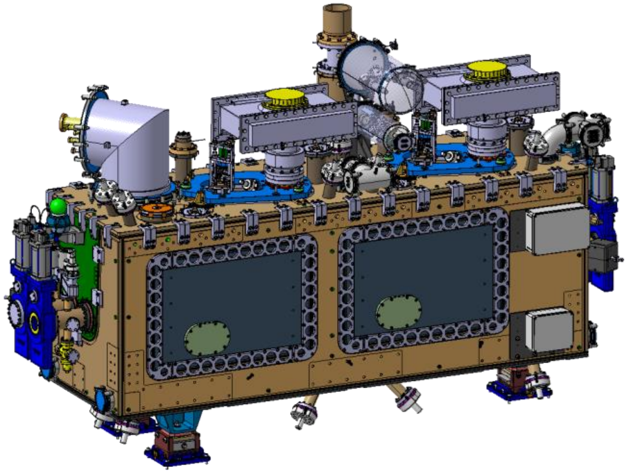
RFD-SPS Cryomodule Repair

Overview and Highlights



Simon Barrière, Joanna Święszek – CERN

on behalf of the HL-WP4 team

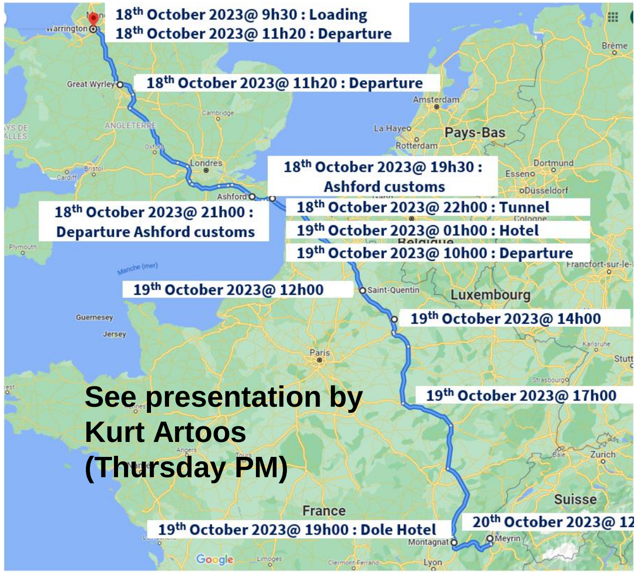
14th HL-LHC Collaboration Meeting – Genoa, Italy – 09th October 2024

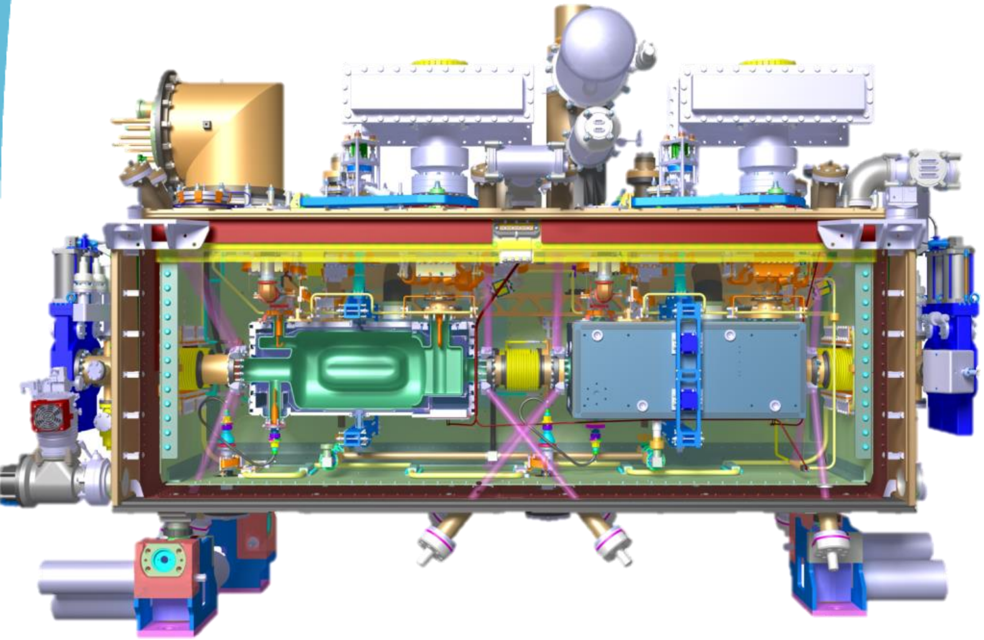
Outlook

- The RFD cryomodule and the NC
- Strategies for repair & challenges
- Calculations & numerical simulations
- Repairs activities
- Conclusion

The RFD-SPS cryomodule

- First RFD version crab cavities cryomodule (prototype for SPS tests)
- Assembled in UK-STFC Daresbury Laboratory
- Transport to CERN in Oct. 2023

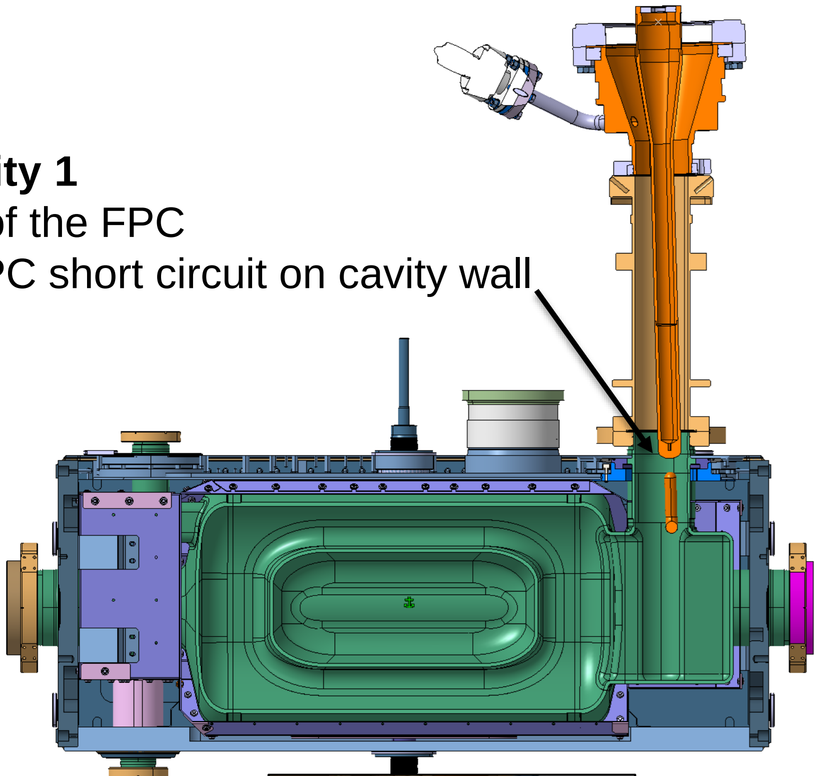




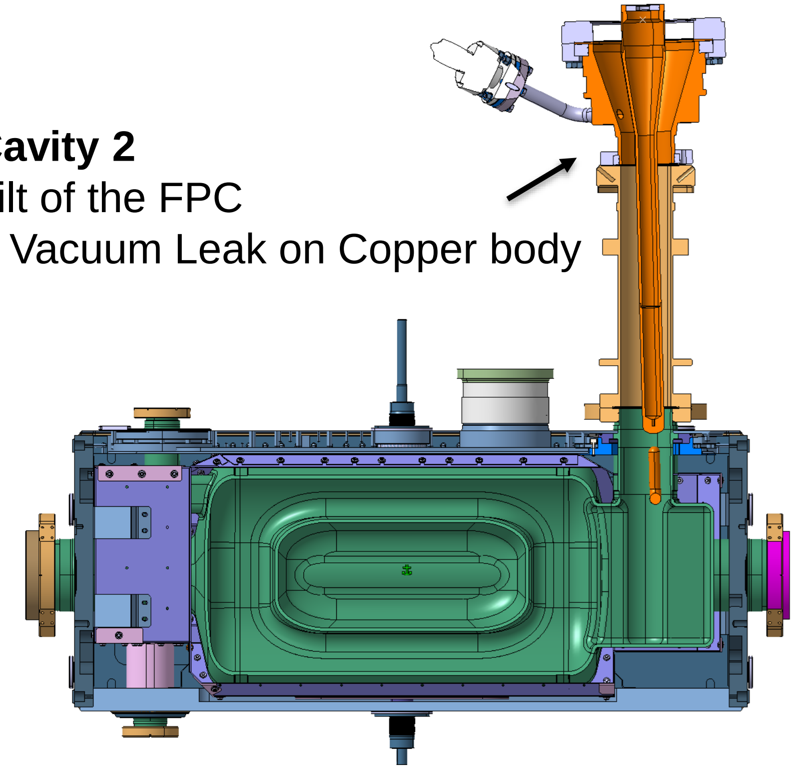
The NCs

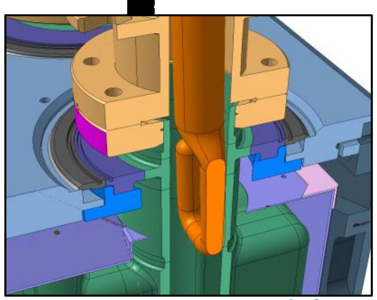
- During reception checks, two critical NC have been identified (consequence of clash between vacuum vessel top plate and FPC plate during assembly, see Edward Jordan’s talk this afternoon)

Cavity 1
Tilt of the FPC
+ FPC short circuit on cavity wall



Cavity 2
Tilt of the FPC
+ Vacuum Leak on Copper body





Theoretical clash
= 0.5 mm
(hook on cavity wall)

