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Studying Target Erosion in Planar Sputtering Magnetrons Using a Discrete Model for Energetic Electrons

C. Feist* | CENUMERICS | Austria
A. Plankensteiner, J. Winkler | PLANSEE SE | Austria

COMSOL CONFERENCE
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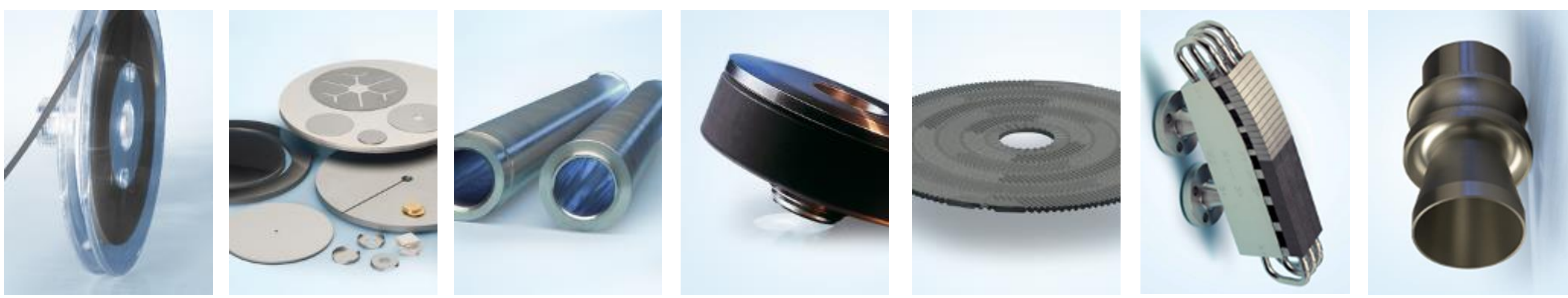
PLANSEE

PLANSEE SE

- founded in 1921 for production of molybdenum (Mo) and tungsten (W) wires
- annual turnover: € 1,500 M+ • employees: 6,000+ worldwide (2012)
- world market leader in P/M production of refractory metals

used in wide range of high-tech applications and industries:
lighting, medical, power generation, aerospace ...



unique combination of material properties:

- high melting point
- excellent high temperature strength

Sputtering process

- PVD (physical vapor deposition) process
- for thin film deposition
- on various substrates
- source material (e.g. Mo and W)
- sputtered from “targets” by ion bombardment
- established by gas discharge

In-line sputtering system for display panel production (*Ulvac*)

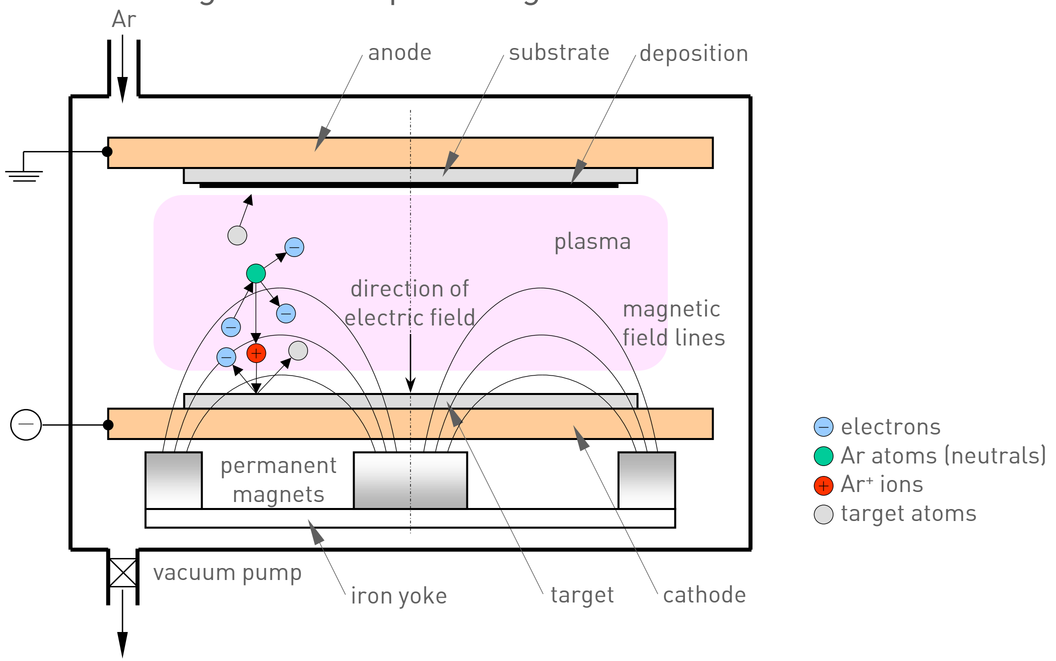
PLANSEE‘s twofold role in sputtering

- supplier of targets made from Mo and W
- user of sputtering process for in-house coating

