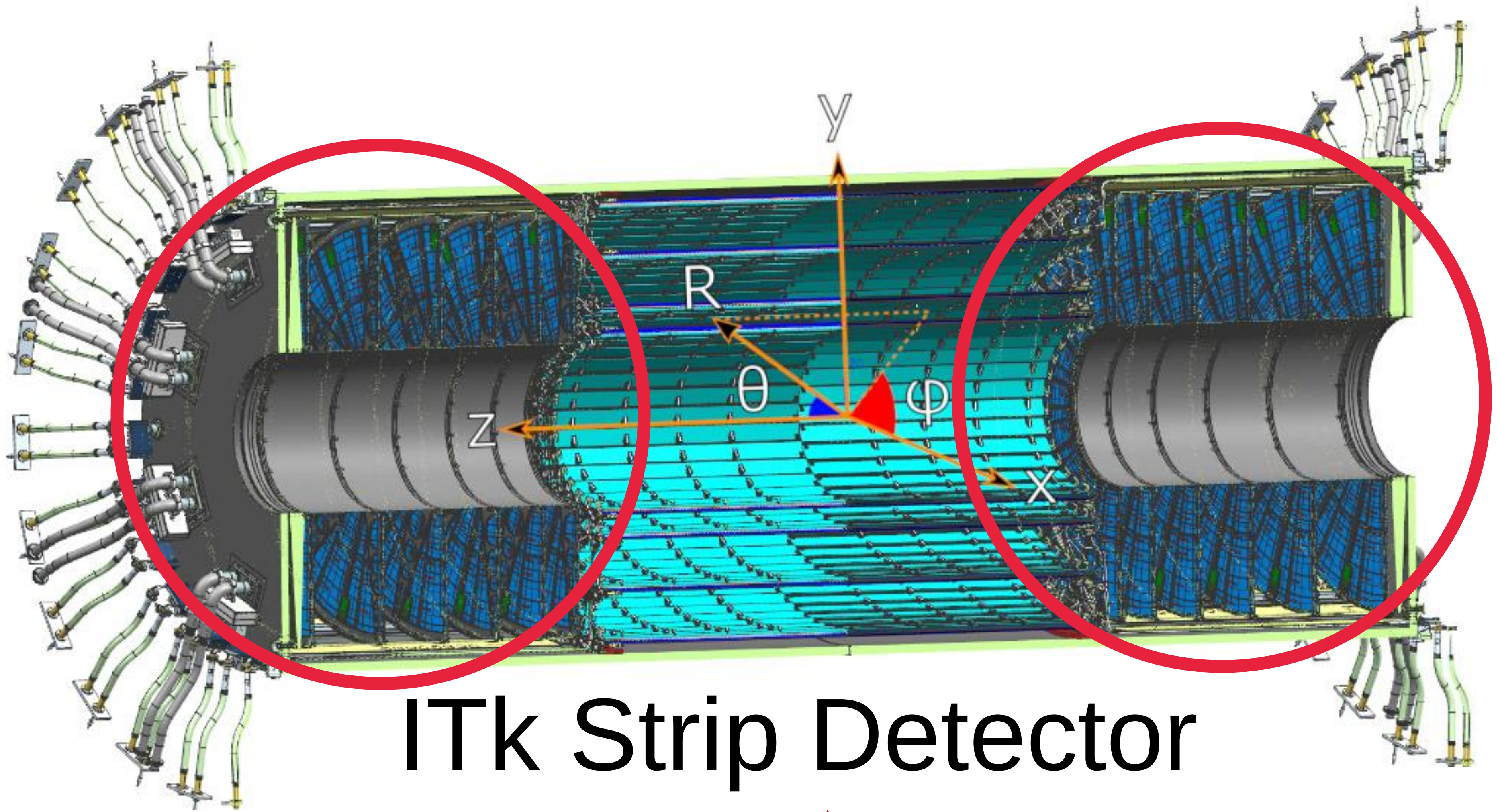


2026 HL-LHC

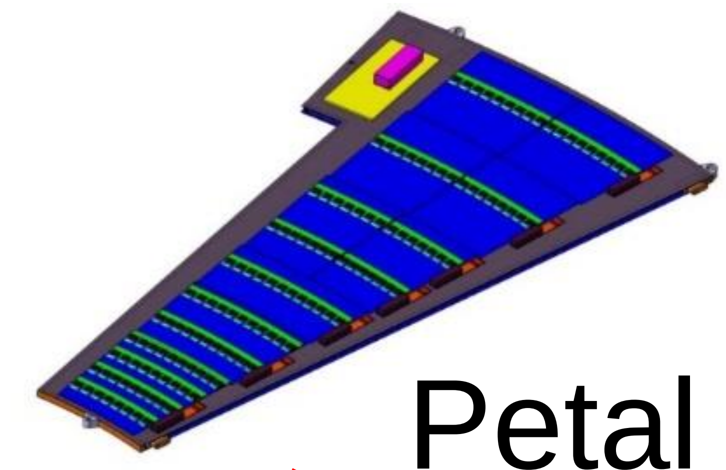


Inner Tracker (ITk)

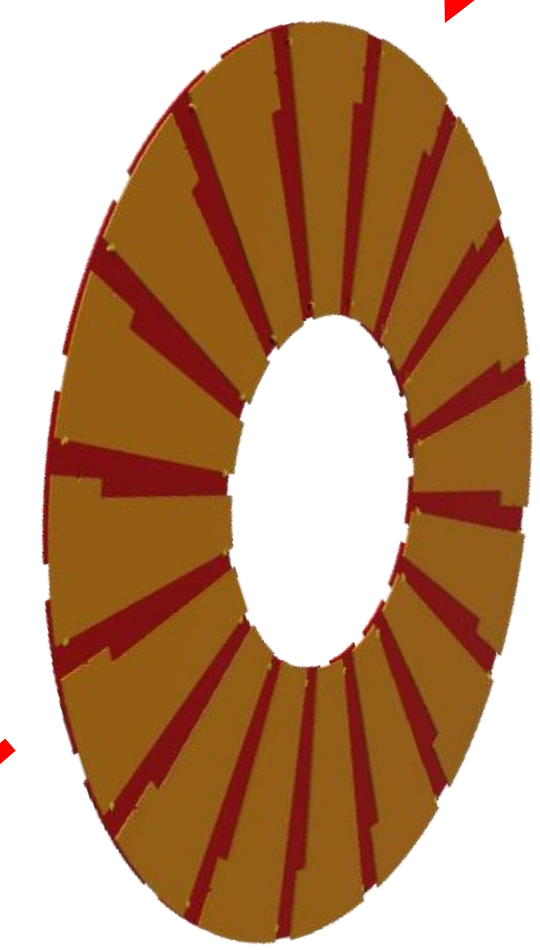
INNERTRACKER (ITK) STRIP ENDCAP GLOBAL SUPPORT



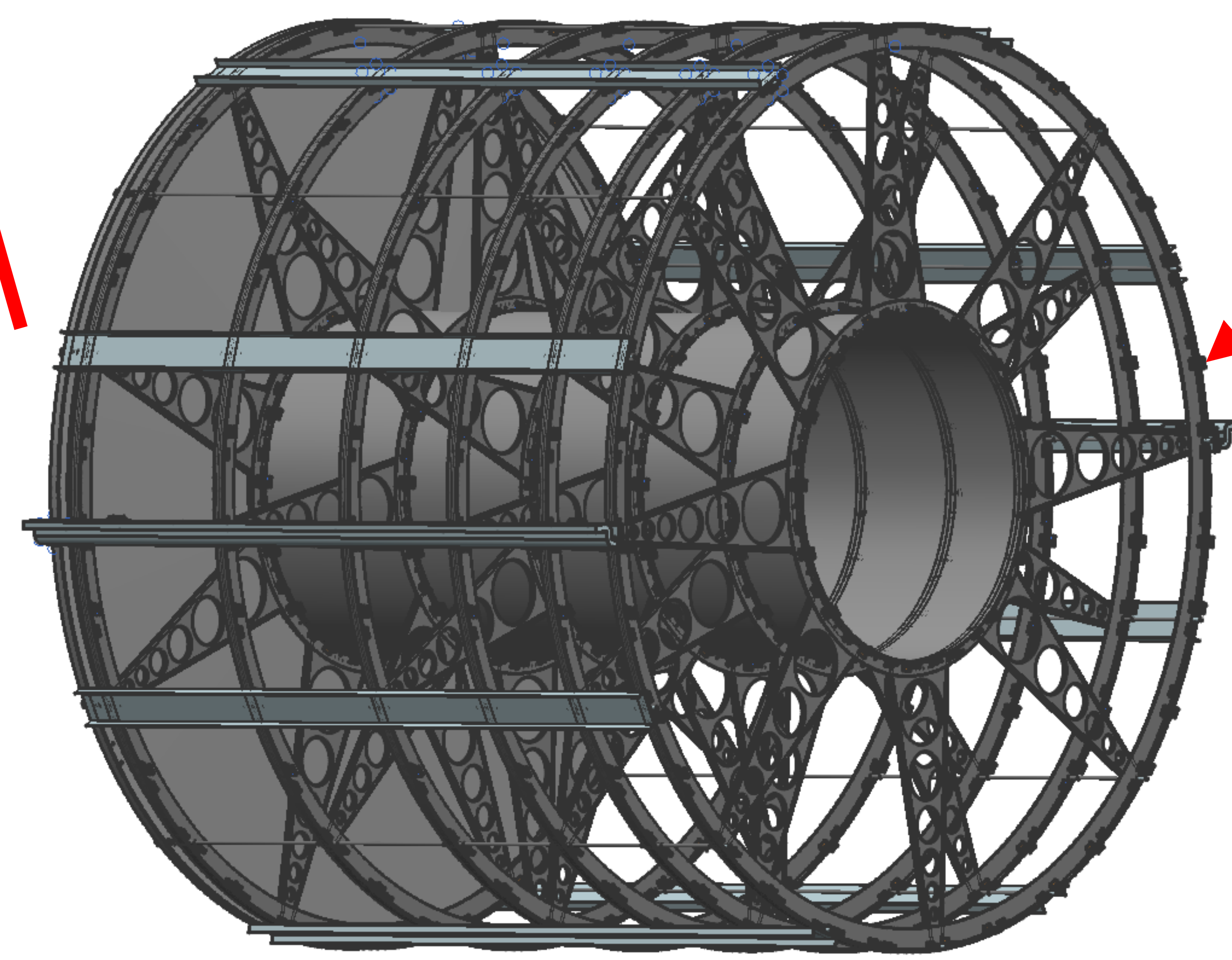
ITk Strip Detector



Petal



Wheel of Petals



Strip Endcap (EC) Global Support

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Work by:

REQUIREMENTS & TASK

Goal of the ITk Strip Endcap (EC):
Measurement of particle tracks/paths after collision at the interaction point

Work Environment:
- Radioactive environment (0.5MGy)
- Environment temperature -25 °C
- Dry (Flushed with Nitrogen)

Requirements for the global support:
- Radiation length <10% of Petal in a track → Low Mass
- Stability Structure (short term) < 2um → High Stiffness

Direction	Stability requirement	As Built Min Frequency Requirements	FEA Design Min Frequency Requirements
Z (beamdir)	20 µm	3.2Hz	6.7Hz
R	20 µm	3.2Hz	6.7Hz
Rφ	2 µm	14.4Hz	31.6Hz

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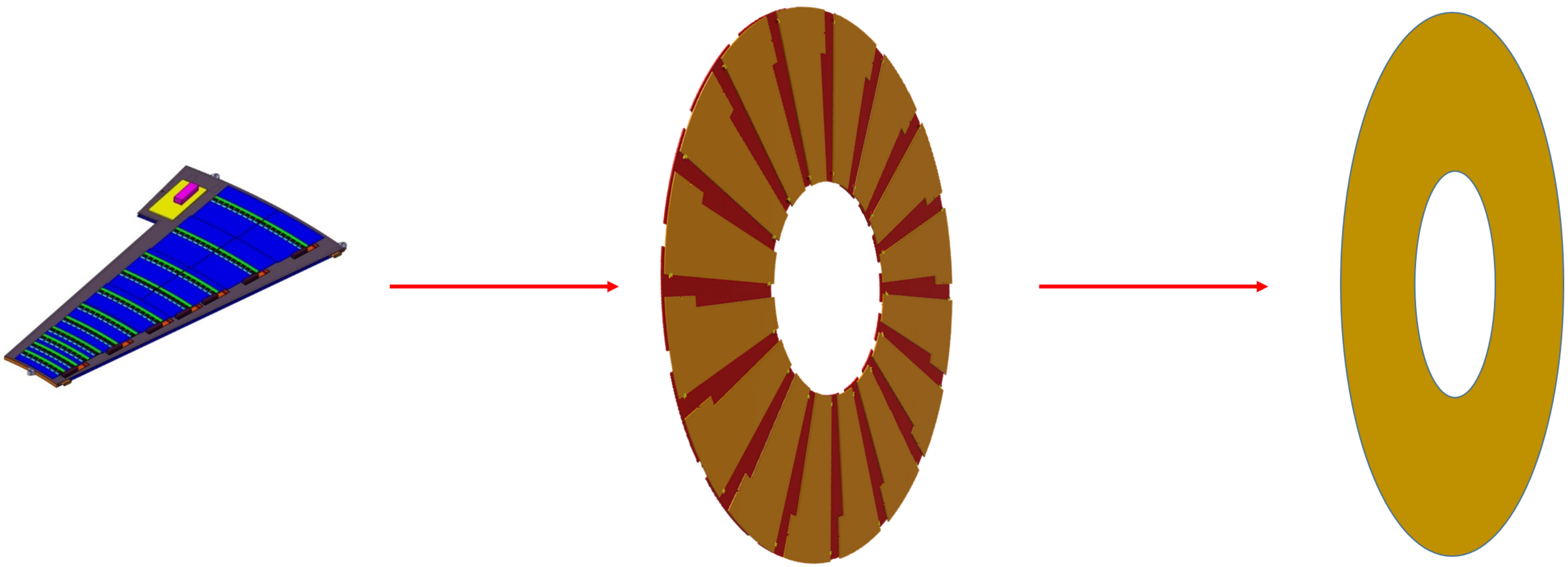
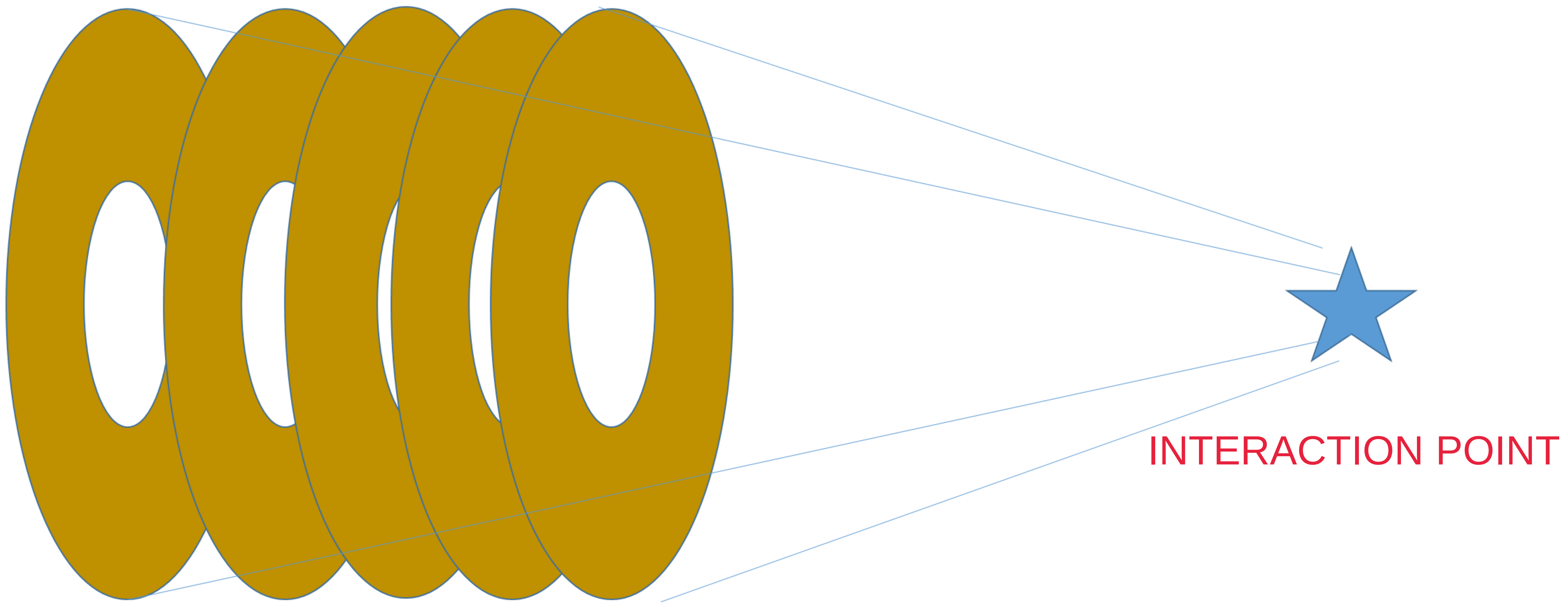
Work by:

BASIC DESIGN IDEA

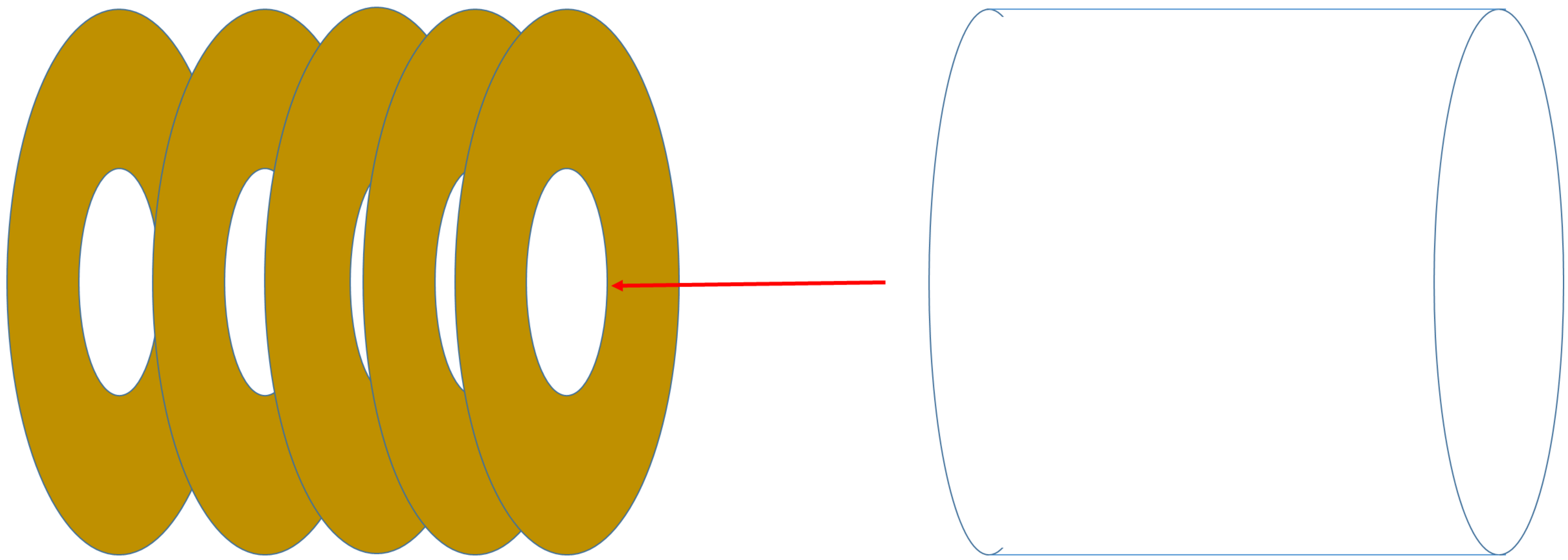


BASIC DESIGN IDEA



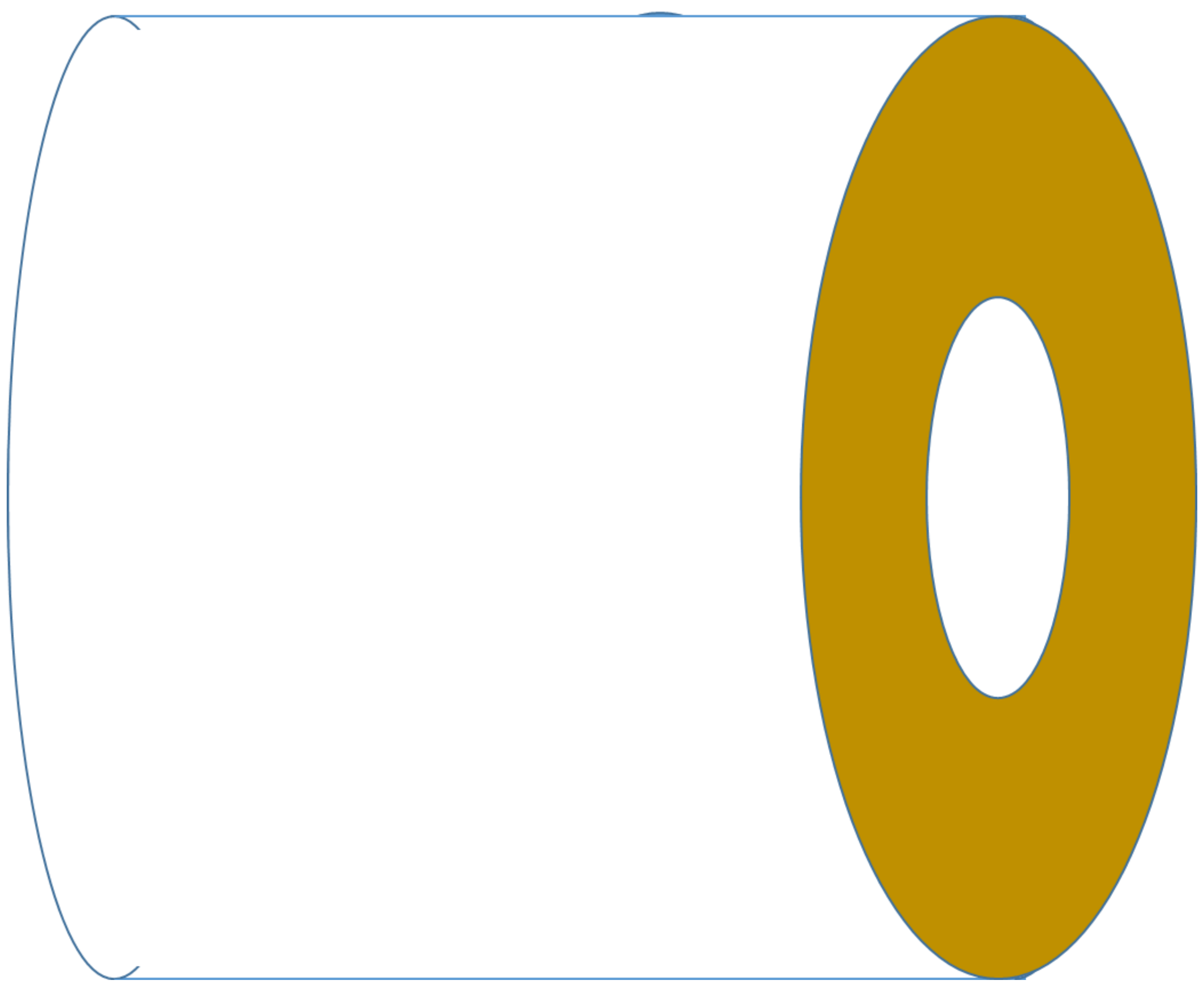
GOAL: HIGH STIFFNESS & LOW MASS FRAME, WHICH MINIMALLY BLOCKS TRACKS

BASIC DESIGN IDEA

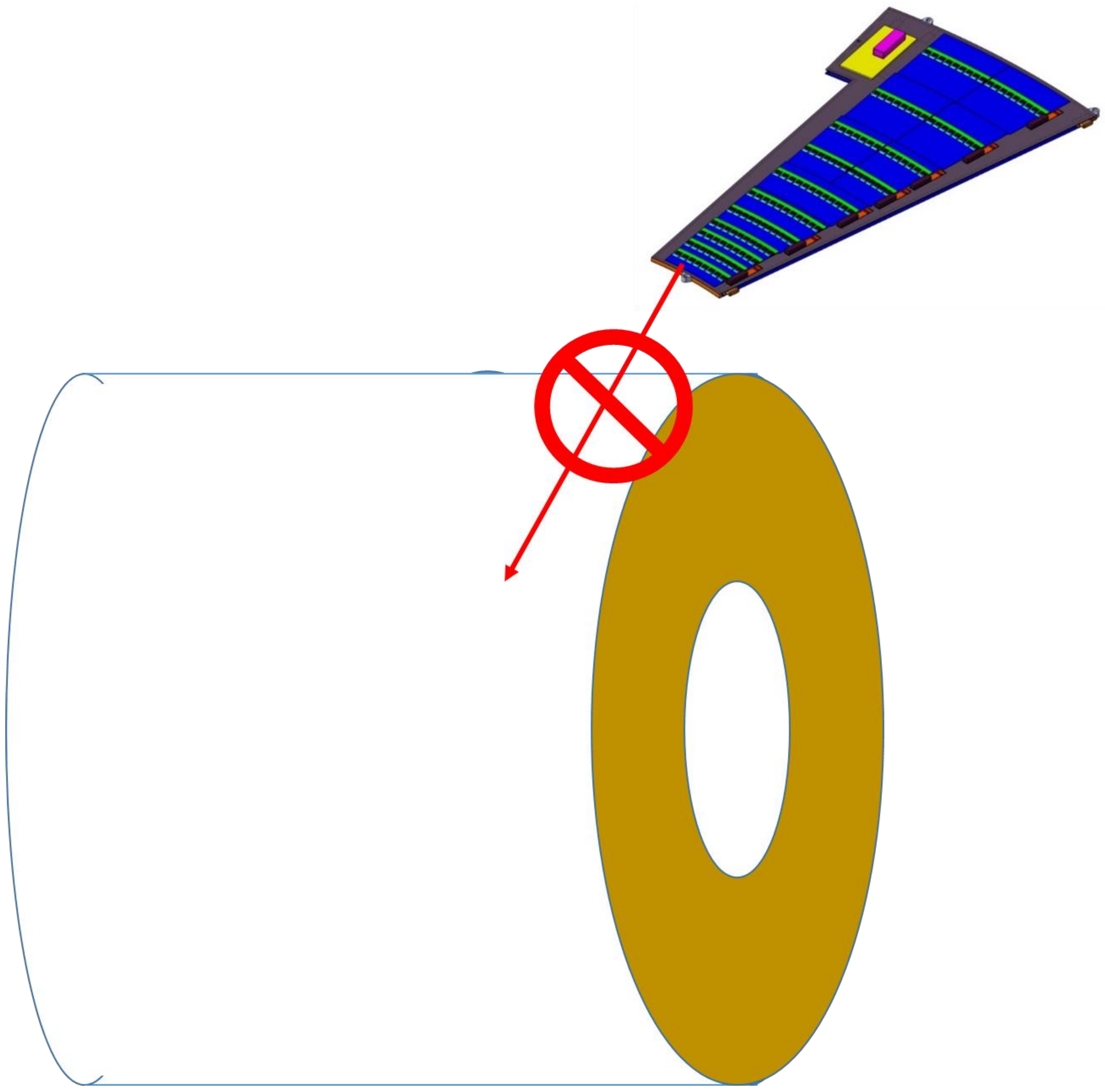


STRUCTURE FOR CONNECTING WHEELS

BASIC DESIGN IDEA

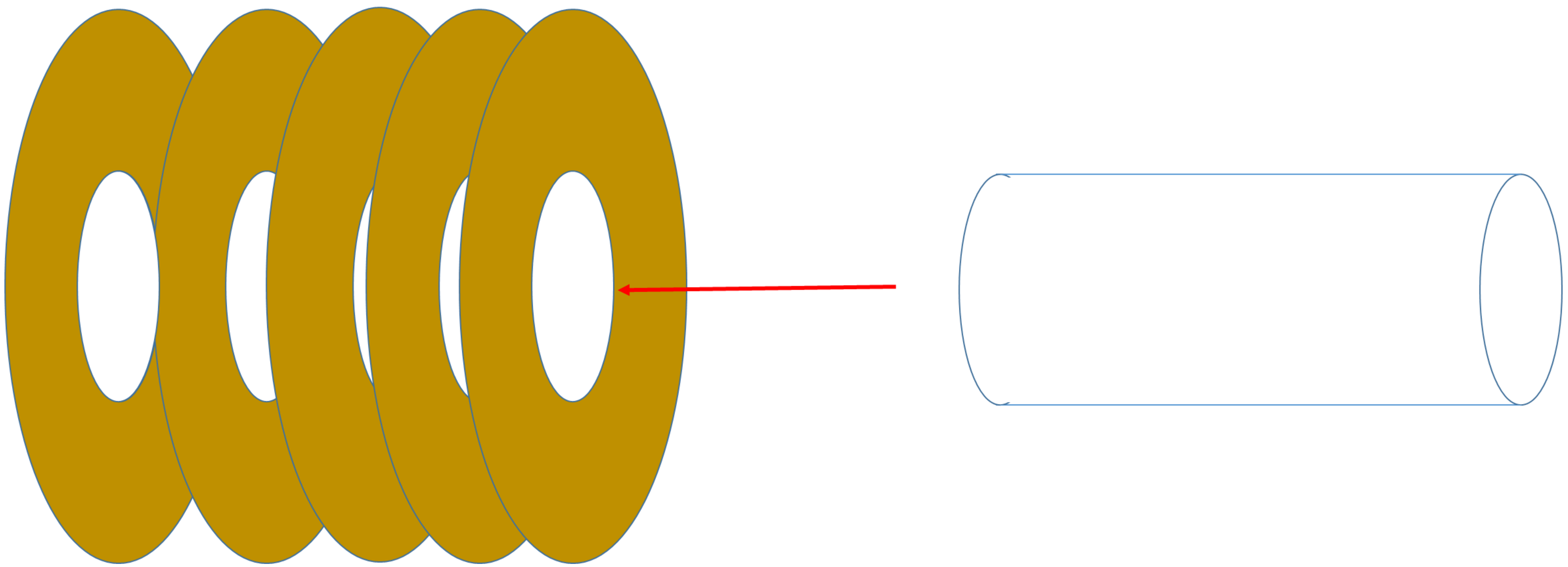


BASIC DESIGN IDEA



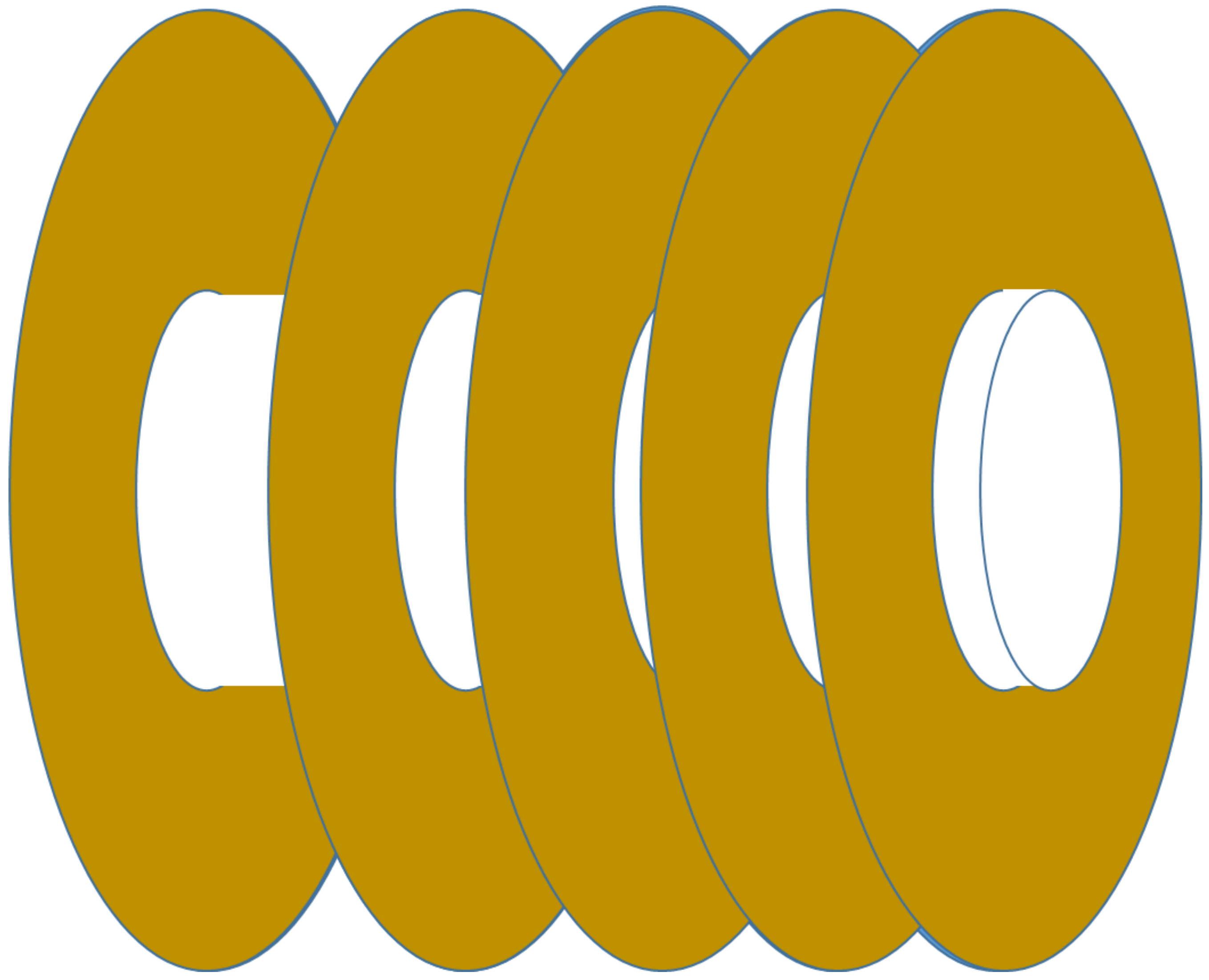
DELICATE PETALS CANNOT BE INSERTED AFTER FRAME IS ASSEMBLIED

