CERN

Experiments and modelling for glow discharge plasmas applied to sputter deposition in superconducting radiofrequency cavities

Review of PhD first year

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VSC Seminar - 22.01.2016

Outline

I. Context and objectives
   1. Thin-film coating for SRF cavities
   2. Motivation for numerical simulations

II. First results
   1. Experimental system
   2. Study of sputtered atoms transmission
   3. First plasma simulations

III. Future experimental upgrades and simulation plan

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Thin-film coating for SRF cavities

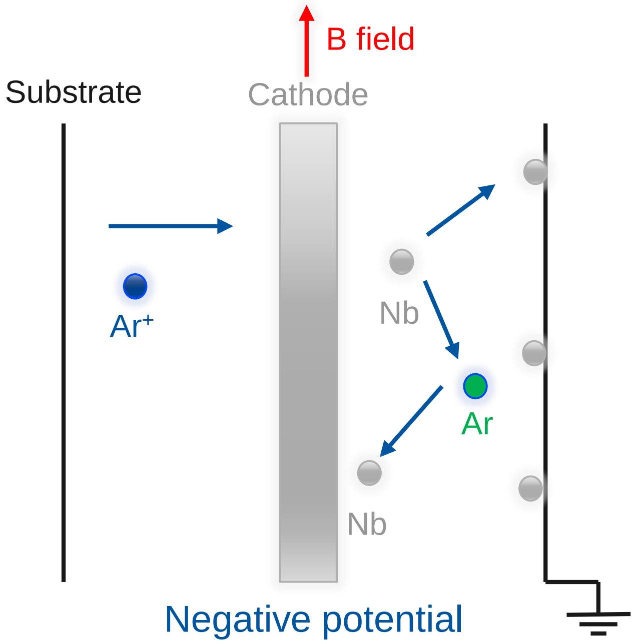
- Superconductive Radio-Frequency cavities used for particle beam acceleration

- Study focused on niobium-on-copper thin film coating

- Different plasma-based sputtering techniques used :
  - DC diode
  - DC magnetron

Principle of plasma-based sputtering

- Sputtering : removal of atoms from a target by particle bombardment
- In our case, the sputtering source is the ions from the glow discharge plasma
- For rotational symmetry geometries (e.g. tubes, some RF cavities…), a cylindrical electrode configuration is desirable



DC cylindrical diode

- No magnetic field
- “High” pressure
- Low deposition rate

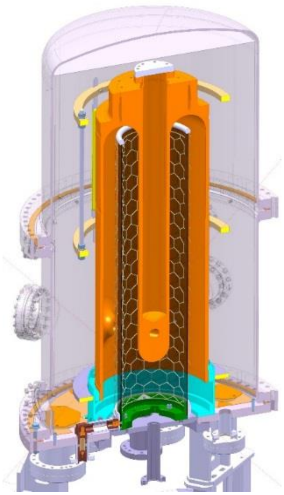
DC cylindrical magnetron

- Axial magnetic field
- Lower pressure
- Higher deposition rate
- **B** : increase electron path before collection on electrodes

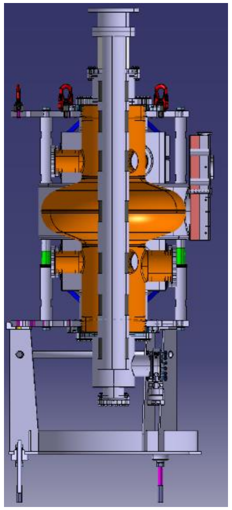
Motivation for numerical simulations

- Optimize the coating parameters while reducing the R&D trial-and-error phase:
  - Uniformity of film thickness on different complex geometries
  - Bombardment of particles…
  - … and energy/angle of sputtered atoms influencing the film growth

➢ Numerical modelling from plasma generation to niobium transport



HIE-ISOLDE type



LHC type

Approach

Input parameters :
- Given geometry, e.g. SRF cavity
- Pressure
- Power
- *Magnetic field …*

Experiment

Simulation

Physics

Numerical model
- Electromagnetic solver
- Particle "pusher"
- Reactions on surfaces and in buffer gas …

Outputs
- Plasma characteristics (density, impedance, …)
- Thin film characteristics (thickness, morphology, …)

Benchmarking of the numerical model on a simple geometry

Prediction for real complex geometries

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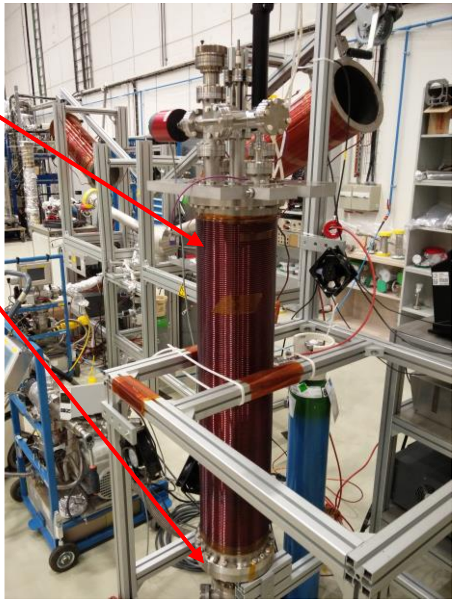
Experimental System

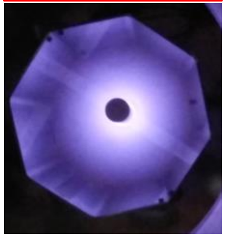
Aim : provide data for comparison with simulations

UHV chamber with solenoid



Installed in building 181

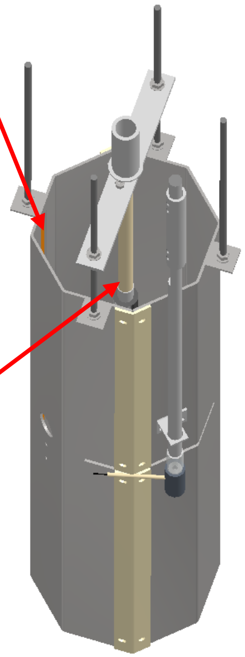
Viewport

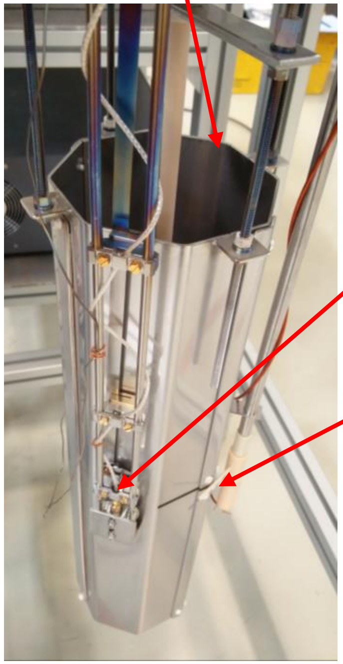


Copper strip for thickness profile

Octagonal anode (500 mm height)

Niobium cathode (303 mm length)
- DC bias diode
- DCMS





Instruments:
RFEA (ion energy on substrate)
Quartz balance (deposition rate)

Langmuir probe (plasma density)

