# Development of coating system for the Wide Open Waveguide (WOW) crab cavity

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TTC, 5th February 2020

# Outline

- Introduction
  - The WOW cavity coating challenge
  - HiPIMS alternatives

- HiPIMS + positive pulse R&D
  1. Ion energy increase
  2. Film morphology
  3. SRF performances: QPR results

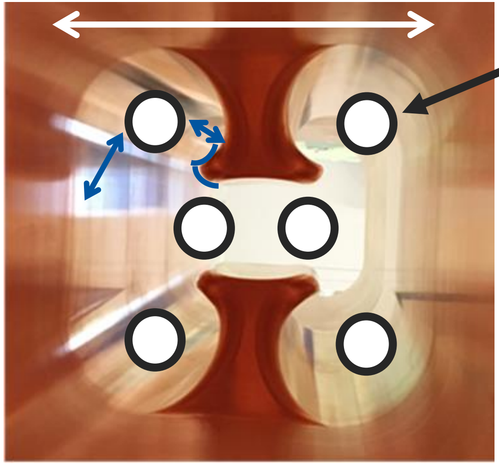
- Conclusions

# The WOW cavity coating challenge

Wide-Open Waveguide (WOW) crab cavity (Nb/Cu), 1st prototype completed in 2018.

1.4m / 290kg

252mm



x6 Cylindrical magnetrons

BUT!....

- Distances (20 – 80 mm)
- Angles of incidence (0 – 90°)

## Optimized features:

1. **Film thickness homogeneity** (coating setup design)
2. **Void-free Nb film** (technique)

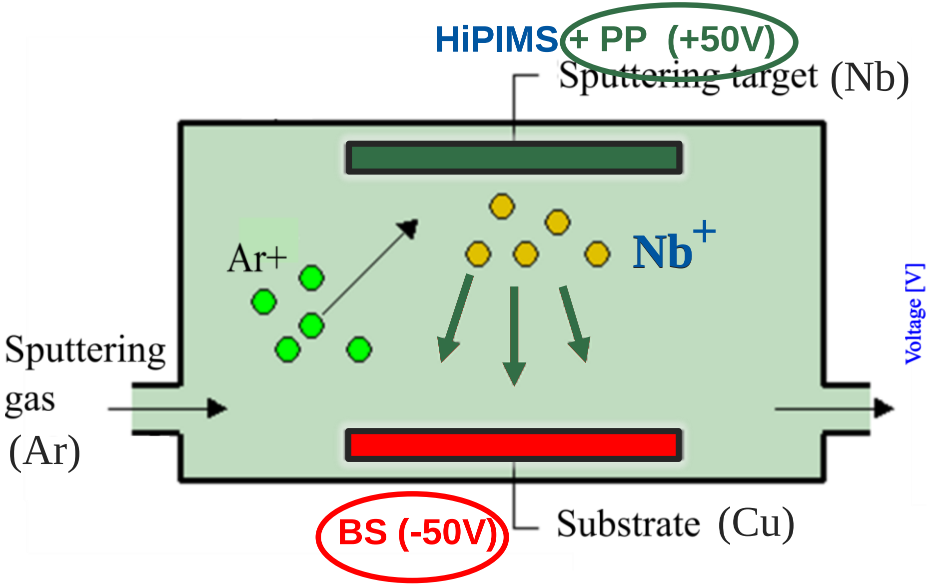
**HiPIMS** + 
- **negatively biased substrate**
- **positive pulse**

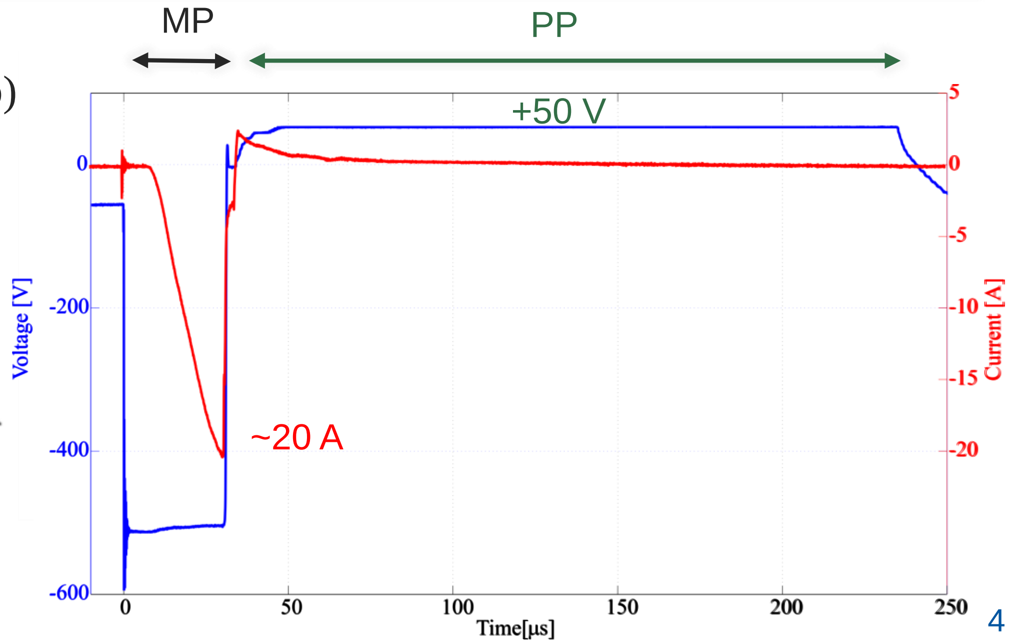
HiPIMS → More metal ions

negatively biased substrate / positive pulse → High energy metal ions to densify the film

# HiPIMS alternatives

1. **HiPIMS + negatively biased substrate (BS)**
2. **HiPIMS + positive pulse at the cathode (PP)** **PROMISING CANDIDATE?**



