Session 2: Low-frequency oscillations and structures

Chairs: Yevgeny Raitses and Igor Kaganovich
Panelists: J.P. Boeuf, L. Xu, M. Panjan, I. Romadanov, D. Smith, J. Bak, J. Szabo

ExB Plasmas Workshop 2022

Madrid, online event

Universidad Carlos III de Madrid, February 16-18, 2022

Session 2: Low-frequency oscillations and structures

February 16, 2022, 12:15 - 14:00 EST.

Chaired by Yevgeny Raitses and Igor Kaganovich

1. Opening remarks (session chairs)
2. “Rotating spokes in ExB plasma of planar magnetron”, Jean-Pierre Boeuf, LAPLACE, CNRS, Toulouse, France
3. “On the driving mechanism behind the formation of a rotating spoke”, Liang Xu, Ruhr-University, Bochum, Germany
4. “Spokes in RF and DC magnetron discharges”, Matjaž Panjan, Jožef Stefan Institute, Ljubljana, Slovenia
5. “Control of Coherent Structures via External Drive of the Breathing Mode”, Ivan Romadanov, PPPL, Princeton, NJ, USA
6. “Constricted orbiting mode in high current, magnetized rare-gas plasma”, David Smith, General Electric Research, NY, USA
7. Discussions
   - Need and feasibility of controlling plasma structures (contributor: Junhwi Bak, Texas A&M, Collage Station, TX, USA)
   - Methods of prototyping new thrusters and whole device modeling, rationale for 3-D modeling: (contributor: James Szabo, Busek Co. Inc., Natick, MA USA)
8. Closing remarks: *year since the last workshop and next perspectives* (session chairs)

Rotating spokes in ExB plasmas of dc planar magnetrons

Jean-Pierre BOEUF
LAPLACE, CNRS, University of Toulouse

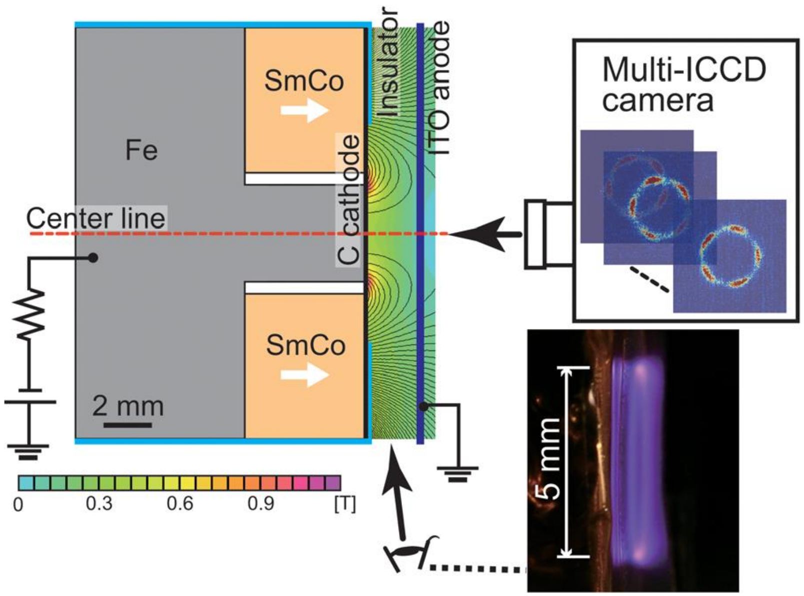
Université Fédérale Toulouse Midi-Pyrénées

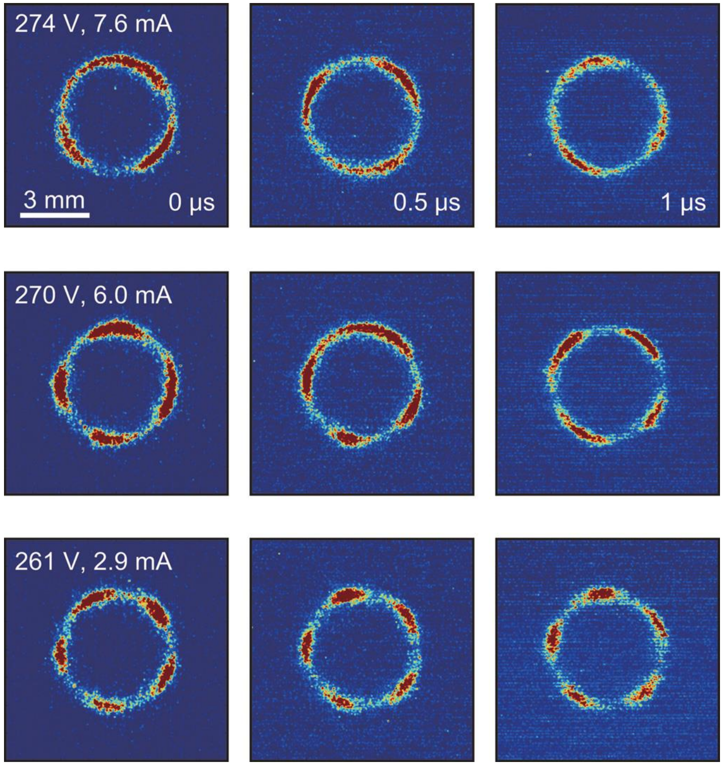
ExB Workshop 2022

Refs.: JP Boeuf and M Takahashi, Phys Rev. Lett. **124** 185005 (2020)
JP Boeuf and M Takahashi, Phys. Plasmas **27** 083520 (2020)

PIC-MCC model of a dc magnetron

- Experiment
  - T Ito, CV Young, & MA Cappelli
    Appl. Phys. Lett. 106, 254104 (2015)
  - Small magnetron
    argon, 2mm gap, p=150 mtorr, Bmax=1 T , 260 V
  - Observation of rotating spokes in -ExB direction

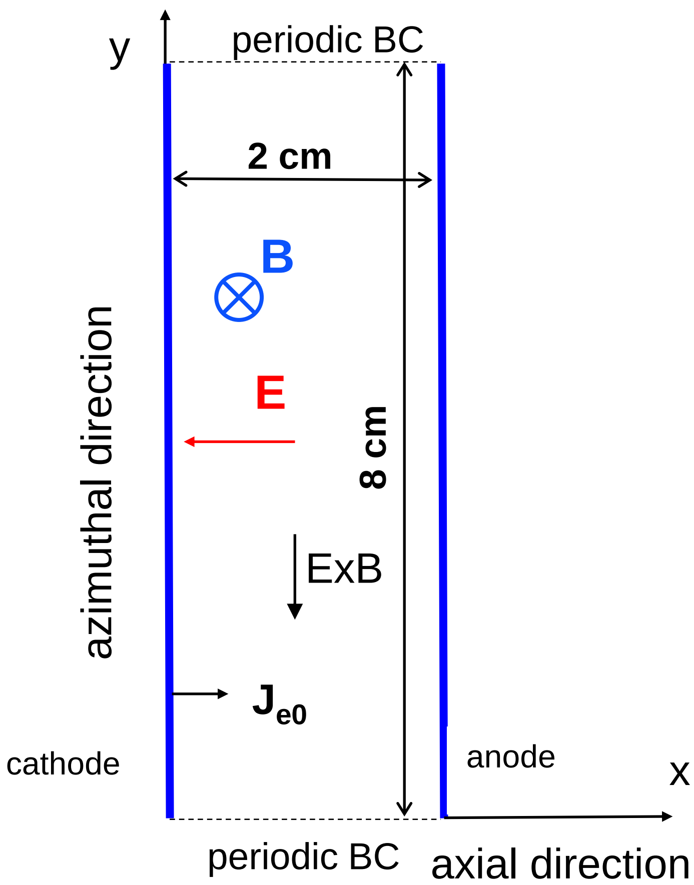


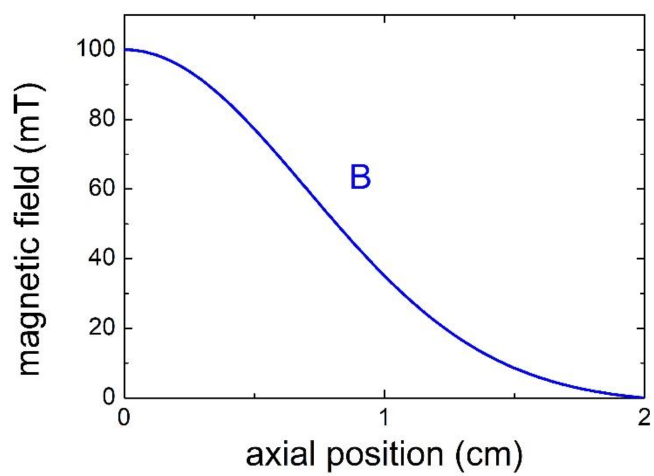


PIC-MCC model of a dc magnetron

- Model
  - 2D axial-azimuthal PIC-MCC
  - Scaling x10/experiment

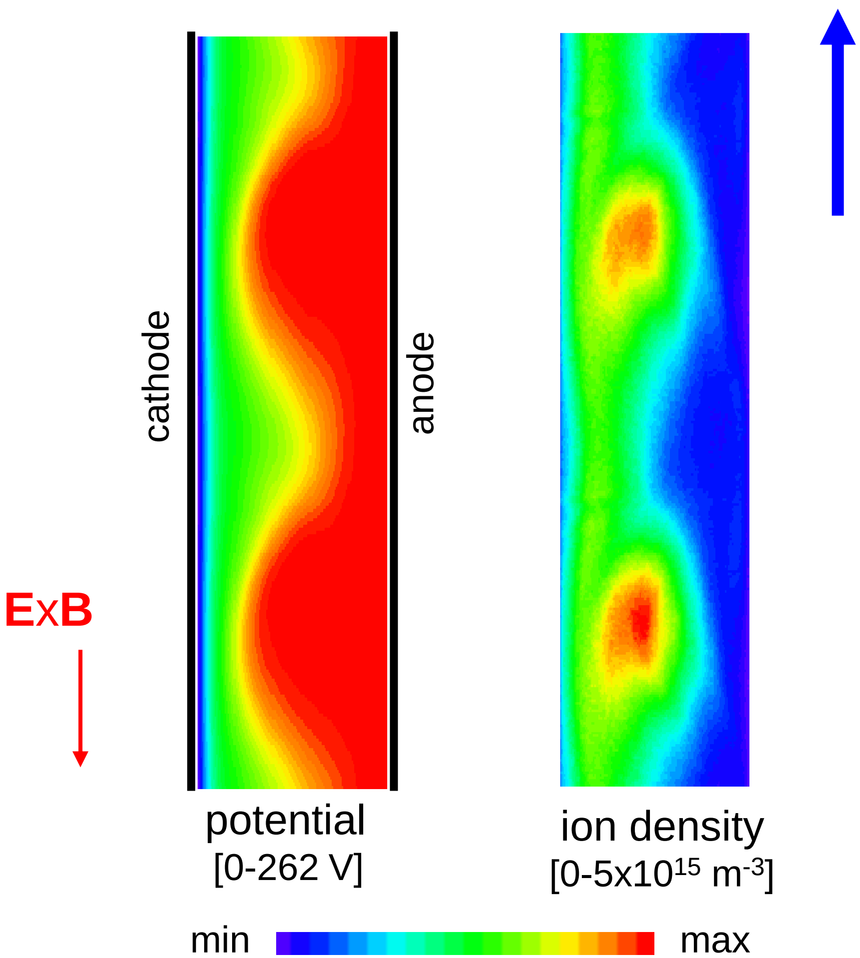
argon – 15 mtorr
2 cm gap, 8 cm azimuthal direction
B_{max} = 0.1 T
V_a = 260 V (dc)
J_{e0} = 25 mA/m^2
Uniform initial plasma density (n_e=n_i=5x10^{14} m^{-3})





