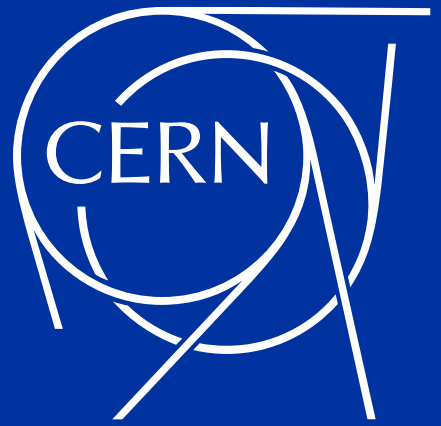

The Wide-Open Waveguide Crab Cavity – Progress and Status

Fabian Manke, Alban Sublet, Mauro Taborelli, Alexej Grudiev, Lucie Baudin, Ana Teresa Perez Fontenla, Stephan Pfeiffer

08/06/2023

FCC Week 2023

Outline

1. The Wide-Open Waveguide Crab Cavity
2. Coating recipe validation
3. Process planning
4. Status at full scale
5. The last steps

Outline

1. **The Wide-Open Waveguide Crab Cavity**
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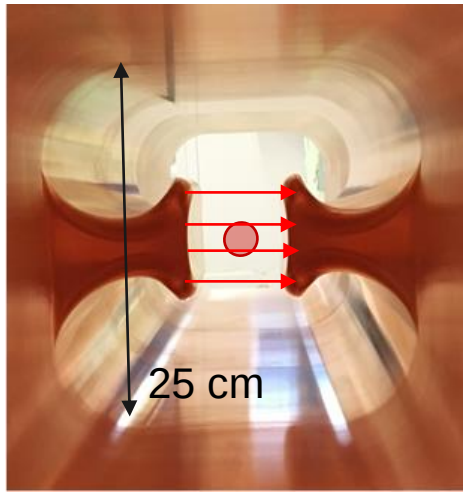
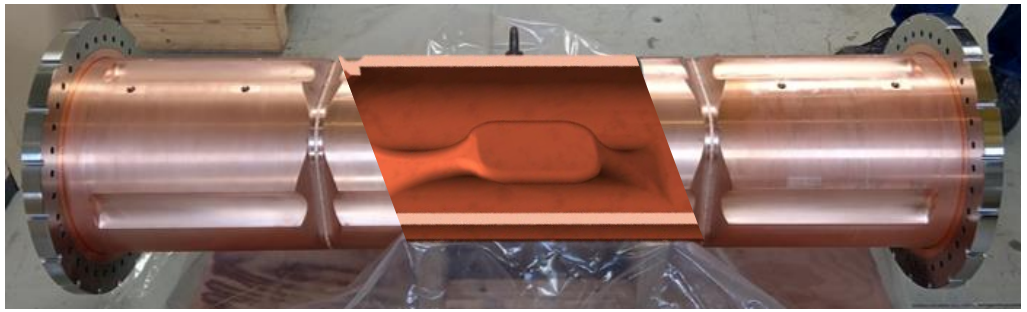
1 The Wide-Open Waveguide Crab Cavity

- **luminosity leveling in FCC-hh**
- **key design features:**
  - optimized E-field homogeneity
  - low shunt impedances for RF waves
  - fields and losses manageable for SRF
  - Nb on Cu: stable operation at 4.5 K
  - **design compatible with coating**

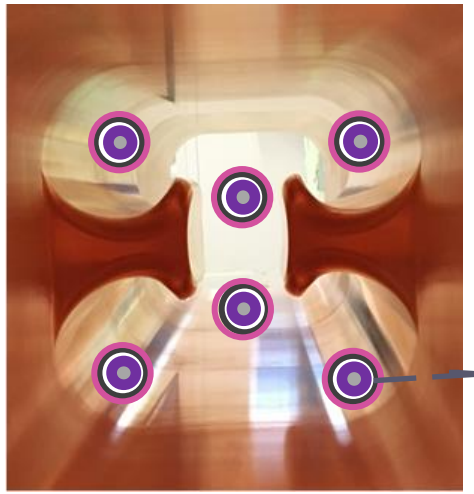




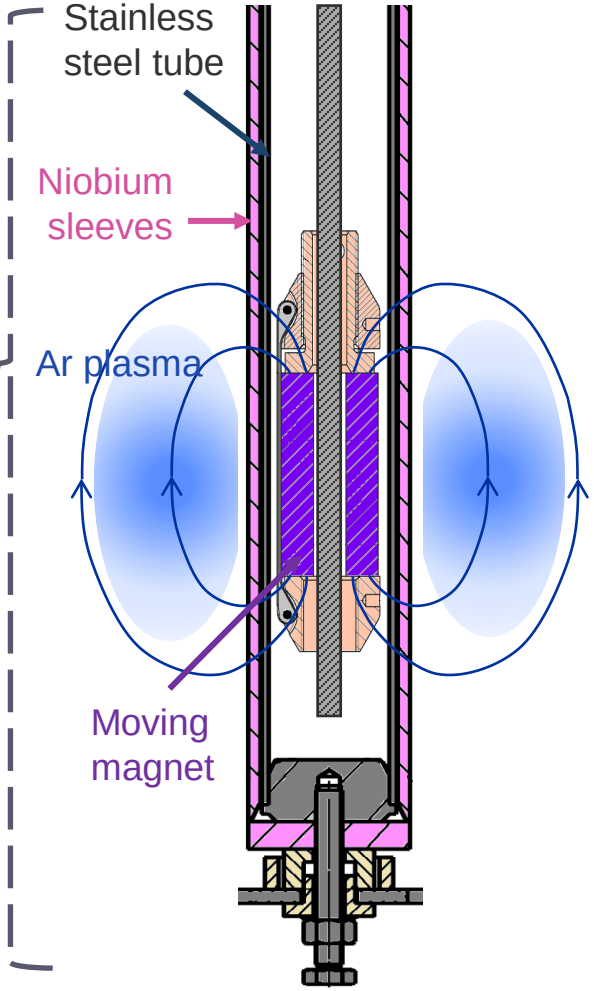
K. Papke et al, Phys. Rev. Accel. Beams 22, 072001, 2019

1 Multi-cathode coating set-up

- **Six independent cylindrical magnetrons**
- **Cathode tubes along full cavity length**
- **Air-cooled movable magnets**
- **Bipolar HiPIMS technique in Argon**



F. Avino et al, TTC, 05.02.2020, Geneva



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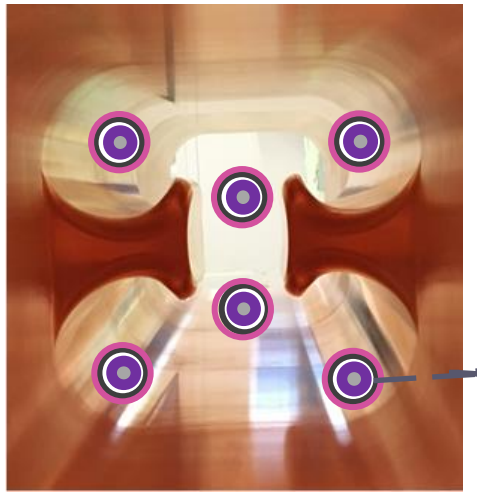

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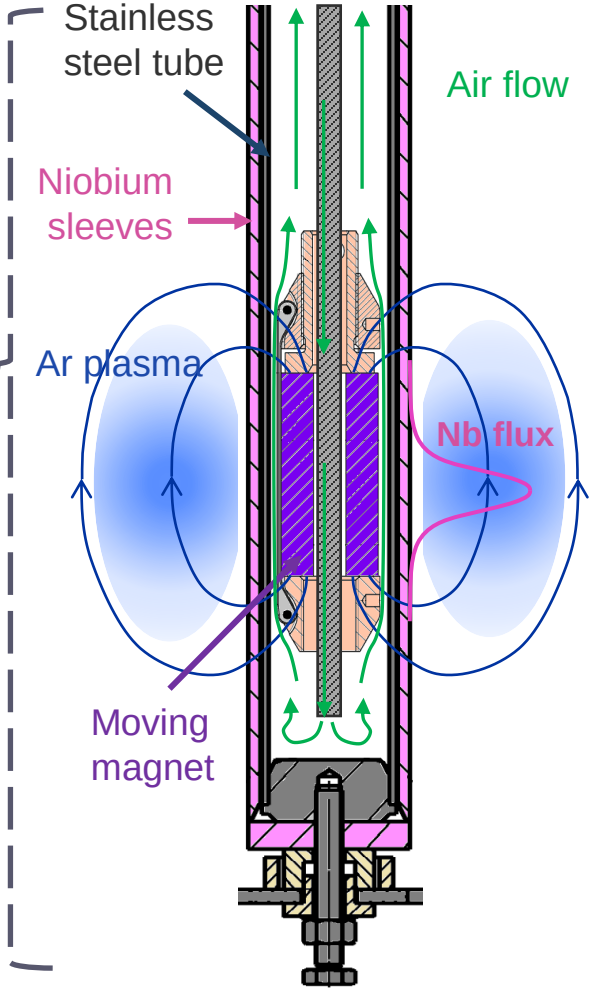
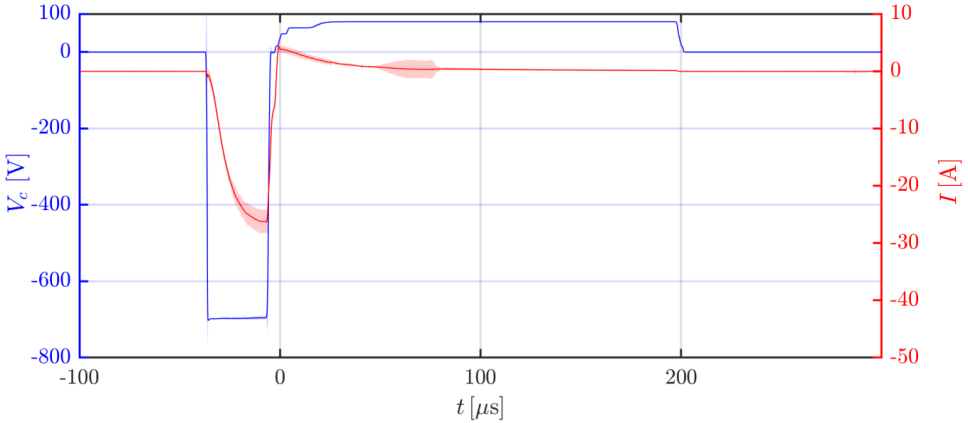
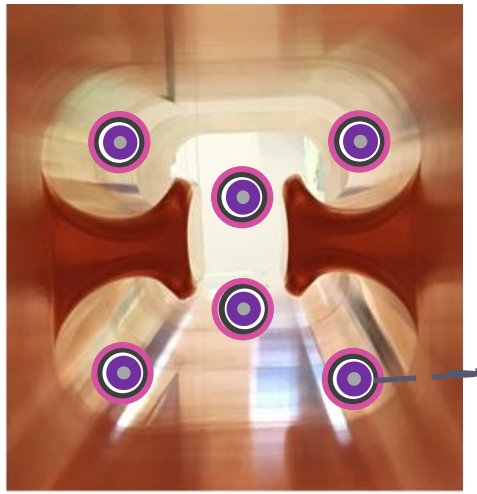


1 Defining the coating recipe

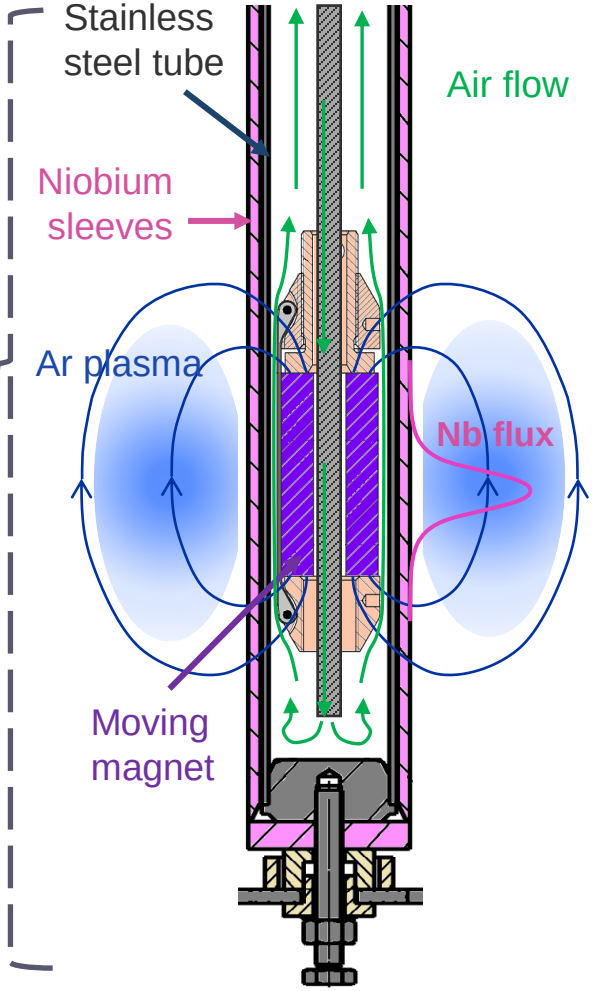
- **Six independent cylindrical magnetrons**
- **Cathode tubes along full cavity length**
- **Air-cooled movable magnets**
- **Bipolar HiPIMS technique in Argon**



Synchronized Voltage pulses applied to each cathode



F. Avino et al, TTC, 05.02.2020, Geneva



→ **Ionized niobium flux directed towards complex surface**

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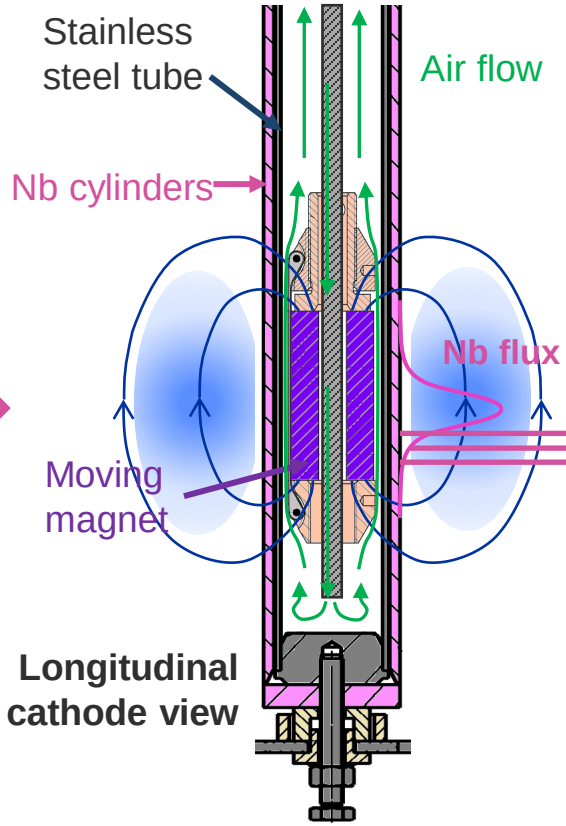
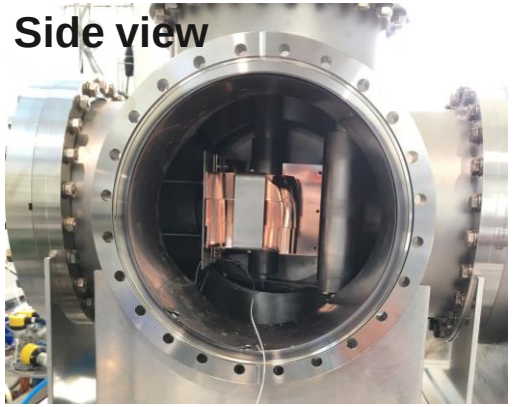
2. Coating testbench

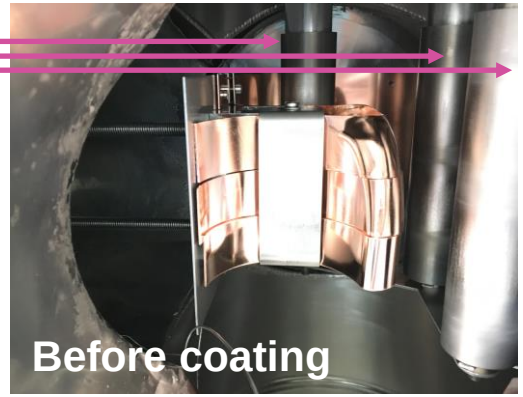
- **Validate pulsing, power, magnets for desired film uniformity and morphology**

Three cathode coating testbench

- **The six-way cross**







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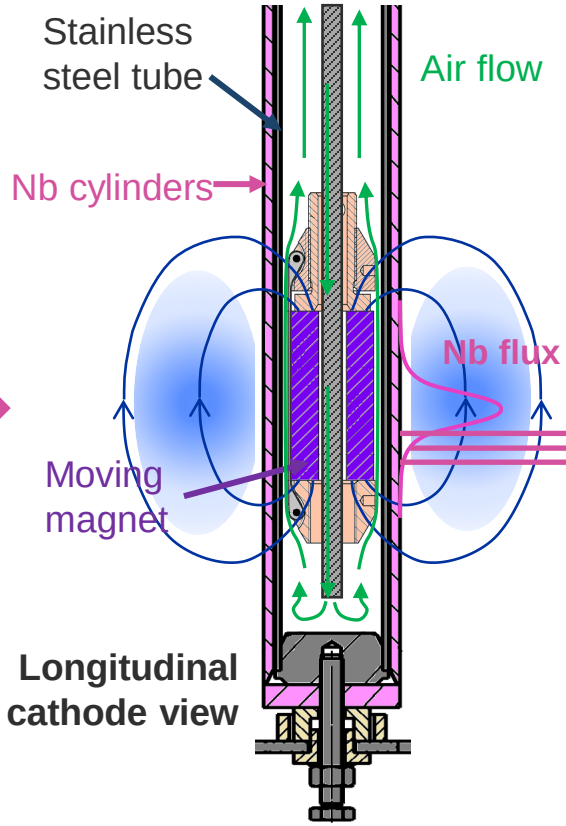

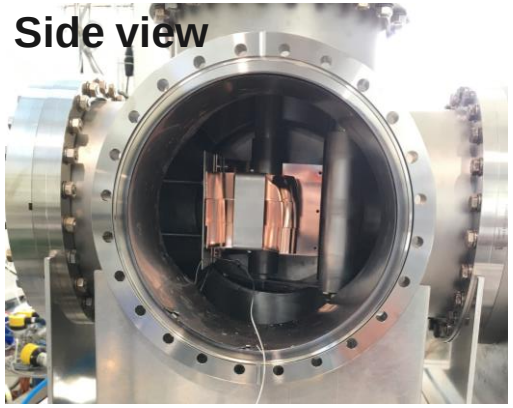

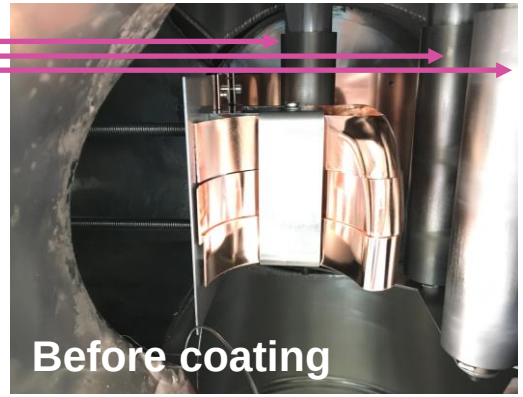

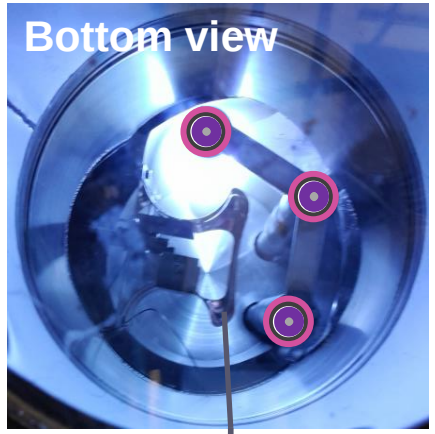

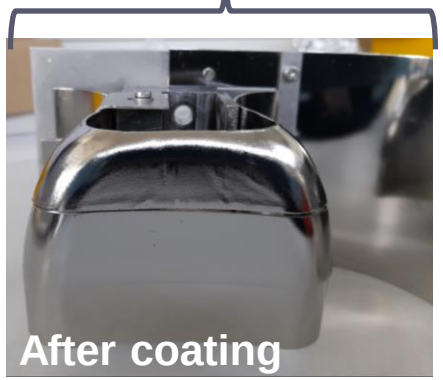

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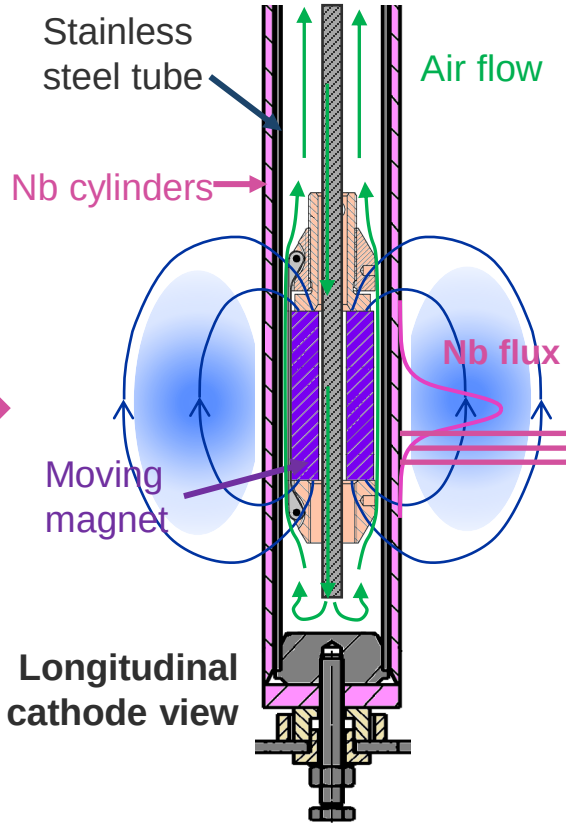