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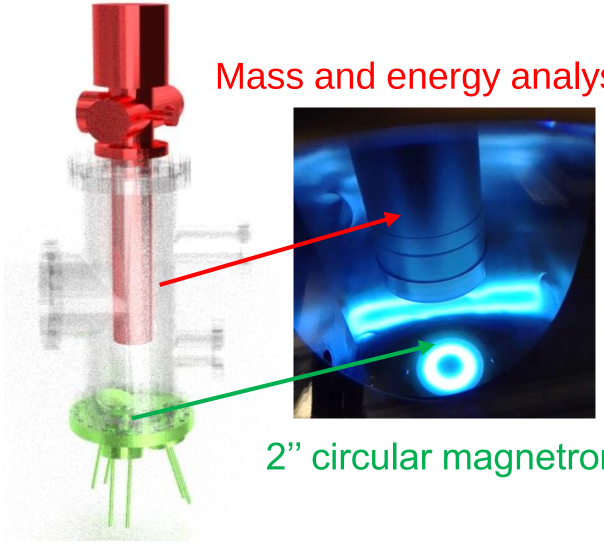
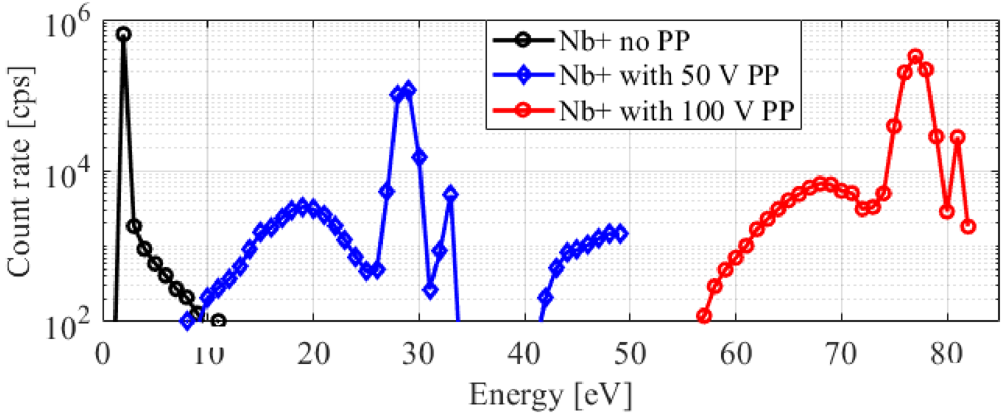
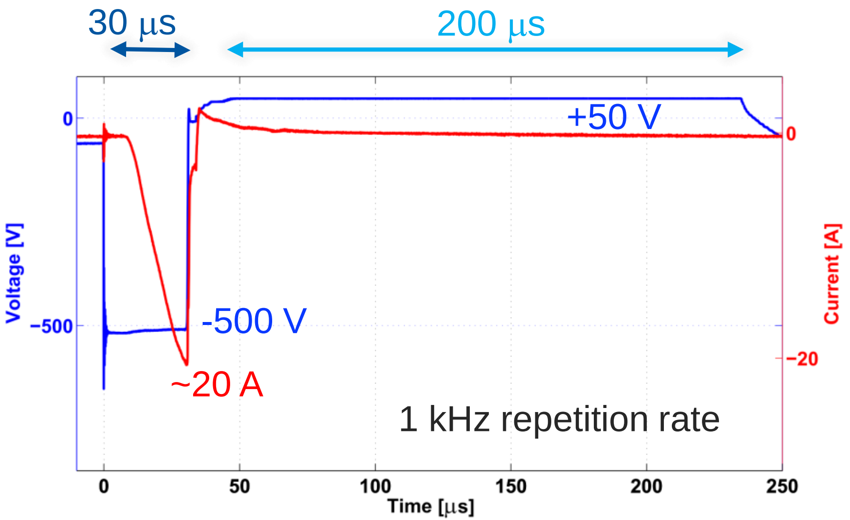
# 1.Ion energy increase by positive pulse



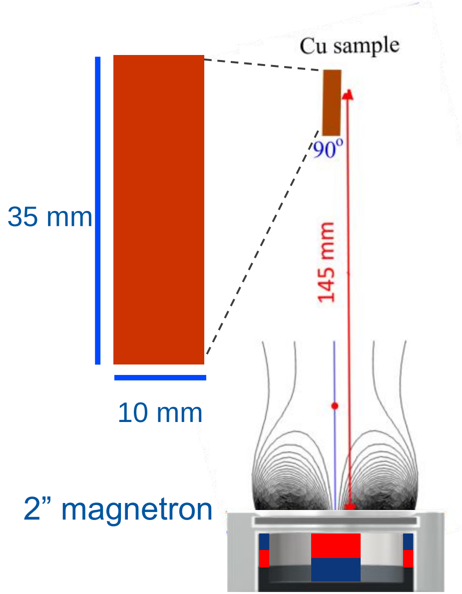



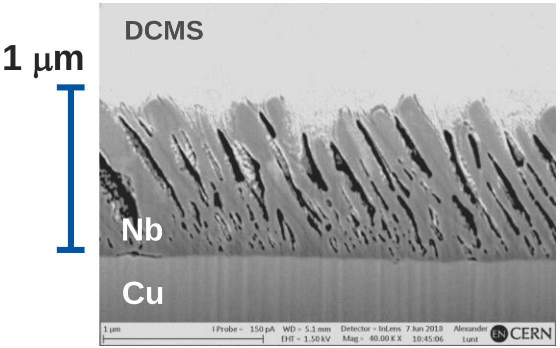

✓ Verified $Nb^+$ energy increase

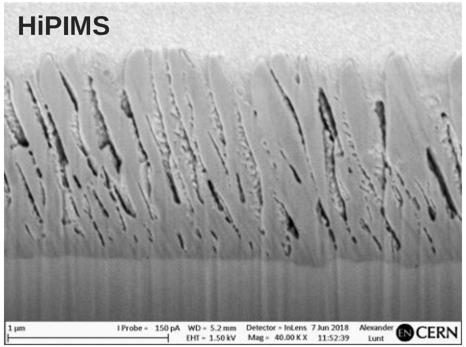
F. Avino *et al*, *Plasma Sources Sci. Technol.* **28** 01LT03, 2019

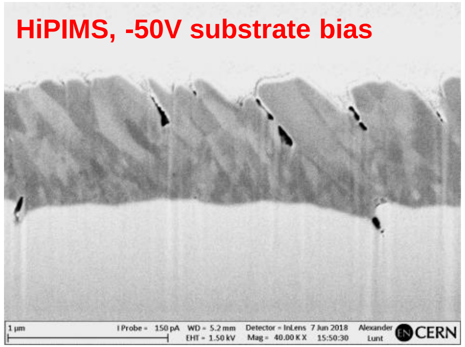
# 2. Film morphology

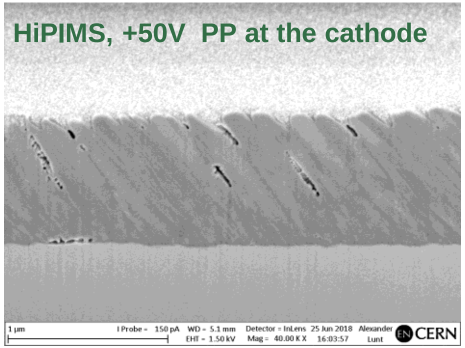
## FIB of flat samples at 90° incidence angle

