Optimization of Target Utilization in Planar Circular Sputtering Magnetron Using PIC-MCC Modeling

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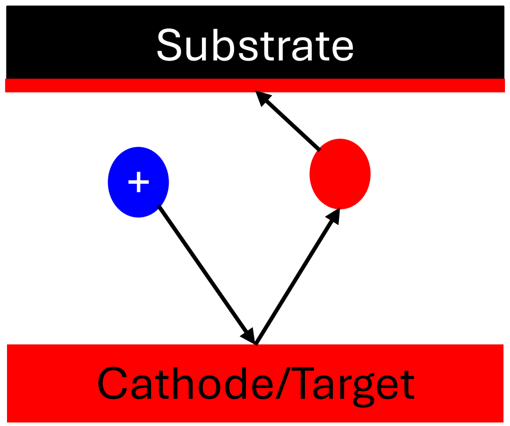
Outline

- Introduction
- Magnetic field configuration and transport in magnetized plasmas
- PIC-MCC modeling of a DC magnetron
- Example of output and optimization
- Improvement of real device
- Conclusion

Introduction

- Sputtering: A PVD Technique
  - Ion bombardment on a **cathode/target surface** ejects atoms
  - Ejected atoms are deposited on a **substrate** to form a thin film
- Pressure Trade-Offs
  - Low pressure: Promotes transport of target atoms to the substrate (👍), but reduces ionization rate (fewer collisions)👎
  - High pressure: Promotes ionization rate (👍), but reduces transport of target atoms to the substrate (more scattering) 👎
- Early 1970's: **Magnetic field** introduced to trap electrons and increase local ionization at low pressure enabling optimal trade-off for typical pressure ~5mTorr



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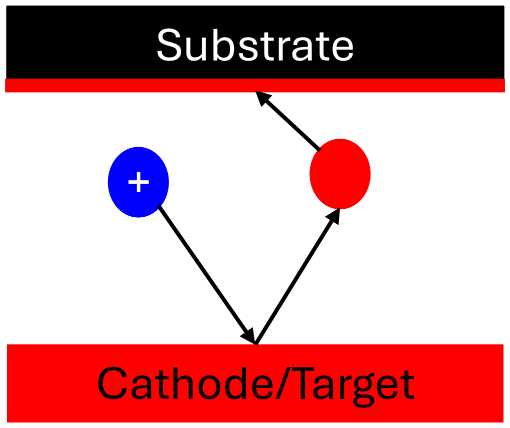
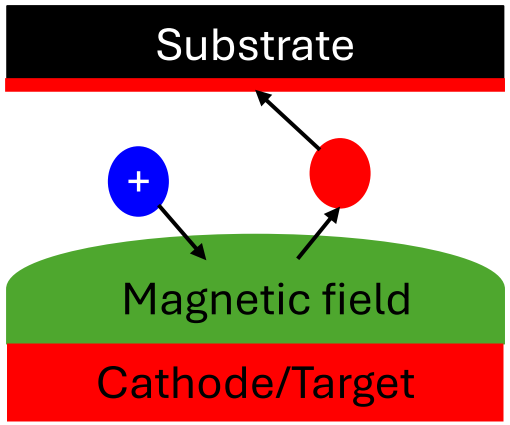