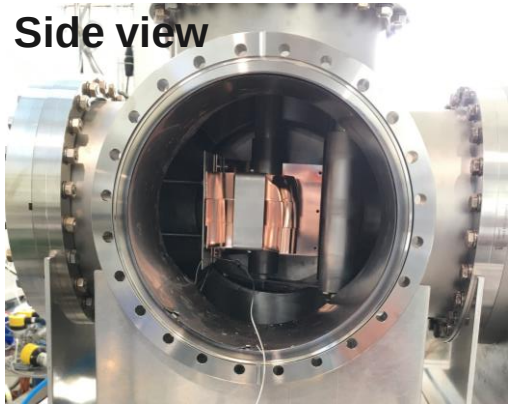

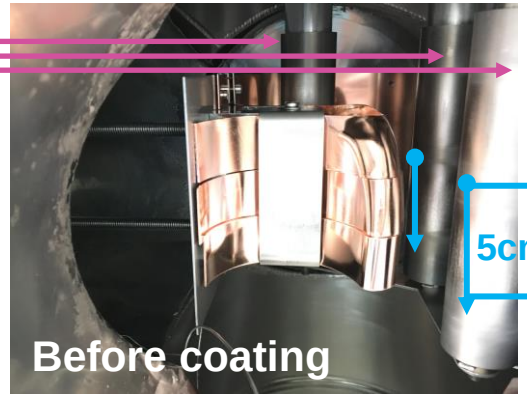

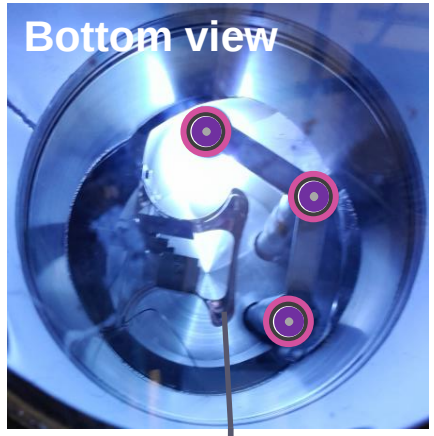

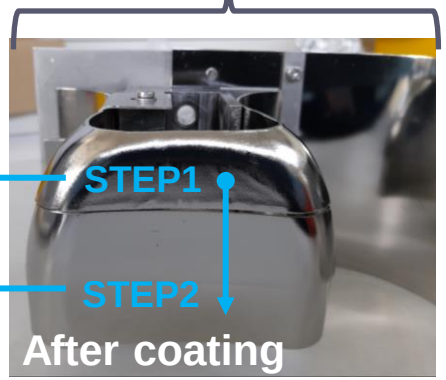

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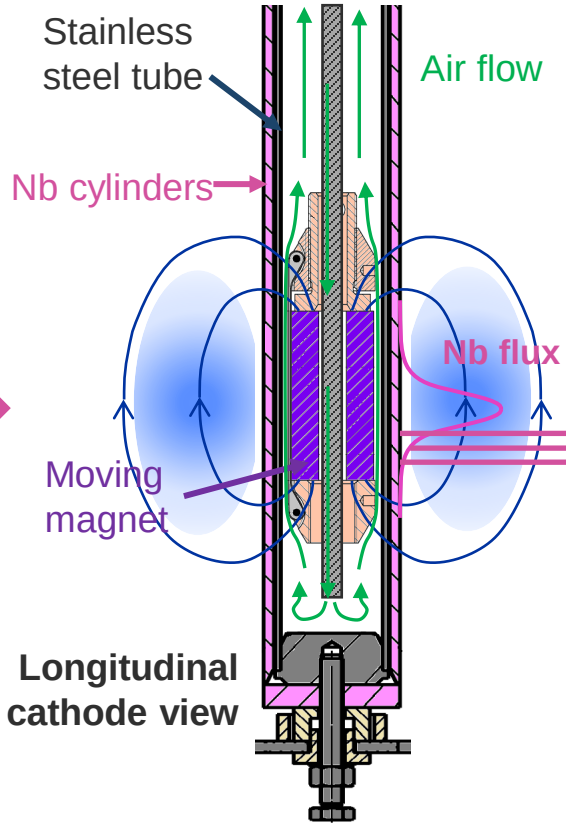

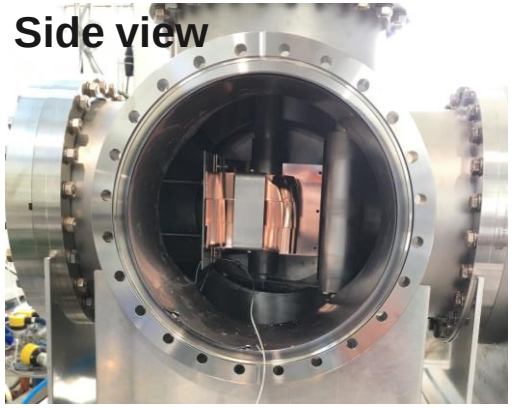

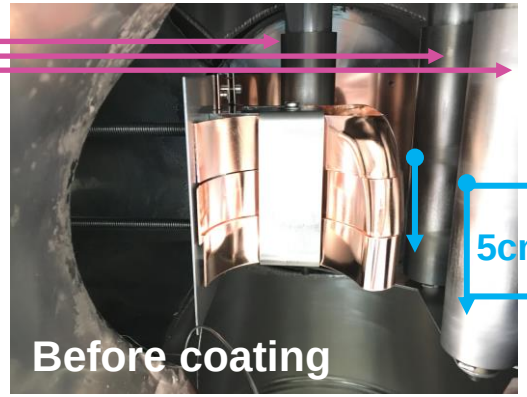

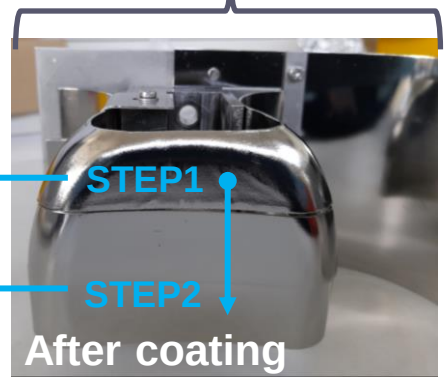

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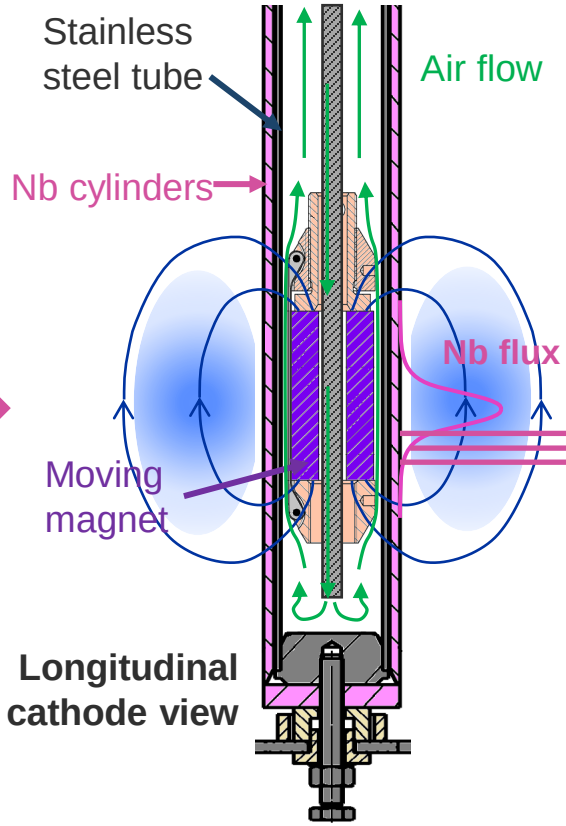

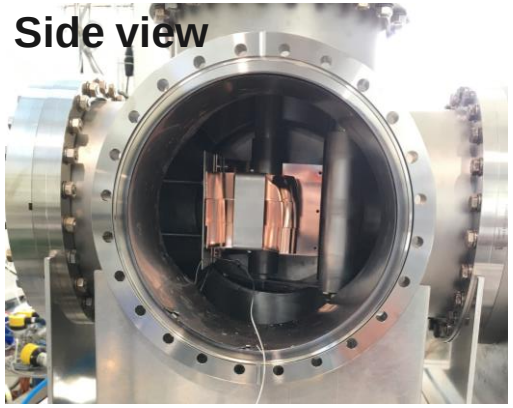

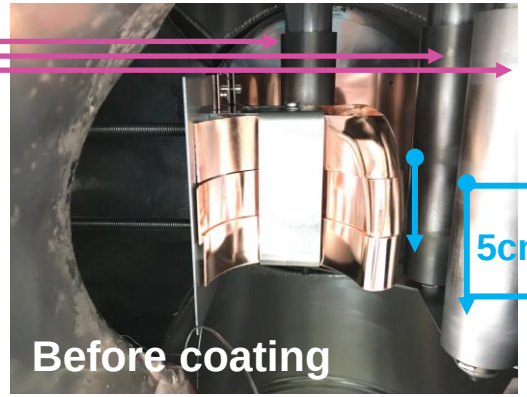

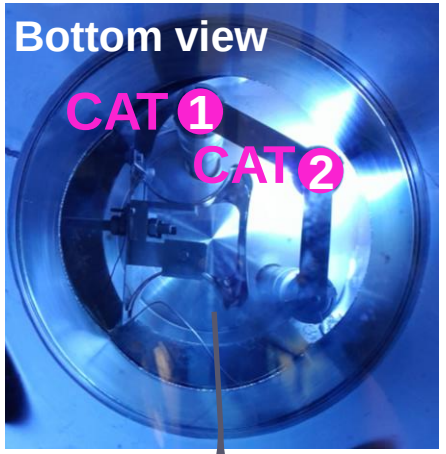

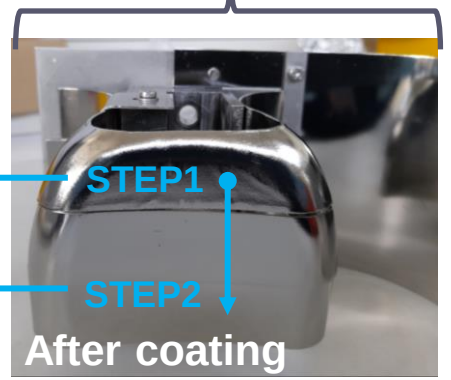

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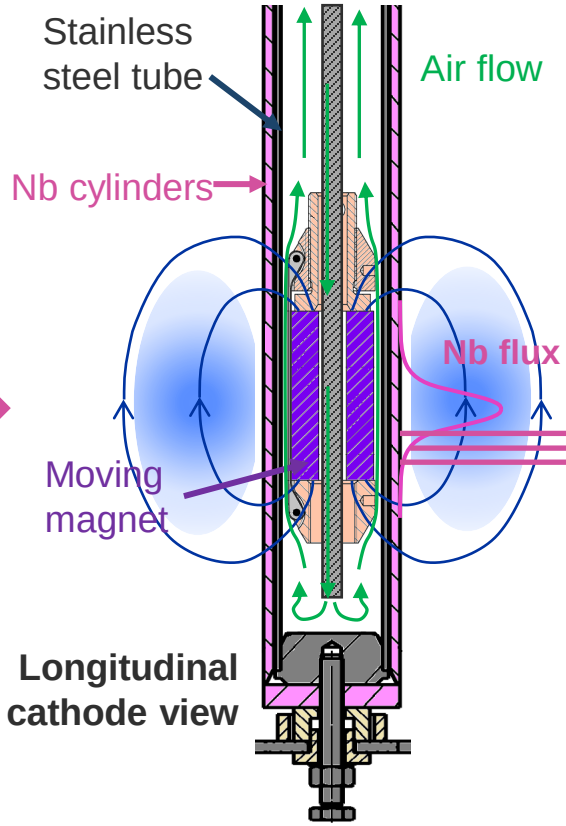

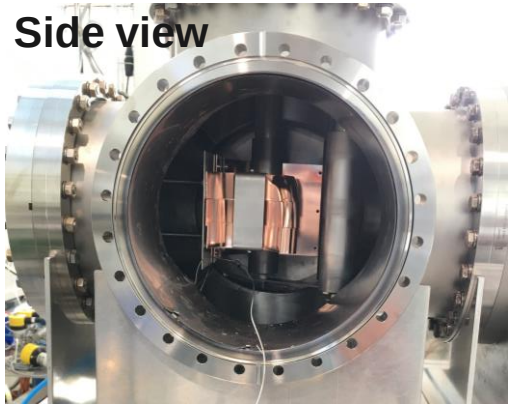

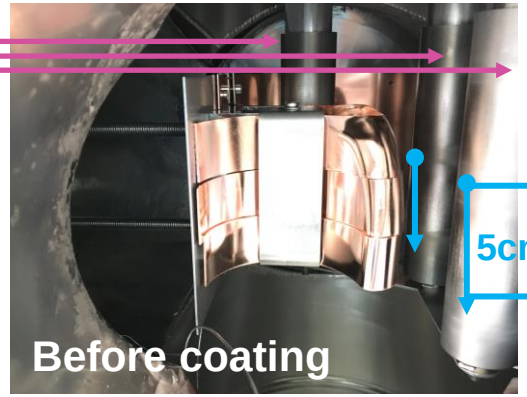

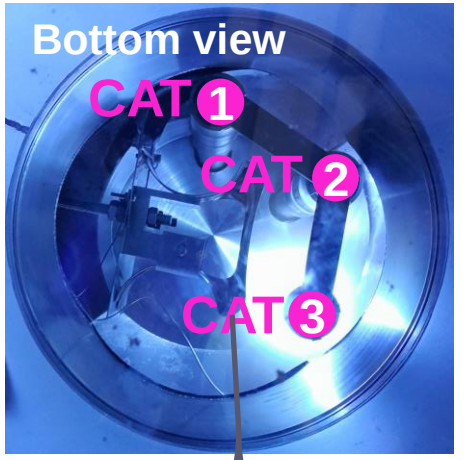

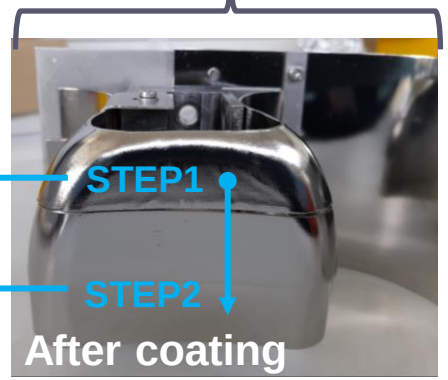

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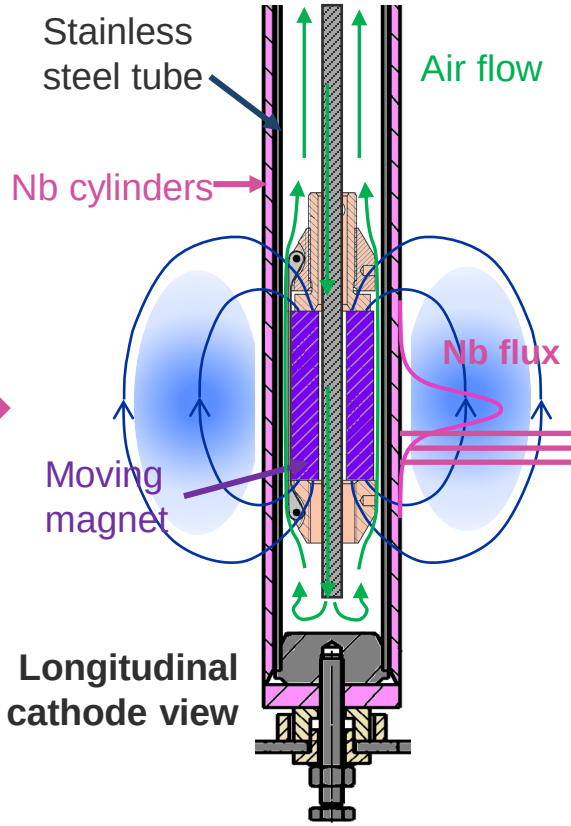
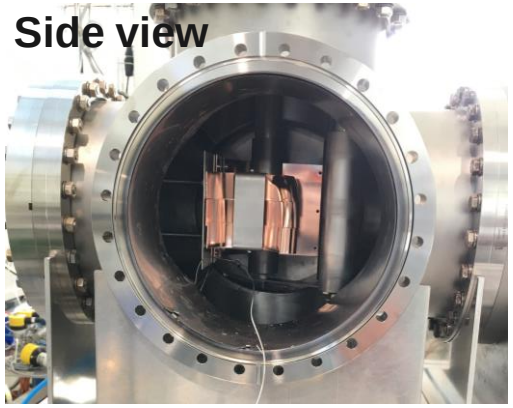
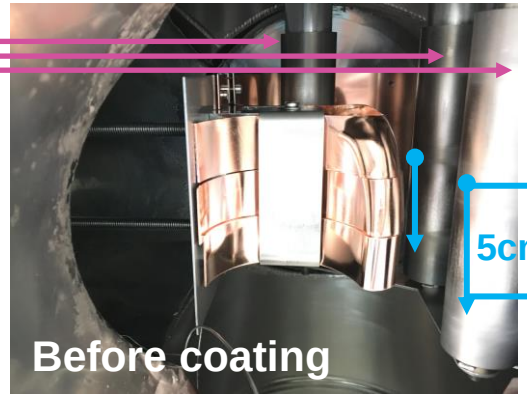
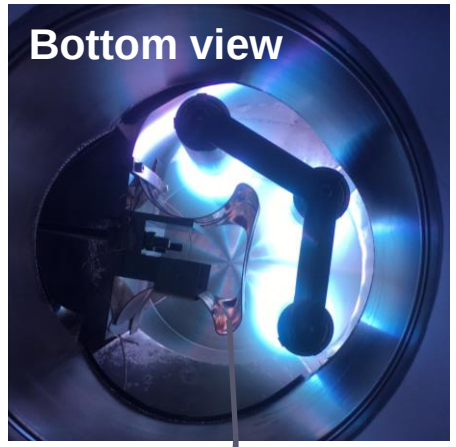
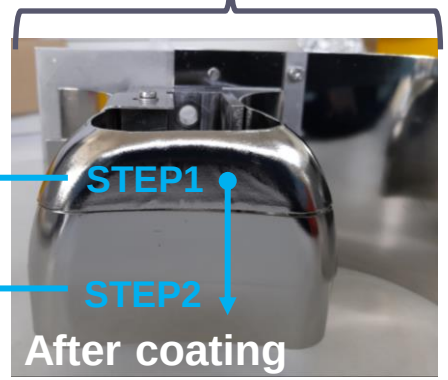








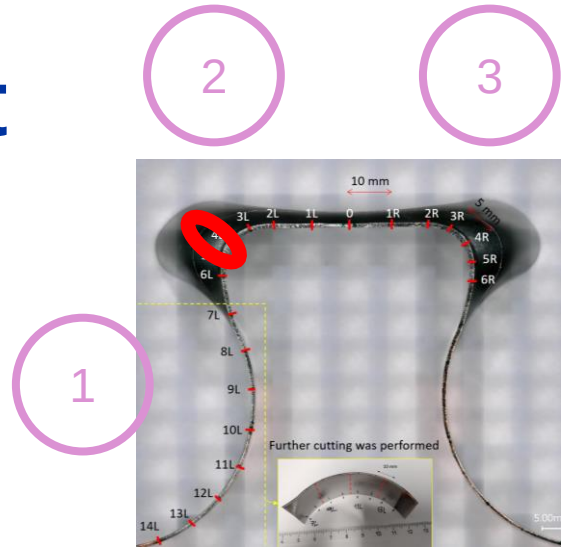


2. Thin film densification : RF hot spot

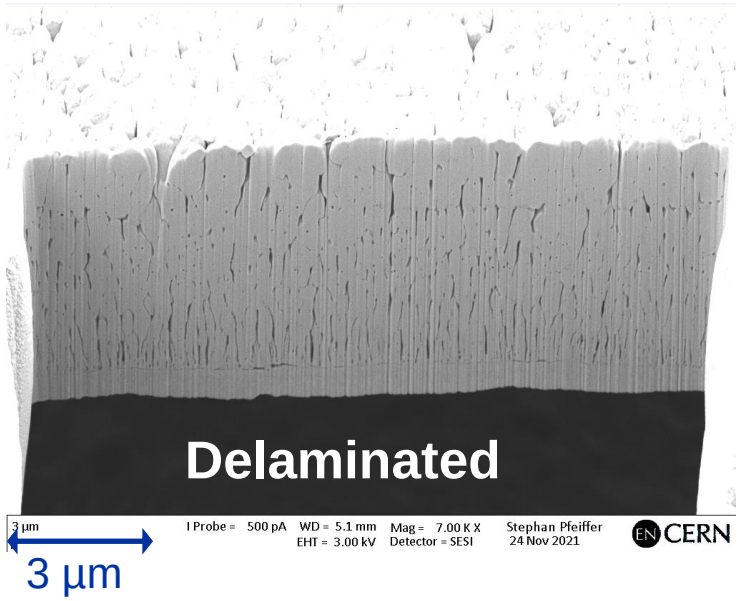
- **STRONG tilt along cathode axis and curve in plane**

→ **Film entirely porous and delaminated in DCMS**

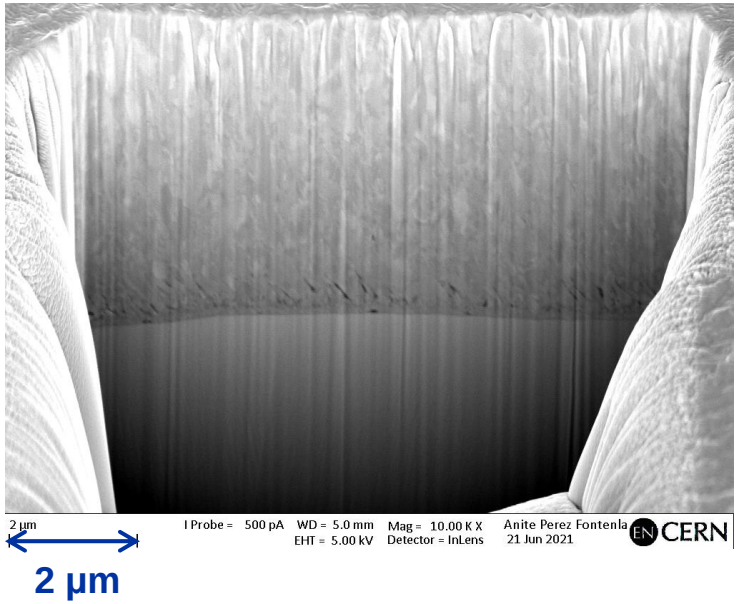
- **Still voids near substrate at 500W sequential Bipolar HiPIMS**



DCMS, parallel, 3x1kW



BP, HiPIMS sequential, 500W



F. Manke et al, HiPIMS Today, 22/03/2023

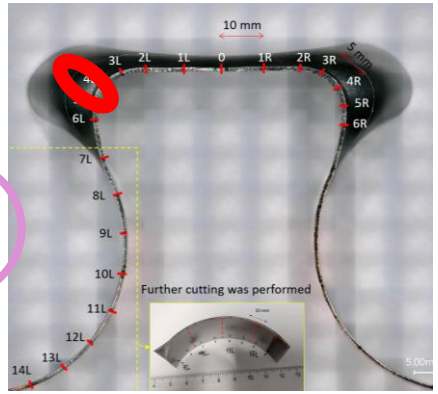
2. Thin film densification : RF hot spot

