Prototyping the Nb coating of the copper Wide Open Waveguide Crab Cavity for FCC-hh

Fabian Manke, Fabio Avino, Alexej Grudiev, Ana Teresa Perez Fontenla, Thibaut Richard, Alban Sublet, Mauro Taborelli

01/07/2021

FCC week 2021

Outline

1. The WOWCC and its coating process
2. The coating recipe: HiPIMS with Positive Pulse
3. Coatings on a small-scale mock-up
4. Prototyping at full-scale

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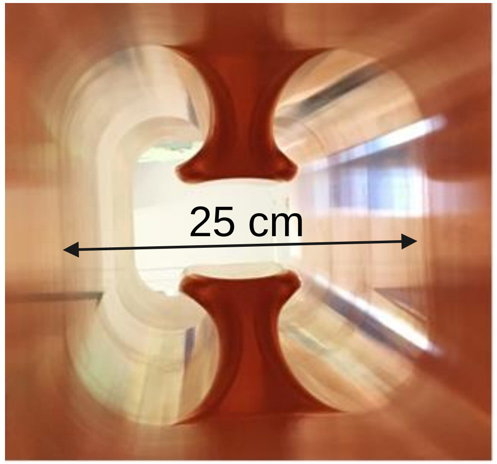
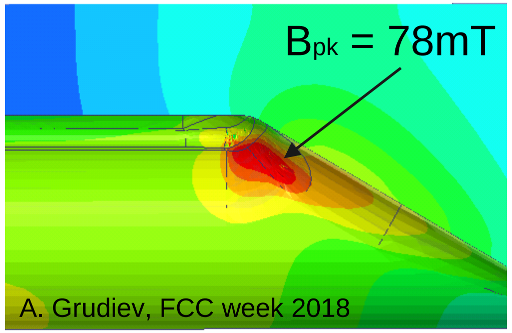
1 The Wide-Open Waveguide Crab Cavity

- **bunch tilting for head-on collisions**
- **key design features:**
  - low shunt impedances
  - outside HOM damping
  - optimized deflecting field quality
  - Nb/Cu: stable operation at 4.5 K
  - **design compatible with coating**



$Q_0 = 4 \times 10^8$
P_{loss} = 67 W at 3MV

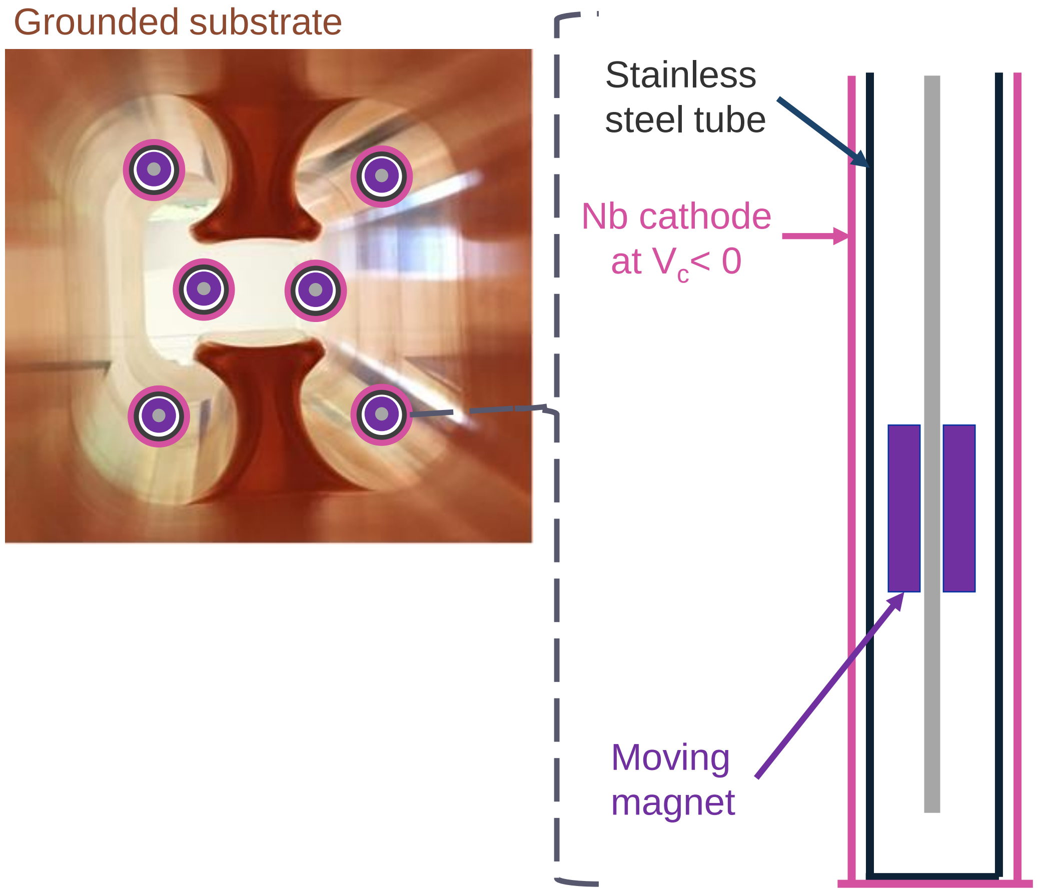


140 cm

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

1 Multi-cathode coating set-up

- **Assembly of six independent cylindrical cathodes**



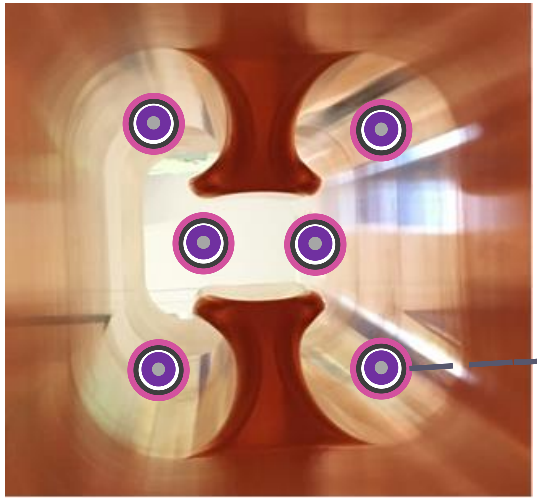
F. Avino et al, TTC, 5th February 2020, Geneva

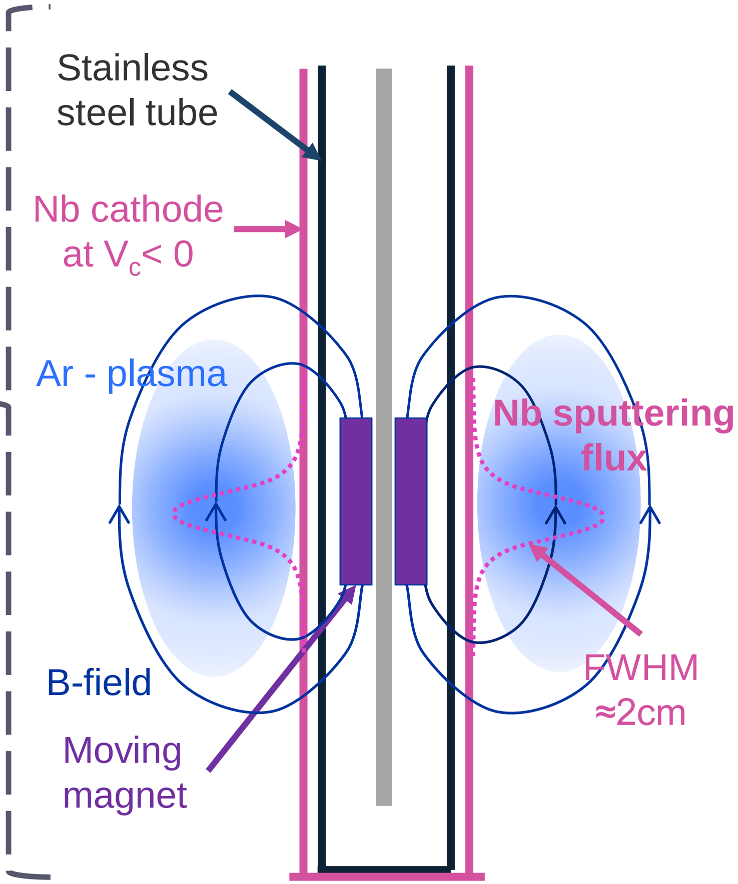
1 Multi-cathode coating set-up

- **Assembly of six independent cylindrical cathodes**

→ Magnetron sputtering

Grounded substrate





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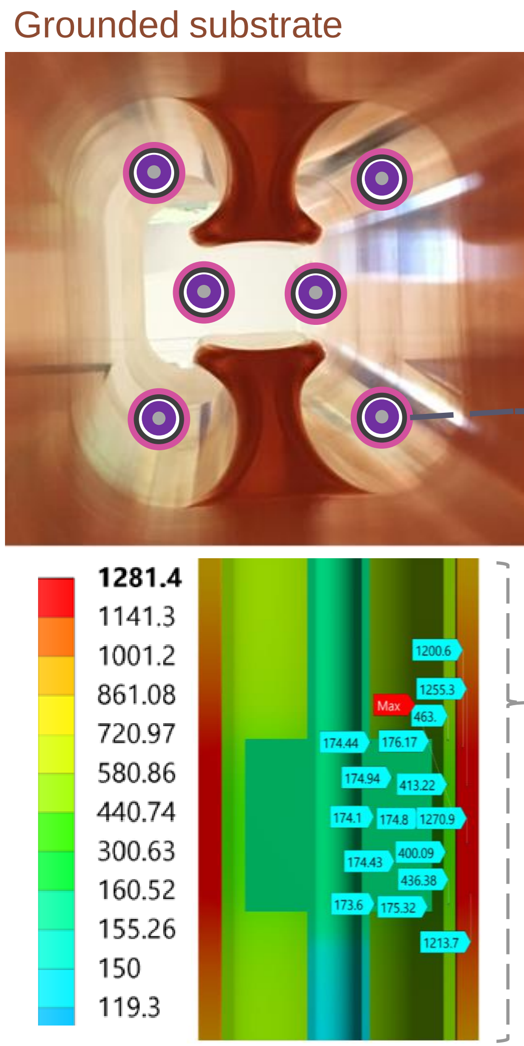
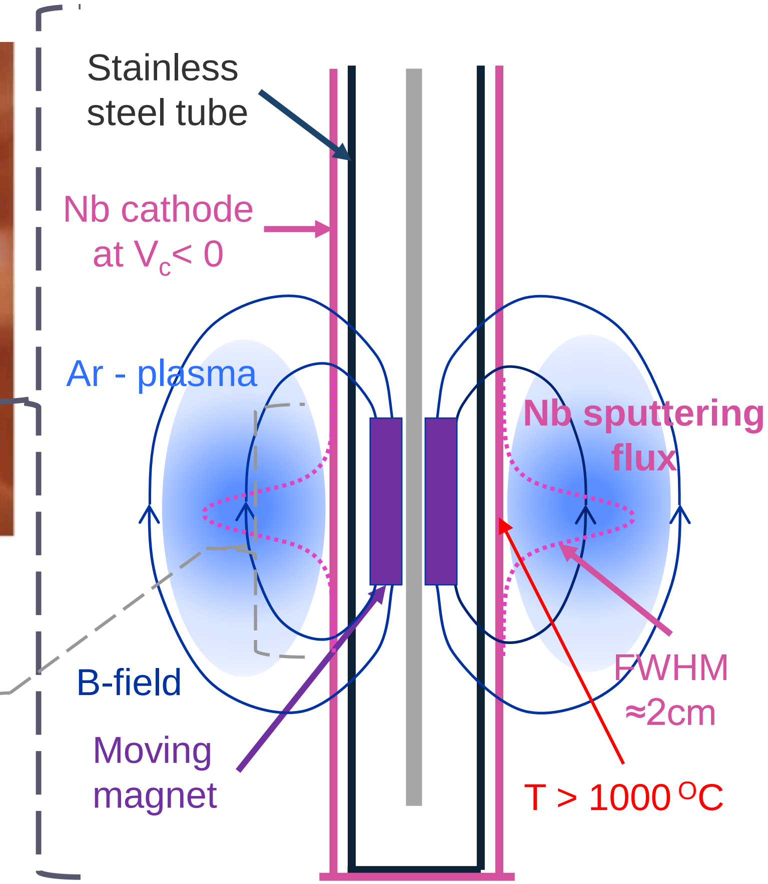
- **Assembly of six independent cylindrical cathodes**