*confirmed by survey measurement, RF checks & X-rays

Strategy for repair

- Very limited access inside the cryomodule, making tooling installation difficult

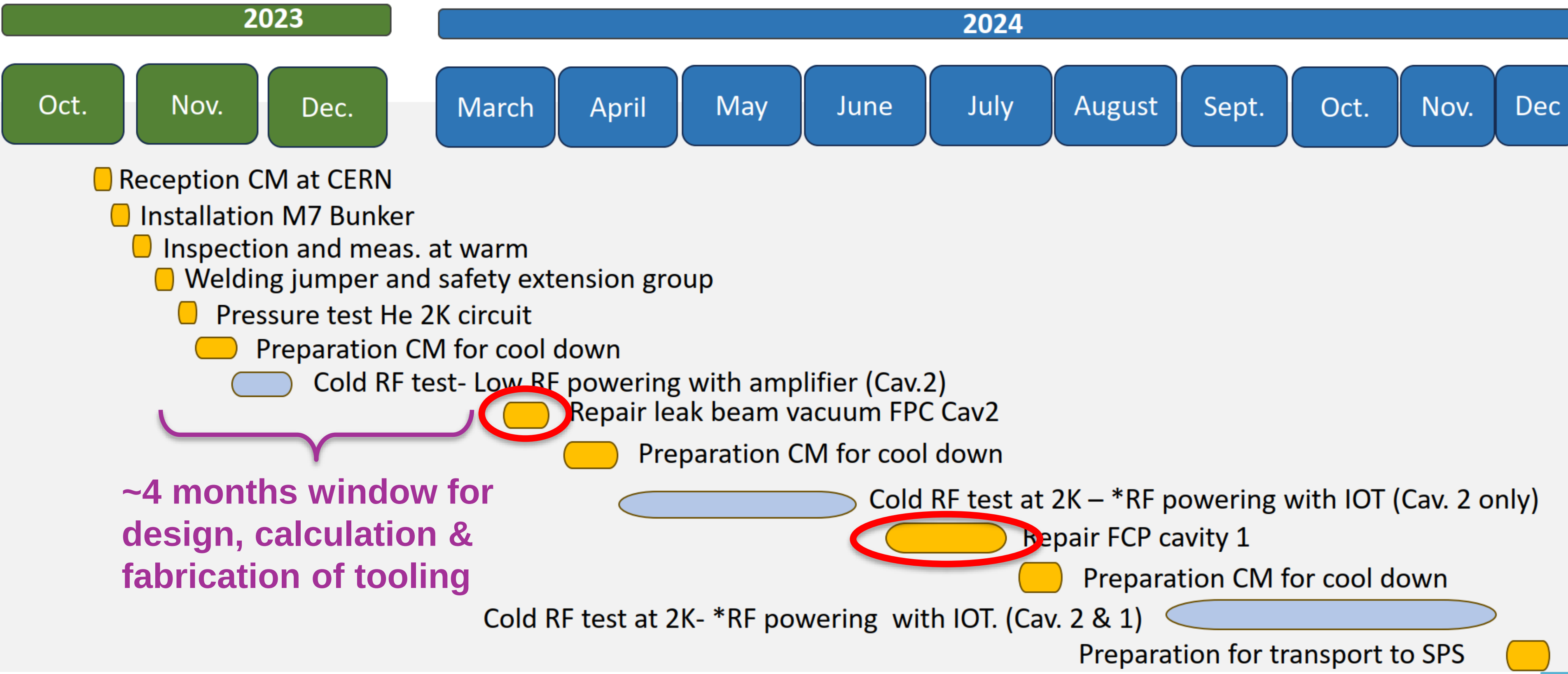
- Need to remove the cavity support plates: **delicate operation**, load transfer of the cavities step-by-step and with real-time position and strains monitoring

- Following discussion and recommendations from all the experts involved (RF, manufacturing, vacuum & alignment) and considering that straightening FPC body represent a risk of critical damage that could jeopardize cryomodule and cavities cold test, the following plan has been agreed between STFC and CERN:

  - 1 : Cavity #2 FPC leak repair (no straightening)
  - 2 : Cold test of the cryomodule (Cavity #2)
  - 3 : Cavity #1 FPC straightening
  - 4 : Cold test of the cryomodule (Cav #2 + Cav #1)

Planning

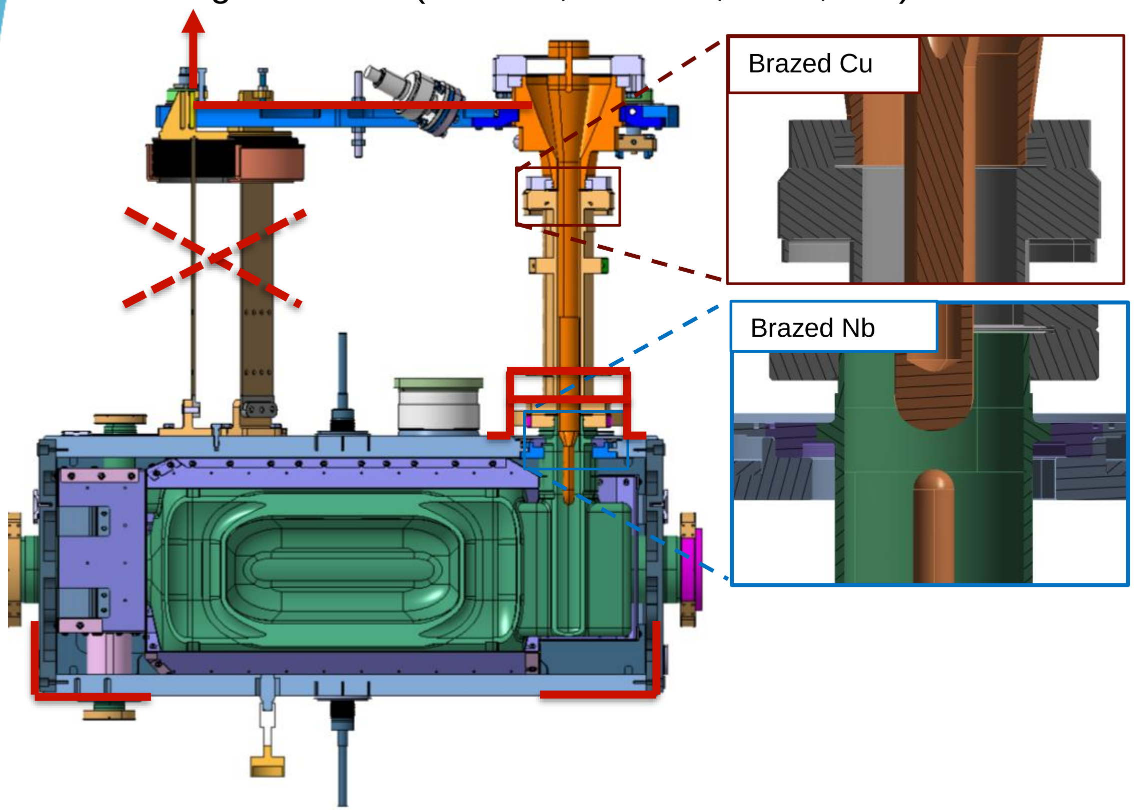
- Two windows of repair to match planning of cold testing in SM18

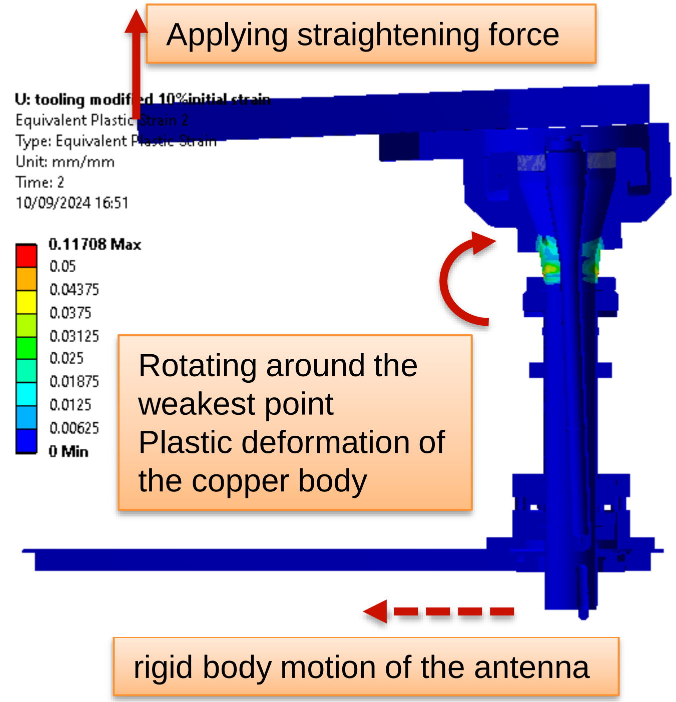


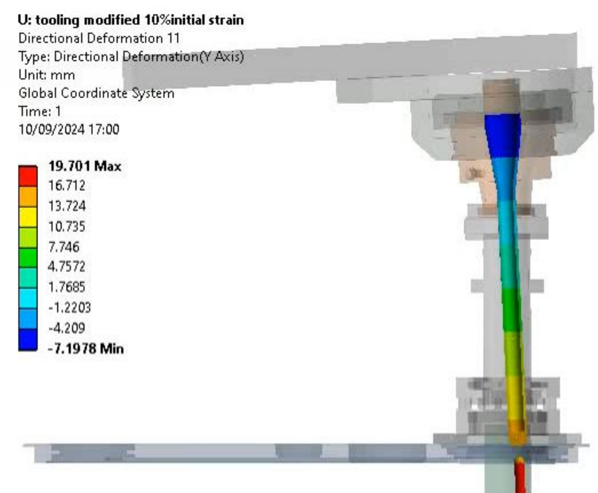
Repair principle, simulations

Simulation scope:

- Define the most appropriate repair method
- Understand system behavior and critical parameters, no stress on ceramic feedthrough!
- Design the tools (material, stiffness, force, etc.)