- **STRONG tilt along cathode axis and curve in plane**

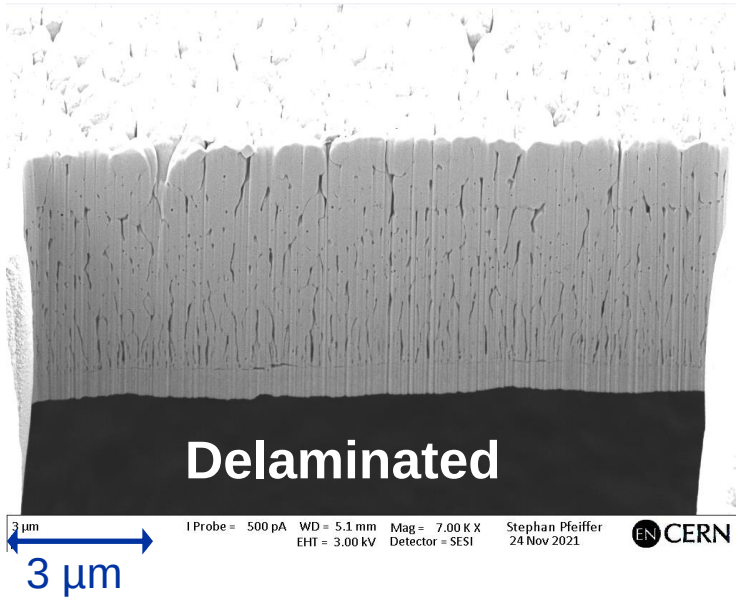
→ **Film entirely porous and delaminated in DCMS**

- **Dense films achieved for 1kW Bipolar HiPIMS**

→ Preparing publication of 3D sample results

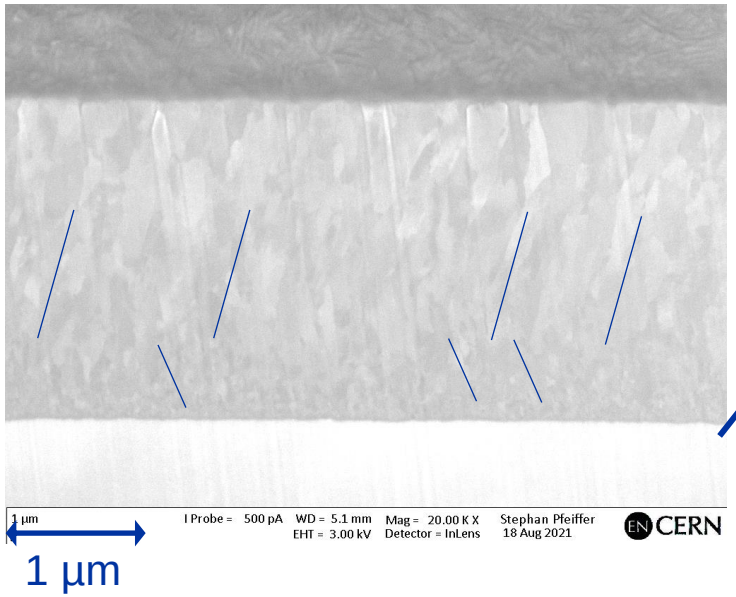


DCMS, parallel, 3x1kW



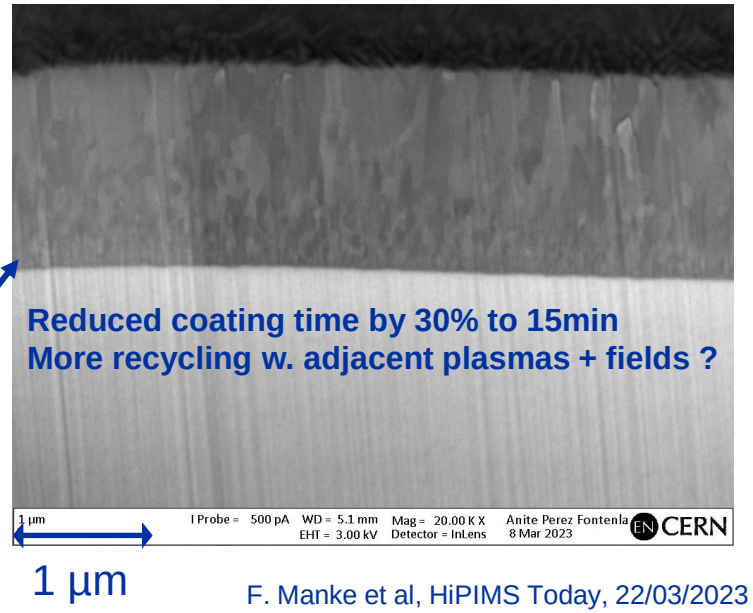
3 µm

BP HiPIMS, sequential, 1kW



1 µm

BP HiPIMS, parallel, 3x1kW



1 µm

F. Manke et al, HiPIMS Today, 22/03/2023

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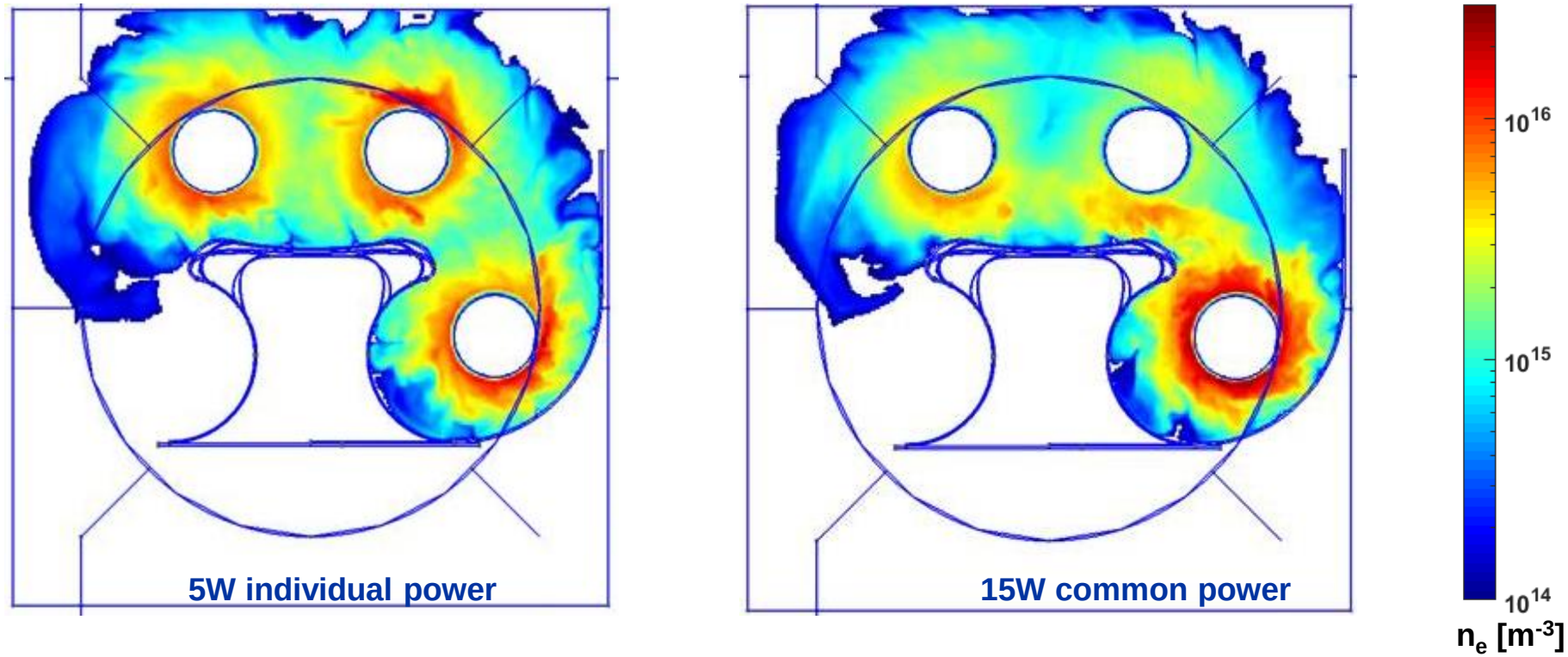
3. Simulations: mock-up geometry

Simulation: T. Richard

→ **Confirms importance of individual powering + <u>insulation</u>**



→ **Breakdown voltage of -270V at 15W power matches experiment within 10%**

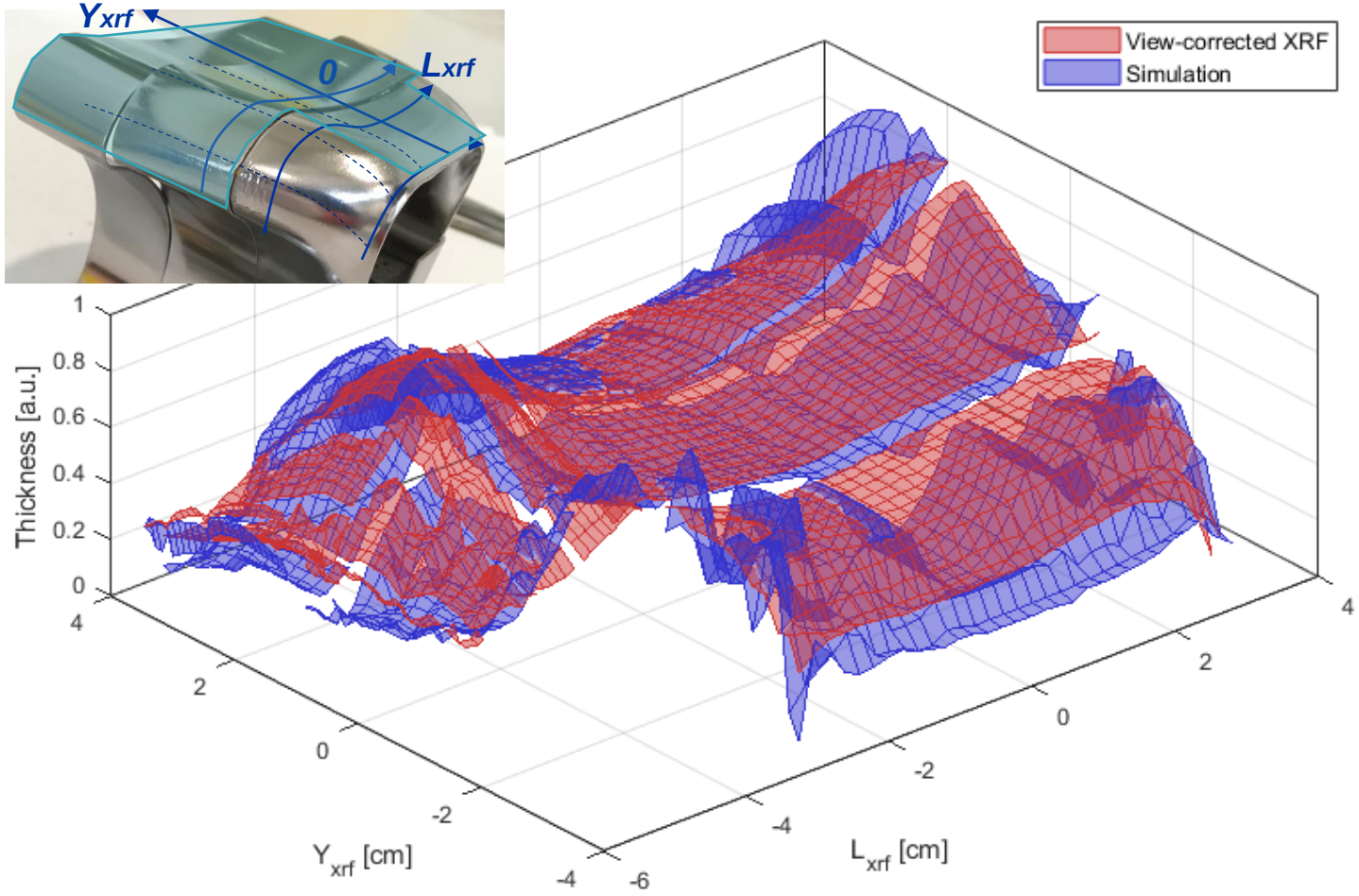
A. Pflug, DSMC/PIC-MC Code Documentation, **Fraunhofer IST, Braunschweig**, Germany,, https://simulation.ist.fraunhofer.de/doku.php?id=start

3. Benchmarking of XRF thickness measurements

- **Obtain Nb deposition profile from subsequent MC transport simulation**
- **Compare to experimental thickness measurements with XRF**

→ **Use synthetic diagnostic for post-processing in MATLAB**

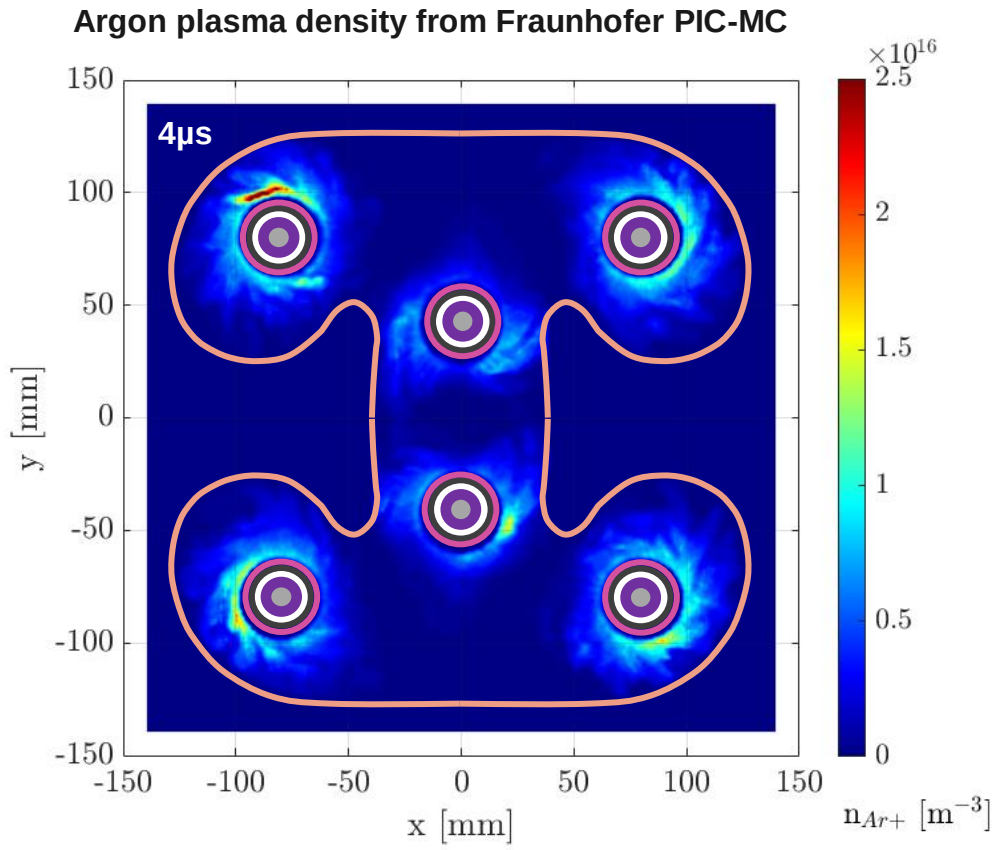
→ **Overall strong agreement (within ≈ 20%), pending local MC counting errors and slight shift of source**



F. Manke et al, PLATHINIUM, 09/2021

3. Full WOWCC simulations

- **PICMC / DSMC simulations to establish cross-sectional Nb deposition profiles**

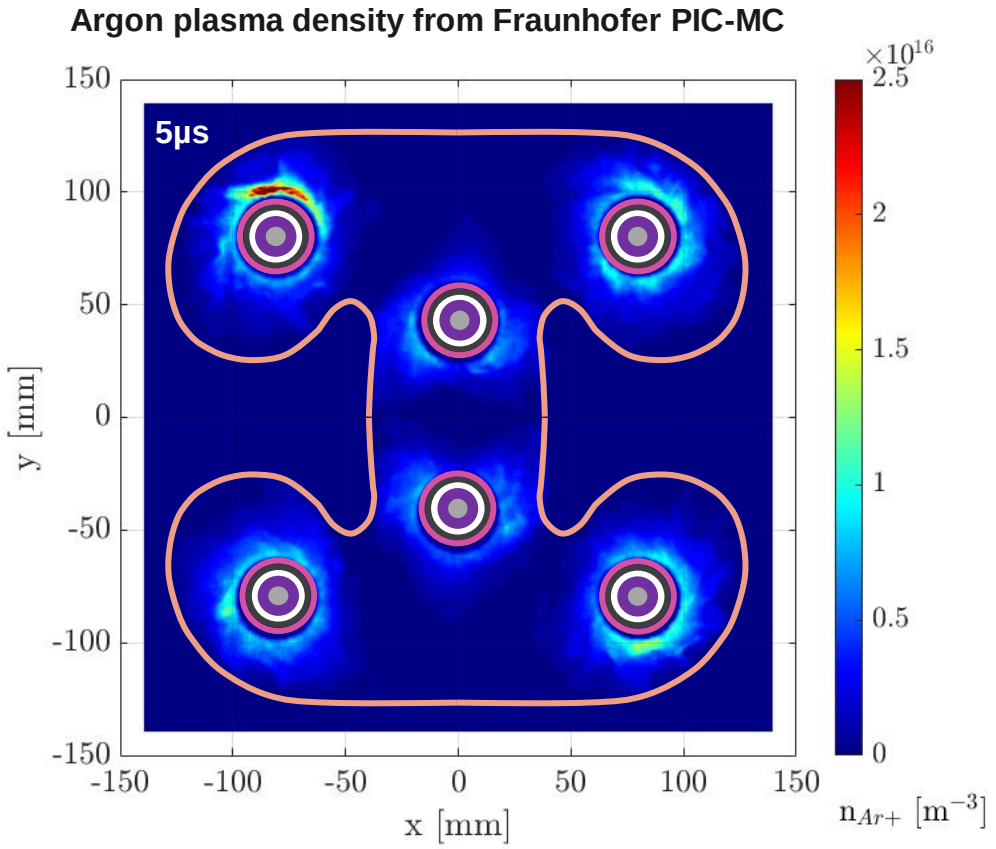


Simulation: T. Richard

F. Manke et al, 18th PSE, Erfurt 2022

3. Full WOWCC simulations

- **PICMC / DSMC simulations to establish cross-sectional Nb deposition profiles**



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F. Manke et al, 18th PSE, Erfurt 2022

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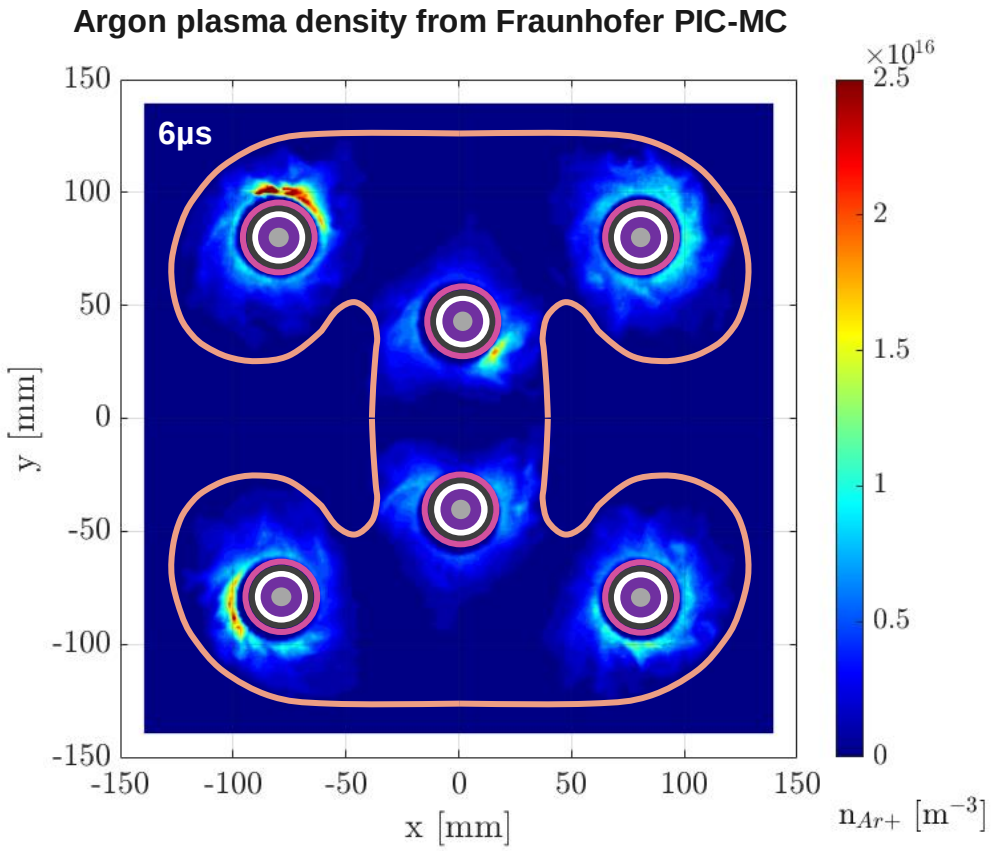