→ Magnetron sputtering

→ Cathode heats quickly





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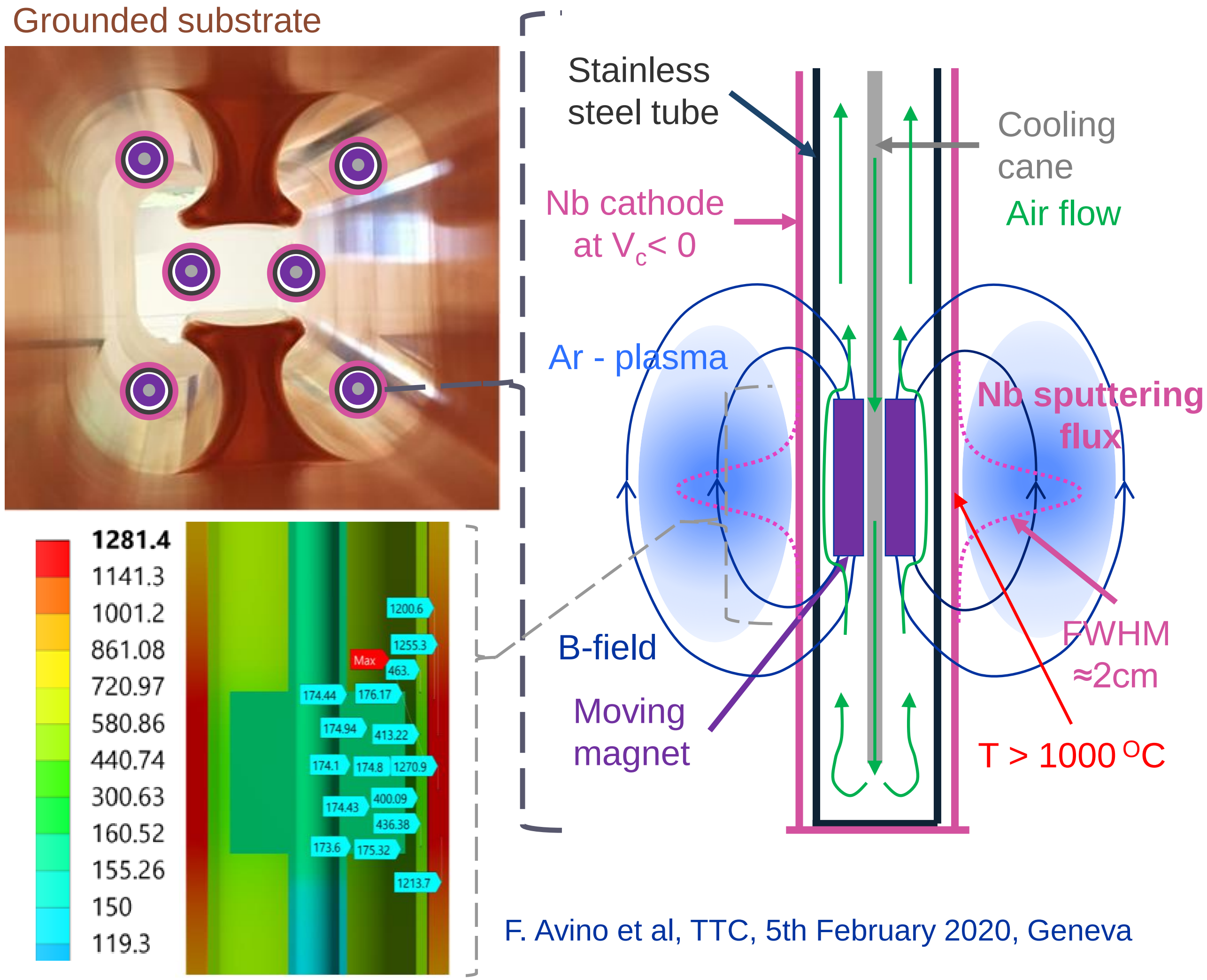
- **Assembly of six independent cylindrical cathodes**

→ Magnetron sputtering

→ Cathode heats quickly

→ Require magnet cooling



F. Avino et al, TTC, 5th February 2020, Geneva

1 Multi-cathode coating set-up

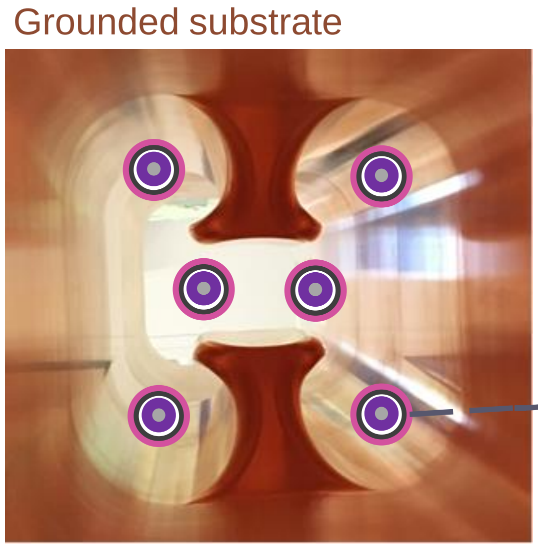
- Assembly of six independent cylindrical cathodes

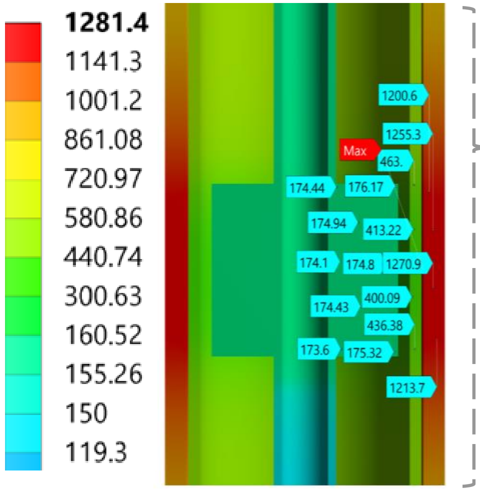
→ Magnetron sputtering

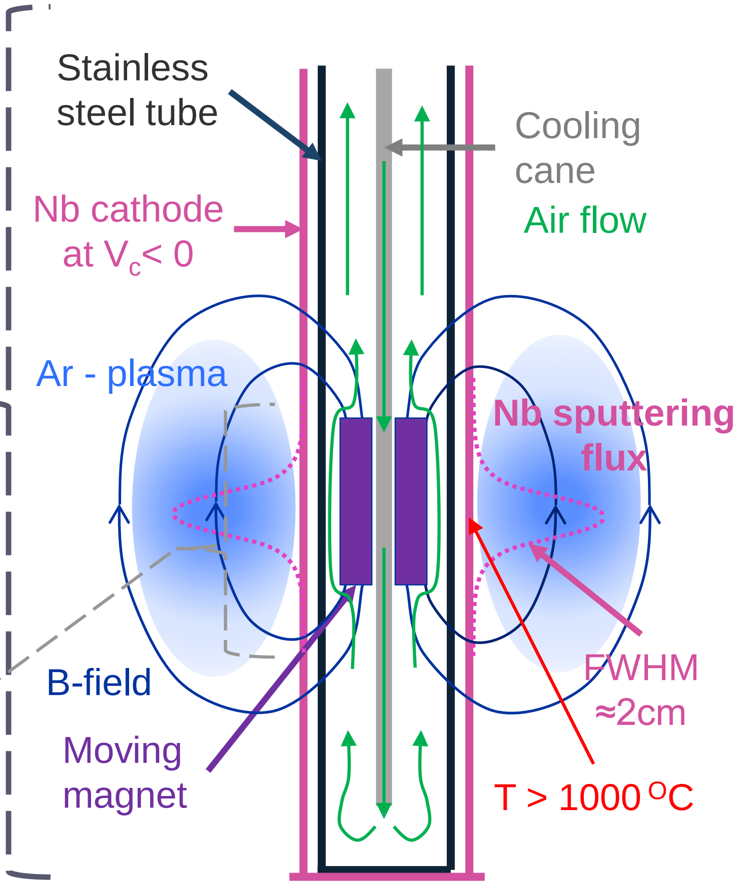
→ Cathode heats quickly

→ Require magnet cooling

- Coating uniformity factor ×2





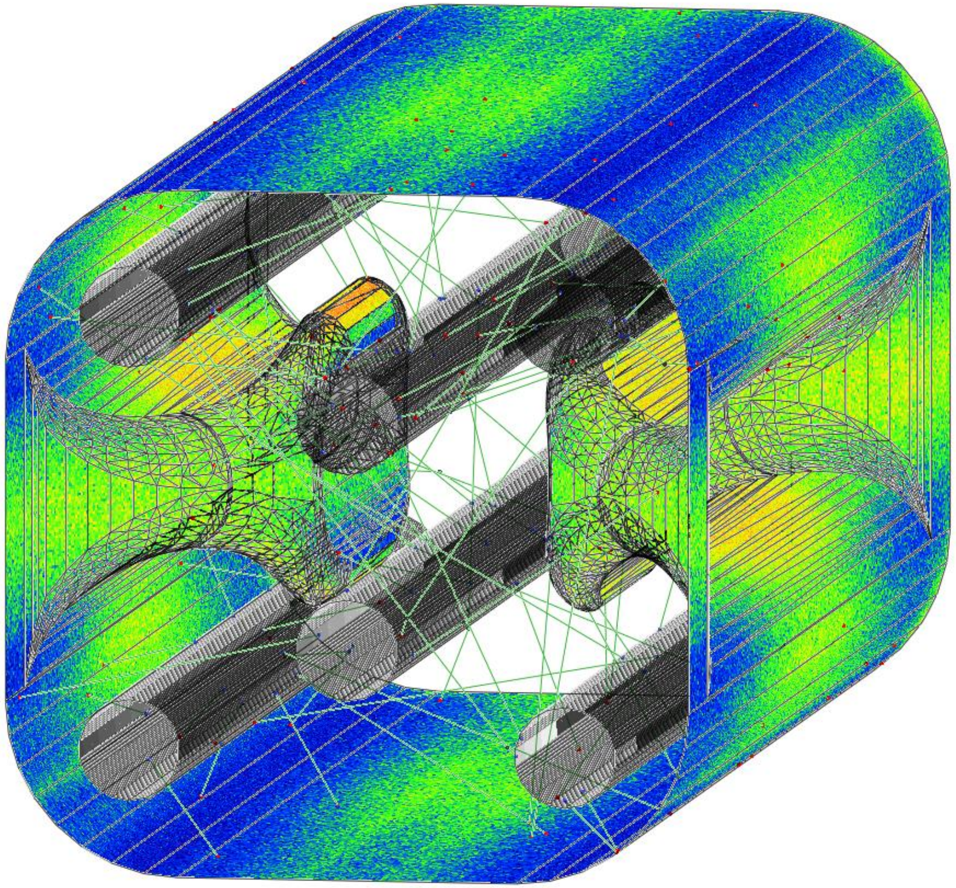


F. Avino et al, TTC, 5th February 2020, Geneva

1 Process planning with *Molflow*[1]

- **in-house ray-tracing based MC code**
- **simulates ideal gas in closed system**