PIC-MCC simulation results

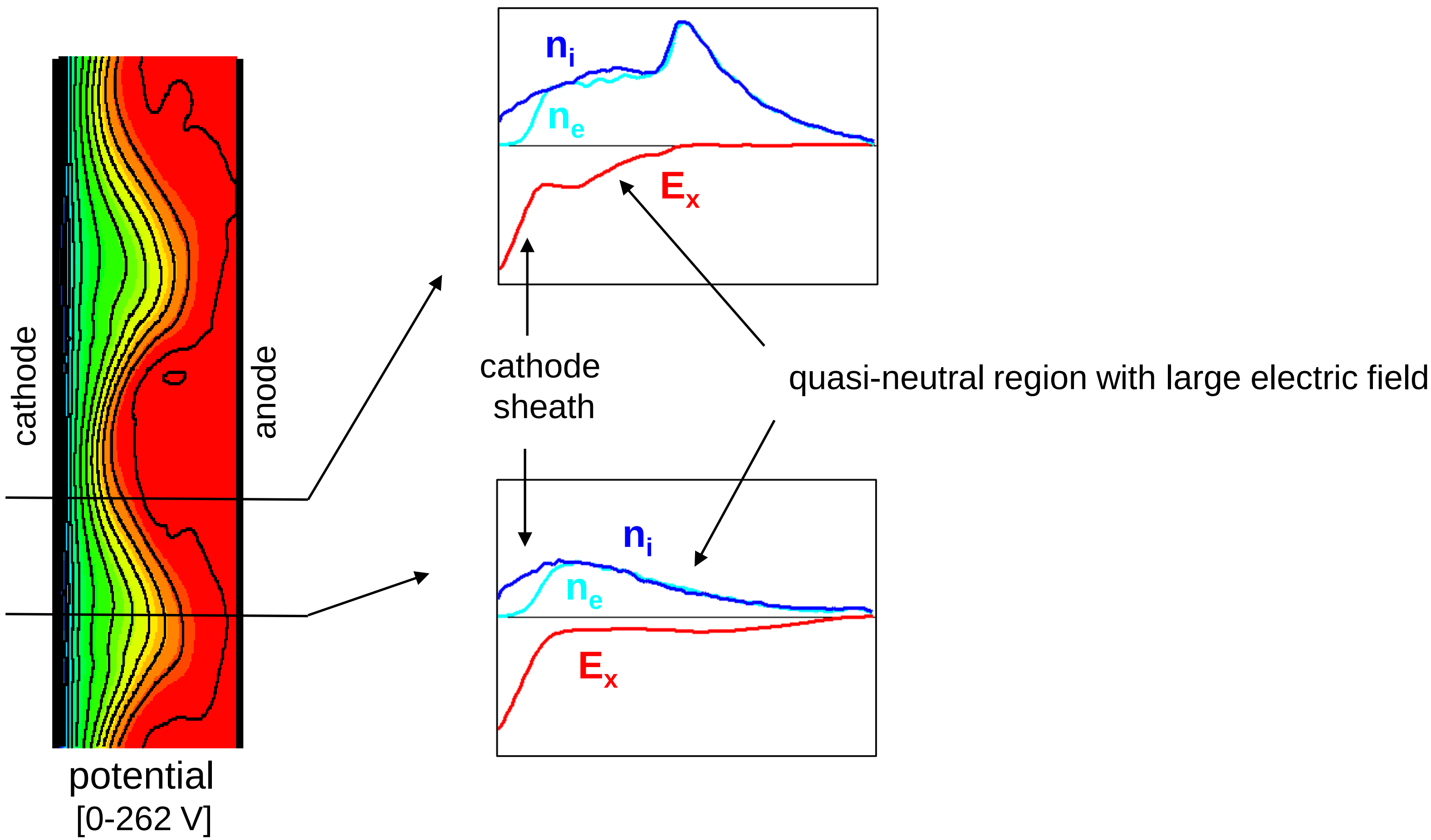
- Time evolution of electric potential and ion density



- Formation of azimuthal non-uniformities
- Wave moving in the azimuthal, -ExB direction
- Velocity v ~ 10 km/s consistent with exp,

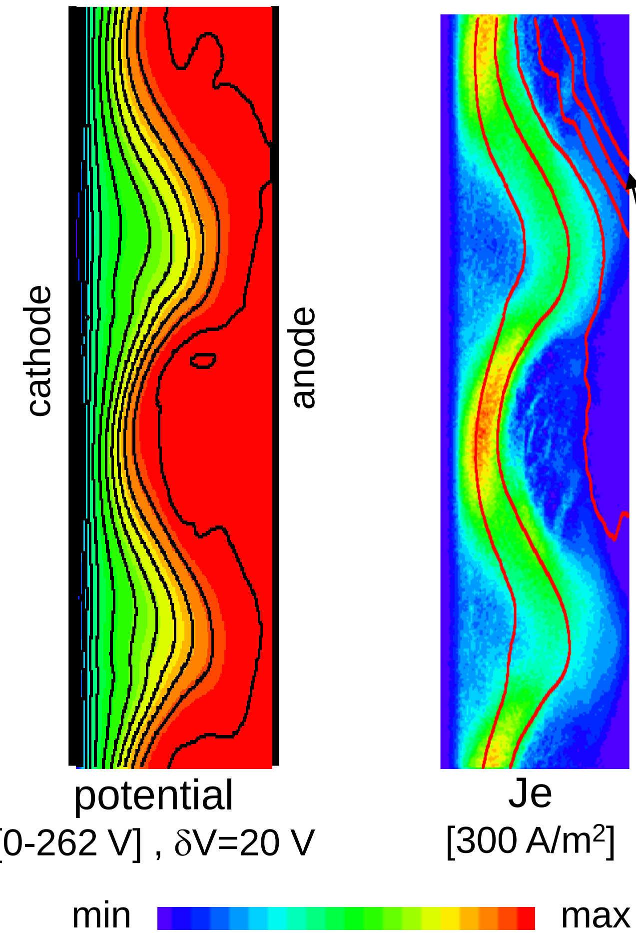
PIC-MCC simulation results

- Electric potential – E field penetration in quasineutral plasma



PIC-MCC simulation results

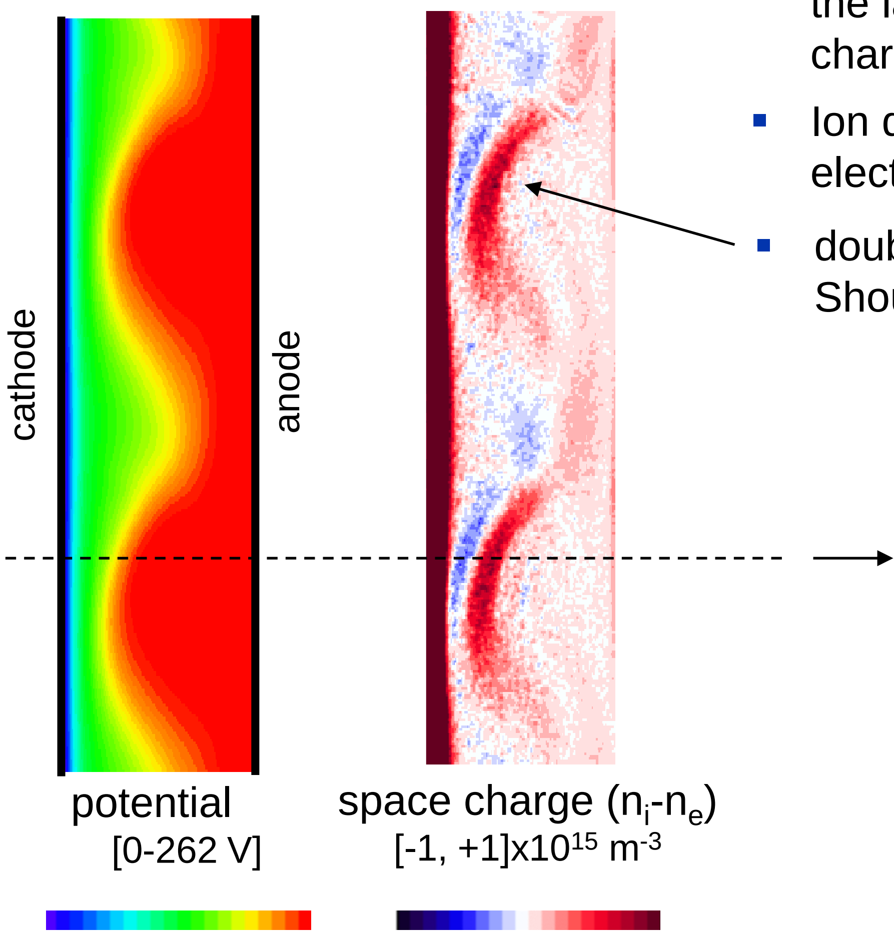
➢ Equipotential contours and electron current density



- Electric field is perpendicular to equipotential contours
  → **ExB drift follows equipotential lines**
- Current follows equipotential lines with some diffusion
- Current density is larger along the equipotential line at the interface between low field region and larger field region
- The electric potential distribution creates a kind of « short-circuit » allowing electrons to reach the anode in spite of the strongly reduced axial mobility

PIC-MCC simulation results

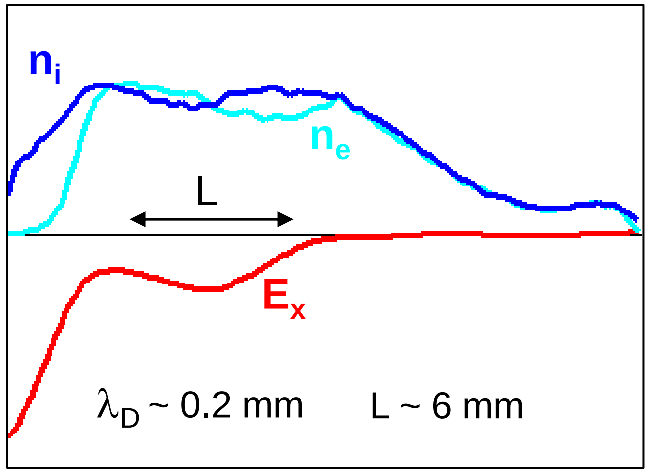
- Electric potential – Space charge



potential
[0-262 V]