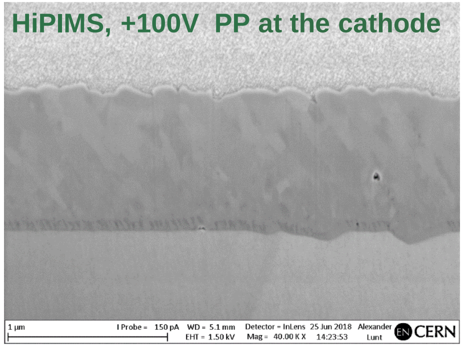


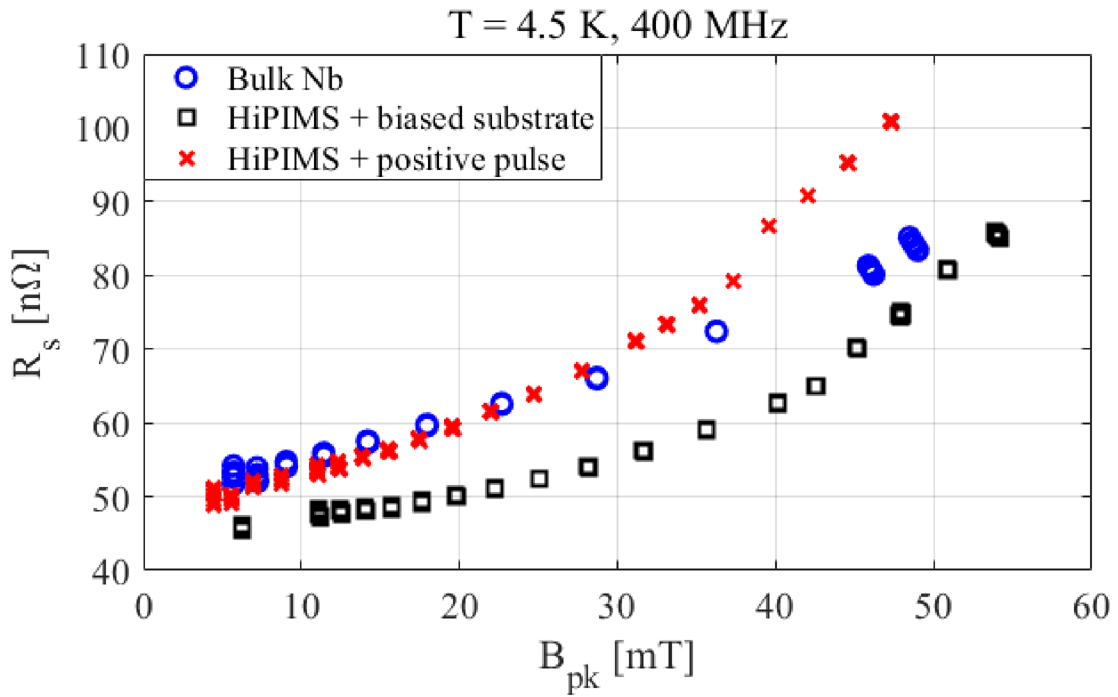



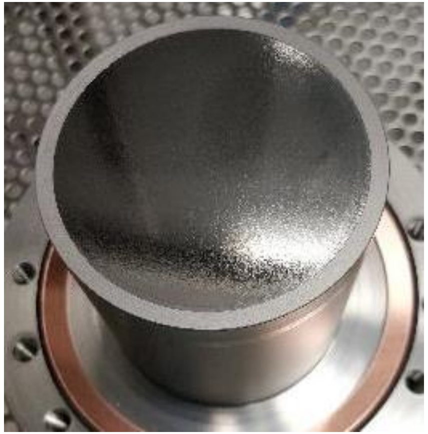

✓ Densification at 90° incidence angle in HiPIMS + PP

F. Avino *et al*, submitted to *Thin Solid Films*

# 3. SRF performances: QPR results




Nb/Cu coated QPR sample (0° incidence angle)



✓ Nb/Cu QPR samples in HiPIMS competitive with bulk Nb with 2 different recipes

# Conclusions

✓ Verified ion energy increase with HiPIMS + positive pulse

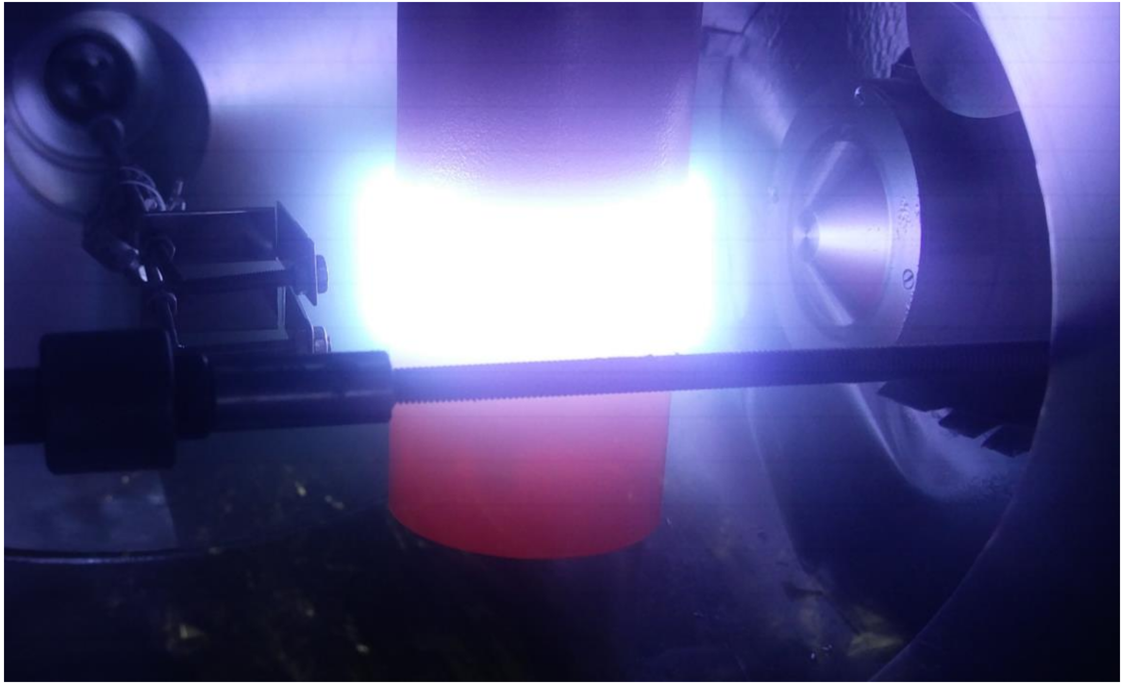
✓ Confirmed film densification on samples at 90°

✓ Nb/Cu QPR samples in HiPIMS competitive with bulk Nb

1st coating of the WOW crab cavity prototype scheduled for summer 2020

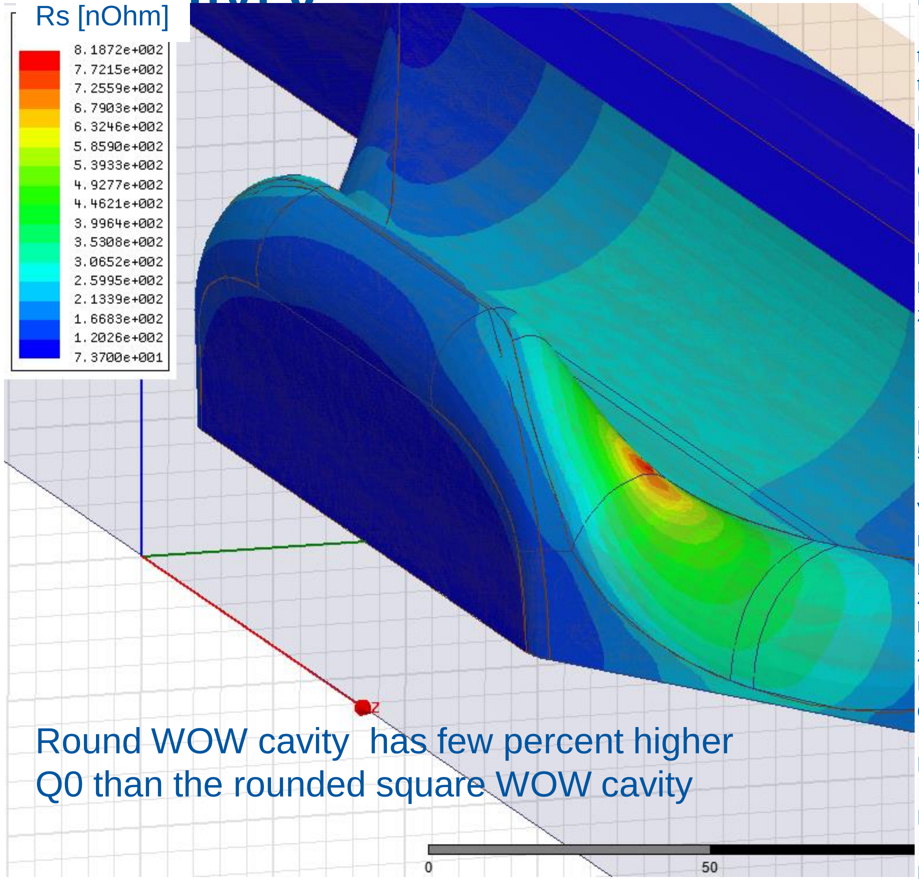
# Open questions:

1. Sputtering gas? (Ar / Kr)
2. Gas content measurements?
3. Gas content effects on SRF properties?
4. WOW cavity coating procedure (steps)?