BASIC DESIGN IDEA

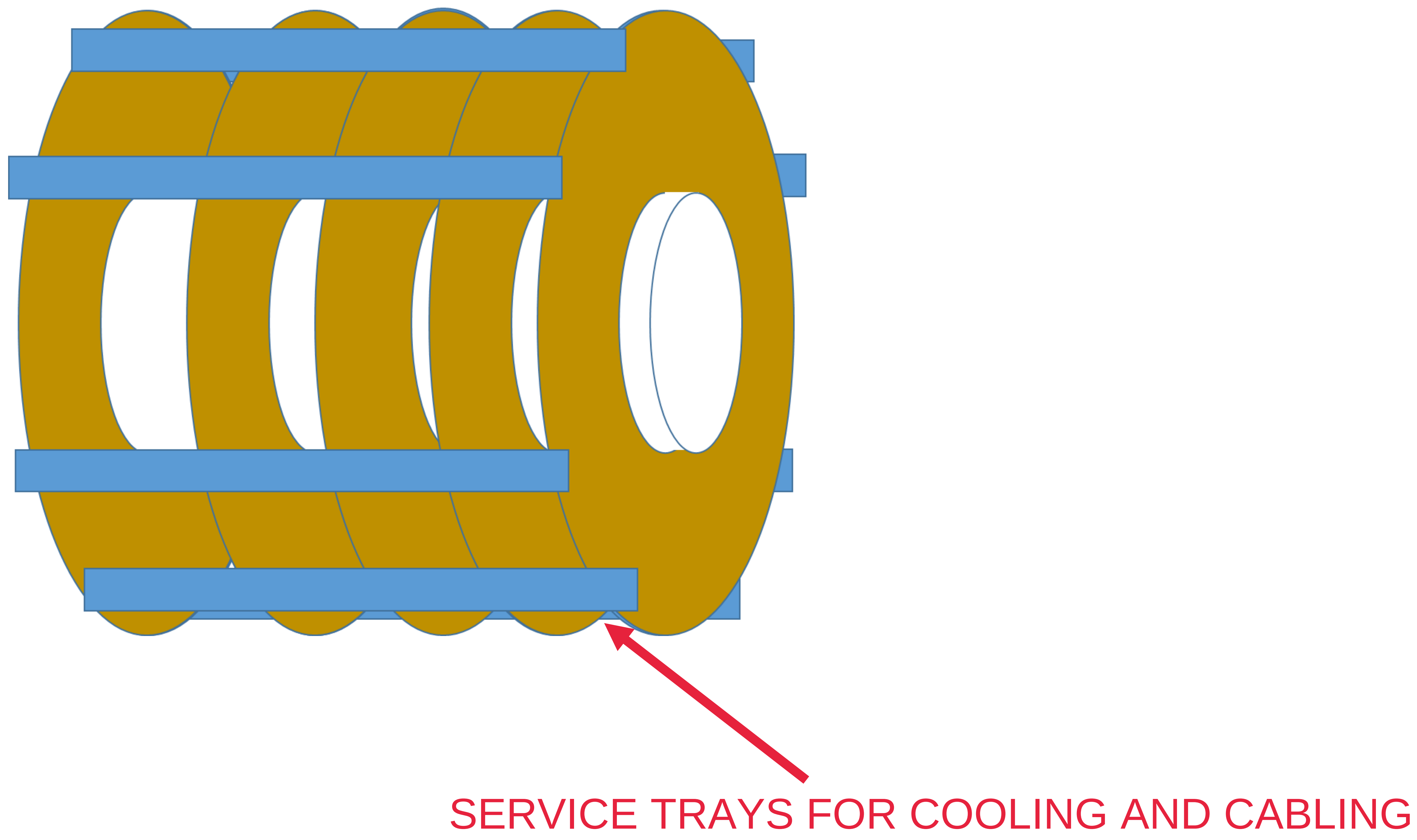


STRUCTURE CONNECTING WHEELS

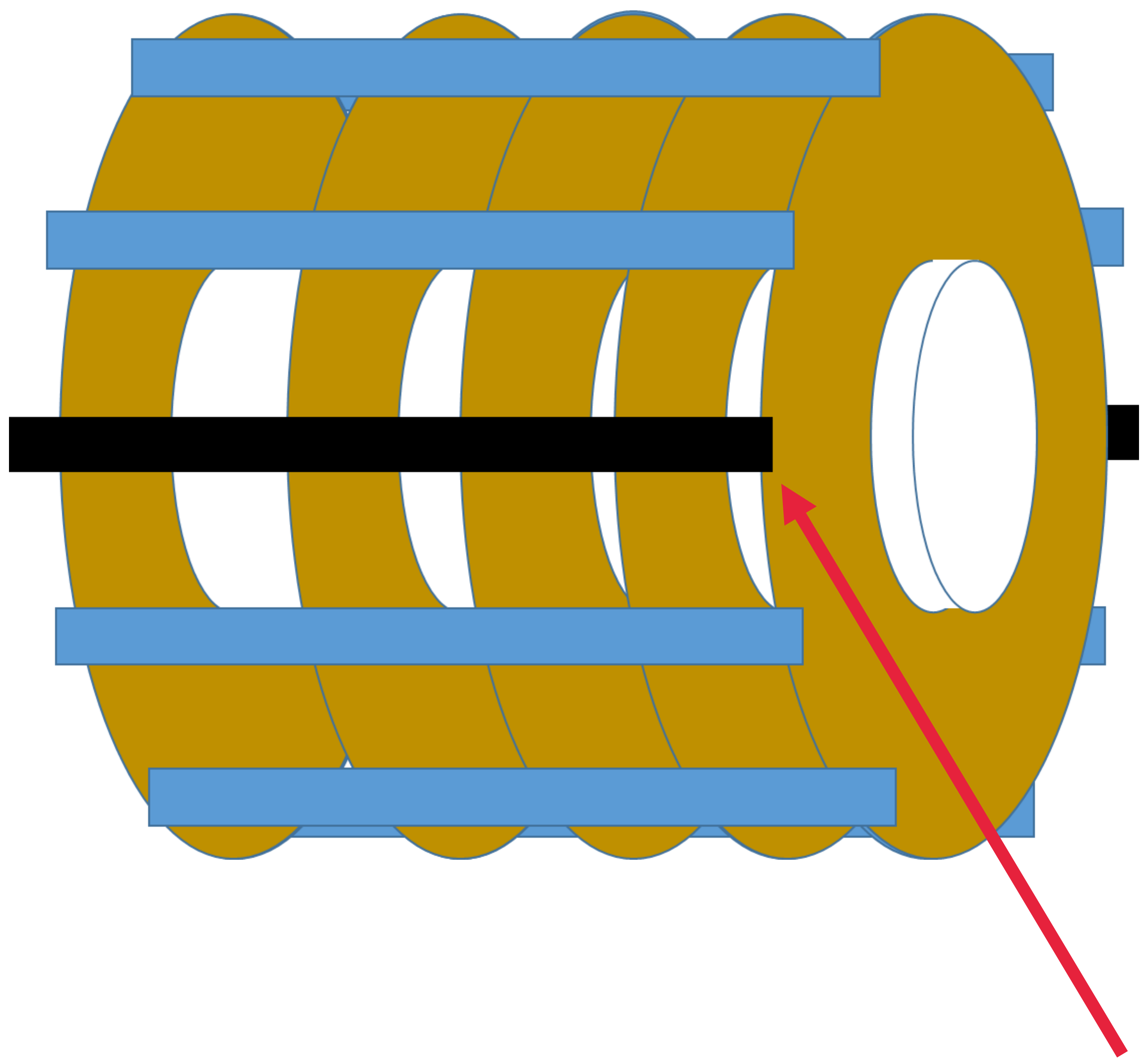
BASIC DESIGN IDEA



BASIC DESIGN IDEA

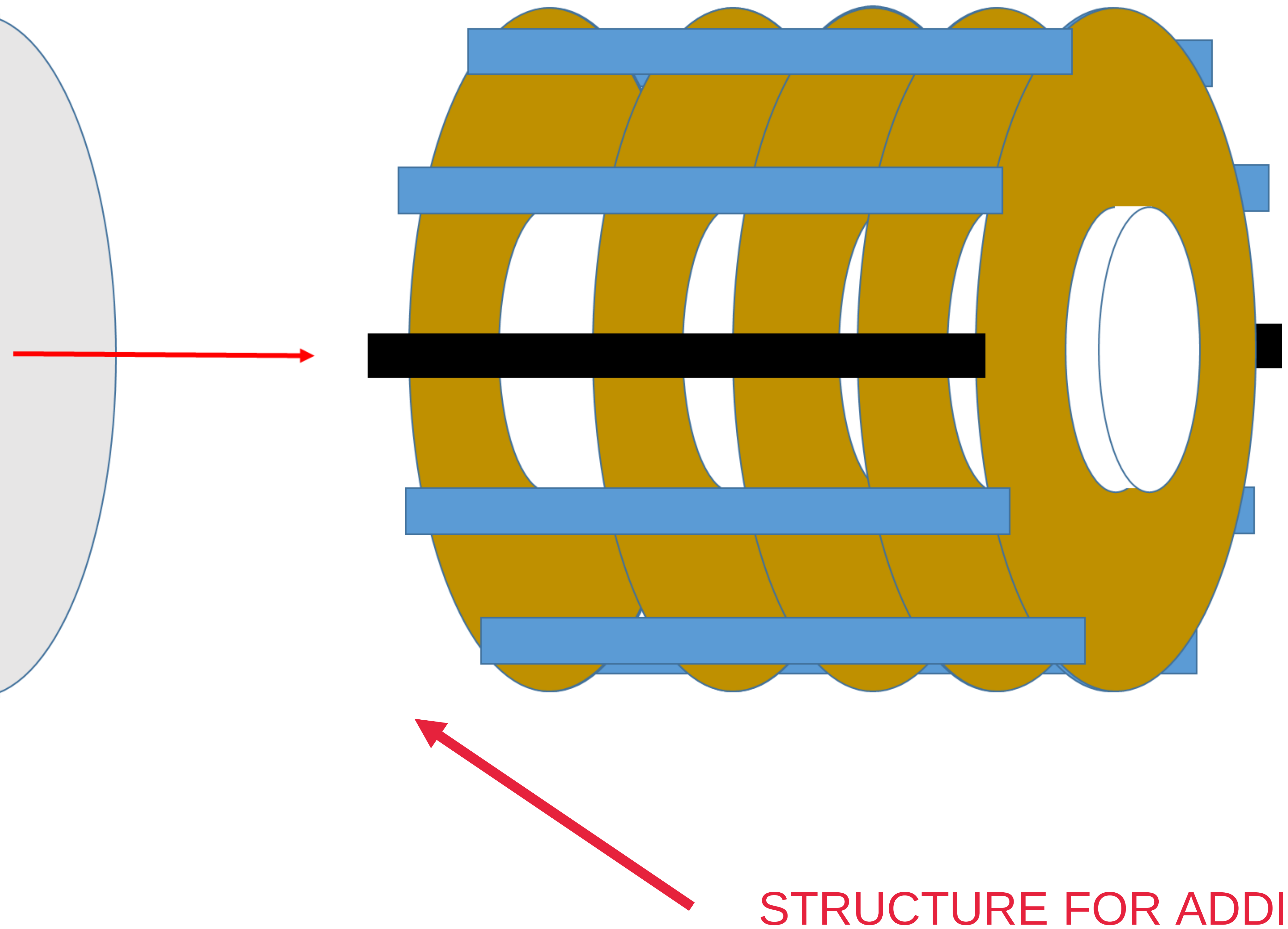


BASIC DESIGN IDEA



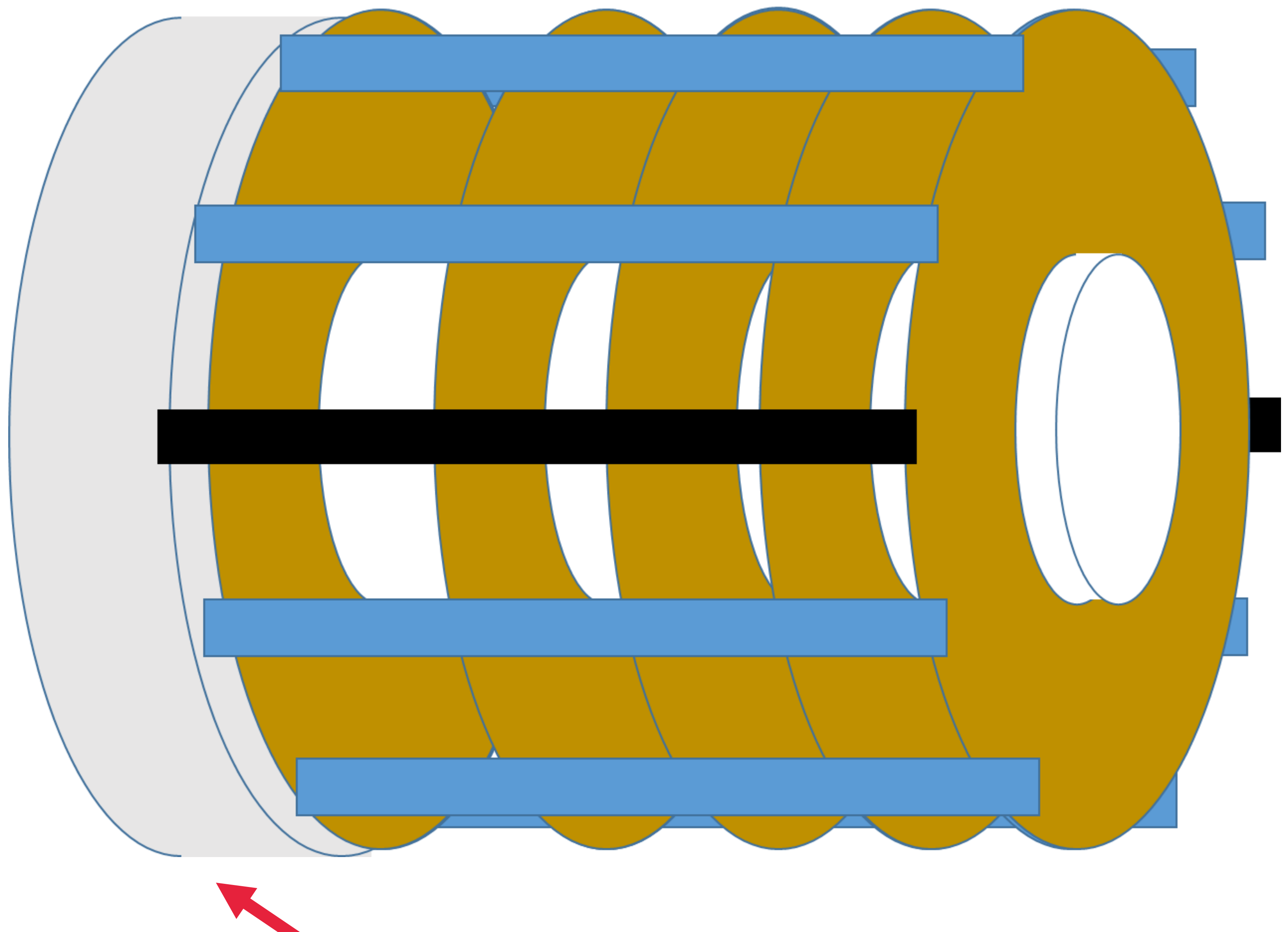
RAILS FOR MOUNTING TO OUTER CYLINDER

BASIC DESIGN IDEA



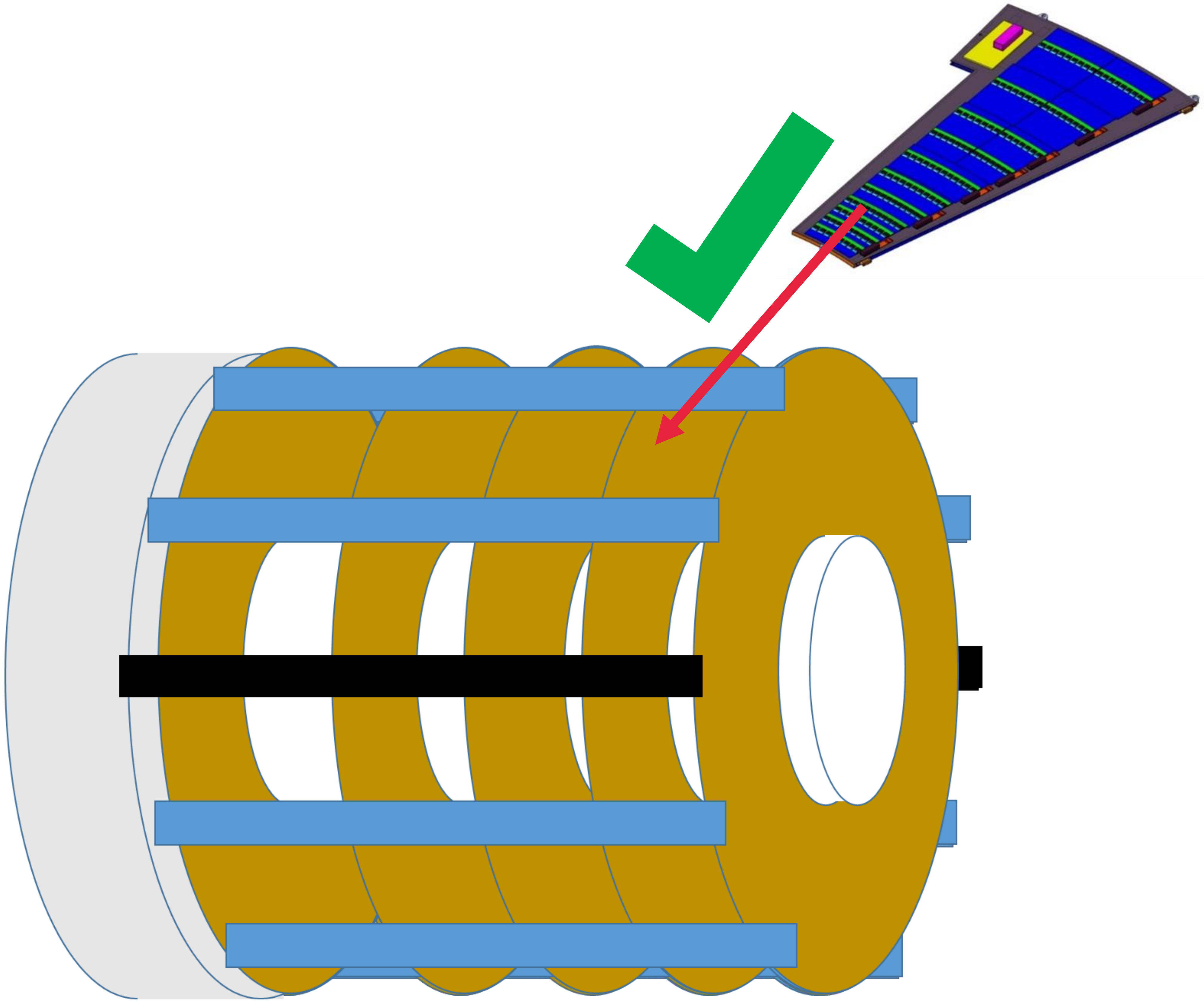
STRUCTURE FOR ADDING ADDITIONAL STIFFNESS

BASIC DESIGN IDEA



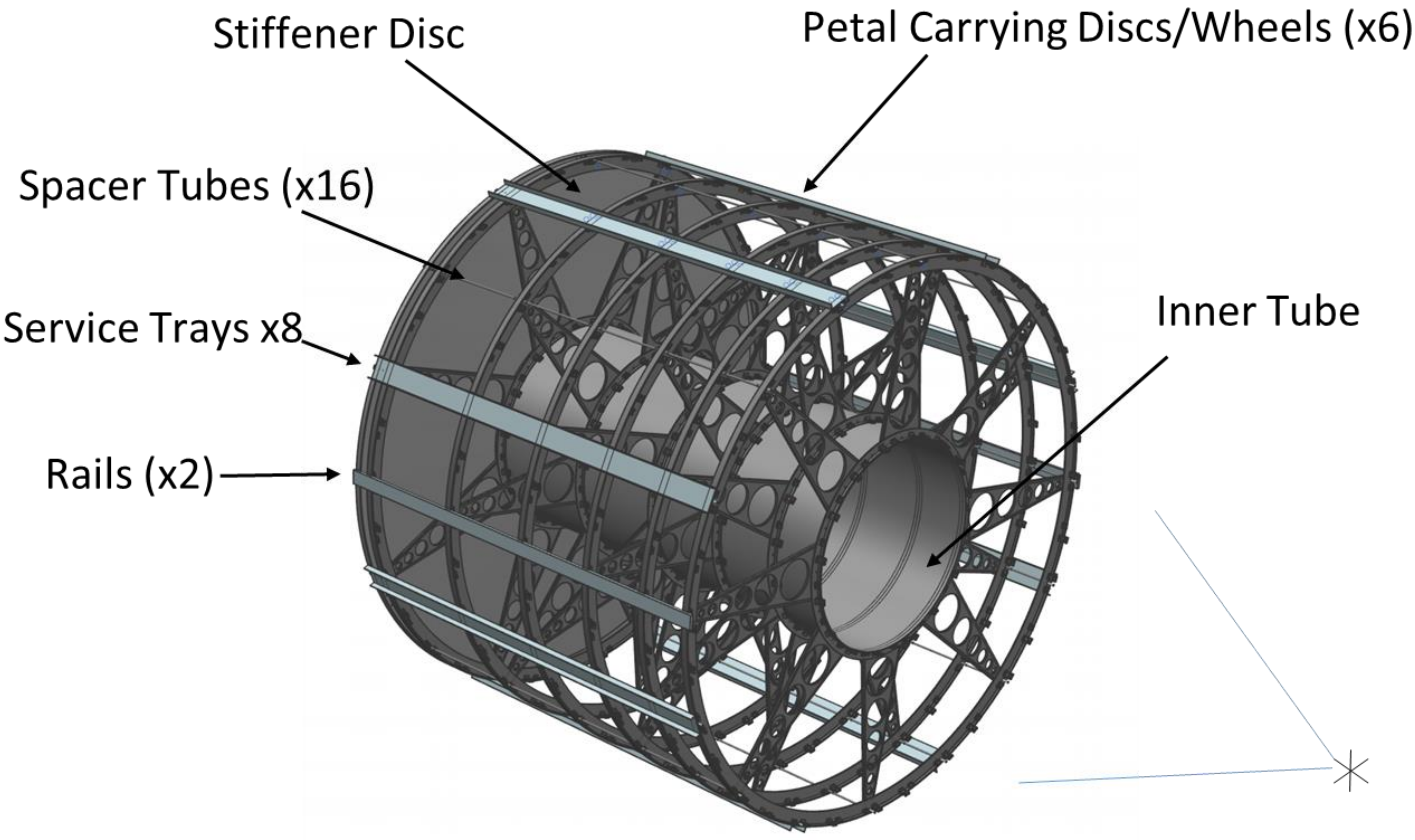
STRUCTURE FOR ADDING ADDITIONAL STIFFNESS

BASIC DESIGN IDEA

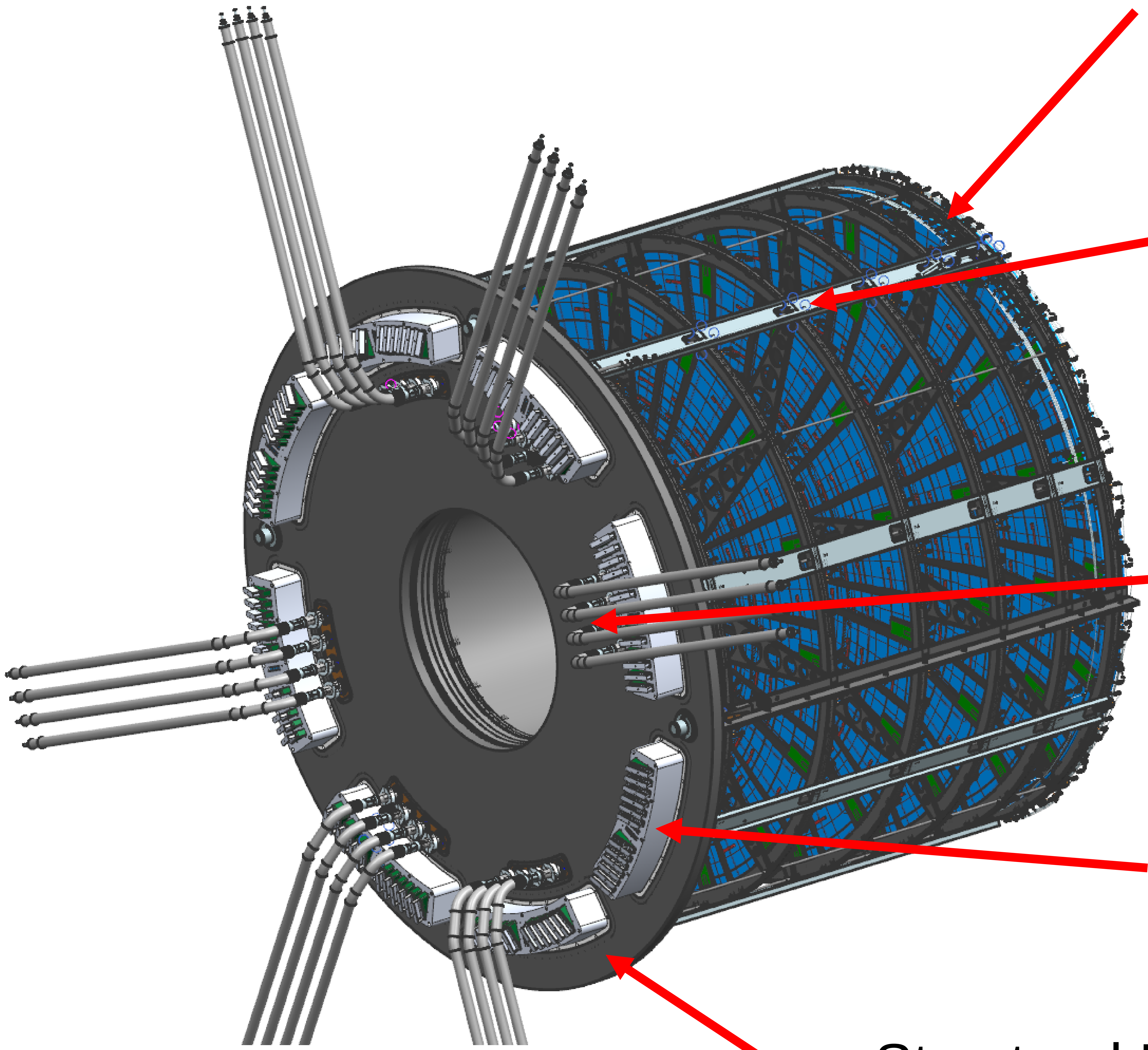


DELICATE PETALS CAN BE INSERTED AFTER FULL FRAME IS ASSEMBLED

ENDCAP (EC) GLOBAL SUPPORT OVERVIEW



ENDCAP (EC) DETECTOR OVERVIEW



6 Wheels with 32 Petals

8 Service Trays, providing cabling and cooling to wheels

12 in- and outlet cooling connectors

8 panels with electrical and optical connectors

Structural Bulkhead (Different object from Stiffeningdisc to be kinematically independent)

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Work by:

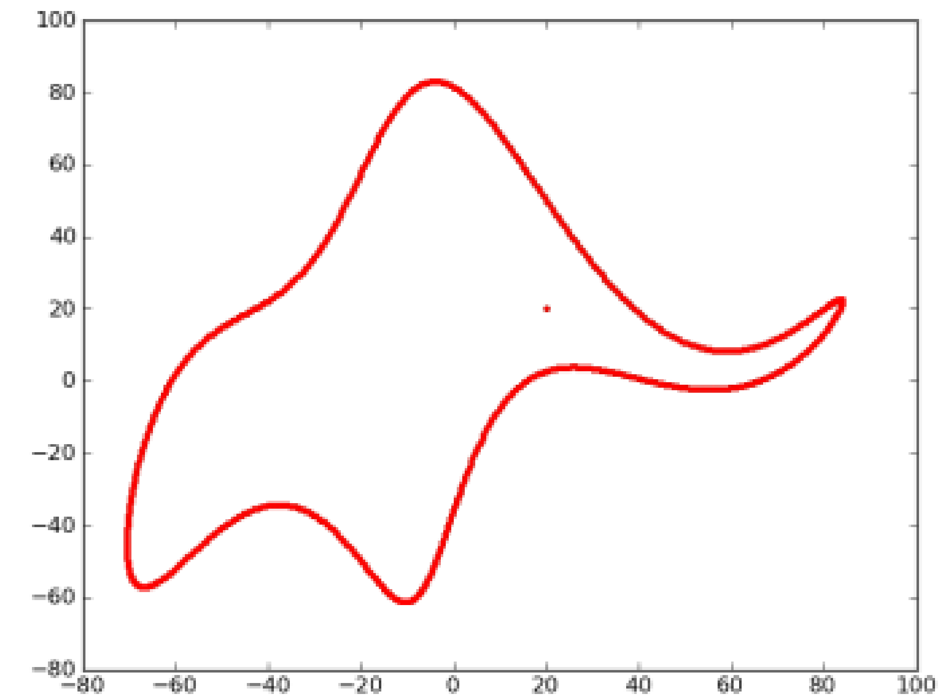
SIMULATION GOAL

- Build a model of the detector
- Do tests and experiments on a simulated model (save time & money)

Plan to validate simulations

- Manual Calculations
- FEM Calculations
- Cocurrent simulation
- Prototype tests

Important that simulations match reality. Warning: you always get pretty pictures!!!



"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk". - John von Neumann

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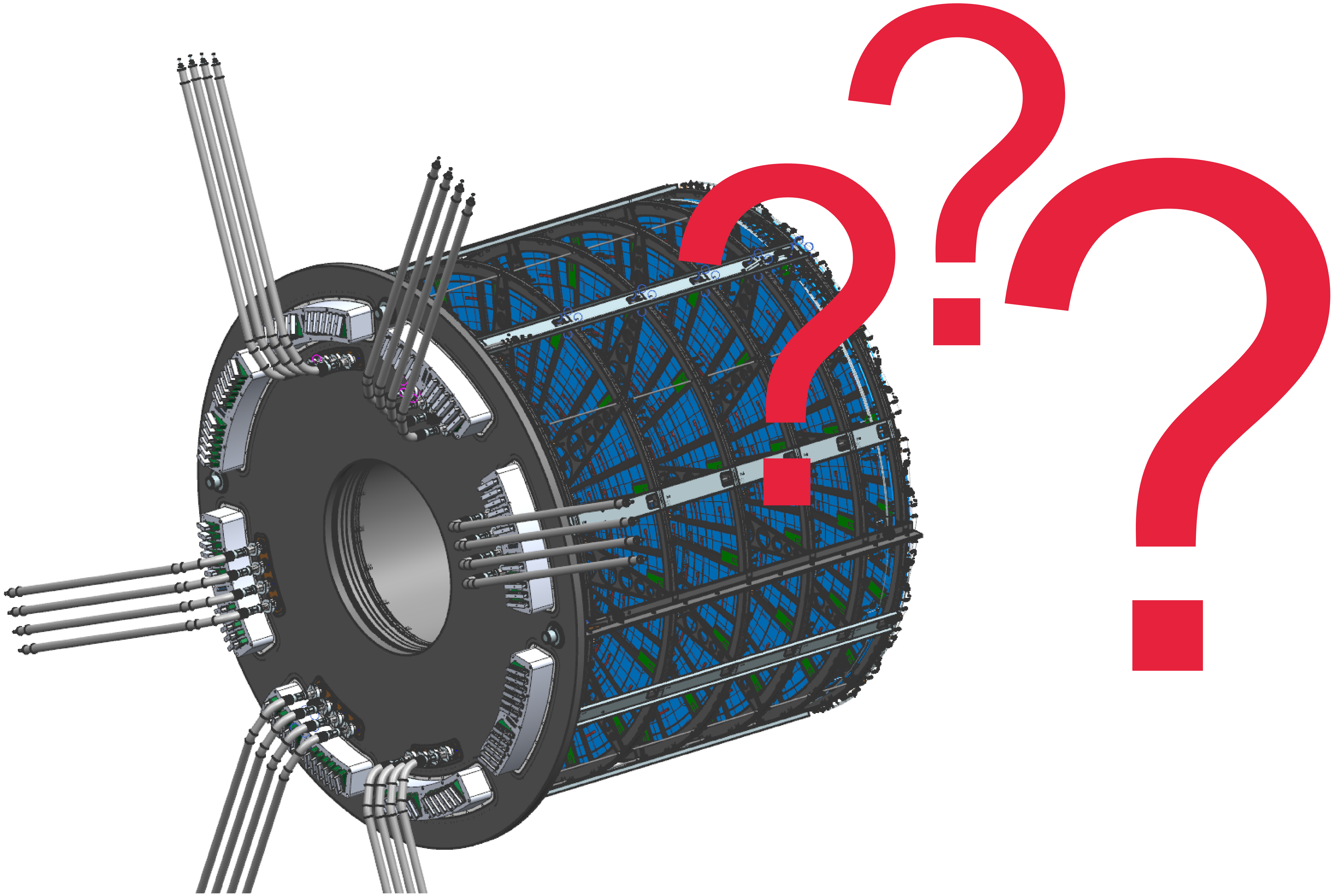
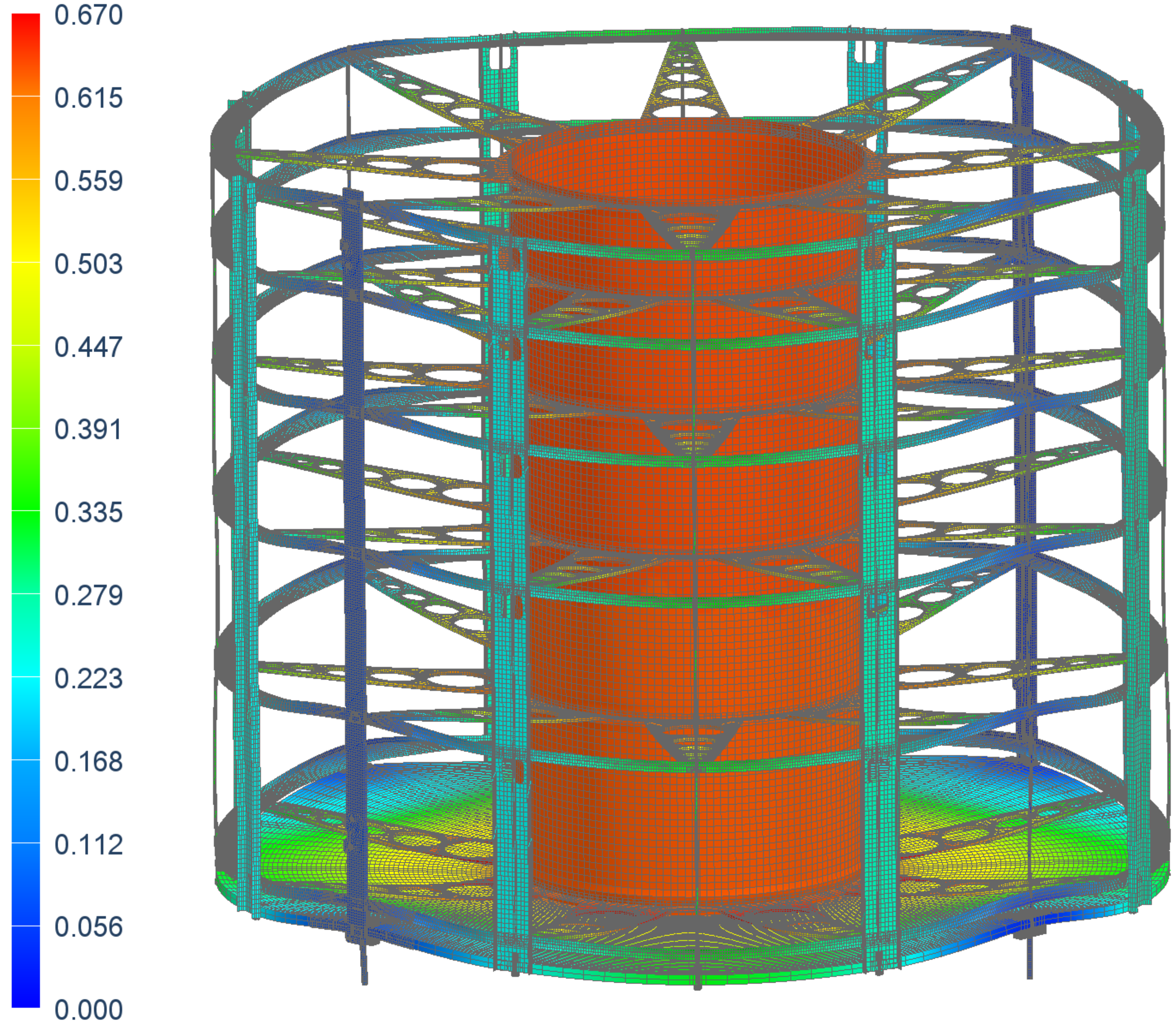
Work by:

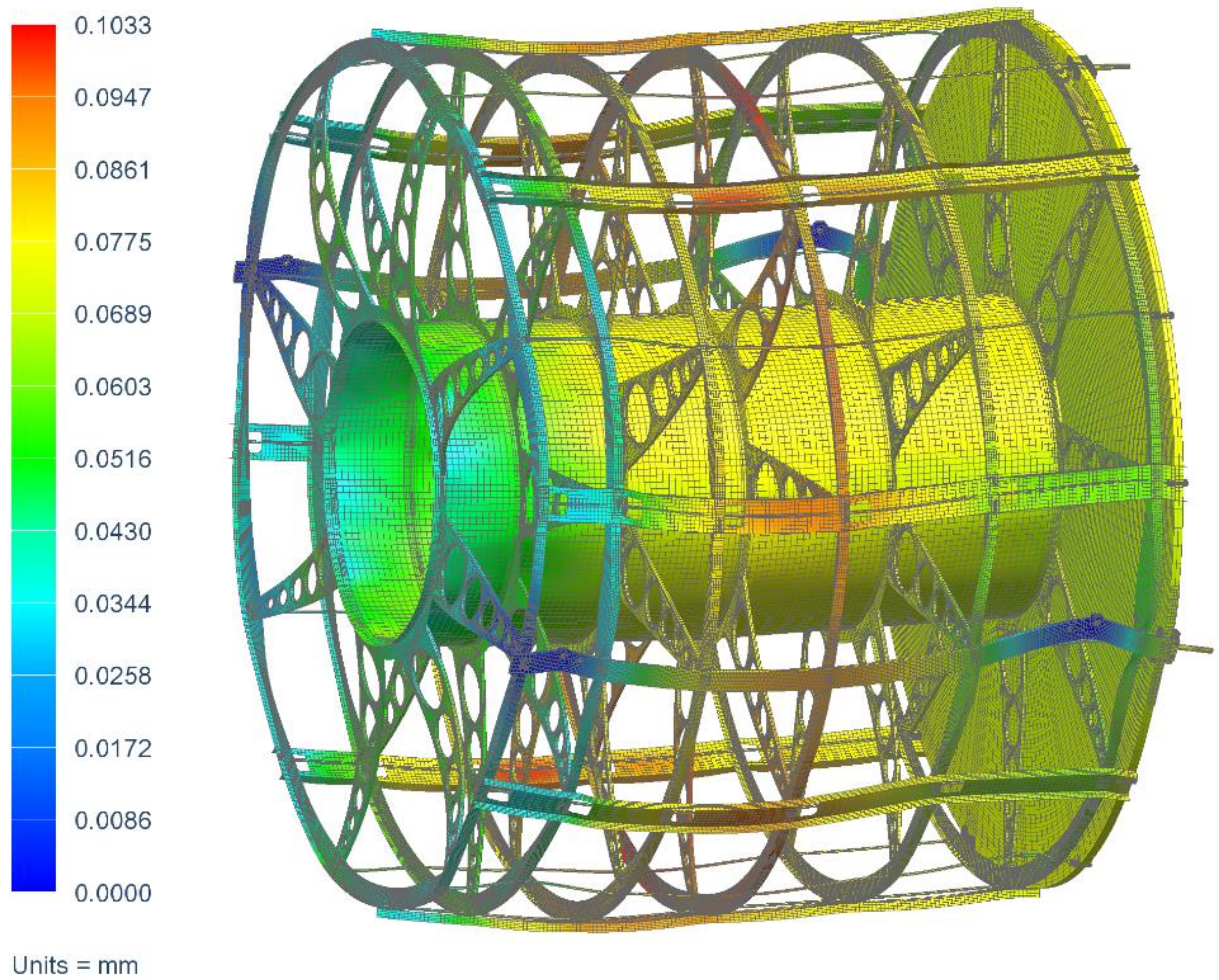
FULL DETECTOR PERFORMANCE ?



CALCULATED GRAVITY DEFORMATIONS

Petals & Services simulated as added mass





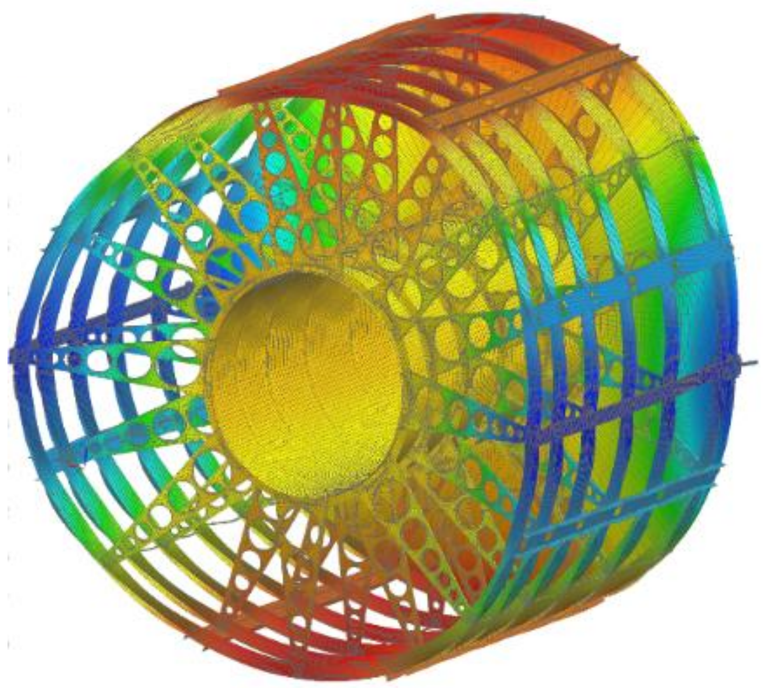
Assembly Position **0.670 [mm]** (Supported on transport locks, will deform less with Airex and could be supported at center)

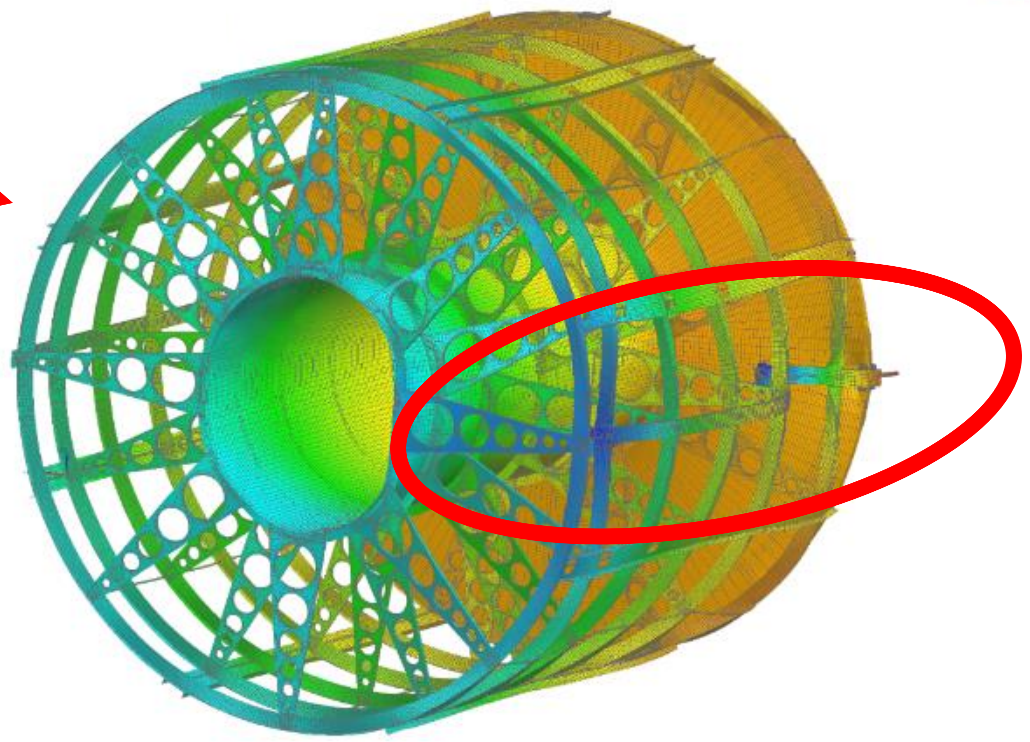
Operation Position **0.1 [mm]** (Supported on rails)

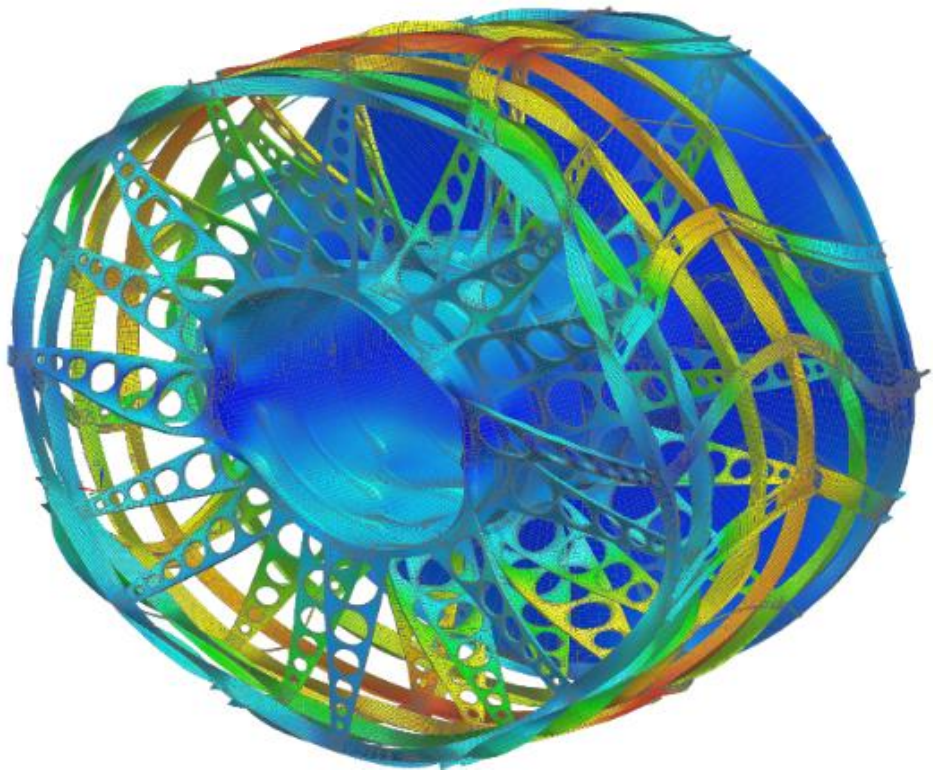
SIMULATED FULL SYSTEM EIGEN FREQUENCIES

Petals & Services simulated as added mass

Mode	Frequency	Mode Shape	Affected DOF
1	13 Hz	Pringle	Z
2	16 Hz	Collapsingcabinet-Y	Z
3	18 Hz	Railslide	**X**
4	27 Hz	Squish	**X**
5	28 Hz	Diagonal Pringle	Z
6	30 Hz	Telescoping	Z
7	32 Hz	Collapsingcabinet-X	Z
8	47 Hz	Diagonal Pringle	Z
9	49 Hz	Twist	**PHI**
10	51 Hz	Servicetray Telescoping	Z

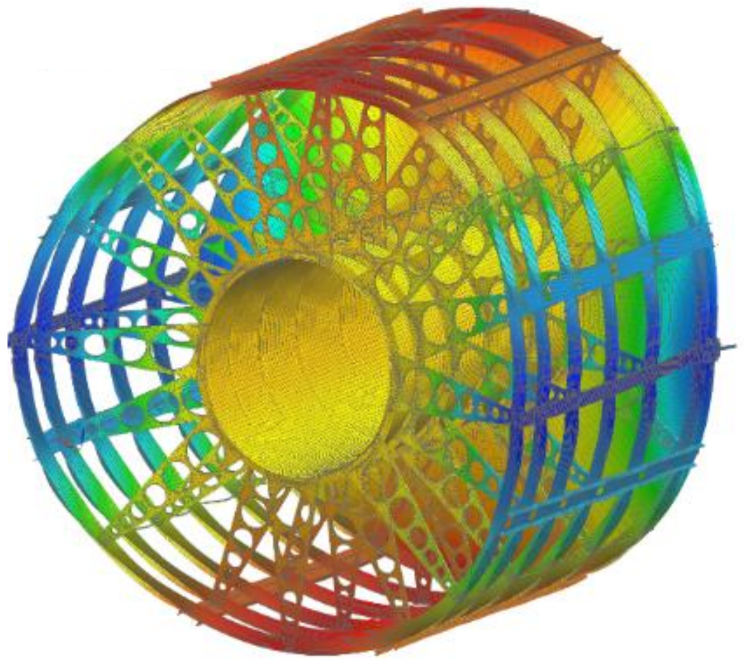




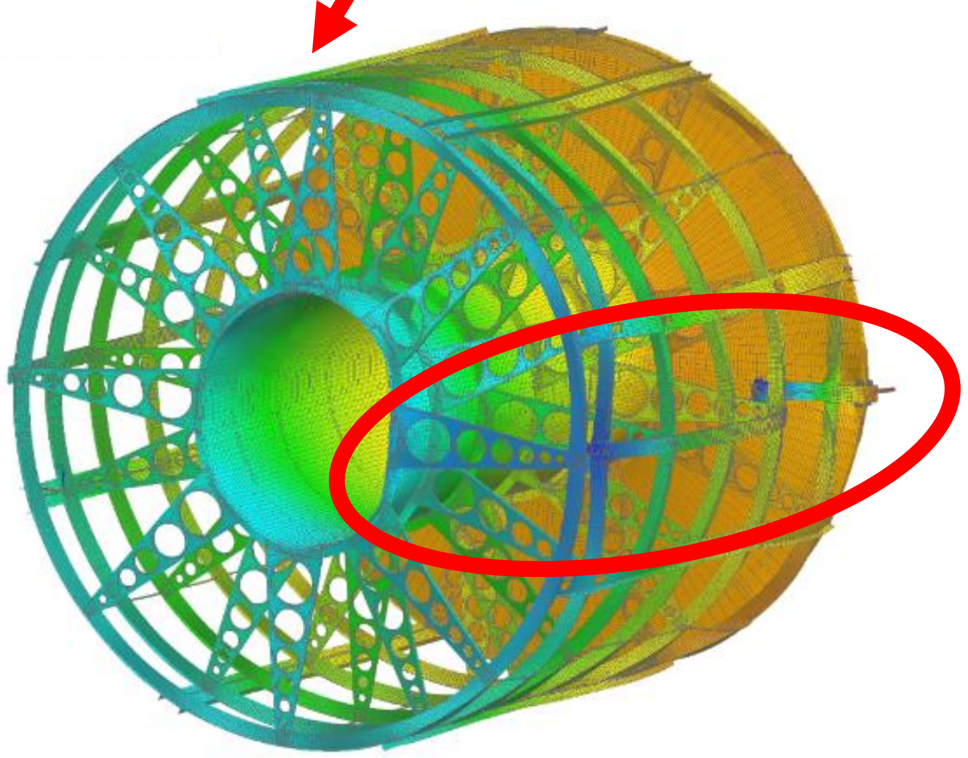


REQUIREMENTS VS CAE RESULTS

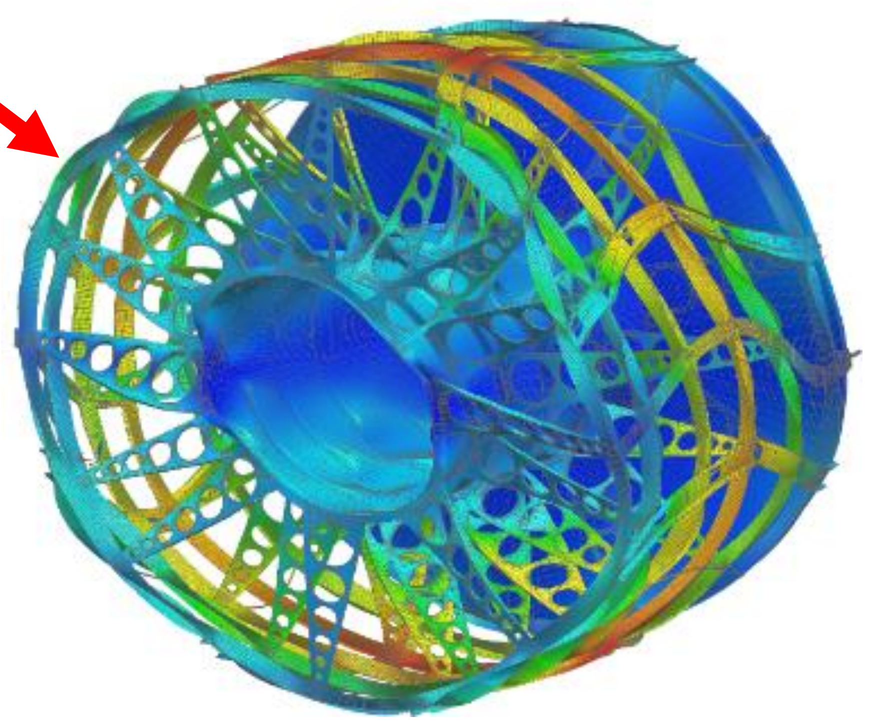
Direction	Stability requirement	As Built Min Frequency Requirements	FEA Design Min Frequency Requirements
Z	20 µm	3.2Hz	6.7Hz
R	20 µm	3.2Hz	6.7Hz
Rφ	2 µm	14.4Hz	31.6Hz



13Hz (Z)



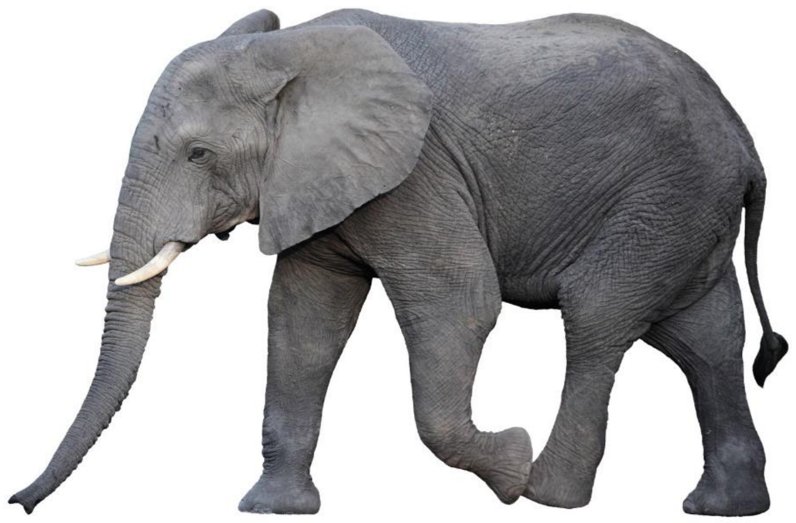
18Hz (X)



49Hz (Rφ)

SIMULATION DISCUSSION

- The Rail Support bar should be more optimized
- Otherwise the system agrees to CAE requirements.