→ ONLY Nb atoms from input-profiles



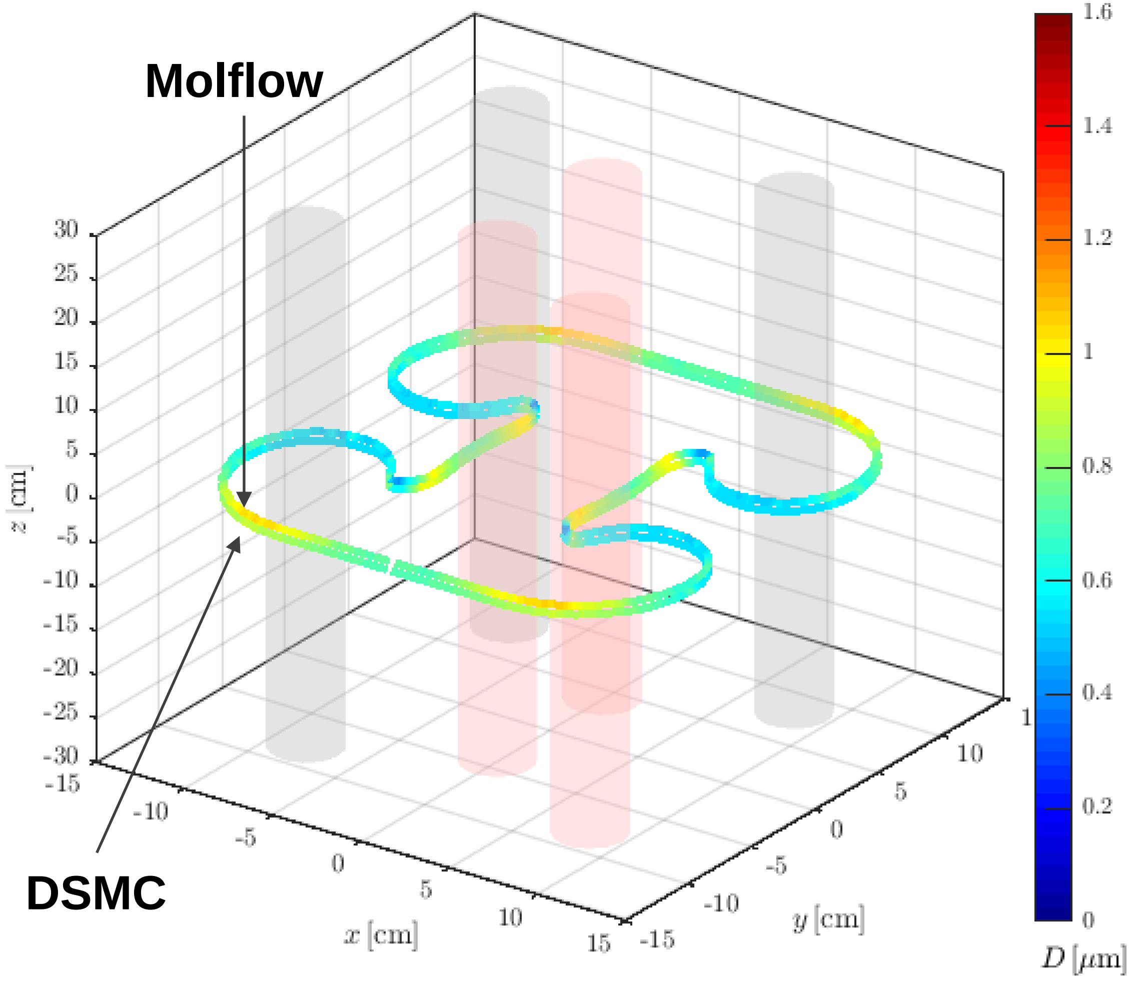
[1] M. Ady, R. Kersevan, 10th Int. Particle Accelerator Conf., Melbourne, 2019, doi:10.18429/JACoW-IPAC2019-TUPMP037

1 Process planning with *Molflow*

- in- house ray-tracing based MC code
- simulates ideal gas in closed system

→ ONLY Nb atoms from input-profiles

→ Find at worst local ≈ 25% deviation from fully collisional DSMC code[2,3]

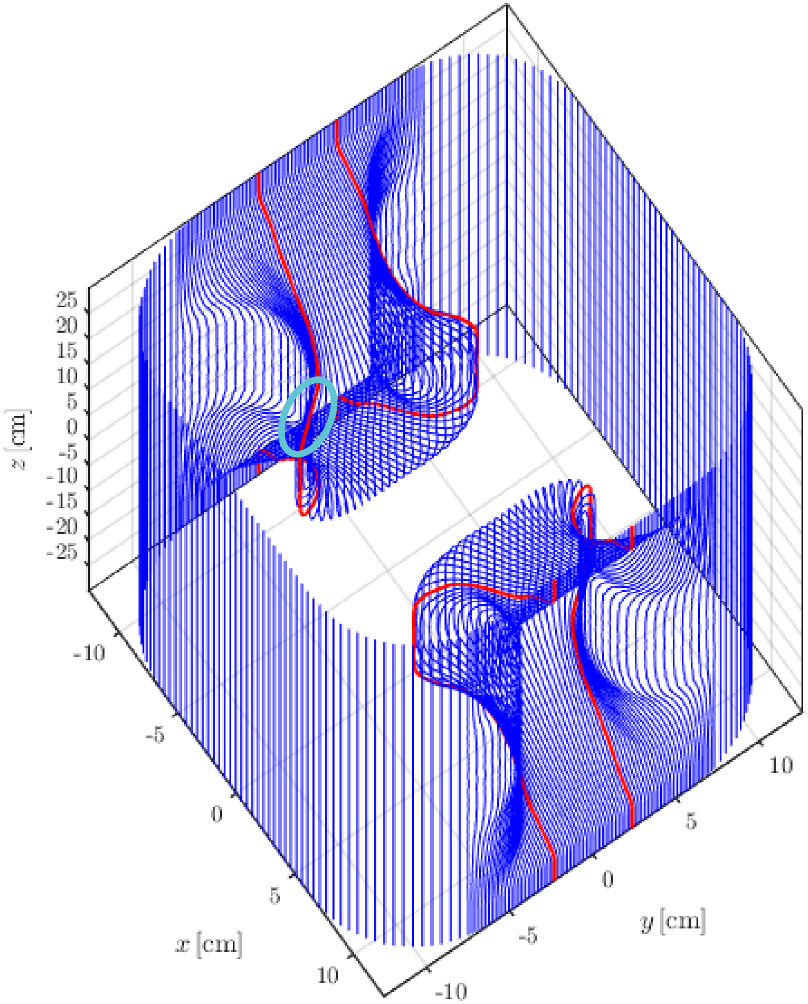


[2] A. Pflug, DSMC/PIC-MC Code Documentation, **Fraunhofer IST, Braunschweig**, Germany, https://simulation.ist.fraunhofer.de/doku.php?id=start

[3] F. Avino et al, TTC, 5th February 2020 Geneva

1 Process planning with *Molflow*

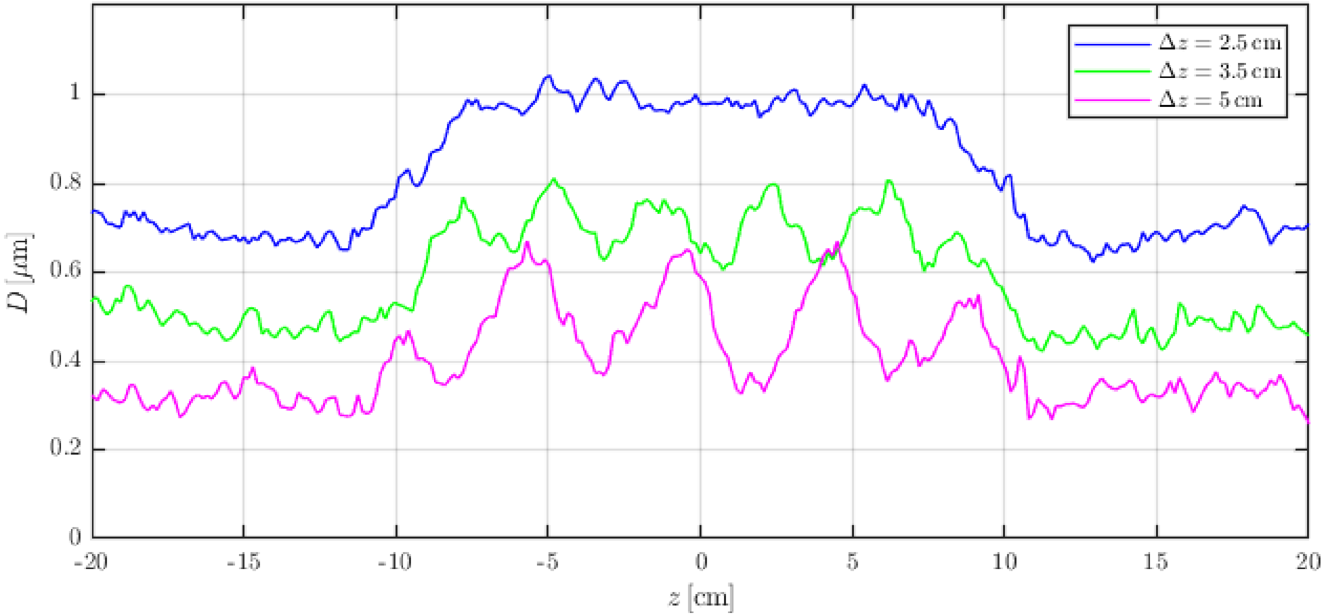
- **Axial profiles along relevant regions (e.g. RF hotspot)**