# Rs distribution at Vx=3MV

2015/05/29




Round WOW cavity has few percent higher Q0 than the rounded square WOW cavity

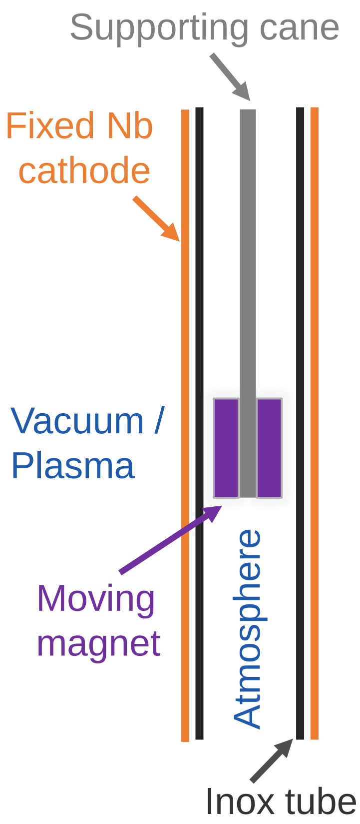
| | | WOW | RoundWOW |
|---|---|---|---|
| Parameter | Unit | | |
| | | VariaRR | VariaRR |
| tA | [deg] | 60 | 60 |
| tapering angle | [deg] | 30 | 30 |
| Lr | [mm] | 70 | 70 |
| b | [mm] | 124.68 | 142.035 |
| Q0_Cu | | 20820 | **21496** |
| Rx/Q | [Ohm] | 344 | 343 |
| Rx_Cu | [MOhm] | 7.17 | 7.37 |
| max(Esurf)/Vx | [1/m] | 15 | 15 |
| max(Hsurf)/Vx | [1/Ohm*m] | 0.018 | 0.018 |
| z0max(Hsurf)/Vx | [1/Ohm*m] | 0.012 | 0.012 |
| | | | |
| | | | |
| 100mT = 80kA/m | | | |
| Rs_Cu = 5.2mOhm | | | |
| | | | |
| Values for Vx=3MV | | | |
| maxEsurf | [MV/m] | 45 | 45 |
| maxHsurf | [kA/m] | 54 | 54 |
| z0maxHsurf | [kA/m] | 36 | 36 |
| maxBsurf | [mT] | 67.5 | 67.5 |
| z0maxBsurf | [mT] | 45 | 45 |
| Rs_Nb | [nOhm] | 270 | 270 |
| Q0_Nb@4K | | 400977778 | 413997037 |
| Rx_Nb@4k | [Ohm] | 1.379E+11 | 1.42001E+11 |
| Ploss@4k | [W] | 65.247483 | 63.37984263 |
| | | | |
| Rs_Nb(bsurf) [nOhm] = 54.7+19.0*exp(54*Bsurf[T]) | | | |
| | | | **54.8331929** |

# HiPIMS + BS / PP: pros & cons

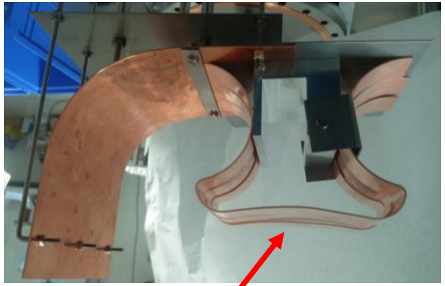
| Differences: | **Negatively biased substrate** | **Positive pulse** |
| --- | --- | --- |
| • Cavity bias: | Negative | **BEST CANDIDATE?** |
| • Number power supplies: | 2 | |
| • Magnetron design: | mobile / more complex | |

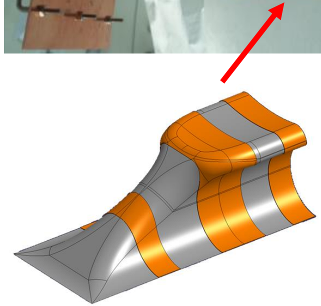
# 4. Film homogeneity on WOW samples

## WOW coating configuration with cylindrical magnetron (cathode OD = 51mm)



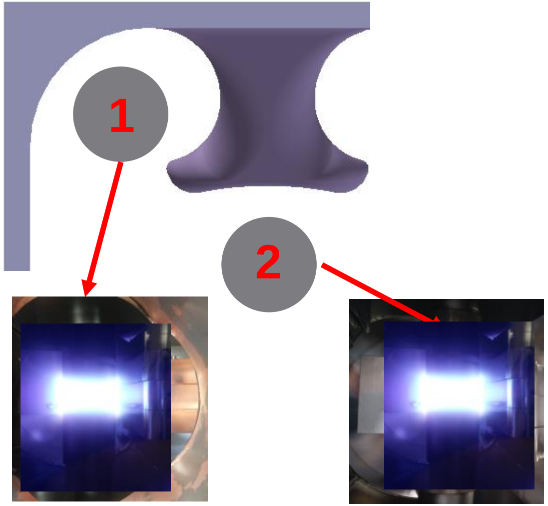

6-way cross setup

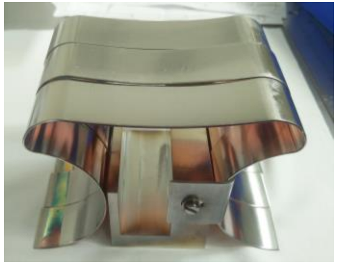




Copper samples reproducing the cavity center

~ ¼ of cavity

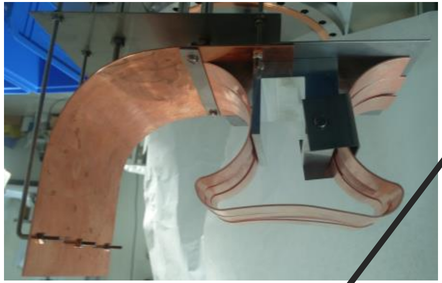


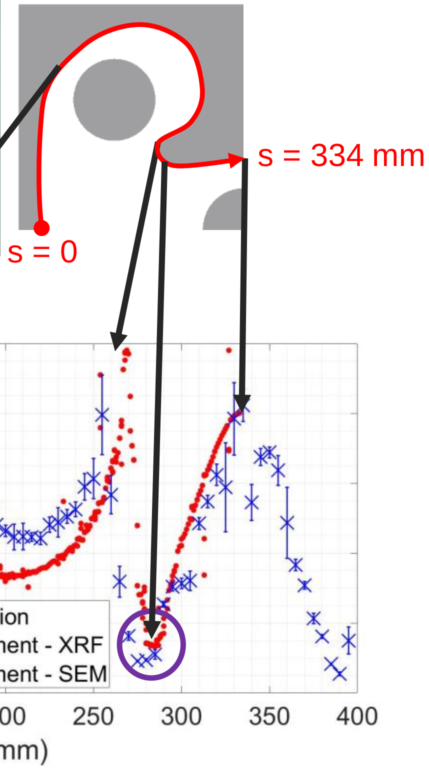



# Comparison of exp. vs sim. thickness profiles

PICMC/DSMC parallel code installed on CERN High Performance Computing cluster

→ Predict plasma parameters
→ Predict thin film thickness profile






Predictive, despite sim = DCMS / exp. = HiPIMS:

- location of thickness' maxima
- location of thickness' minimum

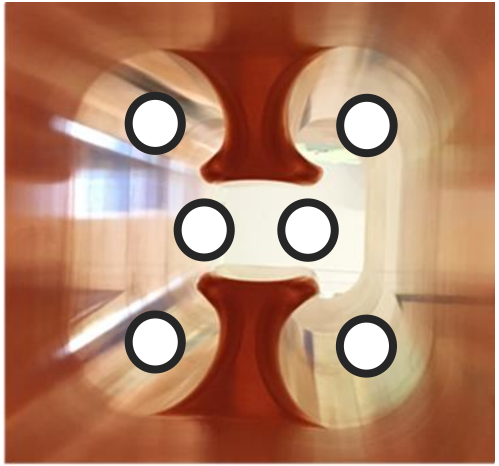
✓ Assessed 5 cathodes config:
max/min thickness = 8

Minimum = 1 μm ⟶ Maximum = 8 μm

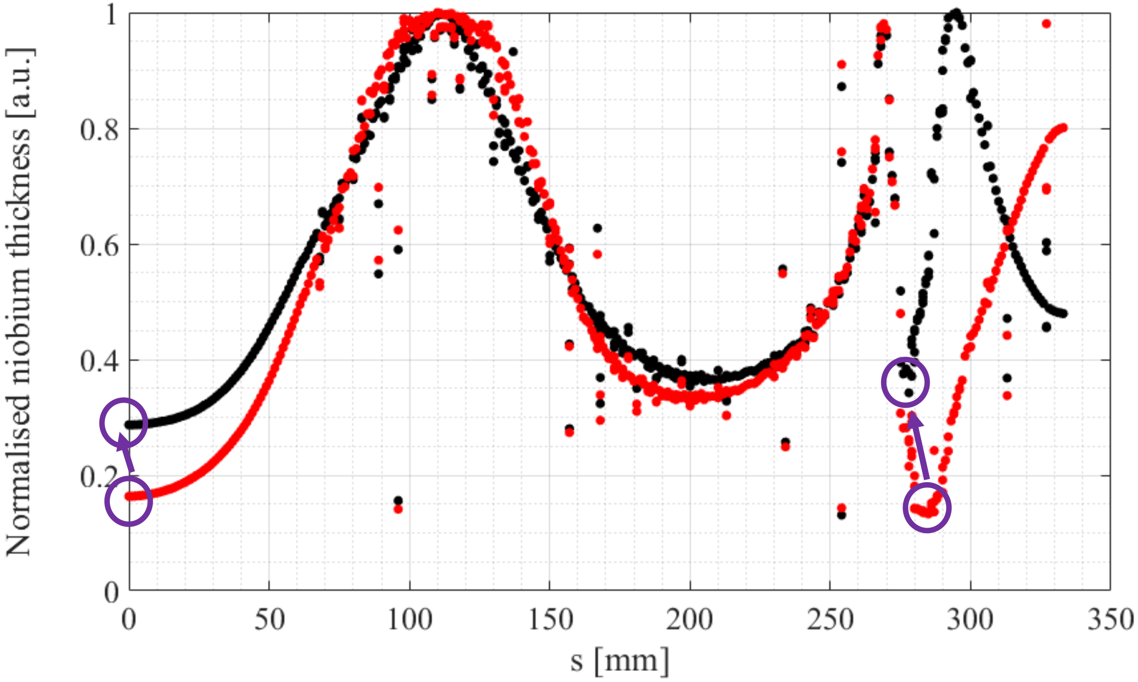
# Final configuration with 6 cathodes

From 5 cathodes config.

To 6 cathodes config.



Simulated profiles

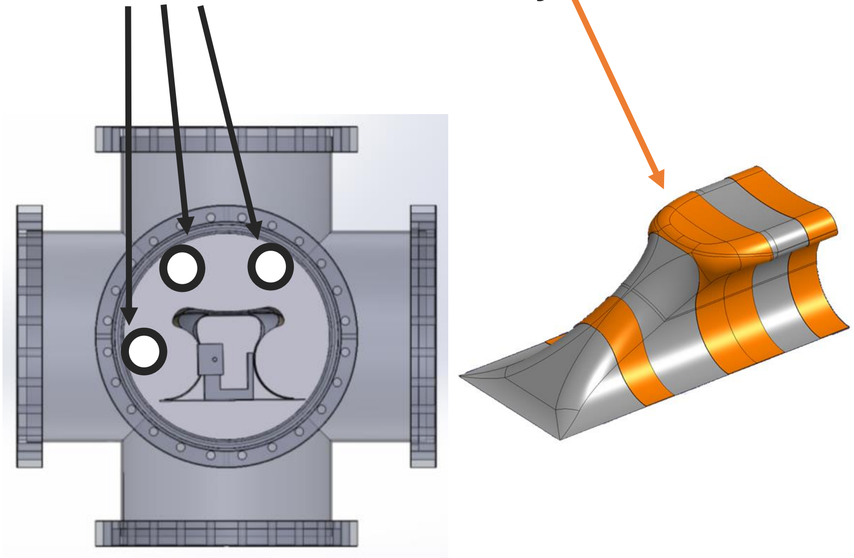



6 cathodes configuration: simulated max/min thickness ratio = 3

# 5. Future R&D

## Experiments:

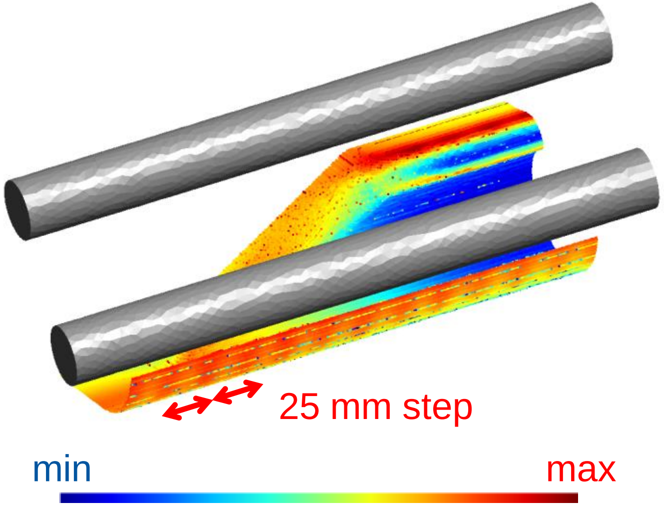
Coatings of WOW samples with
3 cathodes in the 6-way cross