Simulations outcome:

- Rigid tooling to fix the FPC double tube to He tank, to avoid deforming cavity port.

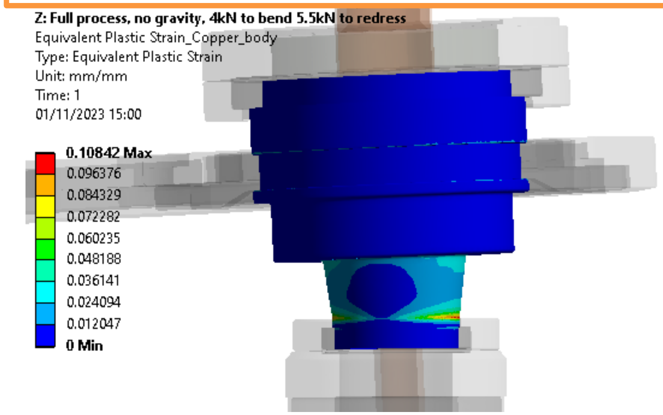
Modelling challenges and unknowns

Simulation scope:

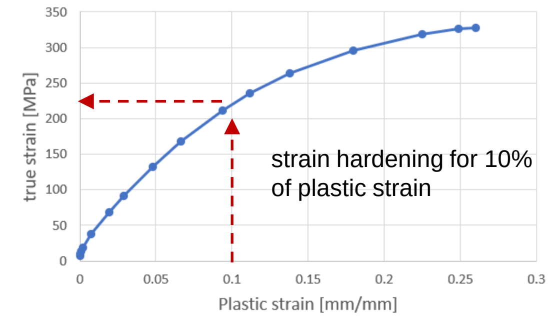
- Estimate the maximum force to be applied → input for the tooling design

What is the root cause of the antenna deformation?

physical collision → permanent deformations in plastic domain → Strain hardening



Material hardening due to the plastic deformation



Simulations outcome:

Assumption: the antenna position shifted only due the physical impact

- ~10% plastic strain introduced in the copper body
- max straightening force of 6.2 kN was defined, used for tooling design

Is the antenna position shifted to due the impact or misalignment, or both?
What is the initial state of the material?

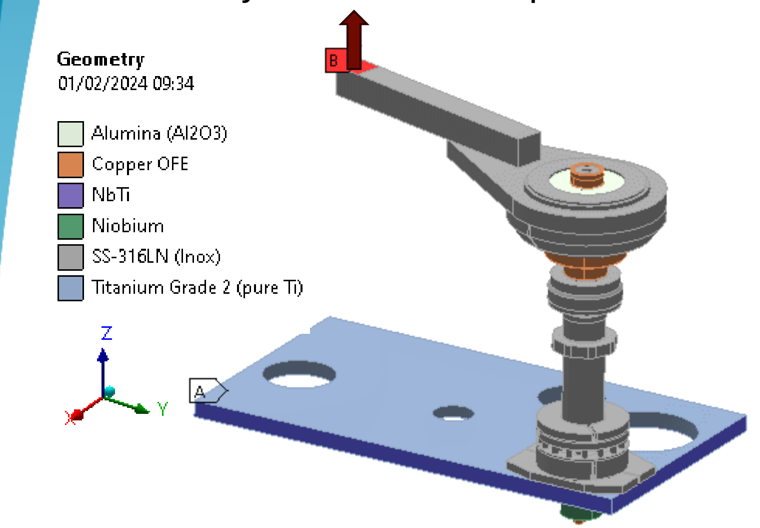
WE DO NOT KNOW IT IN ADVANCE

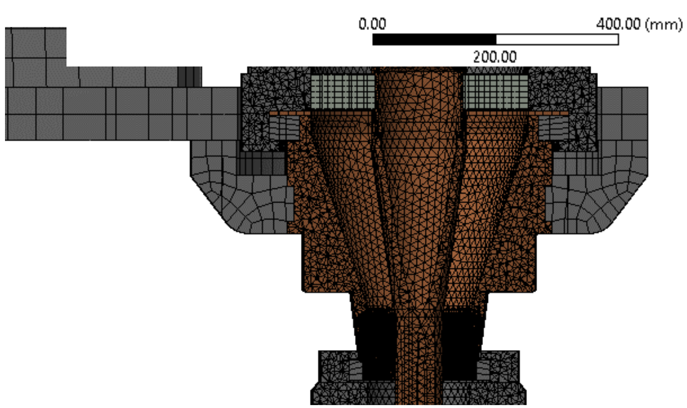
Several scenarios were simulated

Numerical model and methods

Simulation methods:

- Simulating initial copper strain hardening: applying "impact" force to obtain pre-deformed shape and more realistic local change of copper properties
- Analysis done in 4 steps





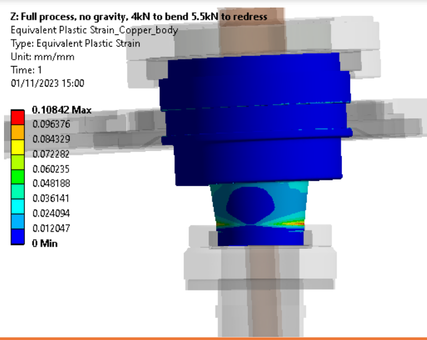
Mesh heavily refined in the copper body region undergoing plastic deformations.

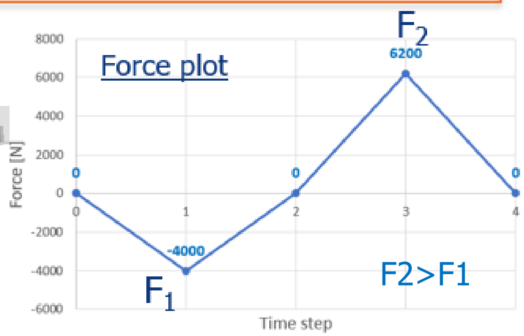
Different initial strain hardening is simulated

Introductory analysis
Simulating the initial impact on the FPC copper body

1) Applying bending force F_1 (downwards)
2) Springback (realizing the force)

Getting pre-deformed shape and copper material hardening for the redressing analysis





Actual simulation of the FPC antenna redressing

3) **Applying counter force F_2** (upwards)
4) **Springback**

Estimate the force needed to deform back

Material model:
- all copper parts are initially in full annealed state;
- multilinear isotropic hardening defined;
- elastic perfectly plastic model used for other parts

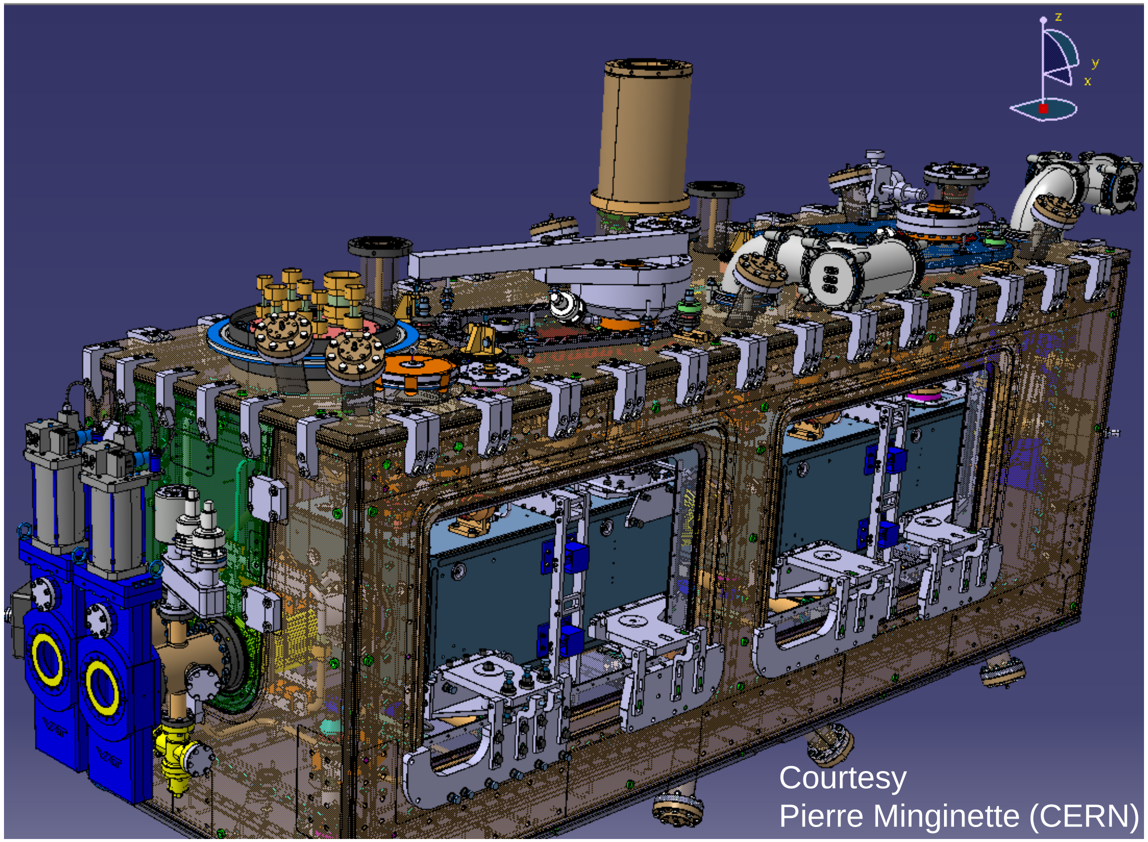
The Tooling

3 main functions:

i) Transfer the weight of the cavities to the vacuum vessel without additional stress