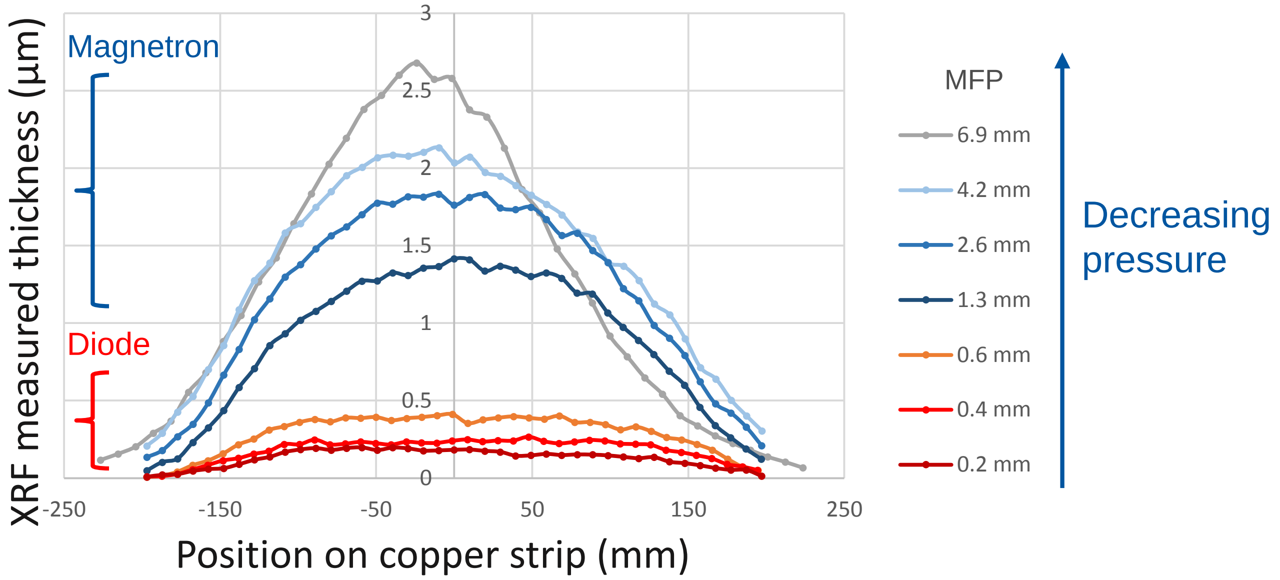
And current / voltage probes

Study of sputtered atoms transmission: experiment

- Aim : evaluate the effect of collisions (i.e. pressure) on niobium transport and compare with simulations

- Input parameters:
  - Constant power (100 W) and coating time (5 hours)
  - 7 different pressures (from 1,5.10^{-2} mbar to 0.65 mbar)

- Conversion of pressure into mean free path of niobium sputtered atoms in the argon buffer gas
  - $mfp = \frac{4k_B T}{\pi\sqrt{2}P(\delta_{Nb}+\delta_{Ar})^2} \propto \frac{1}{P}$



First approach on numerical modelling

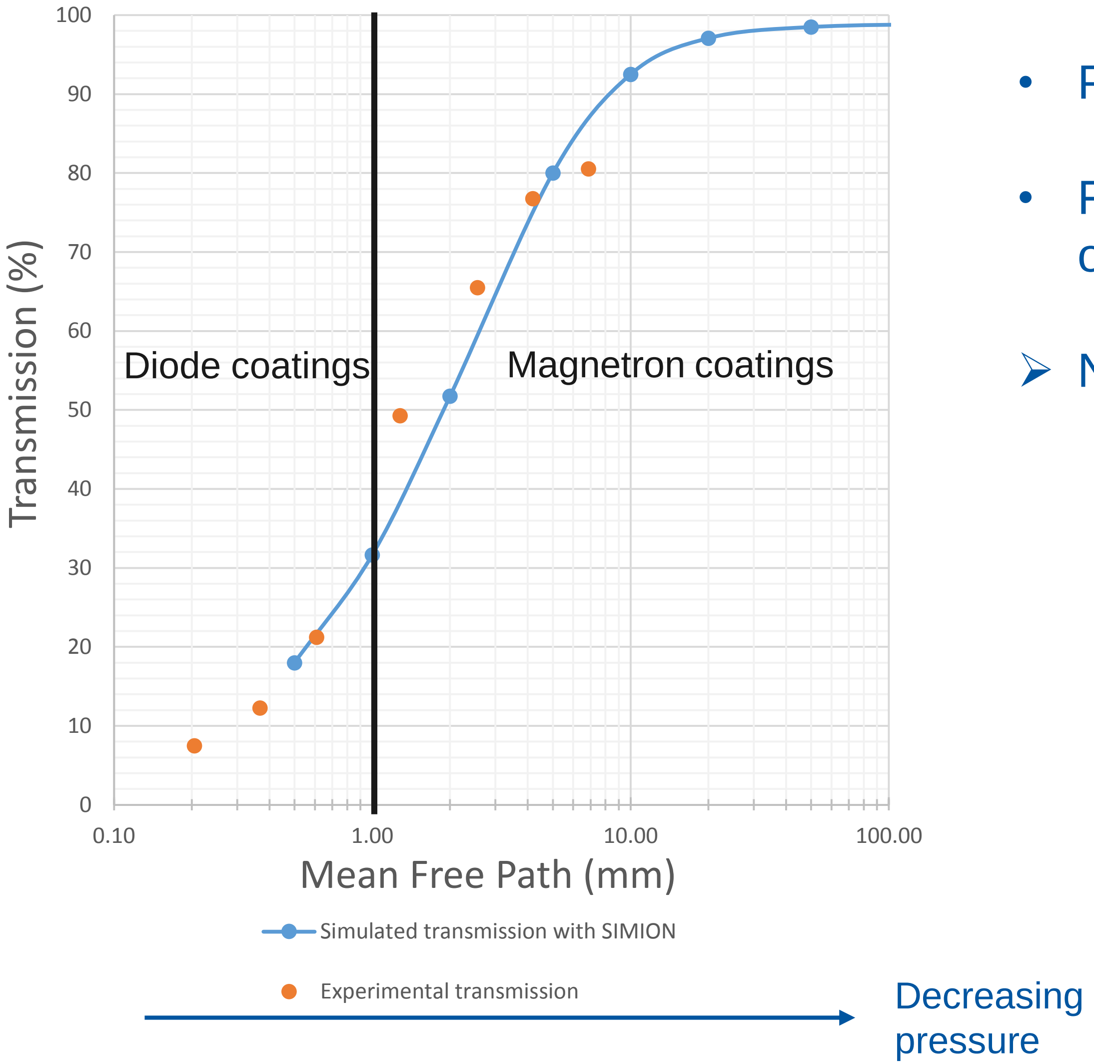
- SIMION software : atom transport with **hard-spheres binary collisions model**

- Simulation inputs :
  - Geometry
  - Argon buffer gas and sputtered niobium atomic masses
  - Mean free path
  - Cosine emission angular distribution
  - Uniform sputtering flux along cathode with $E_{initial}$ = 5 eV
- Simulation output : transmission of sputtered atoms with respect to mfp

- Conversion of experimental thickness profiles to transmission percentage

$$Transmission = \frac{Number\ of\ deposited\ atoms}{Number\ of\ sputtered\ atoms} \propto \frac{film\ thickness}{current \times time}$$