- Confirm thickness profile and max/min ~ 3
- Magnetic & plasma cross talk
- Adhesion tests

## Simulations:

- Optimization axial steps



# Simulation code and modelling workflow

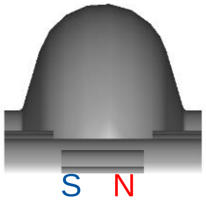
- Requirements:
  - Suitability for low pressure processes ($10^{-4}$ – $10^{-1}$ mbar)

    → Boltzmann equation solver
  - Computational efficiency
- PICMC/DSMC[1] parallel code[2] installed on CERN High Performance Computing cluster

**Input parameters :**

- **System geometry**
- Process pressure
- Discharge power
- **Target material**
- Sputtering gas
- **Magnetic configuration**

Example:
1.3 GHz elliptical cell

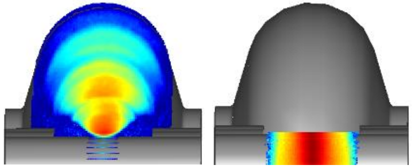



**PICMC:** Plasma module

→ Discharge current/voltage

→ **Plasma densities**/energies

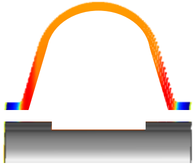
→ **Sputtered atoms fluxes**



**DSMC:** Neutral transport module

Deposited atoms properties

→ **Fluxes**, angles/energies



→ Predict **plasma parameters**

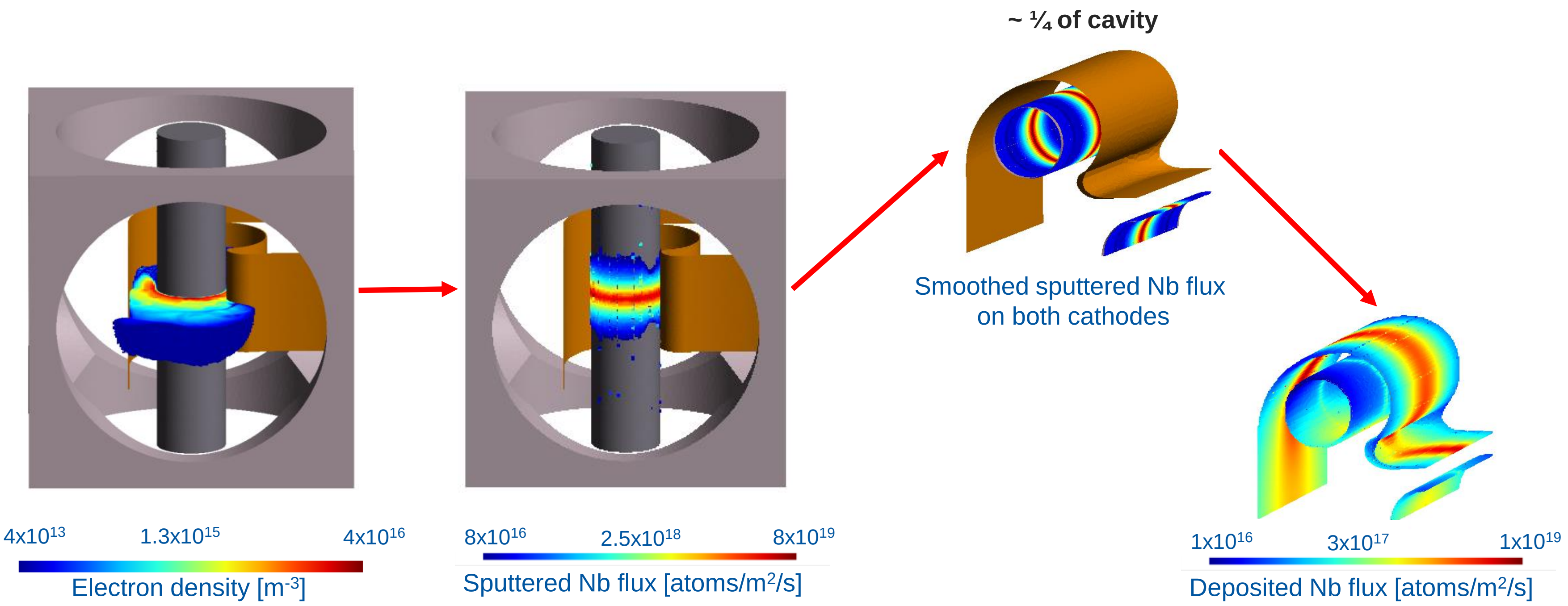
→ Predict thin film **thickness profile**

→ Estimate **absolute thickness**

[1] *Particle-In-Cell Monte Carlo/ Direct Simulation Monte Carlo*

[2] *Fraunhofer IST, https://www.ist.fraunhofer.de/en/our-services/simulation.html*