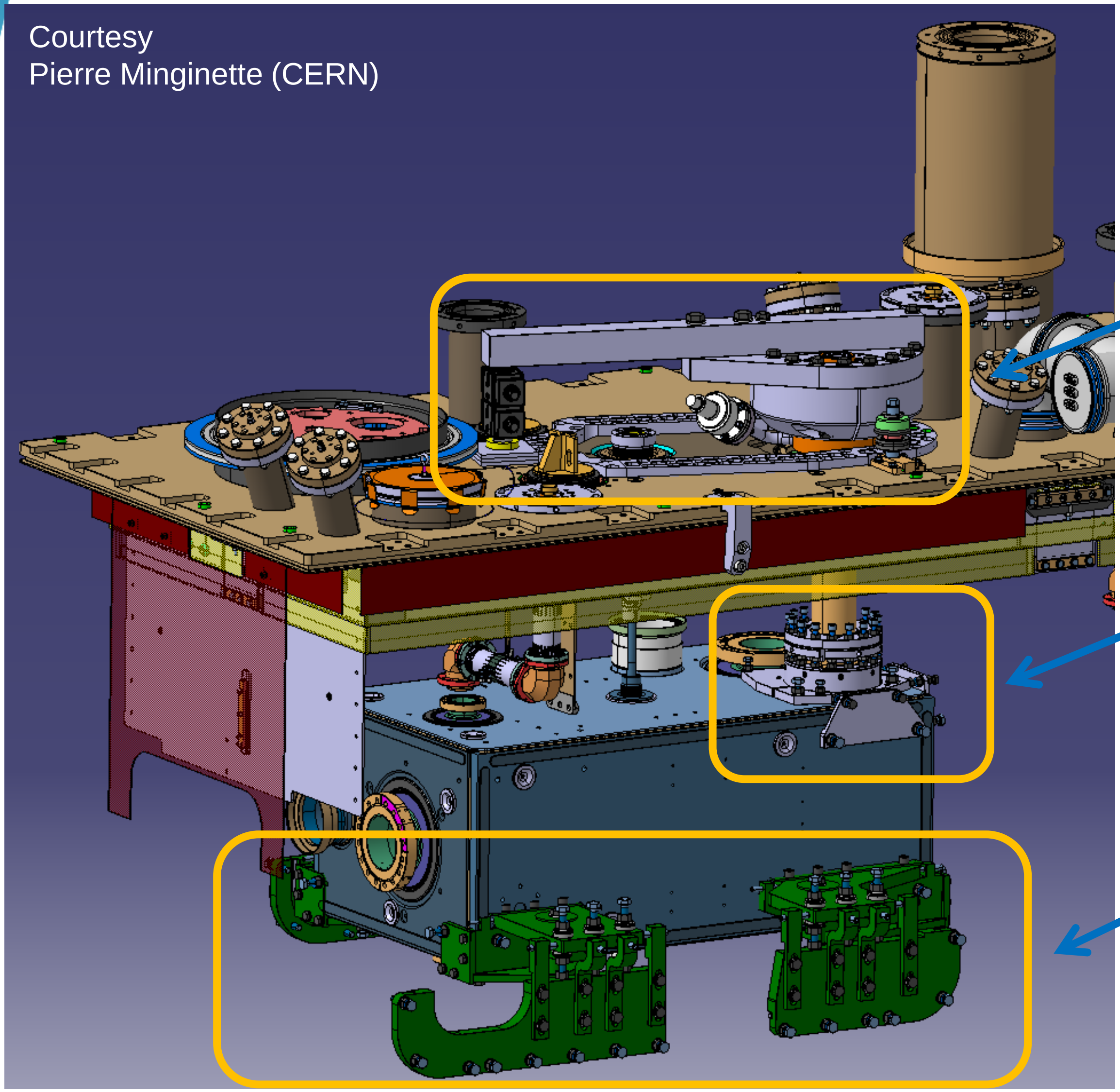
ii) Fix in position the cavities during straightening

iii) Allow progressive and safe straightening of the copper body while protecting potential highstress zones



- Details procedure & drawings for tooling assembly and mechanical activities (EDMS 3120529)
- **Discussed and approved with STFC team (diagnostics, procedure, design of tooling)**

The Tooling



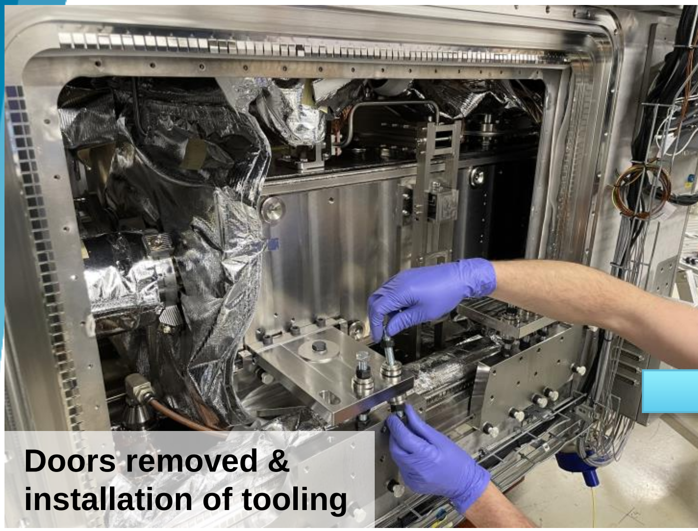
III- Straightening lever (oriented w.r.t. antenna deformation axis)

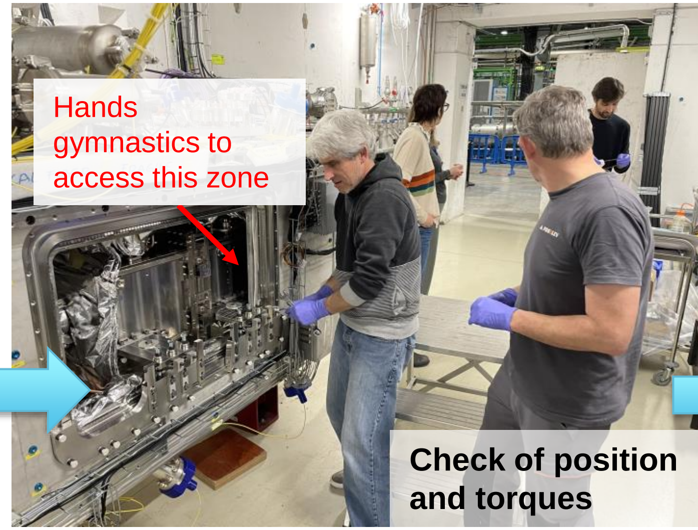
II- Base locking shell to lock the FPC double tube

I- Support of cavity on vacuum tank

For leak repair of Cavity 2, only this bottom support is needed

Repair of Cavity #2 FPC (Leak)