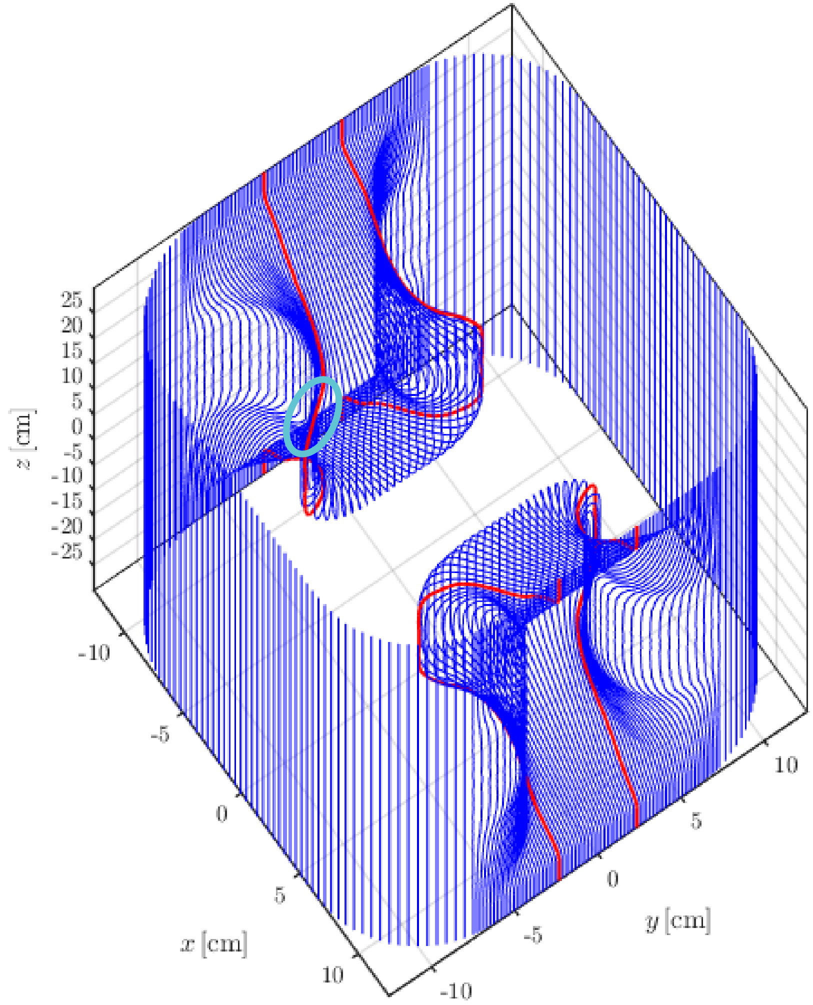


1 Process planning with *Molflow*

- **Axial profiles along relevant regions (e.g. RF hotspot)**

→ Identify *2.5 cm* as minimum process step-size, especially in critical areas





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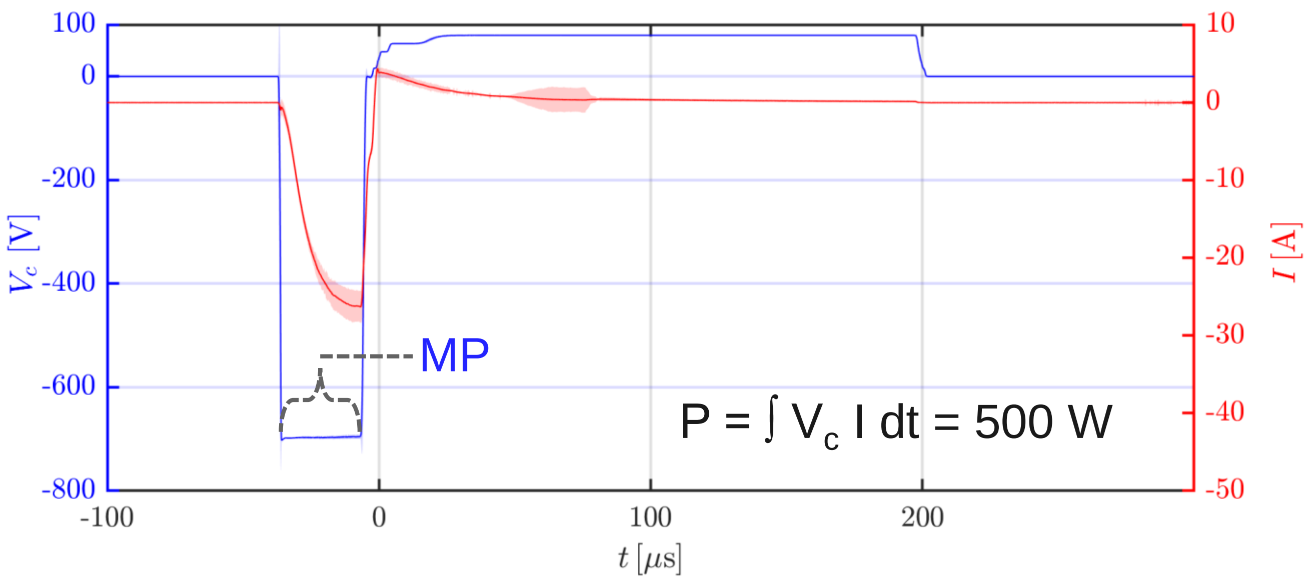
2 HiPIMS coating recipe

- **High Power Impulse Magnetron Suttering**
  - V_c during Main Pulses (MP), at 1kHz with <10% duty cycle
  - same time-average power fix-points as DC Magnetron Sputtering



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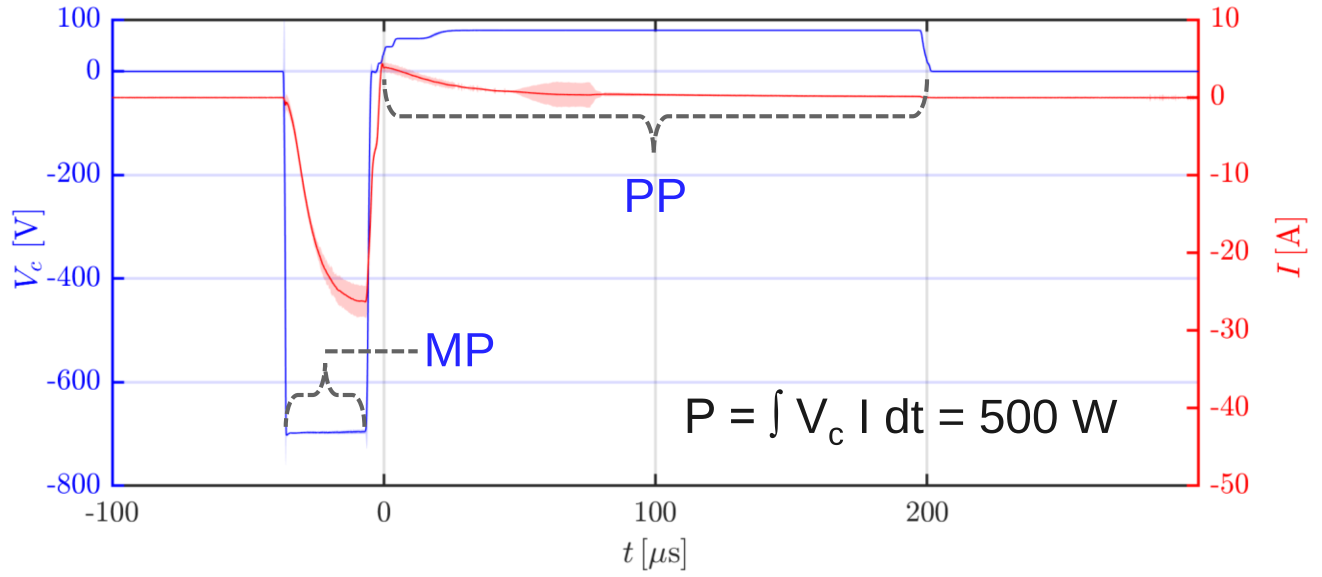
  - → Denser plasmas (x10) with higher fraction of Nb^+
  - → Accelerate Nb^+ by Positive Pulses (PP) for denser, less columnar films



2 Thin film densification

- **High Power Impulse Magnetron Suttering**
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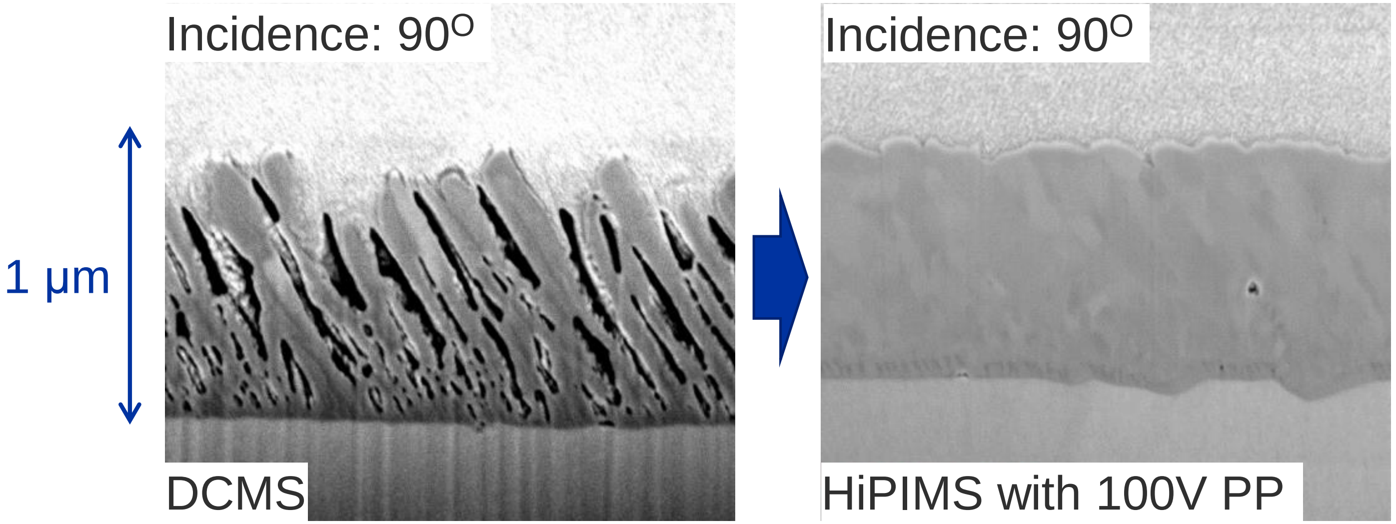
→ **Very promising on planar samples, especially at *grazing* incidence**



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

2 Moving to the WOWCC geometry

- **High Power Impulse Magnetron Suttering**
  - V_c during Main Pulses (MP), at 1kHz with <10% duty cycle
  - Same time-average power fix-points as DC Magnetron Sputtering
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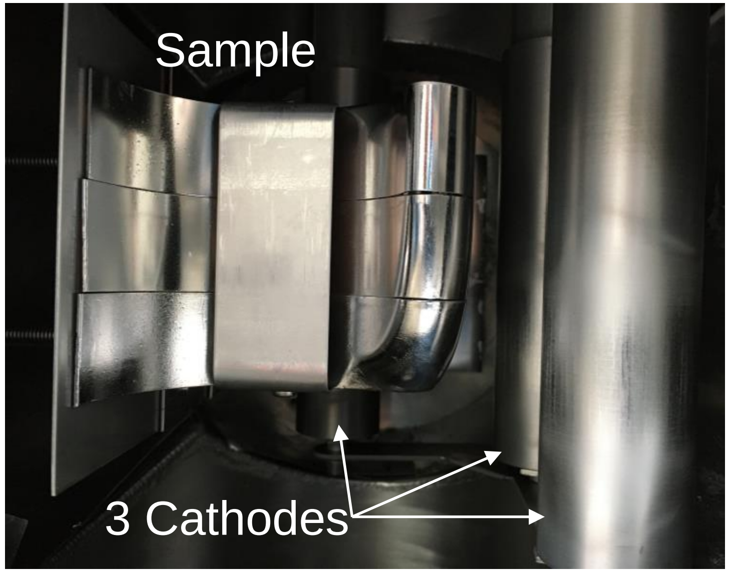
→ **Very promising on planar samples, especially at grazing incidence**