Study of sputtered atoms transmission



- Pressure ↘ : transmission ↗
- First approach: transport only

➢ Next step: plasma modelling

First plasma simulations: simulation code

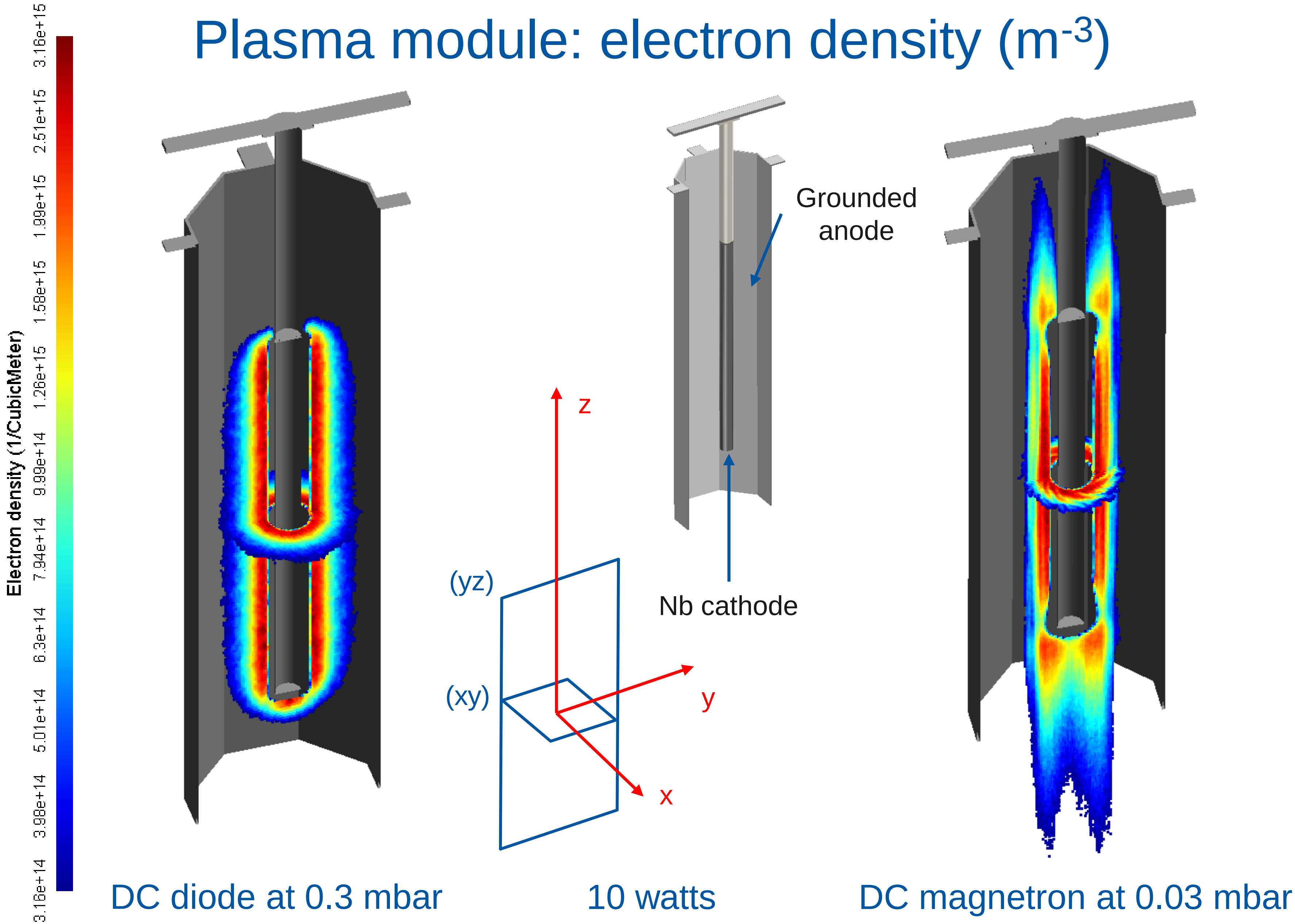
- PICMC/DSMC[1] parallel computing code from Fraunhofer Institute (Braunschweig) acquired in September 2015
  - Plasma simulation module
  - Gas flow and neutral transport module
    - Statistical method for solving the Boltzmann equation
    - Especially suited for rarefied gas flows where fluid models do not apply
  - Different time scales for plasma and transport: decoupling of the two

- Installed on CERN Linux server (10 nodes of 16 CPU each)

- Quite resource demanding :
  - 3D Plasma simulation of experimental system = 1 week for 10 μs on 144 CPU

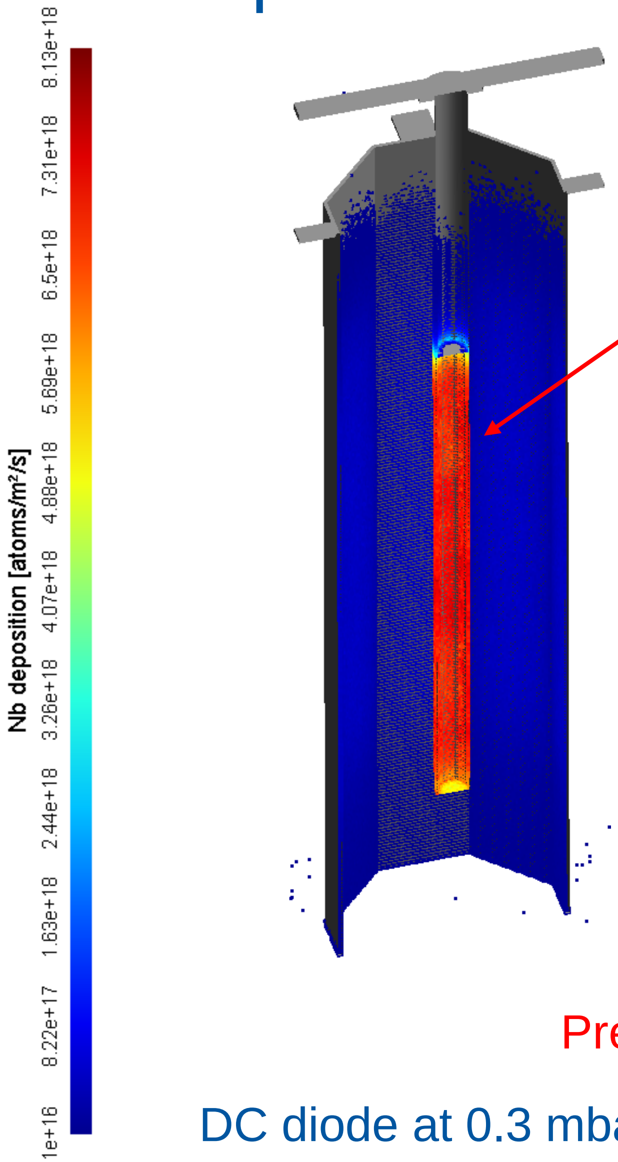
[1] *Particle-in-Cell Monte Carlo/Direct Simulation Monte Carlo*
http://www.ist.fraunhofer.de/en/services/simulation.html

Plasma module: electron density (m^{-3})