Doors removed & installation of tooling

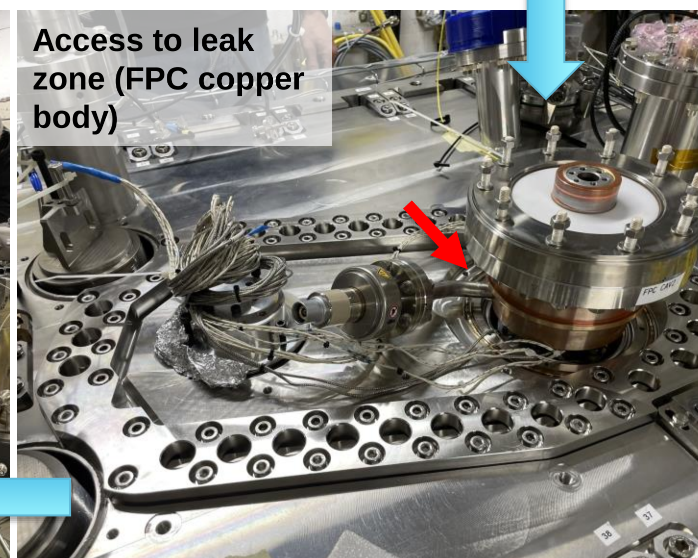


Check of position and torques


Removal of cavity supporting plate


Leak repair

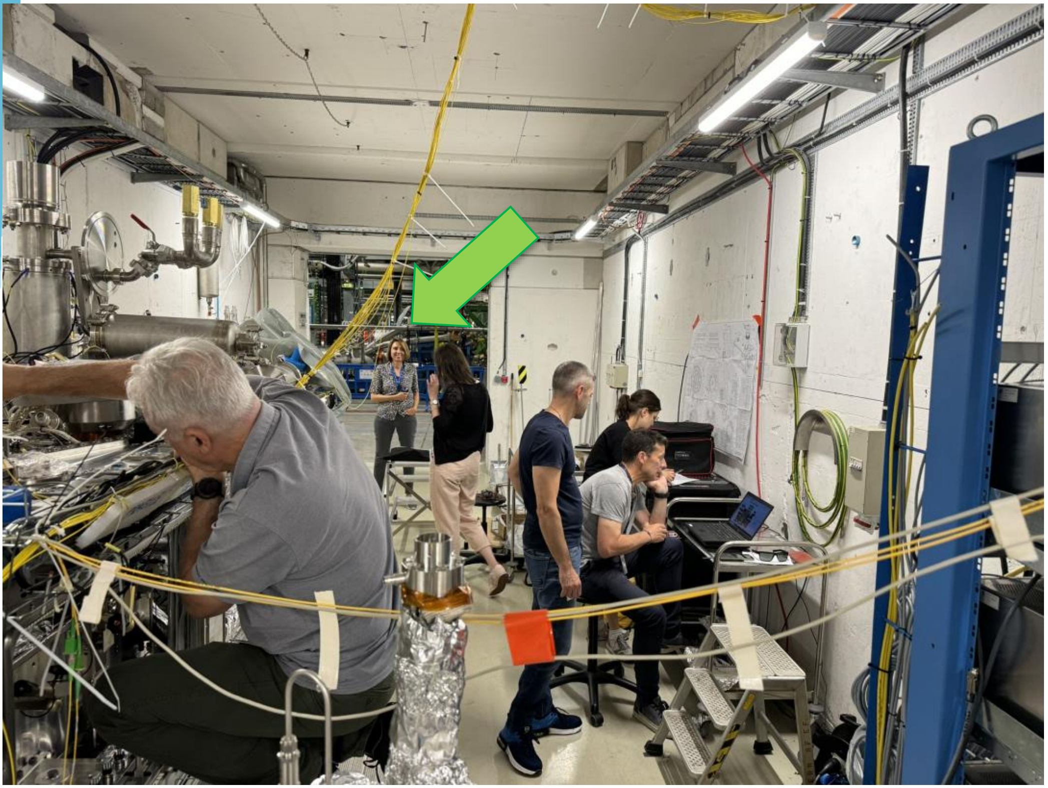

Live monitoring (survey) of cavity and FPC during all activities

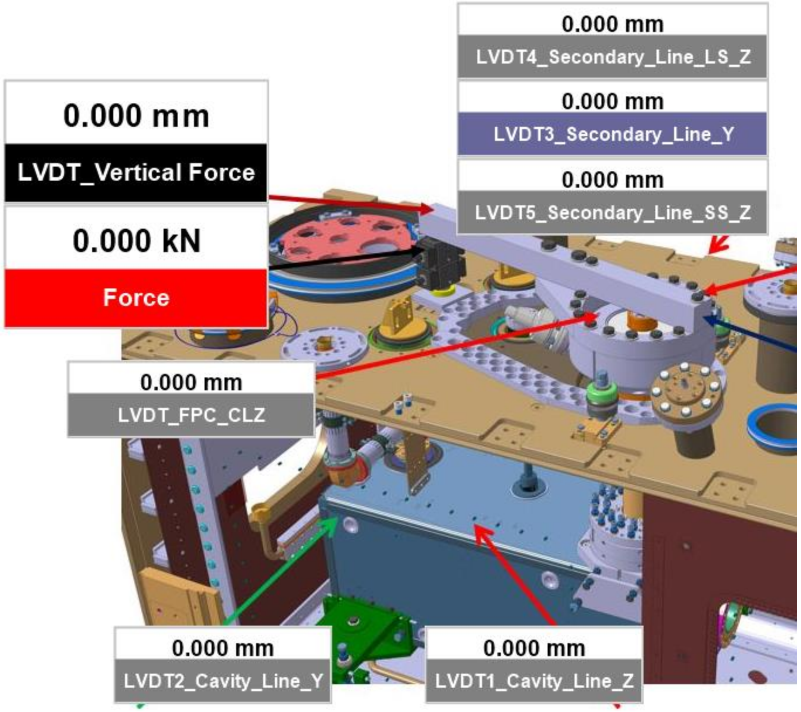

Access to leak zone (FPC copper body)

✓ Leak closed, allowing cold test of C2 (see presentations this morning)

Repair of Cavity #1 FPC (Straigthening)

- Comparisons between calculations & measurements of paramount importance (force vs displacement vs strains)
- After installation of tooling (similar procedure as Cavity 2), test set-up installed and straigthening in 3 steps





LVDT set up

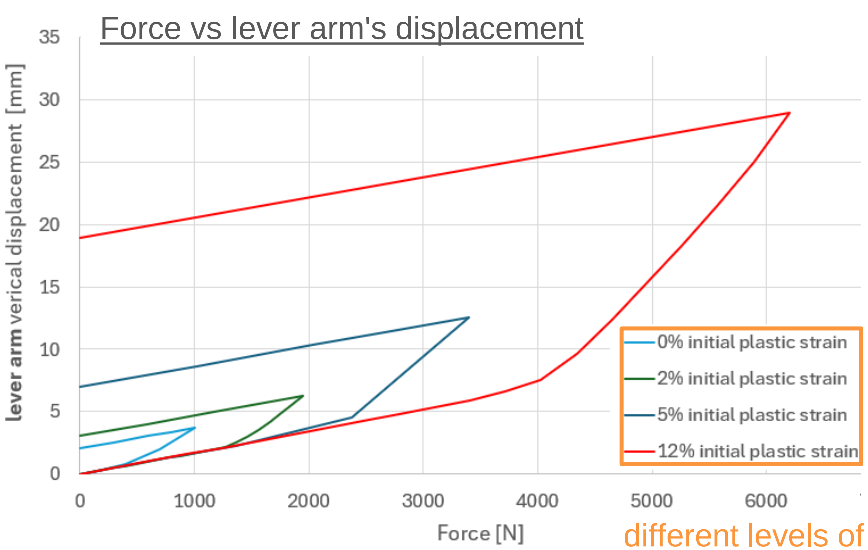
Simulation predictions

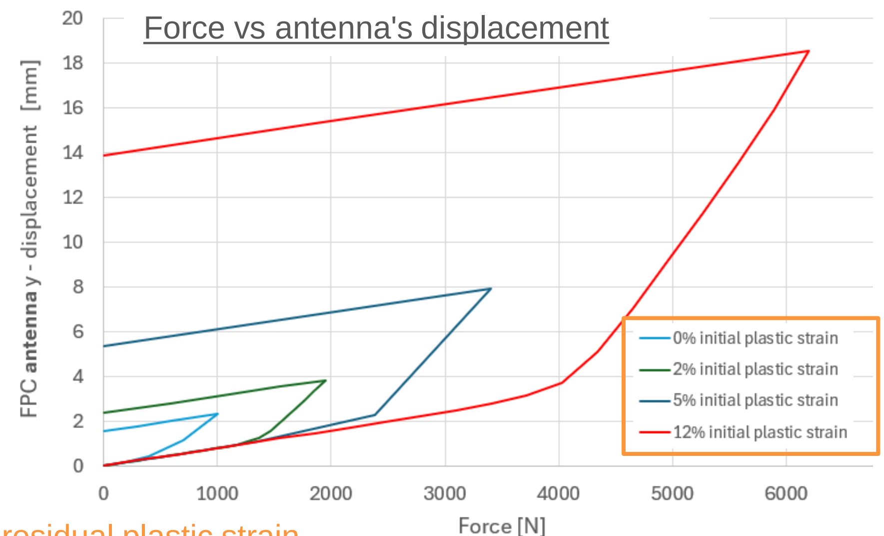
Simulation scope:

- Find a correlation between lever arm displacement/force and antenna displacement, considering initial strain hardening in the material.
- By applying different “collision” force, different copper hardening is obtained.

Simulations outcome:

- Force/displacement plots for different initial hardening scenario.





different levels of residual plastic strain in FPC copper body

Strategy:

- **Measuring** force and lever arm’s displacement
- **Superposing** measurement curves on the simulation curves
- **Comparing** sims and measurements to indicate the initial hardening of FPC copper body
- **Choosing** a curve for estimation of the antenna’s displacement

Antenna's displacement estimated through simulations, not possible to measure

Heavily relying on simulations!

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Straightening strategy and limitations

Simulations outcome and general recommendations:

- calculated force is to be applied incrementally
- electrical checks done simultaneously when applying the force, and after realizing the force
- springback effect should not be neglected

Straightening actions divided in 3 steps:

Run 1: test
Run 2: test

real time model benchmarking: sensors checking, strain comparison, system response

BUT !

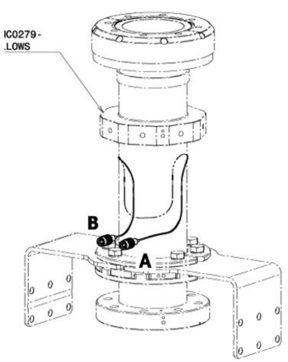
with each step we are hardening material even more

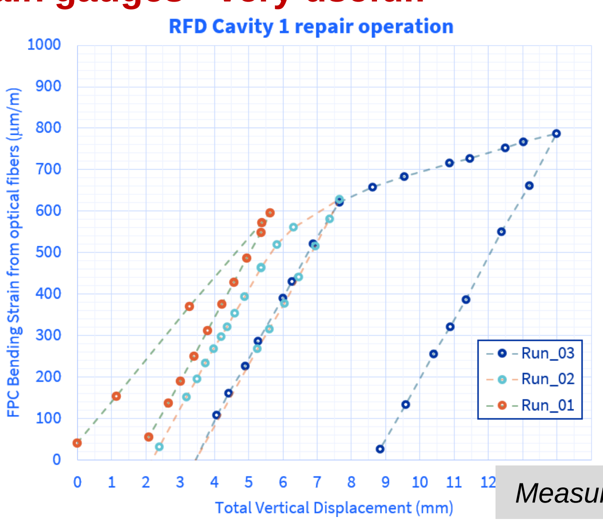
Run 3: final straightening action

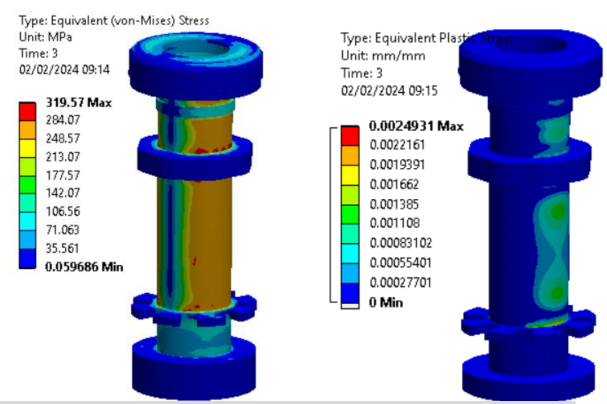
Simulations outcome:

- limiting component is FPC tube: 0.2% of plastic strain in the FPC tube if applying 6.2 kN force
- careful monitoring of the FPC tube strain

Presence of strain gauges - very useful!