→ **Tests in 3-cathode mock-up system**

→ **Samples mimic hot-spot region 1:1**



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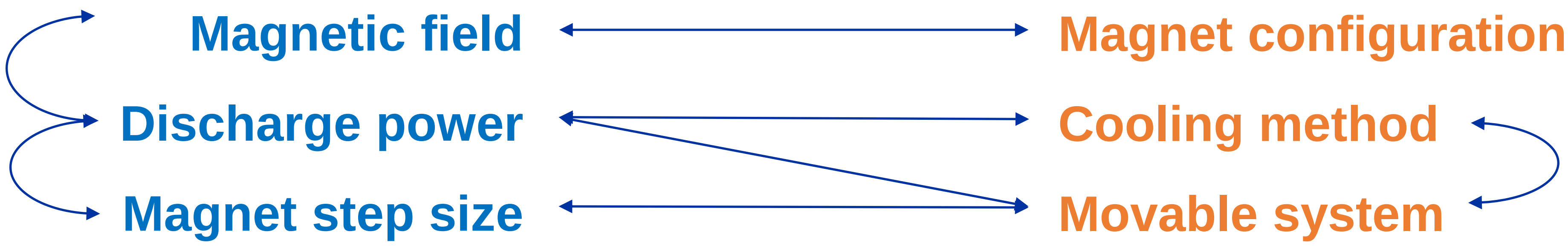
2 Three-cathode coatings on mock-up samples

- **Qualify coating thickness and morphology in critical areas (RF hotspot)**
- **Define *process parameters* and *prototype equipment***



2 Three-cathode coatings on mock-up samples

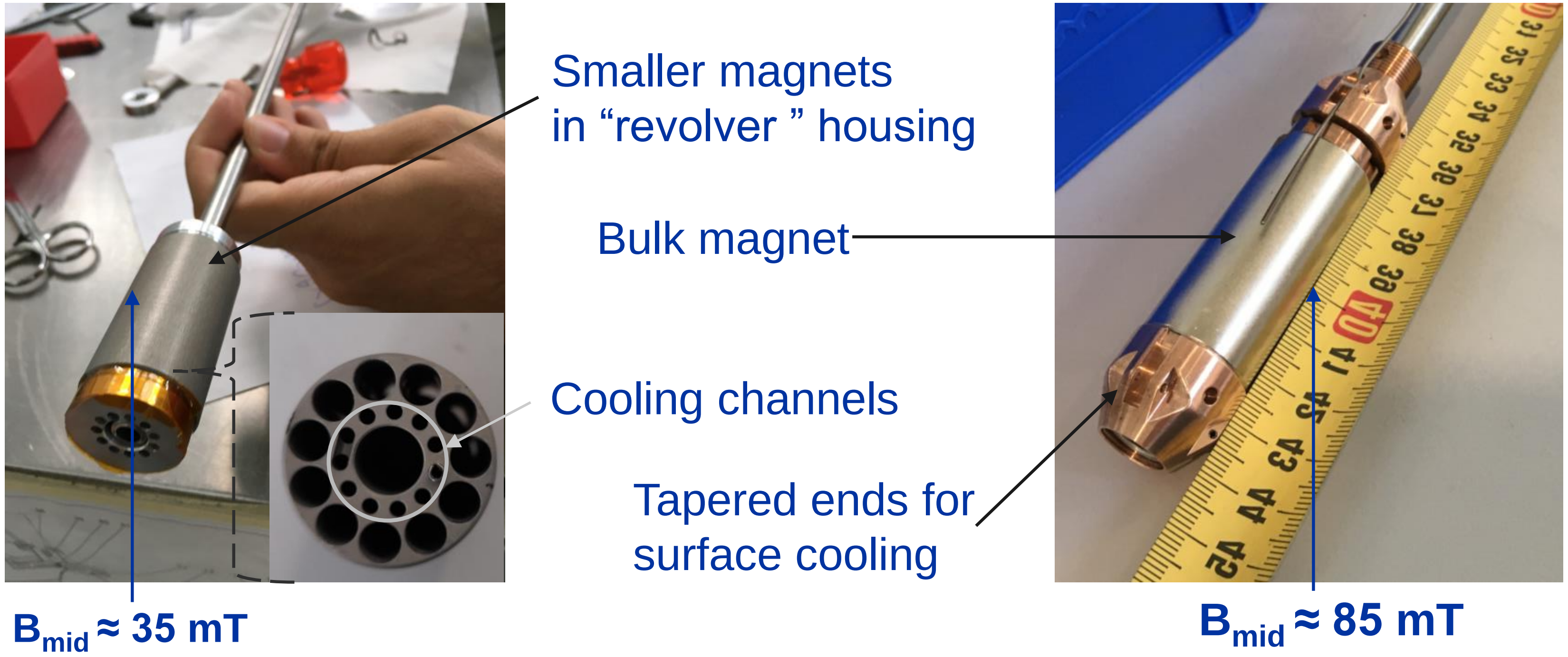
- **Qualify coating thickness and morphology in critical areas (RF hotspot)**
- **Define *process parameters* and *prototype equipment***

Magnetic field	**Magnet configuration**
Discharge power	**Cooling method**
Magnet step size	**Movable system**

- **Practical constraints:**
  - Heat loads on magnet and substrate
  - Mechanical precision and reliability
  - Handling on full-scale

2 Composite "revolver" vs. bulk magnet

→ **Better cooling vs. stronger field (better confinement)**



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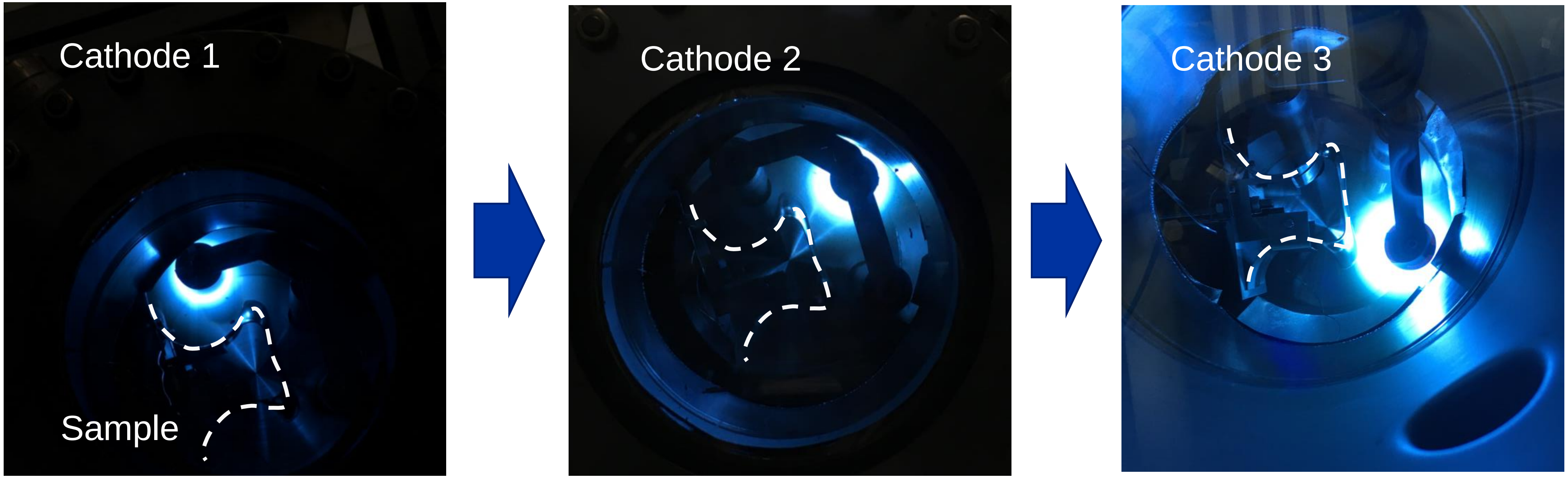
→ **Better cooling vs. stronger field (better confinement)**

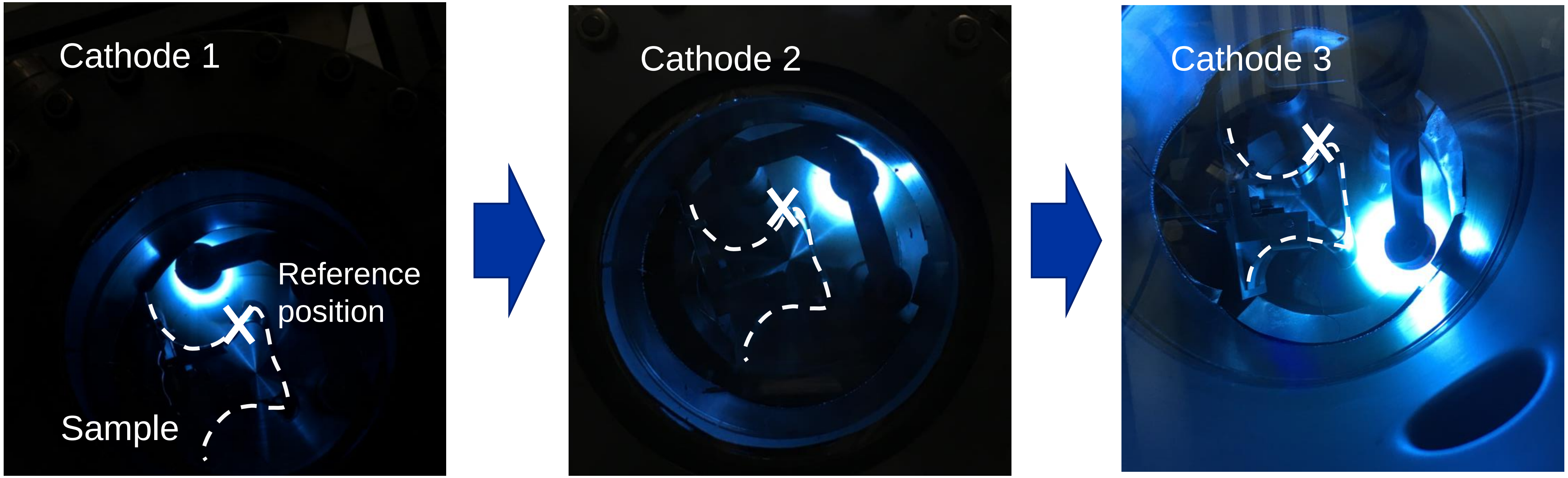
- **Baseline tests at P=500W for 40 mins, cathodes in sequence:**