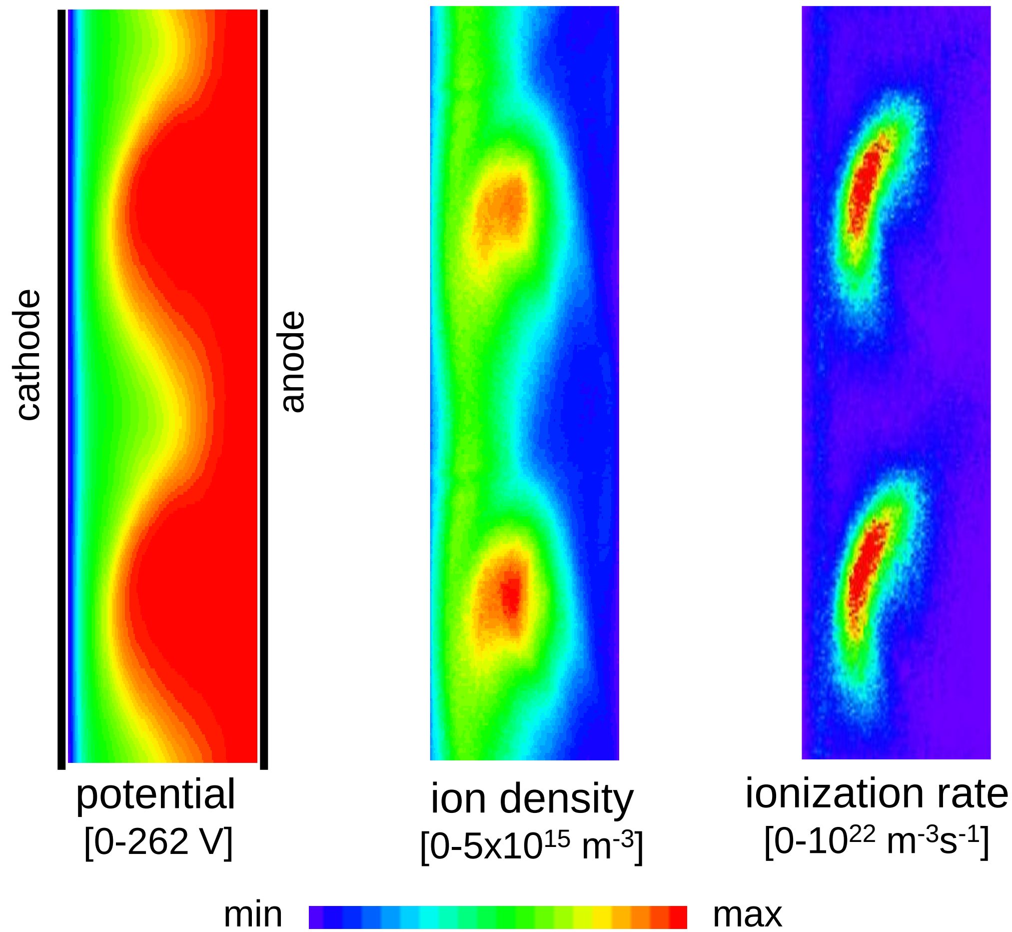
space charge (n_i-n_e)
[-1, +1]x10^{15} m^{-3}

- Formation of a **double layer** at the interface between the large field and low field regions (positive space charge in red, negative in blue)
- Ion density larger than electron density because electrons leaving the equipotential line to anode region
- double layer is several mm in these conditions. Should be much smaller for larger plasma densities?



PIC-MCC simulation results

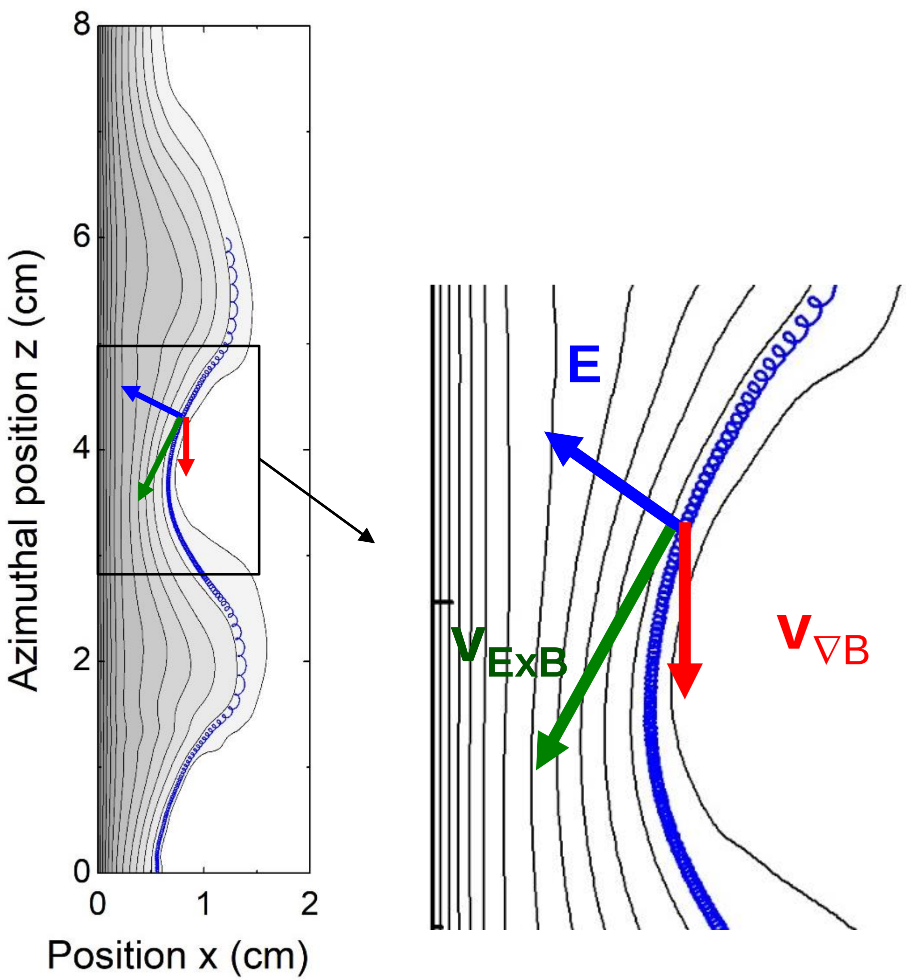
- Electric potential – Ion density – Ionization rate



- Distribution of ionization rate close to distribution of emitted light → spoke is an ionization wave
- Spoke is located in the double layer, above the maximum plasma density
  → moves up, i.e. in the –ExB direction
- Ionization rate is much larger in the spoke than in the cathode sheath
- What are the mechanisms of electron heating in the spoke ?

PIC-MCC simulation results

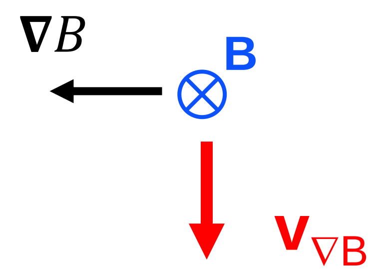
➢ Electron heating in the spoke



- Electron trajectory follows equipotential line
- Not exactly !: small vertical drift down
- Vertical drift due to grad B

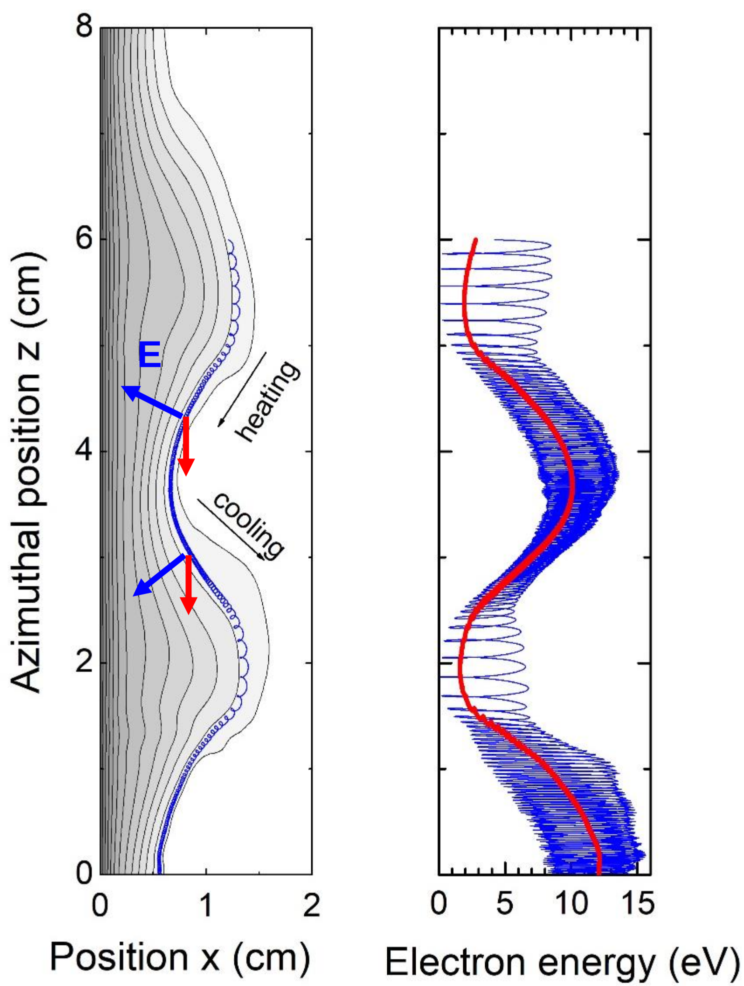
Grad B drift velocity $\boldsymbol{v}_{\nabla B}$

$$\boldsymbol{v}_{\nabla B} = 1/2\, \rho_e v_\perp \boldsymbol{B} \times \nabla B / B^2$$



PIC-MCC simulation results

➢ Electron heating in the spoke



- Electron energy varies along trajectory

- Because of grad B drift

→ electrons gain energy on one side of potential wave

→ lose energy on the other side

- Electron energy gain proportional to scalar product of electron mean velocity and electric field

$$\partial_t \varepsilon_\perp = -\boldsymbol{v}_{\nabla B}.\boldsymbol{E}$$

- Changes sign because grad B drift is vertical and vertical component of E changes sign

CONCLUSION

- PIC-MCC results consistent with experiments in low power planar dc magnetrons:
  -ExB rotation, velocity, frequency, current density.

- Model shows that the non-uniformity of the plasma results from a **Simon-Hoh instability evolving into a spoke, which is an ionization wave in these conditions**. Most of the ionization takes place in the spoke (very little in the cathode sheath)

- The **rotating spoke forms in a double layer separating two plasma regions of different properties**. Electrons gain energy in crossing the double layer. (consistent with exp., see, e.g. Panjan and Anders, J. Appl. Phys. 121 063302 (2017)

- **Electron drift due to GradB enhances the electron energy gain in the spoke**

- Spoke can rotate in +ExB direction (e.g. for lower magnetic fields)

- Similar results can be obtained in the conditions of Hall thrusters (xenon, lower pressure, smaller magnetic field). Effect of neutral depletion and coupling with breathing mode needs to be investigated.