Target-configuration for metal strip coating (*Von Ardenne*)

The magnetron sputtering process

- operated in vacuum chamber (typical pressure: 10^{-1} – 10^{0} Pa)
- target bonded onto cathode
- geometric layouts depending on field of application
- DC discharge:
  - stationary electric field between grounded anode and
  - cathode subjected to negative bias (typically: -200 to –400 V)
  - formation of plasma with cathode fall (plasma sheath)
  - using background gas, e.g. argon (Ar)
- magnetically enhanced: static magnetic field providing "confinement" to electrons



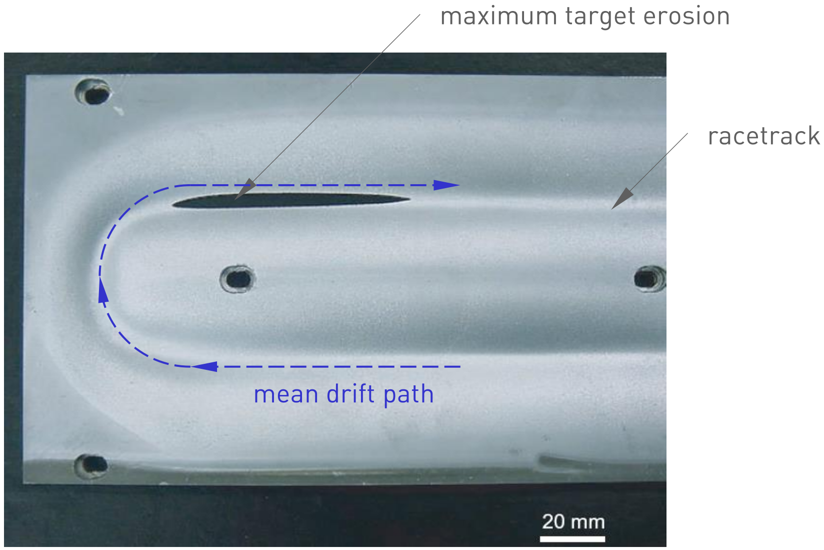
Magnetic confinement of energetic electrons

advantages:

- increased ionization and sputtering rate
- → allows reducing operating pressure
- → reduced spurious depositions
- → higher deposition quality

drawbacks:

- non-uniform ion flux onto target
- → non-uniform target erosion
- → reduced target utilization (typically: ~ 20 – 40 %)
- rectangular targets: *cross corner effect* (CCE)



Q.H. Fan et al.; J.Phys. D: Appl. Phys. 36(2003) 244-251.

Objective

- improve uniformity of target erosion
- increase target utilization
- by means of numerical simulation

→ implementation and verification of model

→ for prediction of relative ion flux and target erosion

Trajectories of charged particles without collisions

Lorentz force

acting on particle of charge q

from electromagnetic fields **E** and **B**

$$\mathbf{F} = q\,\mathbf{E} + q\,\dot{\mathbf{x}} \times \mathbf{B}$$

\+ *Newton*'s equation of motion

for particle of constant mass m

= system of second order ODEs

in terms of components of particle position vector **x**

to be solved for each particle under consideration

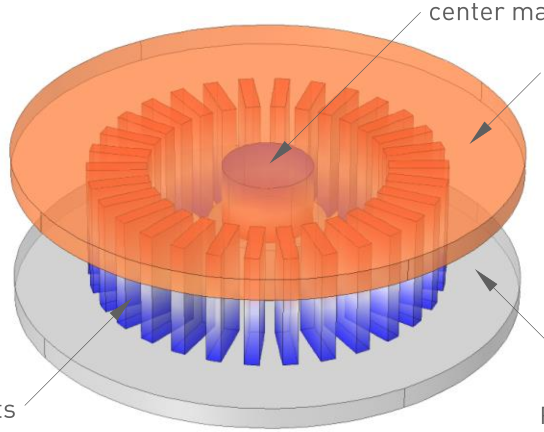
$$\ddot{\mathbf{x}} = \frac{q}{m}\left(\mathbf{E}(\mathbf{x}) + \dot{\mathbf{x}} \times \mathbf{B}(\mathbf{x})\right)$$