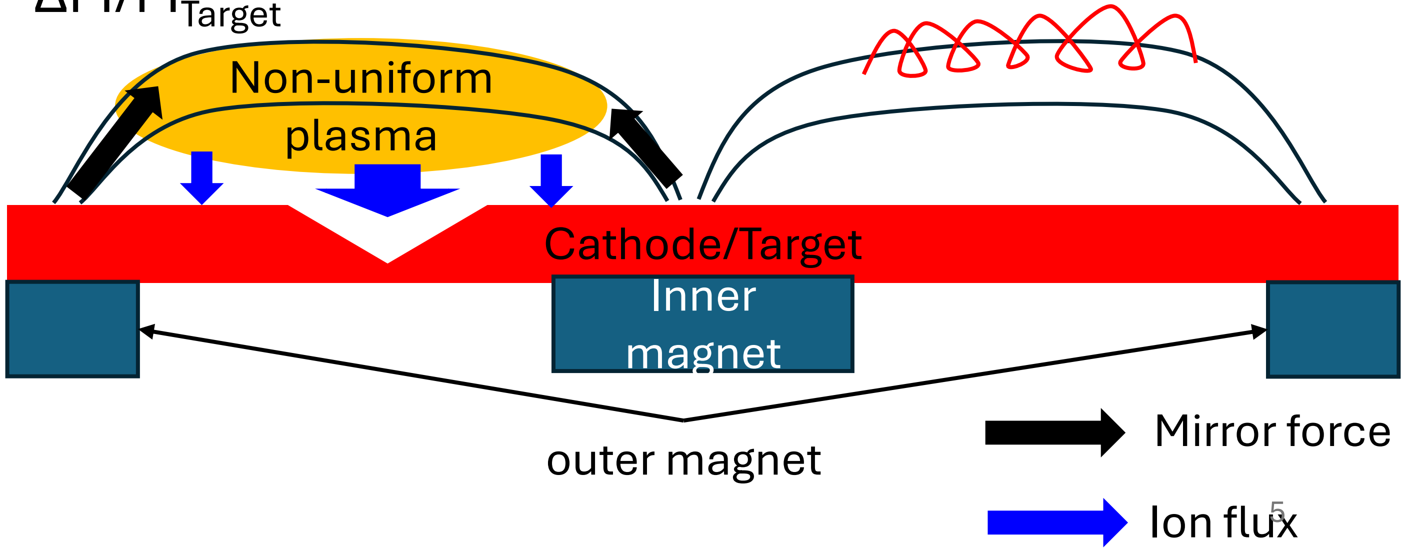
Magnetic field configuration

- Electron trajectory wrap around magnetic field line.
- Electron transport across magnetic field lines requires collisions (with gas atoms or localized perturbations)
- Successive magnetic field lines form a "magnetic bottle":
- Mirror force reflects electrons toward the center
- Non-uniform plasma density and ion bombardment
- Target utilization is introduced to measure the degree of non-uniformity of ion bombardment. $K_M = \Delta M / M_{Target}$
- Higher target utilization reduces:
  - Material waste
  - Production costs
  - Maintenance frequency

$$\boldsymbol{\mu}_{\mathbf{e}} = \begin{pmatrix} \mu_{//} & 0 & 0 \\ 0 & \mu_{\perp} & \mu_{\times} \\ 0 & -\mu_{\times} & \mu_{\perp} \end{pmatrix} \qquad \mu_{//} = \frac{e}{m_e \nu}$$

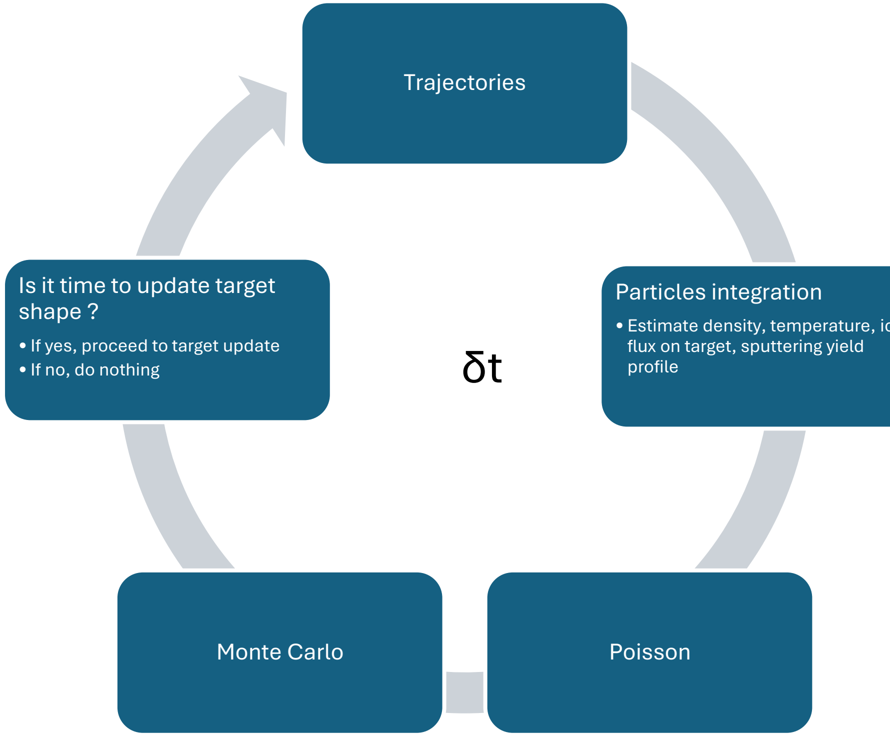
$$\mu_{\perp} = \mu_{//} \frac{1}{1+(\omega_{ce}/\nu)^2}$$