QUESTIONS

- Would be useful to confirm and better understand presence of double layer and role of Grad B with benchmark simulations. Larger plasma densities ? Anybody interested ?

- Is “double layer” the right term ? Space charge wave ? Scaling with Debye length ?

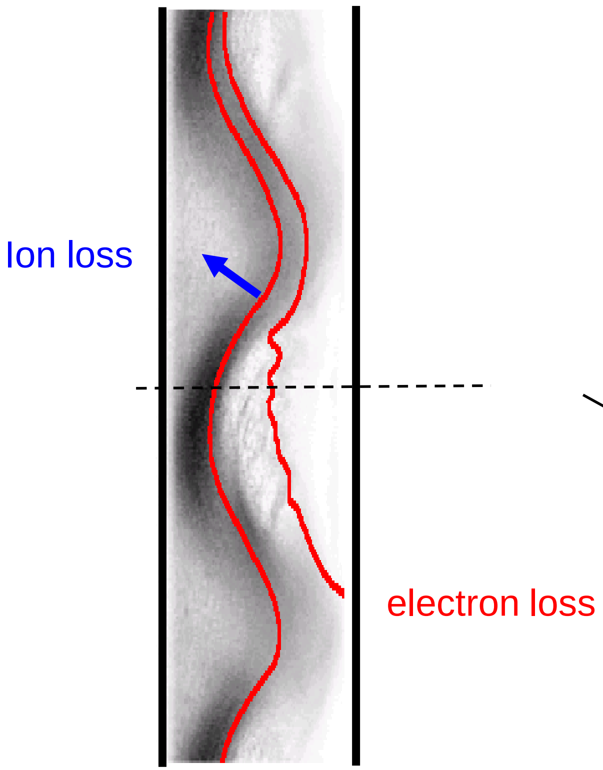
- Neutral depletion probably plays a role in spoke properties in Hall thrusters and high power magnetrons. Coupling with breathing oscillations ? Any experimental evidence ?

- Is it possible to describe Grad B effects in fluid models ?

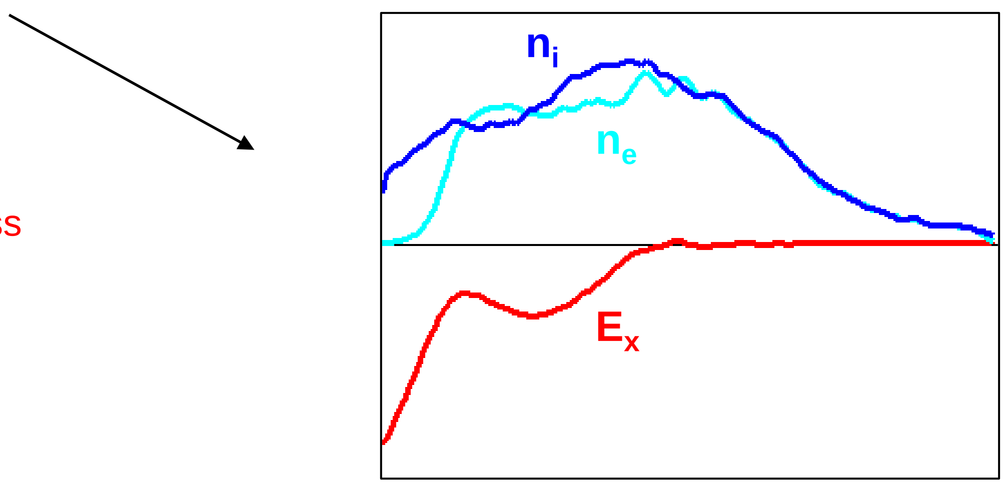
- Any evidence of Grad B effect in experiments ?

PIC-MCC simulation results

- electron and ion fluxes

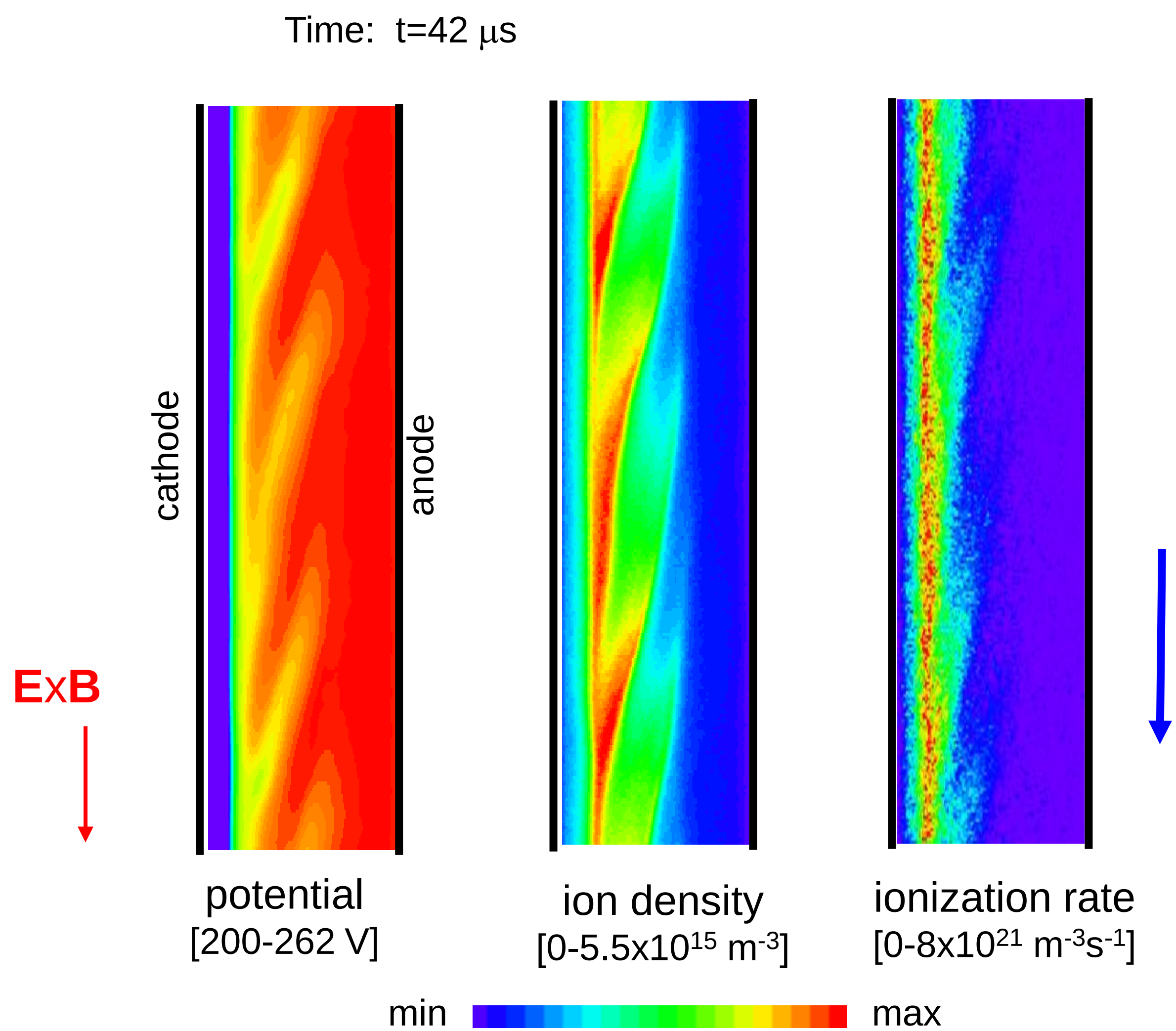


- Double layer generated by electron losses to the anode or to the low magnetic field region
- Electron losses along the line → deficit of electrons → ion sheath → potential drop → potential expels ions from the line → double layer



PIC-MCC simulation results

➢ example of Rotation in +ExB direction



argon – 15 mtorr
2 cm gap, 8 cm azimuthal direction
B_{max} = 300 G
V_a = 260 V (dc)
J_{e0} = 250 mA/m^2

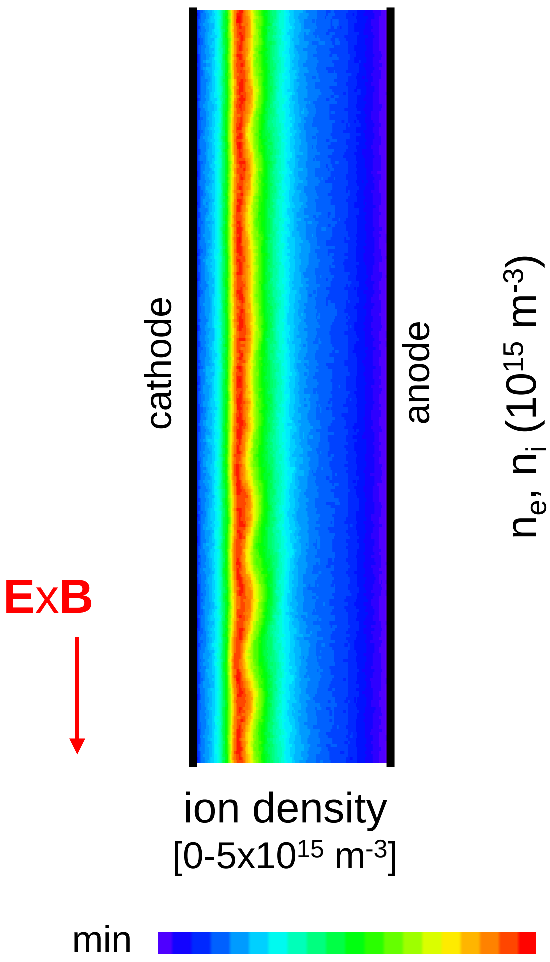
- **+ExB rotation**
- **Simon-Hoh + Ionization**