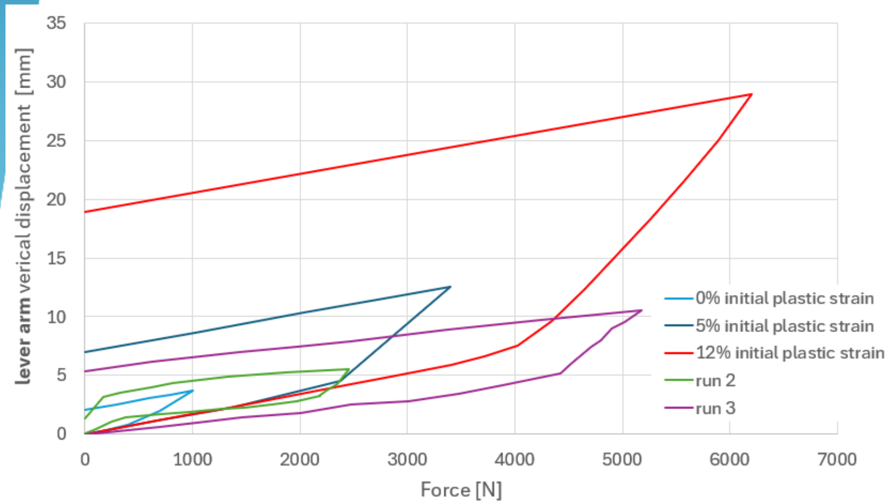




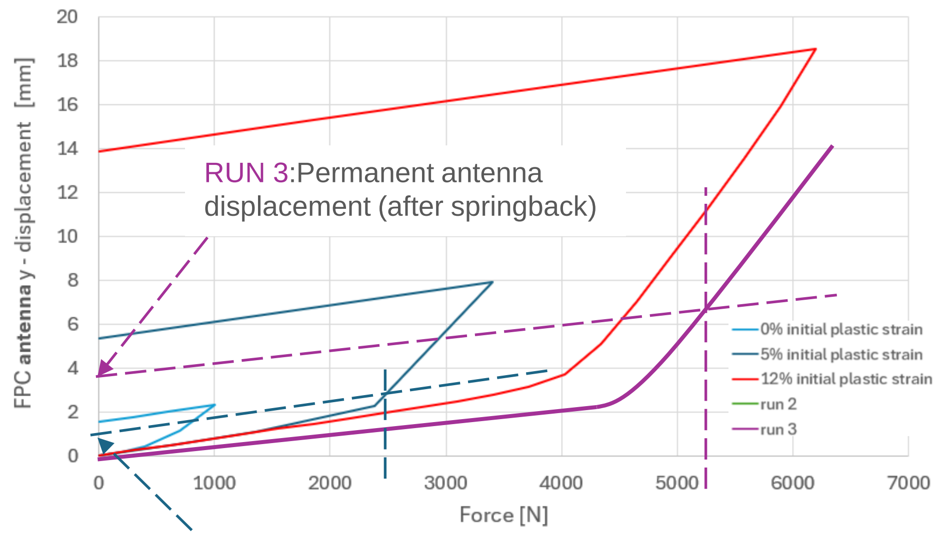
*Measurements done by **Michael Guinchard & David Thuliez***

Simulations & Measurement

Force vs lever arm's displacement



Force vs antenna's displacement



RUN 2: permanent antenna displacement (after springback)

Run 1: apply a force to test structure response, closing gaps in contacts, tool put in place

- Applied force: 1 kN

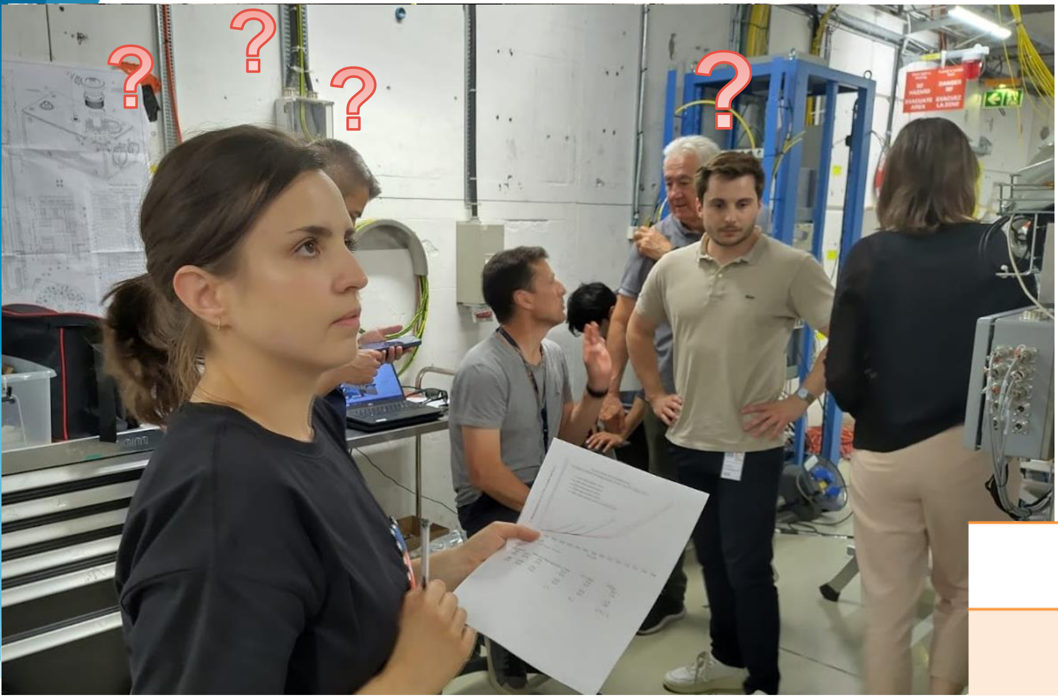
Run 2: apply a force to test structure response, springback slope, hardening level

- Applied force: 2.5 kN
- Following "5% initial plastic strain" curve
- Springback slope confirmed
- Estimated displacement of the FPC hook: 1mm

Run 3: apply a displacement corresponding to the straightening objective set

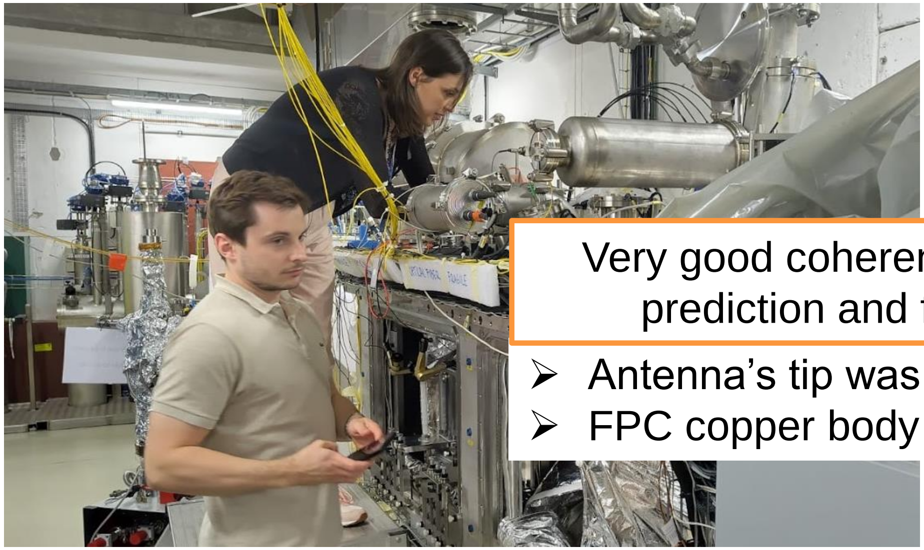
- Applied displacement: 10.5 mm
- Measured force: 5.2 kN
  ~15% plastic strain, strain hardening after run 2
- Estimated displacement of the FPC hook: 3.6 mm
- Approaching admissible stress limit for the FPC tube

Results



ANNTENNA's DISPLACEMENT		
	SIMULATION	MEASUREMENT
1st run	1 mm	0.9 mm
2nd run	1 mm	1.1 mm
3rd run	3.6 mm	4.1 mm
TOTAL	5.6 mm	6.1 mm

Laser tracker measurement and FSI Validation
Praneeth Sarvade
Vivien Rude
Teddy Capelli



Very good coherence between simulation prediction and final measurements!

- Antenna's tip was permanently moved by 6.1 mm
- FPC copper body was plastically deformed

Results

Conclusion

- Following the identification of the two non-conformities on the FPC, a repair plan has been defined by CERN in collaboration with STFC.