$$\mu_{\times} = \mu_{//} \frac{\omega_{ce}/\nu}{1+(\omega_{ce}/\nu)^2}$$



PIC-MCC

- Electron and ion trajectory solved via Boris's algorithm
- Particles integration to estimate plasma properties and sputtering yield.
- Electric field is calculated by solving Poisson equation via Successive Over Relaxation method
- Interaction between charged particles and atoms are solved via Monte Carlo Collision method with realistic cross sections
- Target is divided into volume elements (pixels)
  - Eroded progressively based on ion flux
  - Enables calculation of mass removal and target utilization



Trajectories

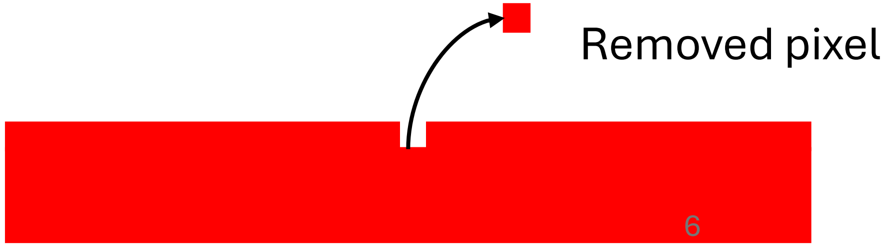
Particles integration
- Estimate density, temperature, io
  flux on target, sputtering yield
  profile

Poisson

Monte Carlo

Is it time to update target shape ?
- If yes, proceed to target update
- If no, do nothing

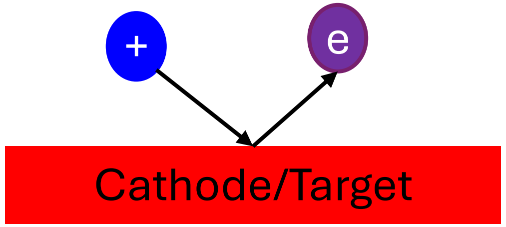
δt



Plasma surface interaction and dynamic Target Shape Management

- Secondary electron emission:
  - Managed with a Monte Carlo procedure assuming a simplistic constant factor $\gamma=0.082$ (no justification, only for simplicity)

- Target sputtering:
  - Run PIC-MCC to get steady-state
  - Compute sputtering yield from ion energy, type and target material
  - Accumulate sputtering yield over time (from steady state to steady state) per surface pixel
  - Remove pixel/material based on accumulated yield
  - Update target shape accordingly
  - Recalculate ion trajectories on new geometry
  - Repeat until the target is pierced



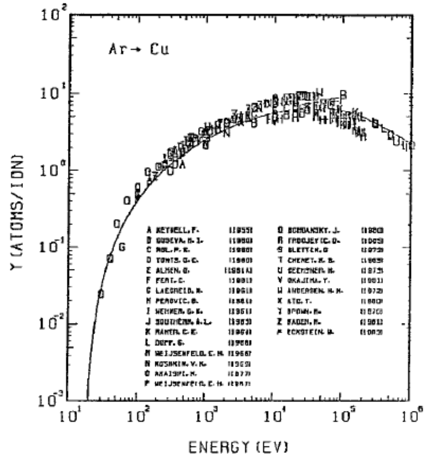
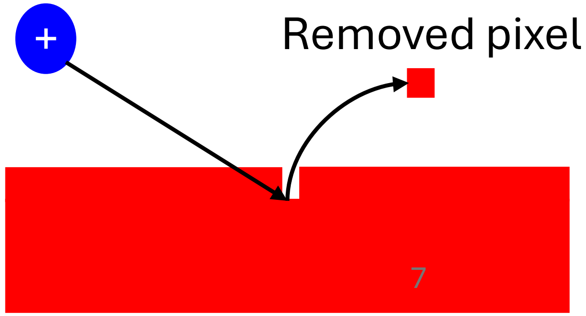