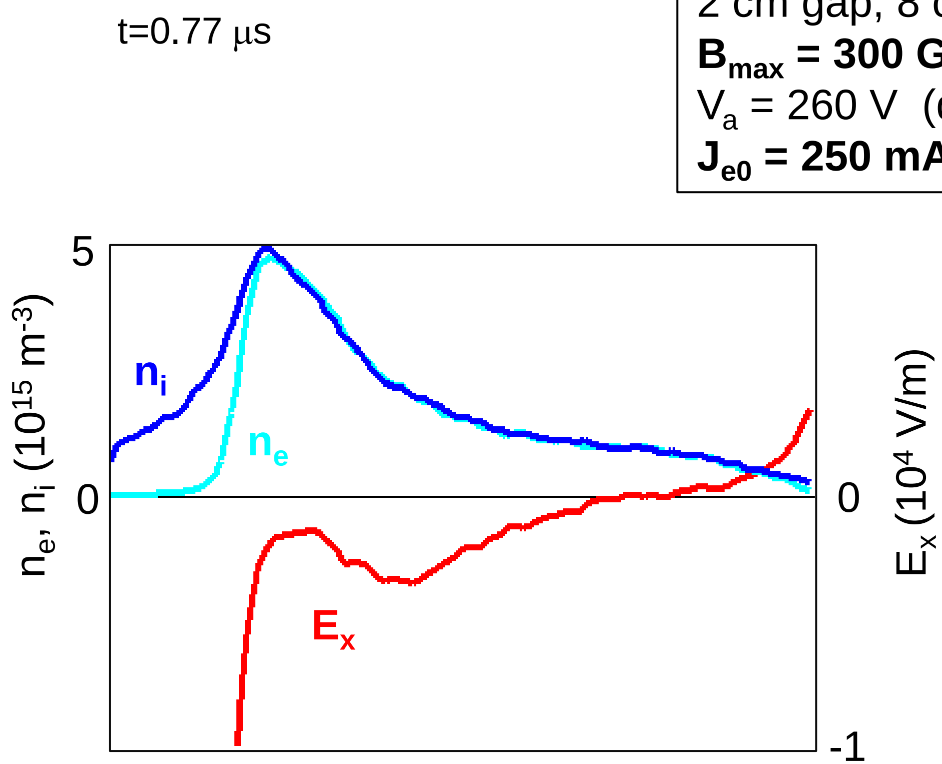
Phase velocity ~15-20 km/s

PIC-MCC simulation results

- exemple of Rotation in +ExB direction

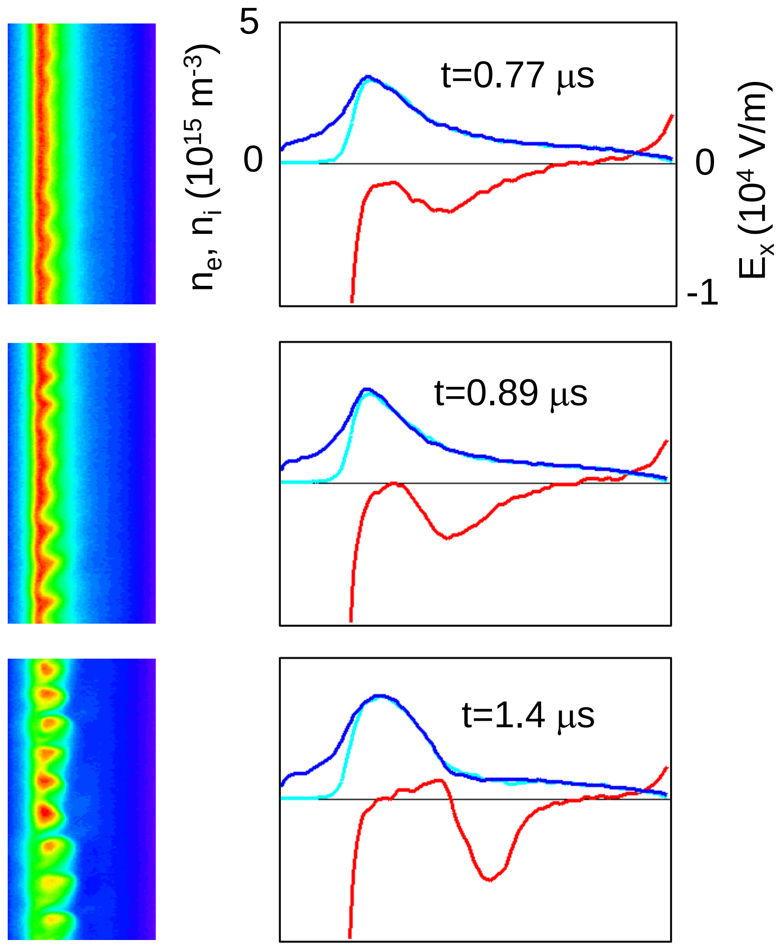
argon – 15 mtorr
2 cm gap, 8 cm azimuthal direction
B_{max} = 300 G
V_a = 260 V (dc)
J_{e0} = 250 mA/m^2





PIC-MCC simulation results

- example of Rotation in +ExB direction



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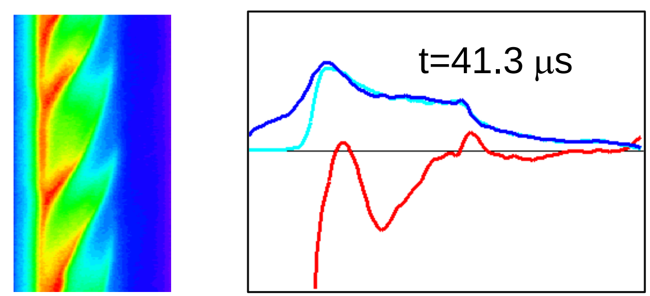
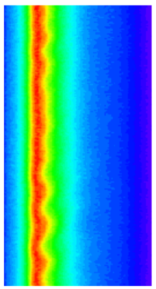
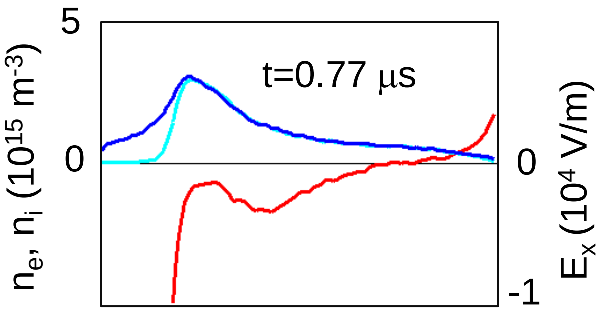


PIC-MCC simulation results

- Dispersion relation





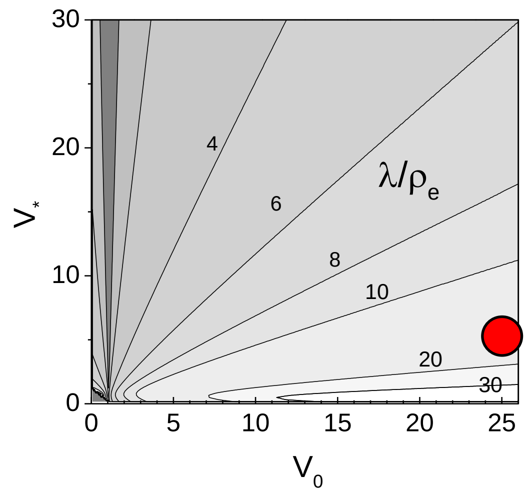
argon – 15 mtorr
2 cm gap, 8 cm azimuthal direction
B_{max} = 300 G
V_a = 260 V (dc)
J_{e0} = 250 mA/m²

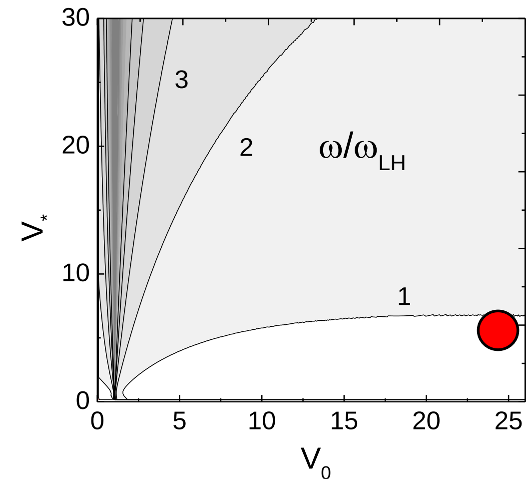
$$\frac{\omega_* + k^2\rho_e^2(\omega-\omega_0+i\nu_{en})}{\omega-\omega_0+k^2\rho_e^2(\omega-\omega_0+i\nu_{en})} = \frac{k^2 c_s^2}{\omega^2}$$

Wavelength $\lambda \sim 1$ cm
Larmor radius $\rho_e \sim 0.5$ mm

$E_x \sim 3.\ 10^3$ V/m
B ~ 200 G
Te ~ 5 eV
Cs ~ $3.\ 10^4$ m/s
Ln ~ 10^{-2} m

$V_0 = E/(B\ Cs)$ ~ 30-50
$V^* = T_e/(BL_nCs)$ ~ 5-10
$\omega_{LH} \sim 10^7\ s^{-1}$





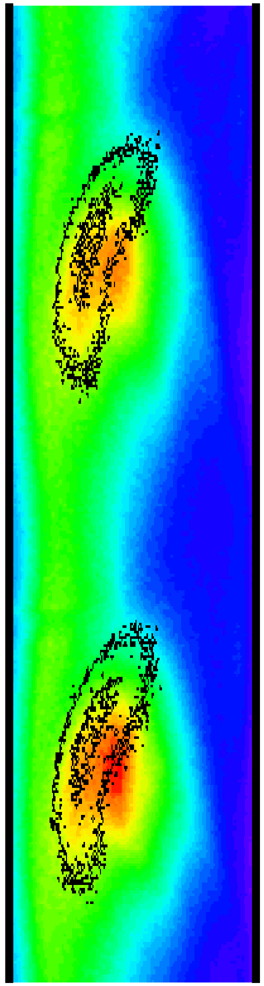
$\lambda/\rho_e \sim 20 \rightarrow$ **$\lambda \sim 1$ cm**

$\omega \sim \omega_{LH} \rightarrow$ **v_{ph} ~ 15 km/s**

Wavelength and frequency at maximum growth rate

PIC-MCC simulation results

- Ion density and ionization frequency: -ExB rotation



ExB

argon – 15 mtorr
2 cm gap, 8 cm azimuthal direction
B_{max} = 1000 G
V_a = 260 V (dc)
J_{e0} = 25 mA/m^2