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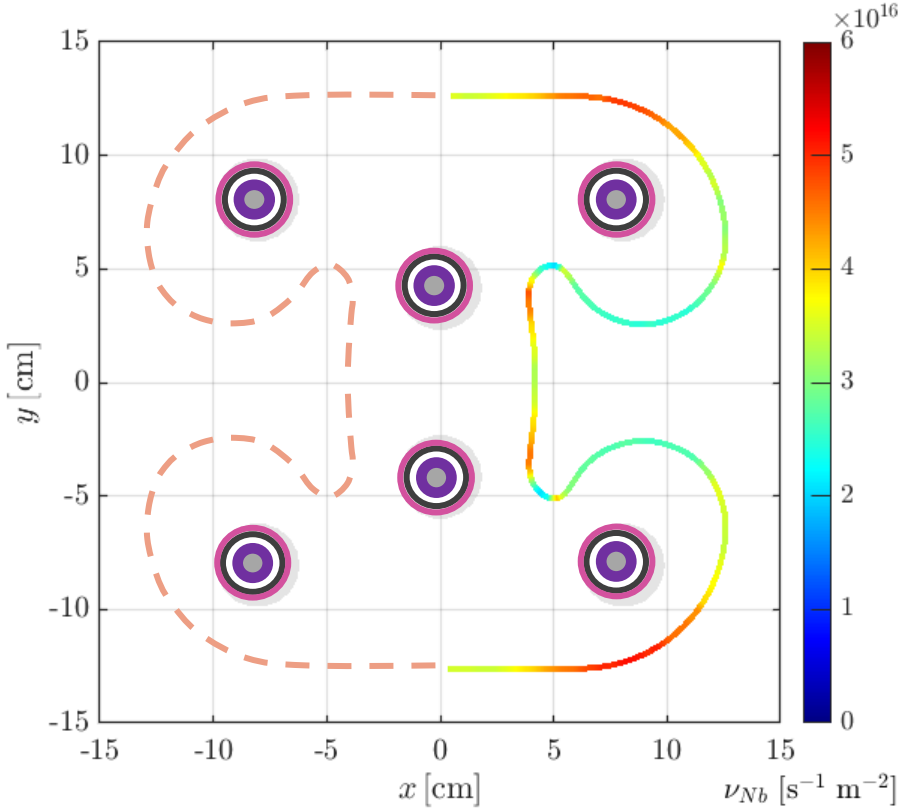
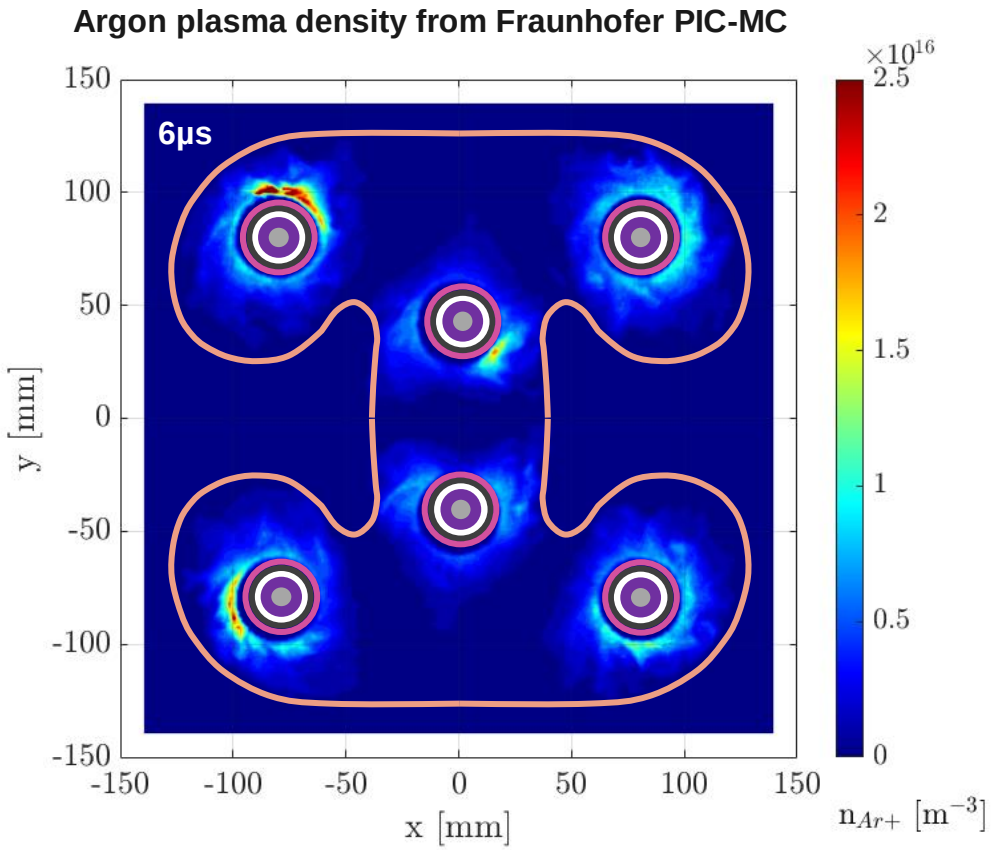
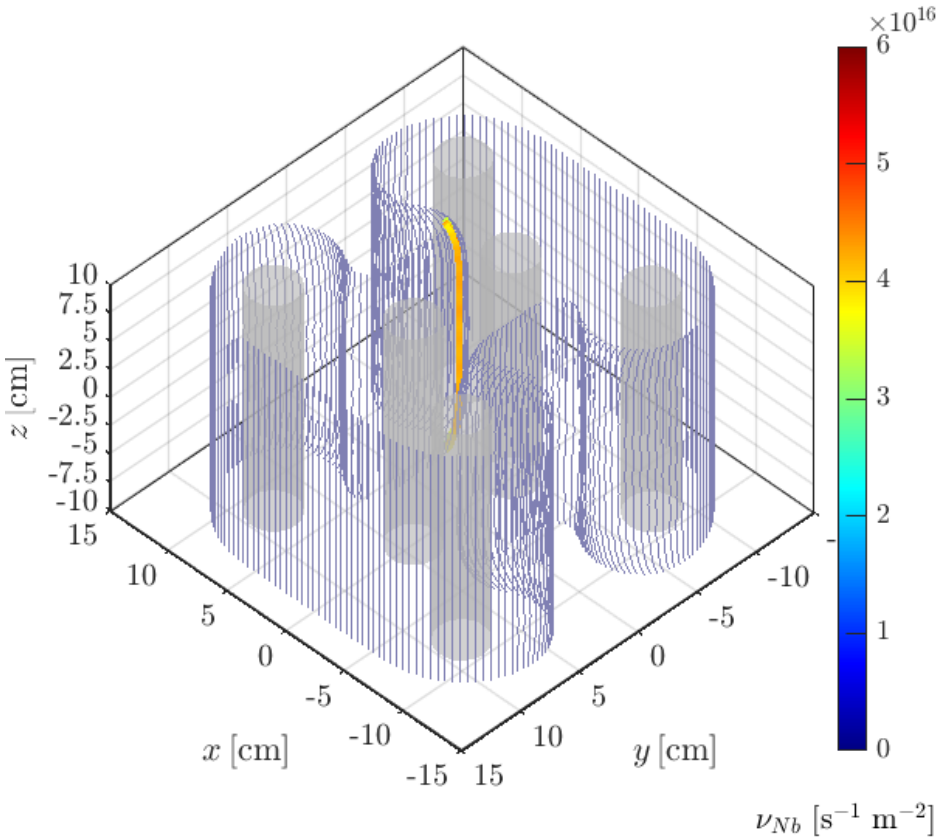


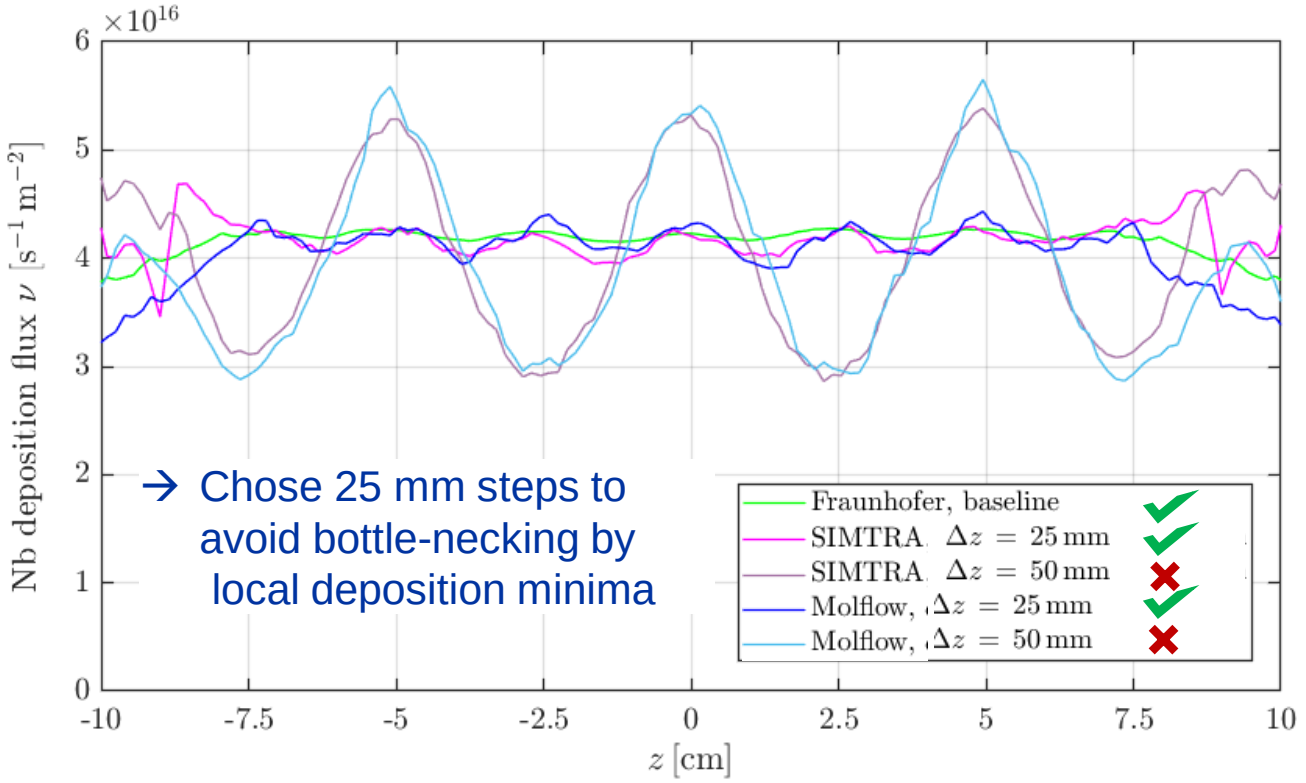


→ **Baseline for benchmarking faster transport codes, such as *Molflow***

3. Process planning: Magnet step size

- **Deposition profile across region of strongest variations + RF hot-spot**





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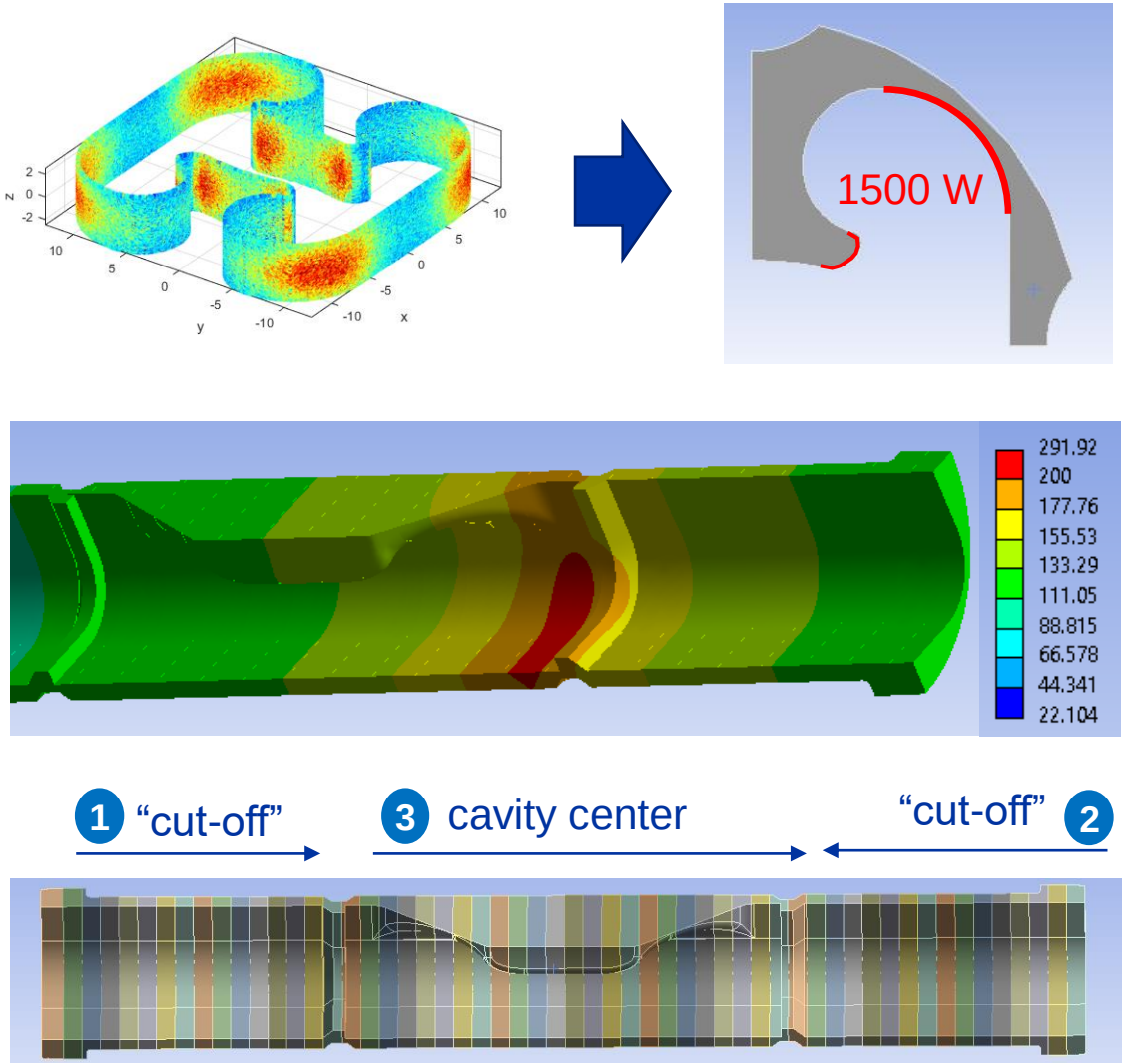
3. Heat load simulations

ANSYS simulations by L. Baudin

- ***Molflow / Synrad* heat deposition profile**
- ***ANSYS* simulations of ¼ WOWCC**
- **Process steps:**
  - **3×5min coating with 200s breaks each, 2.5cm steps along the cavity**



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3. Cooling requirements

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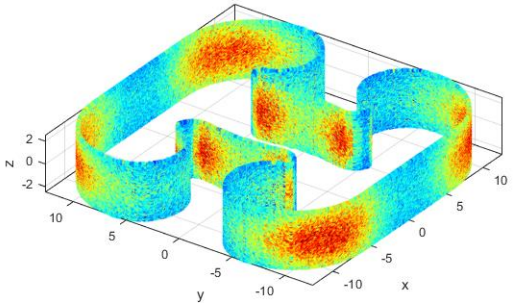

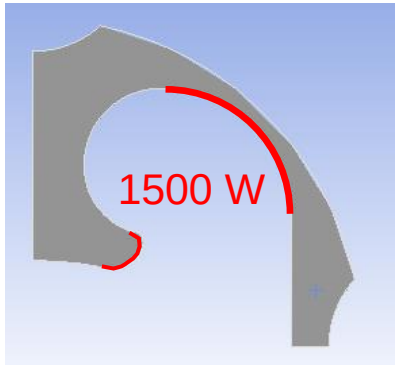

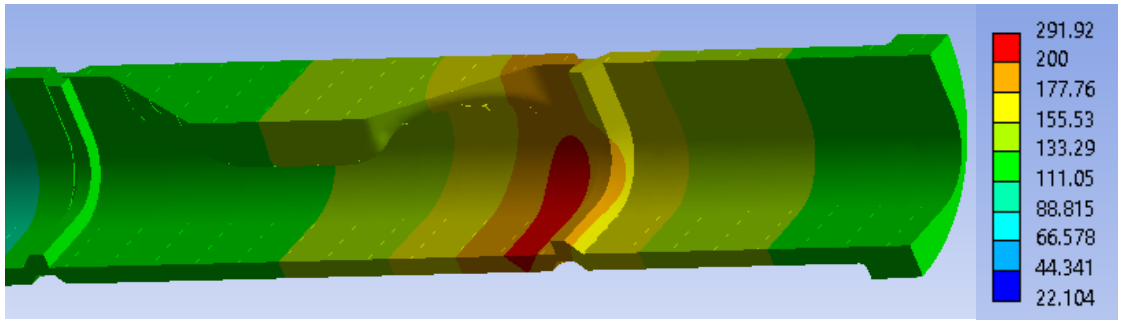

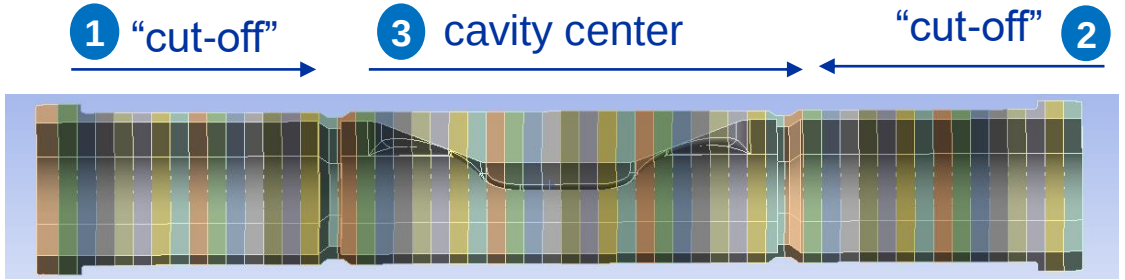

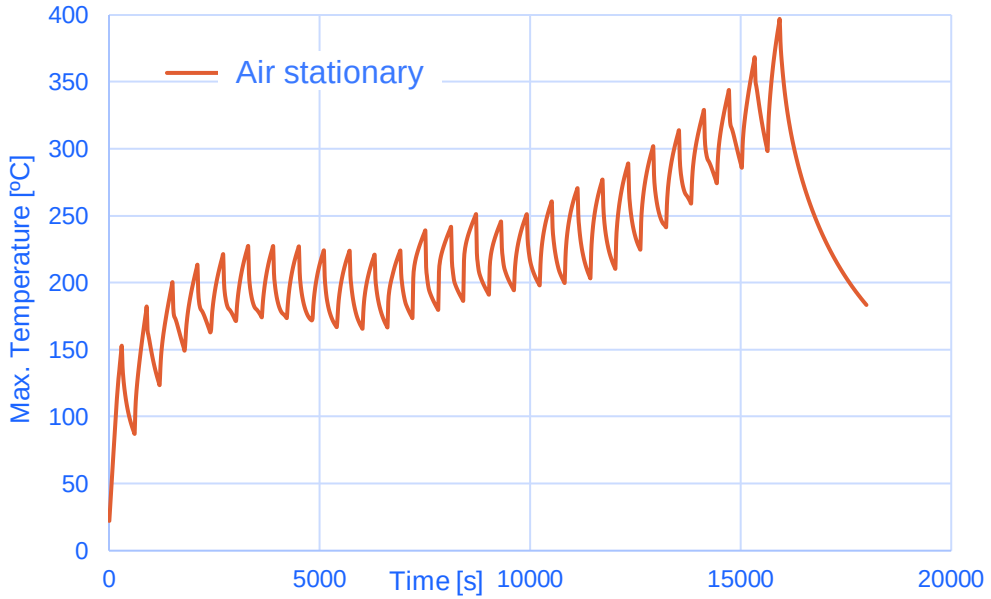

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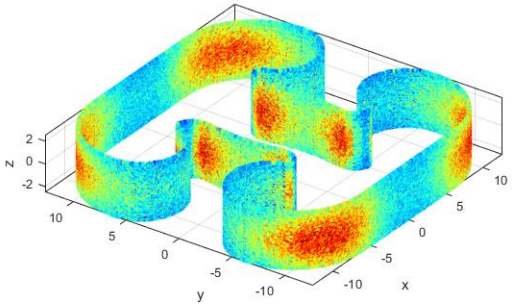

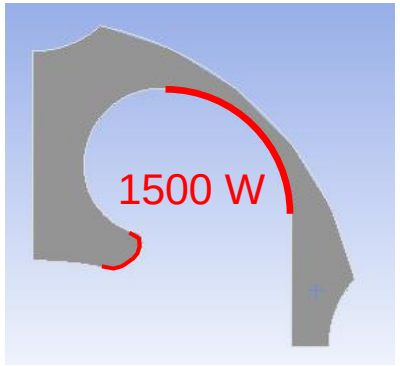

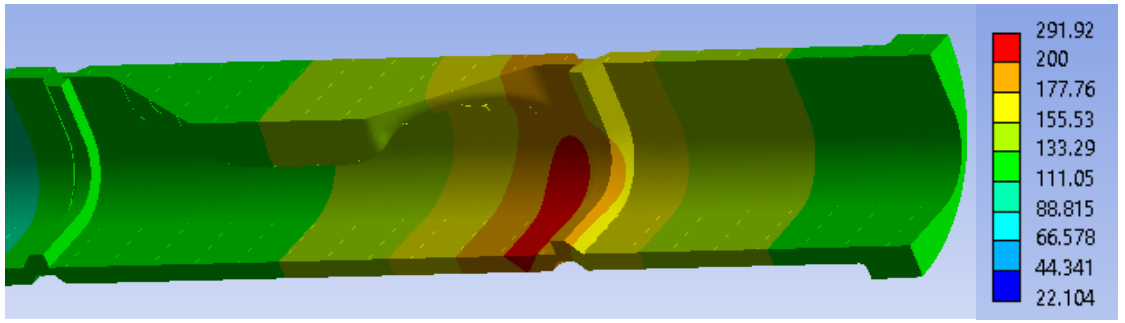

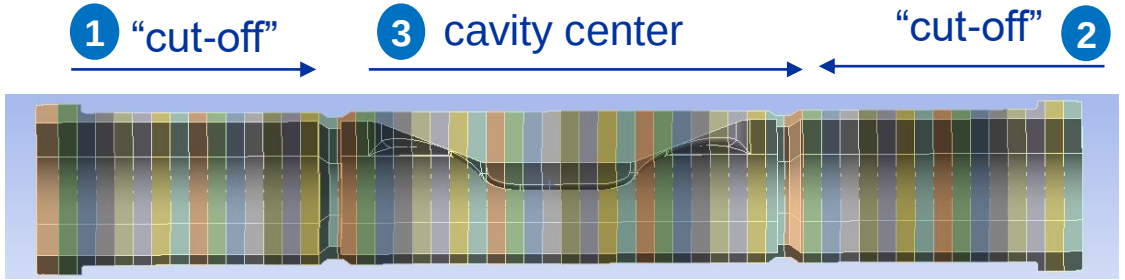

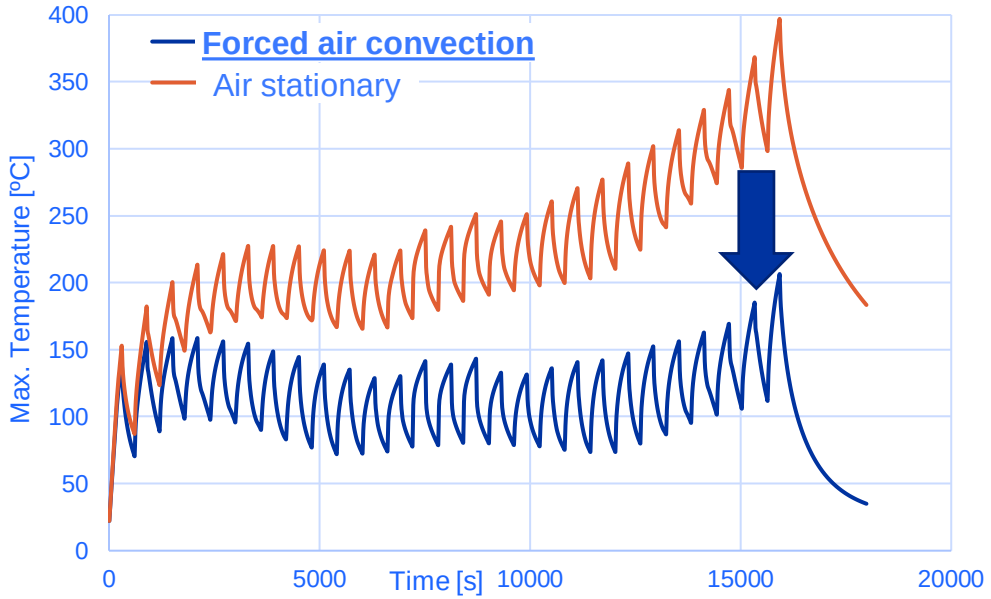

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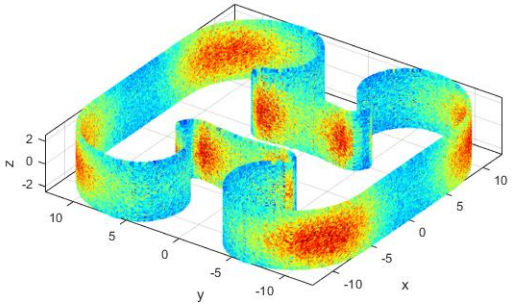
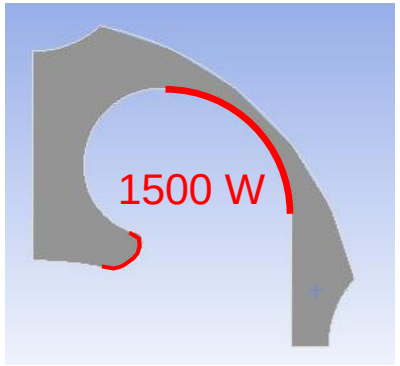
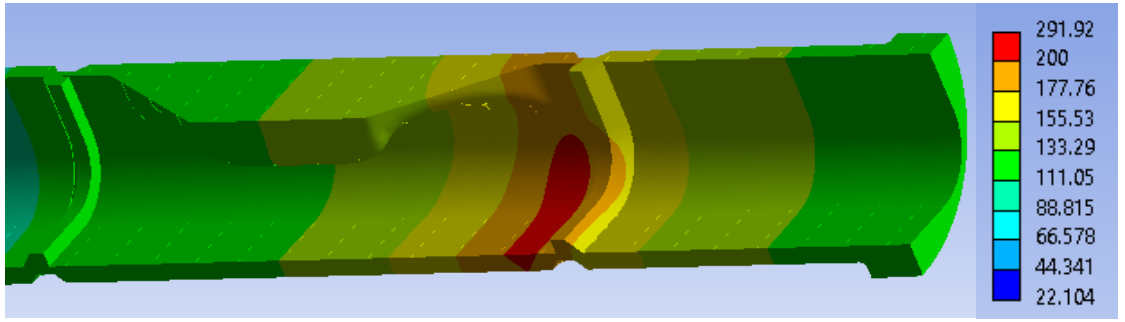
3. Cathode power limits