FIG. 120 ENERGY DEPENDENCE OF THE SPUTTERING YIELD OF CU WITH AR⁺. A= 1.59. Q= 1.00. Us= 3.49EV. s= 2.50. W= 0.21Us.



Plasma property with target having a flat shape (10W-DC discharge)

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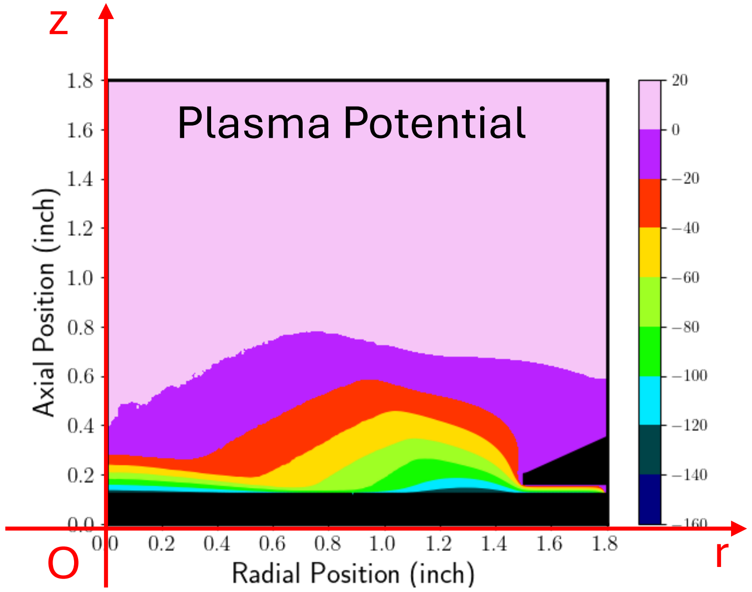
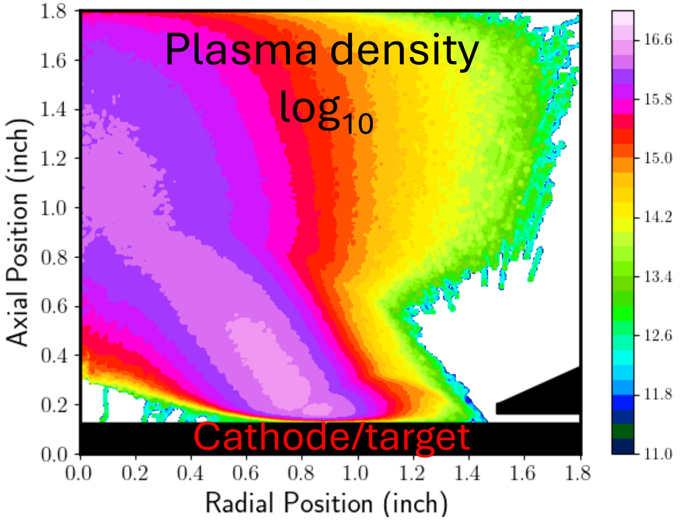
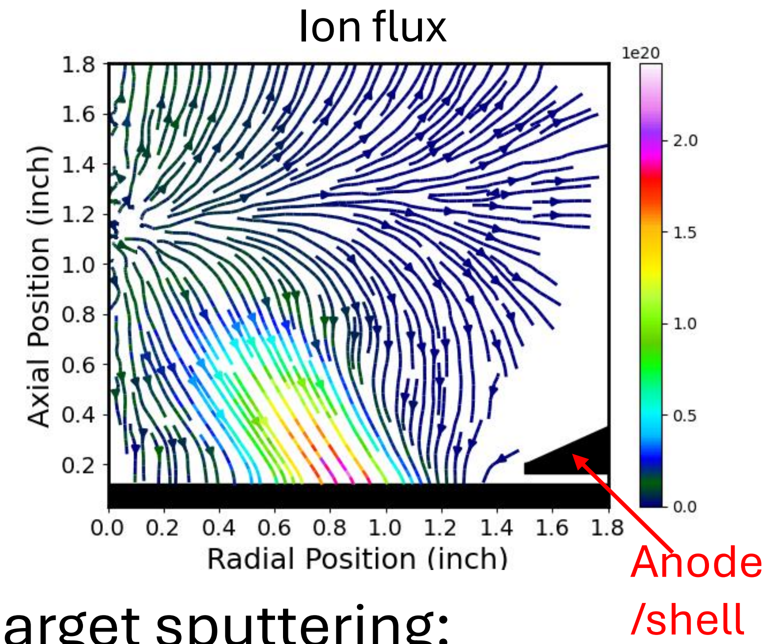
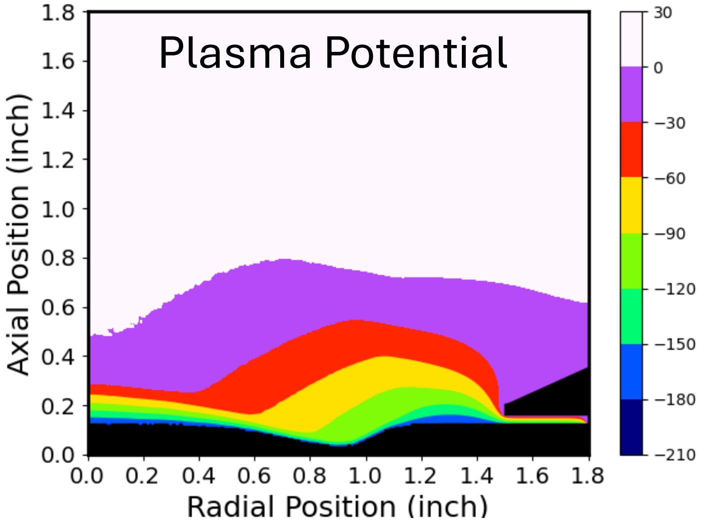