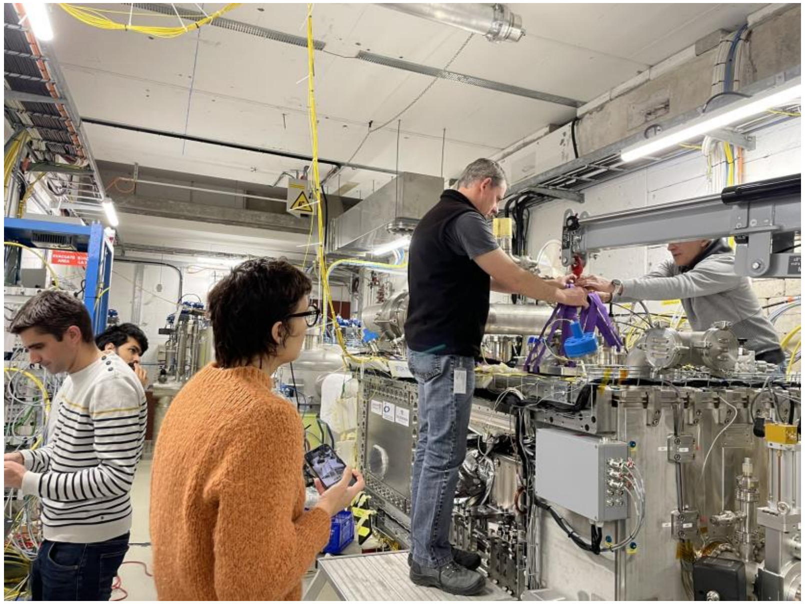
- Advanced simulations have been performed to:

  - create representative model (including hardened copper), define repair steps.
  - identify stress regions in the cavities during repair;
  - give input on tooling design & parameters;

- The two cavities have been repaired following defined procedures; all operations went smoothly thanks to a massive effort from different teams.

- Root causes are being identified and related NCR in preparation, hold points added in the assembly procedures.

Thank you!



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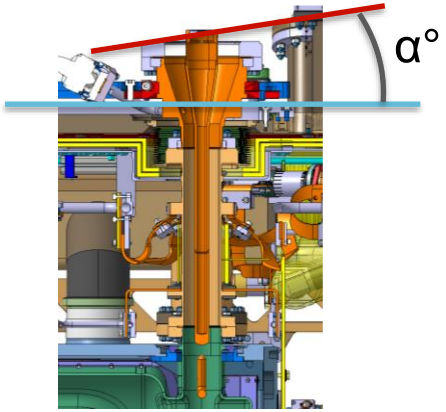
Back-up slides

Courtesy T. Capelli

First observations

- Preliminary RF checks perfomed by E. Montesinos and his team showed a problem on FPC of cavity #1
- A measure of electrical continuity between inner and outer conductor of the FPC showed a contact between the conductors
- Visually, the top flange FPC look tilted WRT the surrounding elements

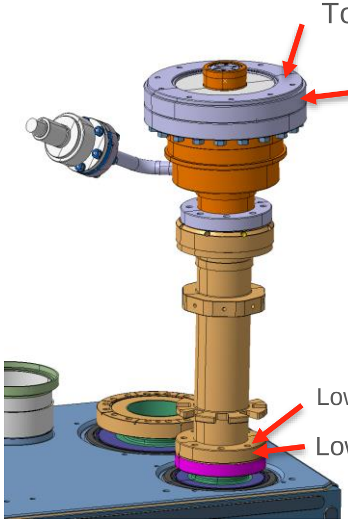


- A similar but smaller deformation is also visible on FPC cavity #2 but without electrical short and no undesired behaviour noticed during RF checks. This bending is very likely to have caused the vacuum leak.

Courtesy T. Capelli

FSI Measures – V.Rude

- A measure of both the top FPC flange and the lower FPC outer pipe flange (Plane + axis for both) show a deviation as described on the sketches bellow :



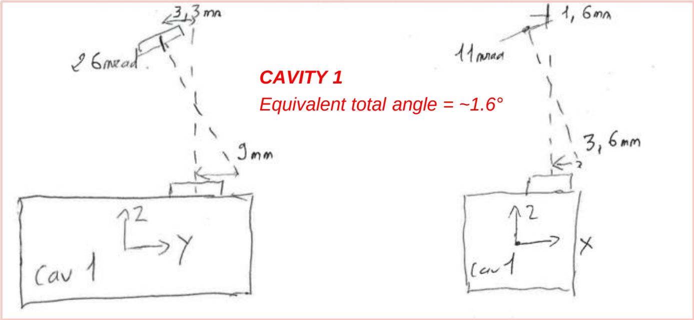


Fig .5 *Measured using laser tracker – V.Rude*

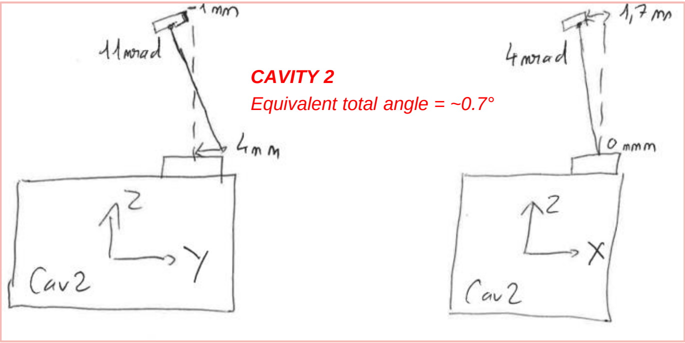


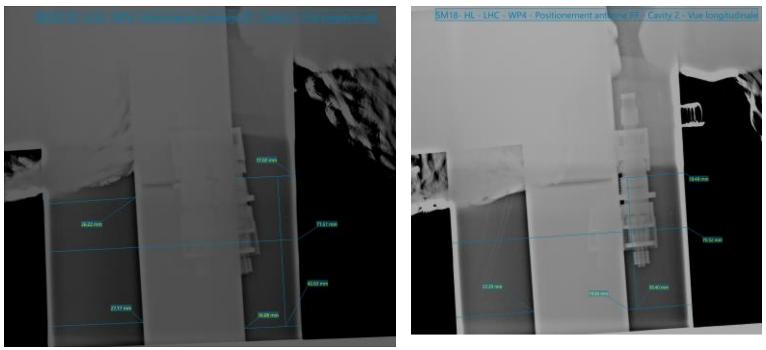
Fig .6 *Measured using laser tracker – courtesy V.Rude*

Courtesy T. Capelli

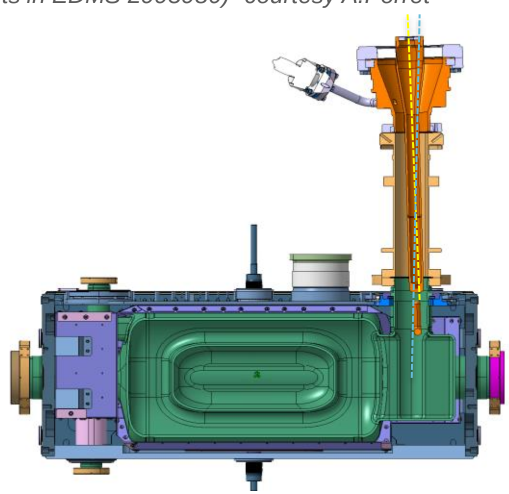
Radiographic measures – A.Porret

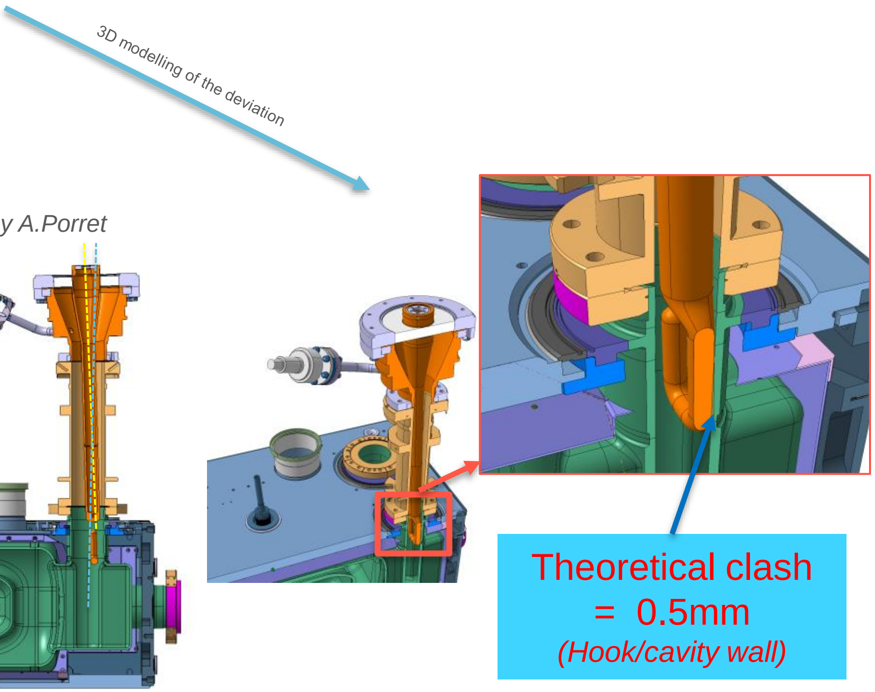
Set up preview - courtesy A.Porret

- X-ray confirms our preliminary observations :
  - The hook isn't bended
  - The deviation starts from the top



Result of radiographic measure (see full results in EDMS 2995980)- courtesy A.Porret