Can we trust the CAE results?

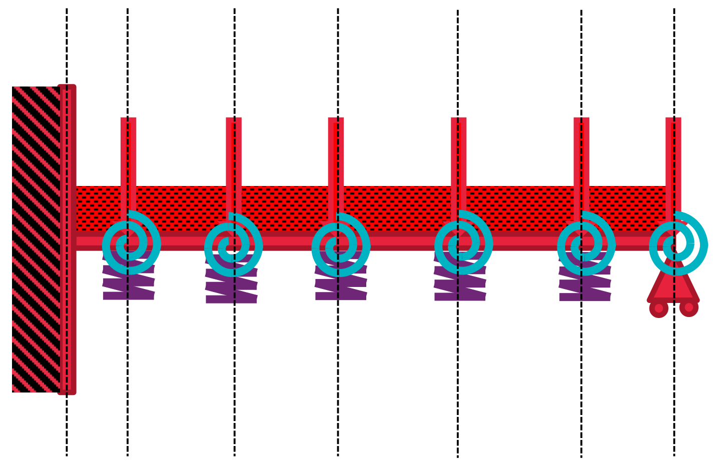
CONTENTS

Work by:

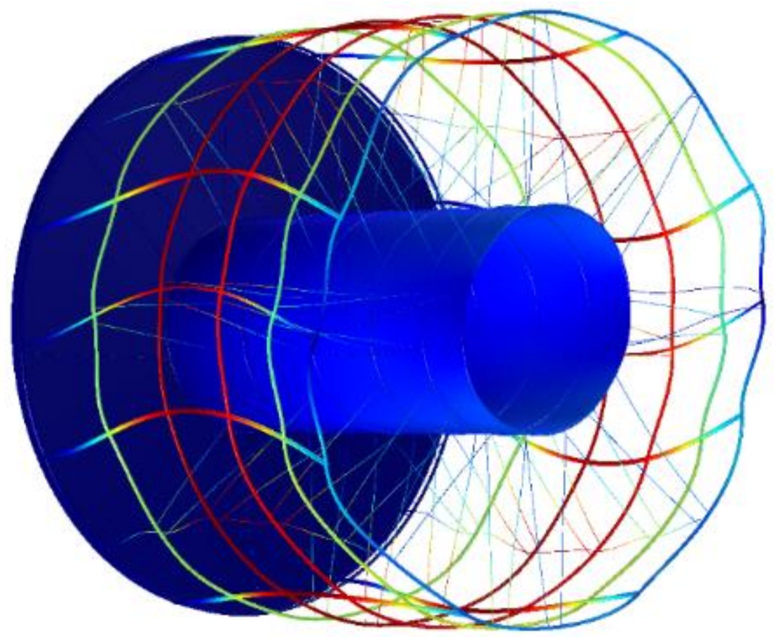
CSIC IFIC INSTITUT DE FÍSICA CORPUSCULAR VNIVERSITAT DE VALÈNCIA DESY

Nikhef

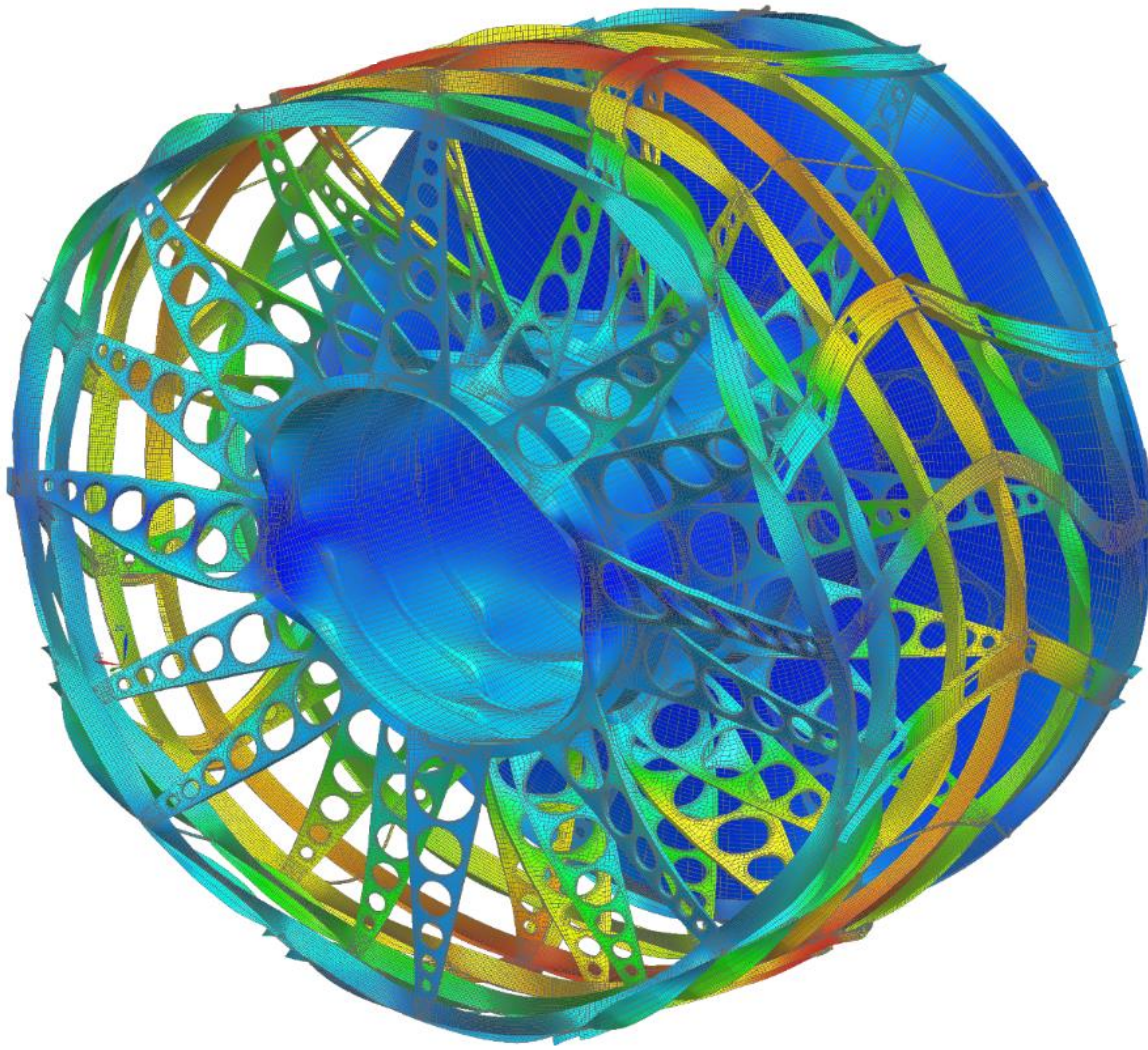
NX VS COMSOL



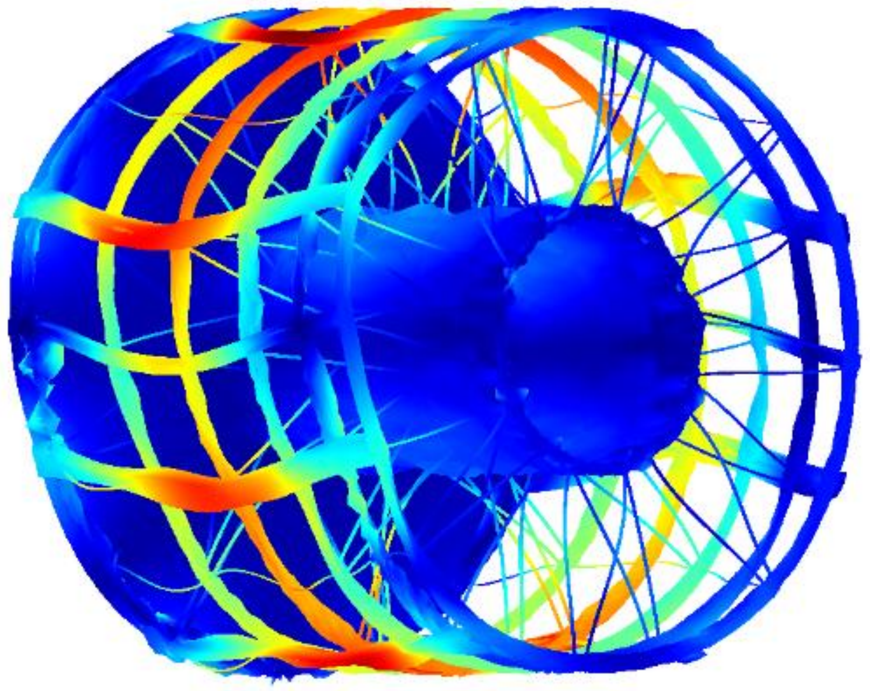
MANUAL CALCULATION
EULER BEAMS 54 HZ



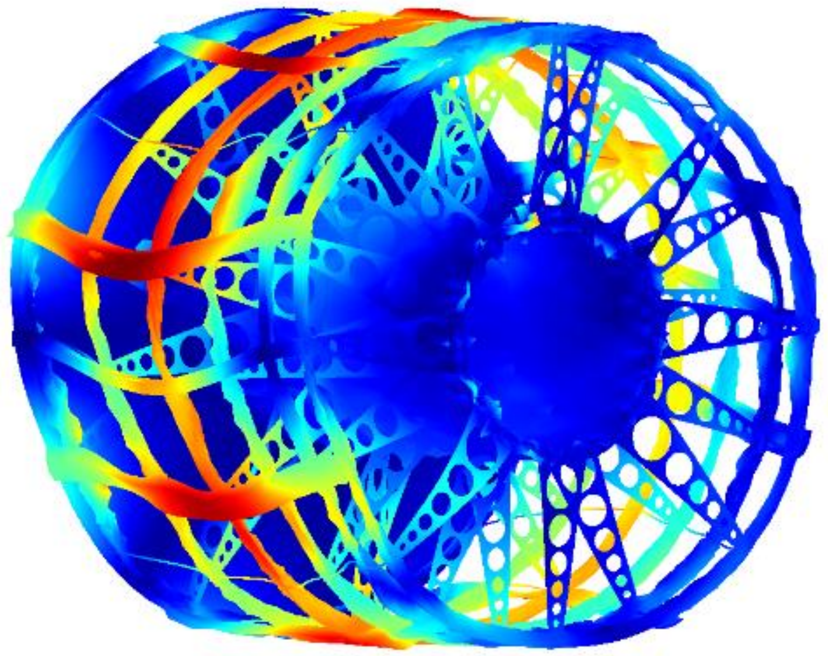
COMSOL BEAM
ISOTROPIC 53 HZ



NX NASTRAN SOLID BLADE
ORTHOTROPIC 49 HZ

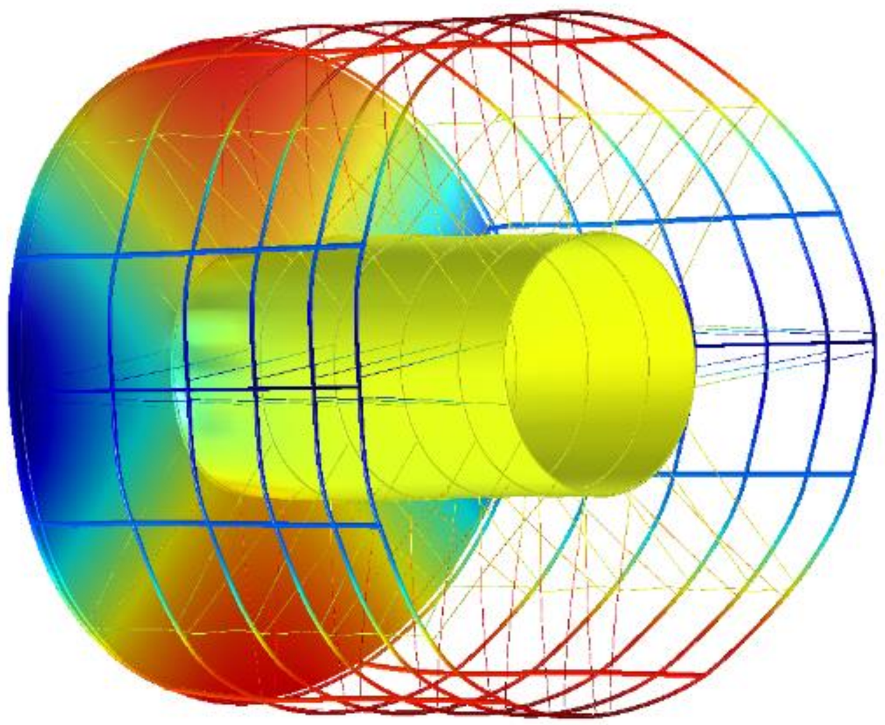


COMSOL SOLID ROD
ORTHOTROPIC 47 HZ

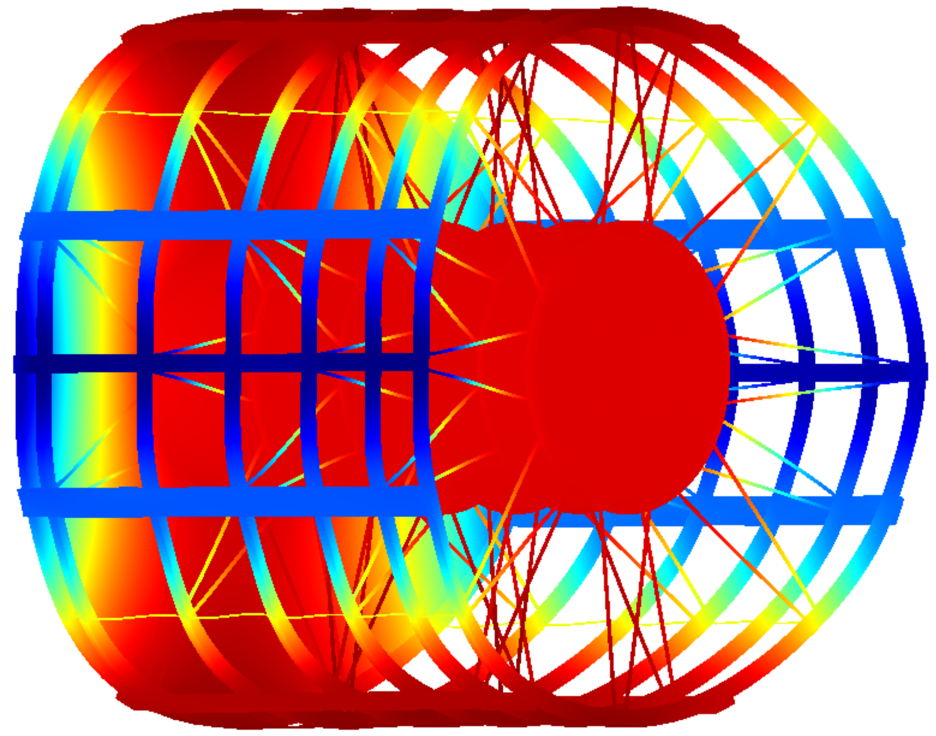


COMSOL SOLID BLADE
ORTHOTROPIC 50 HZ

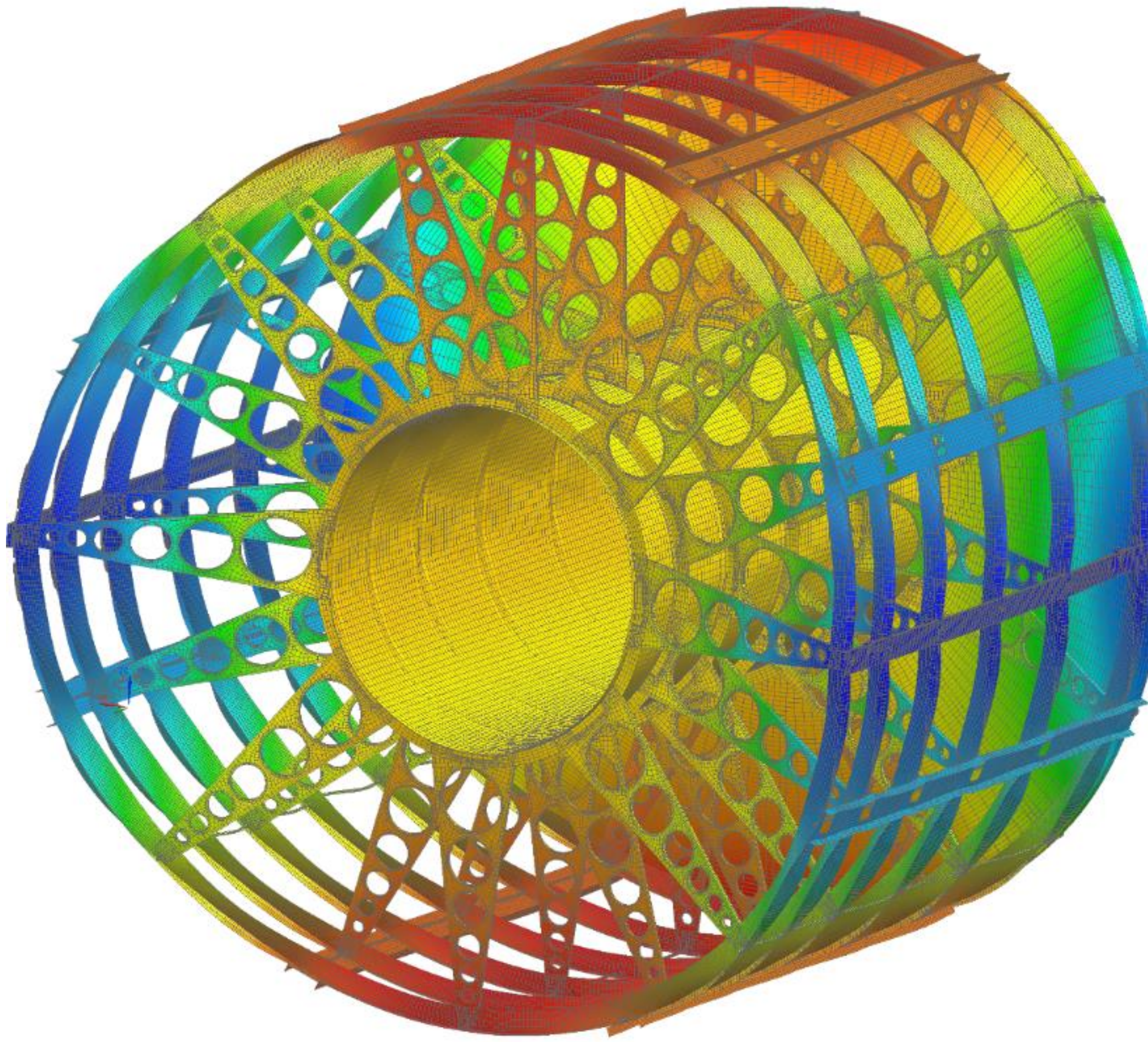
NX VS COMSOL



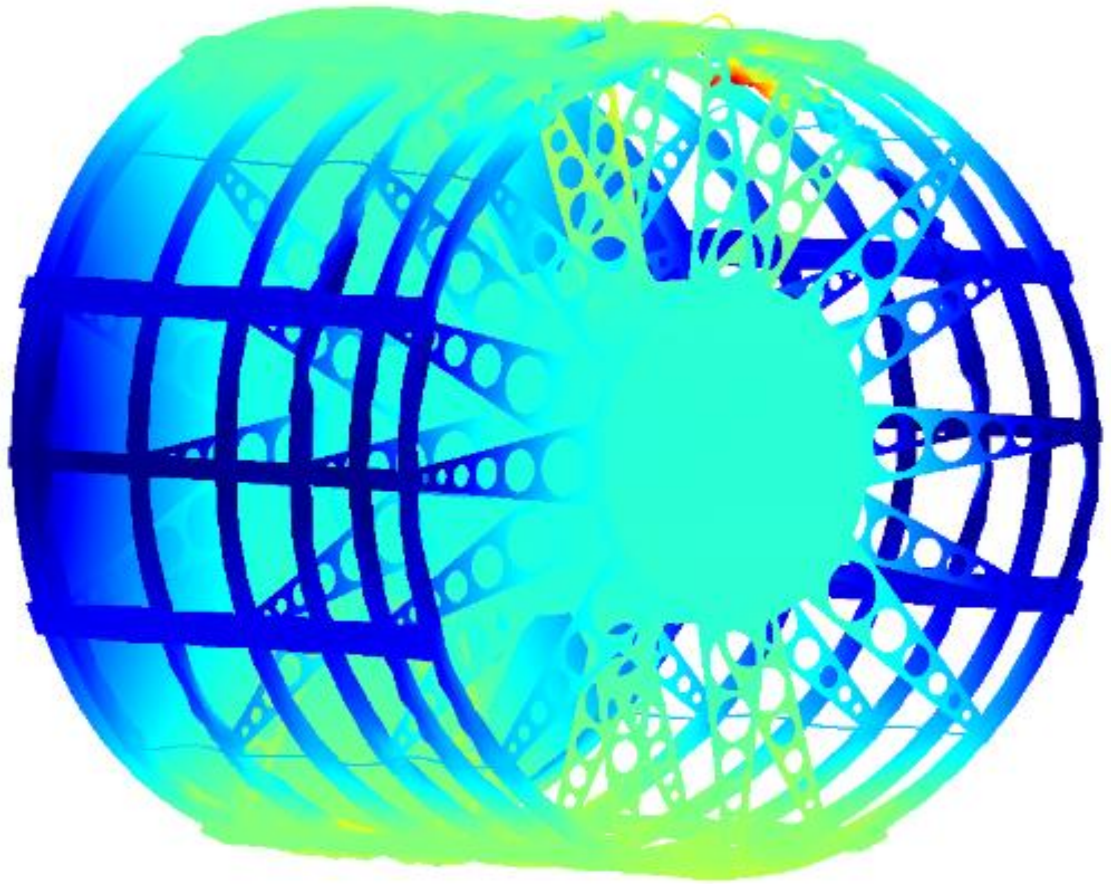
COMSOL BEAM
ISOTROPIC 50 HZ



COMSOL SOLID ROD
ORTHOTROPIC 18 HZ



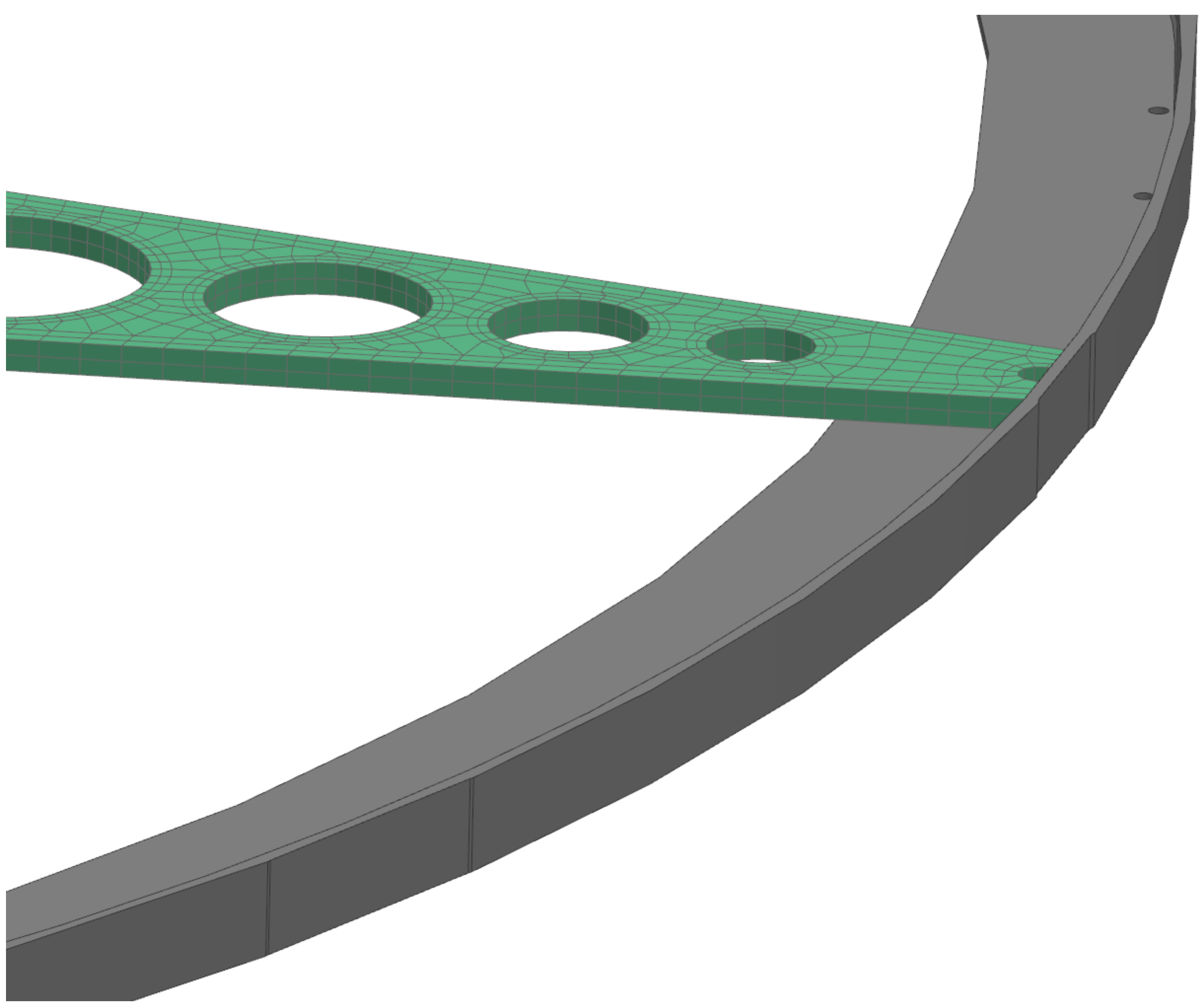
NX NASTRAN SOLID
BLADE ORTHOTROPIC 13 HZ

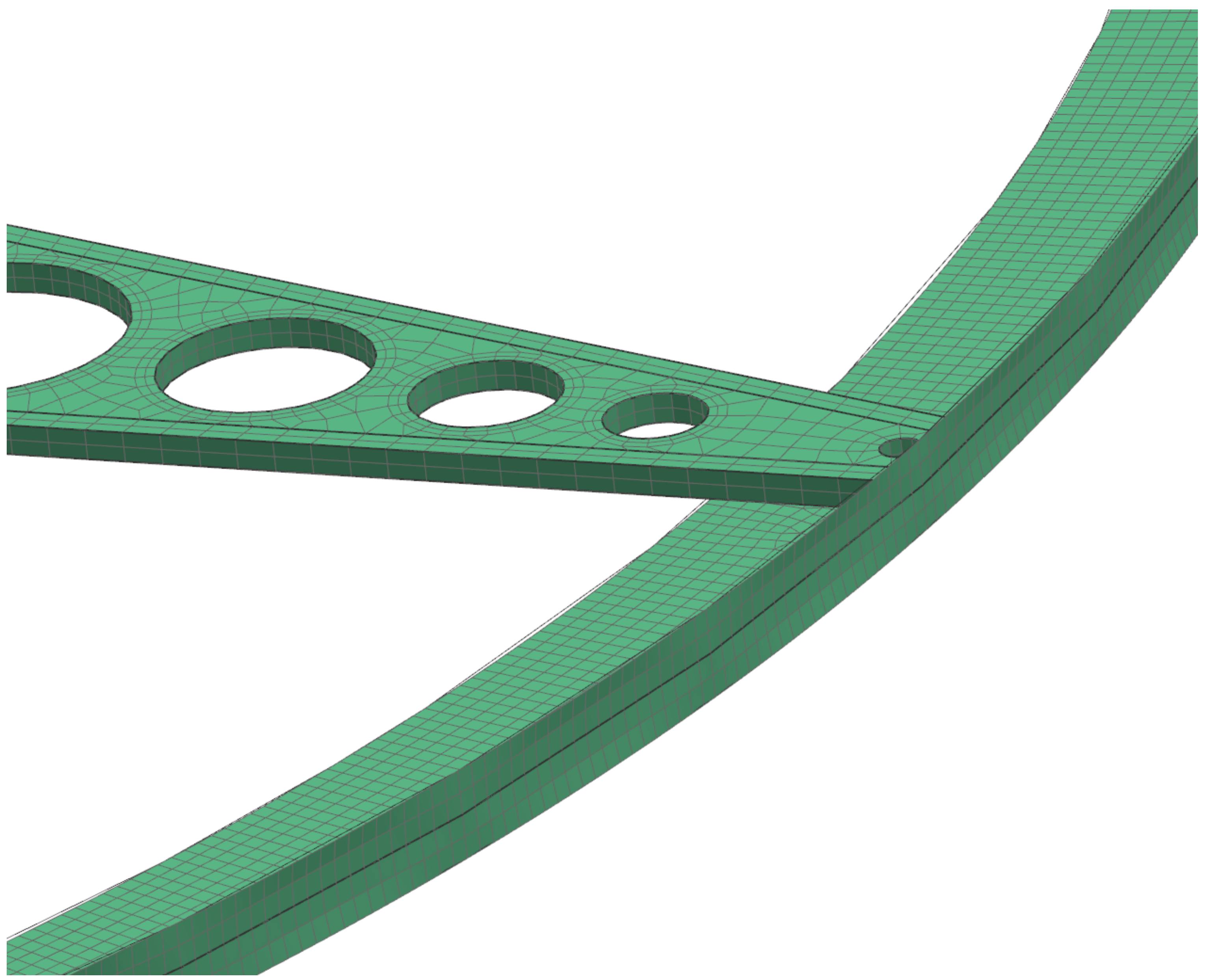


COMSOL SOLID BLADE
ORTHOTROPIC 14 HZ

NIKHEF SWITCHING FROM COMSOL MULTIPHYSICS TO NX NASTRAN

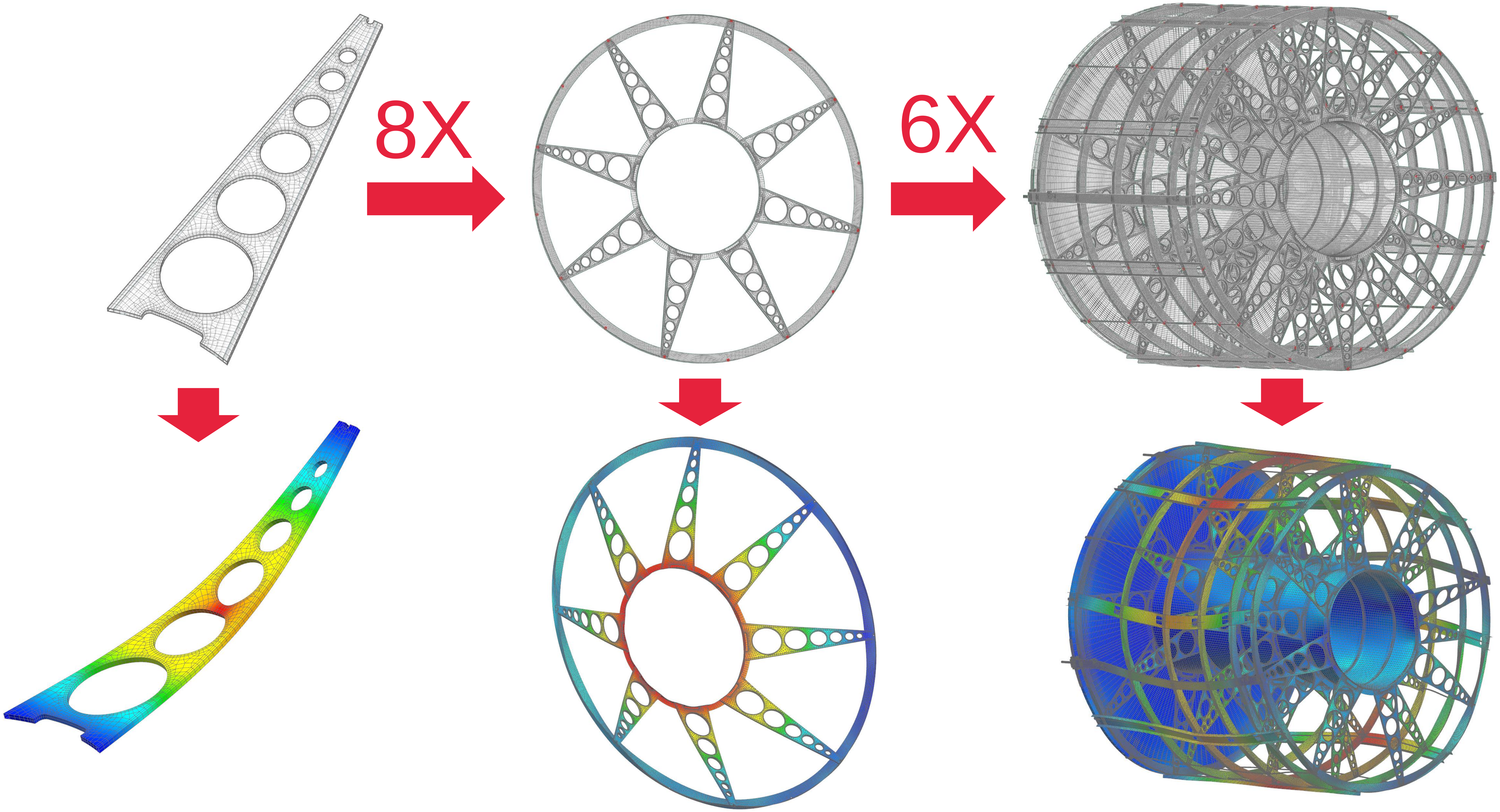
NX for geometry creation → No clunky geometry modeler
→ Same software used for the actual CAD model
→ Can reuse positional and dimensional information even with simplified representations





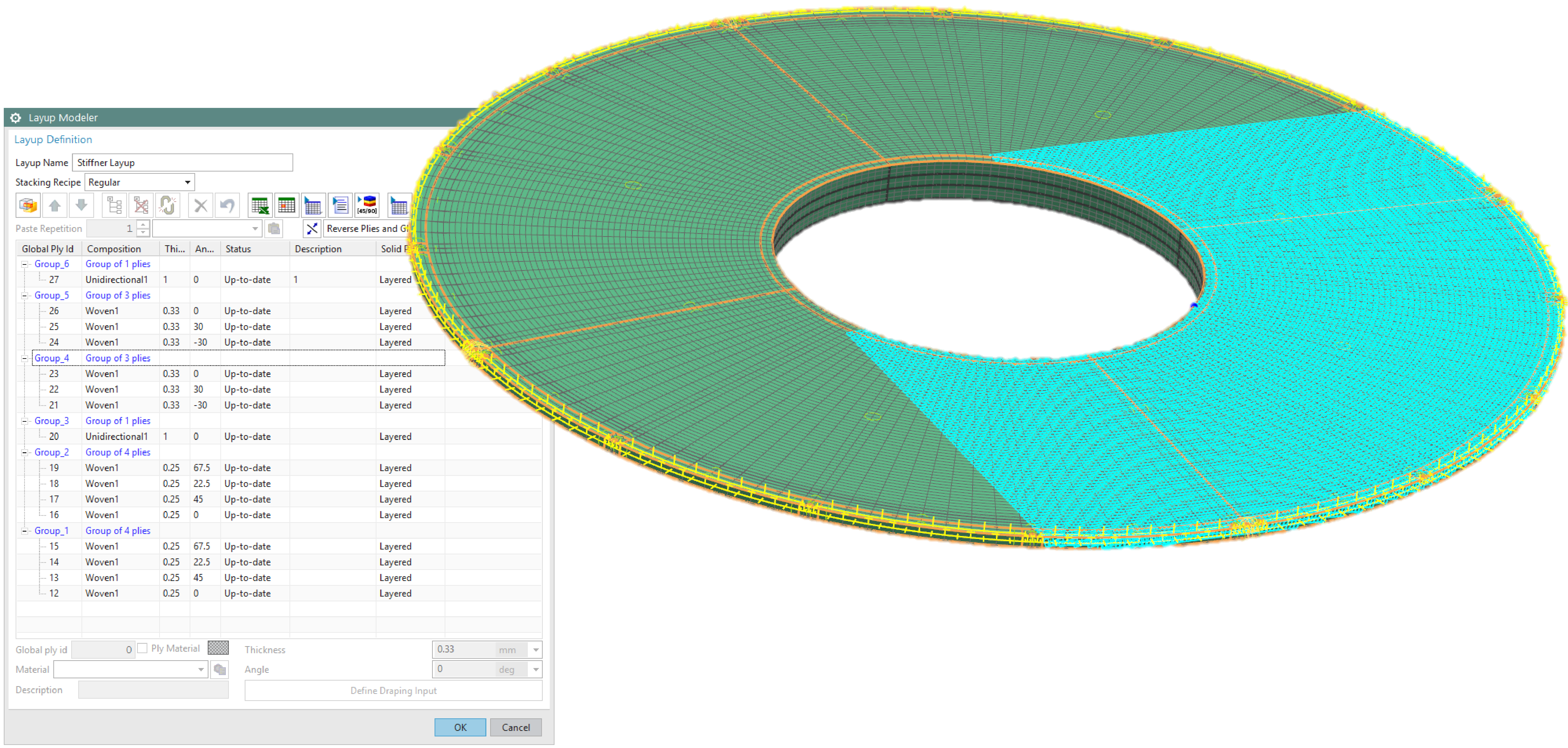
NIKHEF SWITCHING FROM COMSOL MULTIPHYSICS TO NX NASTRAN

Assembly Fem → Simulating finally gets a bit more logical like CAD



NIKHEF SWITCHING FROM COMSOL MULTIPHYSICS TO NX NASTRAN

Laminate Modeller→ No need create new material for every layup
→ Ability to drape "sheets" over surface
→ Ability to check material orientation without solving