Assumptions and involved simplifications

- magnetic field induced by current through plasma neglected (*Maxwell-Ampere*'s law)
  - → static magnetic field from permanent magnets computed *a priori*
- electric field computed *a priori* from reasonable estimate for number densities (*Poisson*'s law)
  - → allows sequential coupling
  - → no self-consistent solution

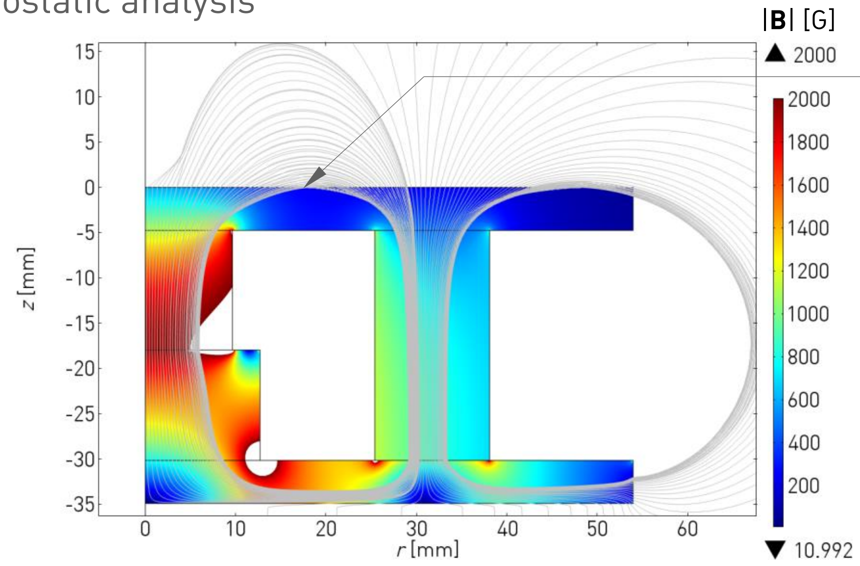
Benchmark example - axisymmetric DC magnetron

geometry



Ref.: T.E. Sheridan et al.; J. Vac. Sci. Technol. A; Vol. 8(1); 1990.

results from magnetostatic analysis

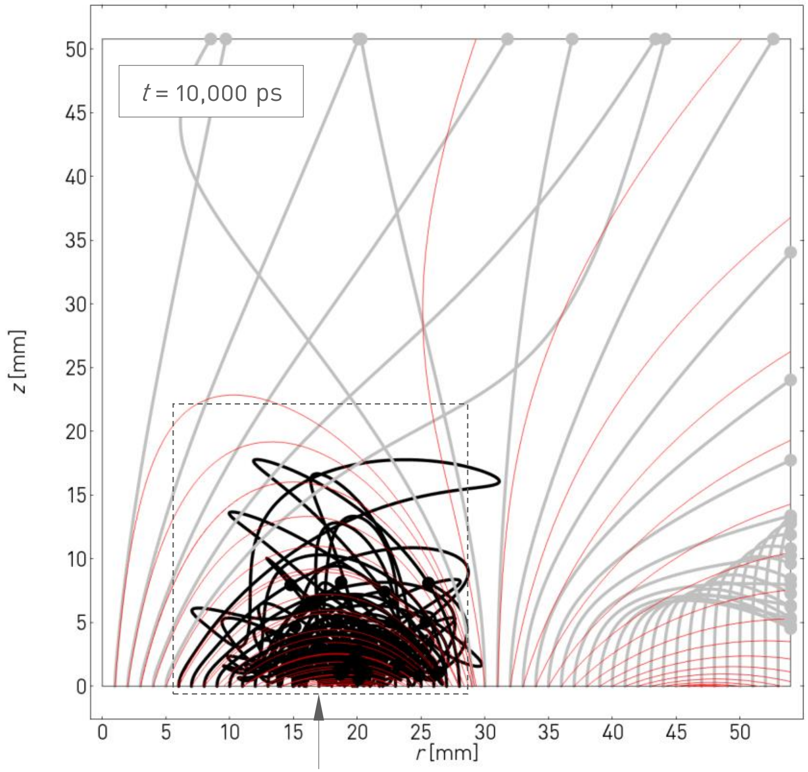


$r \approx 19$ mm: $B_z = 0$
from experience known as
location of maximum erosion