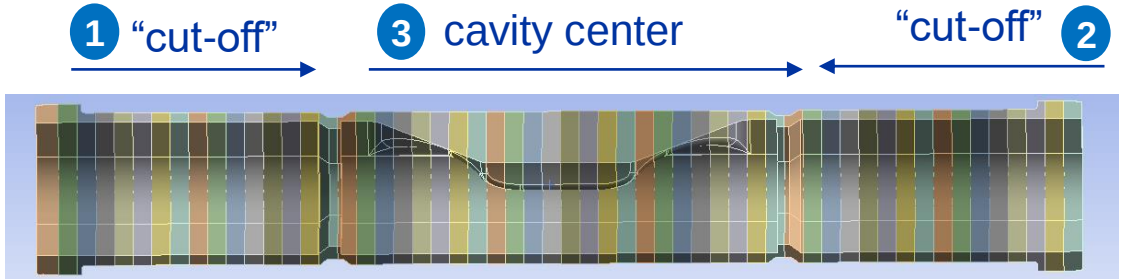
ANSYS simulations by L. Baudin

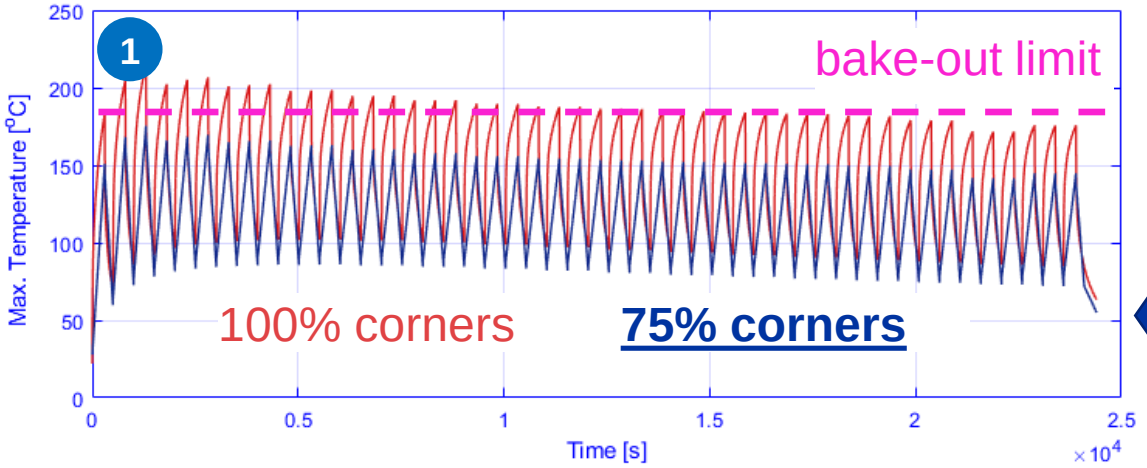
- ***Molflow / Synrad*** **heat deposition profile**
- ***ANSYS*** **simulations of ¼ WOWCC**
- **Process steps:**
  - **3×5min coating with 200s breaks each, 2.5cm steps along the cavity**
- **Forced air cooling required**
- **Corner cathodes at 75% power in cut-offs**











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Outline

1. The Wide-Open Waveguide Crab Cavity
2. Coating recipe validation
3. Process planning
4. **Status at full scale**
5. The last steps

4. Infrastructure upgrade

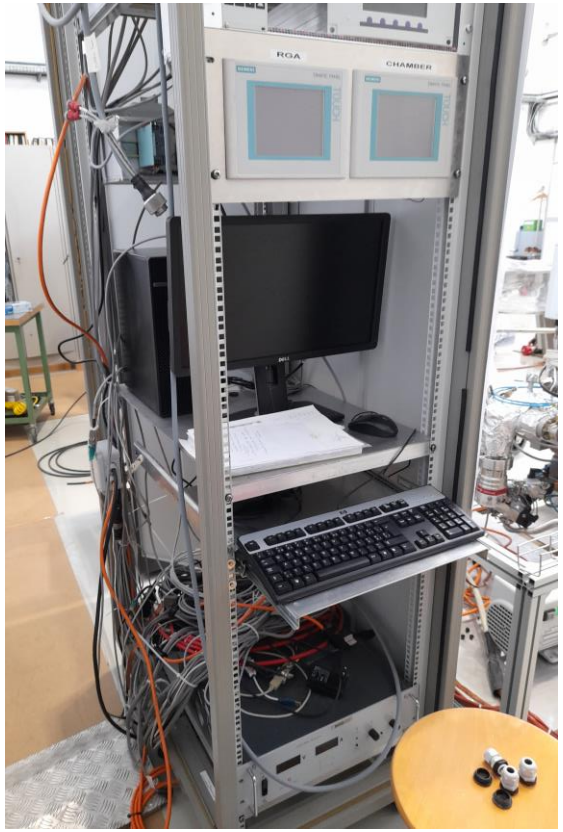
- **Electrical works completed on racks for PC and power supplies**
- **Compressed air connections and argon supply ready**
- **Next: Commissioning of pumping group + bake-out jackets**

→ STILL waiting: 6x HiPIMS power units → lab test in June (?)

WOWCC bake-out jacket set (PTFE coated)

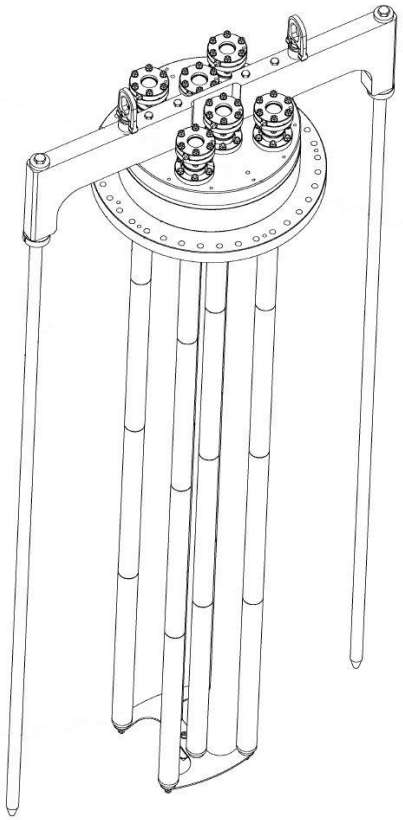
Cabling the power supply rack

Control PC for pumps, bake-out,
Later: motion, cathodes

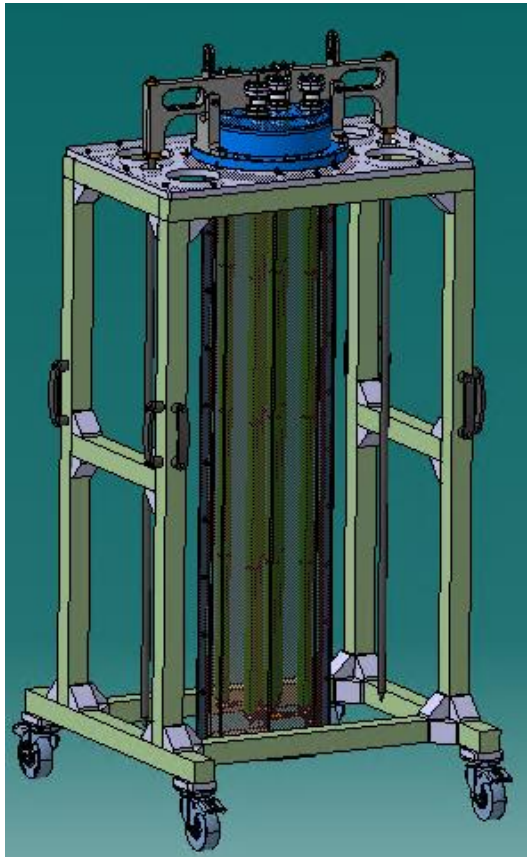


4. Cathode assembly and storage

Cathode assembly needs support and storage



Chariot Design



Courtesy G. Villiger

Implementation

F. Manke et al, 6th CERN SRF Workshop, 02/2023

4. The equipment is “teething”

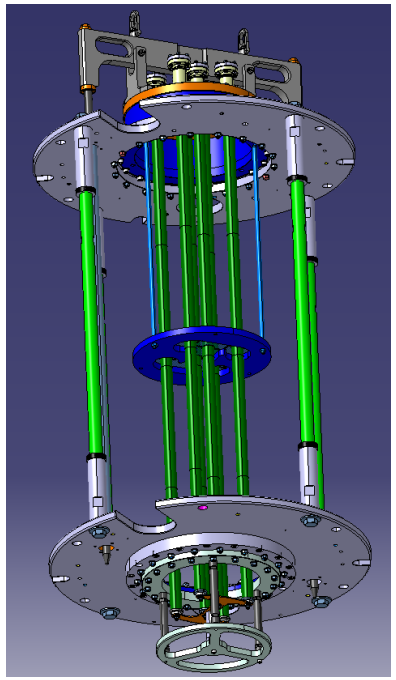
Assessment

Finalization

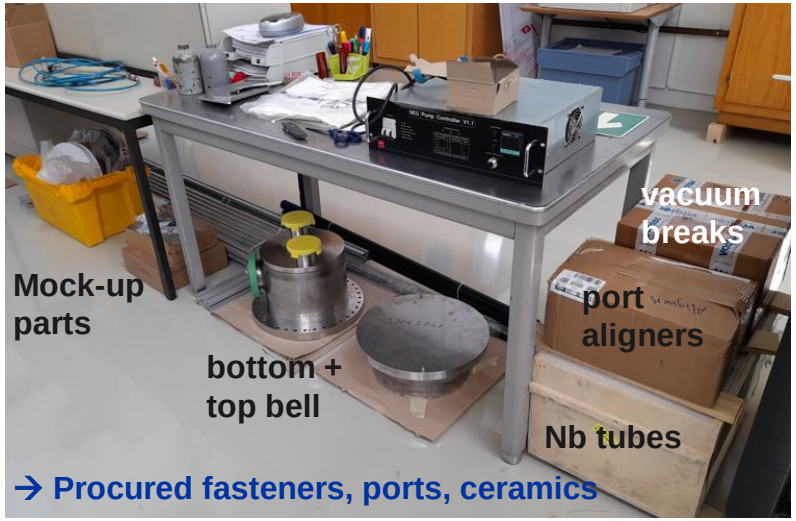
Regular use

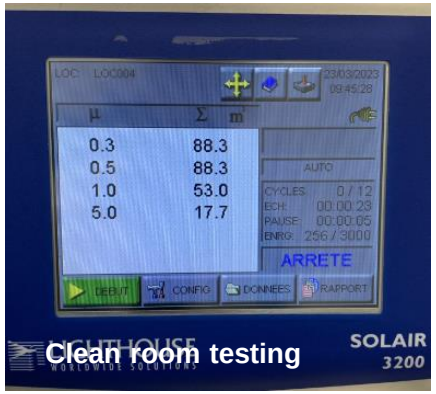
4. Coating set-up assembly

Design with "Mock-up" cavity → **Fabrication** → **Surface Preparation**



Reception of main components from AP





Courtesy: T. Mikkola, G. Villiger, P. Naisson and the AP team

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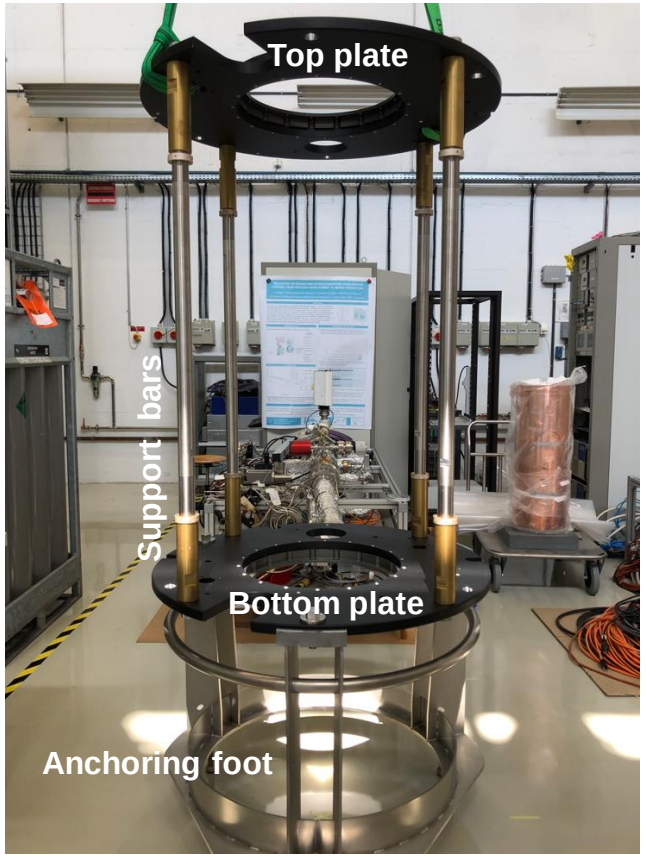
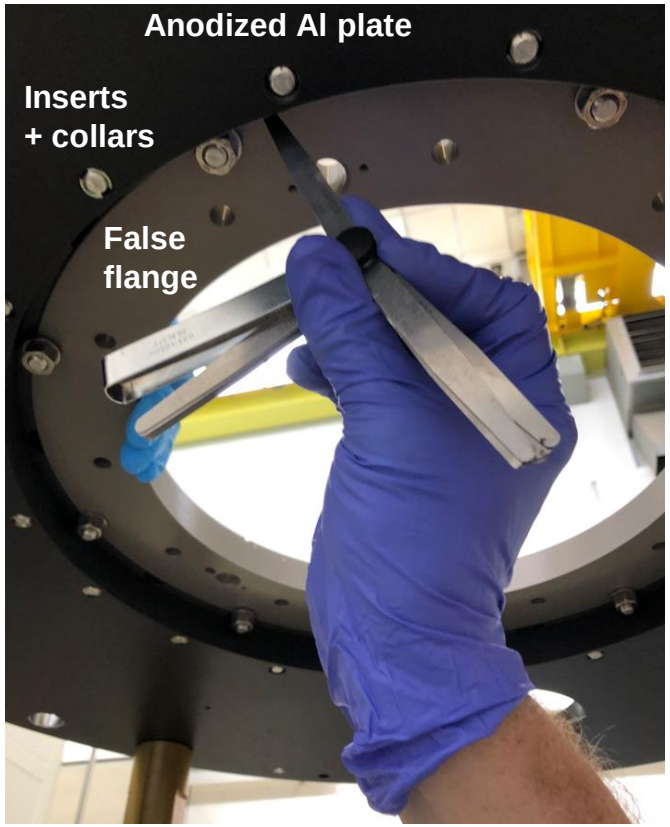
4. Mock-up cavity assembly

Cavity frame on dedicated foot → **Stringent mutual alignment** → **Guides and cavity sections**

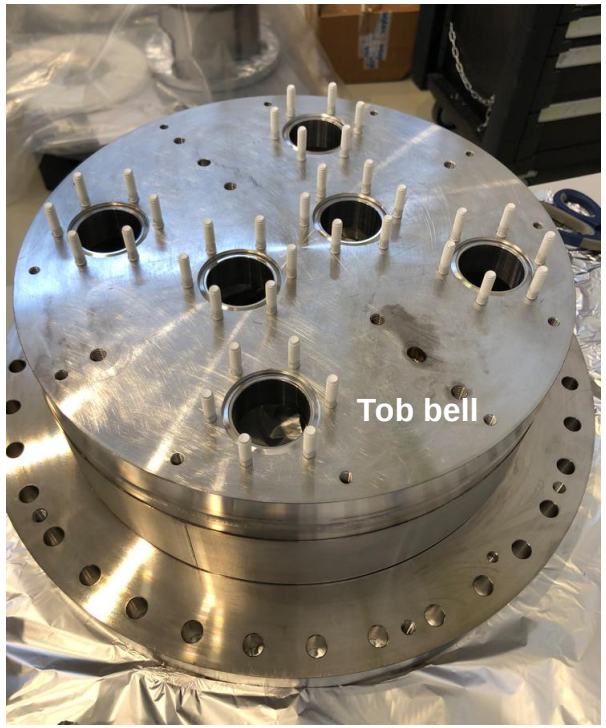




Courtesy: G. Péchaud, A. Cudré-Mauroux, P. Garritty, A. Macpherson

4. Cathode assembly

Top-bell assembly → **Lifting tool qualification** → **Cathode mounting**



Courtesy: G. Péchaud, A. Cudré-Mauroux, P. Garritty, L. Colly, S. Barrière

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Top-bell assembly → **Lifting tool qualification** → **Cathode mounting**

Courtesy: G. Péchaud, A. Cudré-Mauroux, P. Garritty, L. Colly, S. Barrière

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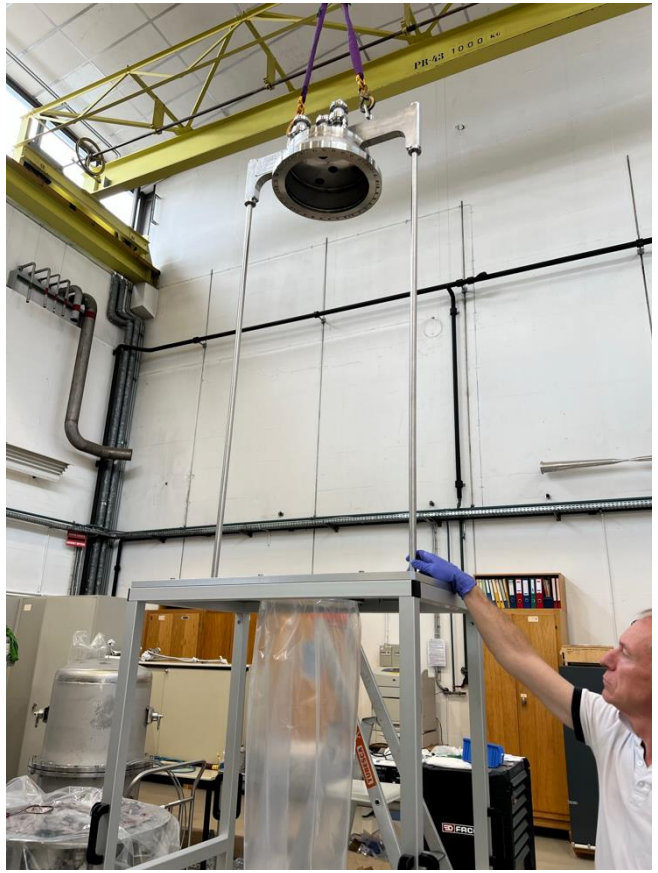
Top-bell assembly

Lifting tool qualification



Cathode mounting

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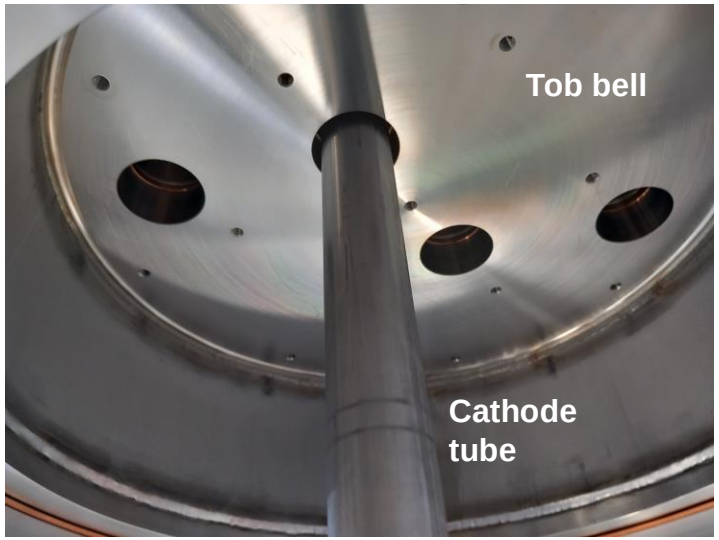

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Top-bell assembly

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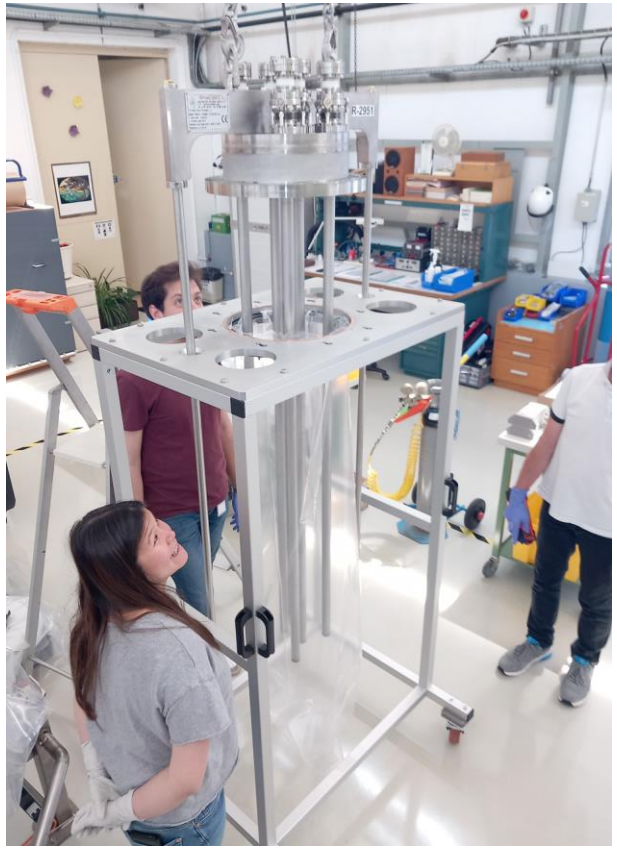
Courtesy: G. Péchaud, A. Cudré-Mauroux, P. Garritty, L. Colly, S. Barrière