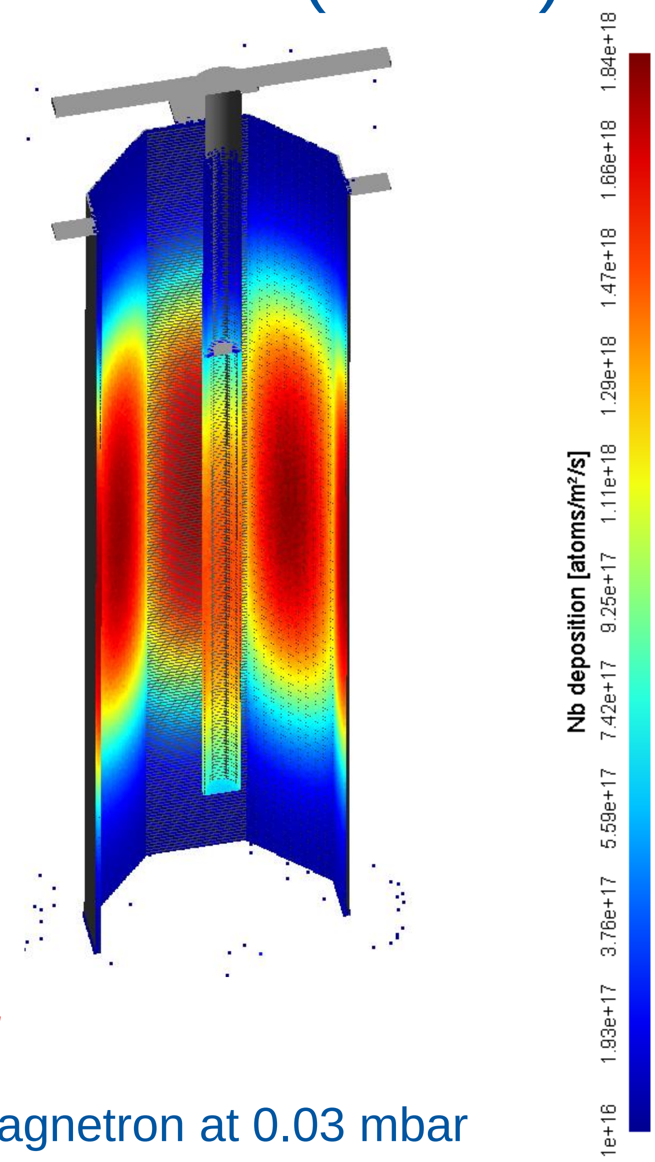


DC diode at 0.3 mbar 10 watts DC magnetron at 0.03 mbar

Transport module: niobium deposition flux (#/m^2/s)



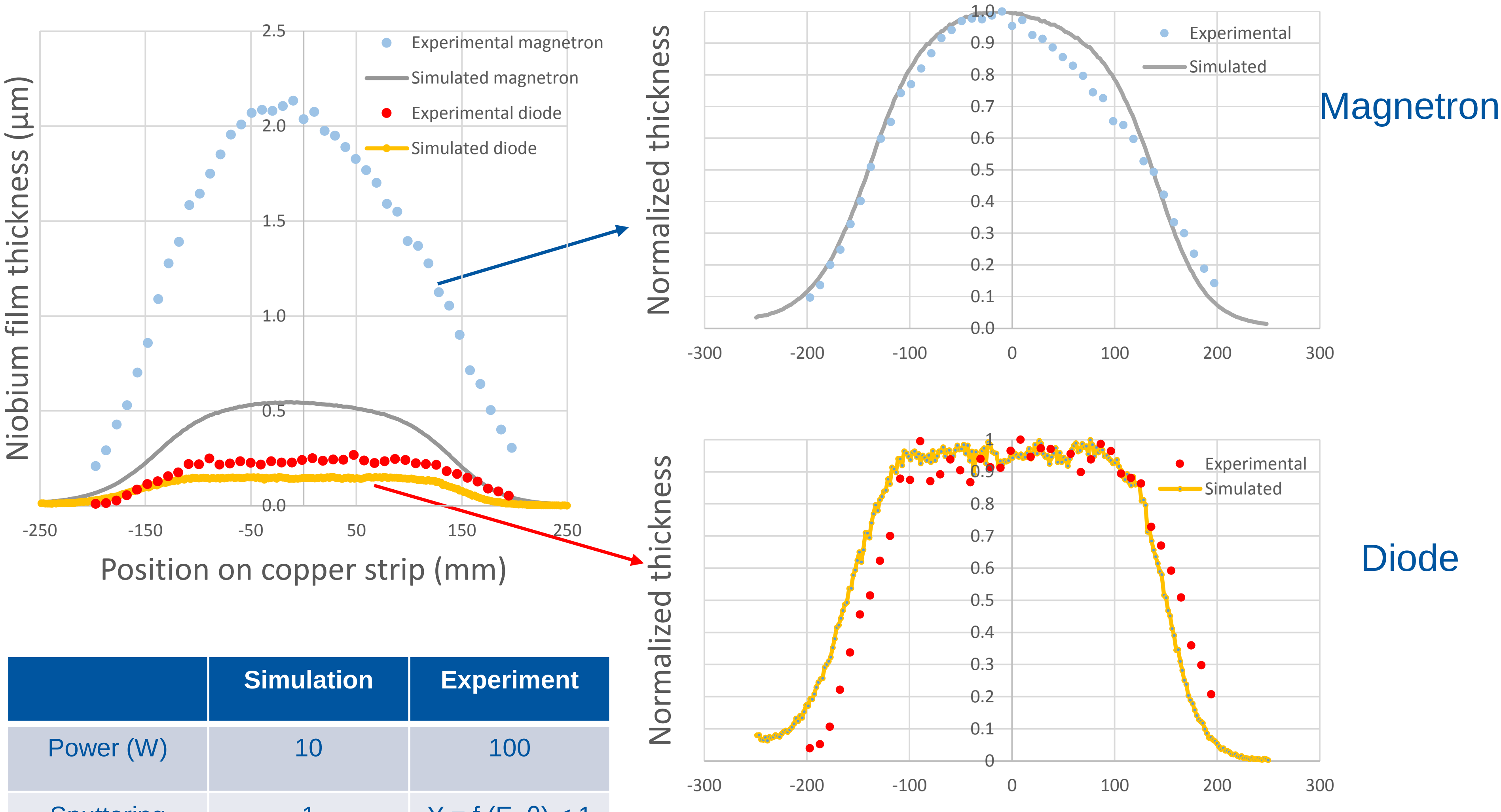
Low transmission :
redeposition on cathode



Pressure ↘ : transmission ↗

DC diode at 0.3 mbar ⟶ DC magnetron at 0.03 mbar

First plasma simulations: niobium thickness profiles



	Simulation	Experiment
Power (W)	10	100
Sputtering yield	1	Y = f (E, θ) < 1

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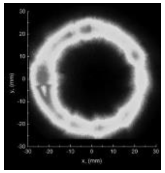
Future experimental upgrades and simulation plan

- Experimental upgrades:
  - Langmuir probe: plasma density, electronic temperature
  - Retarding field energy analyser: ion energy distribution on the substrate
  - Intensified high speed camera: spatial resolution of plasma features (spirals in magnetron ?)



[1]

- Simulation benchmarking:
  - Validation of physical model including sputtering yield = f(E, θ)
  - Influence and scale-up of discharge power
- Model real cavities:
  - HIE-ISOLDE (single and double cathode with grids and bias)
  - Elliptical type

[1] From A. Anders *et al.*, *Drifting localization of ionization runaway: Unraveling the nature of anomalous transport in high power impulse magnetron sputtering*, J. Appl. Phys. **111**, 053304 (2012)

Summary

- The objective is to model glow discharge plasma sputtering for thin-film coatings

- The current phase consists in benchmarking a simulation code on a simple experimental setup equipped with several diagnostic instruments

- The future plan will be to model real complex SRF cavities coating processes

Thank you for your attention!