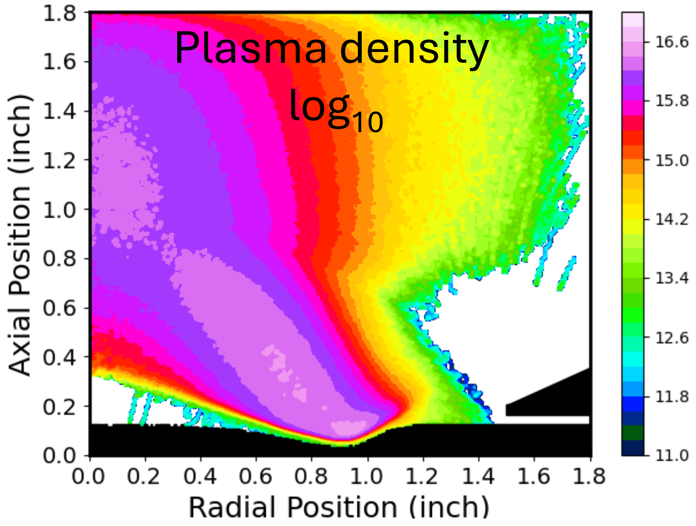


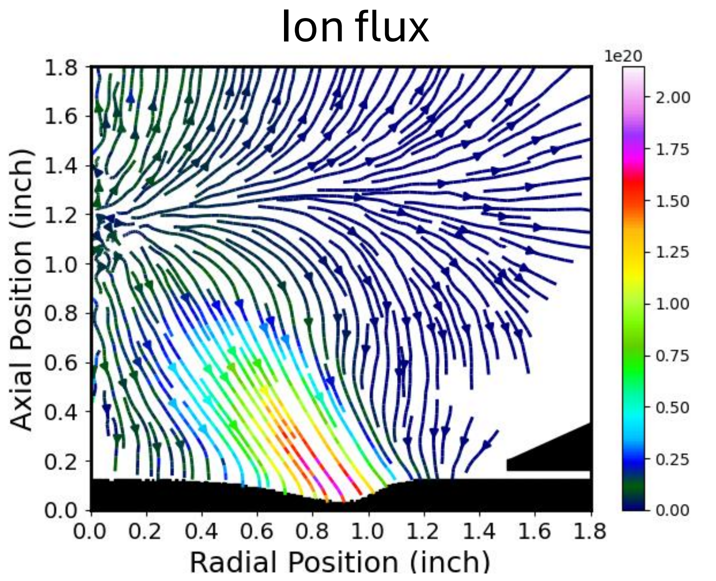


- Plasma properties at steady state prior any significant target sputtering:
  - Equipotential lines have an S shape due to electron mobility anisotropy and plasma density distribution.
  - Plasma density is maximal in the cathode region between the central and outer magnets.
  - Ion bombardment is oblique to the cathode.