4. Cathode insertion test

Removal from chariot → **Alignment with guiding rails** → **Lowering into mock-up**



Courtesy: G. Péchaud, A. Cudré-Mauroux, M. Chiodini

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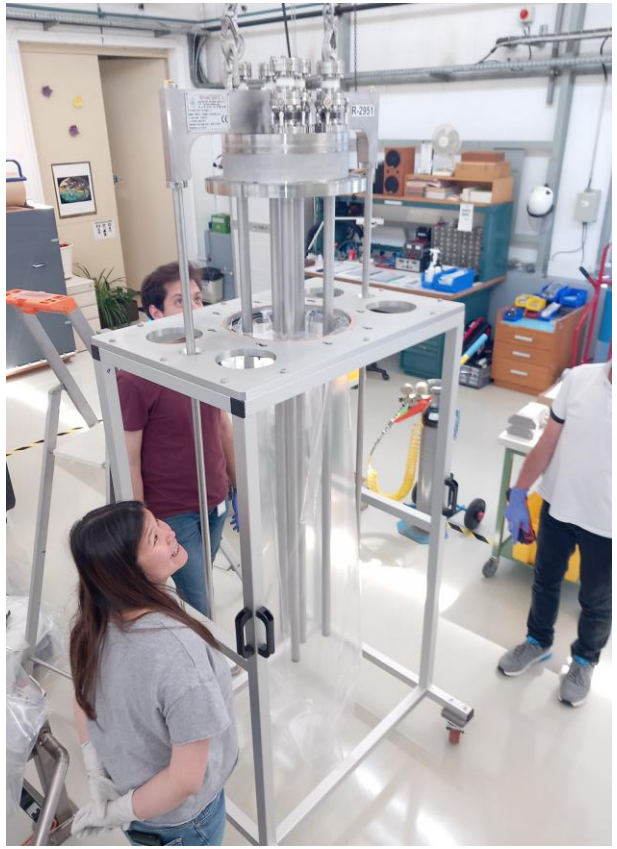
Removal from chariot



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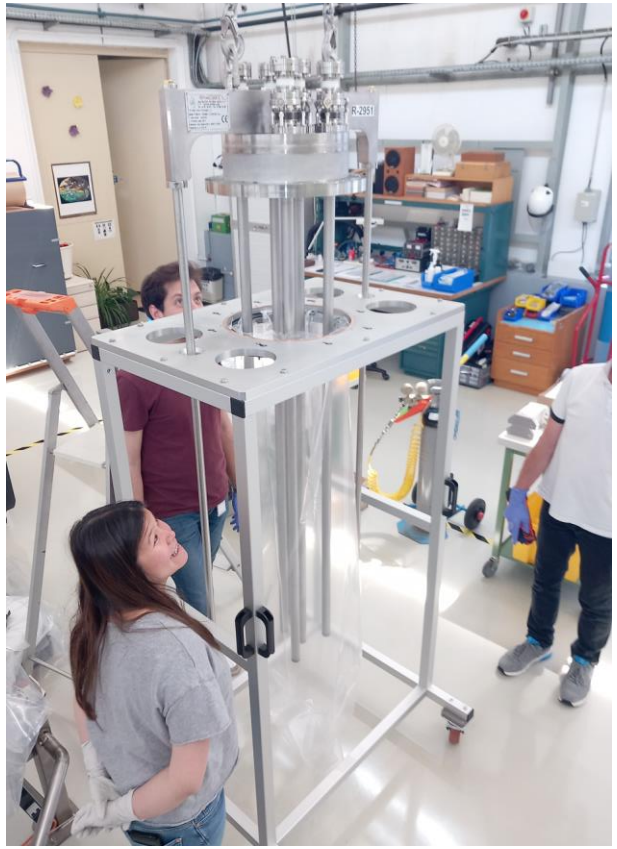

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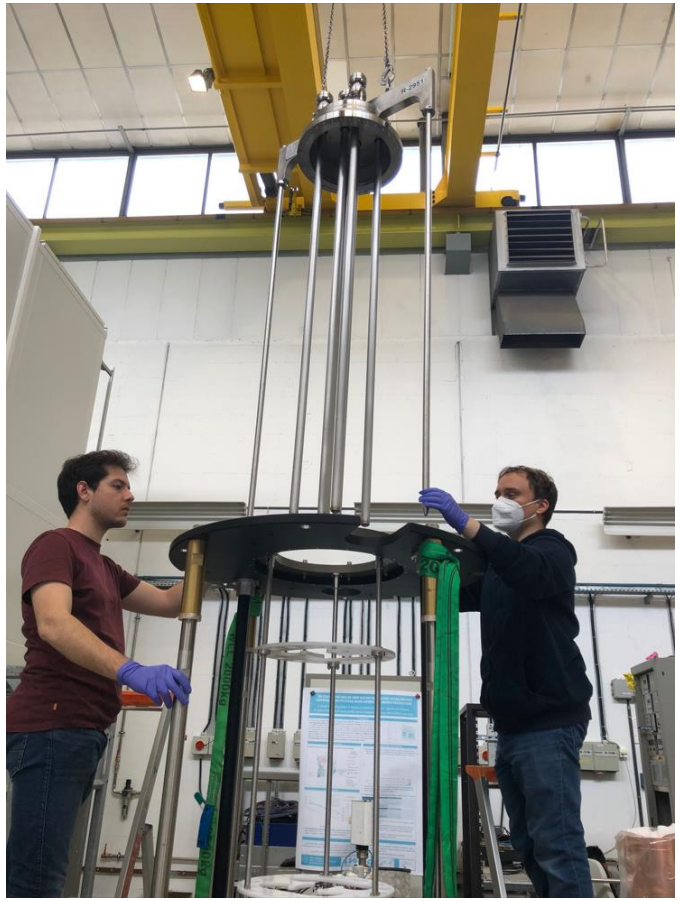

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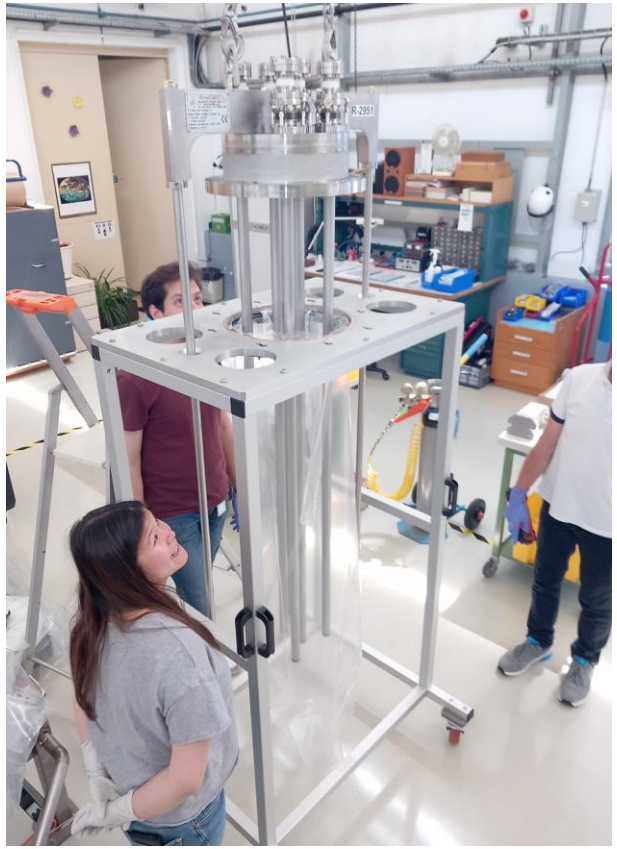

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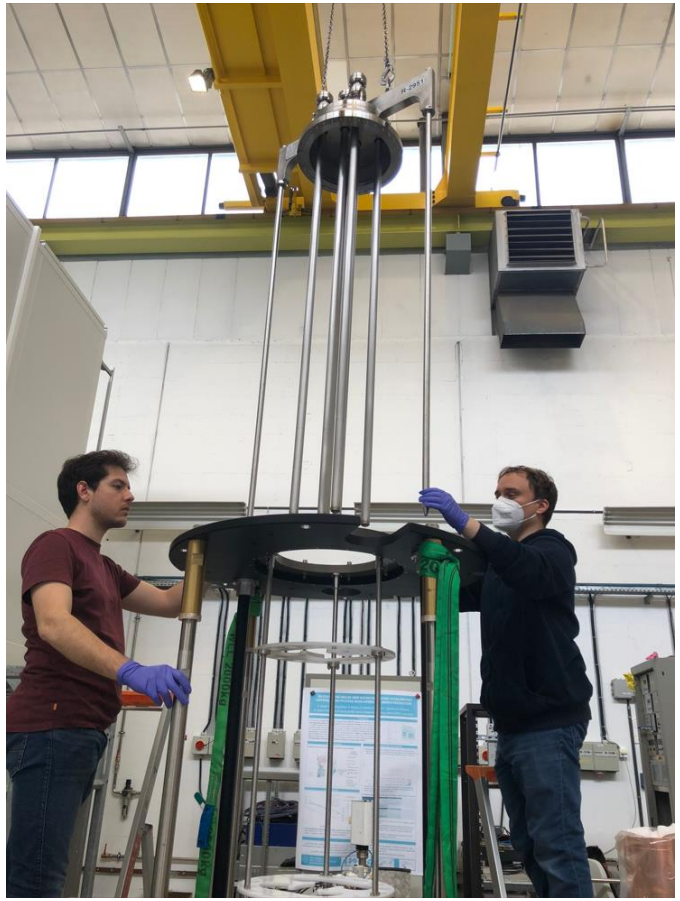

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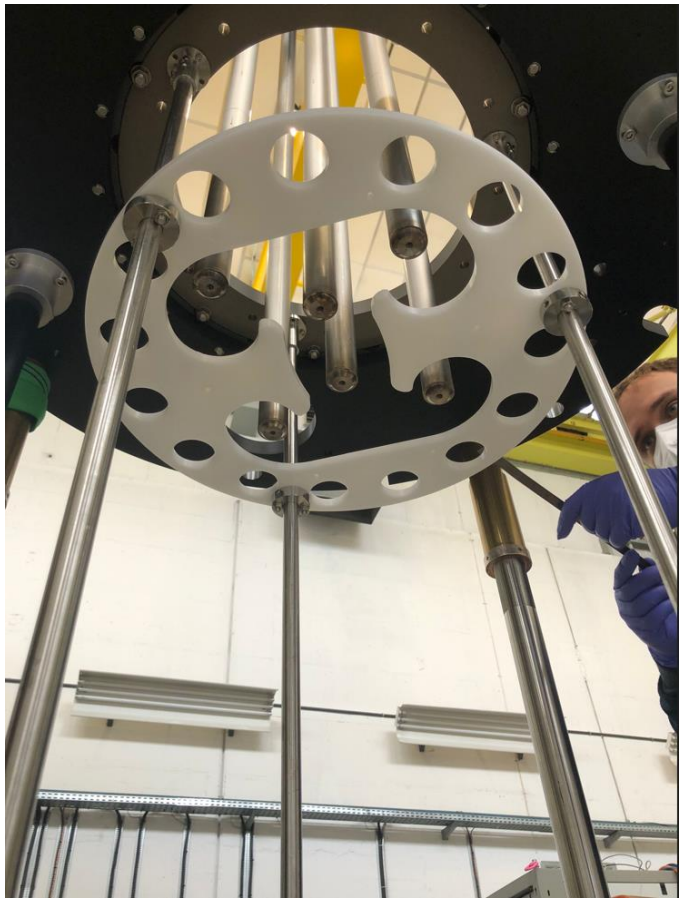

Courtesy: G. Péchaud, A. Cudré-Mauroux, M. Chiodini

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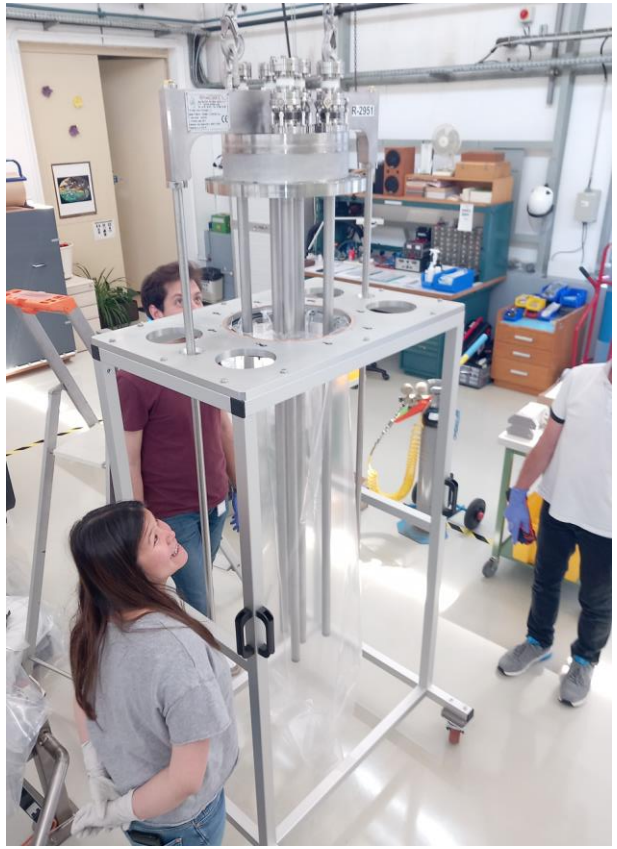

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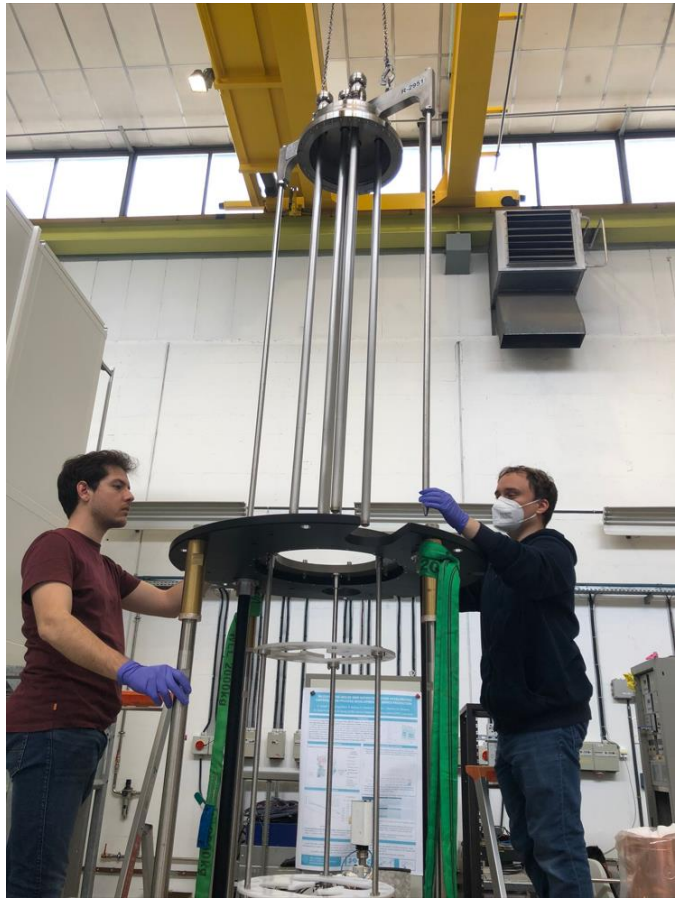

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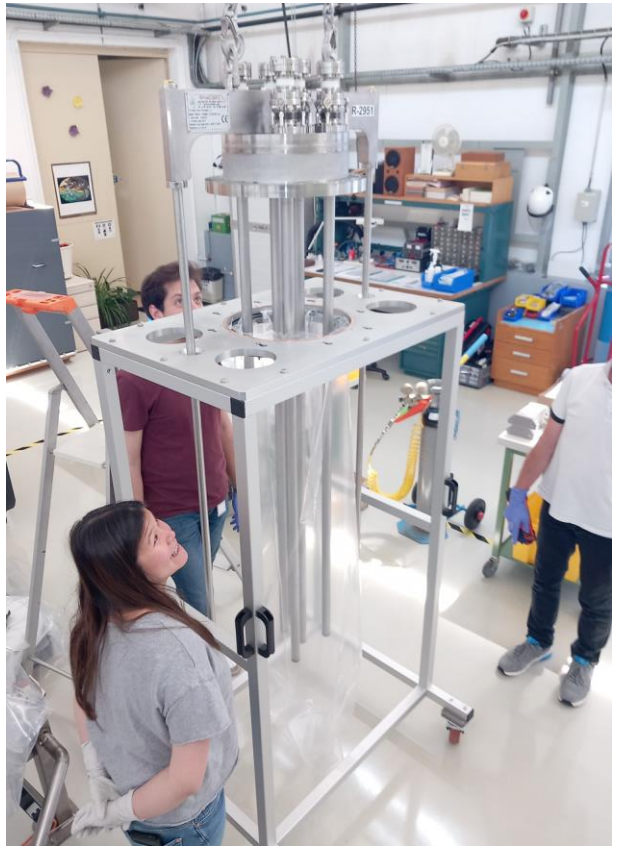

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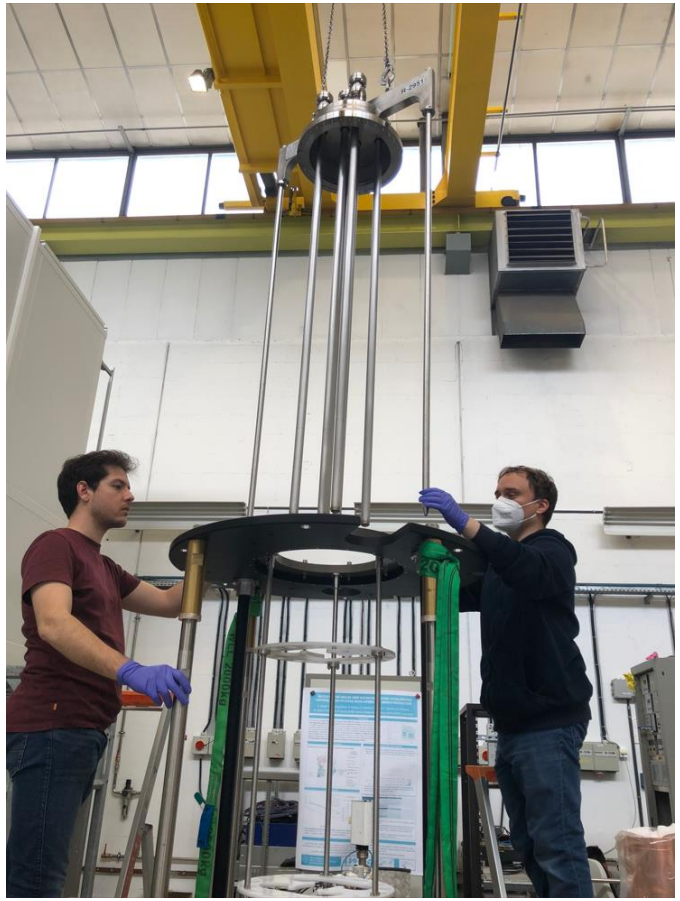

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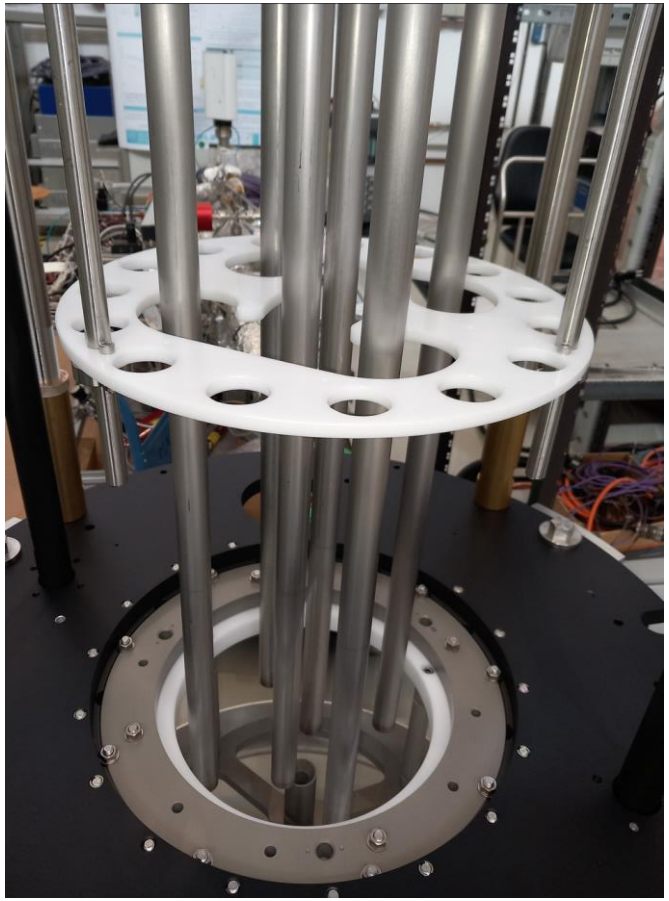

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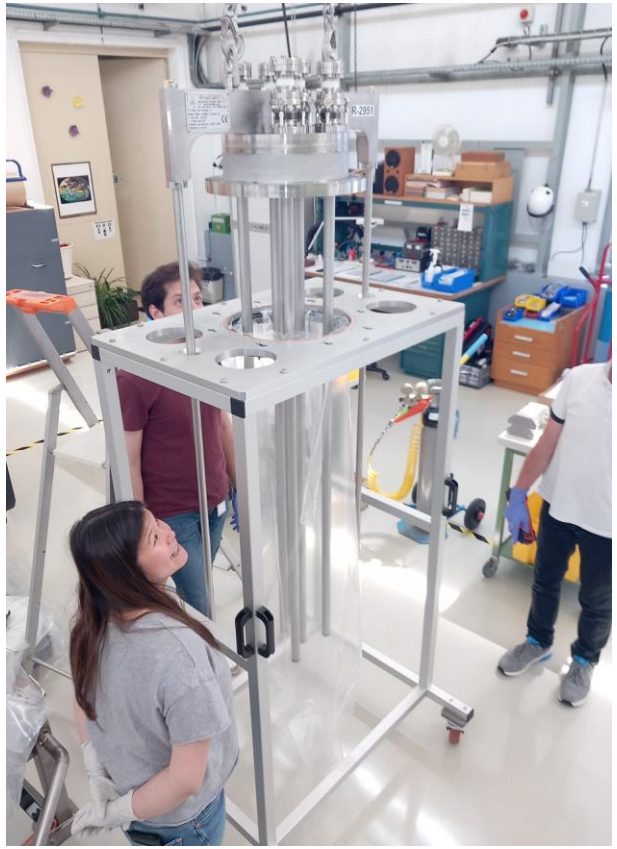