On the driving mechanism behind the formation of a rotating spoke

Liang Xu, Ruhr-University Bochum, Germany

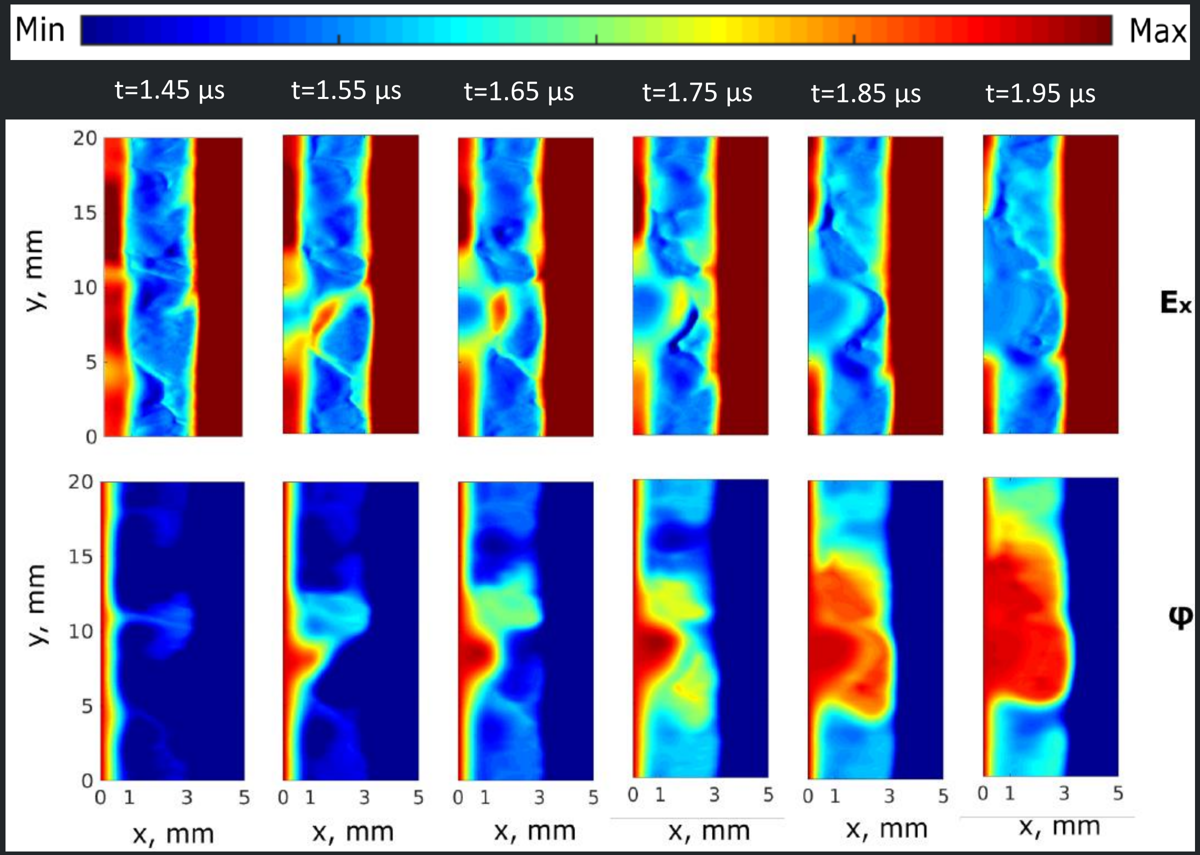


Fig. 2D PIC simulations show how the m=1 lower hybrid mode evolves into the spoke 'potential hump' with uniform B=40mT (anode: x=0; cathode: x=5mm, anode voltage U=200V, P=10 Pa).

❑ Main Finding:

The formation of spoke potential hump is triggered by the positive anode sheath collapse resulting from the lower hybrid instability

(Further information/open questions: in the poster session)

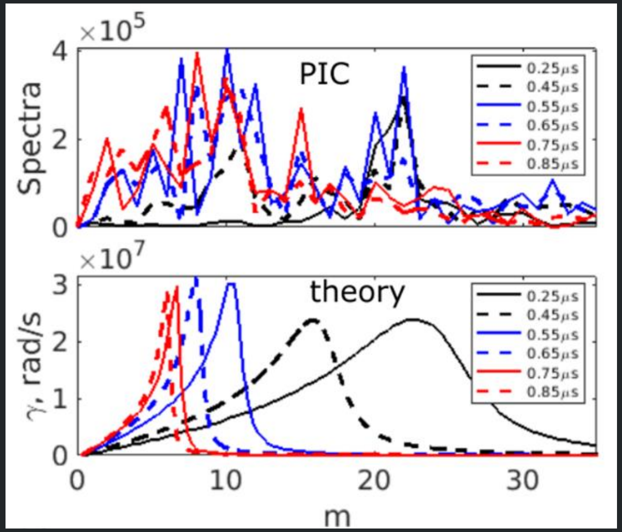


Fig. the m=21 lower hybrid mode in the linear stage transits to the longer wavelength modes.

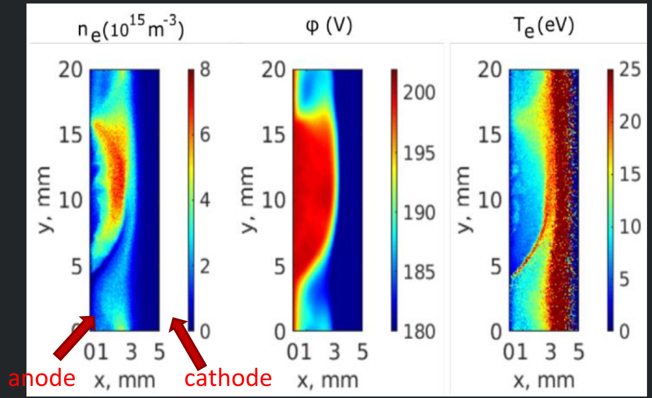


Fig. the saturated spoke rotates azimuthally in + E×B direction with v=7km/s (The electric field directs from anode to cathode in x direction. The azimuthal y direction is periodical. B is uniform and in the z direction.)

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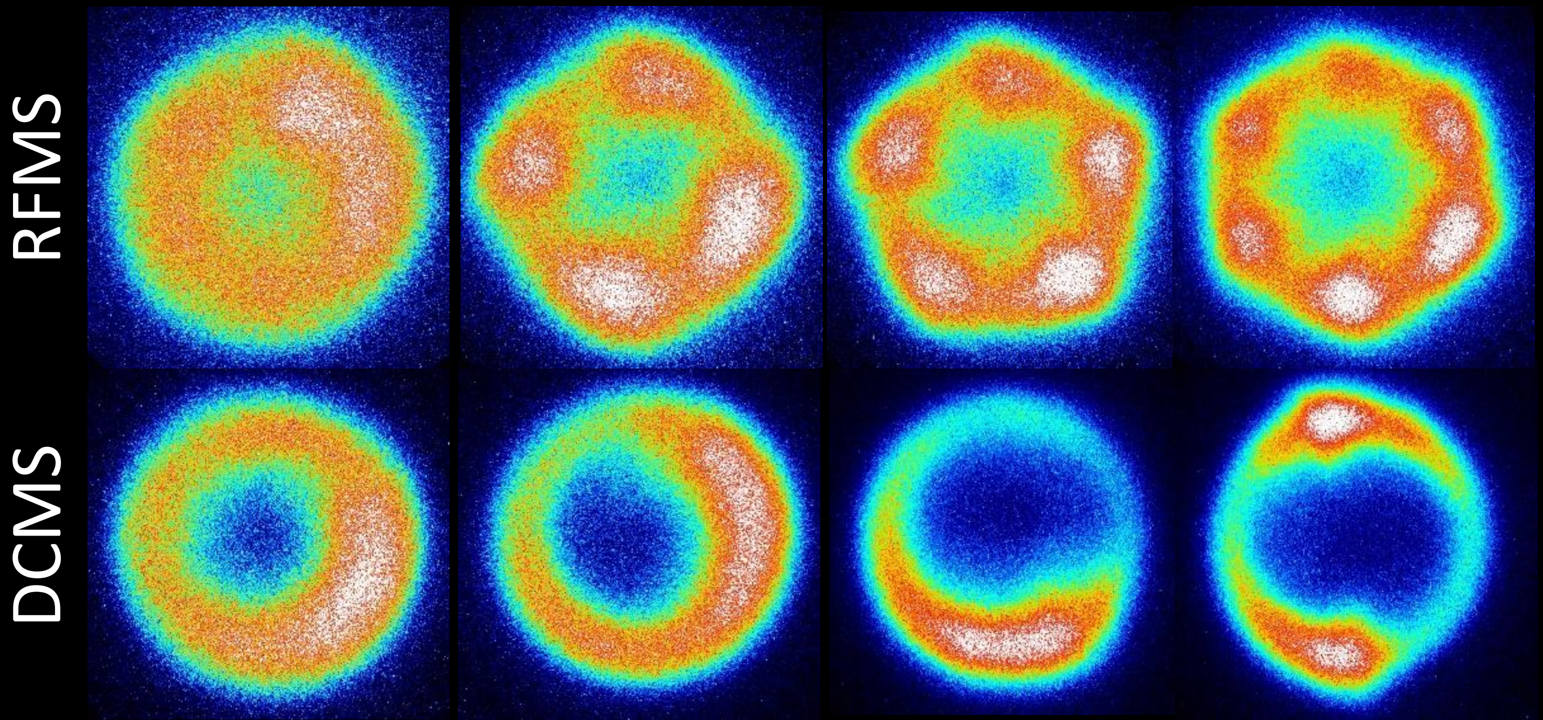
16-18 Feb 2022 – Virtual Meeting