2 Composite “revolver” vs. bulk magnet

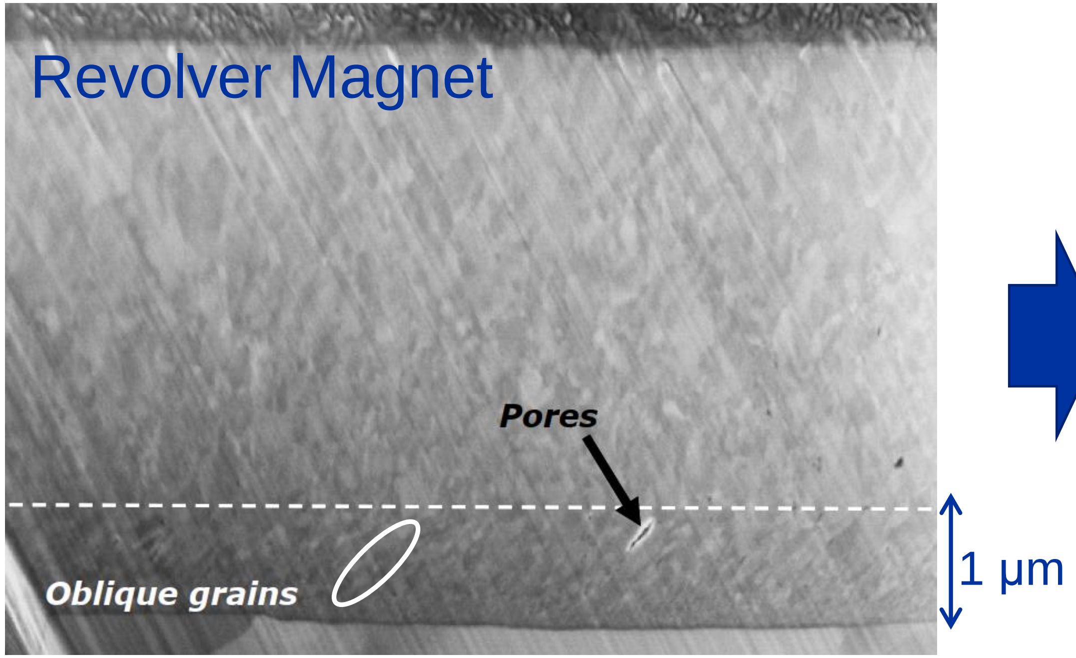
→ **Better cooling vs. stronger field (better confinement)**

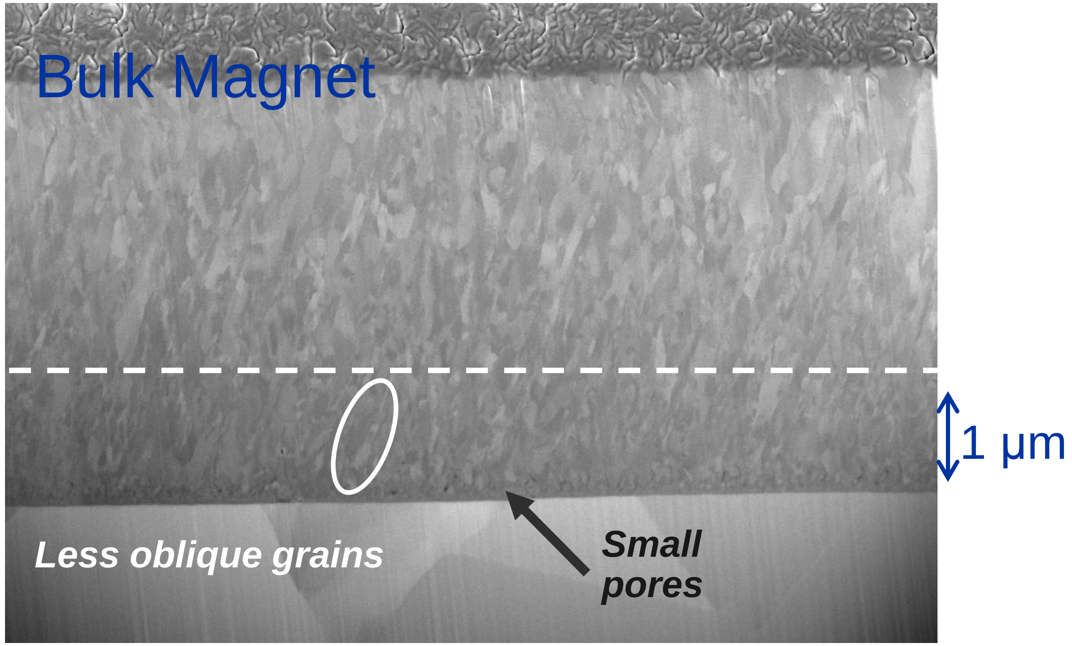
- **Baseline tests at P=500W for 3×40 mins, cathodes in sequence:**



2 Improved coating morphology

→ **bulk magnet provides more Nb^{+} ions reacting to Positive Pulse**

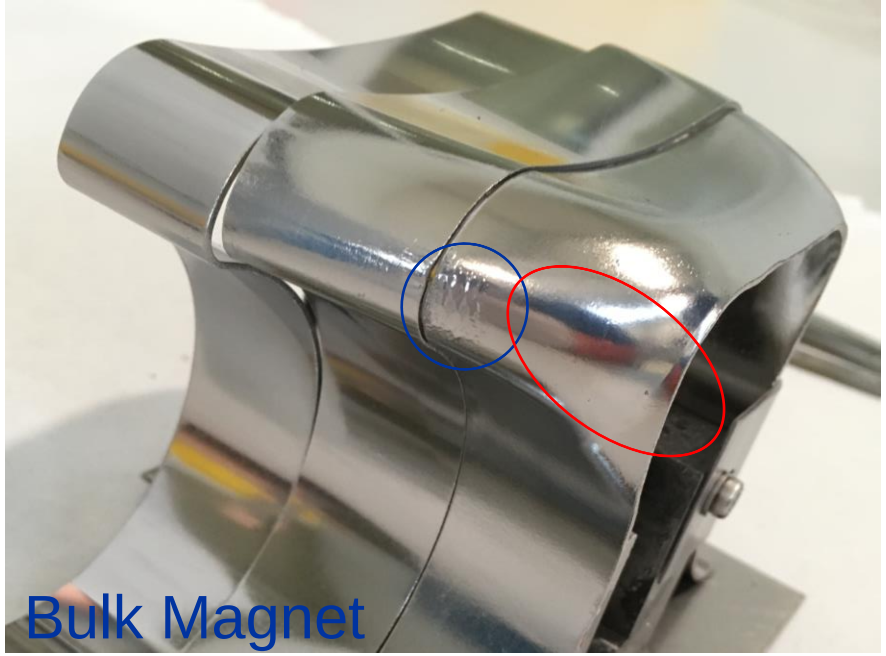




→ **Less oblique grains, small pores only near Nb/Cu interface**

2 Improved coating adhesion

→ **single magnet provides more Nb^+ ions reacting to Positive Pulse**



→ **Better overall adhesion and less delamination near RF hot-spot**

2 Coatings at higher power

- **1kW coating with bulk magnet for 20 mins coating duration**

→ faster coating vs. higher heat load

2 Coatings at higher power

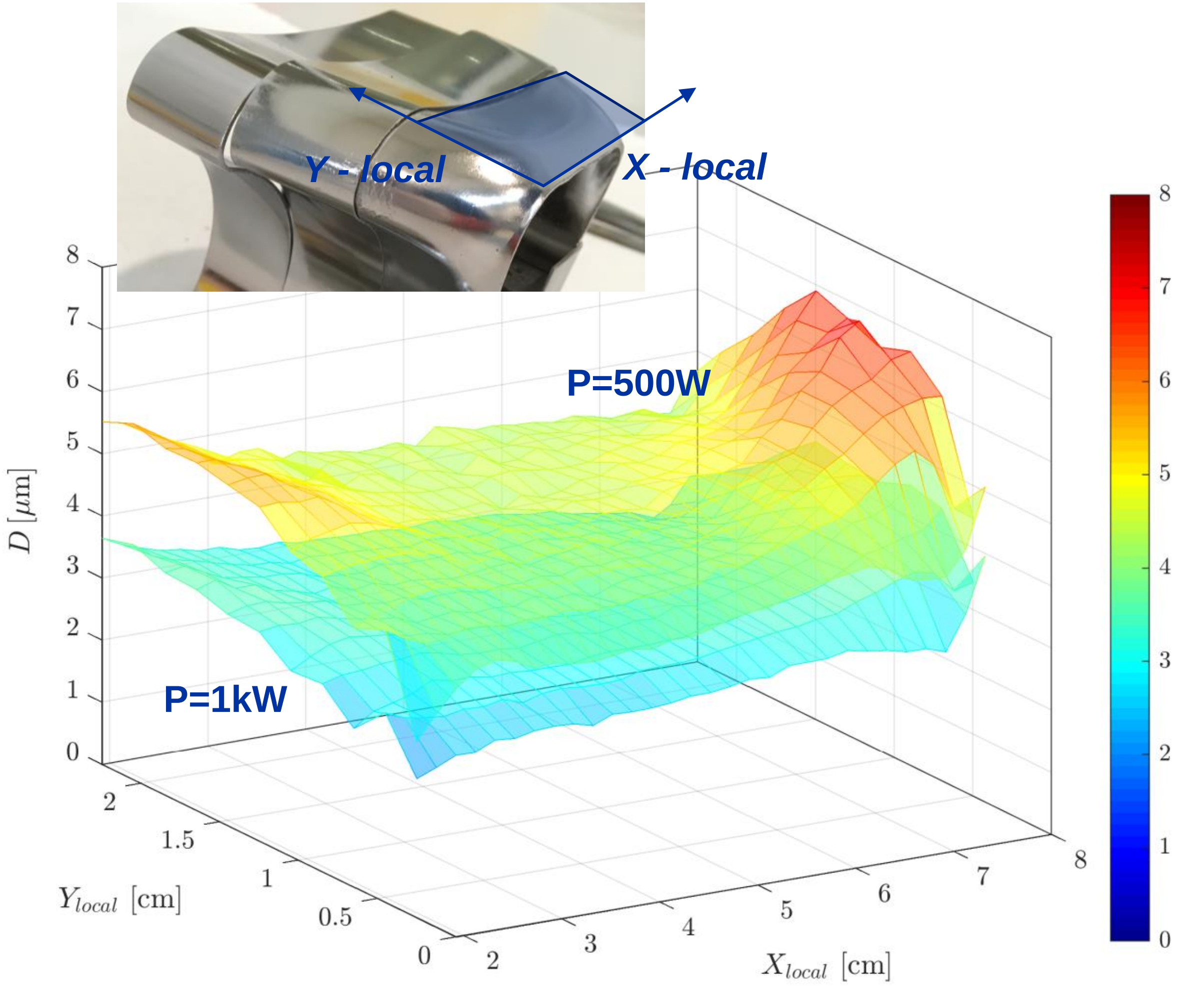
- **1kW coating with bulk magnet for 20 mins coating duration**

→ faster coating vs. higher heat load

- **Expect from basic scaling:**

$$\frac{D(1kW)}{D(500W)} \approx \frac{(P\times t)|_{1kW}}{(P\times t)|_{500W}} \approx 1$$