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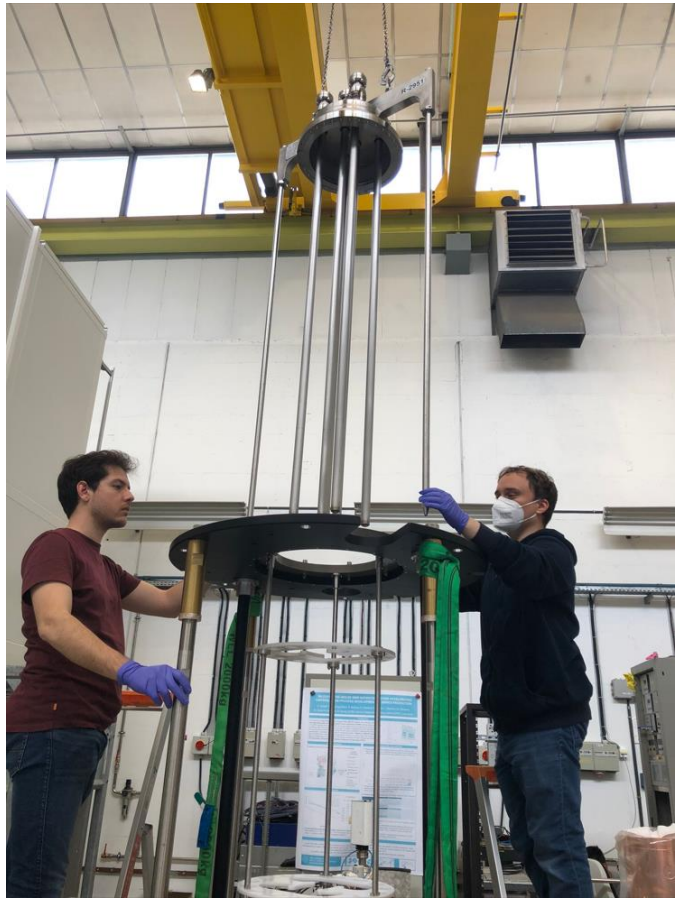

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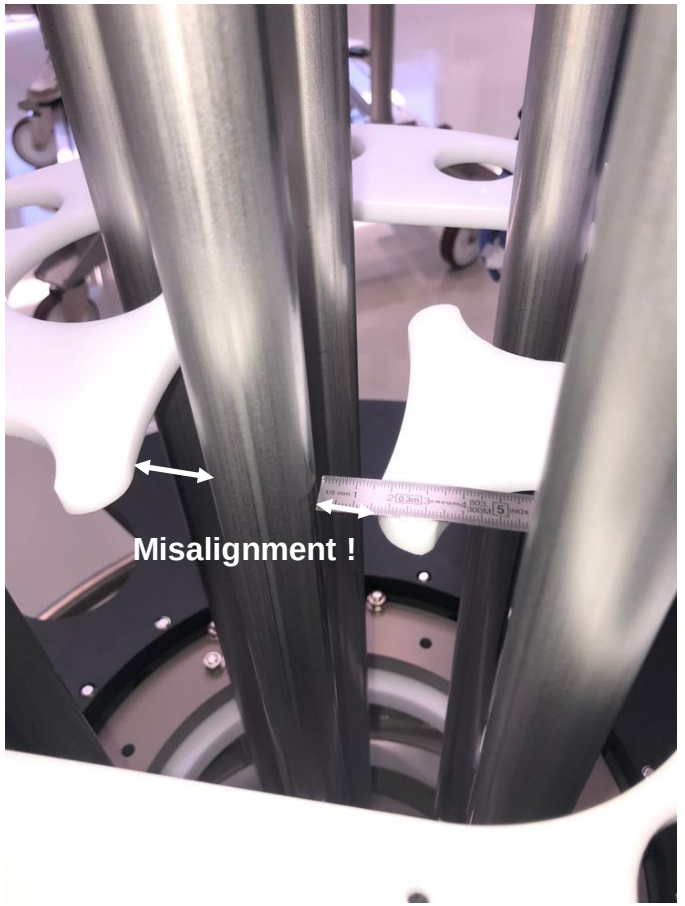
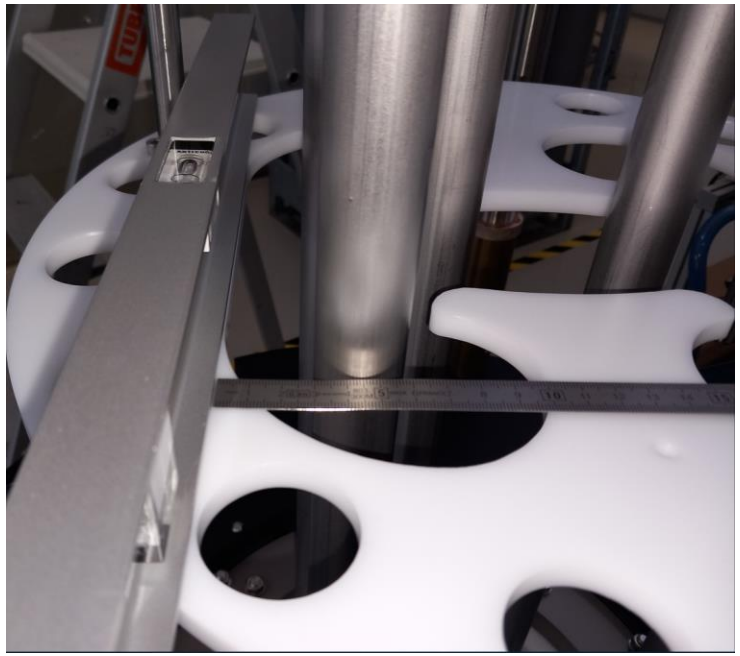
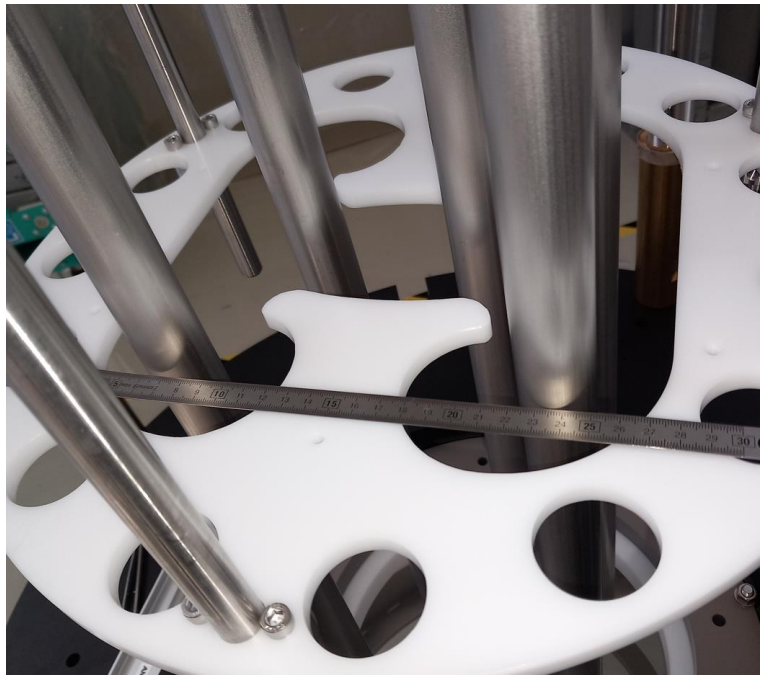


Courtesy: G. Péchaud, A. Cudré-Mauroux, M. Chiodini

4. Fine tuning

Alignment to mock-up → **Distances between cathodes** → **Precision: ±1mm average**





→ **Ready for Nb sleeves, bottom insulation and tie-plate**

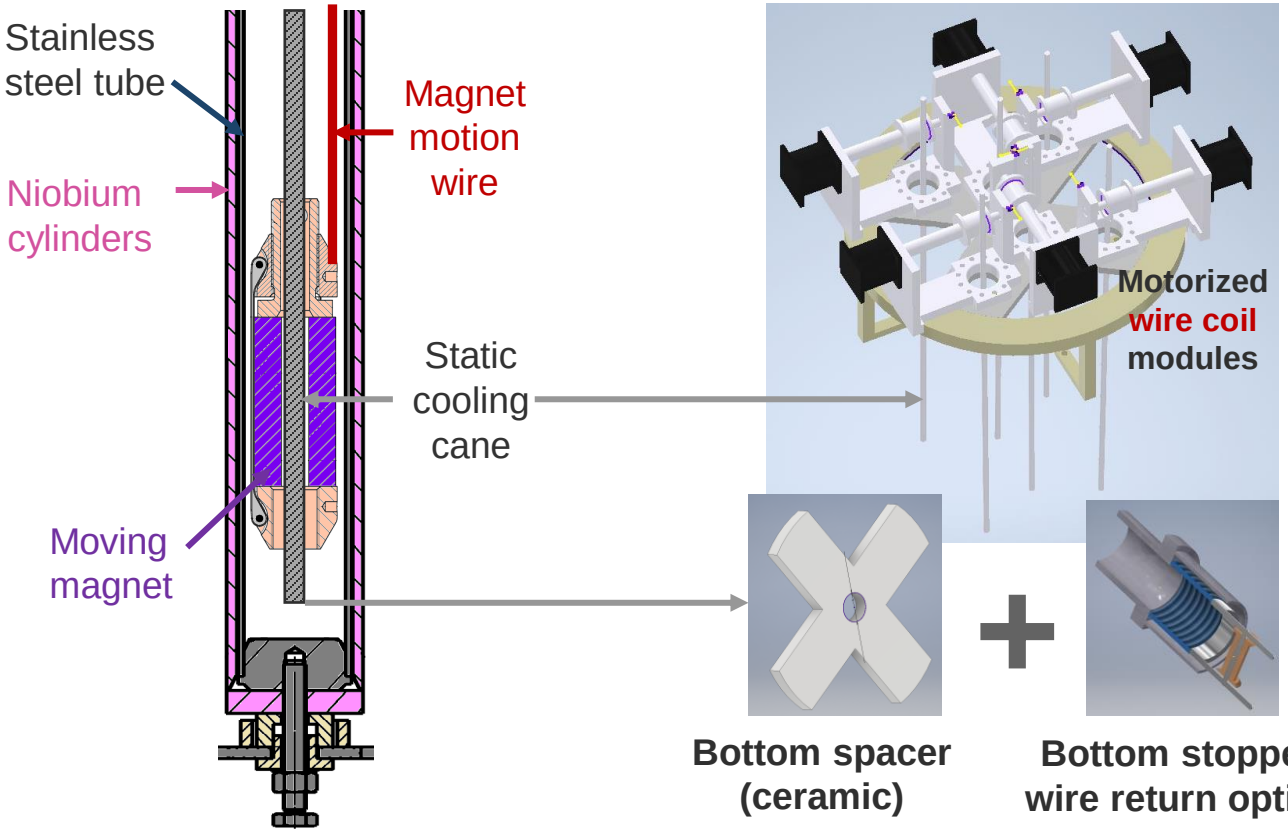
→ **Also checked: Rinsing equipment, cavity rotation, …**

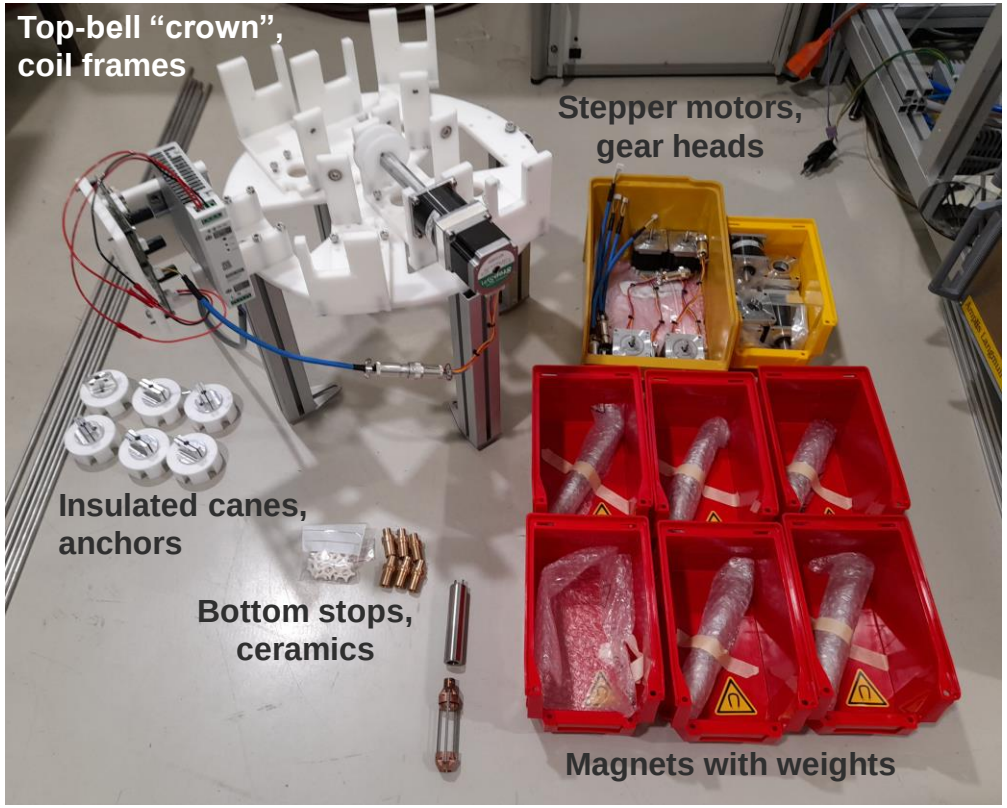
Outline

1. The Wide-Open Waveguide Crab Cavity
2. Coating recipe validation
3. Process planning
4. Status at full scale
5. **The last steps**

5 Full scale magnet motion

Single Cathode Concept → **Six Cathode Design** → **Implementation**





MASSIVE courtesy: P. Garritty

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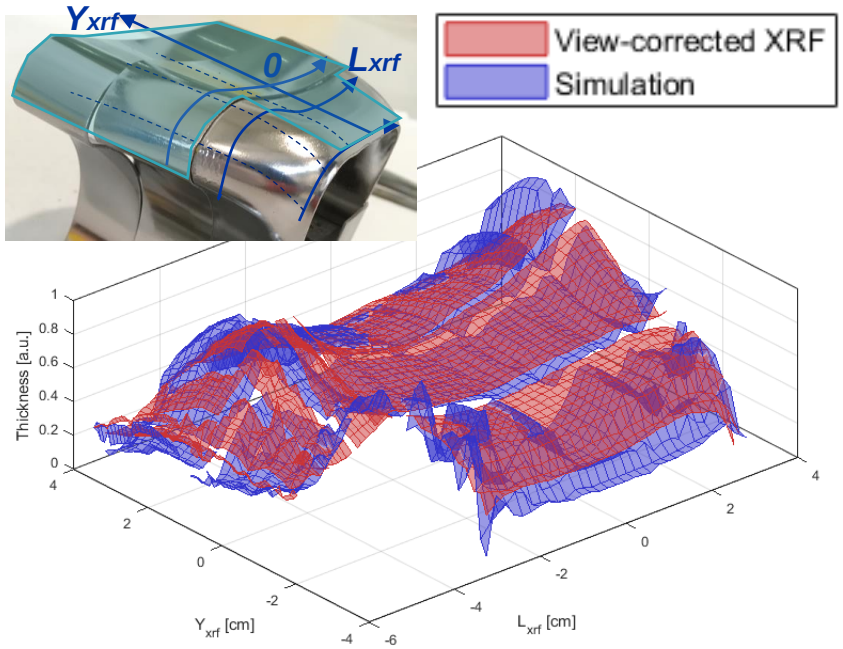
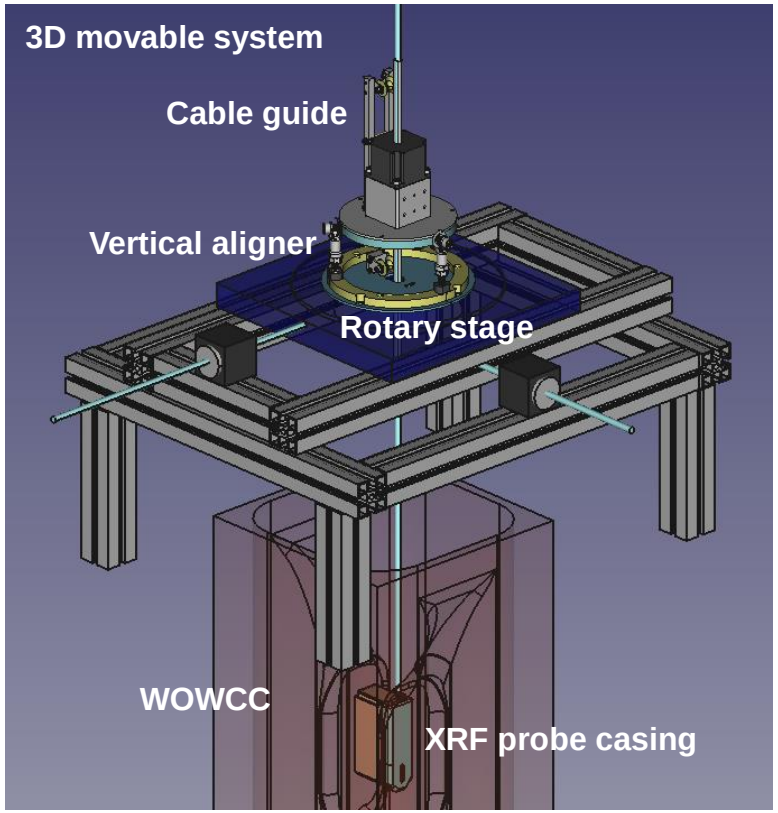
5. In-situ XRF diagnostic

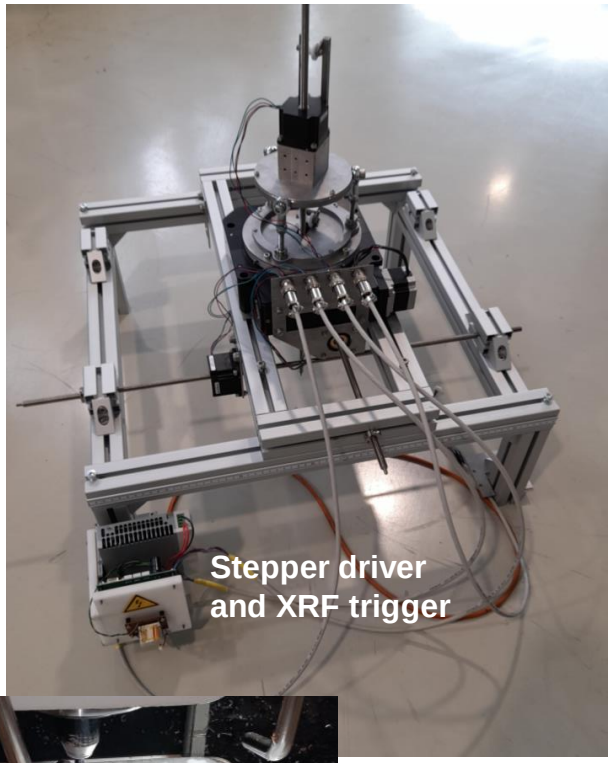
XRF benchmark on samples



In-situ Diagnostic Design



Implementation



Probe casing on the CNC

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5. The next months

→ **June :** Pumping group and magnet motion system

→ **July :** Power supplies and software integration

→ **Q3 : First coating** + In-situ XRF / RF testing

Summary

- **The WOWCC coating is a unique challenge for Nb-Cu technology**

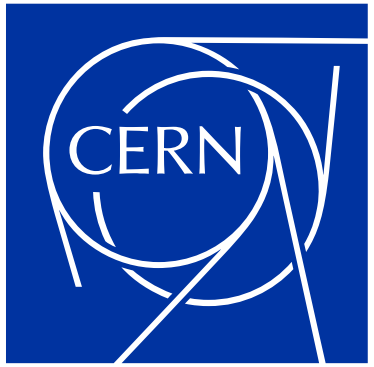
  → **Quality** through HiPIMS on 3D samples → FIB-SEM

  → **Uniformity** through 6 cathode set-up → XRF

  → **Process** steps through transport / heat load simulations

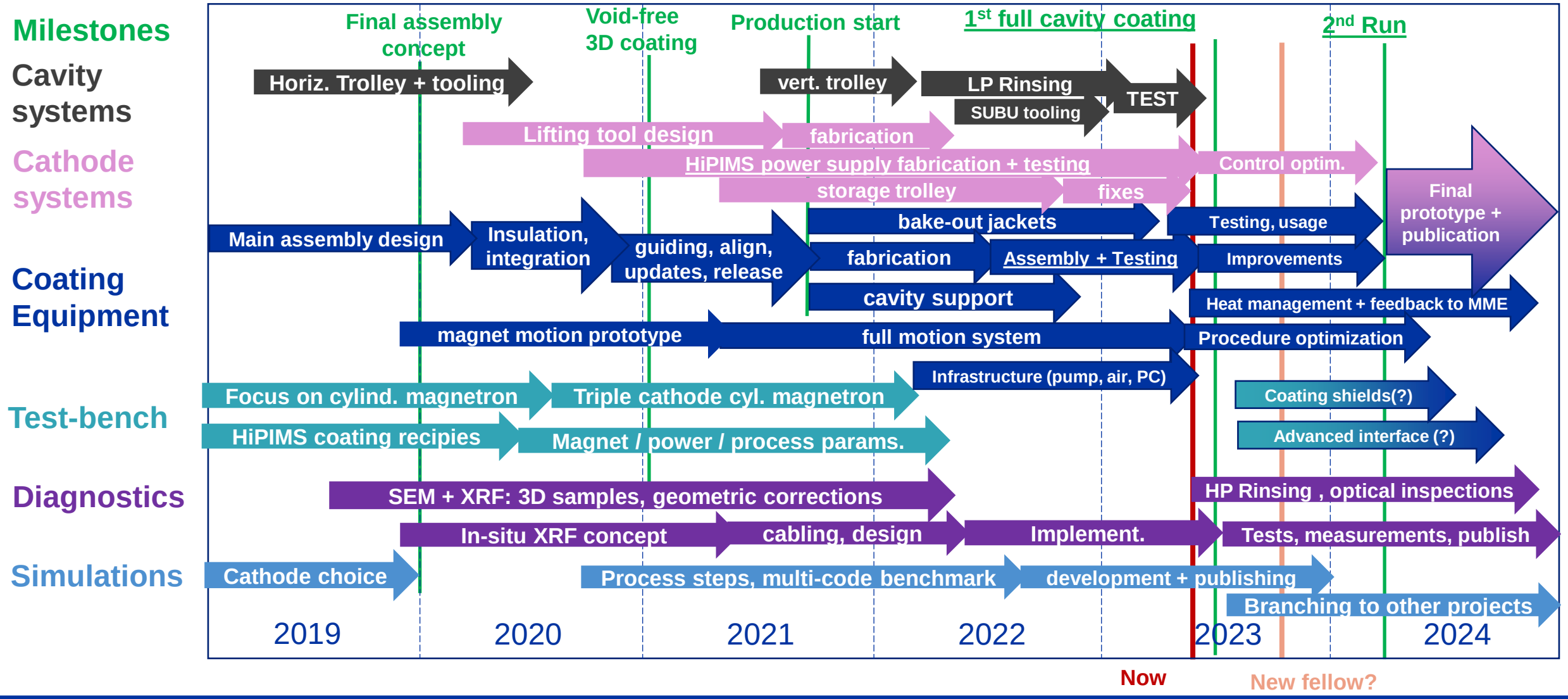
  → **Full-scale** set-up has passed main mechanical tests