Spokes in RF and DC magnetron discharges

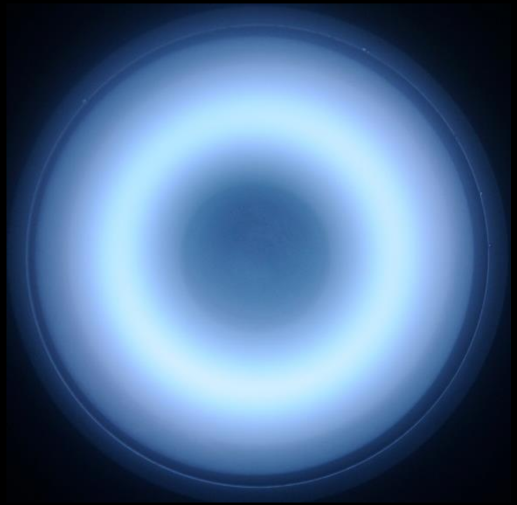
Matjaž Panjan

Jožef Stefan Institute
Ljubljana, Slovenia

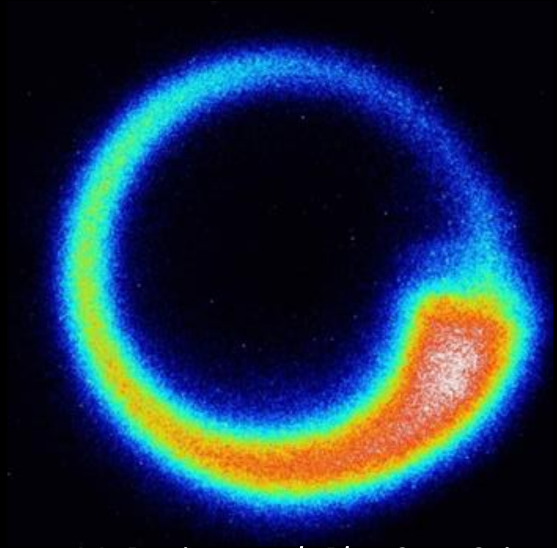


Plasma self-organization in magnetron sputtering discharges

continuous voltage



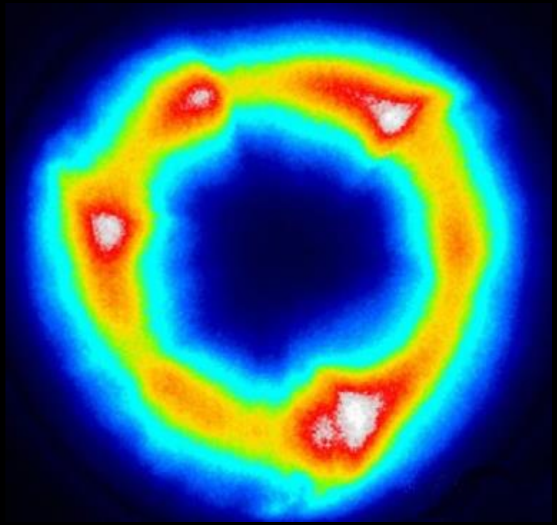
DCMS



M. Panjan *et al. Plas Sour Sci Technol* 24 065010 (2015)

pulsed voltage

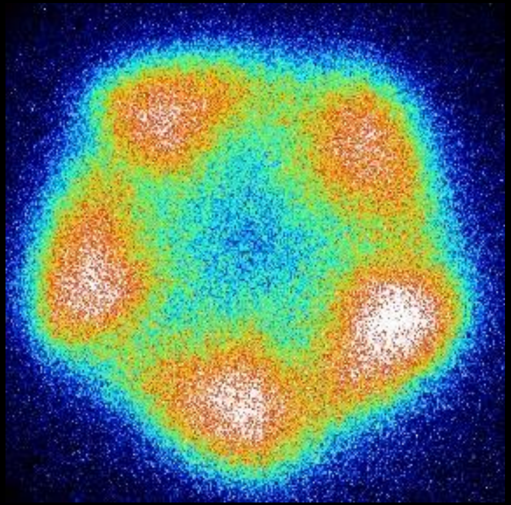
HiPIMS



A. Anders *et al. J App Phys* 111 053304 (2012)

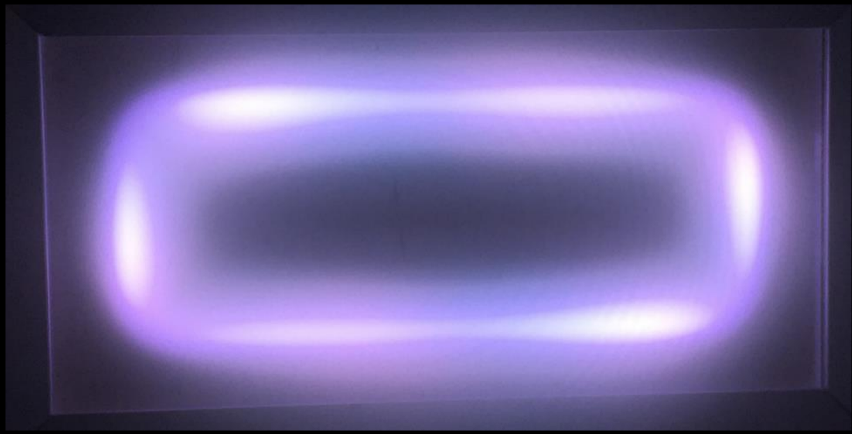
oscillatory voltage

RFMS

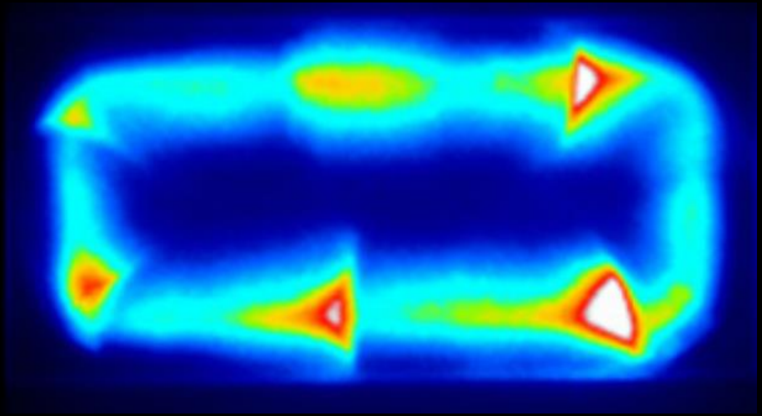


M. Panjan *J App Phys* 125 20 (2019)

rectangular magnetron



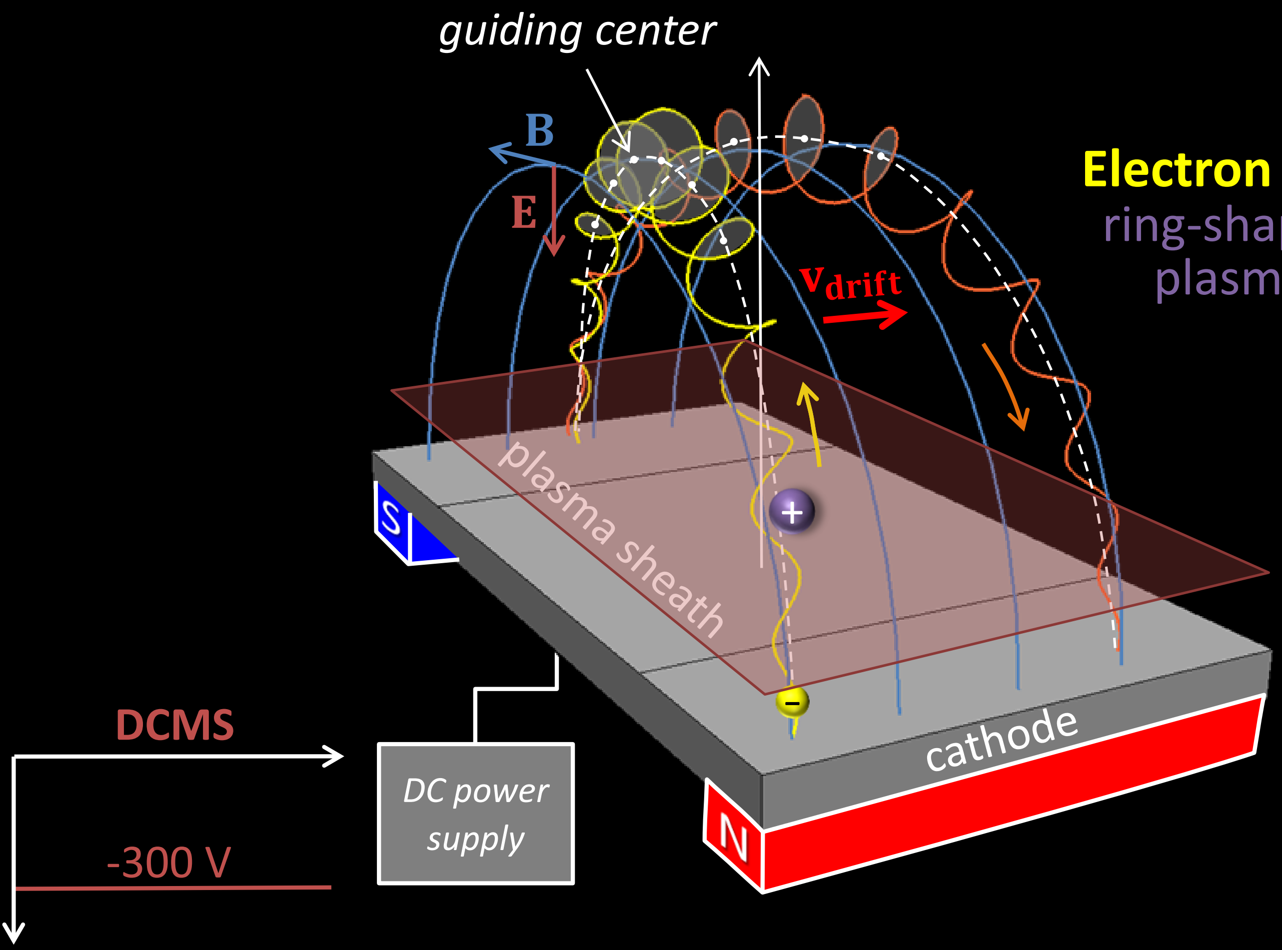
HiPIMS



A. Anders, Y. Yang, *J Appl Phys* 123 043302 (2018)

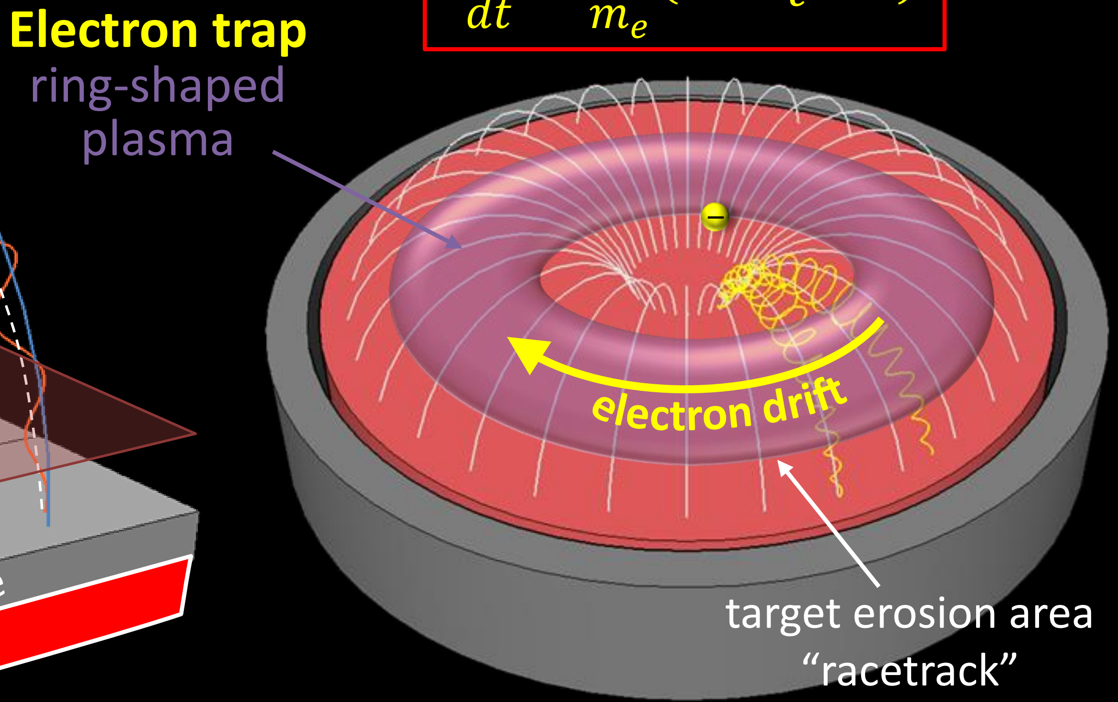
Motion of electrons in DC magnetron sputtering regime

Motion of electron in crossed electric and magnetic field



equation of motion

$$\frac{d\mathbf{v}_e}{dt} = \frac{e}{m_e}(\mathbf{E} + \mathbf{v}_e \times \mathbf{B})$$



E×B drift

$$\mathbf{v}_{\mathbf{E}\times\mathbf{B}} = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

∇B drift

$$\mathbf{v}_{\nabla\mathbf{B}} = \frac{v_\perp r_L}{2}\frac{\nabla\mathrm{B}\times\mathbf{B}}{B^2}$$