Acknowledgements to:

TE-VSC-SCC section

www.cern.ch

Evaluation of experimental number of deposited atoms

$$\textit{Number of deposited atoms} = \frac{NbDensity * FilmThickness * XRFstep * CumulatedAnodeWidth * N_A}{NiobiumMolarMass}$$

Boltzmann Equation

$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \boldsymbol{x}} + \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}).\frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

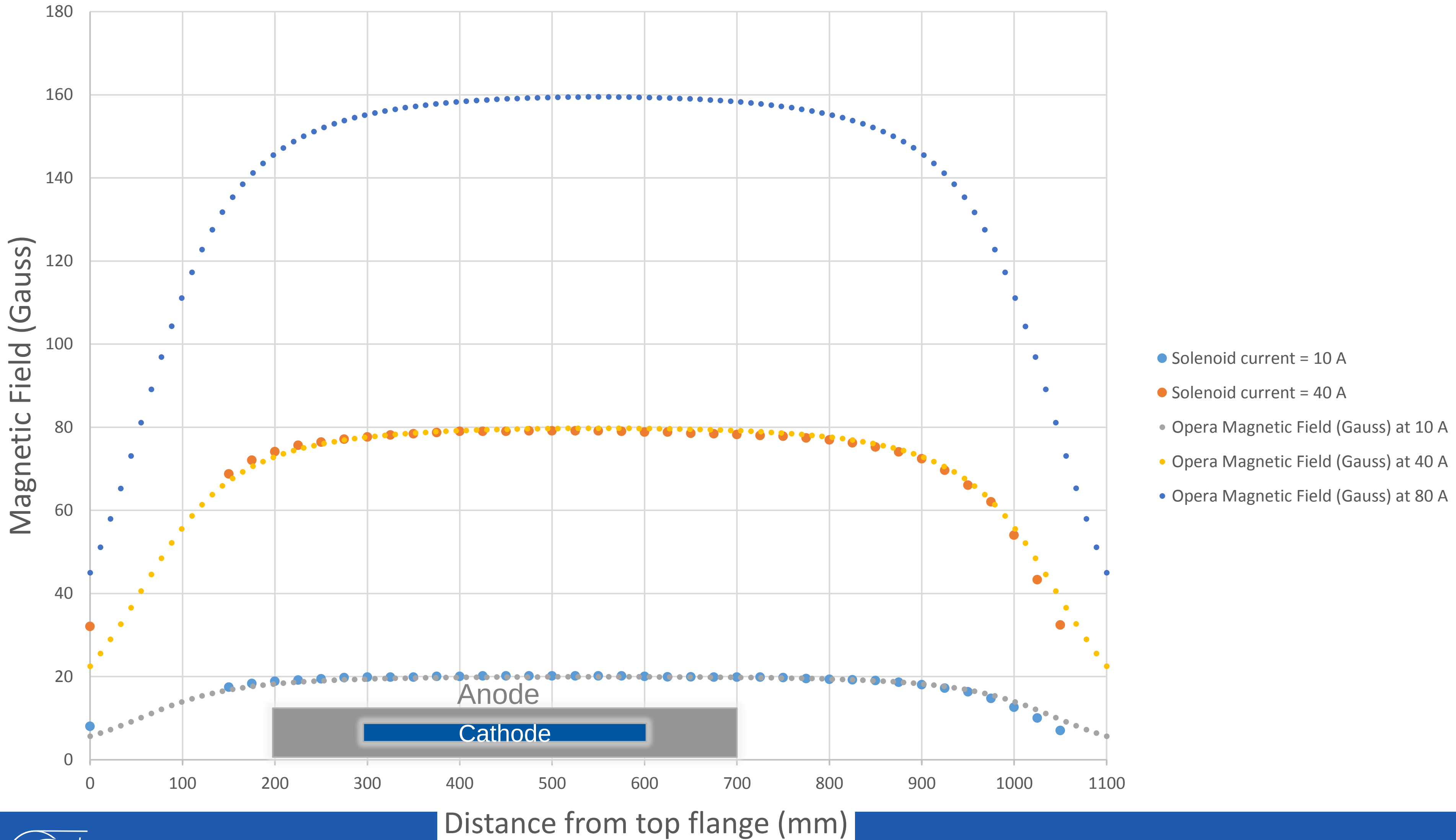
Where *f*(**x**, **v**, t) is the particles distribution function

Conversion of niobium absorption to film growth rate

$$\textit{Film growth rate (nm/s)} = \frac{Absorption(\#/m^2/s) * NiobiumMolarMass(\frac{g}{mol}) * 10^3}{NiobiumVolumicMass\left(\frac{g}{cm^3}\right) * N_A(\frac{1}{mol})}$$

Magnetic field homogeneity

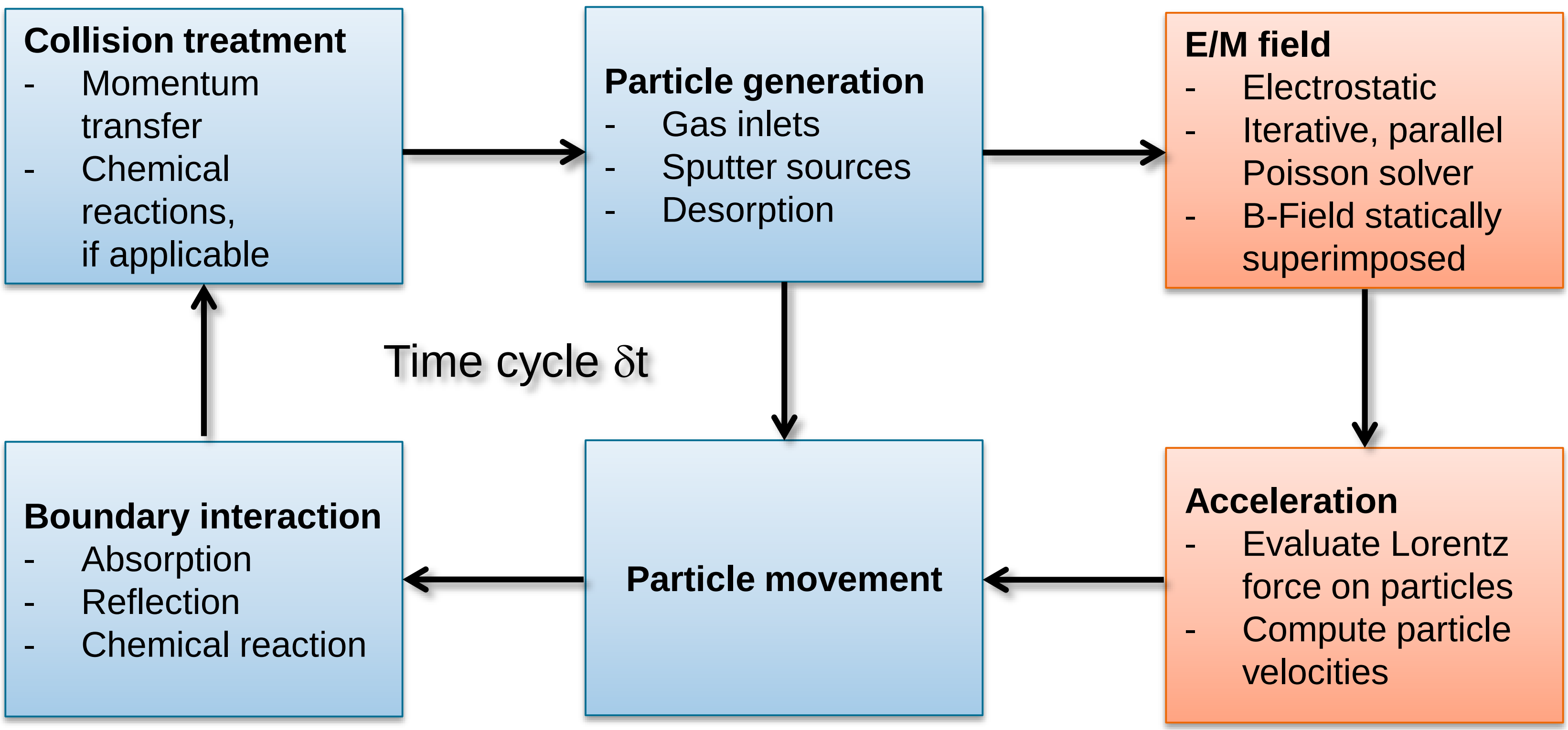
Measured B (Gauss) ~ 2*I_{coil} (A)