→ Now : Finalizing electro-mechanical tests for first coating



home.cern

5. Timeline: State and Planning

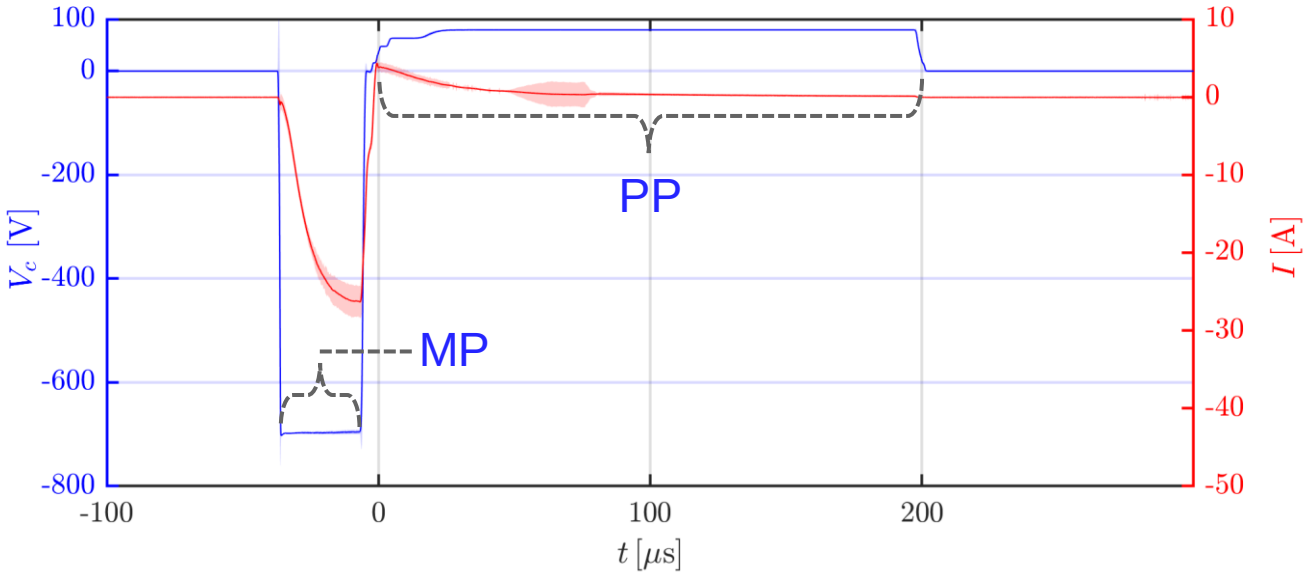


Bipolar HiPIMS coating recipe

- **High Power Impulse Magnetron Sputtering**
  - V_c during **Main Pulses** (MP), at 1kHz with with 30 µs duration (3% duty cycle)
  - Same time-average power P as DC Magnetron Sputtering

→ Denser plasmas (x10) with higher fraction of Nb^+

→ Accelerate Nb^+ by **Positive Pulses** (PP) for denser, less columnar films



Average Power : 500 W

→ Pulse Power : 16.6 kW

3. Synergies: transport comparison

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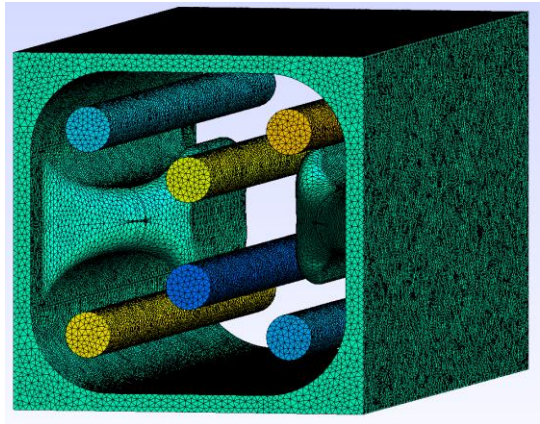
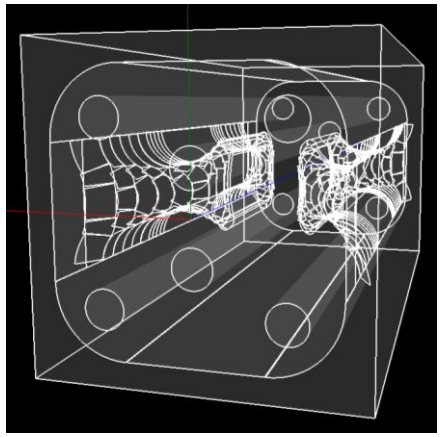
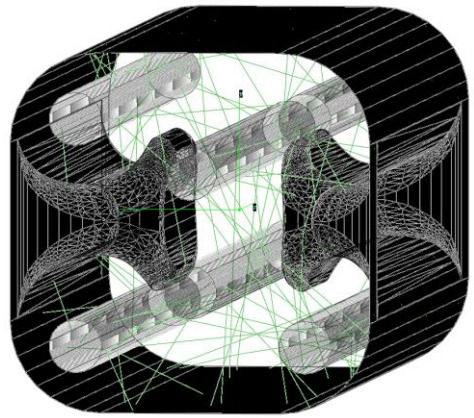
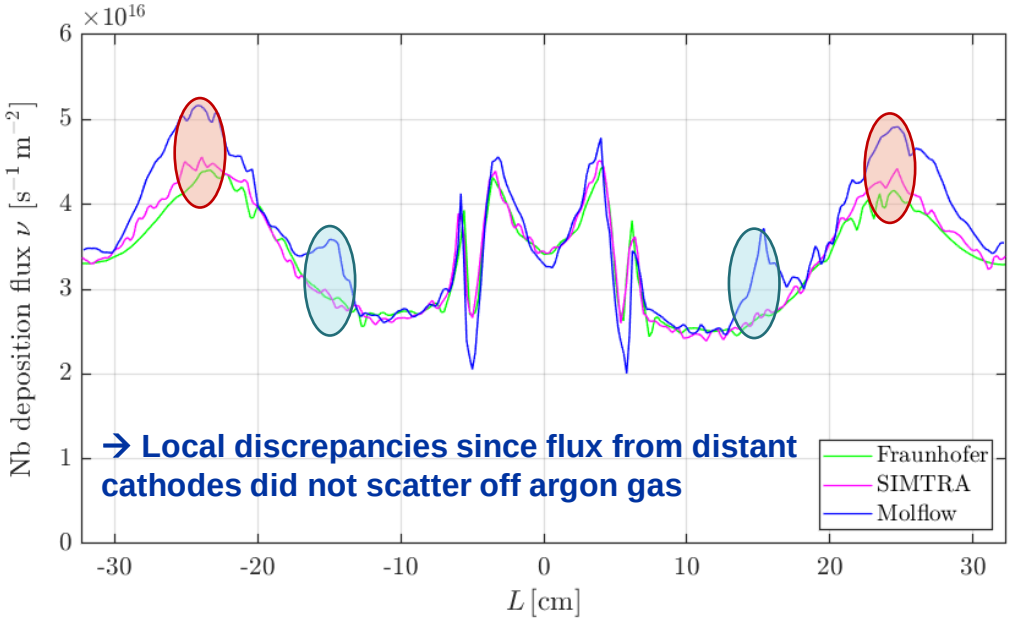
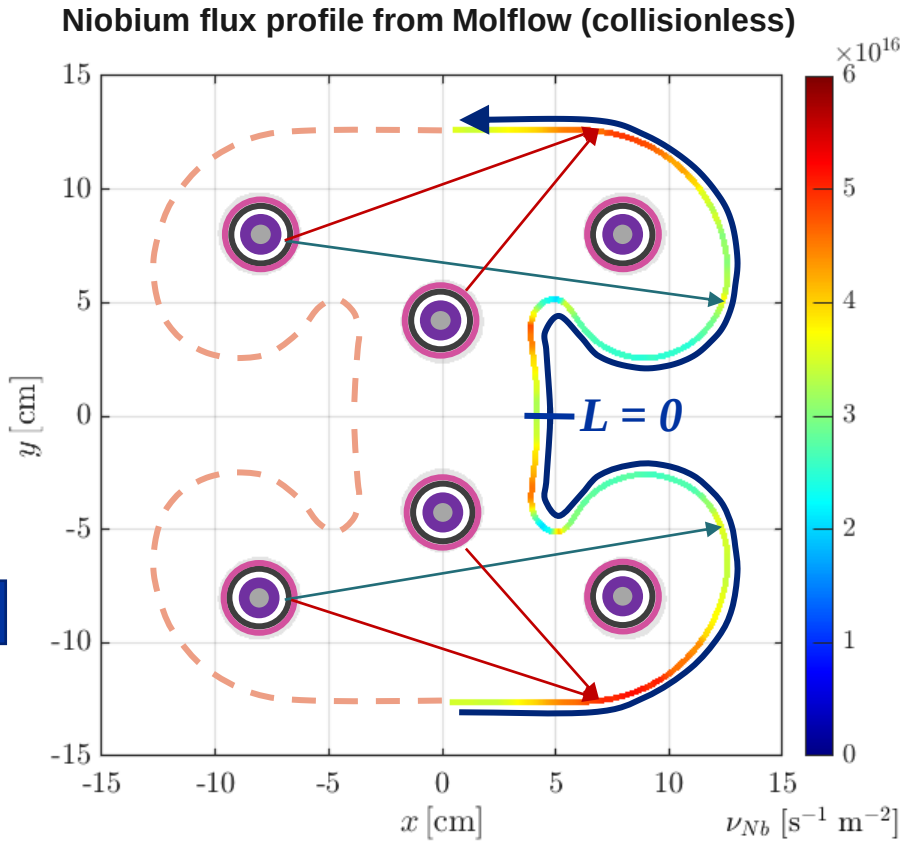
	Fraunhofer DSMC	SIMTRA	Molflow
Erosion profile	PIC-MC, single step	From PIC-MC / fitted	From PIC-MC / fitted
Propagation	MC particle tracker	MC particle tracker	MC ray tracer
Collisions	From customizable cross-section database	Select neutral metal + gas and potential type (Moliere)	None
Geometry	Triangulated by GMSH	Geometric primitives	Re-meshed from .stl
Resources	**HPC, 1 to 10 days** → Reactions + geometry	Desktop PC, ½ to 2 days → Extent of sources	**Desktop PC, ¼ to 2 days** → Nr. of “facets” in mesh
WOWCC imported			

3. Synergies: Code development

- **PICMC / DSMC simulations to establish cross-sectional Nb deposition profiles**

→ Spin-off: Transport code benchmarking and extension to Molflow: gas collisions





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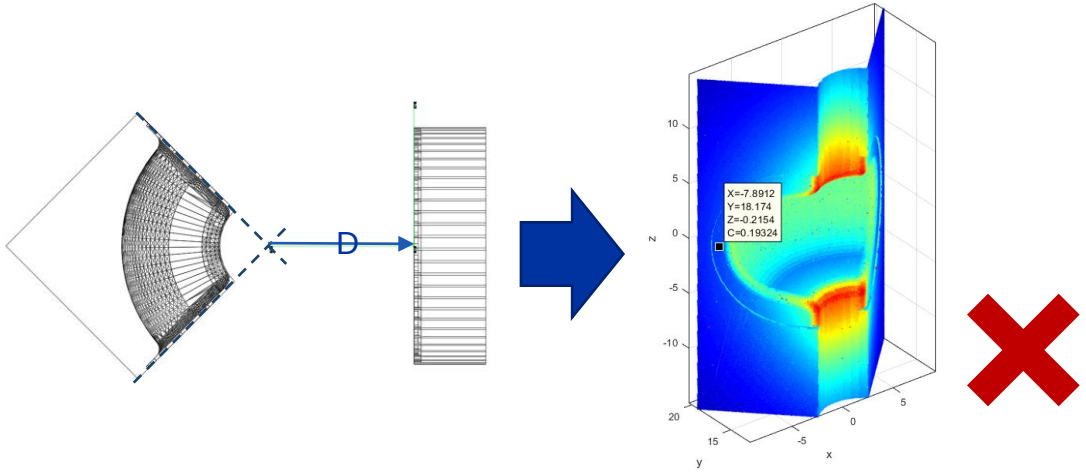
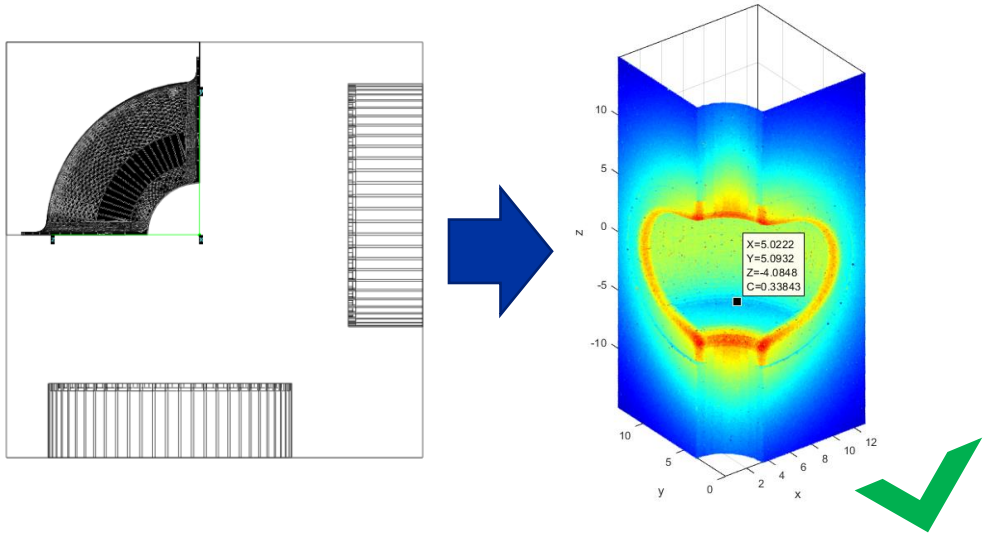
3. Synergies: The SWELL cavity

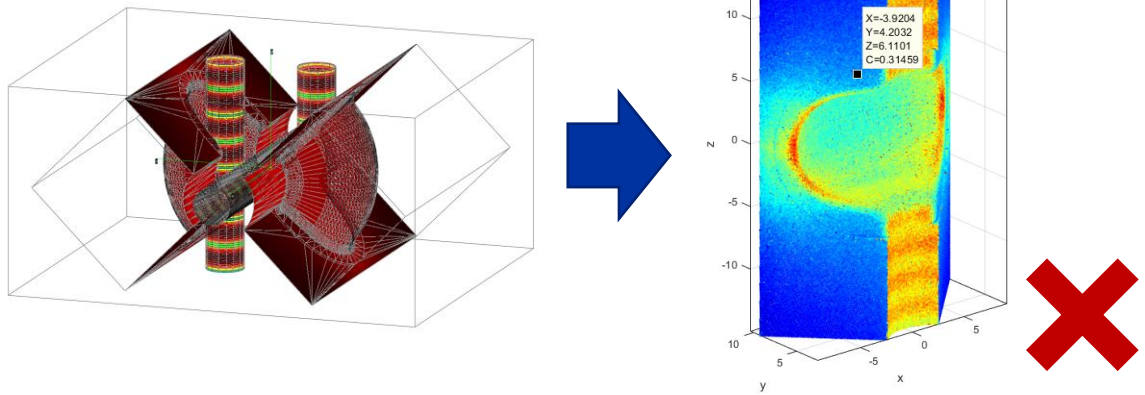
- **PICMC / DSMC simulations to establish cross-sectional Nb deposition profiles**

→ Spin-off: Transport code benchmarking and extension to Molflow: gas collisions

→ Transport simulations for SWELL coating







3 Synergies: Fundamental dynamics

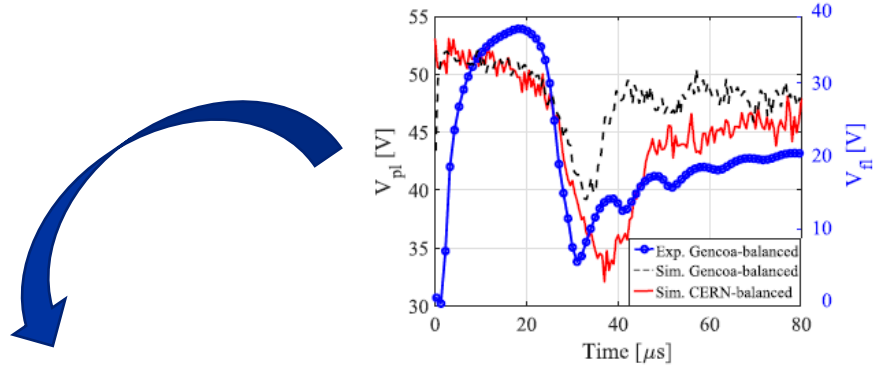
- **Bipolar High Power Impulse Magnetron Sputtering**

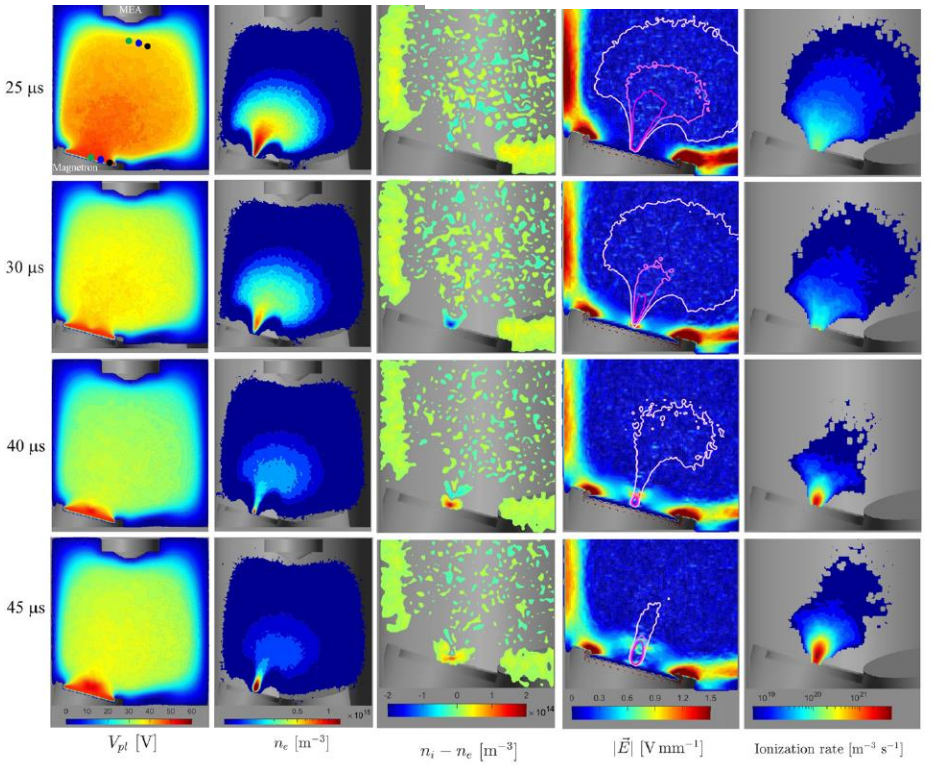
  [2] F. Avino et al, Plasma Sources Sci. Technol. **28**, 01LT03, 2019

  [3] F. Avino et al,Thin Solid Films **706,**138058, 2020

  [4] F. Avino, F. Manke, A. Sublet, T. Richard:

  Plasma Sources Sci. Technol. **30**, 115015, 2021





→ **Comprehensive measurements and deeper fundamental understanding of plasma potential dynamics in bipolar magnetron discharges**

→ Documented Potential Drop-n-Rise in various settings

→ Elucidated electron funneling in balanced configurations

→ Established conditions for a secondary “reverse” discharge

XRF diagnostic implementation

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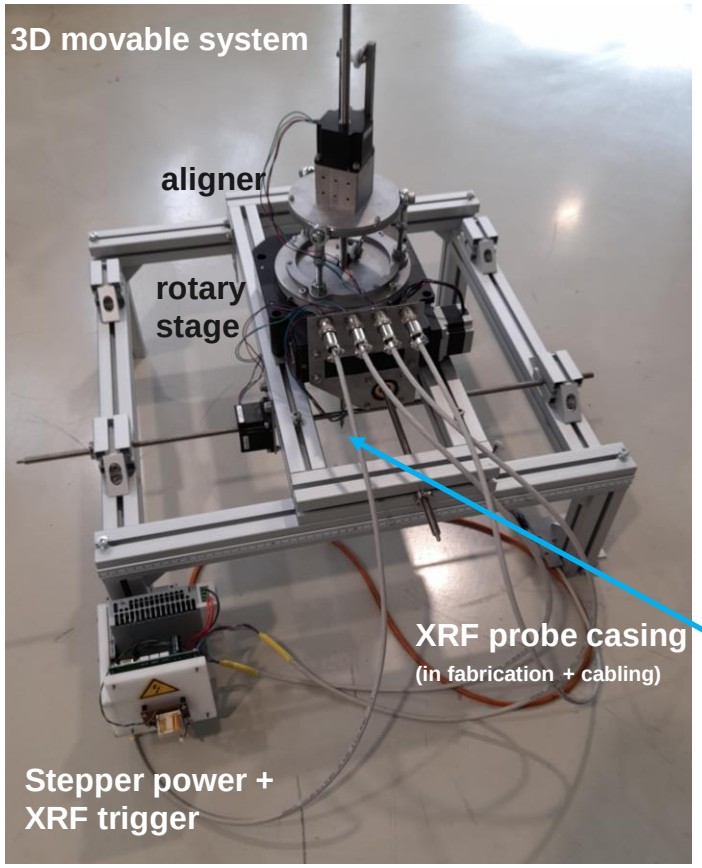
- **Quantifying coating thickness uniformity : Transport simulation vs. Measurement**

- **Movable system currently under testing**
- **Update batch script control (win cmd)**
- **XRF probe head wiring by cabling team**
- **XRF probe casing to be produced on CNC**

→ **Final acquisition + electronics tests by supplier M. Dupayrat thereafter**

→ **Safety sign-off by RP on final diagnostic**

In-situ diagnostic



XRF probe / electronics from lead-paint diagnostic