Benchmark example - axisymmetric DC magnetron

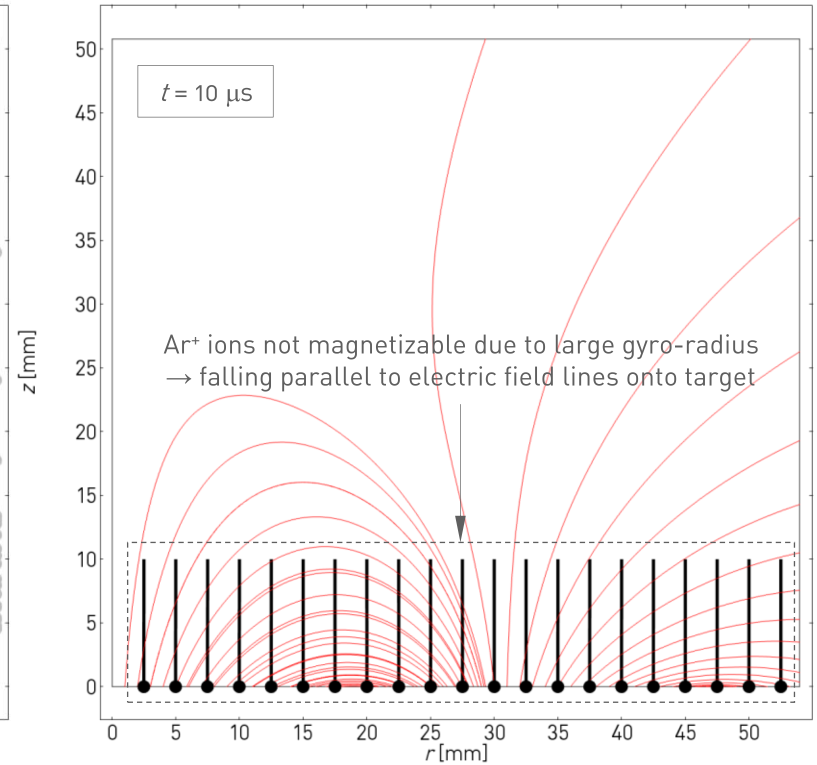
preliminary assessment of trajectories of charged particle species

electrons released from target
(secondary electron emission)



electrons confined by magnetic field

ions created in plasma (ionization)



particle trajectories
unconfined electrons
magnetic flux density streamlines

Modeling strategy

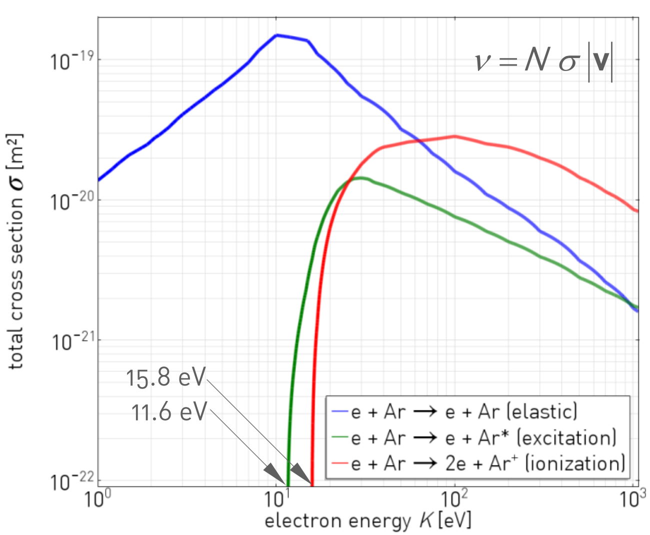
workflow

- initialize electron emission flux distribution $j_e(r)$ on target
- loop over:
  - release set of electrons from target based on $j_e(r)$
  - integrate electron trajectories
  - account for collisions and scattering at random time instants by velocity re-initialization
  - project locations of ionization collisions onto target = ion bombardment flux $j_i(r)$
  - obtain improved electron emission flux distribution $j_e(r) = \gamma \cdot j_i(r)$