Plasma property with partially eroded target

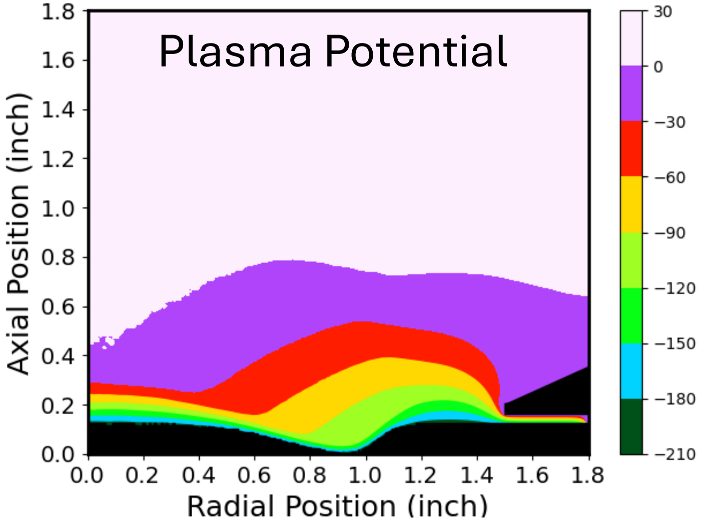


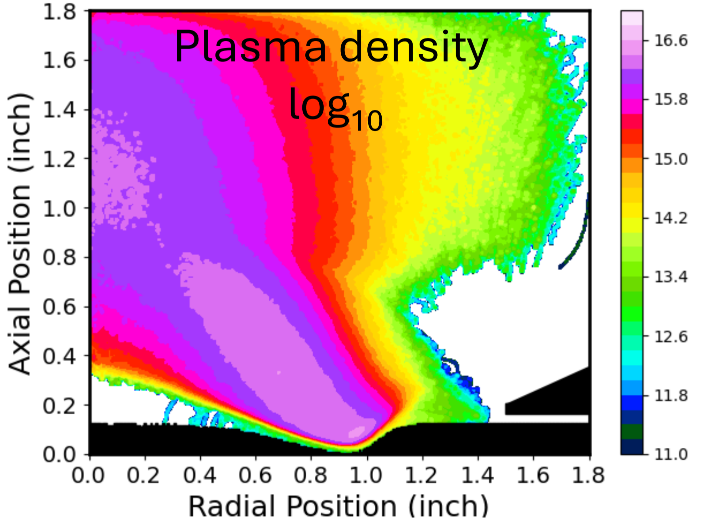


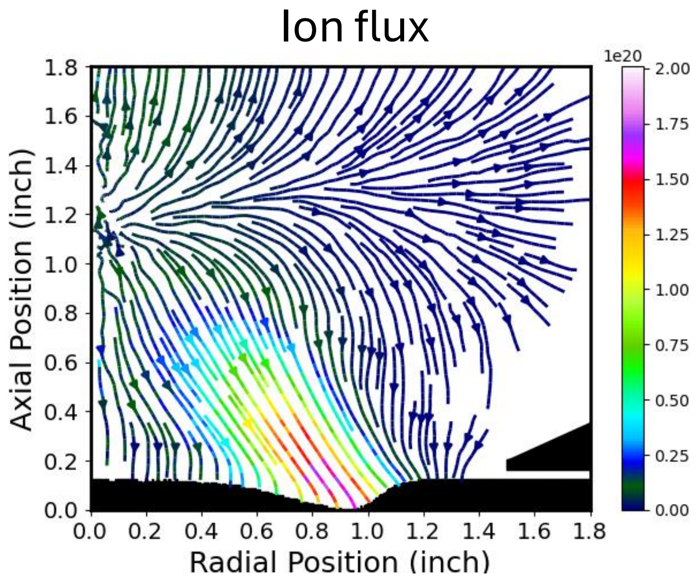


- Cathode shape affects on plasma properties
  - Equipotential surfaces are parallel to the cathode in the cathode vicinity (sheath width)