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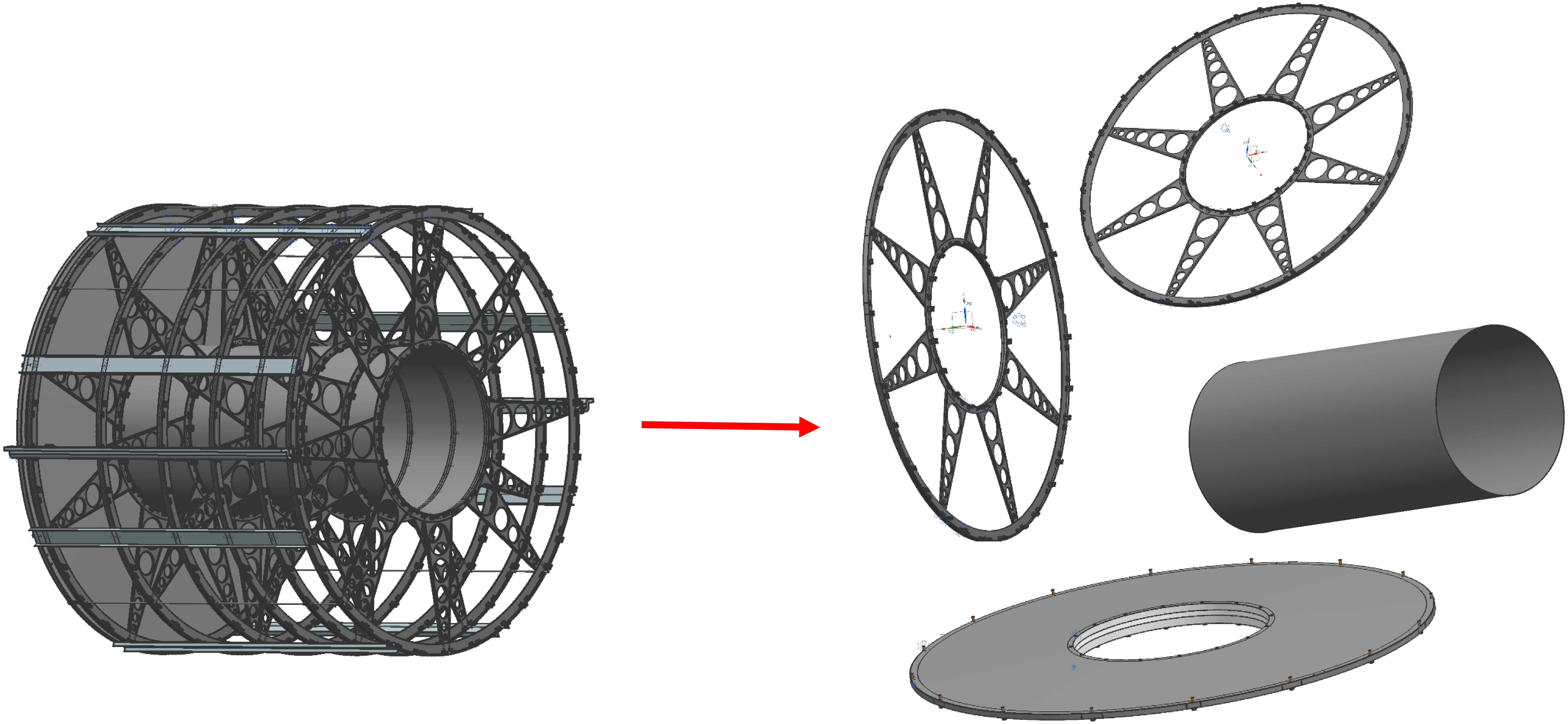
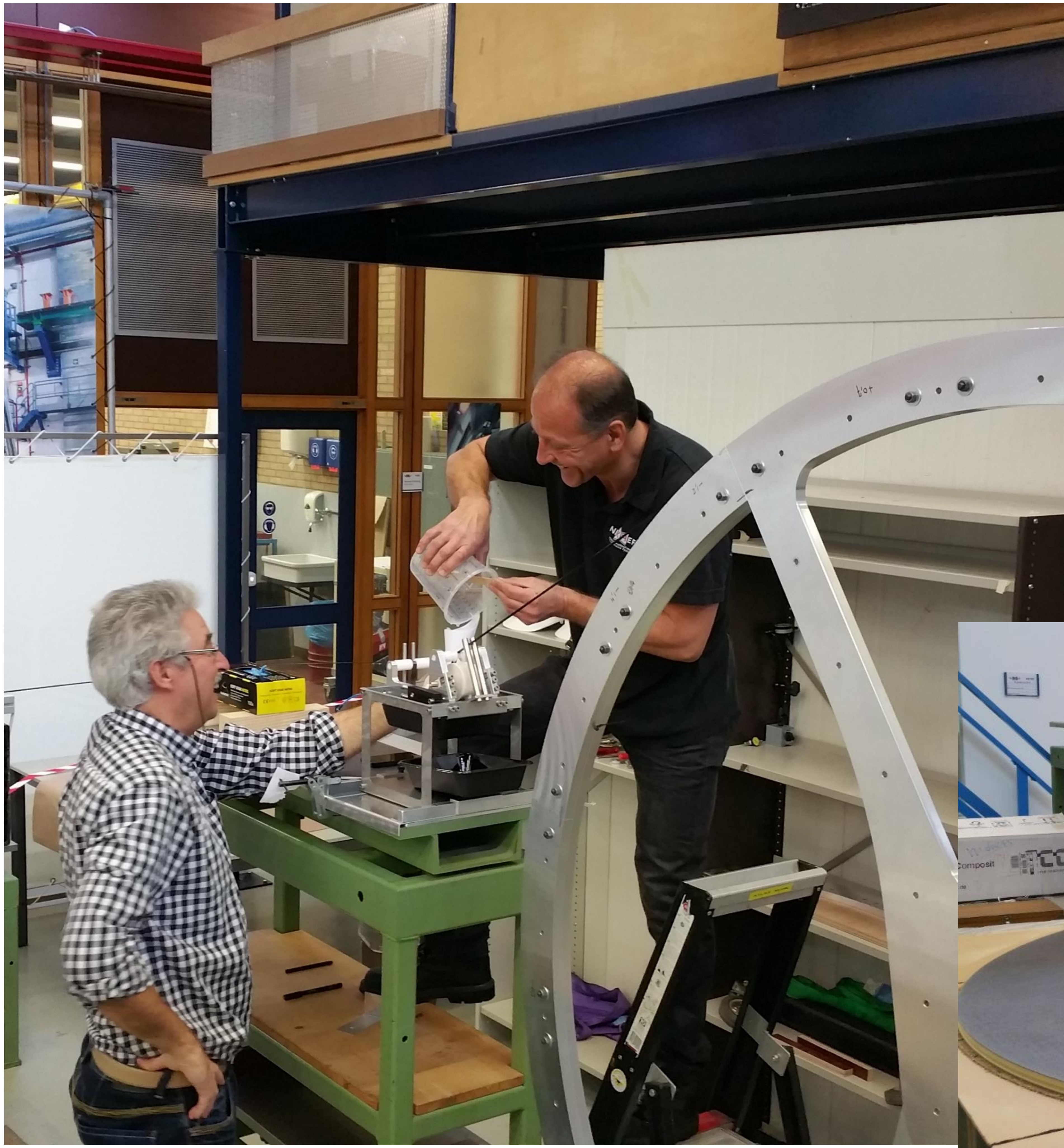
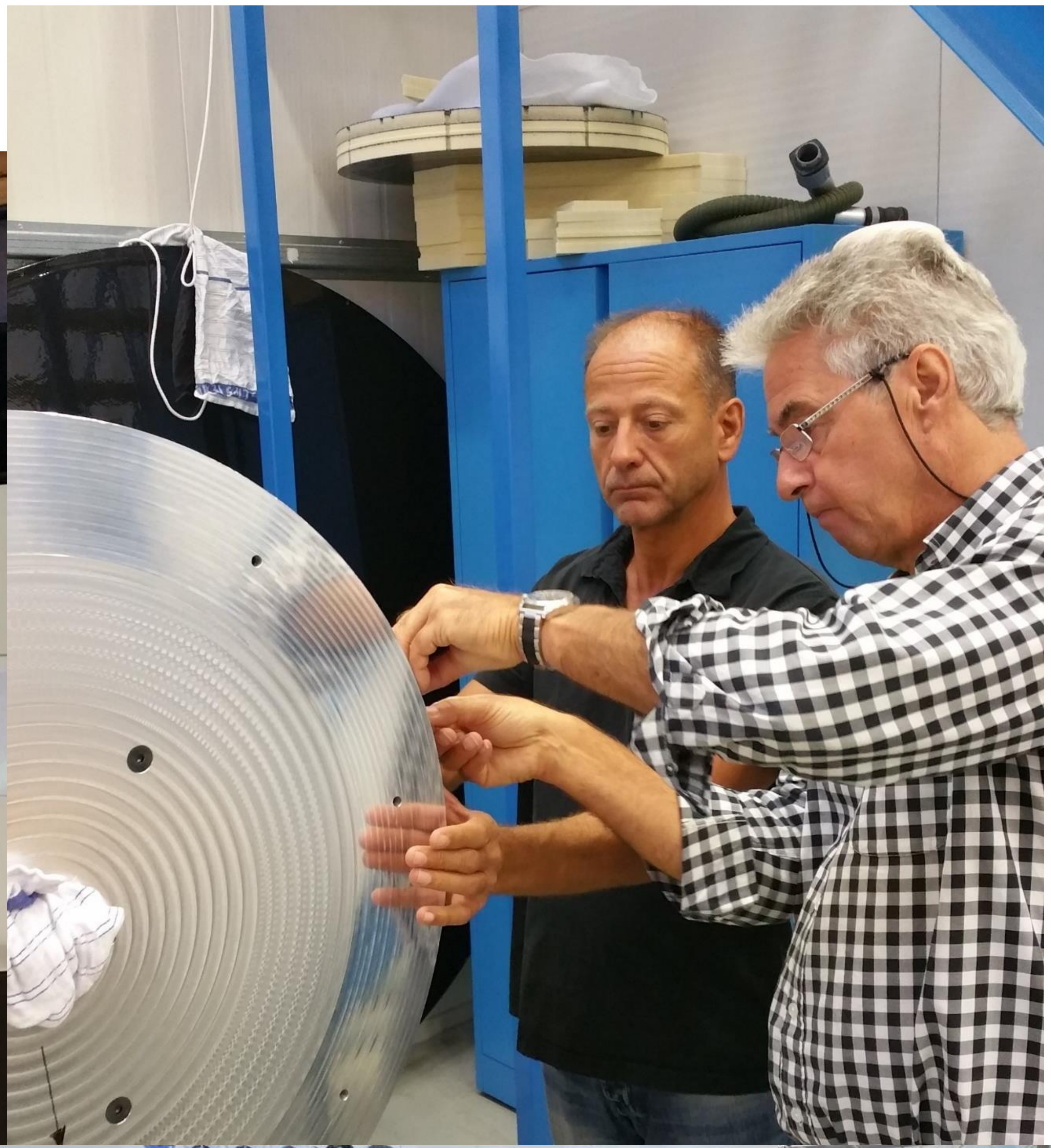
Work by:

BUILDING AND ANALYZING INDIVIDUAL COMPONENTS



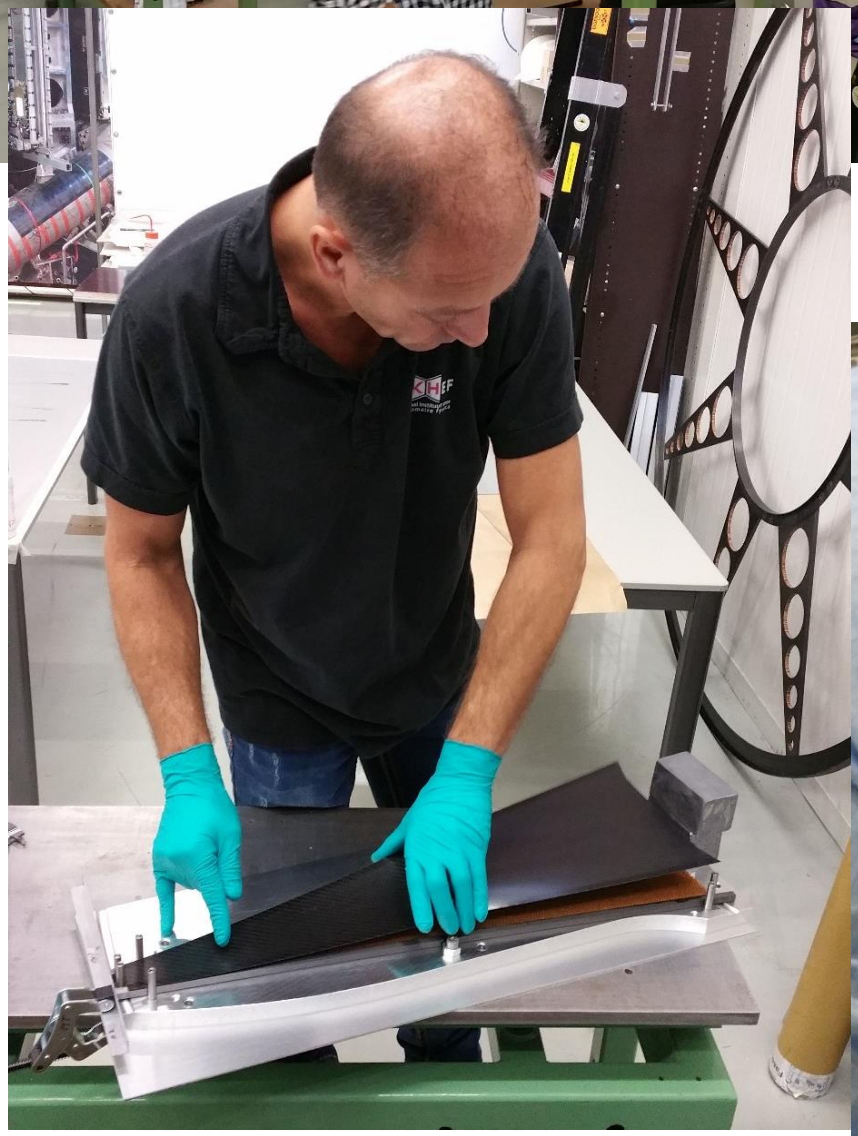
Nikhef





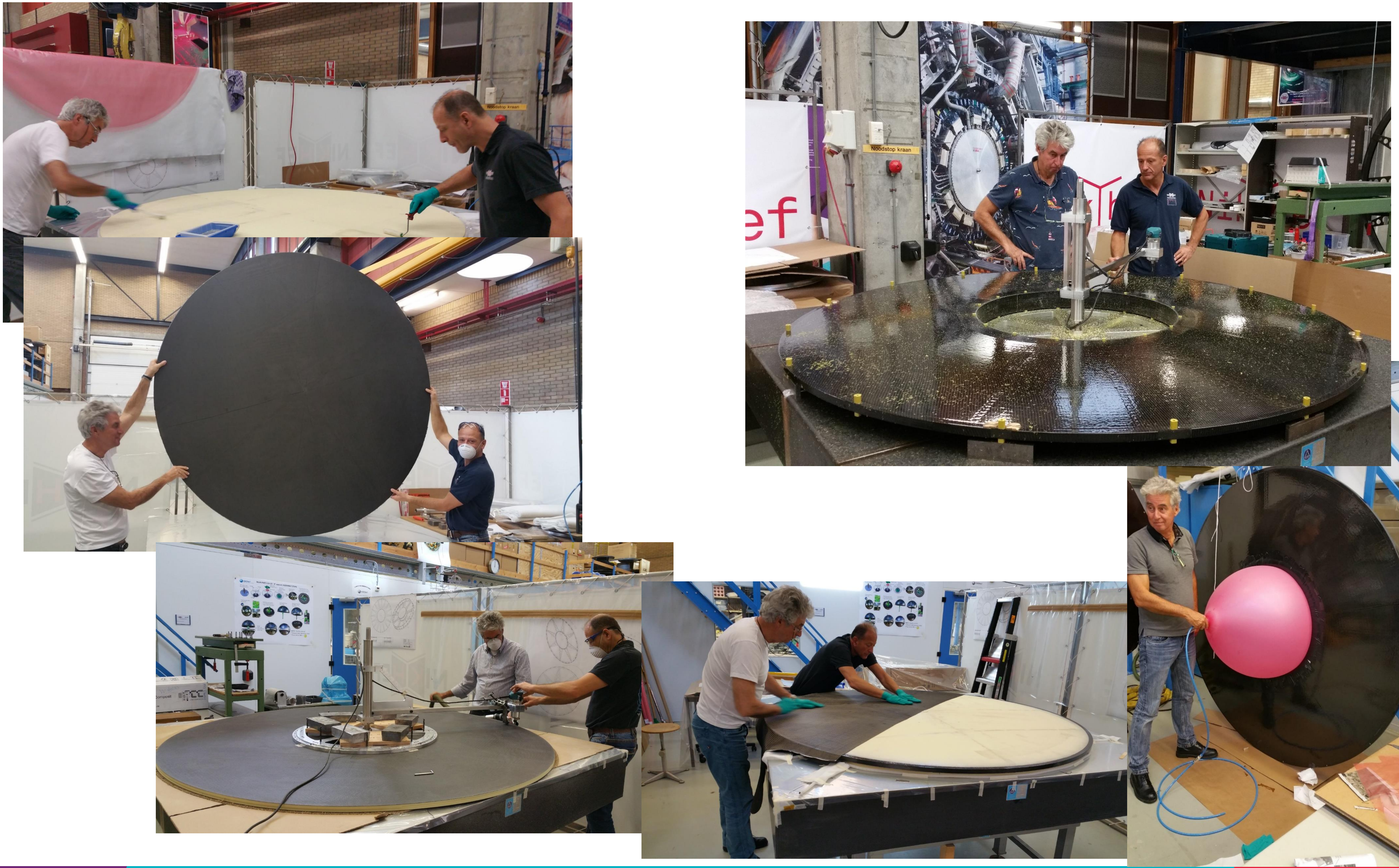
WORK BY: ARNOLD RIETMIJER (RIP)
& MARTIN DOETS

BUILDING THE WHEELS



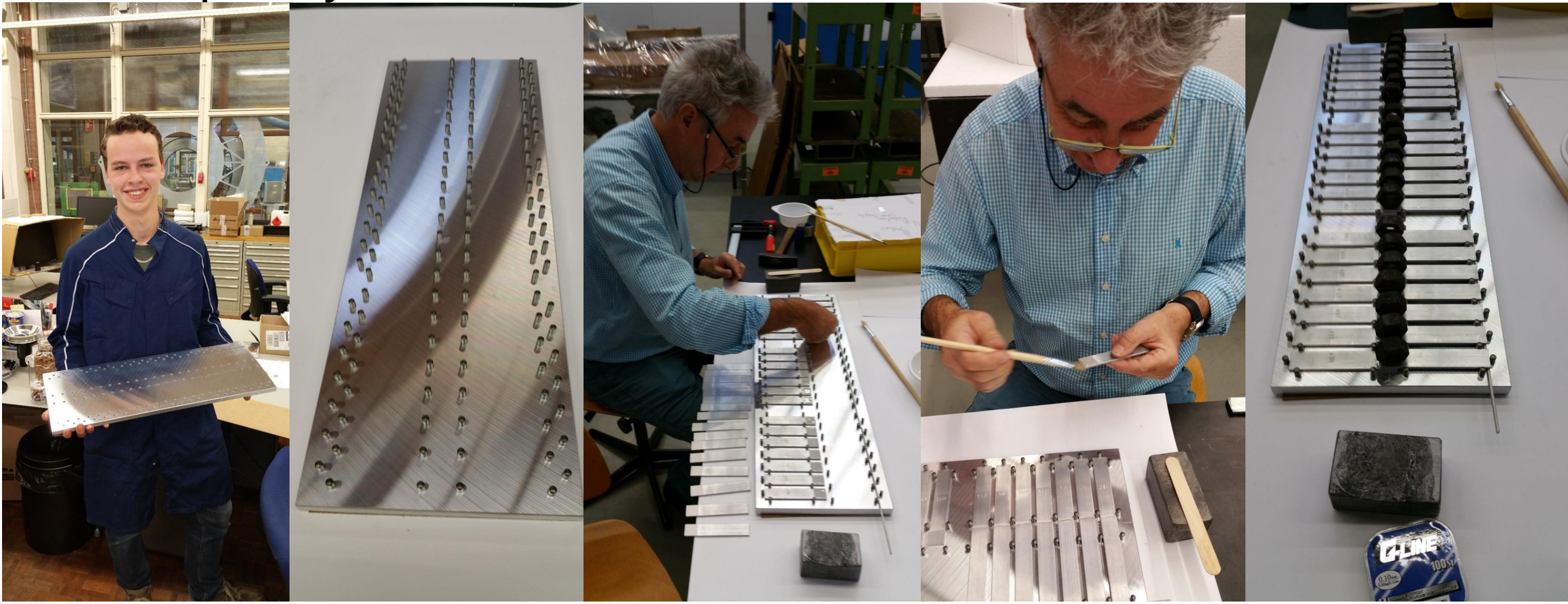
BUILDING THE INNER CYLINDER

BUILDING THE STIFFENER DISC



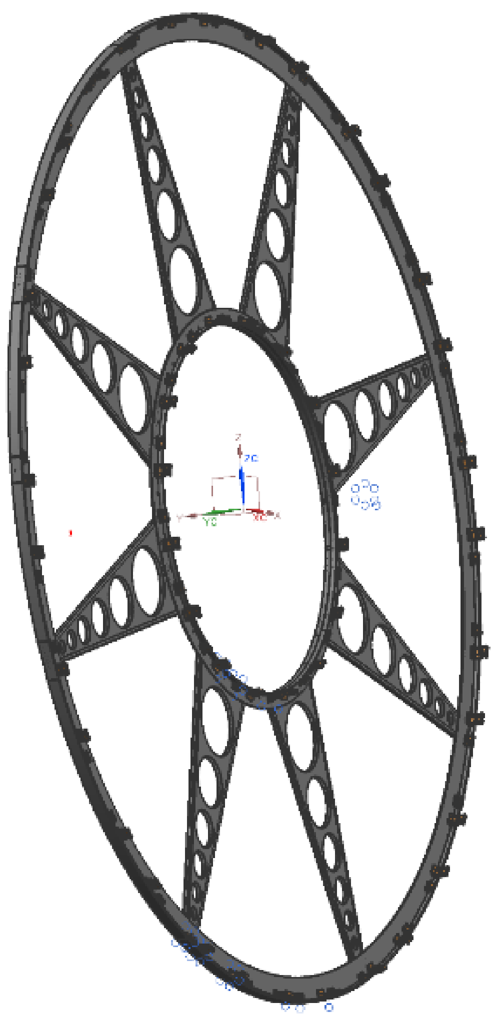
EPOXY RADIATION TESTS

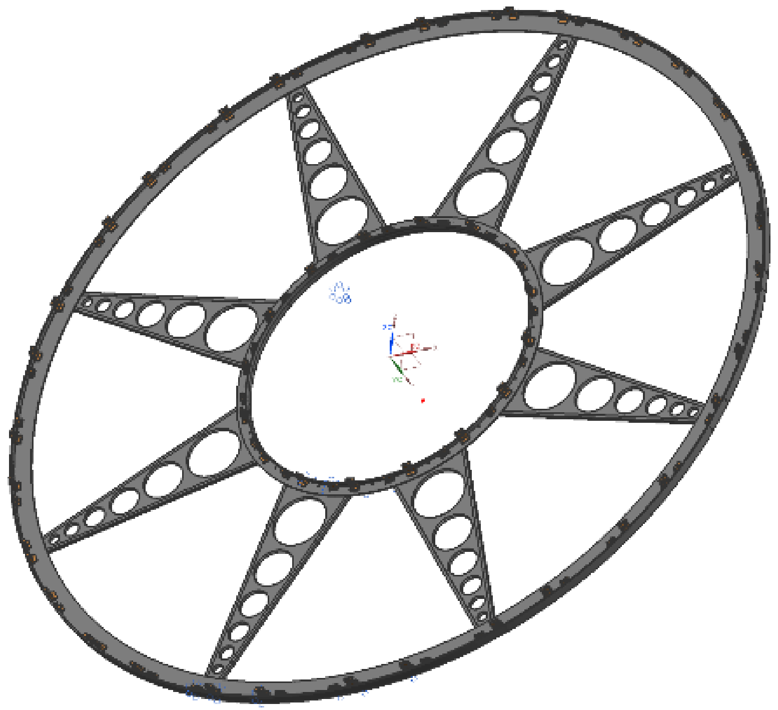
- Epoxy shear samples have been sent to CERN for Radiation hardness testing
- 21 samples per Epoxy type have been made for THV500/355, Hysol AE9396, Harder W300/Resin L
- Hopefully more info will follow soon

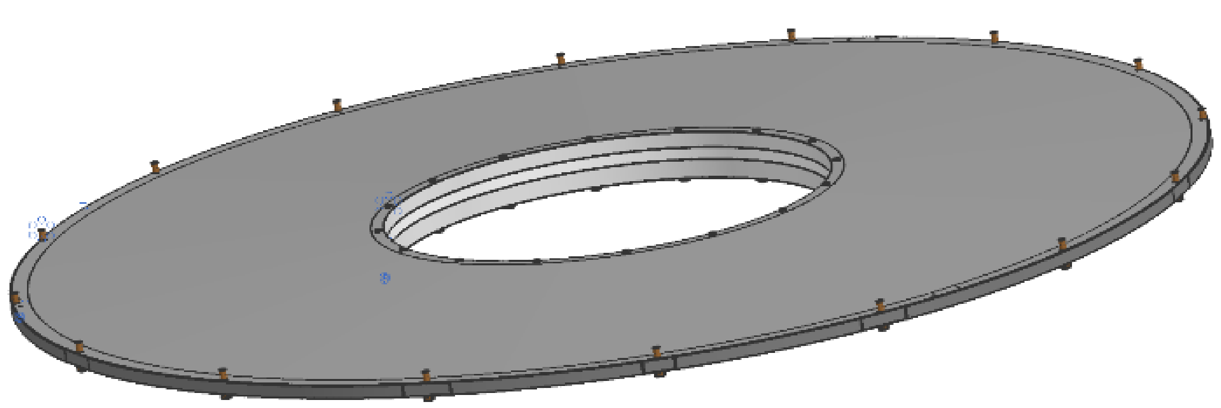


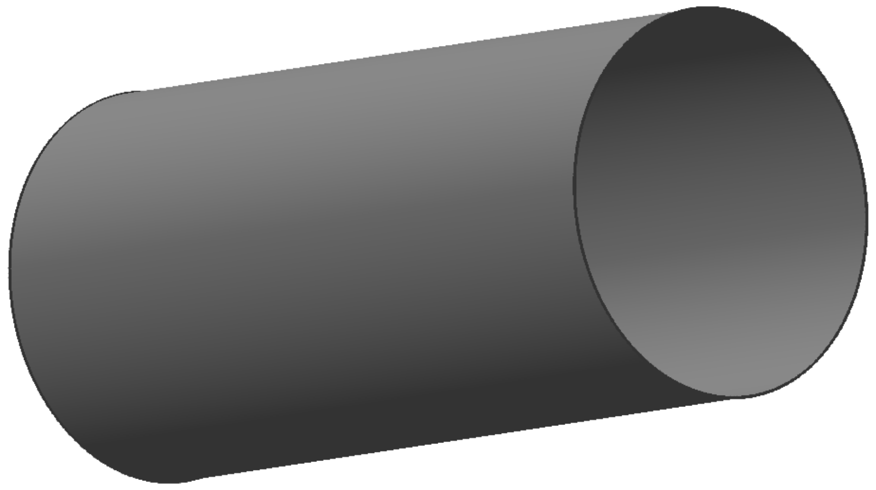
WORK BY TJARDO SASSEN & MARTIN DOETS

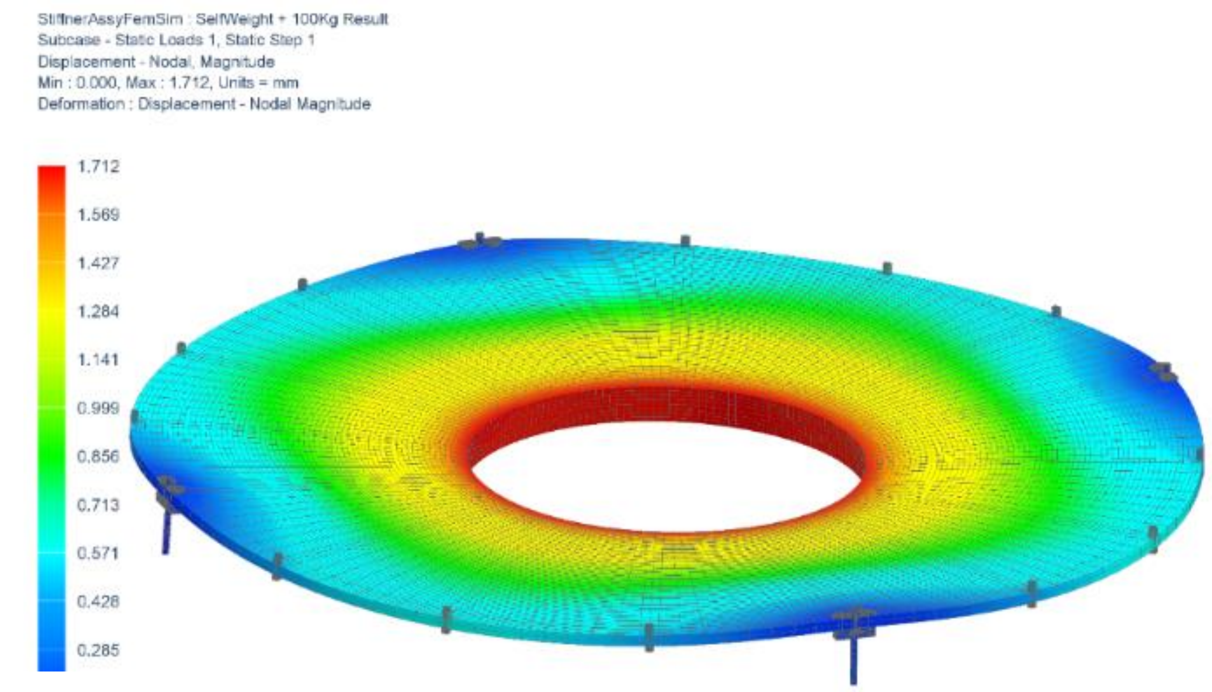
COMPARISON OF COMPONENTS WITH RESPECTIVE SIMULATIONS