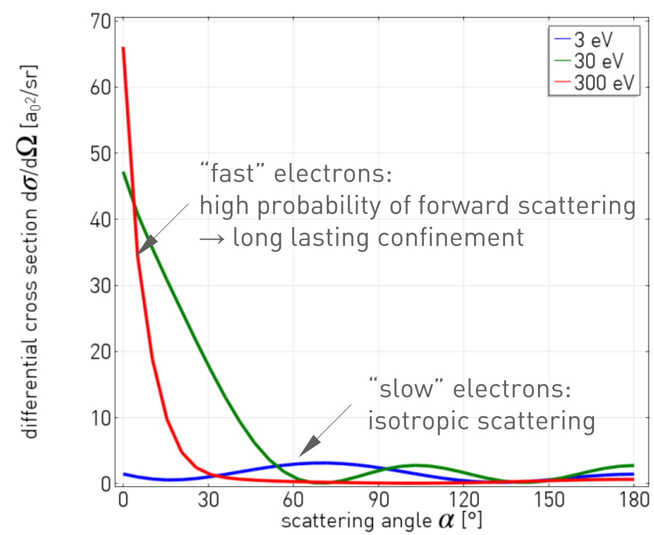
  until $j_e(r)$ converged

electron collision modeling for argon (Ar) as background gas

collision frequency ν from total cross section σ

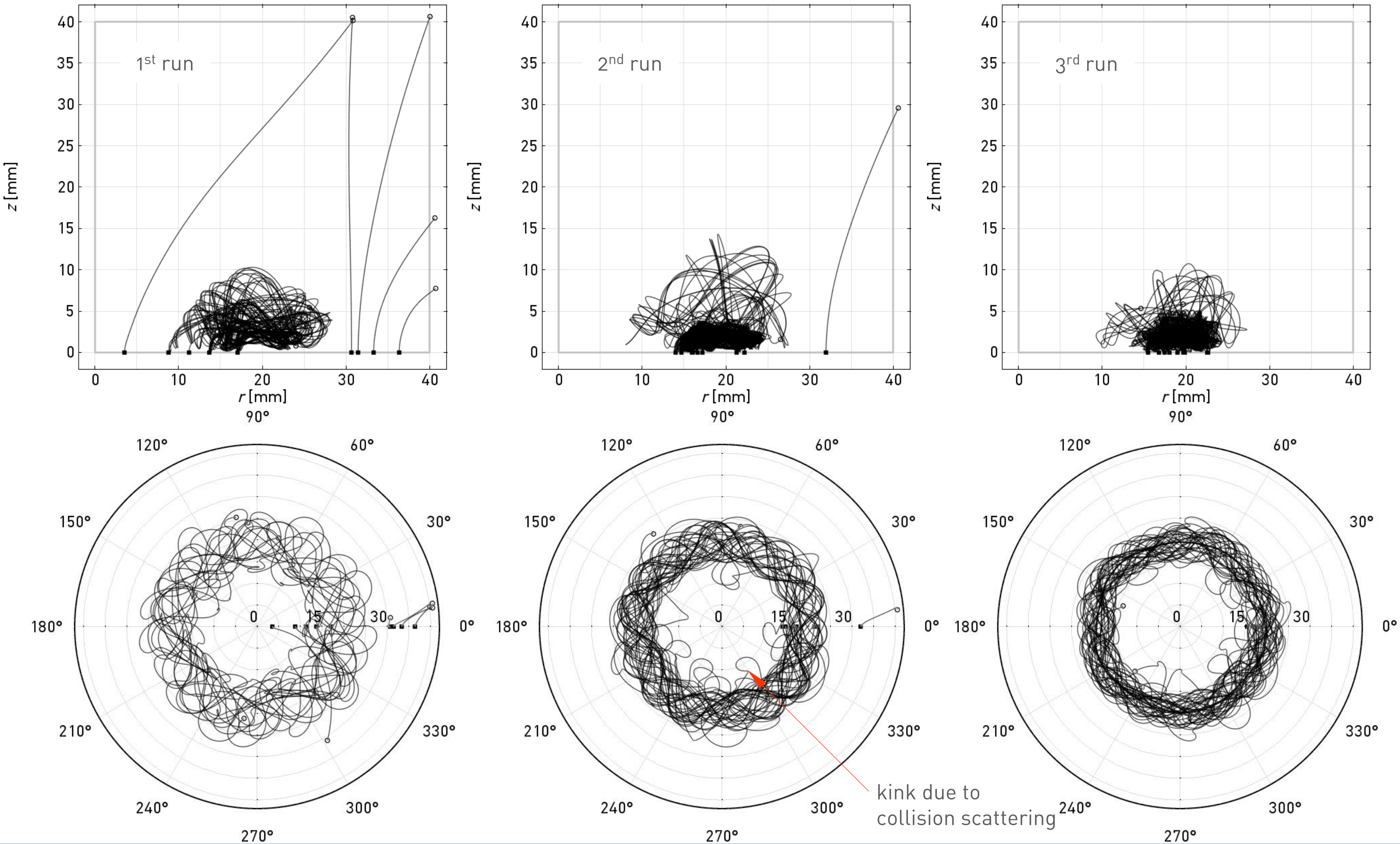


scattering angle α from differential cross section $d\sigma/d\Omega$



Application to benchmark example

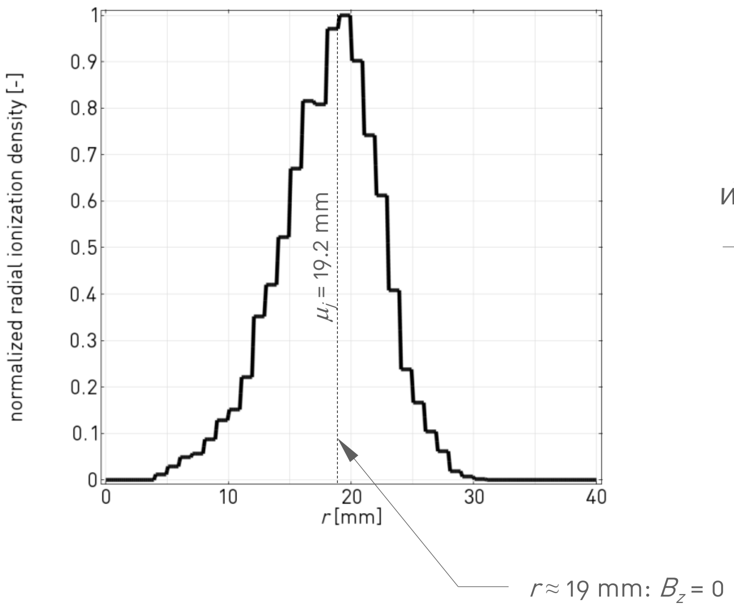
electron trajectories in *rz*- and *rφ*-plane for 3 consecutive runs (after initial 0.1 μs for 10 electrons)



Application to benchmark example

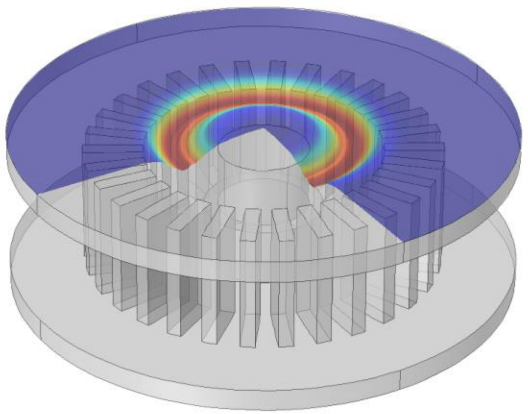
integral results after 7 runs over 1.0 μs

normalized ion flux density on target $j_i(r)$



$\dot{w} \propto j_i(r)$

estimate for relative target erosion w (normalized by target thickness)