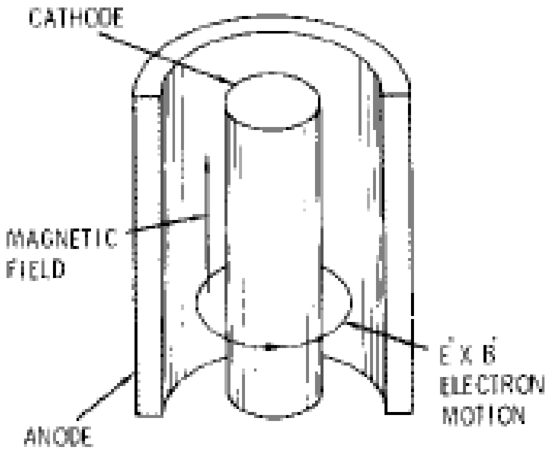
DSMC/PIC-MC method

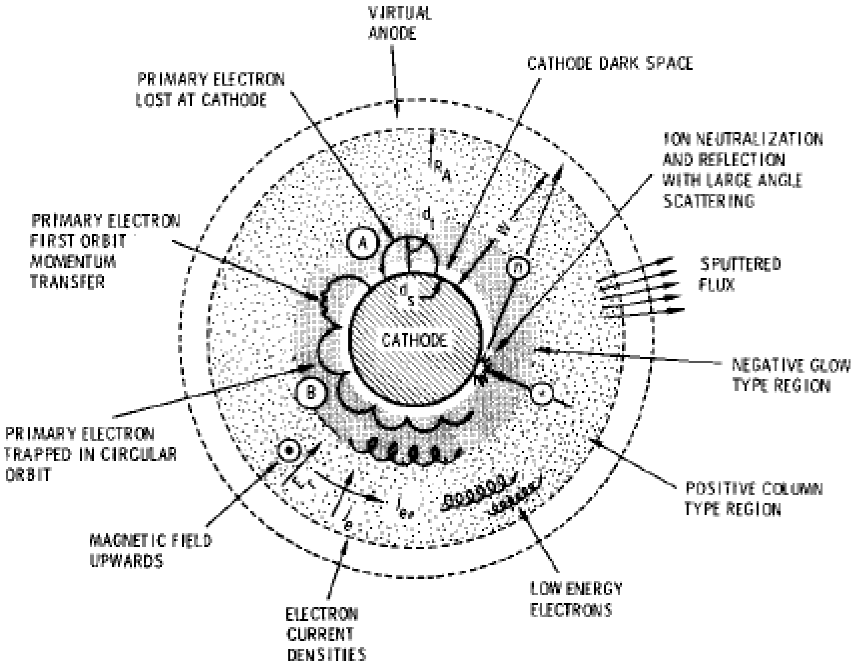
DSMC
Direct Simulation Monte Carlo

PIC-MC
Particle-in-Cell Monte Carlo



Electron trajectories in cylindrical magnetron





From J.A. Thornton, *Magnetron sputtering: basic physics and application to cylindrical magnetrons*, J. Vac. Sci. Technol. **15**, 171-177 (1978)

Niobium sputtering yield from ion argon bombardment

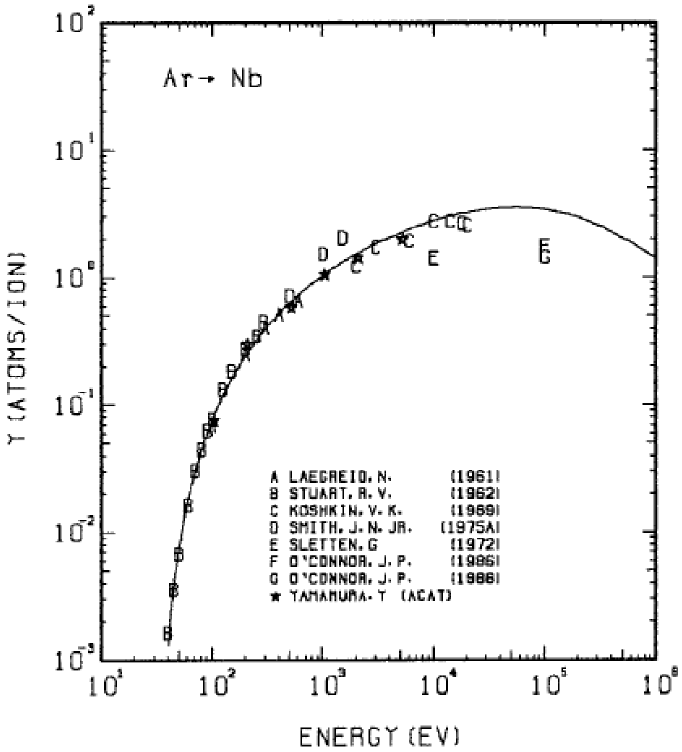
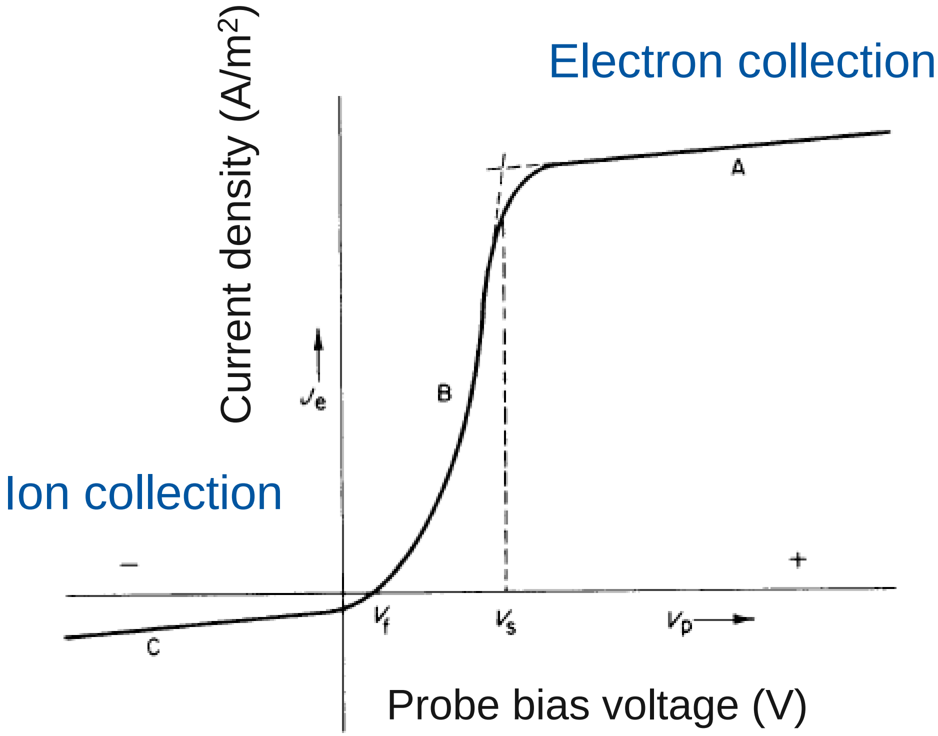


FIG. 157 ENERGY DEPENDENCE OF THE SPUTTERING YIELD OF NB WITH AR⁺.
A= 2.33, Q= 0.93, Us= 7.57EV, S= 2.80, W= 0.35Us.