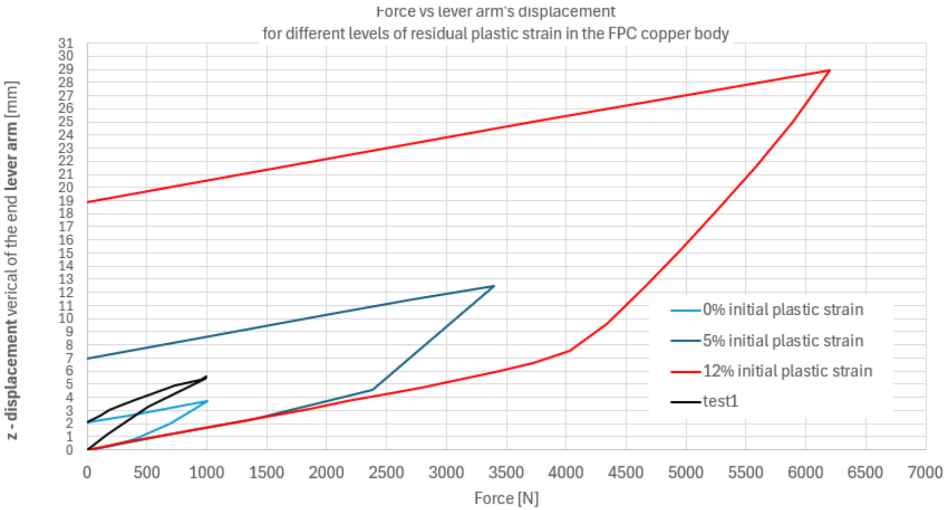


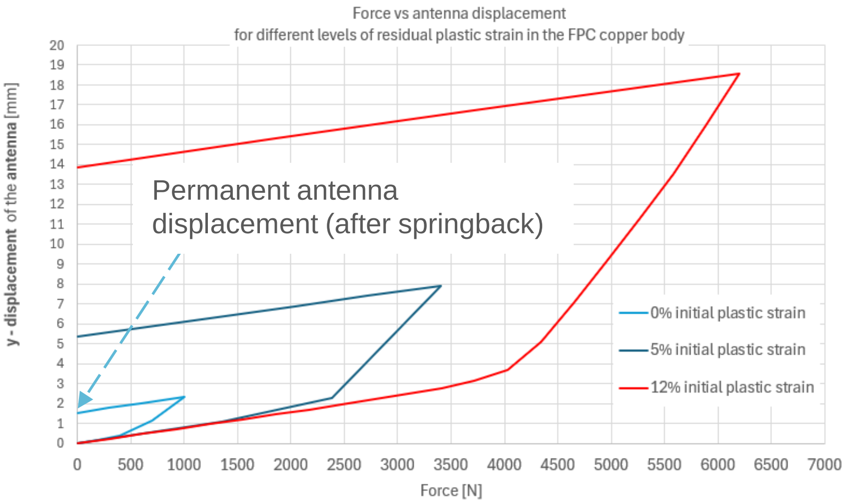


Run 1: Simulations & Measurement

- Measuring force and lever arm's displacement
- Superposing measurement curves on the simulation curves
- Choosing the curve for estimation of the antenna's displacement

→ Antenna's displacement obtained through simulations





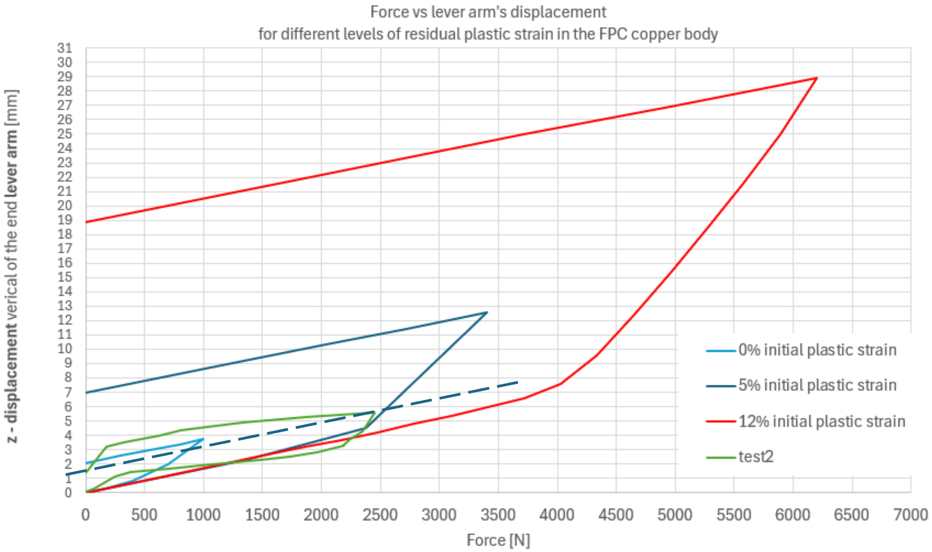
Run 1: apply a small force to test tooling and structure response

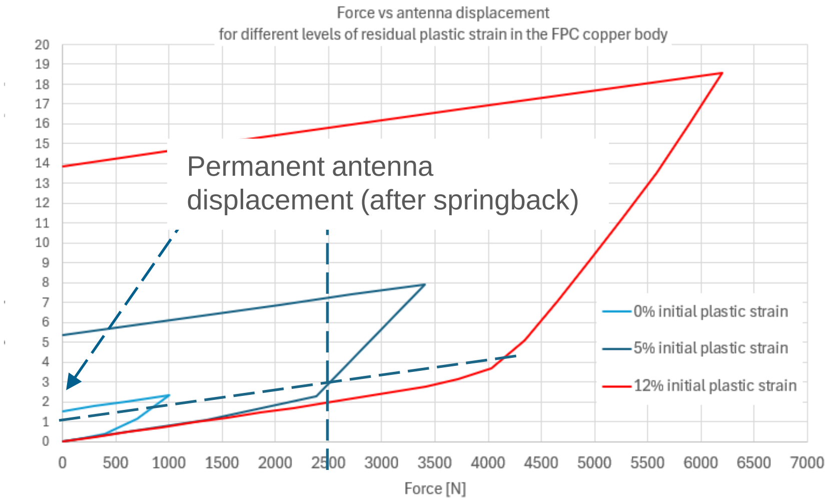
- Applied force: 1kN
  tooling adjustments, contact sliding, actual deformations difficult to estimate
- Estimated displacement of the FPC hook: ~1mm
- Contact removed

Run 2: Simulations & Measurement

- Measuring force and lever arm's displacement
- Superposing measurement curves on the simulation curves
- Choosing the curve for estimation of the antenna's displacement

Antenna's displacement obtained through simulations





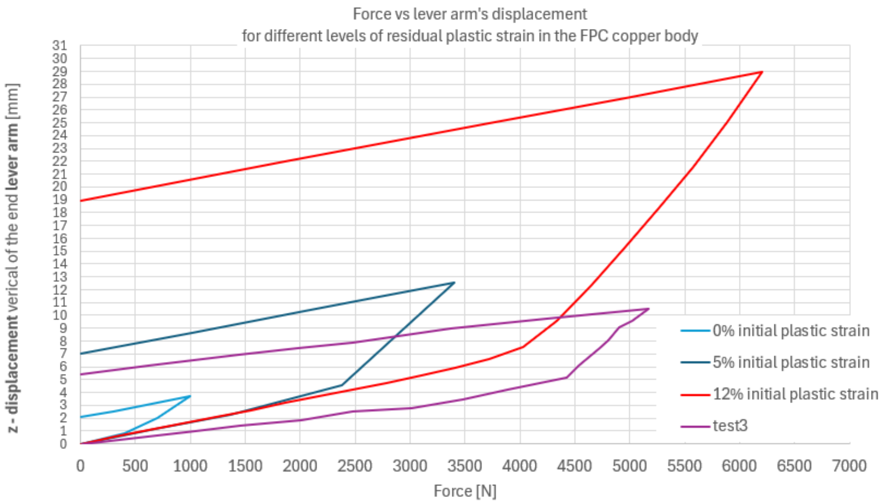
Run 2: apply a force to test structure response, springback slope, hardening level

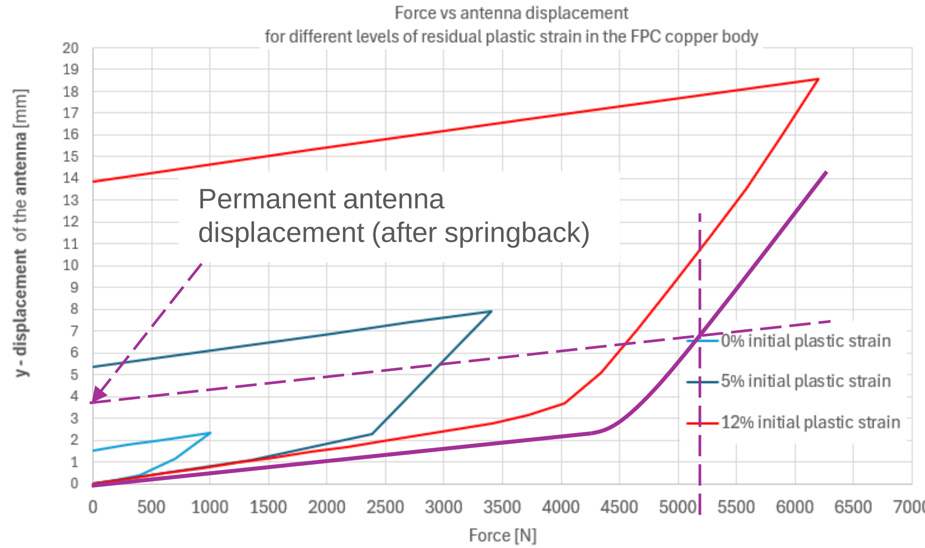
- Applied force: 2.5 kN
- Measured displacement:
  Following dark blue curve – 5% plastic strain
- Estimated displacement of the FPC hook: 1mm
- Springback slope confirmed

Run 3: Simulations & Measurement

- Measuring force and lever arm's displacement
- Superposing measurement curves on the simulation curves
- Choosing the curve for estimation of the antenna's displacement

→ Antenna's displacement obtained through simulations





Run 3: apply a displacement corresponding to the straightening objective set

- Applied displacement: 10.5 mm
- Measured force: 5.2 kN
  ~15% plastic strain, strain hardening after previous tests
- Estimated displacement of the FPC hook: 3.6 mm
- During this test, we approached the admissible stress limit for the FPC tube