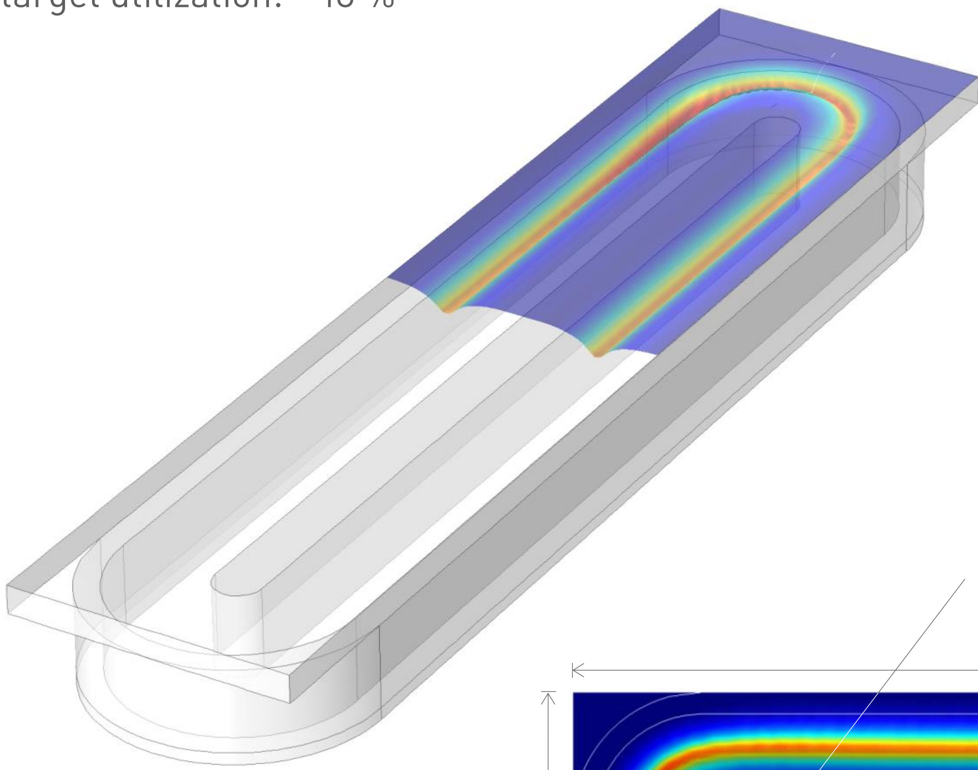
Note:

location of maximum ionization flux and target erosion
= location of vanishing normal magnetic field

Application to rectangular planar magnetron

estimate of target erosion *w* (normalized to target thickness of 12 mm) using 5,000 electrons

target utilization: ~ 18 %



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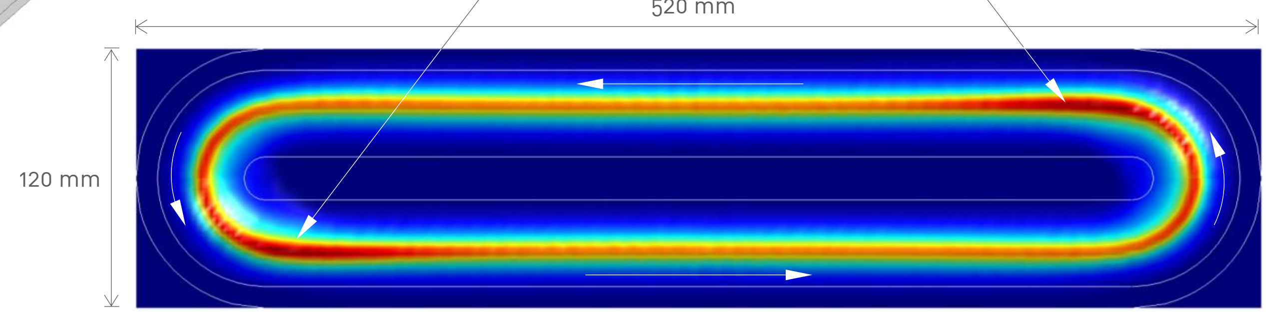

drift direction determined by magnet polarity

Summary

- discrete model for energetic electrons acc. to *Sheridan* and coworkers
- for prediction of relative Ar+ ion flux and erosion rate
- of planar target in DC sputtering magnetron
- to study design modifications for increased target utilization (ongoing work)
- implemented using COMSOL Multiphysics 4.3a
  - benefit: unified framework, no data exchange
- employed interfaces:

B-field:	Magnetic Fields, No Currents (mfnc)
particle trajectories:	Point ODEs and DAEs (pode)
particle collisions:	Events (ev)
collision statistics:	Boundary ODEs and DAEs (bode)

Why not DC Discharge (dc)

- computational costs resulting from required spatial and time discretization
- severe anisotropy of mobility/diffusivity tensors
- simple plasma-physics (Ar)

Why not Charged Particle Tracing (cpt)

- collision feature not available in 4.3a (new in 4.3b)
- collision statistics not feasible (even in 4.3b)
- events interface not usable together with particle tracing

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... thanking you for your interest

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Application to rectangular planar magnetron

exemplary trajectories of electrons starting at $y = 0$ and $x = 18.5 : 10 : 48.5$ mm over 0.428 µs (1 rev)