# WOW cavity: simulation process - DCMS

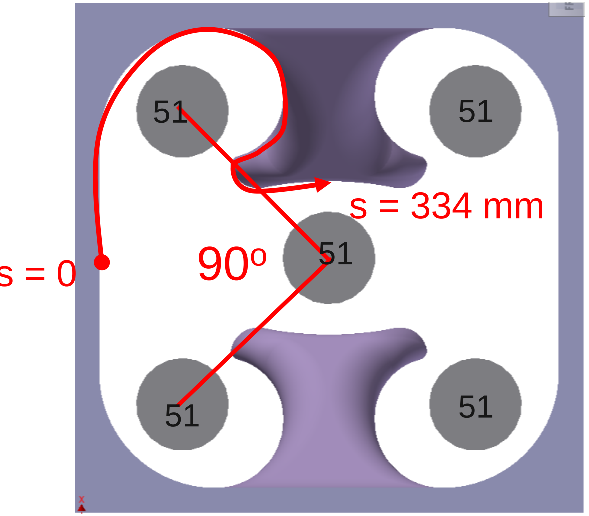



$P_{Ar} = 8.10^{-3}$ mbar, 10 W

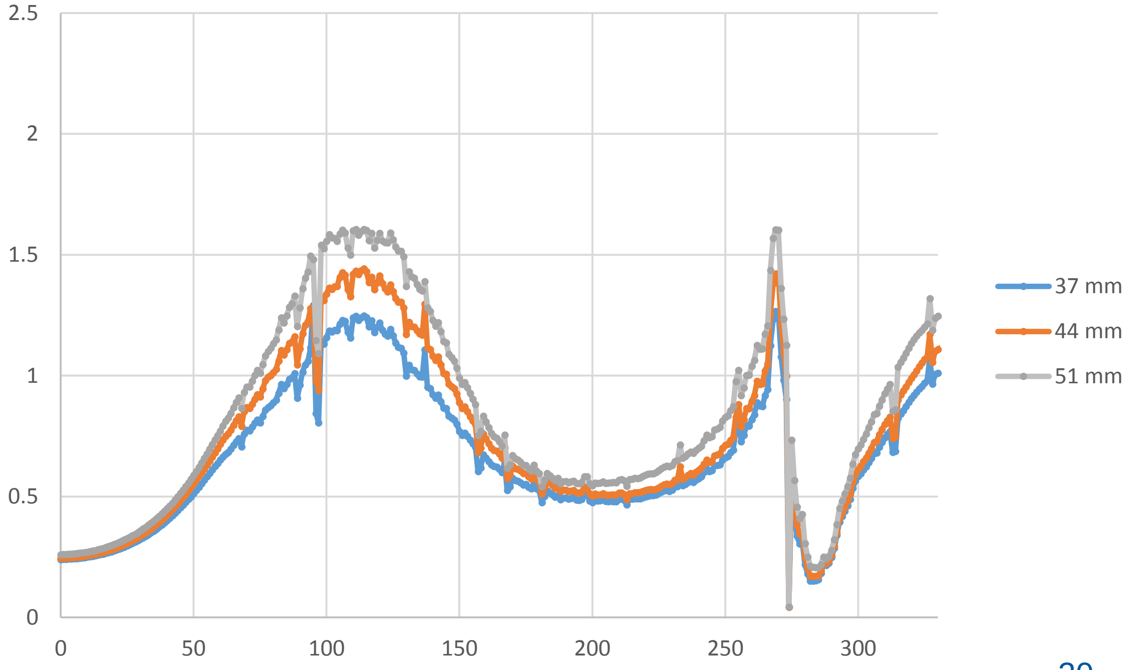
# Do we need to reduce the max/min ratio? If yes how?

## a) x5 cathodes: OD scan 37,44,51 mm

- Based on plasma sim for OD44 on excentered cathode at $5.10^{-3}$ mbar
- Sputtering profile extrapolated for other OD, while total flux constant
- Final thickness profile reconstructed from transport sim on 2 cathodes



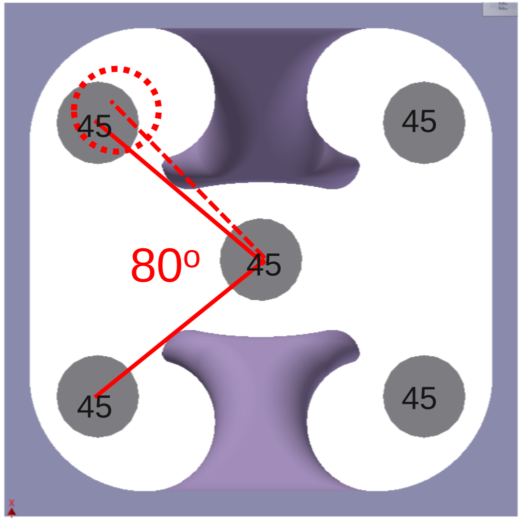

No significant changes



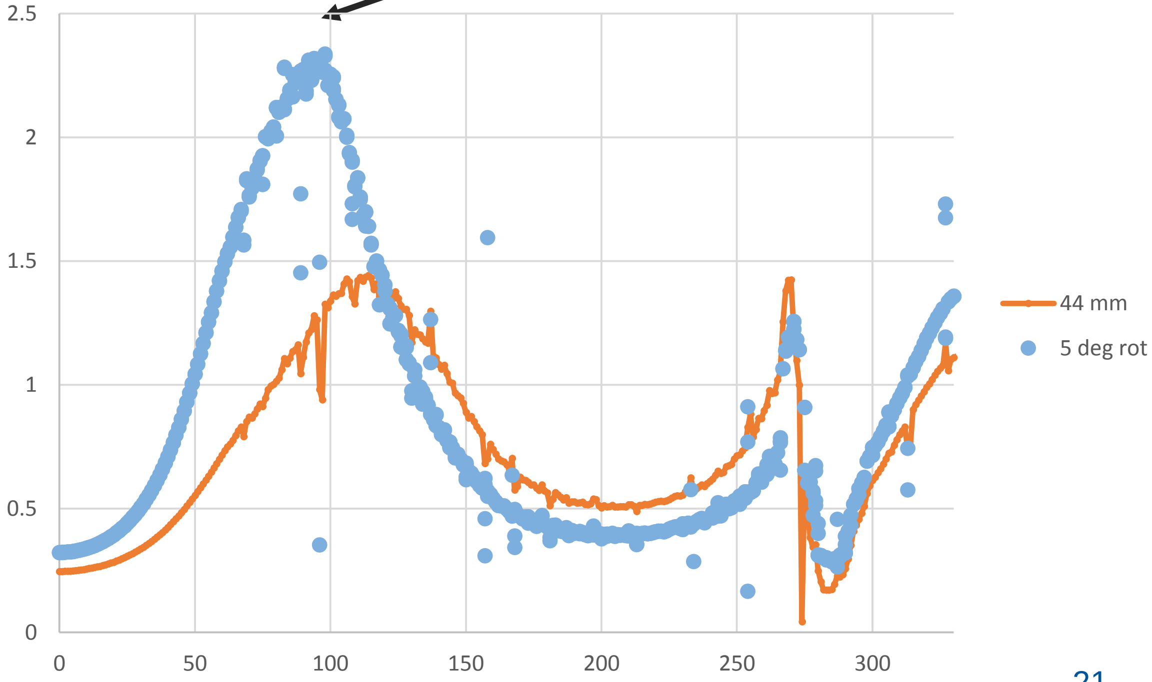
# Do we need to reduce the max/min ratio? If yes how?