  - Plasma density increases locally within the groove in an effect similar to hallow cathode

Plasma property with target at end life

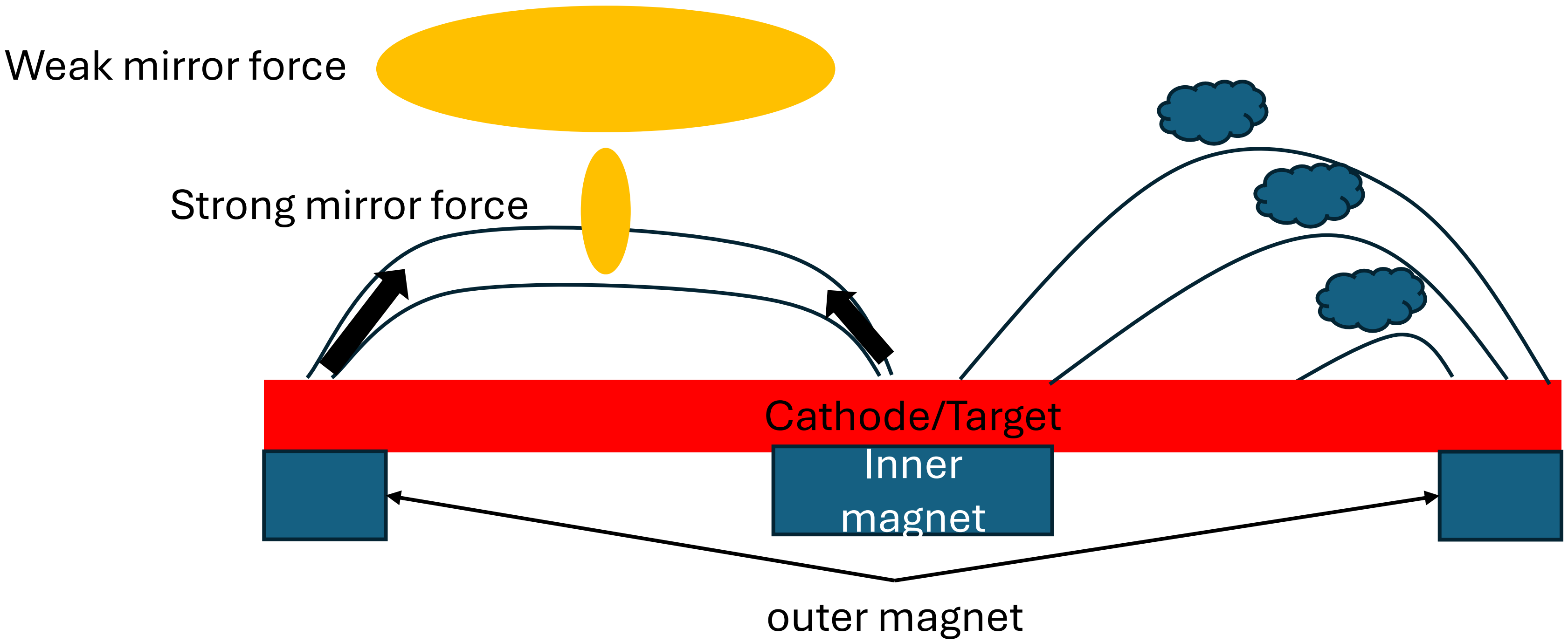






- Plasma density increases locally within the groove like in “hallow cathode effect”