From Y. Yamamura, *Energy dependence of Ion-induced sputtering yields from monoatomic solids at normal incidence*, Atomic Data and Nuclear Data Tables **62**, 149-253 (1996)

Langmuir probe

Many thanks to Luigi and Spyros for manufacturing ☺

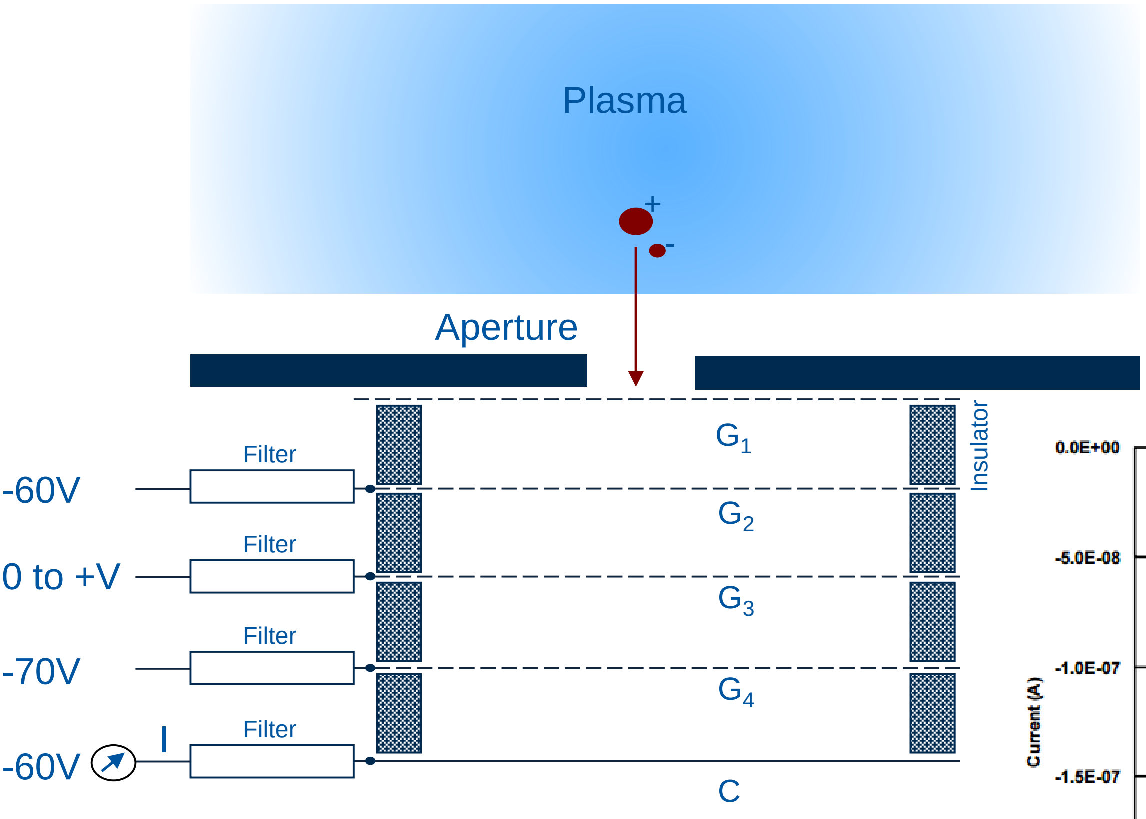


Vf : floating potential
Vs: plasma potential

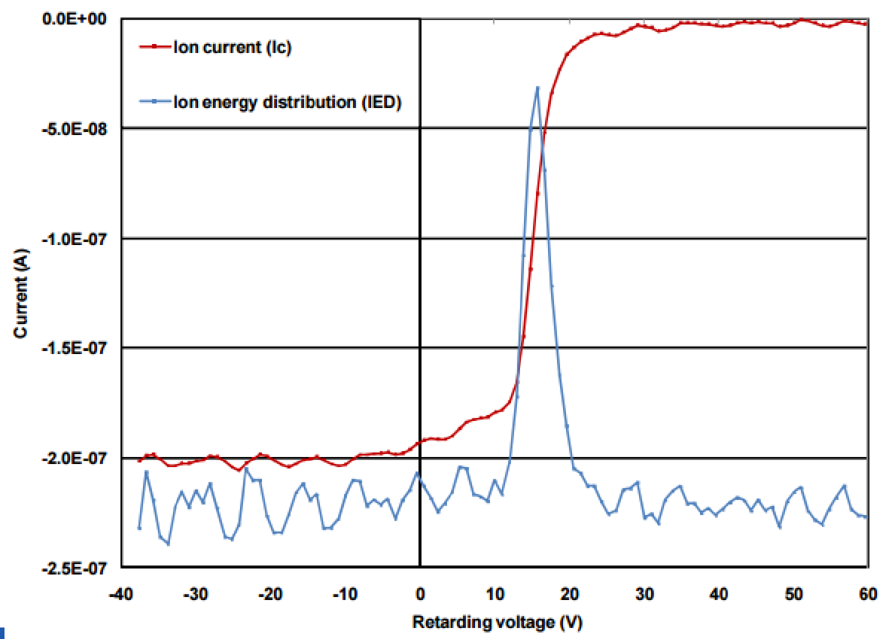
$$I = I_{sat}\left[1 - exp\frac{V \; - Vf}{T_e}\right]$$