- **XRF thickness profile suggests coating rate is ≈ 20-30% lower**



2 Sequential coating heat loads

- Compare magnet and sample temperatures at 500W (dashed) and 1kW

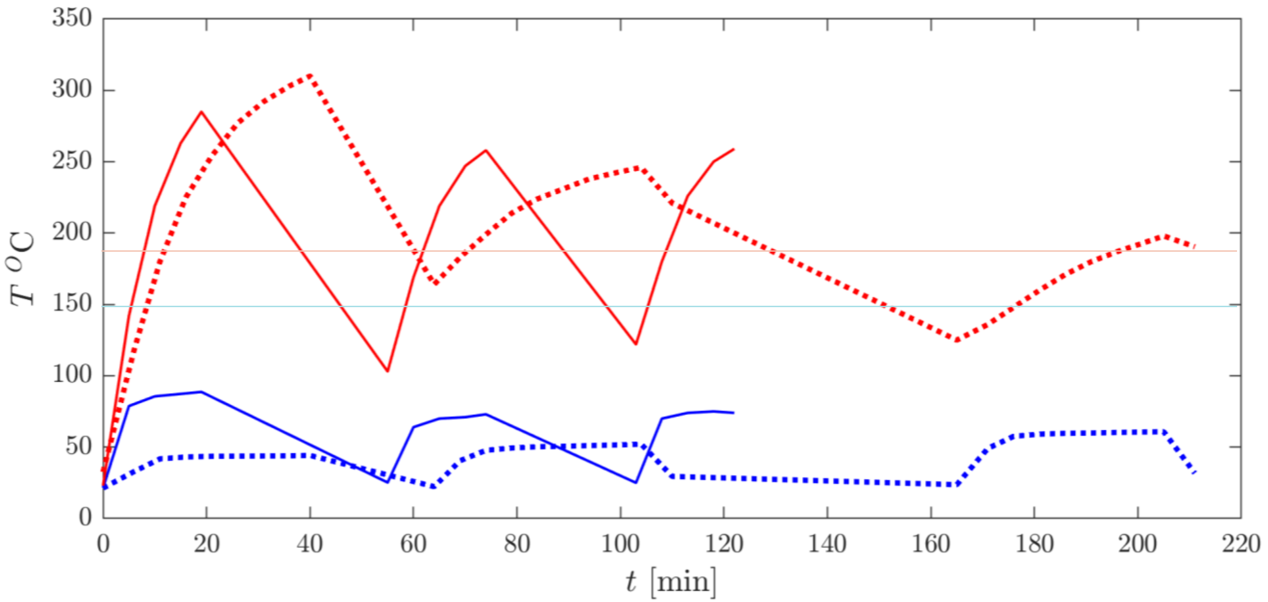
- Magnet below critical 150ºC

→ Air cooling sufficient

- Thin sample as *worst-case* scenario of bulk Cu cavity

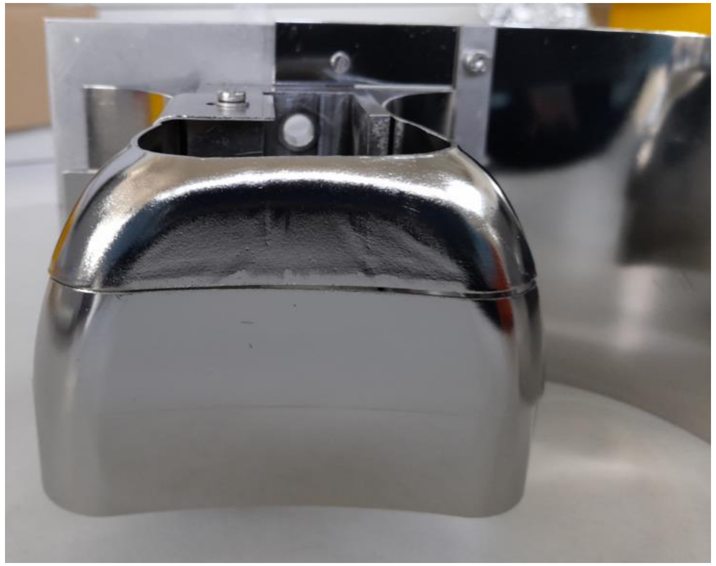
→ $\Delta T \propto P \times t \approx cst$

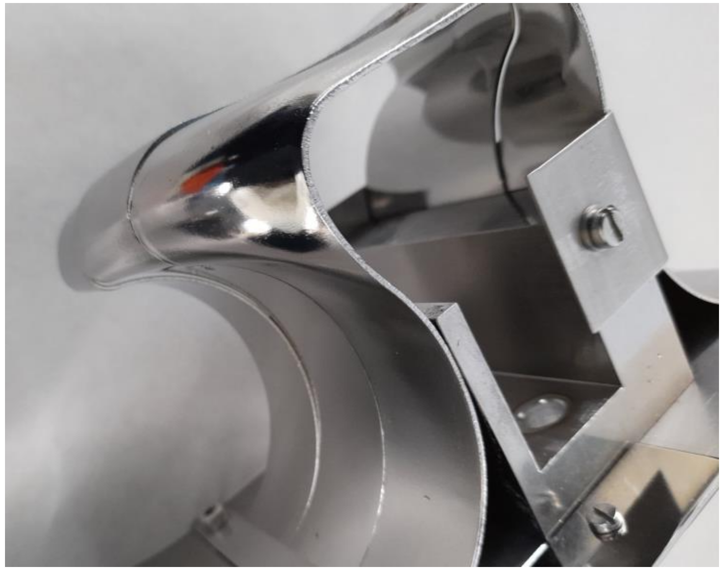
→ Exceed 180ºC of bake-out within few minutes !



2 Sequential coating heat loads

→ YET : have NO visible delamination, due to higher densities and Nb+ fractions

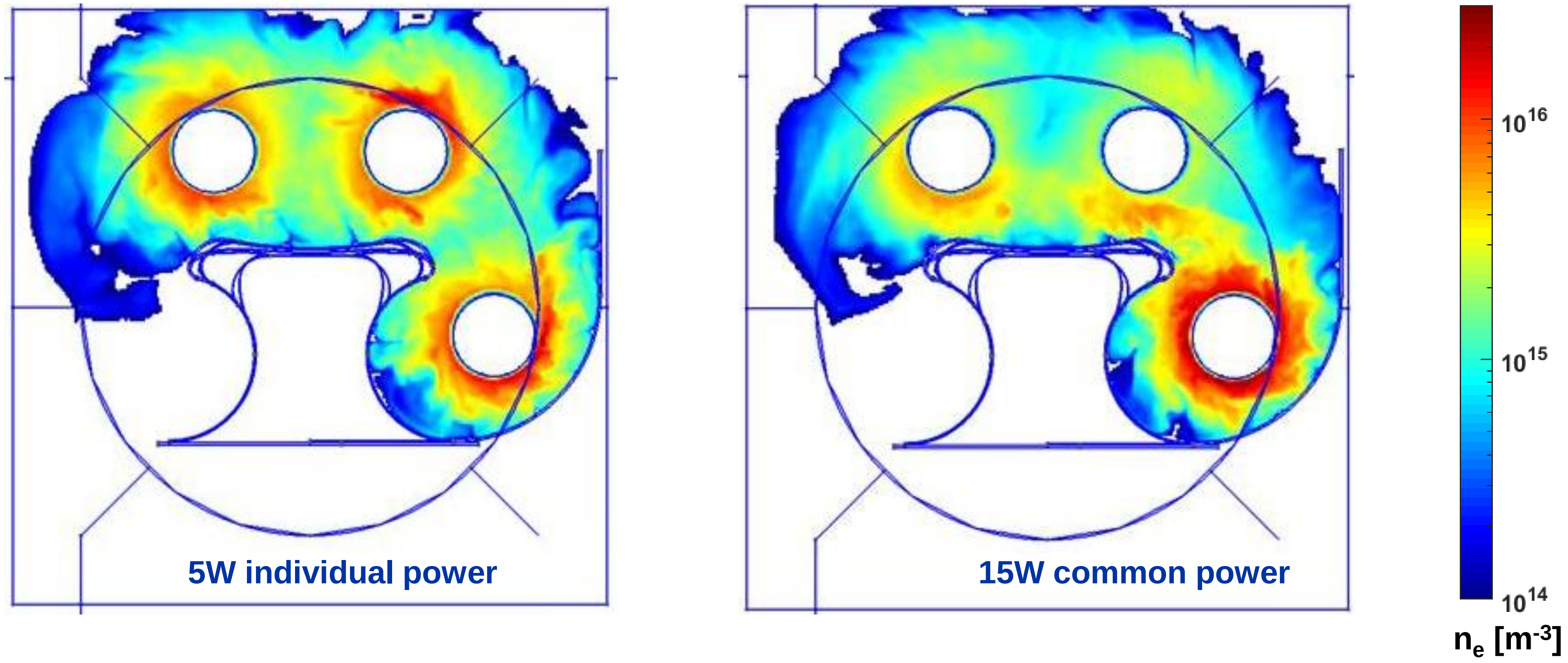




→ What about parallel coatings with 3 cathodes?