## b) x5 45mm OD: side cathode rotation by 5º

From sixWayCross plasma sim profile at $8.10^{-3}$ mbar



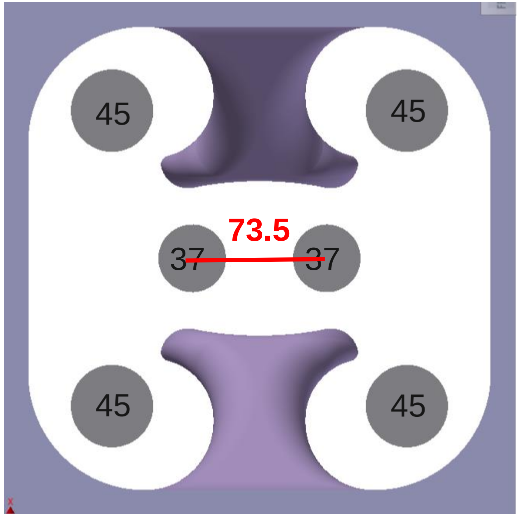

Worse with rotation



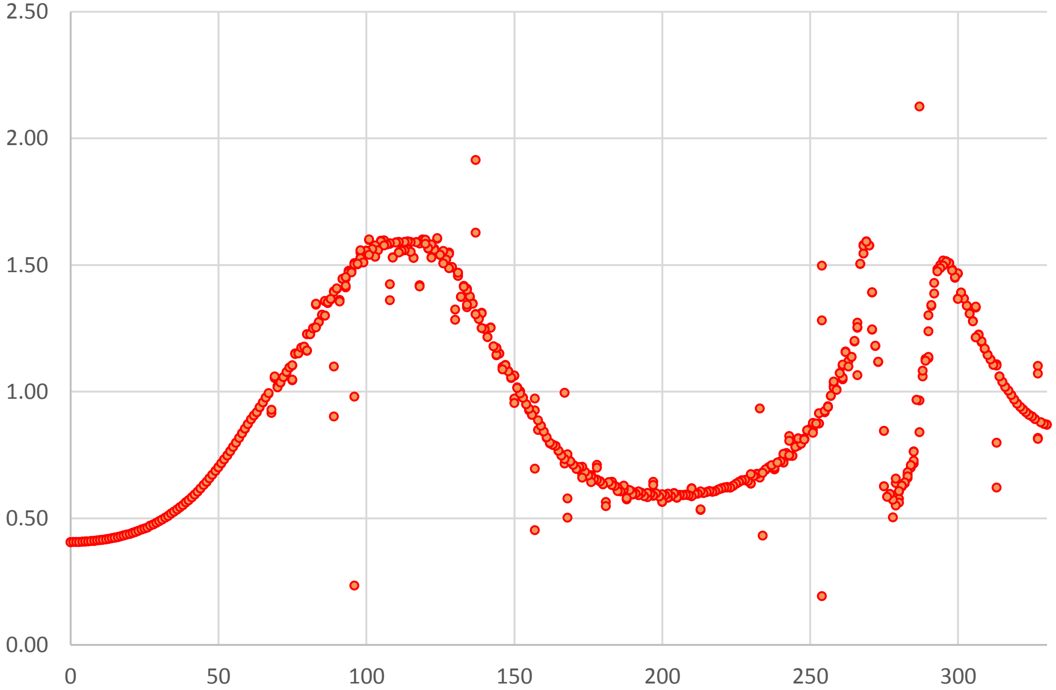
# Do we need to reduce the max/min ratio? If yes how?

## c) Replacing central cathode with x2 37mm OD cathodes

- Under assumption that total sputtering flux is independent from Ø

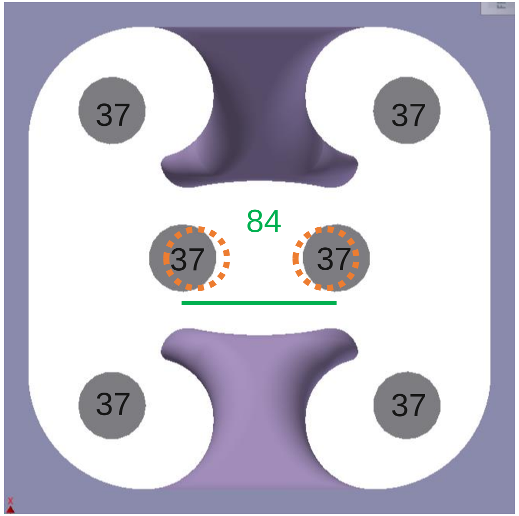


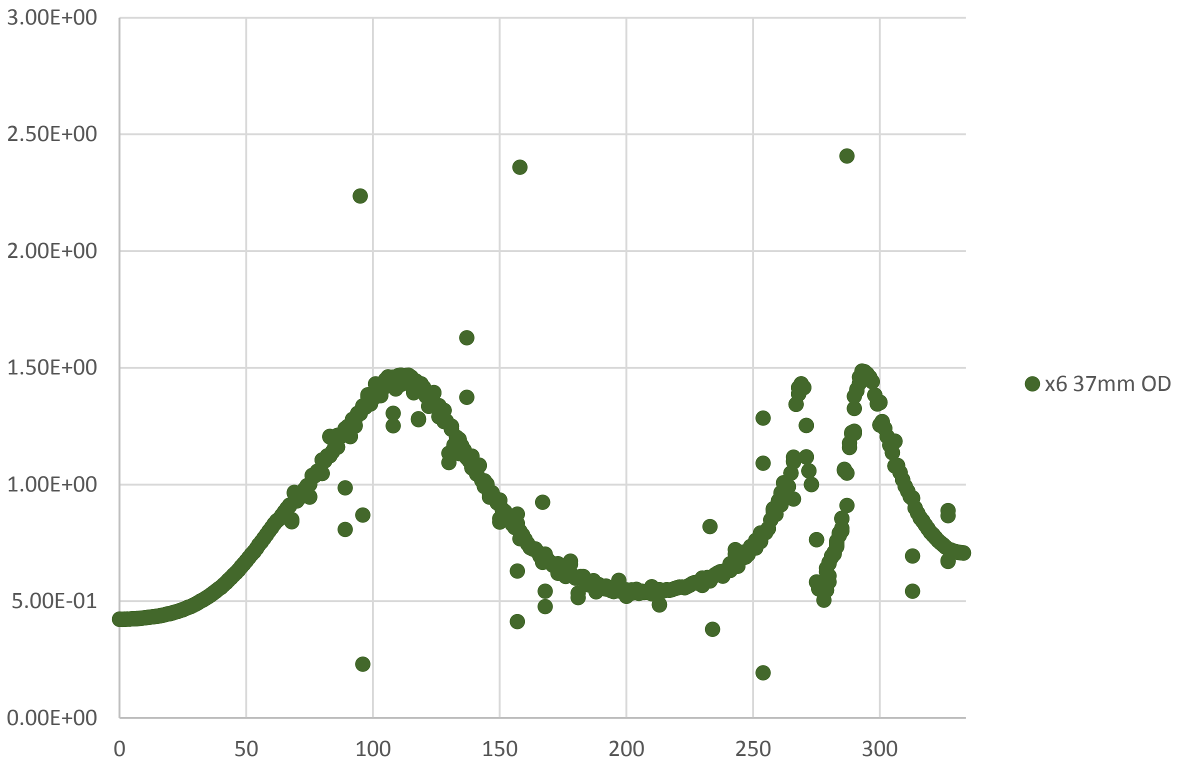

Max/min ration = 3



# Do we need to reduce the max/min ratio? If yes how?

## d) x6 cathodes OD 37mm

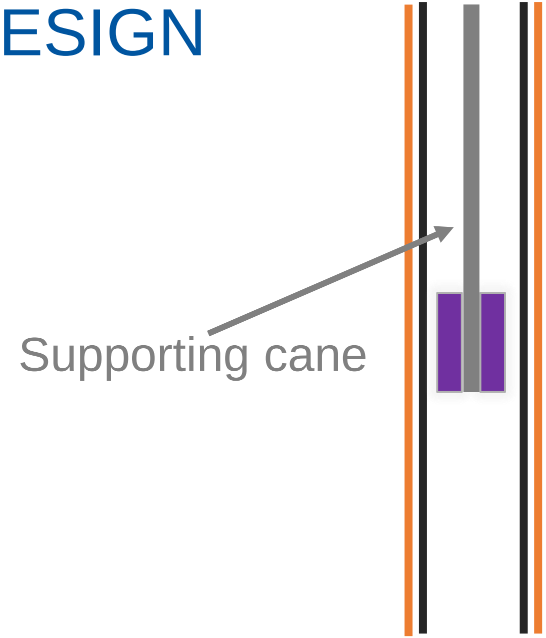



Max/min ration = 3

# FINAL CATHODE DESIGN

x6 cathodes (DN40 flanges on DN350 flange).
Constraint of DN40 breakers (ID 31.8mm)




**STAINLESS STEEL TUBE (std)**

- OD = 30 +- 0.1 mm
- Thickness: 1.5 mm
- ID = 27 +- 0.2 mm

**MAGNET**

- OD = 24 +- t.b.d. (to allow water/air circulation)
- ID = 8 +- t.b.d.

**CATHODE**

- OD = 36 +- 0.2 mm
- ID = 30.5 +- 0.2 mm
- Length = 400 mm (x4)