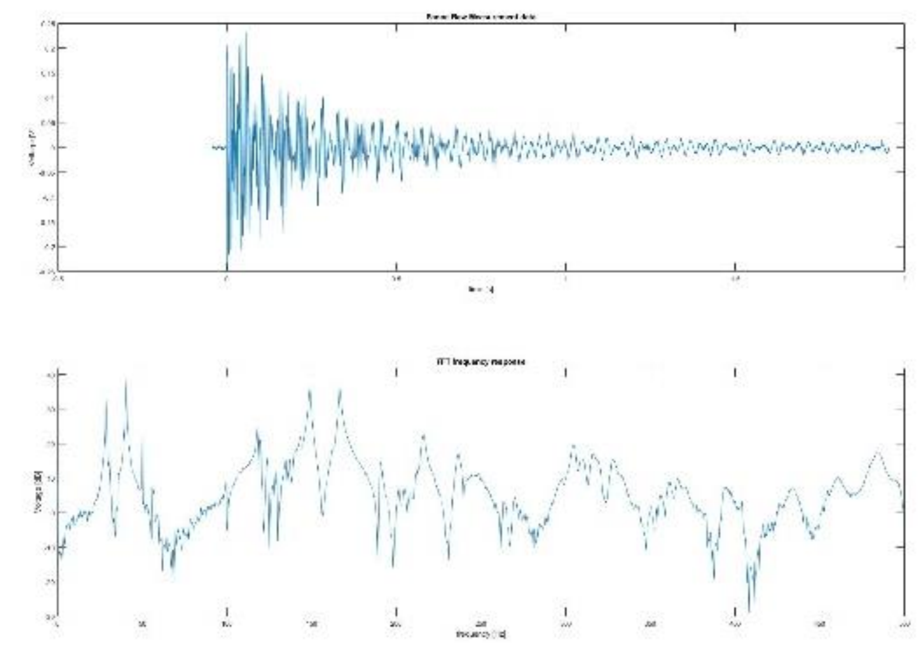


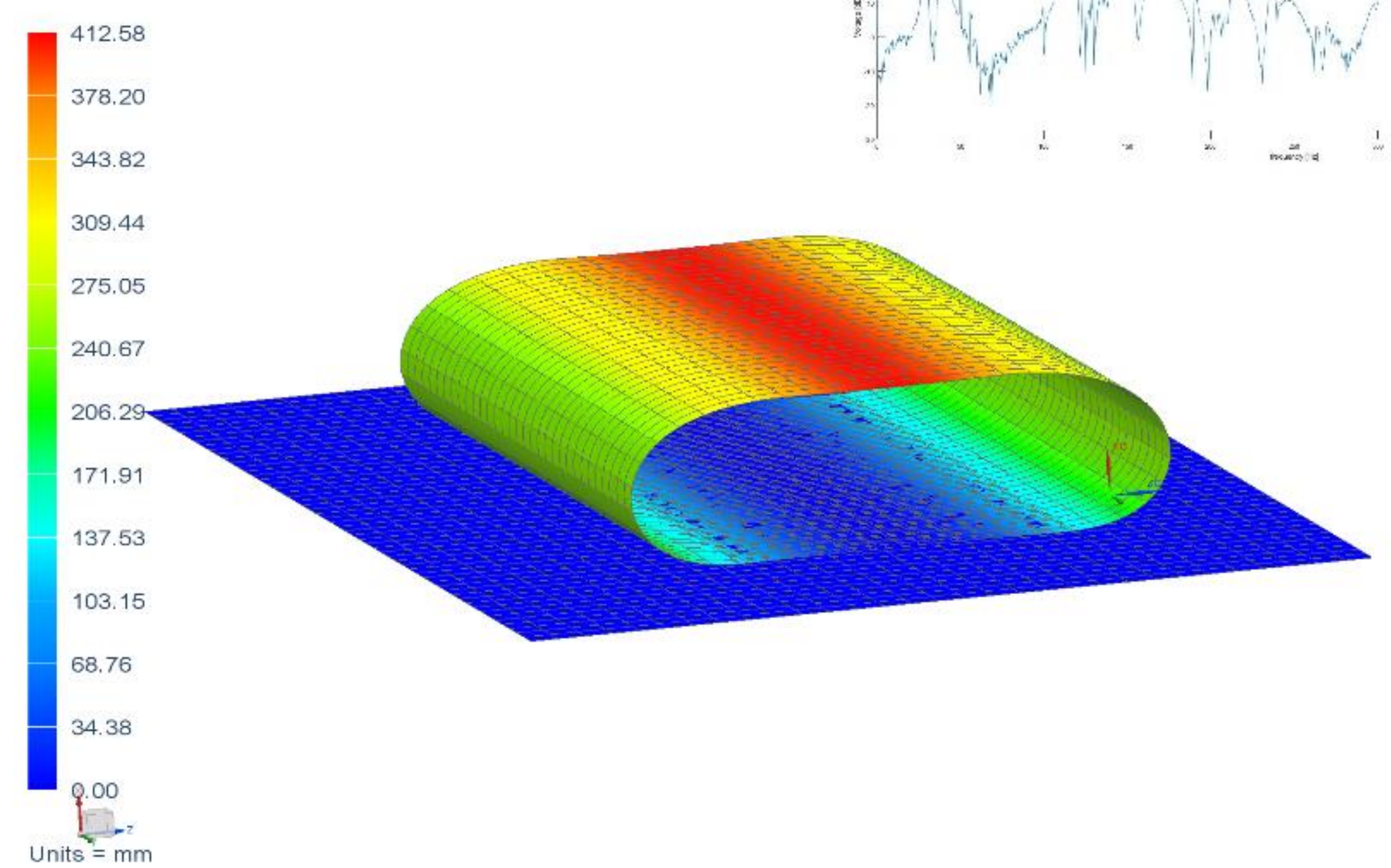




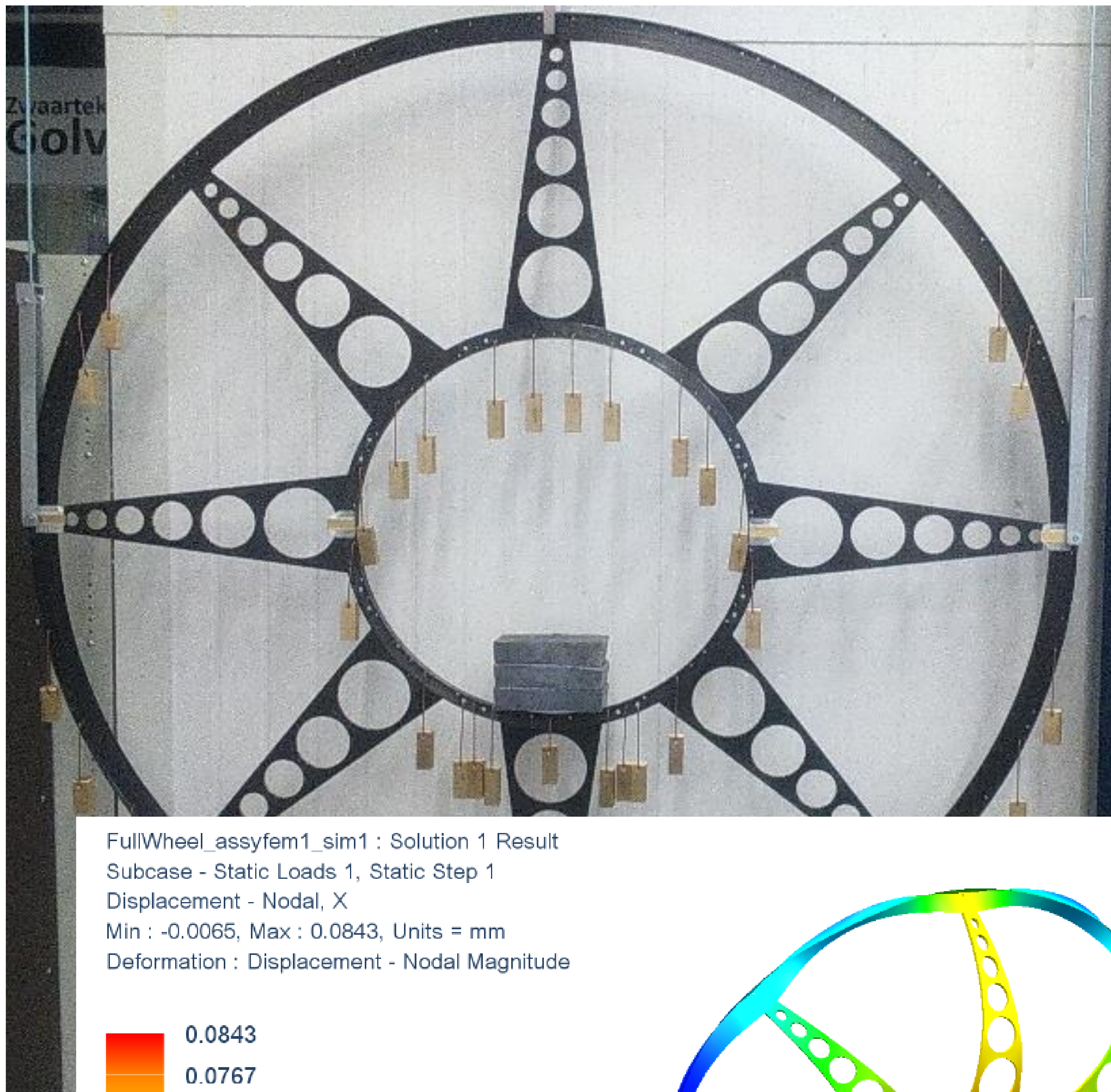


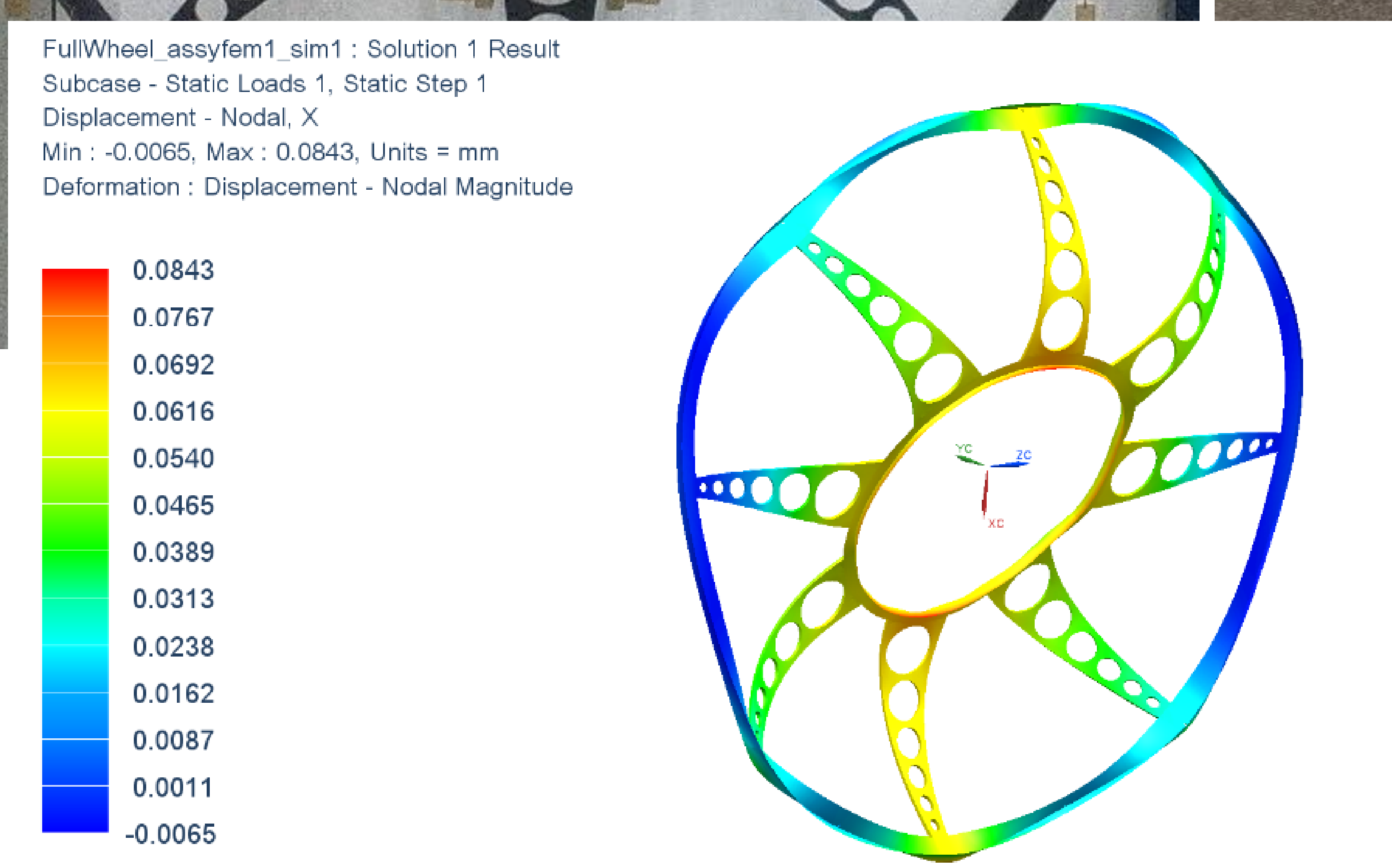


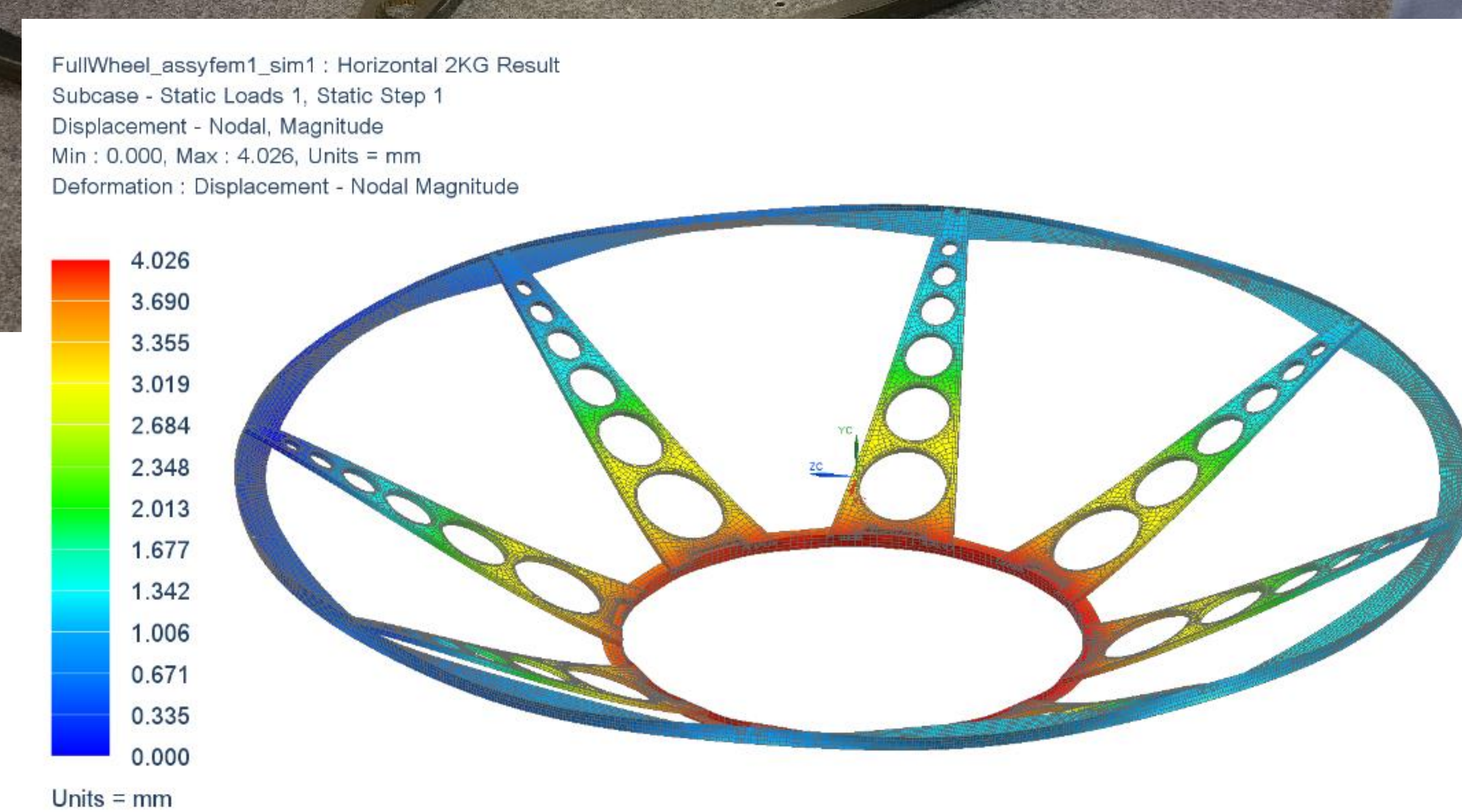




VERTICAL AND HORIZONTAL LOADING OF A WHEEL



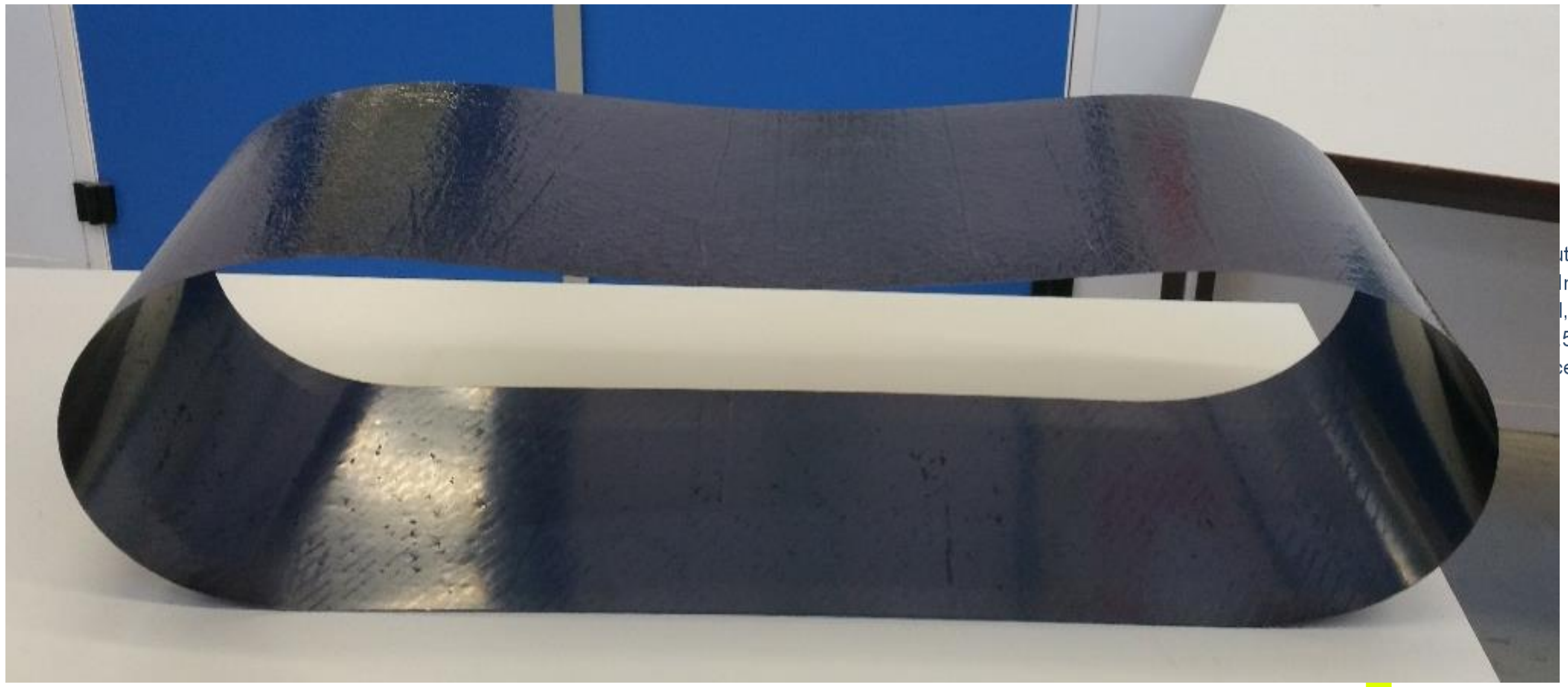


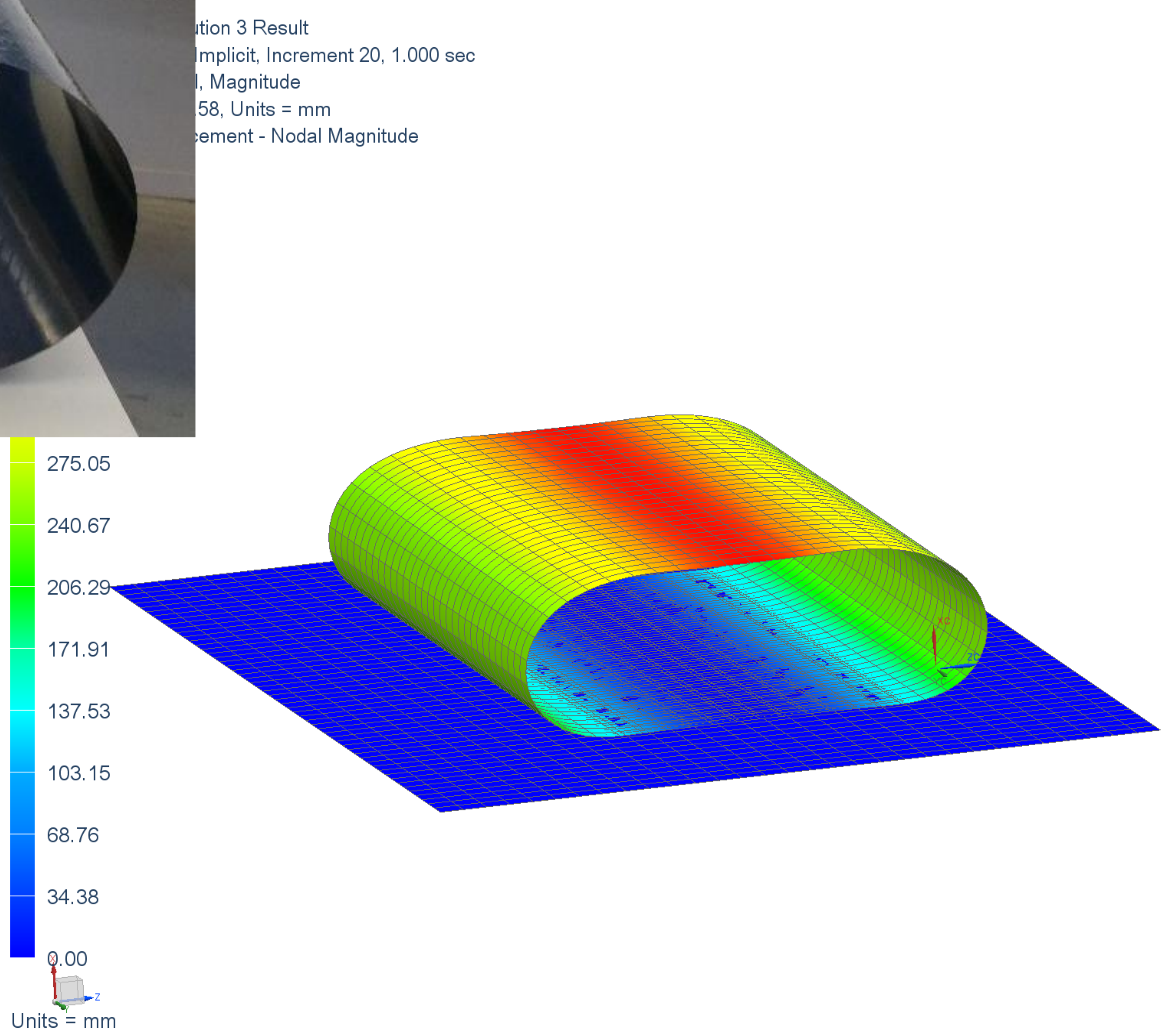


VERTICAL AND HORIZONTAL LOADING OF A WHEEL

TestCase	Vertical 35kg	Horizontal Selfweight	Horizontal 2KG
Physical Test	0.08-0.12mm	1.2 mm	4.1mm
CAE Result	0.08 mm	1.25 mm	4 mm

INNER CYLINDER DEFORMATION



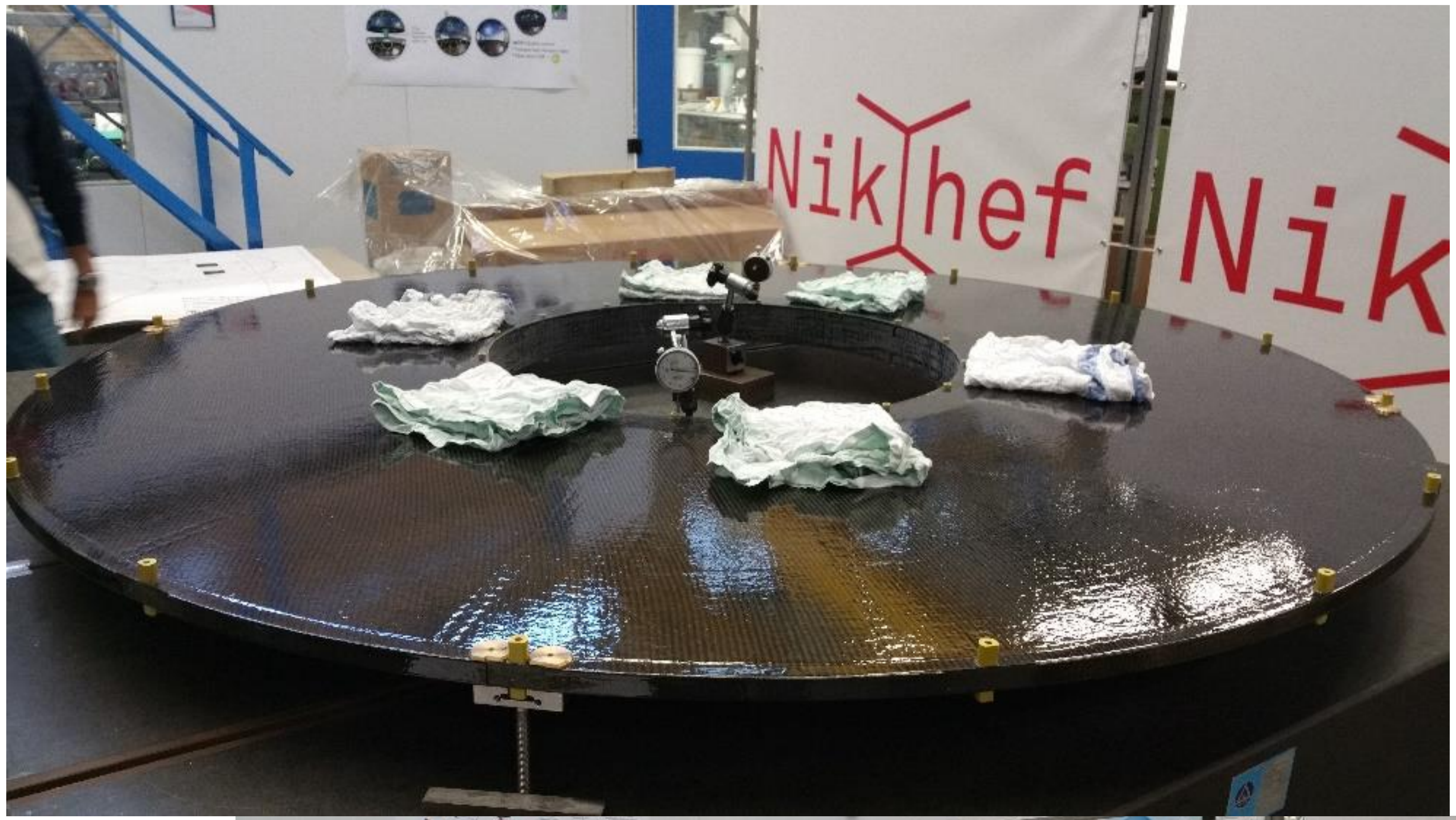


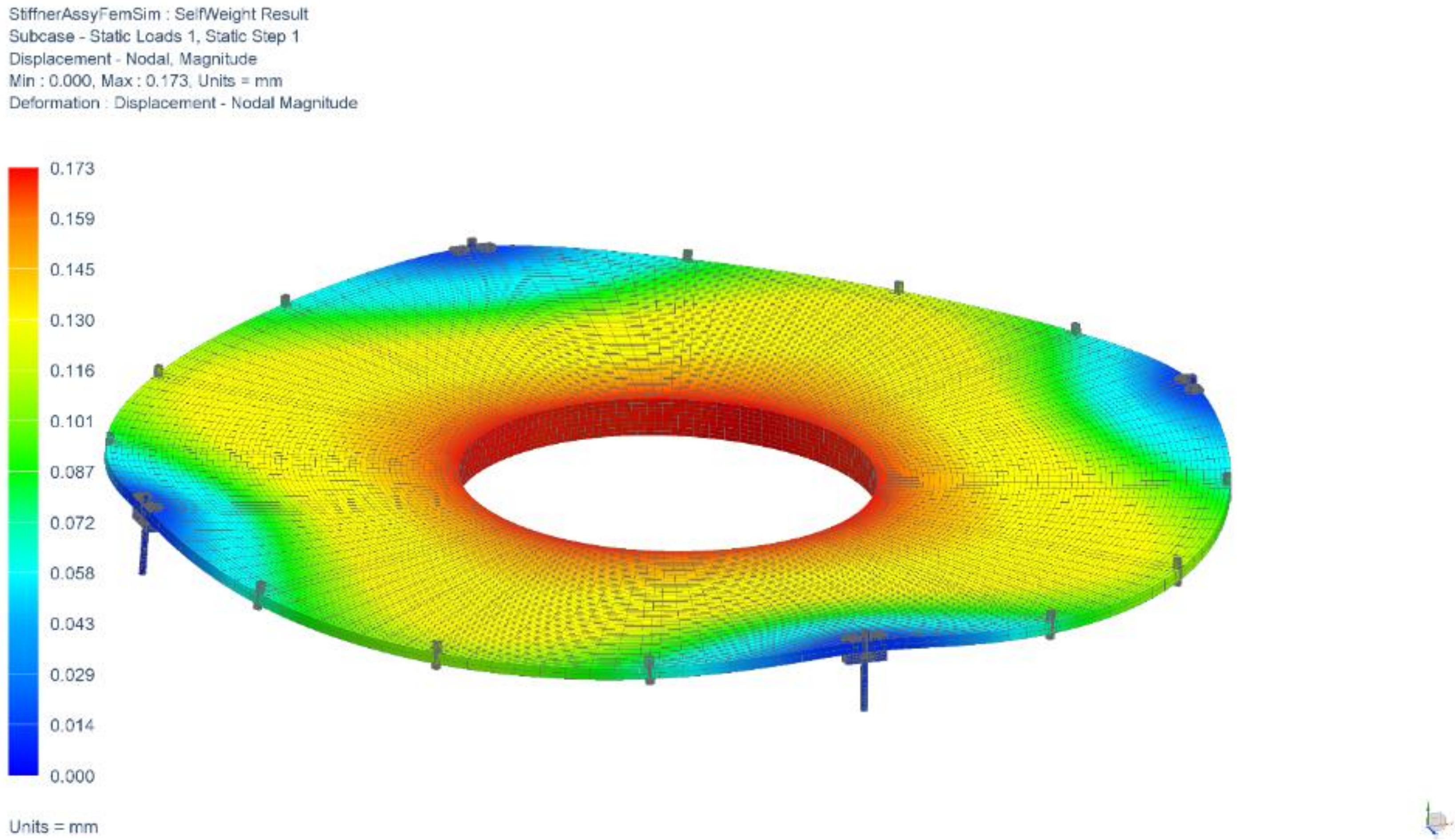
INNER CYLINDER DEFORMATION

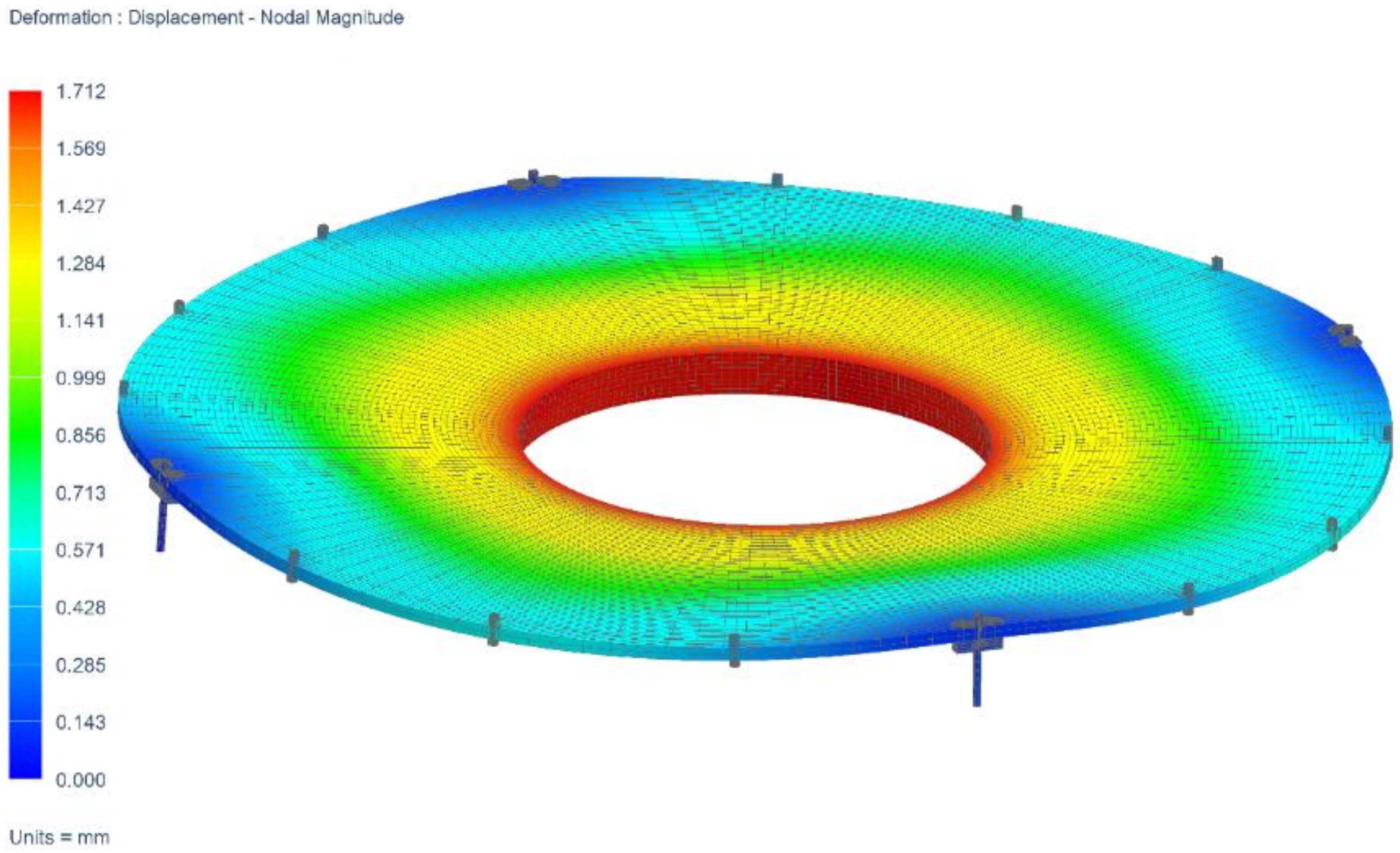
TestCase	Height after deformation
Physical Test	27 – 34 cm (positional dependence)
CAE Result	30 cm

*CAE Test assumes 0.4mm innertube with 55:45 fiber epoxy ratio, with a 2.7GPa Epoxy stiffness

DEFORMATION STIFFENER DISC



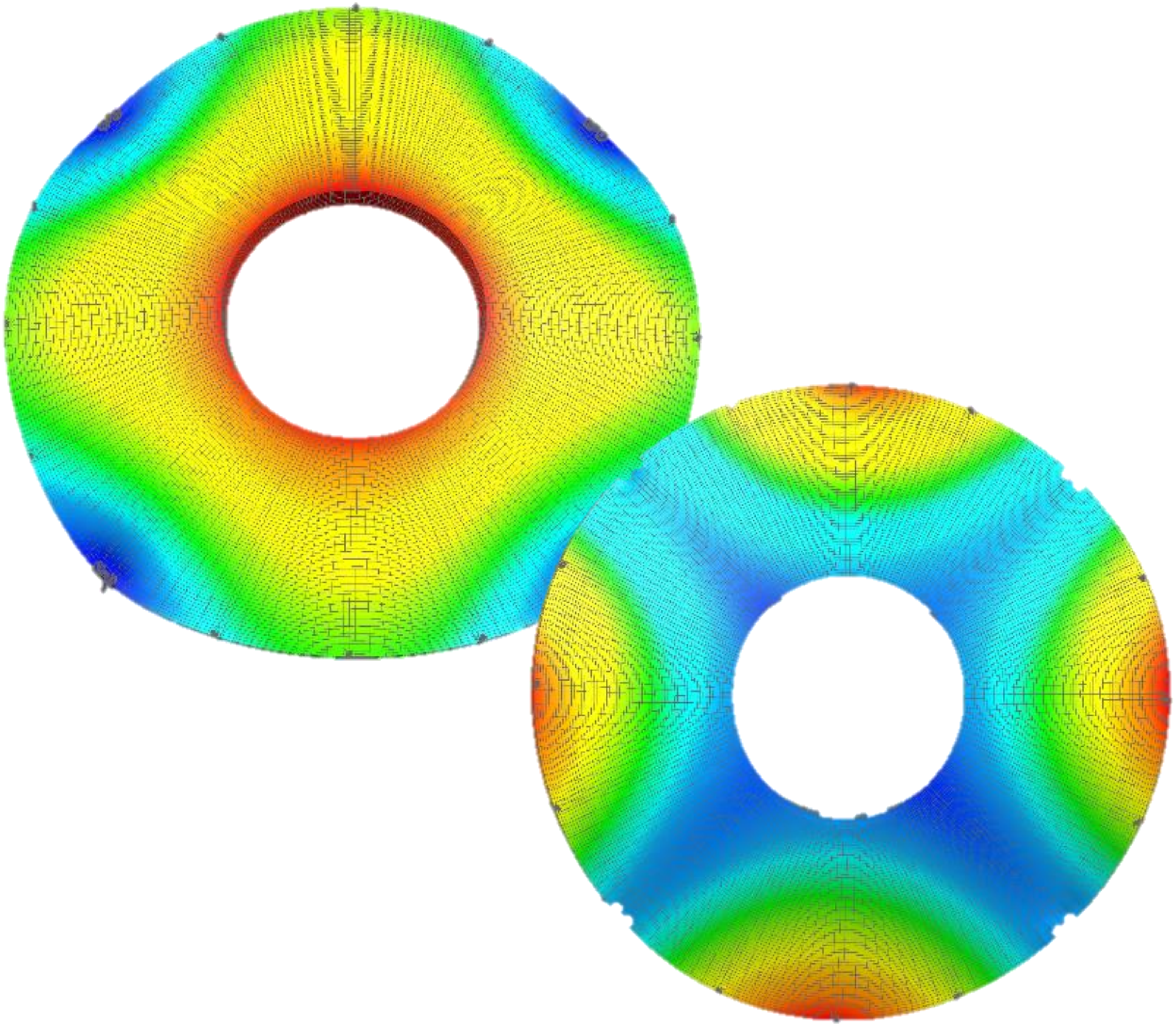




DEFORMATION STIFFENER DISC

TestCase	Displacement under a 100kg load [mm]
Physical Test	1.49mm
CAE Result	1.54mm

STIFFENER DISC EIGEN FREQUENCY



STIFFENER DISC EIGEN FREQUENCY

Frequency [Hz] ------------- TestCase									
Physical Test	43	53	58	124	-	-	-	-	204
CAE Result	44	52	60	124	148	160	177	190	204

* Note no validation regarding modeshapes

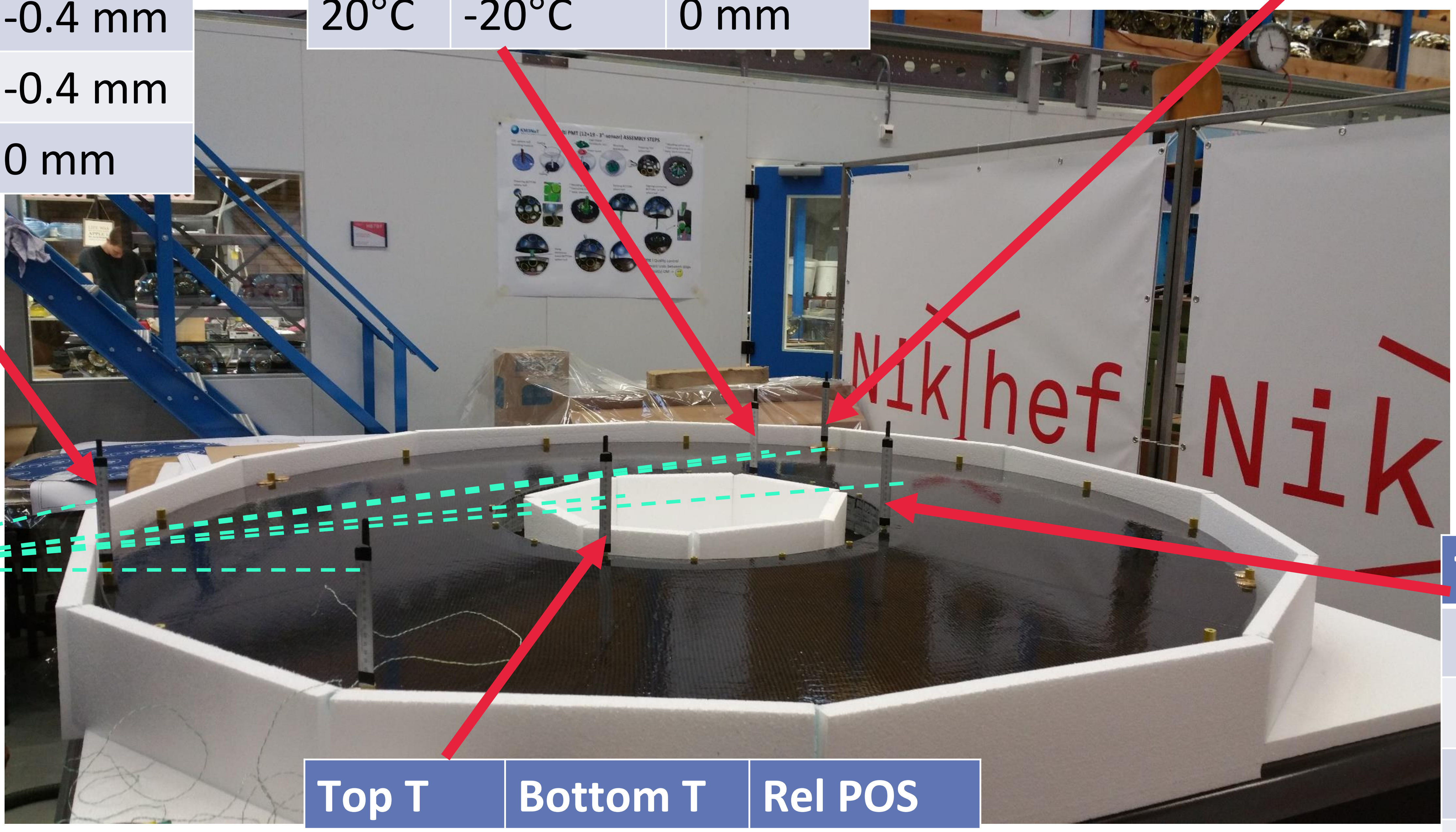
THERMAL DEFORMATION STIFFENER DISC

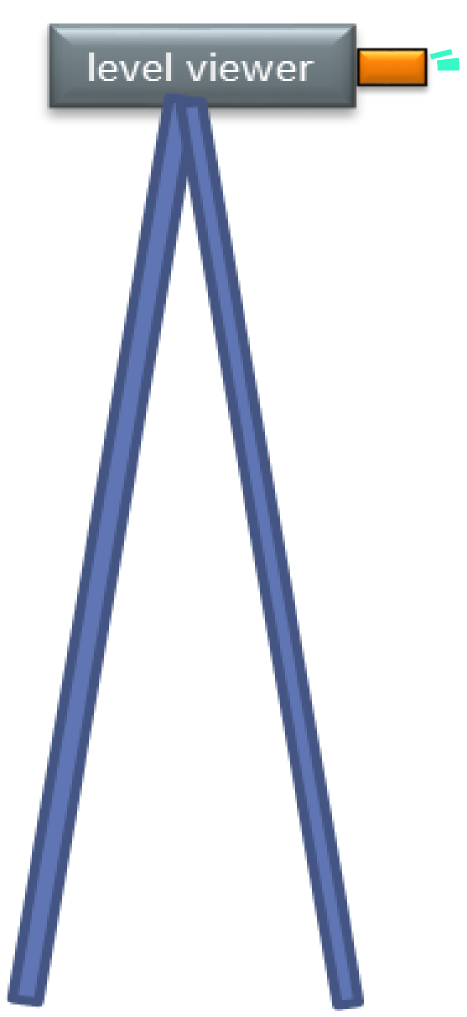
Exact thermal profiles unknown so no FEA comparison

Top T	Bottom T	Rel POS
20°C	20°C	0 mm
20°C	-6°C	-0.3 mm
16°C	-25°C	-0.4 mm
5.8°C	-29°C	-0.4 mm
20°C	20°C	0 mm

Top T	Bottom T	Rel POS
20°C	20°C	0 mm
18°C	-16°C	-1.4 mm
20°C	-20°C	0 mm

Top T	Bottom T	Rel POS
20°C	20°C	0 mm
18°C	-18°C	0.1 mm

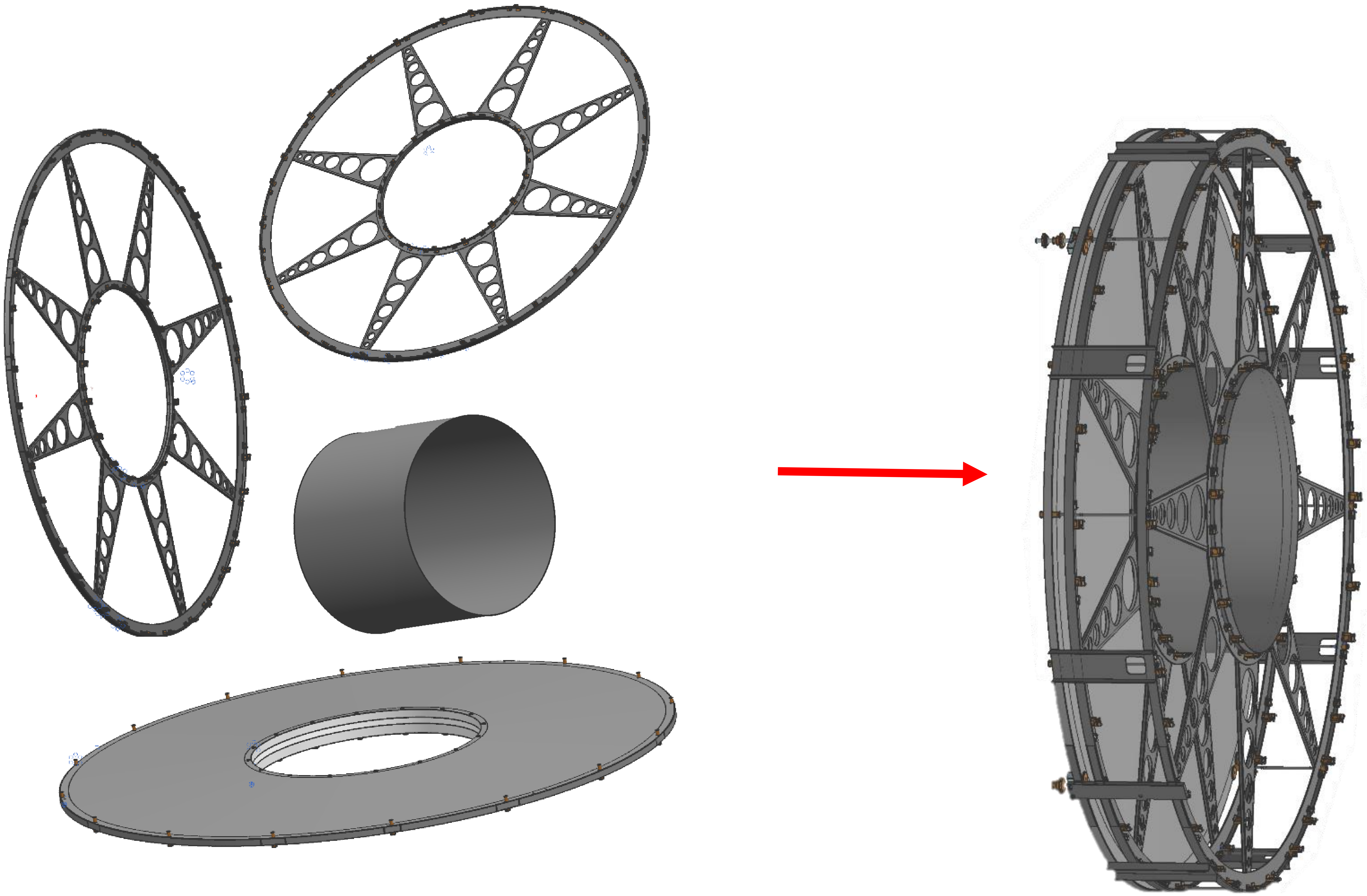


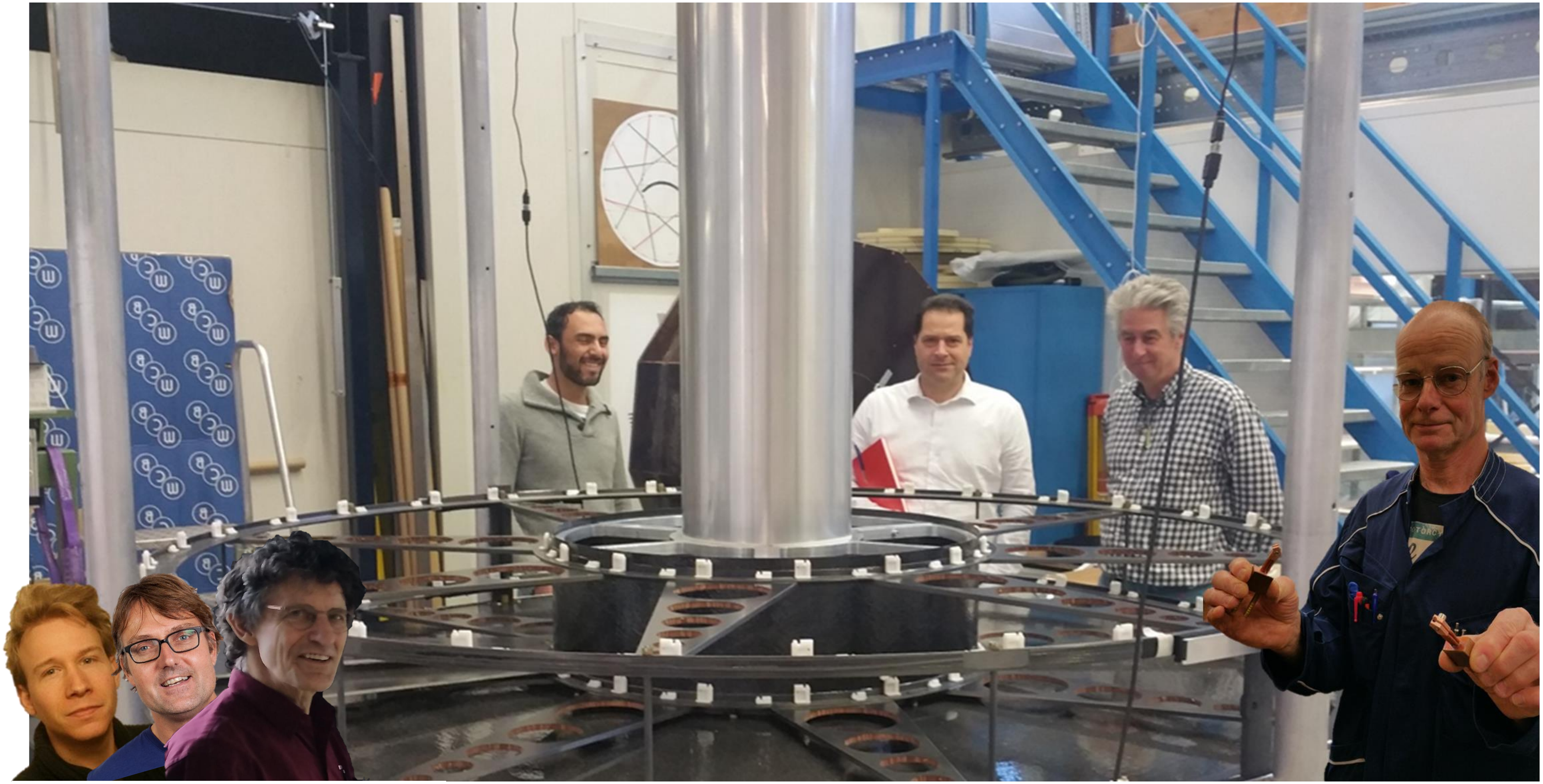


Top T	Bottom T	Rel POS
20°C	20°C	0 mm
19°C	-19°C	-1.5 mm
16°C	-25°C	-1.5 mm
5.8°C	-29°C	-1.3 mm
20°C	20°C	0 mm

Top T	Bottom T	Rel POS
20°C	20°C	0 mm
19°C	-14°C	-1.4 mm
4.8°C	-29.3°C	-1.3 mm
1.5°C	-20°C	-0.9 mm
20°C	20°C	0 mm

CREATING A PHYSICAL (SIMPLIFIED) PROTOTYPE



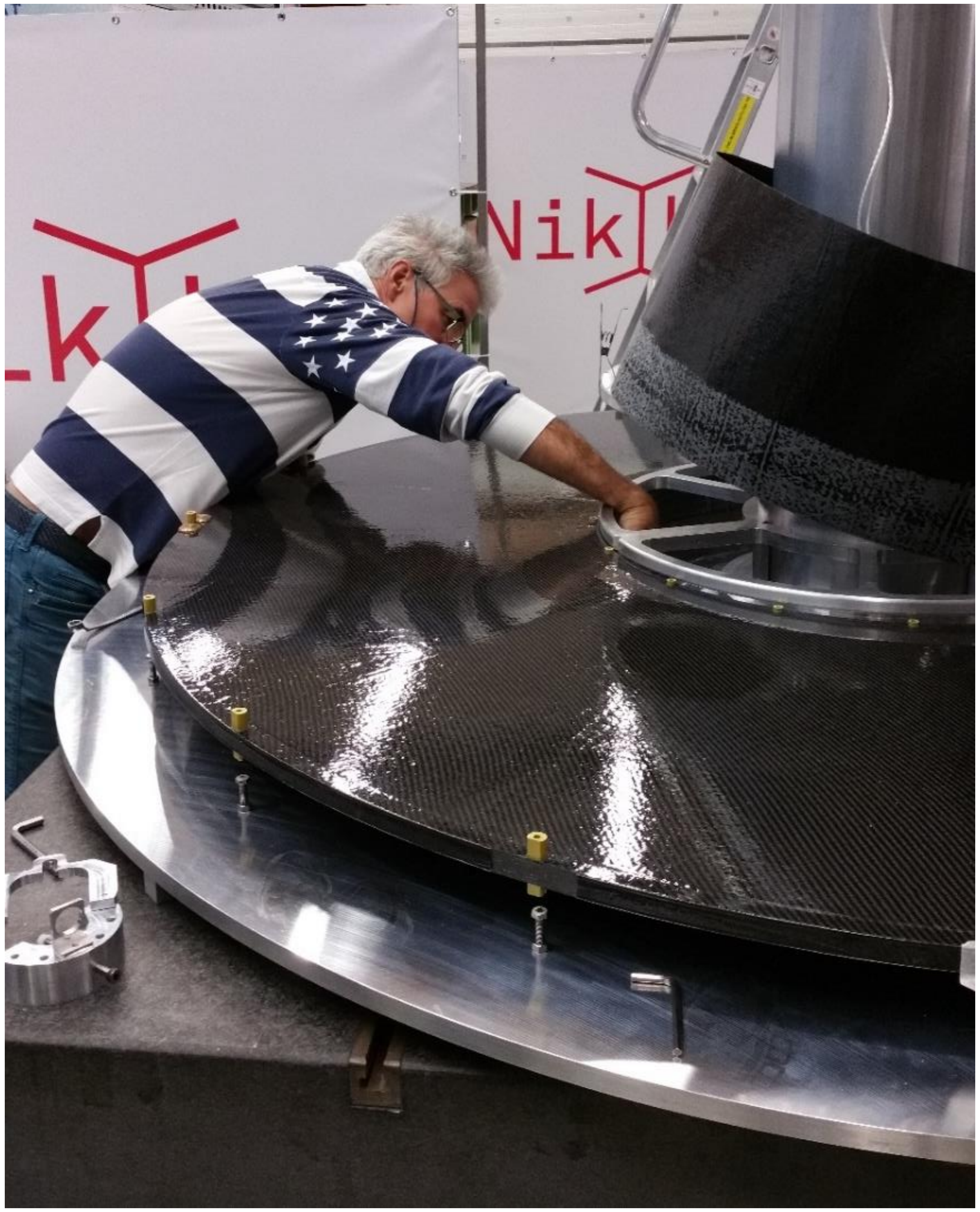


NIKHEF TEAM (RIGHT TO LEFT):
ACTUAL WORK: ROB LEGUYT, MARTIN DOETS
SUPPORT TEAM: MARCEL VREESWIJK, LORENZO QUARTERO, ERIC HENNES, MARCO KRAAN, JESSE VAN DONGEN