From I_{sat} and T_e : n_{plasma}

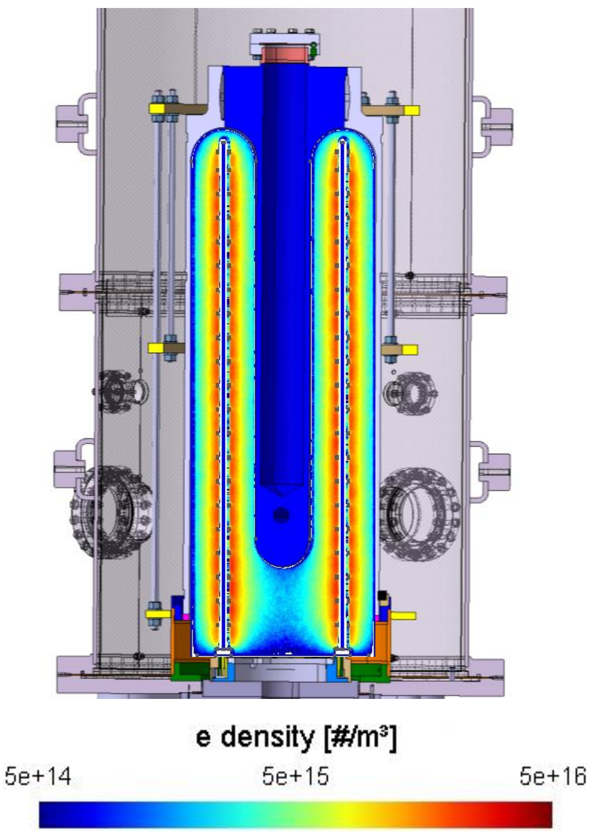
RFEA

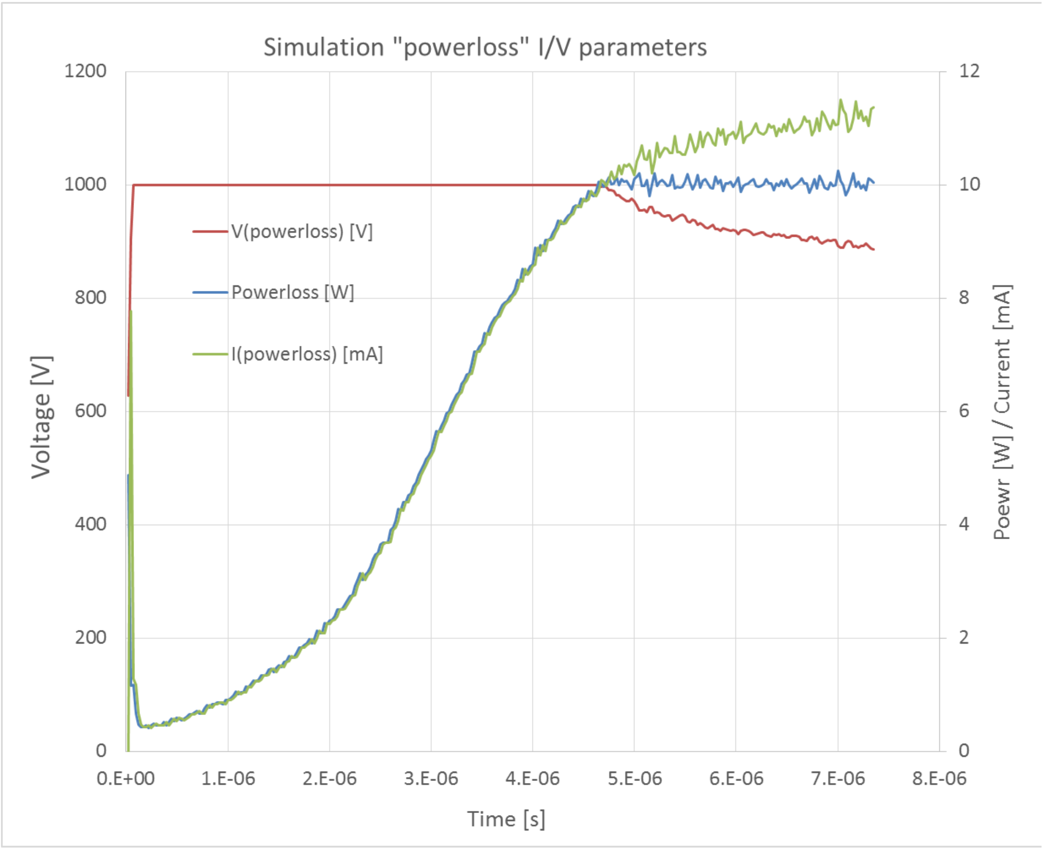


From *Impedans*



HIE-ISOLDE 2D, **very** preliminary plasma and Nb transport simulation

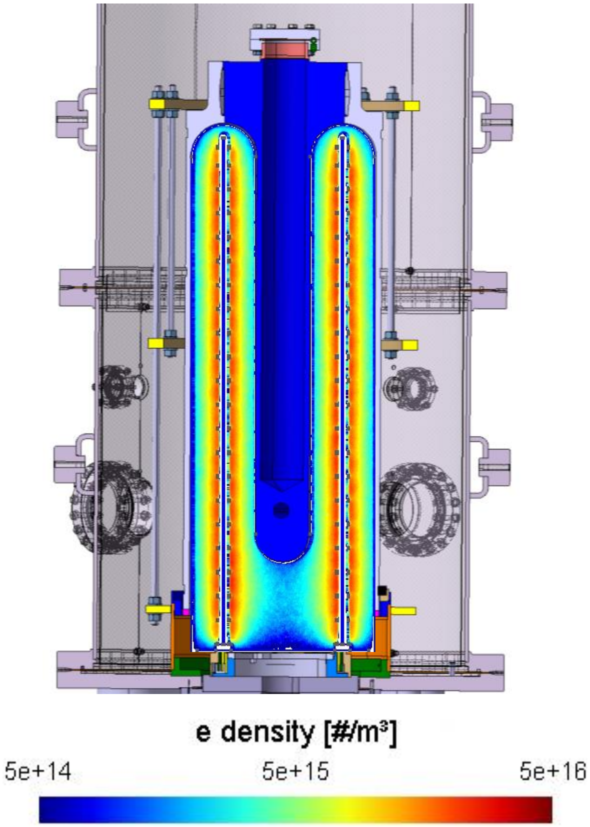


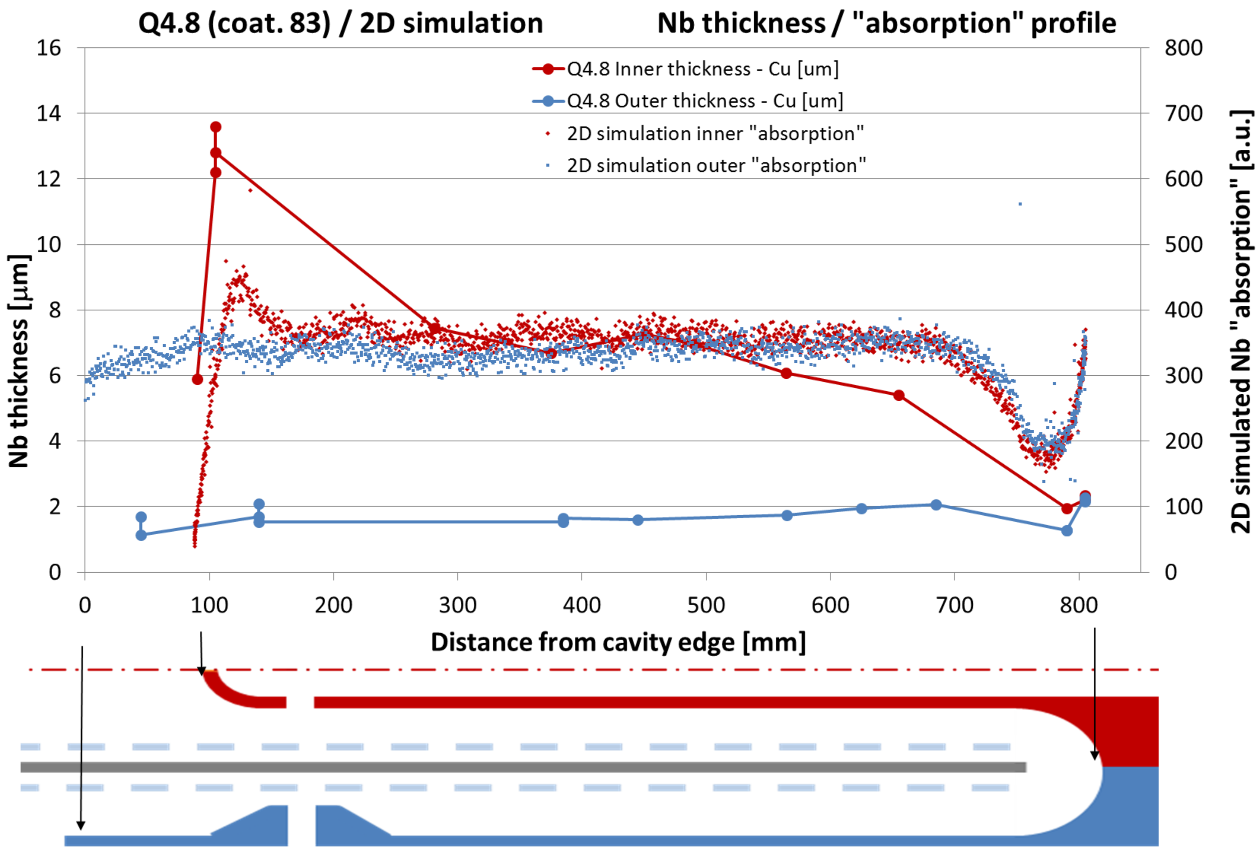


→ **2D slice** of HIE-ISOLDE cavity with periodic boundary conditions

→ Server connection lost after 72% of simulation, steady state not yet reached

HIE-ISOLDE 2D, **very** preliminary plasma and Nb transport simulation





→ **2D slice** of HIE-ISOLDE cavity with periodic boundary conditions

→ Encouraging start, but… we are still in the learning phase

→ Need better understanding/optimization of code and parameters