2 Parallel coating in DCMS

- **Particle-In-Cell Monte-Carlo simulations of low power plasmas**

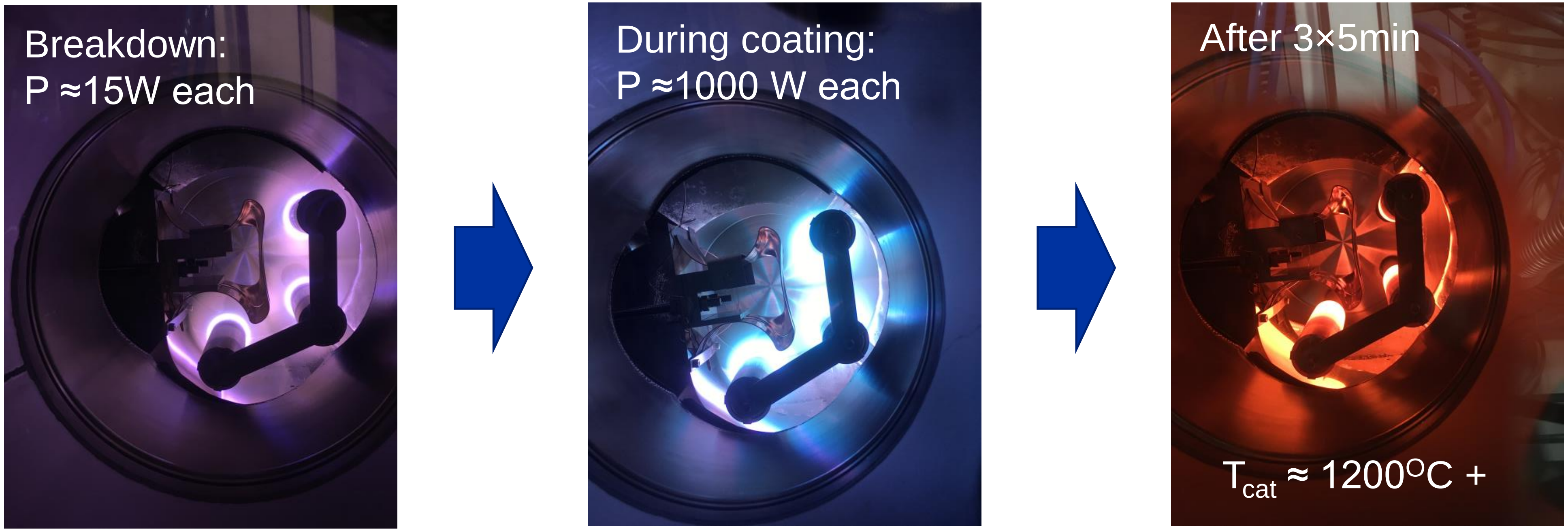


→ Confirms importance of individual powering

Preliminary result with [2], courtesy of T. Richard

2 Parallel coating in DCMS

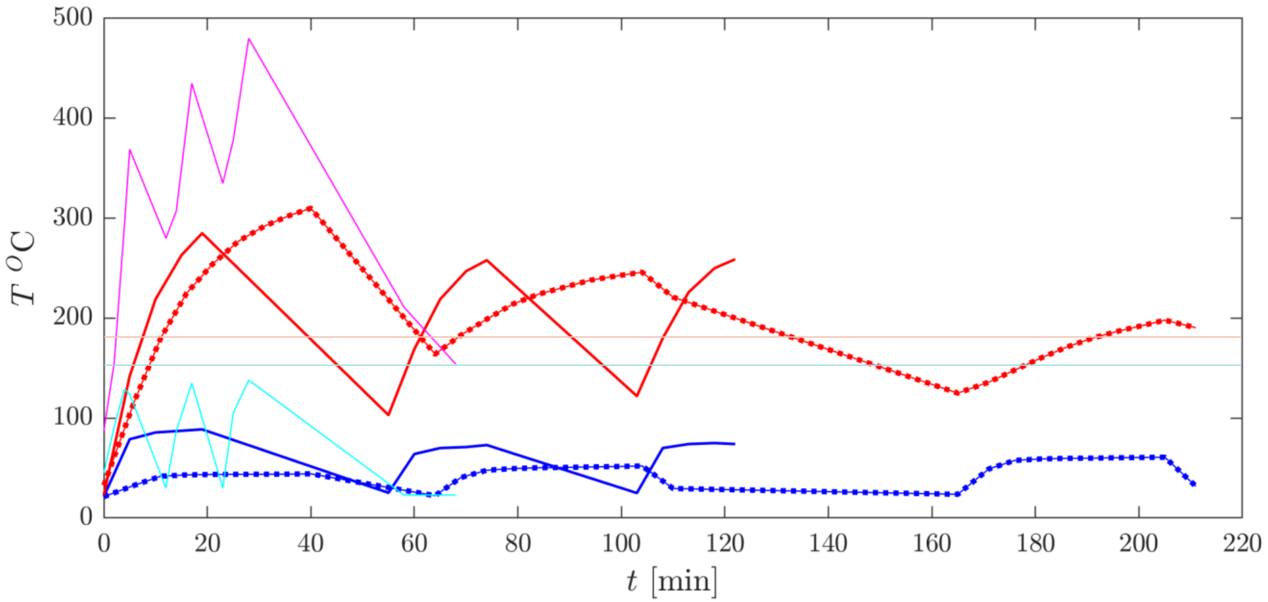
- **Upgraded 3-cathode mock-up with separate bias and cooling system**



→ Simulated V_c≈ 270 V matches experiment within <u>10%</u> at 15 W

2 Parallel coating in DCMS

- Again monitor magnet and sample temperatures



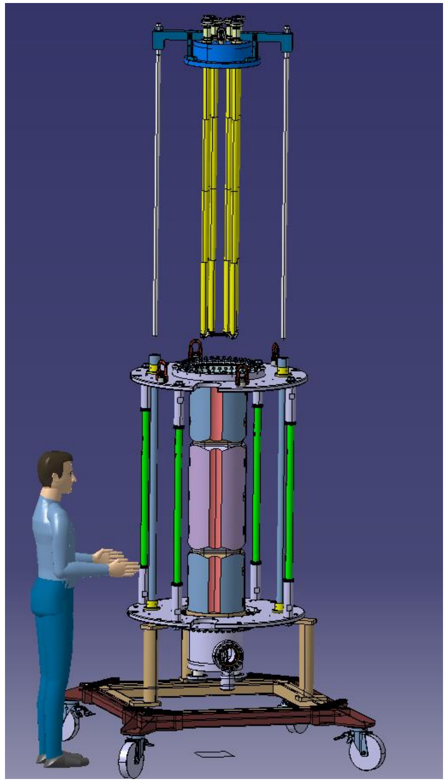
→ **Extreme heat-loads on samples after 2 minutes**

→ **Upcoming: ANSYS simulation of substrate transient temperatures**

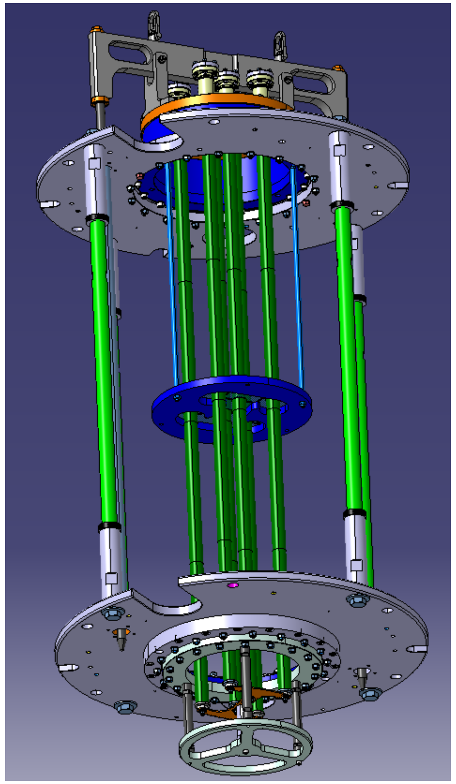
Outline

4 Full-scale design

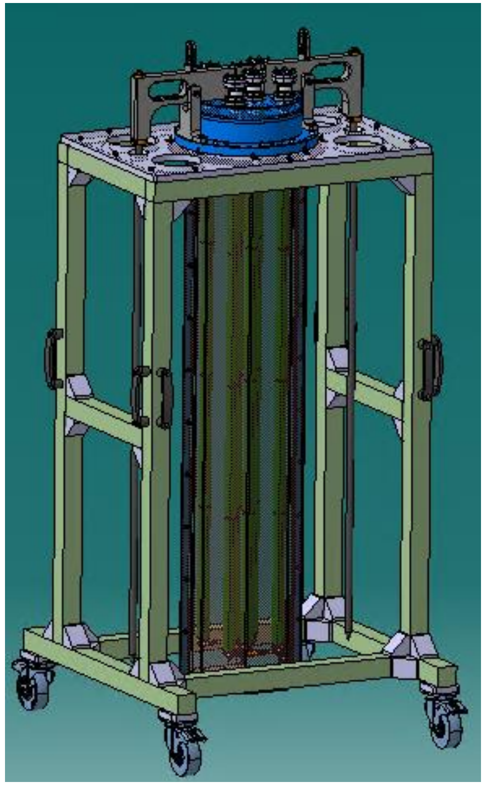
- **Currently validating multiple sub-projects, moving to implementation**



Cathodes during insertion (for scale)



Mock-up assembly



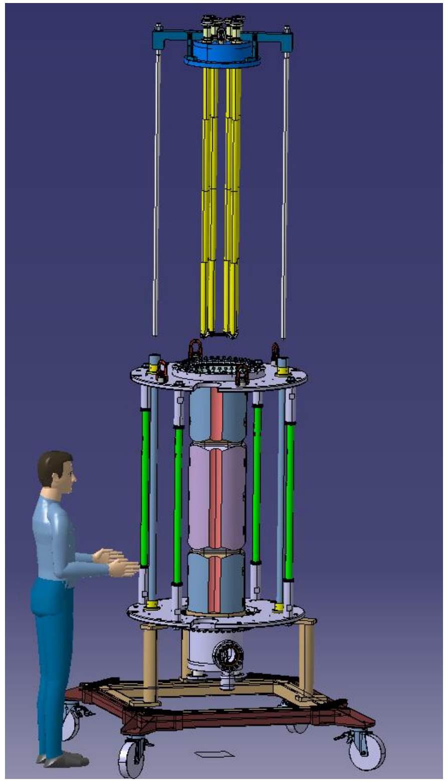
Transport and storage trolley

Courtesy T. Mikkola, G. Villiger

4 Full-scale design

- **Currently validating multiple sub-projects, moving to implementation**

- **Process tuning in 2021**
- **First coating: Q1 2022**



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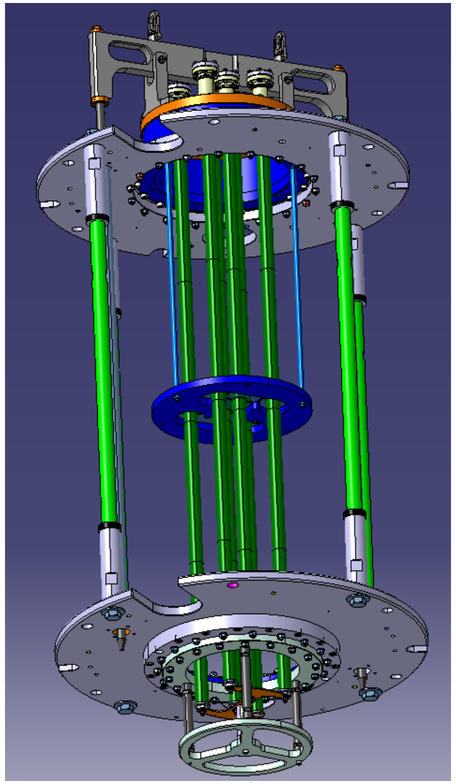

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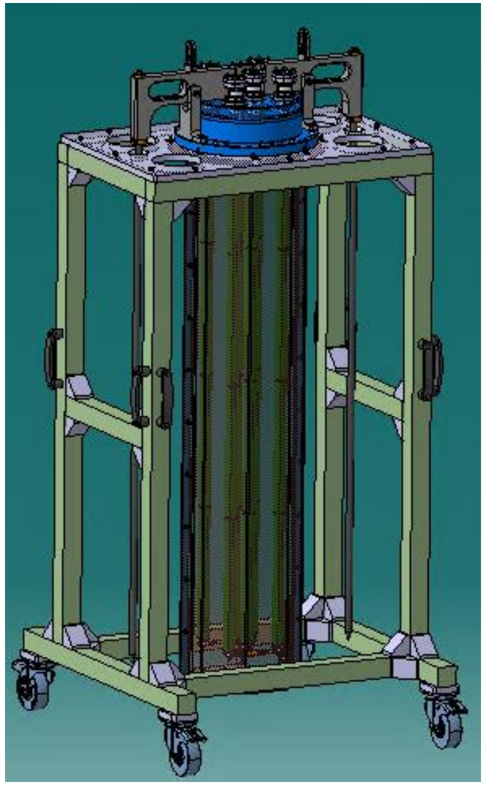

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Thank you for your attention !

Questions ?

Acknowledgements

- We thank the EN-MME group for the discussion and implementation of the full-scale WOWCC coating set up design and all related drawings – in particular: P. Naisson, G. Villiger, L. Dassa, F. Cottenot and formerly T. Mikkola

- Further thanks go to other members of the TE-VSC-SCC section for continued input and support on experimental work – most notably: P. Garritty, G. Rosaz, S. Fiotakis, L. Mourier and W. Vollenberg

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