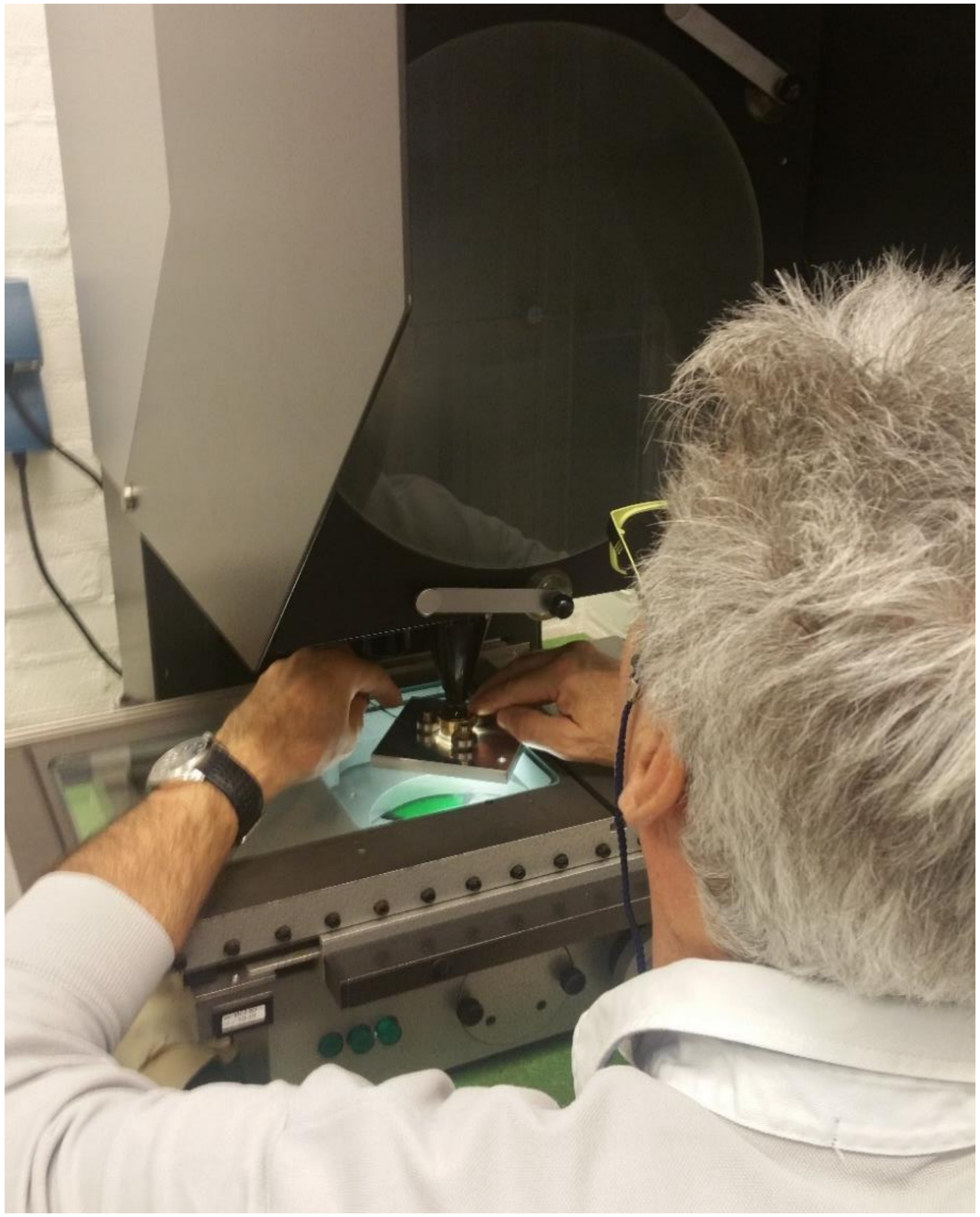
PUTTING TOGETHER THE ASSEMBLY FRAME

Nikhef

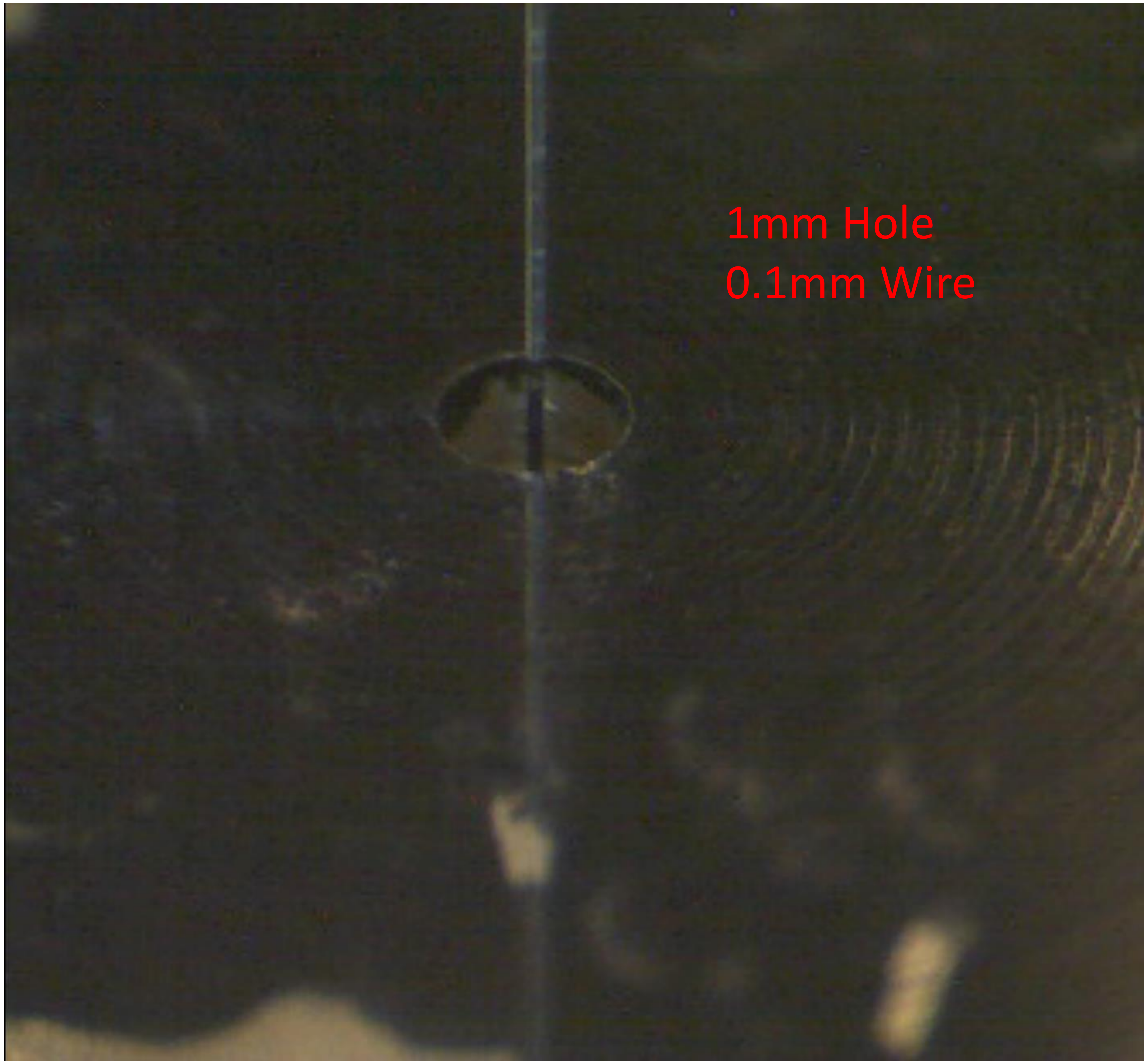
PLACING COMPONENTS OF THE ASSEMBLY FRAME ON THE MOCKUP



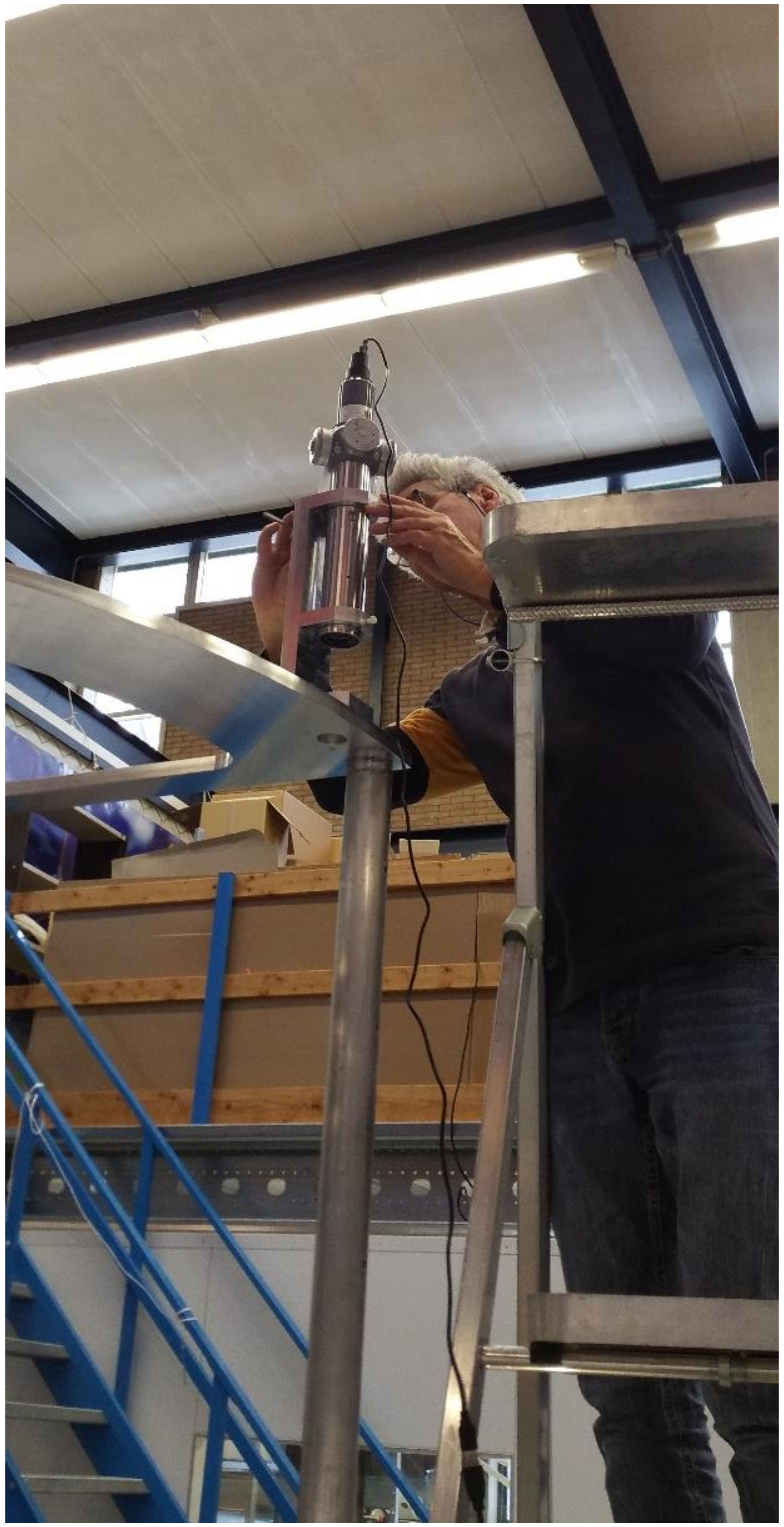
ALIGNING ASSEMBLY CROSSHAIRS

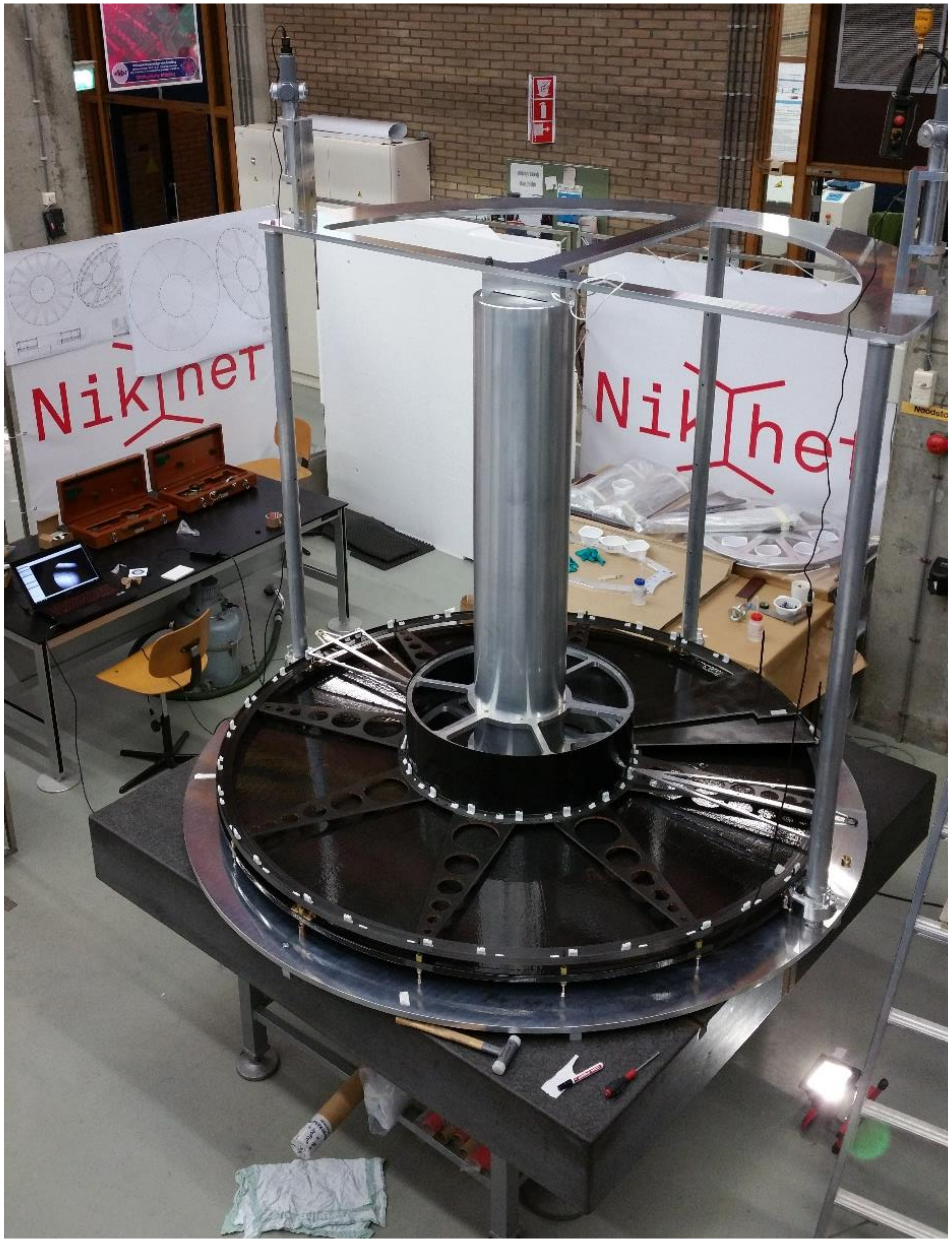


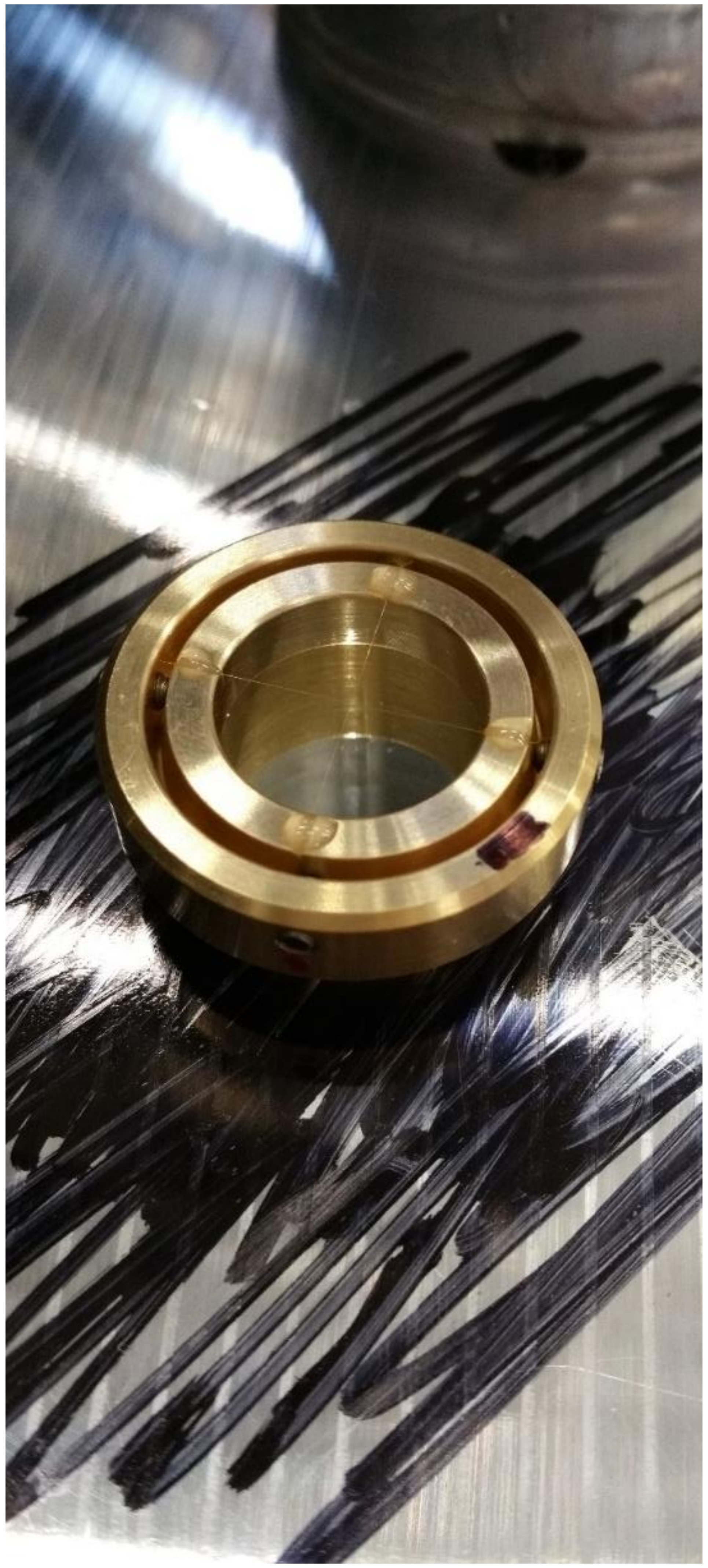
ALIGNING TOP AND BOTTOM OF THE ALIGNMENT FRAME



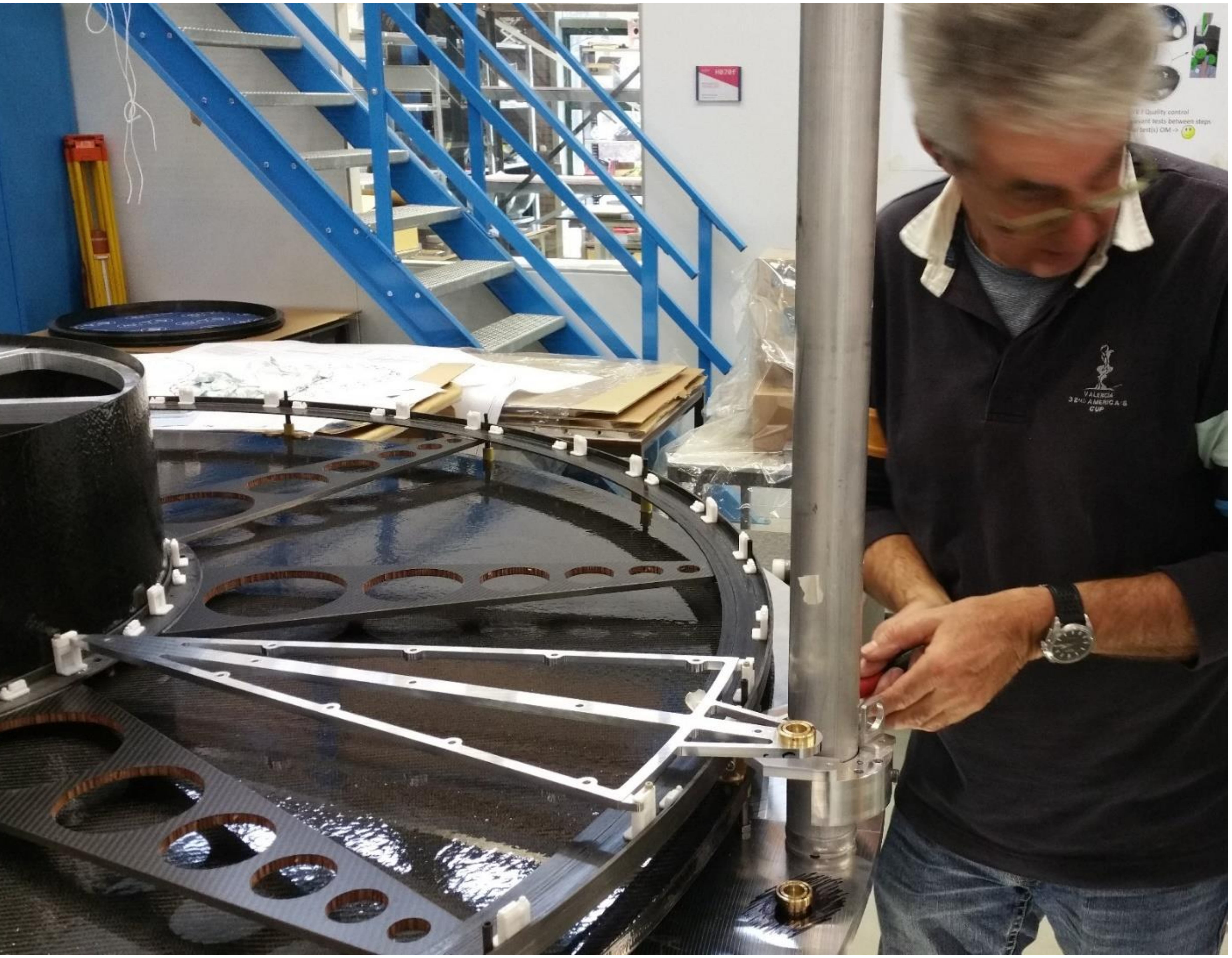
PLACING THE TAYLOR HOBSON ALIGNMENT TELESCOPES

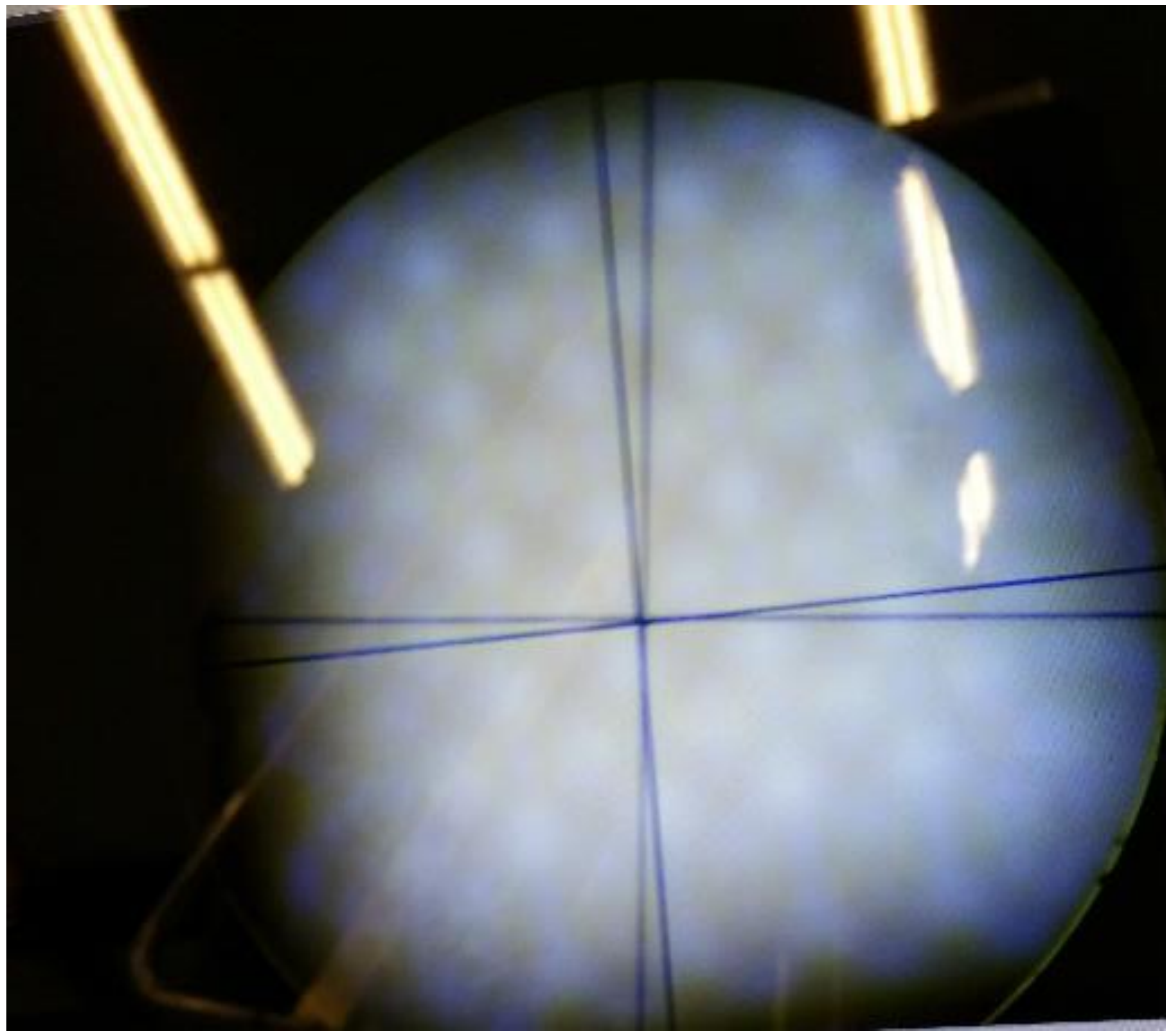




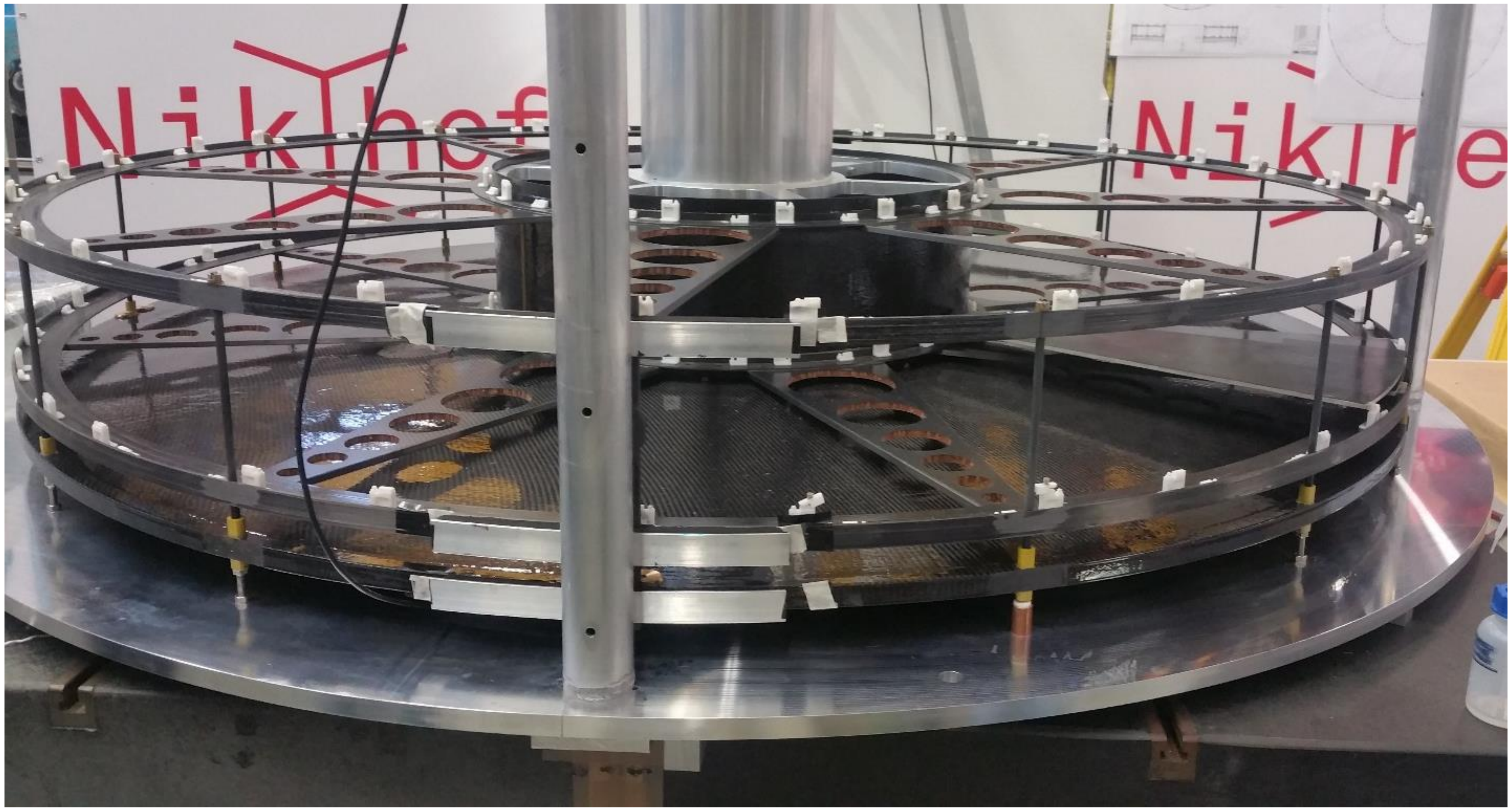


ADJUSTING THE IN PLANE MOVEMENT OF A WHEEL

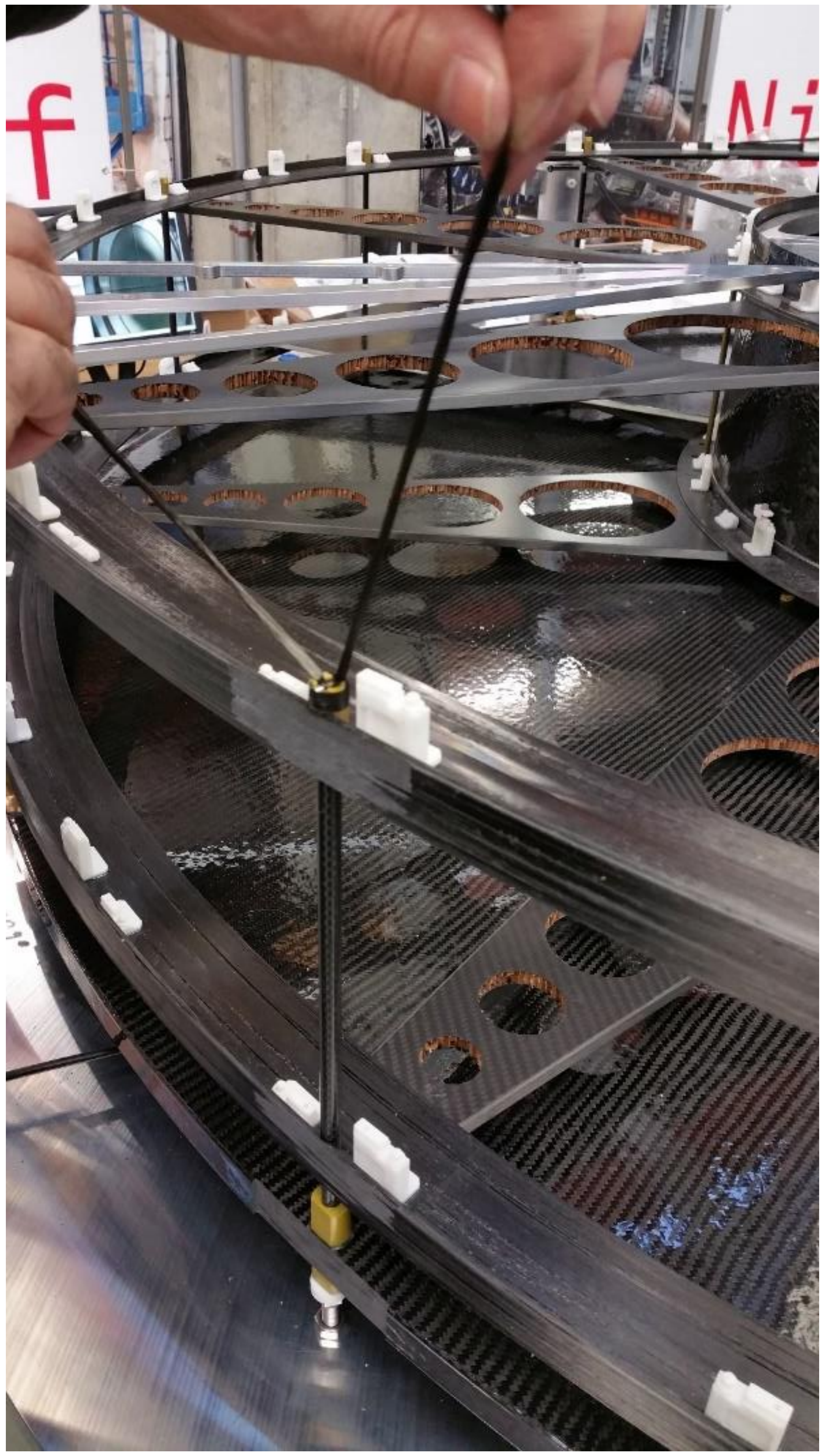


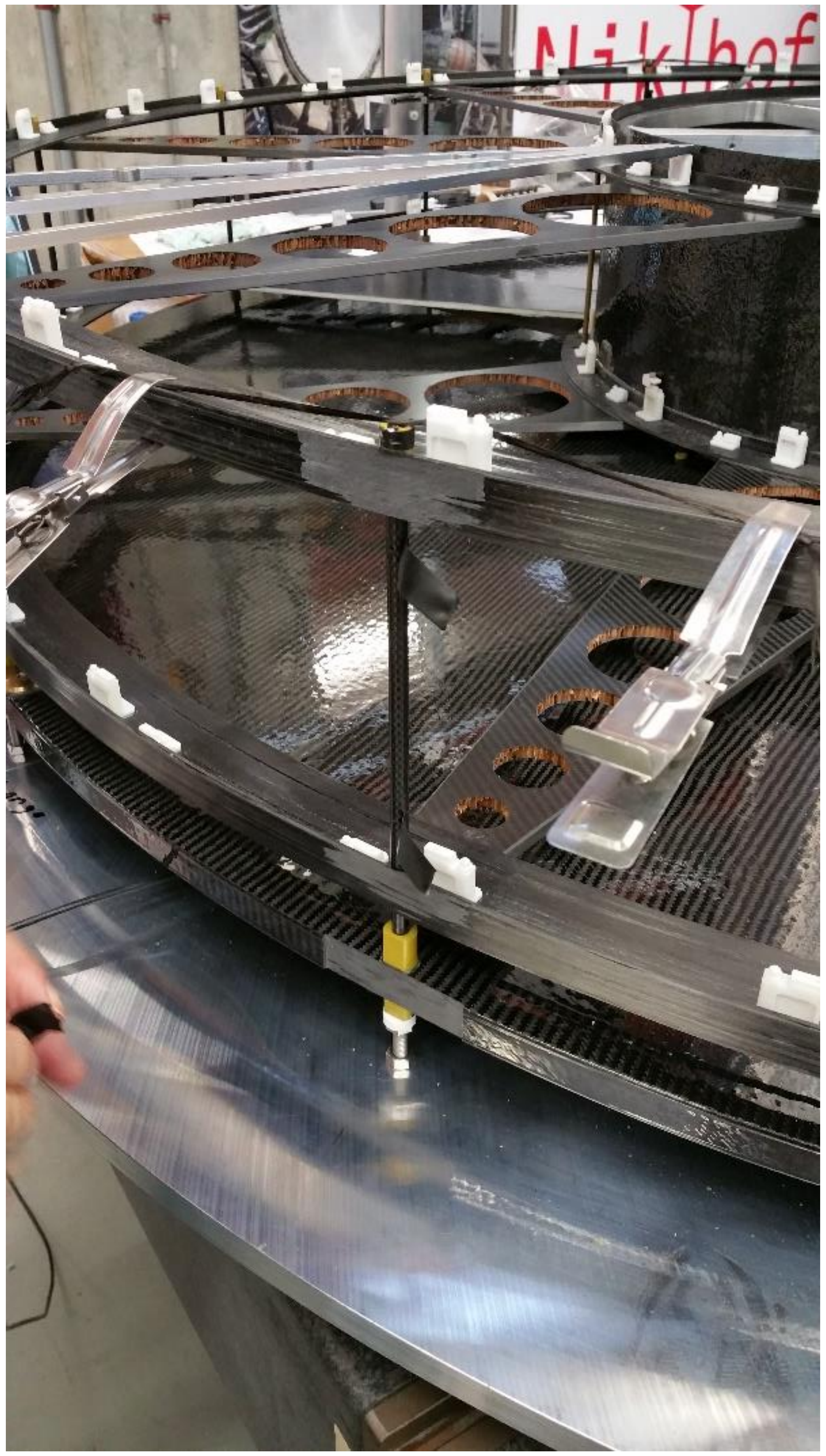


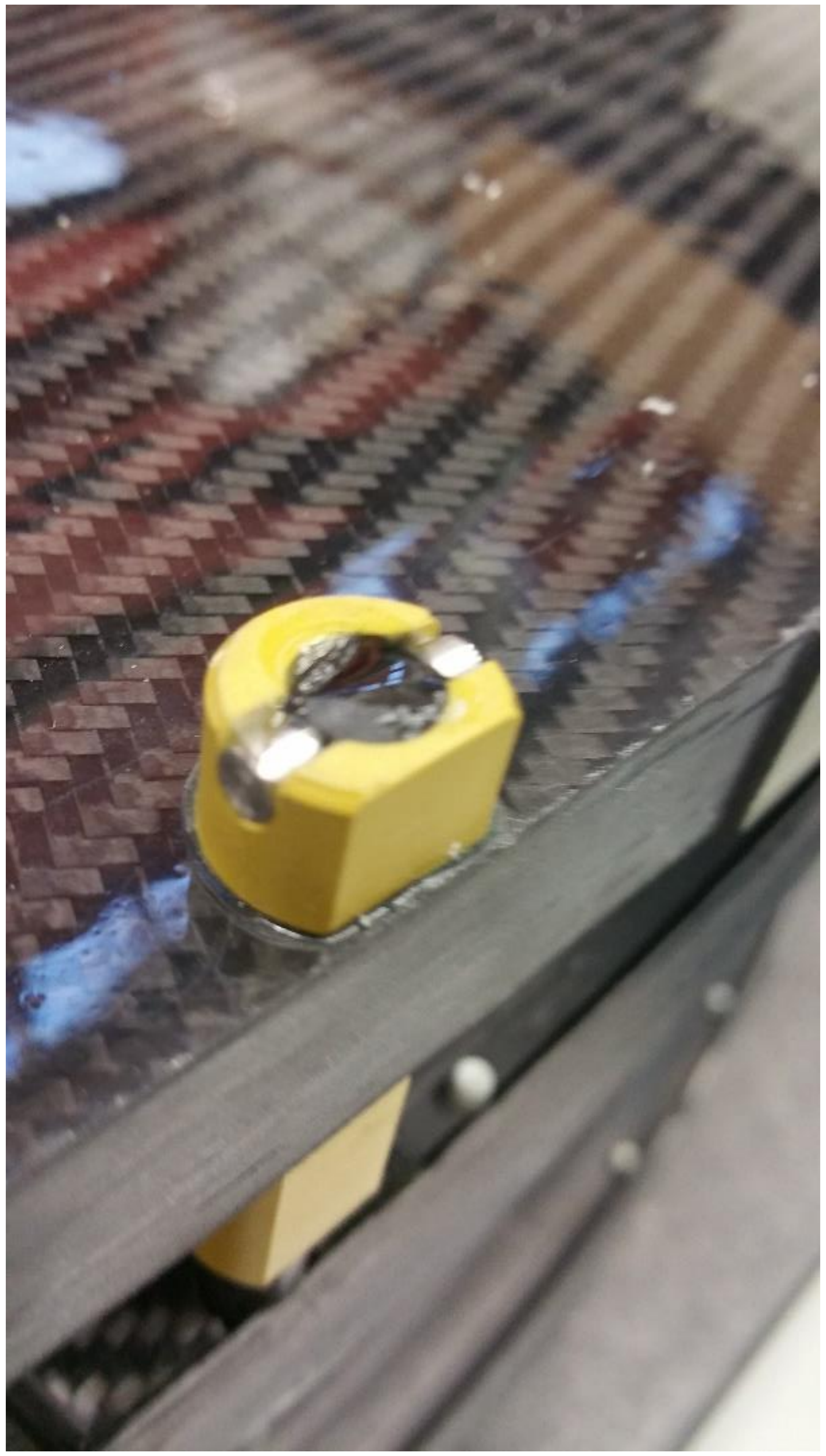
CHECKING WITH A WATER LEVEL IF THE ALL SUPPORT “SPACER TUBES” REACH THE SAME HEIGHT



PUTTING A TENSIONED CABLE INSIDE THE SPACER RODS

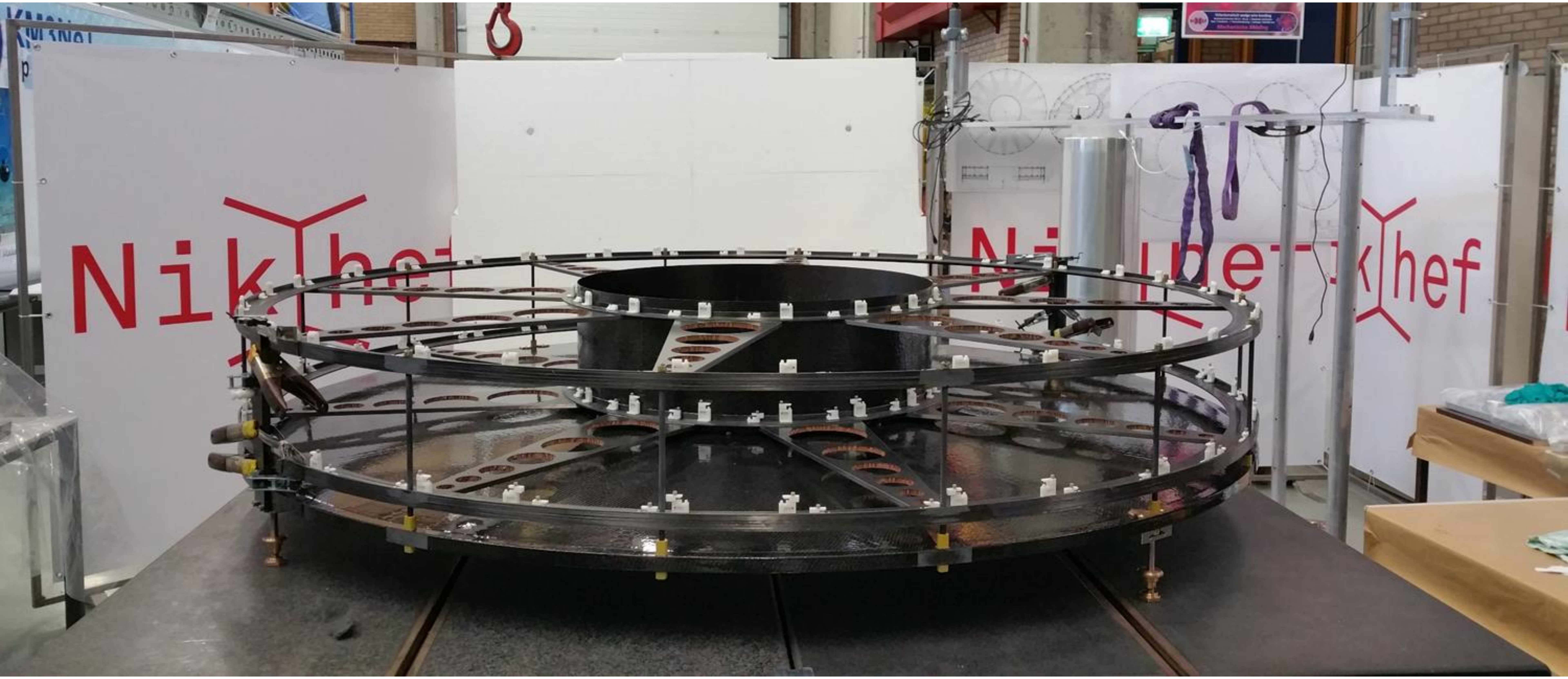






PLACEMENT OF THE RAIL SEGMENT WITH WIDE FLAPS TO INCREASE GLUE SURFACE

FINALIZED PRODUCT REMOVED FROM ASSEMBLY FRAME



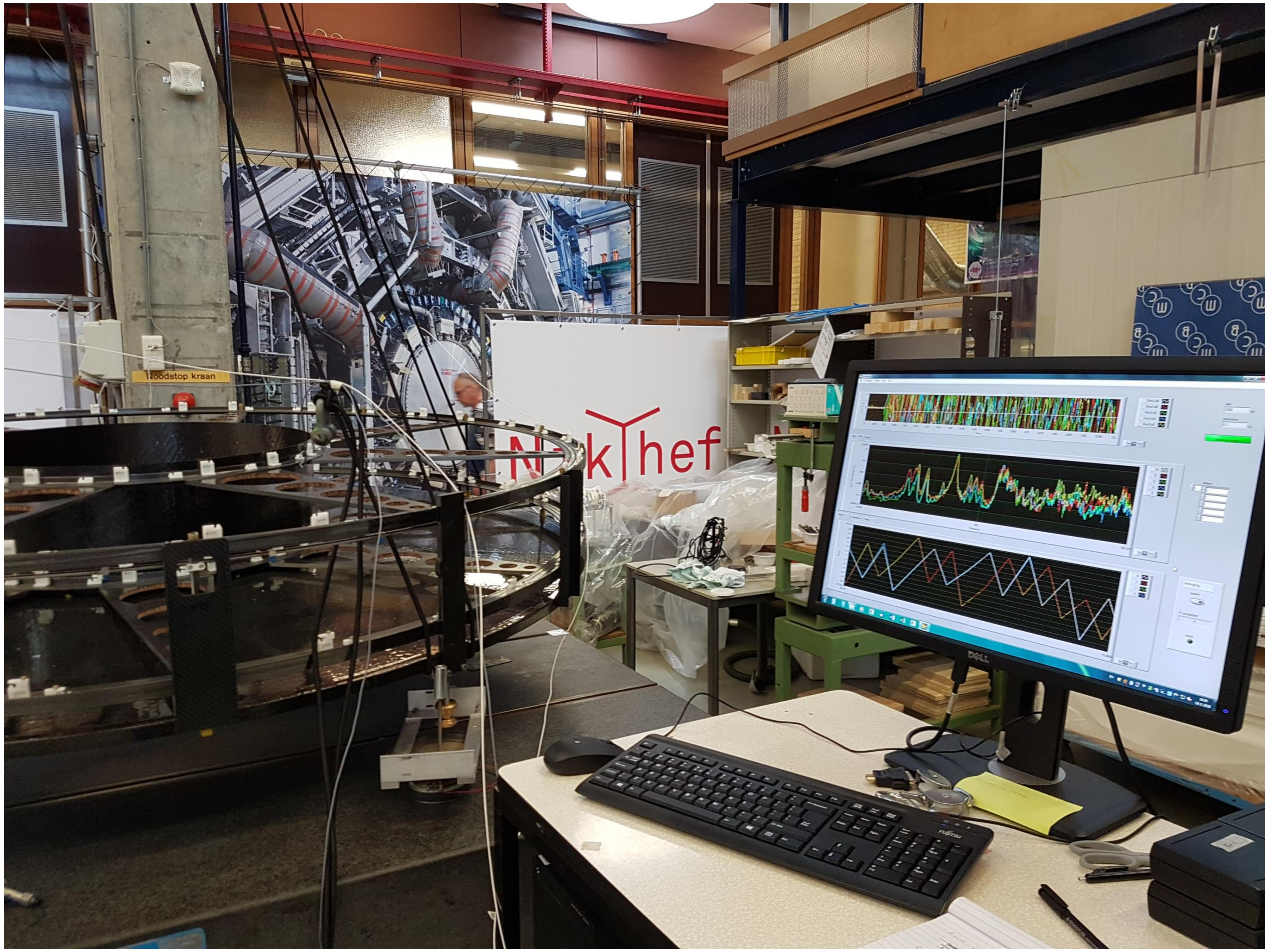
CONTENTS

Work by:

CSIC IFIC INSTITUT DE FÍSICA CORPUSCULAR VNIVERSITAT DE VALÈNCIA DESY

Nikhef

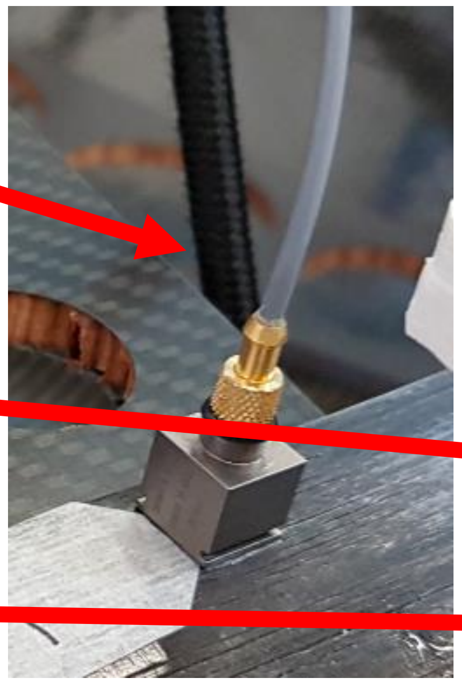
MEASURING THE MOCKUP



WORK BY STUDENT:
LORENZO QUARTERO

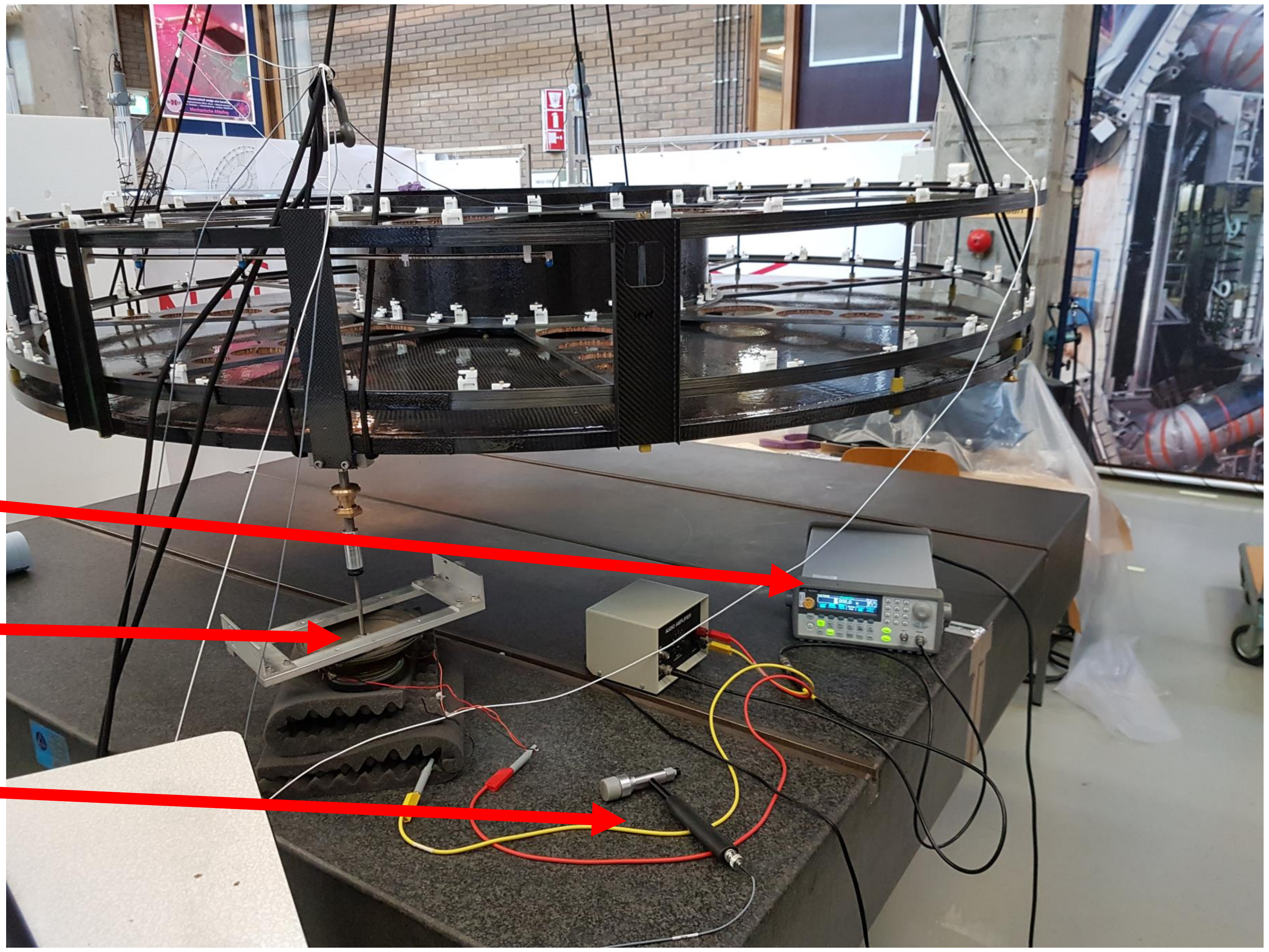
MEASUREMENT SYSTEM

- Sensor: 4x Analog piezo electric accelerometers
- National Instruments DAQ
- Processing: Matlab & Labview



Excitation by impact hammer and sine sweep

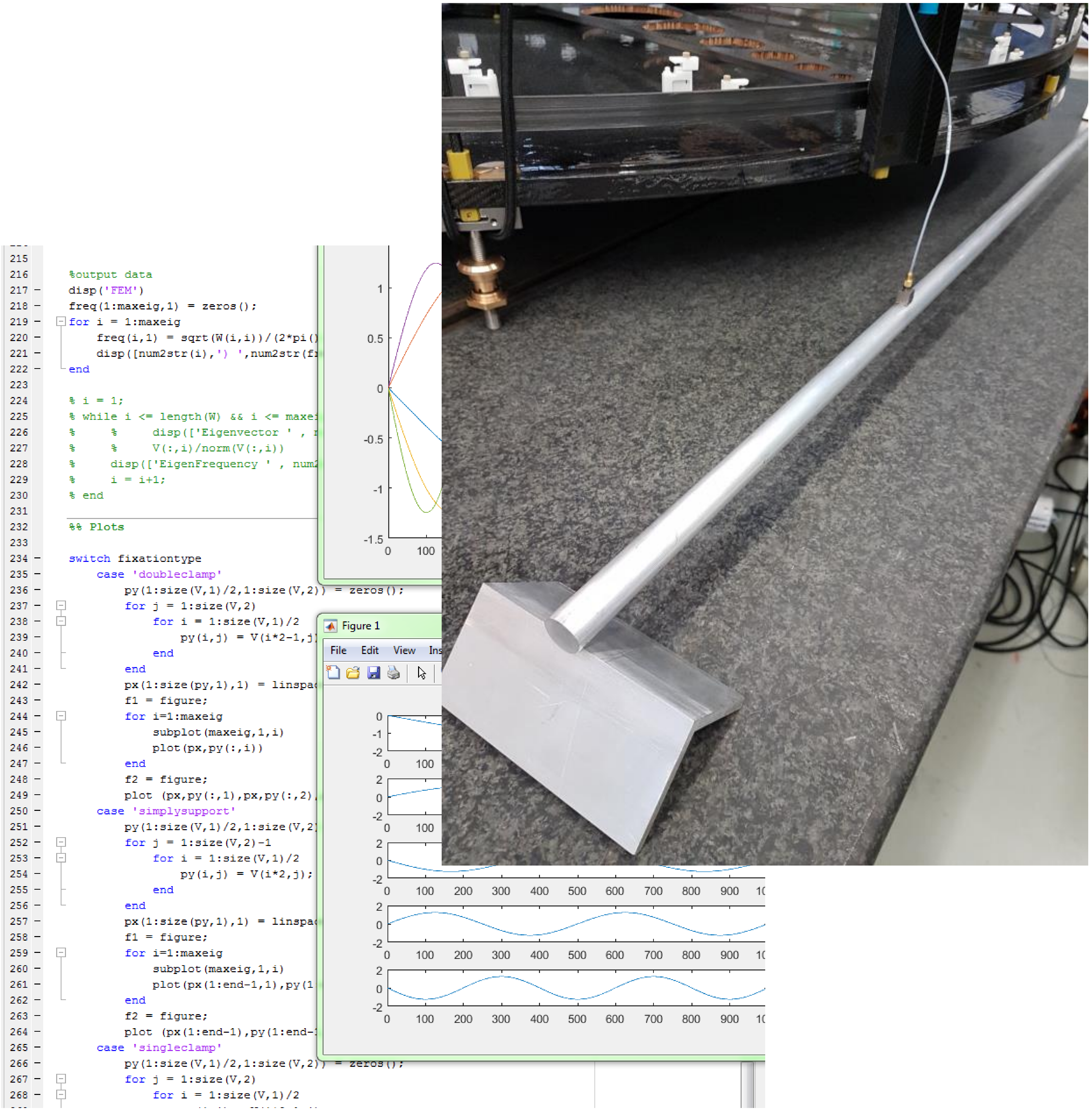
- Signal generator
- Speaker
- Impact hammer



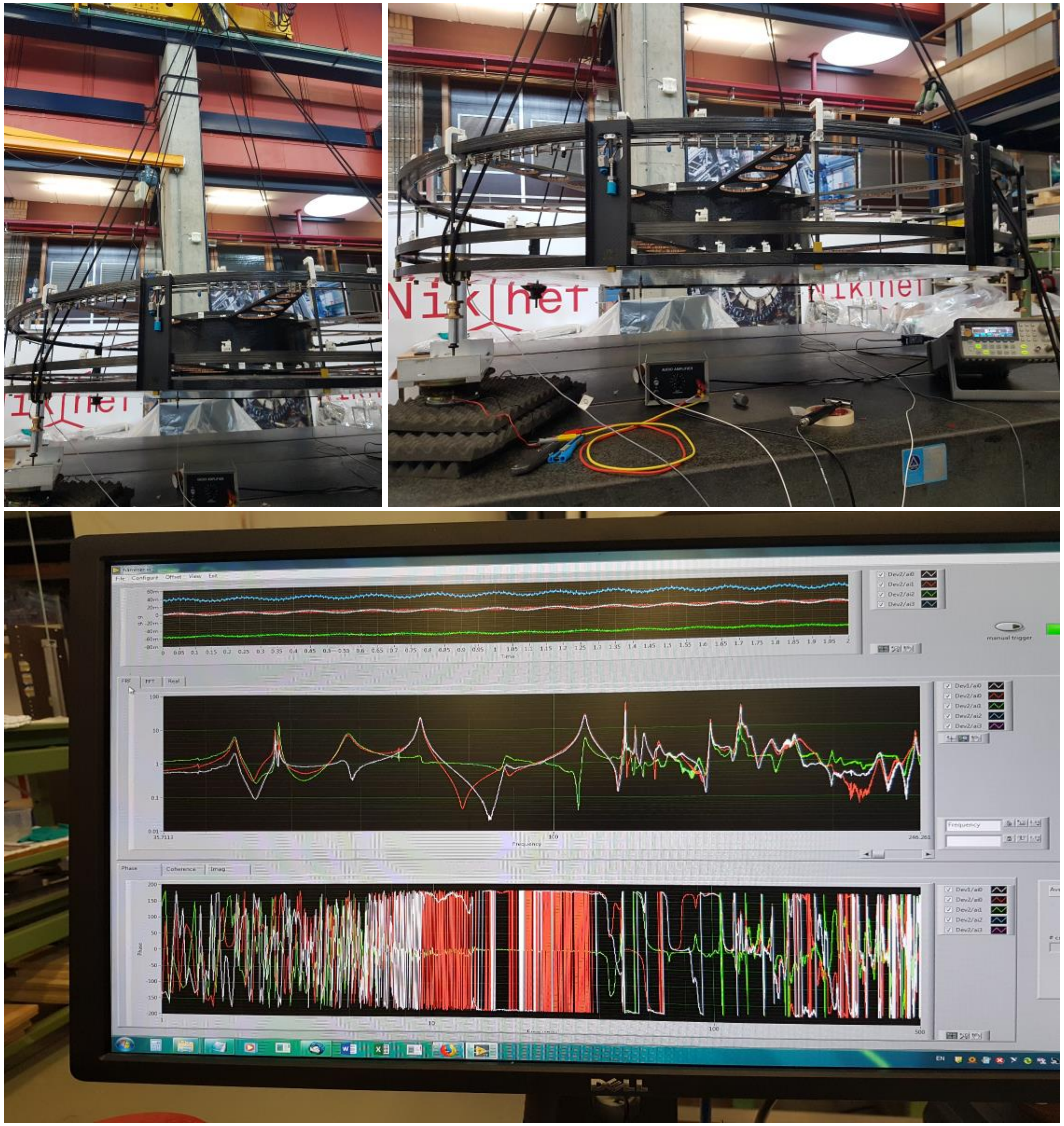
VALIDATION OF THE MEASUREMENT SYSTEM

Validation by comparison of the different methods using simple objects:

- Analytical Solutions
- Homemade MATLAB FEA
- NX FEA
- Actual Measurements



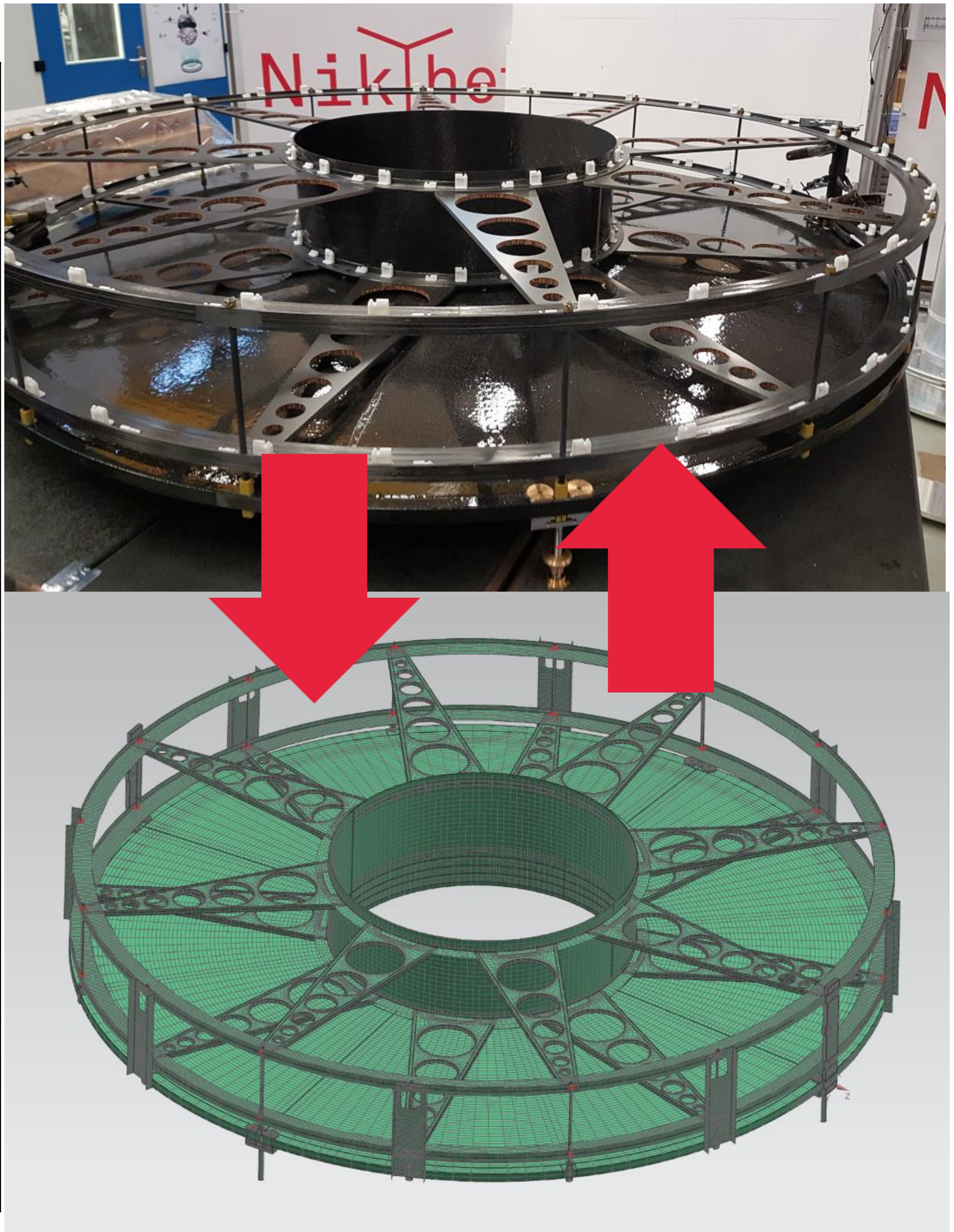
MEASUREMENT SYSTEM WORKS→ TIME TO MEASURE



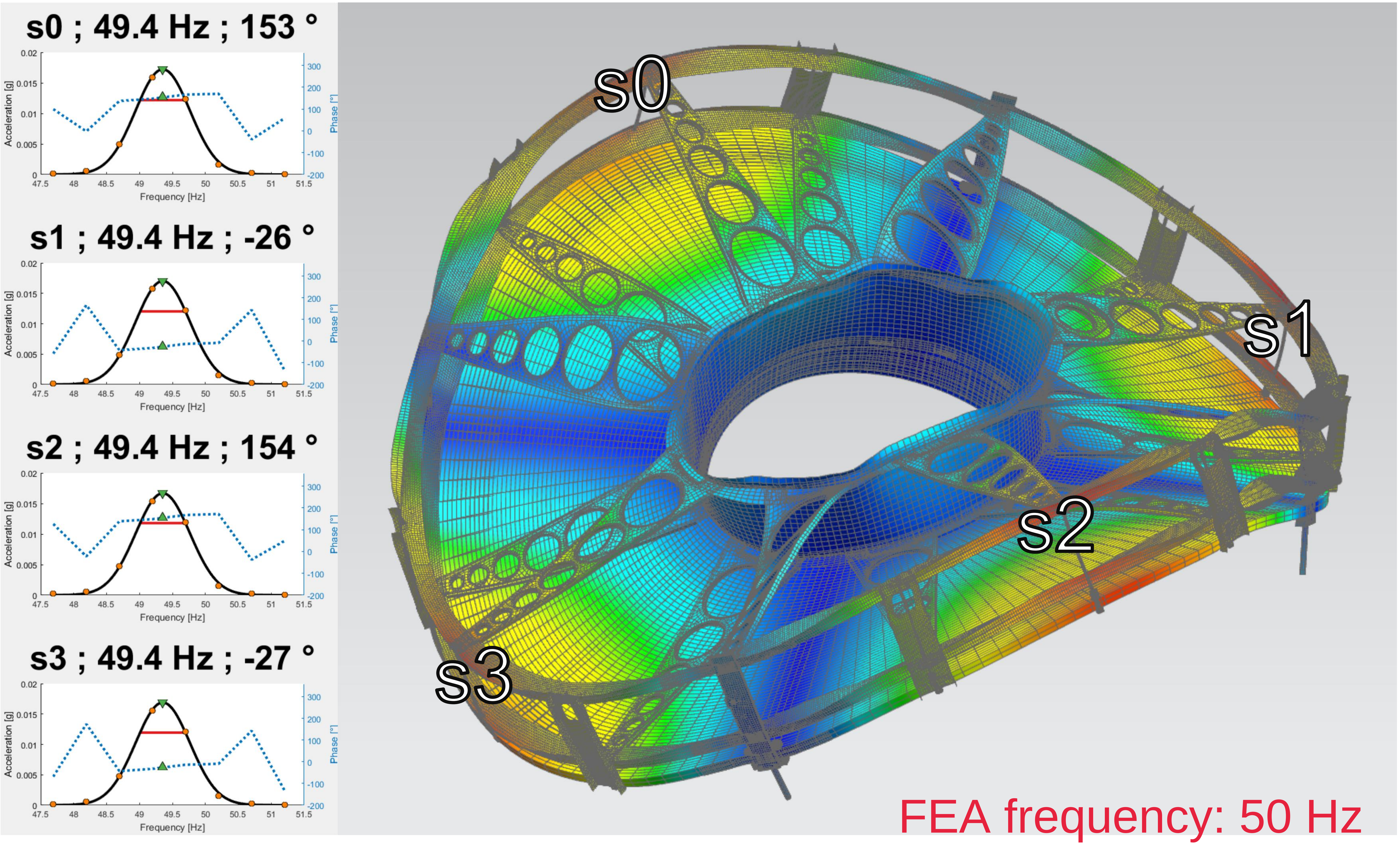
```
for fv = 1:length(x2)
    if xm < x2(1,fv)
        x2m = x2(1,fv-1);
        break
    end
end

% iterate until fitting factor is found
for it = 1:1000
    fitFactor = ym*(1.0 + 0.01*it);
    y2 = 1/(sqrt(2*pi)* sigma ) * exp( - (x2-mu).^2 / (2*sigma^2))*fitFactor;

    % break out when gauss data aligns
    if y2(1,fv-1) > ym
        %disp(fitFactor)
        break
    end
end

% find phase indexes around mu
for phI = 1:size(x,2)
    if x(1,phI) > mu
        phasex1 = phI - 1;
        phasex2 = phI;
        break
    end
end

% find smallest value
if min(y2) < min(yp)
    sv = min(y2);
else
    sv = min(yp);
end

% find phase frequency intersection
xc = [ x(phasex1) mu;  x(phasex2) mu];  % [ start(x1 x2); end(x1 x2)]
yc = [yp(phasex1) yp(phasex1); yp(phasex2) yp(phasex2)];

dx = diff(xc);  % take the differences down each column
dy = diff(yc);
den = dx(1)*dy(2)-dy(1)*dx(2);  % precompute the denominator
ua = (dx(2)*(yc(1)-yc(3))-dy(2)*(xc(1)-xc(3)))/den;
ub = (dx(1)*(yc(1)-yc(3))-dy(1)*(xc(1)-xc(3)))/den;

% phase frequency intersection coordinates
xi = xc(1)+ua*dx(1);
yi = yc(1)+ua*dy(1);

% phase value
%phs = yi*1e5;
phs = yi;

% compute q factor (3db method)
db3 = max(y2)*1/sqrt(2);
c = 1;
f3db(1:2) = zeros();
for i = 1:length(x2)
```

MEASUREMENT RESULTS

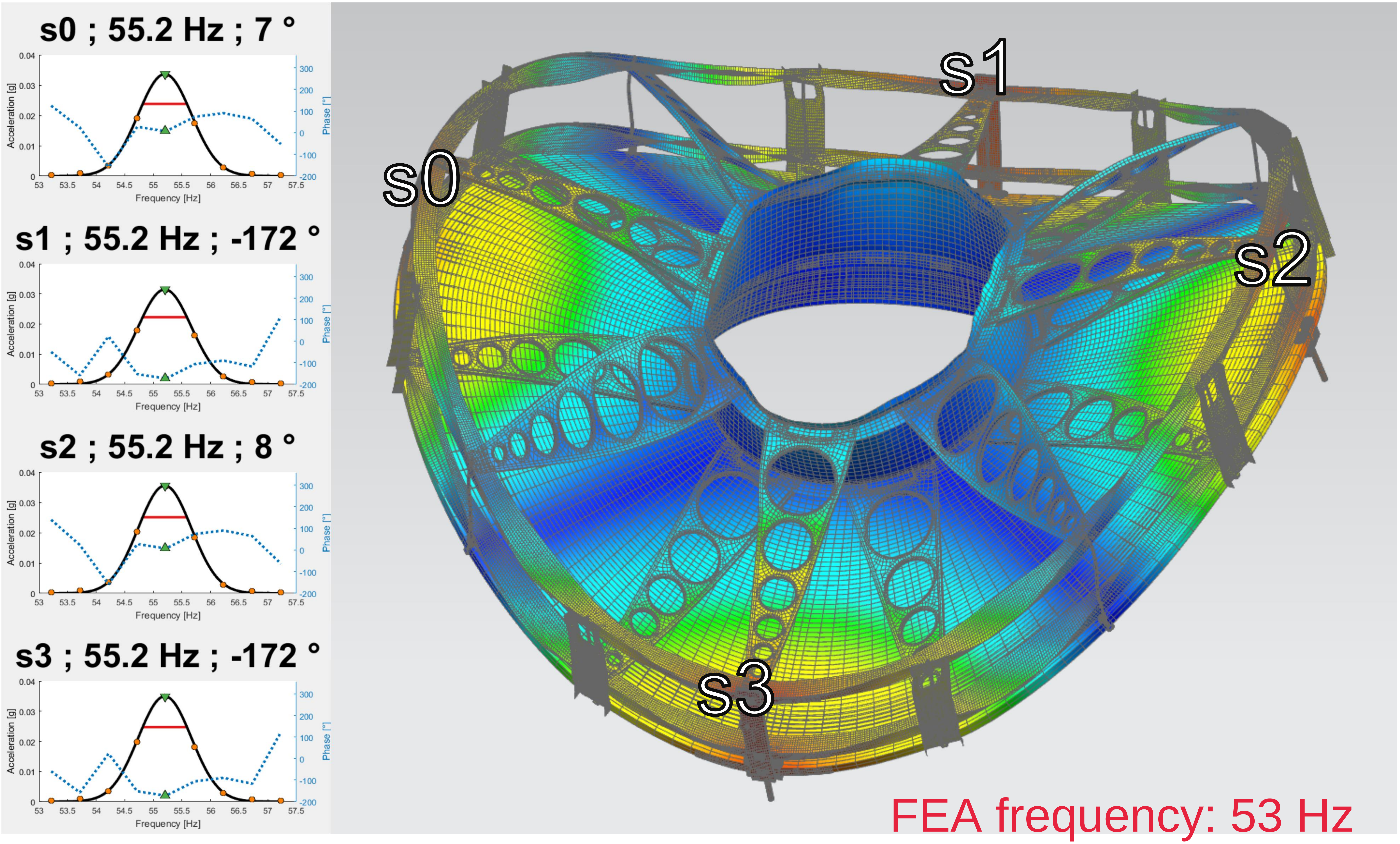
	FEA	Measured	Q factor
Mode 1	50 Hz	49.4 Hz	71
Mode 2	53 Hz	55.2 Hz	71
Mode 3	77 Hz	74.3 Hz	88
Mode 4	88 Hz	87.7 Hz	70
Mode 5	94 Hz	93.7 Hz	90



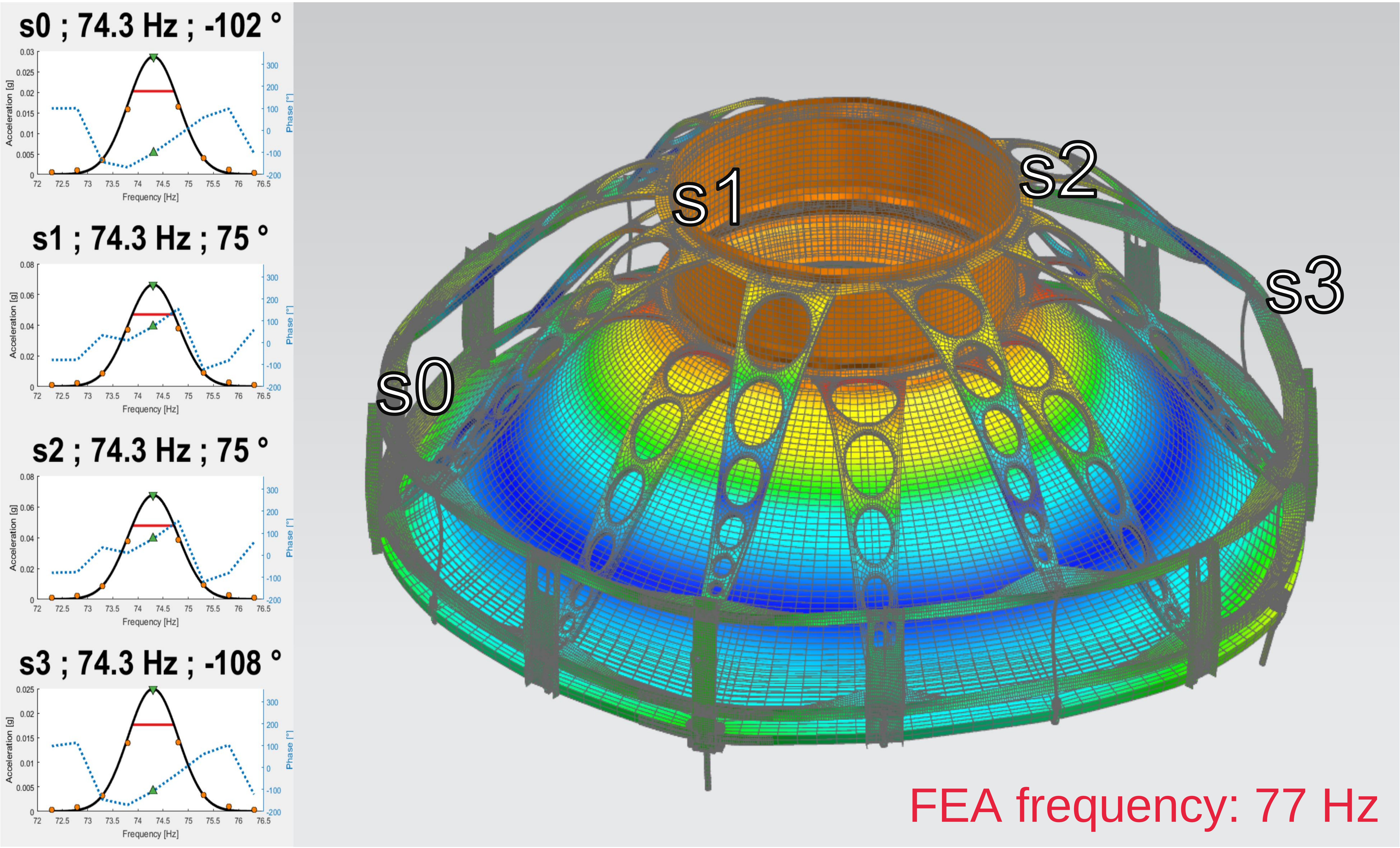
EIGENFREQUENCY 1: MODE SHAPE COMPARISON



EIGENFREQUENCY 2: MODE SHAPE COMPARISON



EIGENFREQUENCY 3: MODE SHAPE COMPARISON



CONTENTS

- Introduction
- Requirements
- Envisioned Design

- Simulation Goal
- Simulating the Endcap
- Endcap Simulation History & Software

- Physical prototype
- Comparing Results

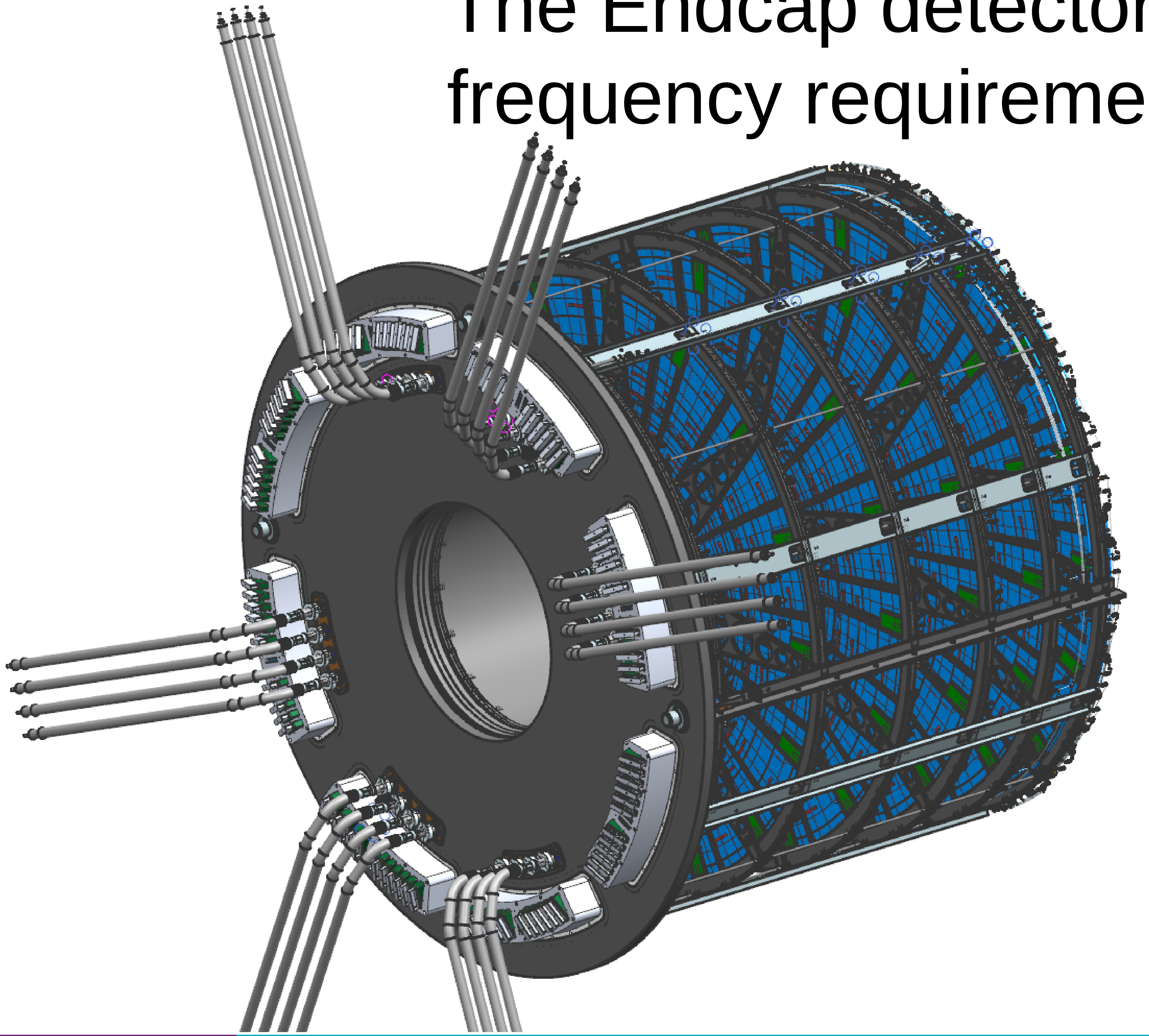
- **Conclusion**

Work by:

CONCLUSION

- A FEA model of the Atlas strip Endcap has been made
- The FEA model appears to correspond well to prototypes
- The FEA model agrees with the requirements

The Endcap detector will likely meet its mechanical frequency requirements.



BACKUP SLIDES

Nikhef

FUTURE WORK

- Setting up frequency based QC tests for produced components
- Updating the EC FEA with new wheel positions
  - Computing displacement with actual measured ASD & Q factor
  - Computing displacement with transport using ASD & Q factor
- Testing the Thermal & Hydroscopic behavior of the Structure and comparing that to the FEA and its materials.

Simulation Details

- Note full system is modelled using the PU80 & 35 foam in the stiffner disc. So I could compare results in NX from previous calculations in Comsol, and with the current prototype.
- Additional mass: 5.33kg per innerrim (1/3rd of petals)
- Additional mass: 12.86kg per outerrim (2/3rd of petals + CO_2 hoops)
- Additional mass 2.375kg per service tray (CO_2 piping + Cabling)

Used Material Properties

Isotropic

	Rho [kg/m3]	Emod [Pa]	Poisson	CTE [m/m-°C]	k [W/m*K]	CP [J/kg-K]
THV500/355	1120	2.7^{e}9	0.33	5.75^{e}-5	0.2	1^{e}3
AE9396	1140	2.75^{e}9	0.33	7^{e}-5	0.2	1^{e}3
ResL/HardW	1098	2.66^{e}9	0.33	5.75^{e}-5	0.2	1^{e}3
Gen Fiber (T700)	1800	230^{e}9	0.2	-3.8^{e}-7	9.37	7.5^{e}2
CT50-4.0/240 (T400)	1800	240^{e}9	0.285	-4.5^{e}-7	10.54	7.5^{e}2
PU80	80	18^{e}6	0.35	6^{e}-5	0.025	1800
PU35	35	4.2^{e}6	0.35	7.2^{e}-5	0.021	1800

Fiber/Epoxy mix ratios: Homemade CFRP : 55/45 ; Industry CFRP 60/40

Orthotropic (same units as isotropic)

	Rho	E1	E2	E3	v12	v23	v13	G12	G13	G23	CTE	k	CP
Aramid Honey Comb	32	1^{e}4	1^{e}4	55^{e}6	0.3	0	0	1^{e}4	26^{e}6	10^{e}6	-4^{e}-6	0.025	1^{e}3
R82.110	110	64^{e}6	64^{e}6	83^{e}6	0.32	0.27	0.27	30^{e}6	30^{e}6	30^{e}6	4^{e}-5	0.04	625

NOTE ON THE Q FACTOR

Remember the frequency requirements?