Suitable magnetic field configuration for high target utilization

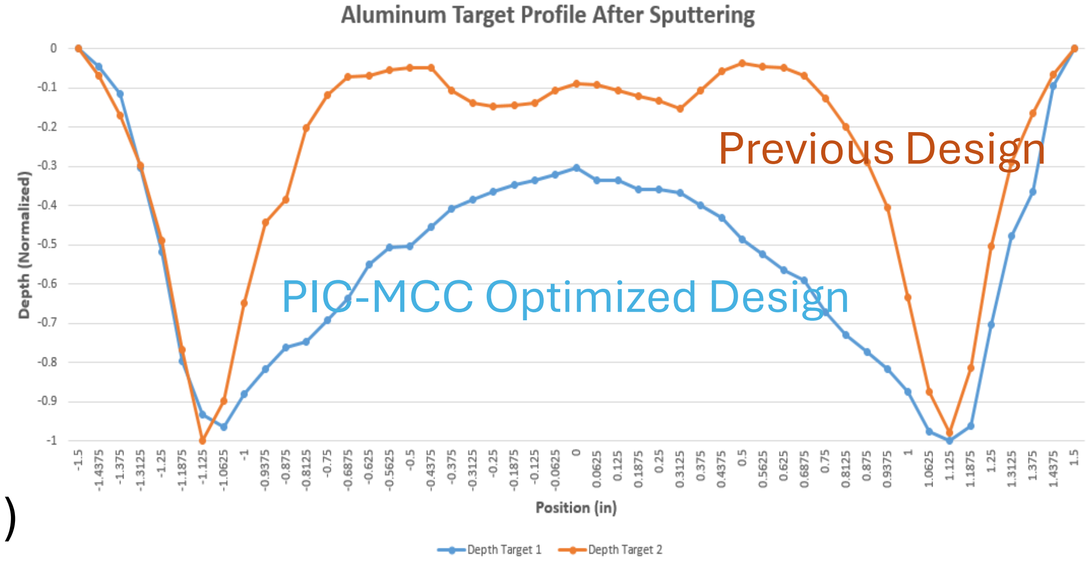


- Use a magnetic field with lines arranged such that $B_z=0$ occurs over a wide range of radial positions.
- Use an appropriate trade-off among electron confinement, mirror force, and electron temperature to achieve optimal performance.

Simulation-Driven Improvement of Target Utilization

- Problems Without Optimization:
  - Initial magnetic configuration → non-uniform erosion
  - Low target utilization about 27%
- PIC-MCC model (20 configurations tested):
  - Ion flux distribution over target surface
  - Influence of magnetic field configuration on erosion profile
  - Magnetic field adjusted based on simulation results (repositioning magnets, play on magnetization grade…)
- Result
  - Improved target utilization to >40%
  - Smoother erosion, reduced waste
  - Faster development with fewer prototypes required

Comparison of Target Erosion Profiles:
Previous Design vs. PIC-MCC Optimized Design



Previous Design: Narrow groove (lower utilization)
PIC-MCC Optimized Design: wide groove (high utilization)

Conclusions

- Simulation model help predicting erosion and utilization and allow us to increase target utilization by about 50%.
- Helps optimize design with **minimal experimental cost** and **time saving**
- The Developed PIC-MCC code is used at Plasmionique Inc to improve its line of magnetrons.
- The developed PIC-MCC code is an excellent tool when dealing with magnetic target where the change of the shape affects the magnetic field distribution too

Thank you for your attention

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- Tadjine et al. 2017 Surface and Coating Technology **309** pp573-578
- G J M Hagelaar and N Oudini 2011 Plasma Phys. Control. Fusion **53** 124032
- Y Yamamura and H Tawara 1996 Atomic Data and Nuclear Data Tables **62**, no.02 149-253