Direction	Stability requirement	As Built Min Frequency Requirements	FEA Design Min Frequency Requirements
Z	20 µm	3.2Hz	6.7Hz
R	20 µm	3.2Hz	6.7Hz
Rφ	2 µm	14.4Hz	31.6Hz

Based on relative translation of the miles equation

$$Y_{RMS} = \sqrt{\frac{Q\,[\,ASD_{input}\,]}{32\pi^3 (f_n)^3}}$$

Assumed Q = 12.5, Q empty structure = ~80

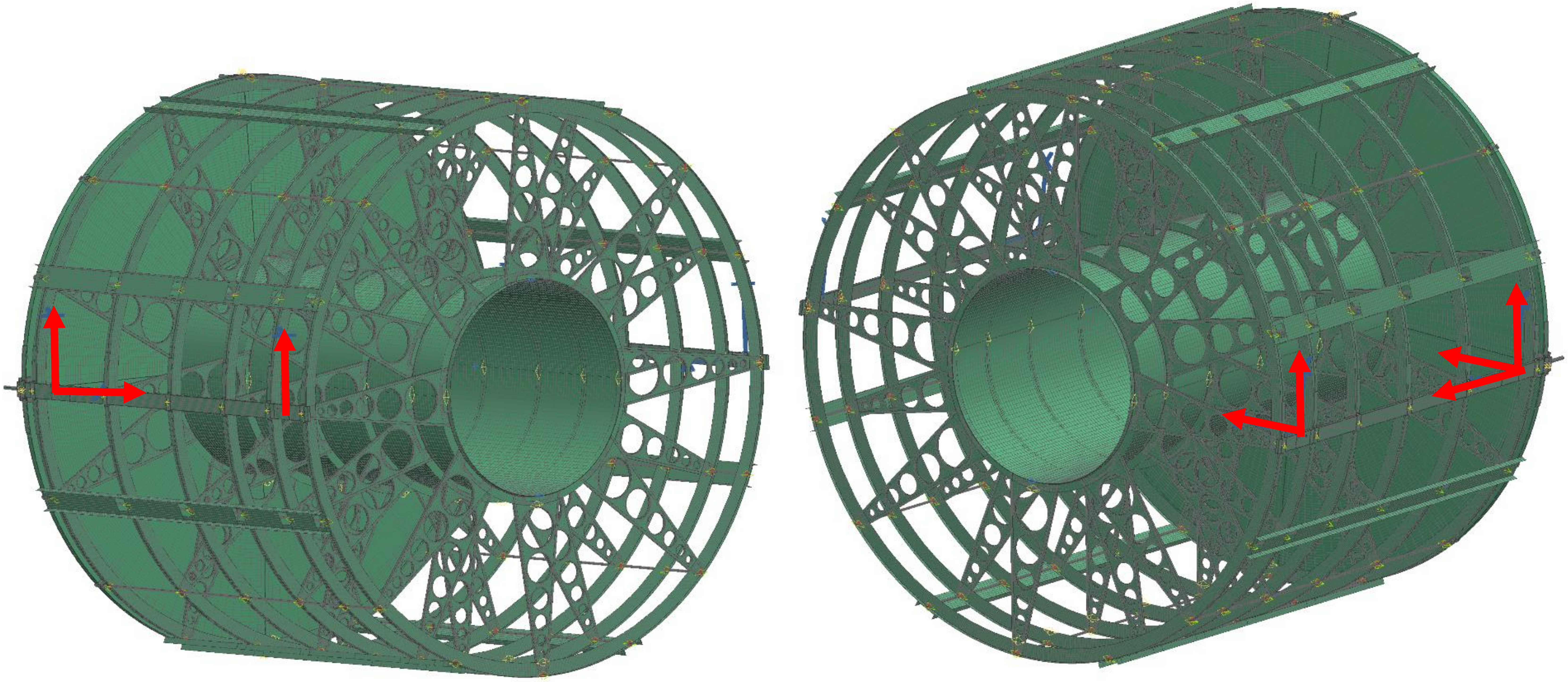
Assumed ASD 10^-7 G^2/Hz FEA

10^-8 G^2/Hz As Built

Actual ASD ~ 10^-10 G^2/Hz

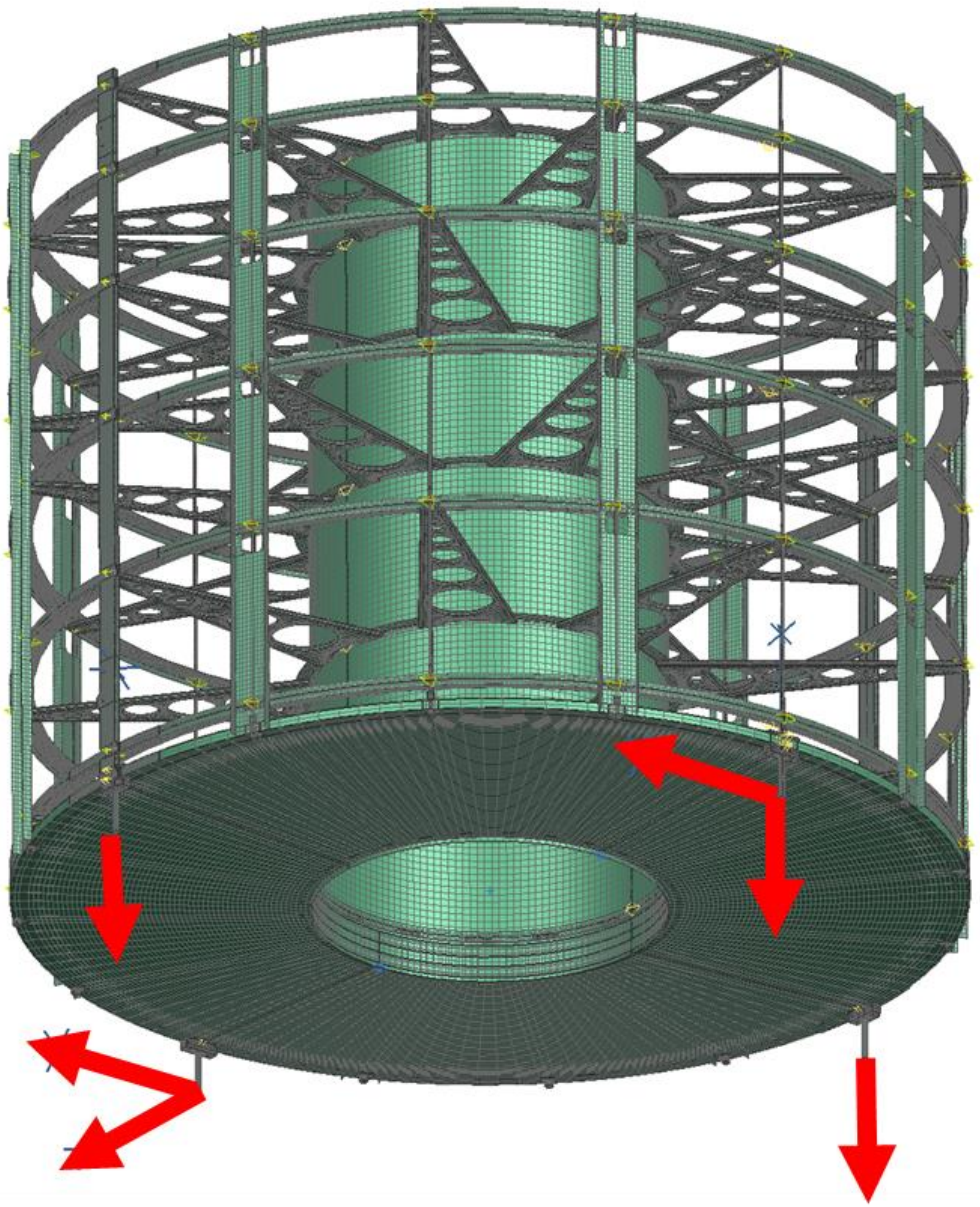
WE SHOULD STILL BE SAFE ☺

USED CONSTRAINTS



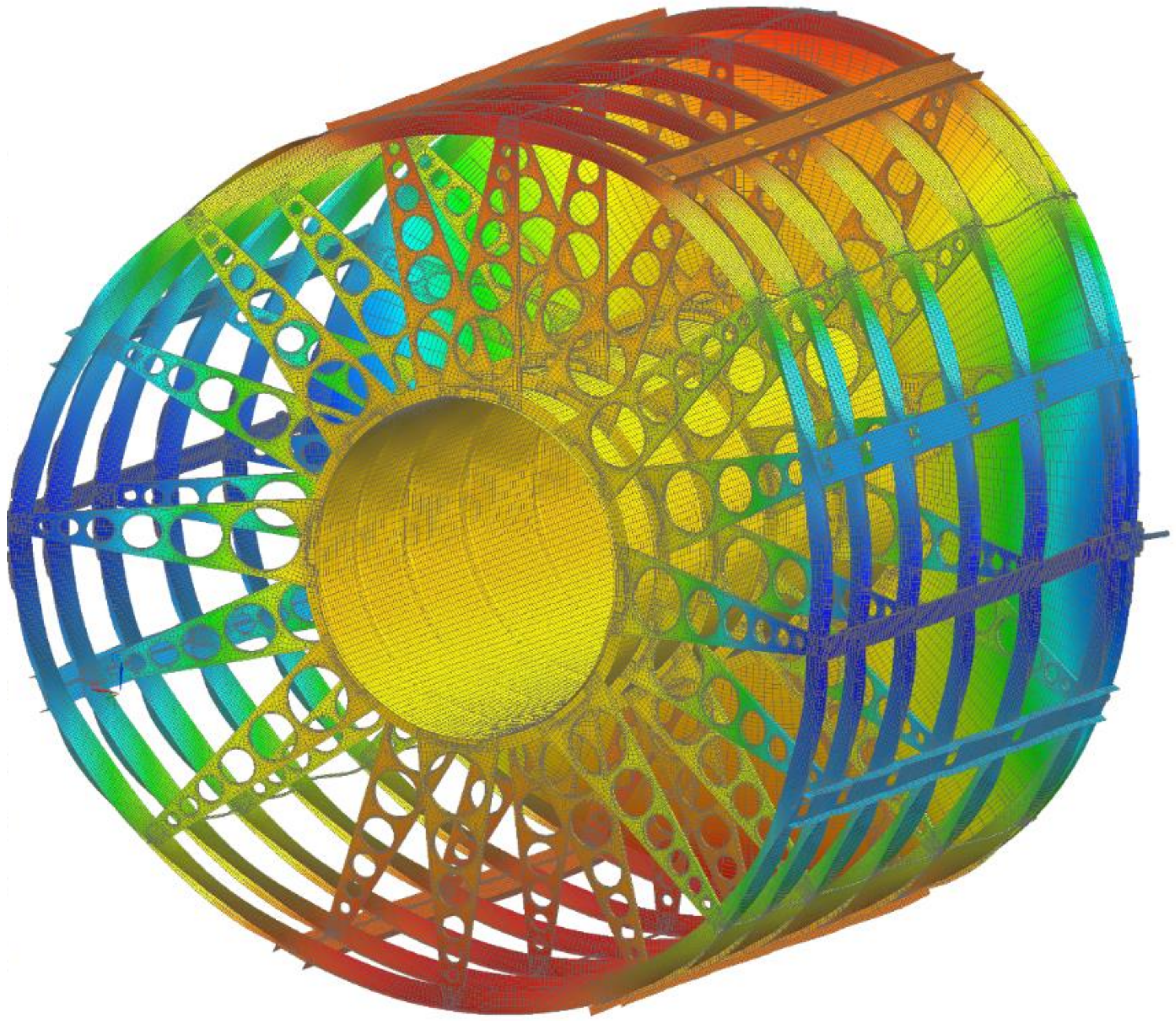
ARROWS POINT IN DIRECTION OF CONSTRAINT

USED CONSTRAINTS (ASSEMBLY POSITION)

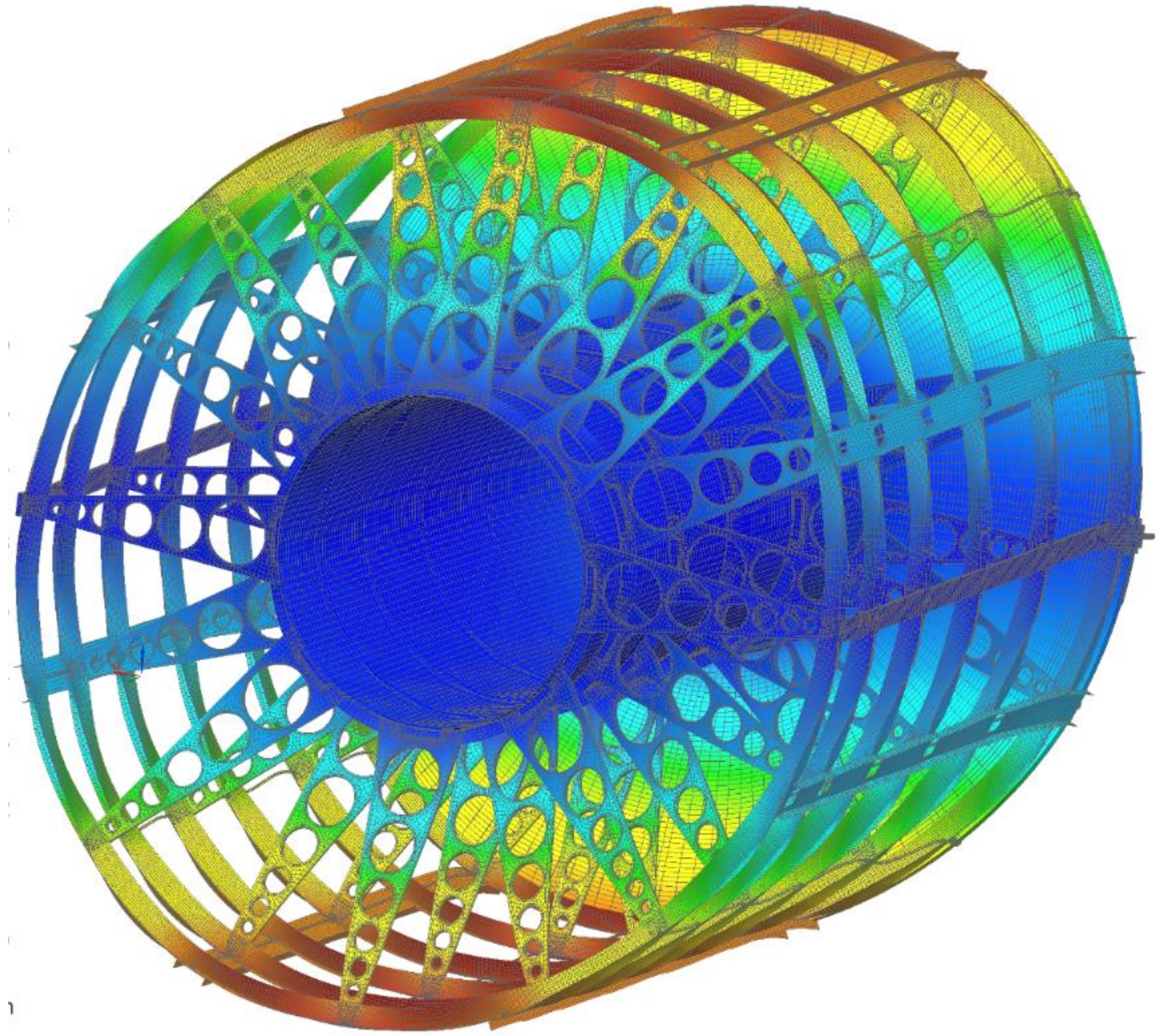


ARROWS POINT IN DIRECTION OF CONSTRAINT

EIGENMODE 1 & 2

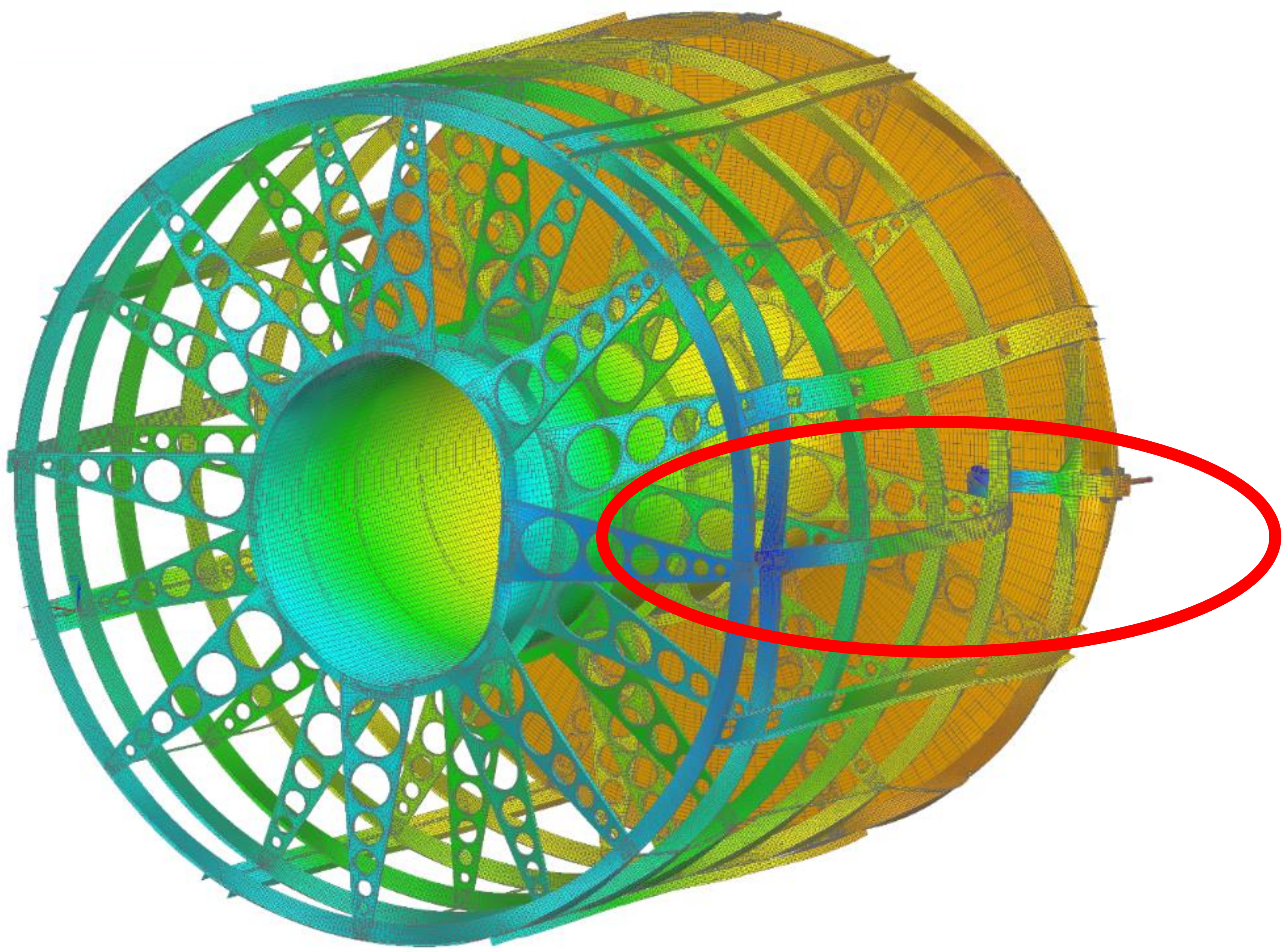


MODE 1, 13HZ "Z-WINGFLAP"

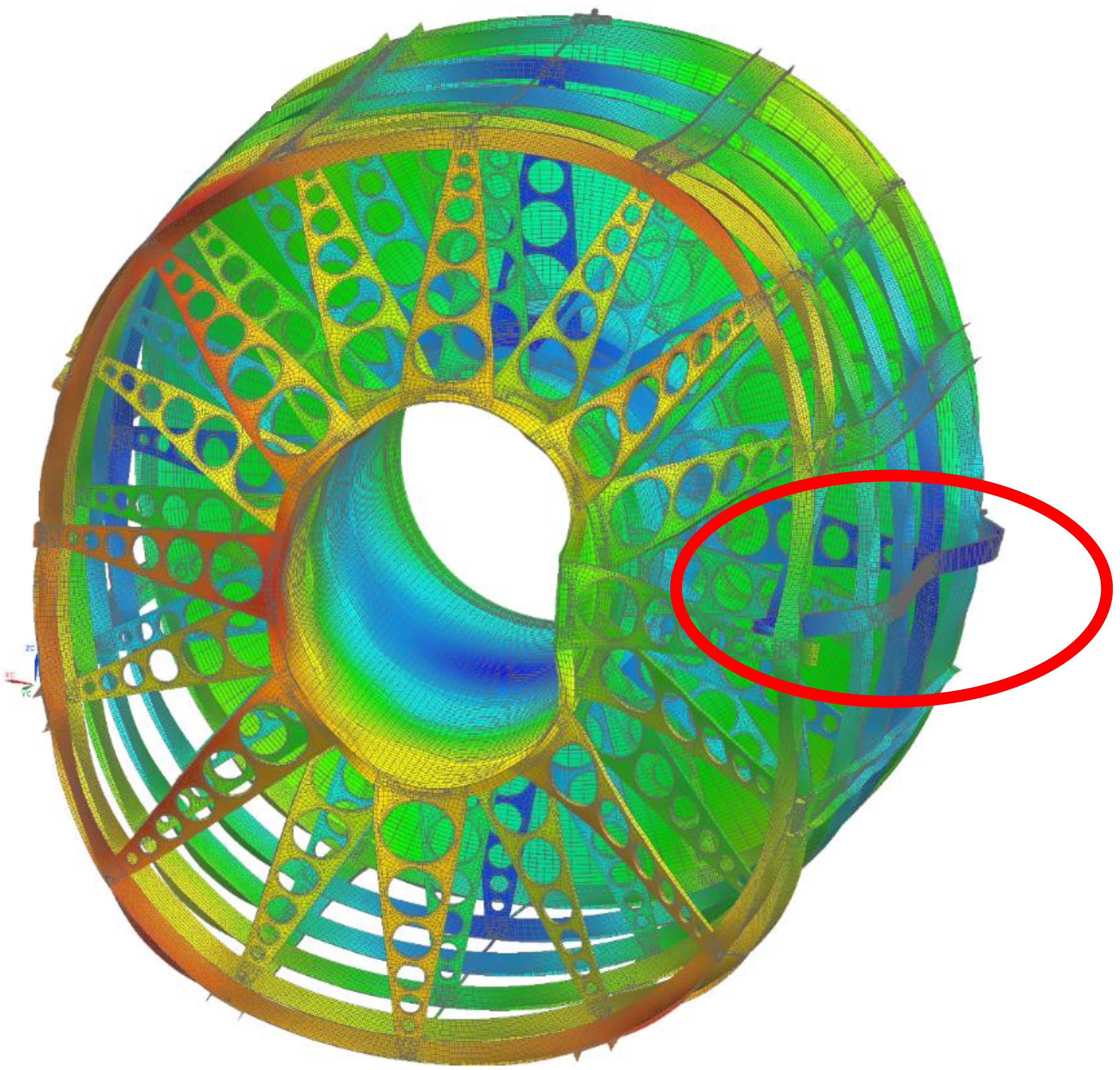


MODE 2, 16HZ "Z-SHEARFLAP"

EIGENMODE 3 & 4

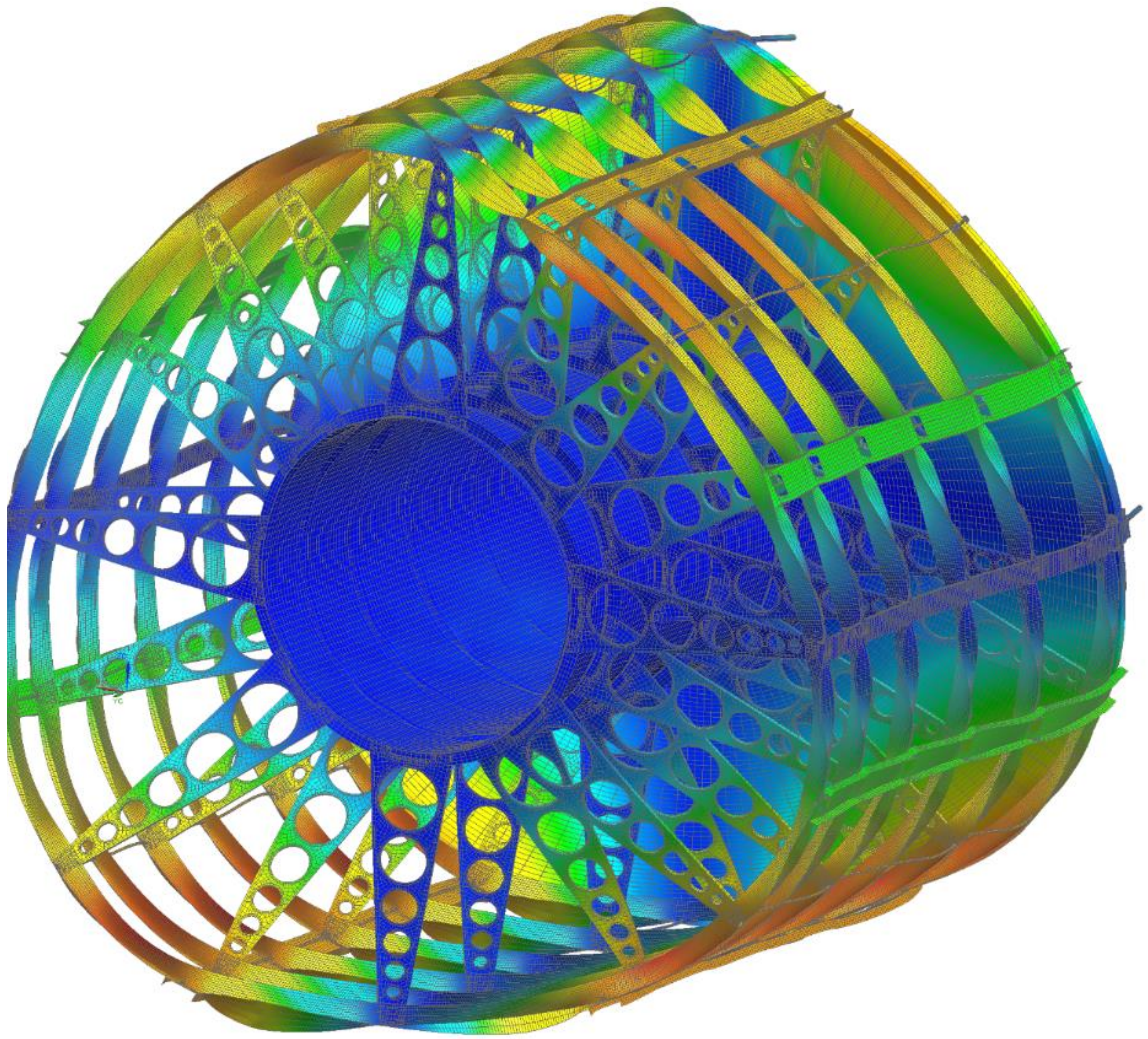


MODE 3, 17.6HZ “X-RAILBEND”

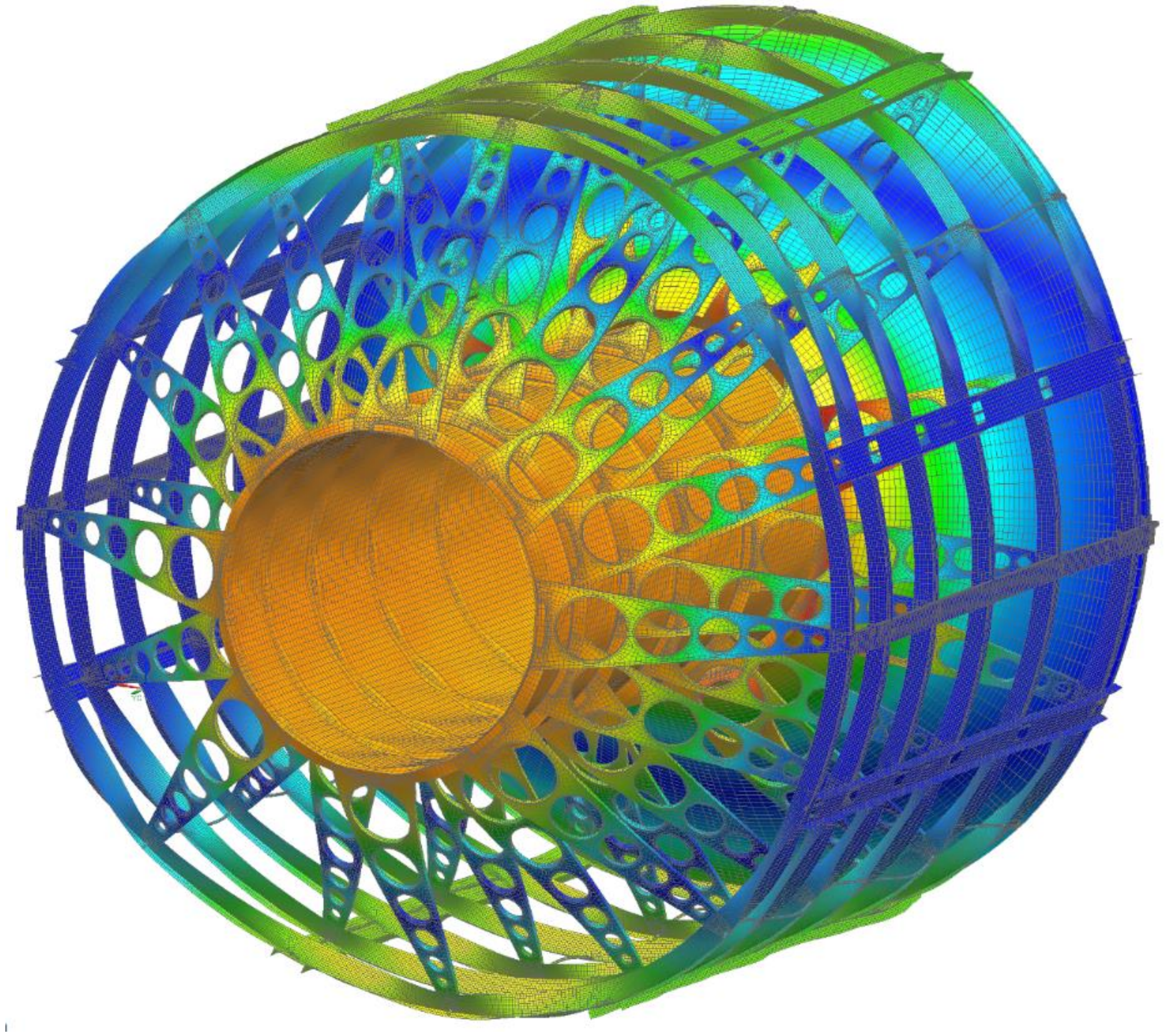


MODE 4, 27HZ

EIGENMODE 5 & 6

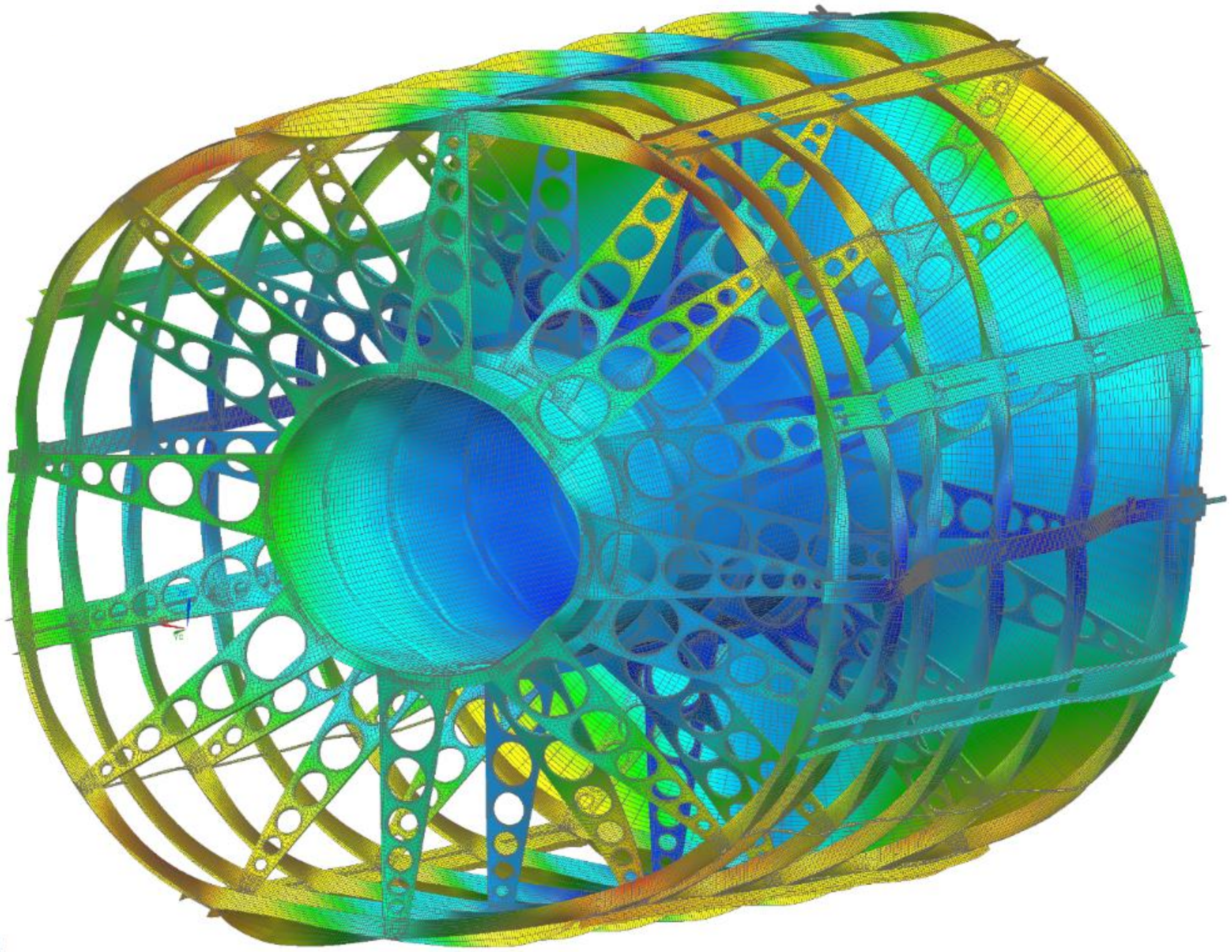


MODE 5, 28HZ “Z-DIAGFLAP”

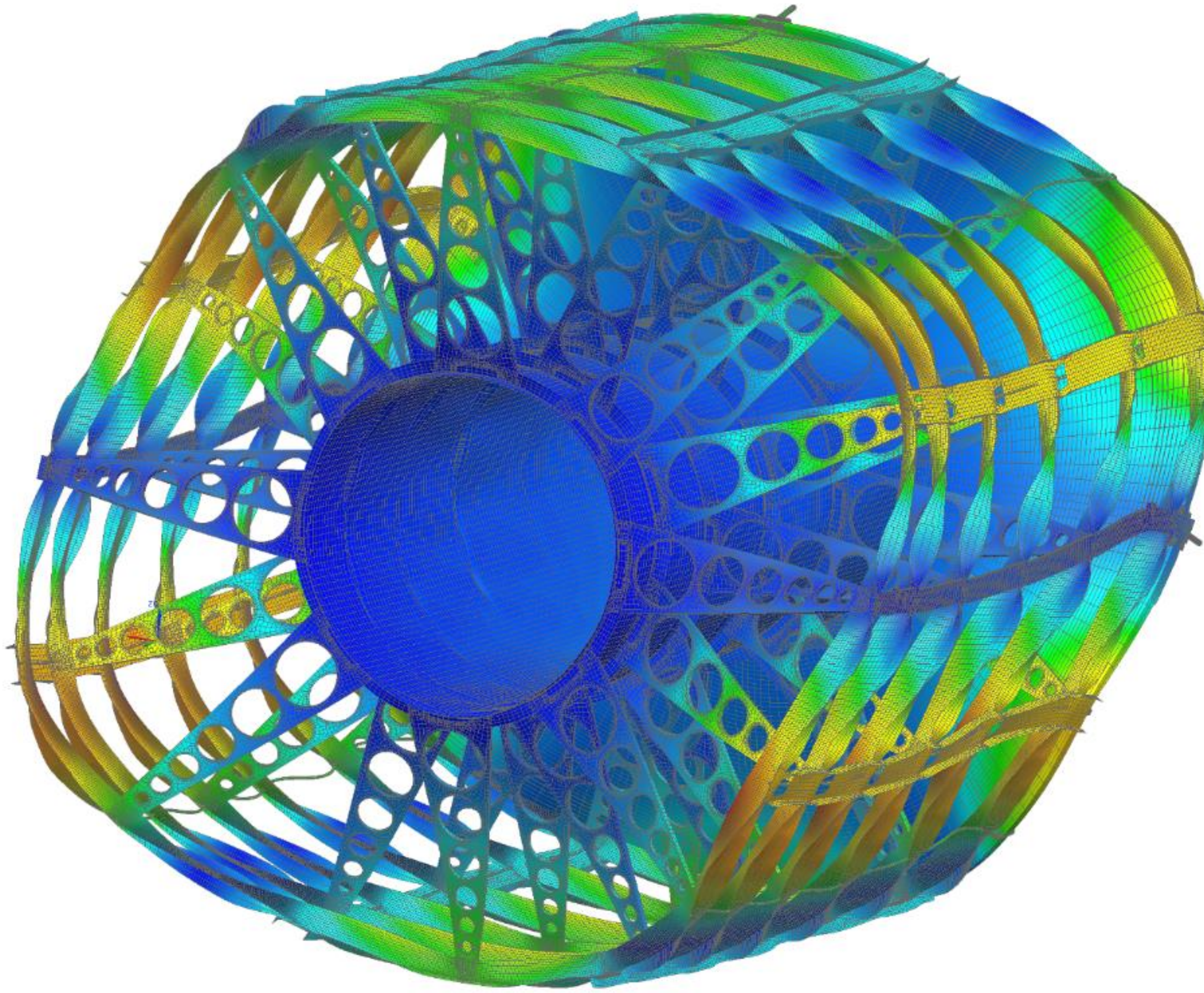


MODE 6, 29.5HZ “Z-TELESCOPE”

EIGENMODE 7 & 8

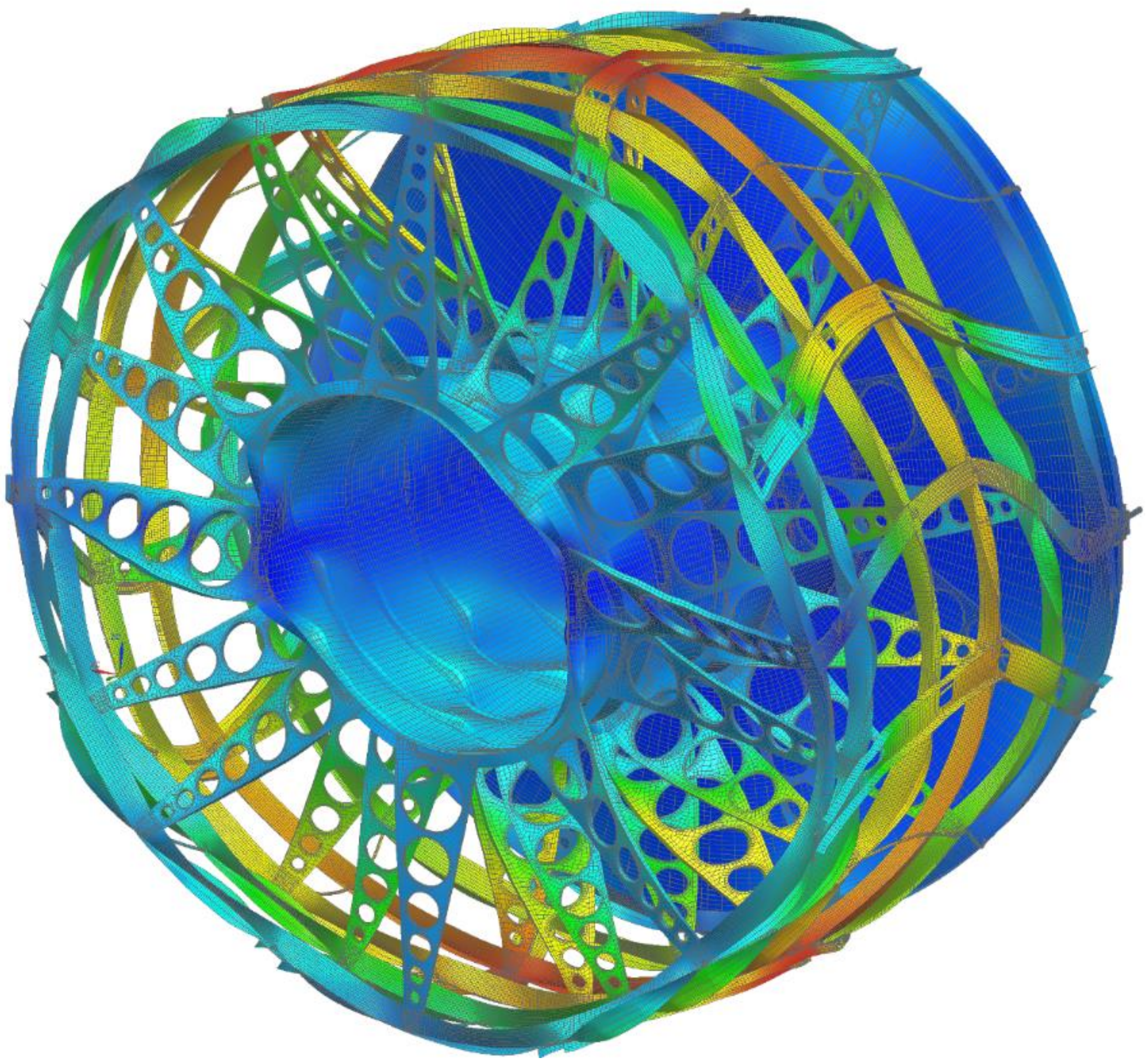


MODE 7, 32HZ “Z-DIAGTELESCOPE”

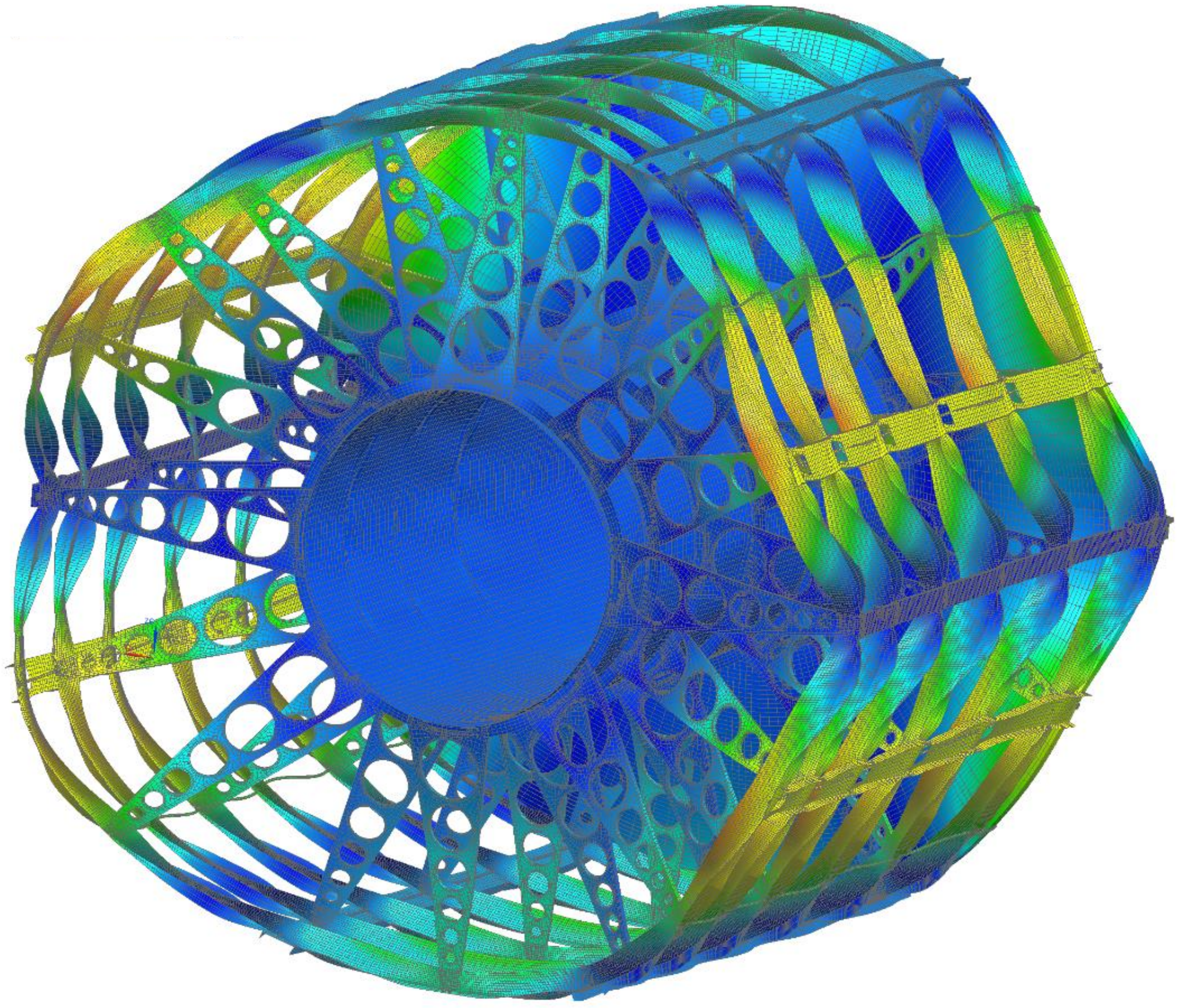


MODE 8, 47HZ “Z-DIAGFLAP”

EIGENMODE 9 & 10



MODE 9, 49HZ “PHI TWIST”



MODE 10, 51HZ
“SERVICE TRAY WOBBLE”

CONTENTS

- Introduction
- Requirements
- Envisioned Design

- Simulation Goal
- Simulating the Endcap
- Endcap Simulation History & Software

- Physical prototype
- Comparing Results

- Conclusion

Work by:

Part 1

- Introduction (1 mins)
- --> Reason for new detector --> HL-LHC --> new electronics --> new support structure
- --> Short Overview of purpose & location of Endcap
- --> Short overview of tasks for Nikhef, Valencia & Desy

- Requirements (2 mins)
- --> Environmental properties
- --> Requirements on structure
- --> Workable requirements --> Miles equation --> Q 12.5

- Basic EC Design (3 mins)
- --> Basic Ideas behind the Endcap Global Support Design

Part 2

- Simulation History (2 mins)
- General simulation problems --> you Always get numbers out are they correct?
- --> Validative Testing
- --> Parallel Calculations Valencia & Nikhef
- --> Manual Calculations
-
- Nikhef Switch from Comsol --> NX --> quick showcase of some handy features NX over Comsol (5 mins)
- --> Laminate modeller
- --> Quick Show of Draping
- --> Directly work on model & Assembly Fem

Part 4

- Mockup & Measurements (5 mins)
- --> Quick intermezzo about building real mockup.
- --> FEA of full system adjusted to represent mockup
- --> Measuring mockup
- --> Comparison Mockup & FEA Mockup

- Discussion NX Analysis (2 mins)
- --> Mockup FEA & Mockup match
- --> Makes it more likely that Real system will match simulation