B-curvature drift

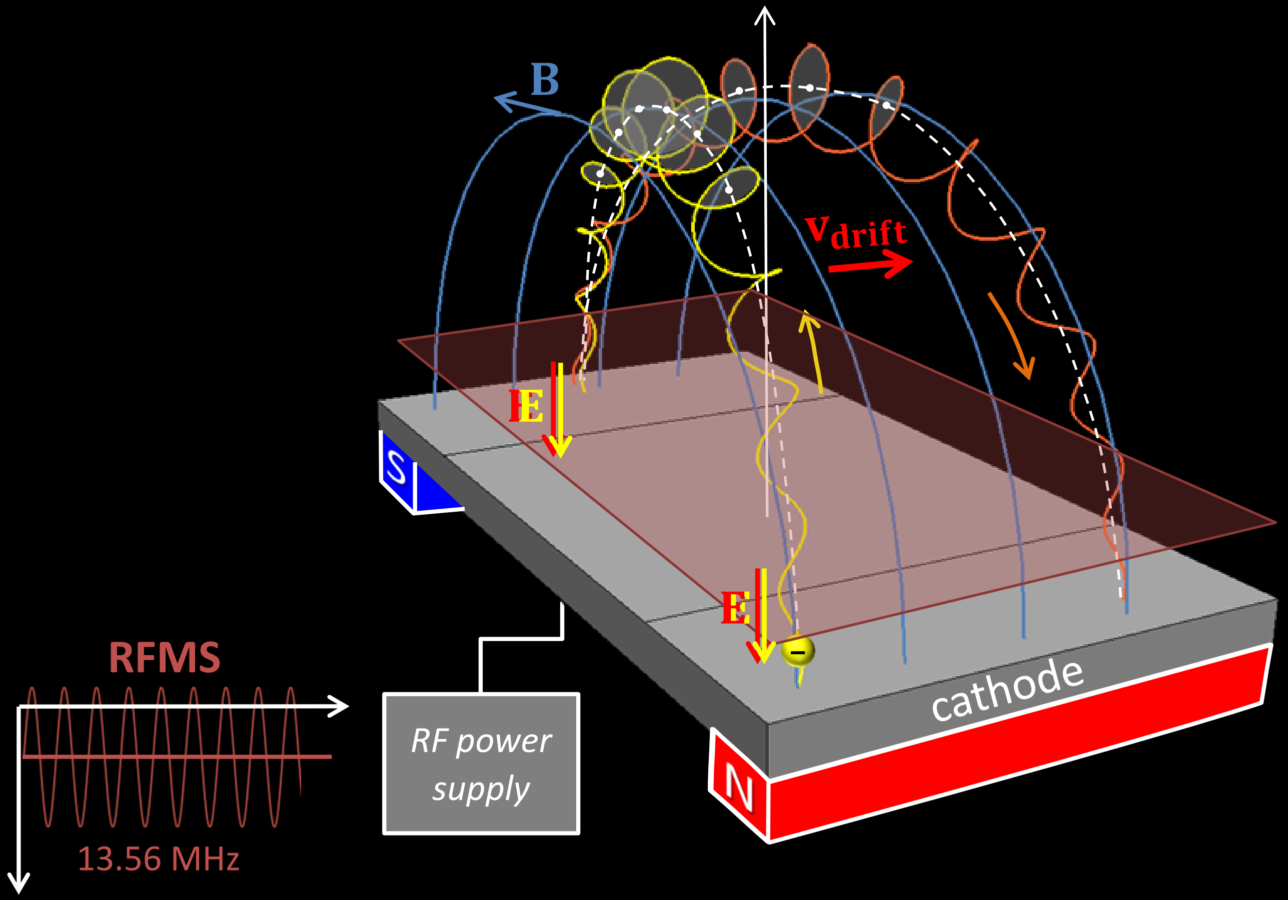
$$\mathbf{v}_R = \frac{m_e v_\parallel^2}{q}\frac{\mathbf{R}_\mathrm{C}\times\mathbf{B}}{\mathbf{R}_\mathrm{C}^2 B^2}$$

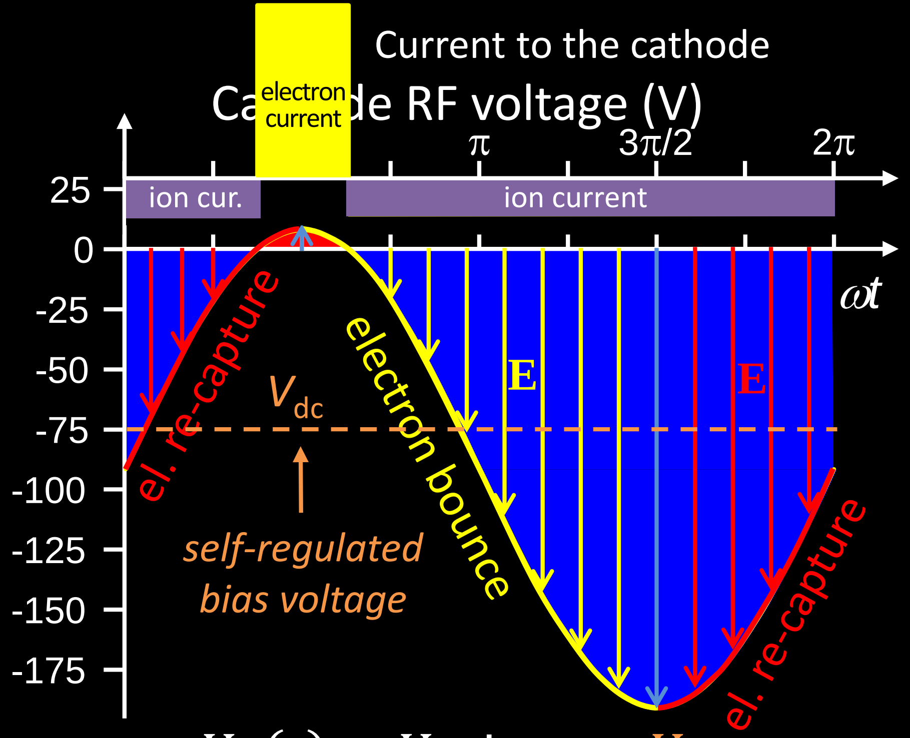
Electron drift velocity

$$\mathbf{v}_{\text{drift}} = \mathbf{v}_{\mathbf{E}\times\mathbf{B}} + \mathbf{v}_{\nabla\mathbf{B}} + \mathbf{v}_R$$

Motion of electrons in RF magnetron sputtering regime

During RF period when E-field decreases electrons will be **recaptured** at the cathode.
When E increases electrons will **bounce** off the sheath potential.





$$V_{\mathrm{rf}}(t) = V_0 \sin \omega t - V_{\mathrm{dc}}$$

- electrons respond to RF voltage
- ions respond to self-bias voltage

E×B drift

$$\mathbf{v}_{\mathbf{E}\times\mathbf{B}} = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

∇B drift

$$\mathbf{v}_{\nabla\mathbf{B}} = \frac{v_\perp r_L}{2}\frac{\nabla \mathrm{B}\times\mathbf{B}}{B^2}$$

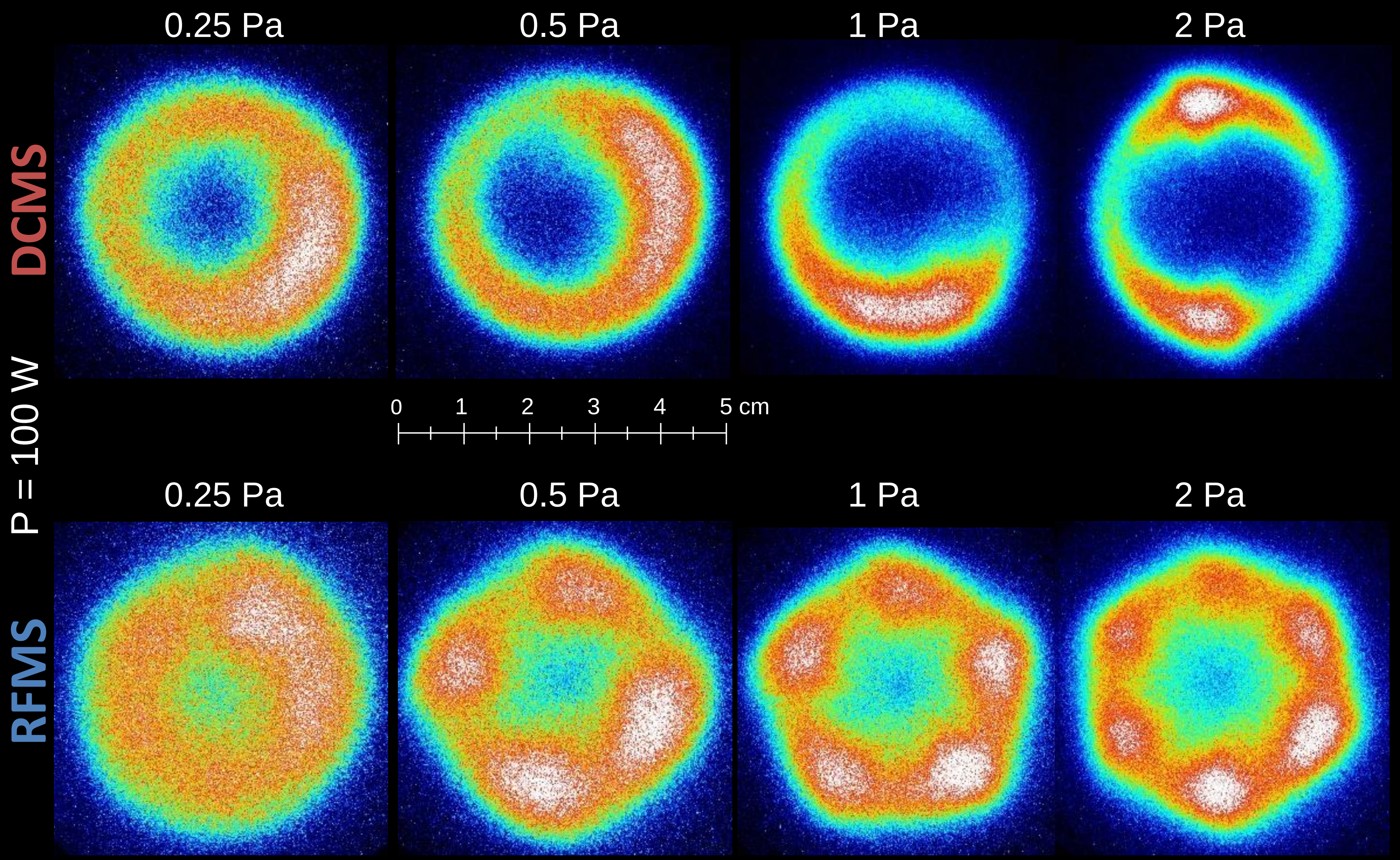
B-curvature drift

$$\mathbf{v}_R = \frac{m_e v_\parallel^2}{q}\frac{\mathbf{R}_\mathbf{C}\times\mathbf{B}}{\mathbf{R}_\mathbf{C}^2 B^2}$$

Electron drift velocity

$$\mathbf{v}_{\mathbf{drift}} = \mathbf{v}_{\mathbf{E}\times\mathbf{B}} + \mathbf{v}_{\nabla\mathbf{B}} + \mathbf{v}_R$$

Spoke patterns in DC and RF magnetron discharges

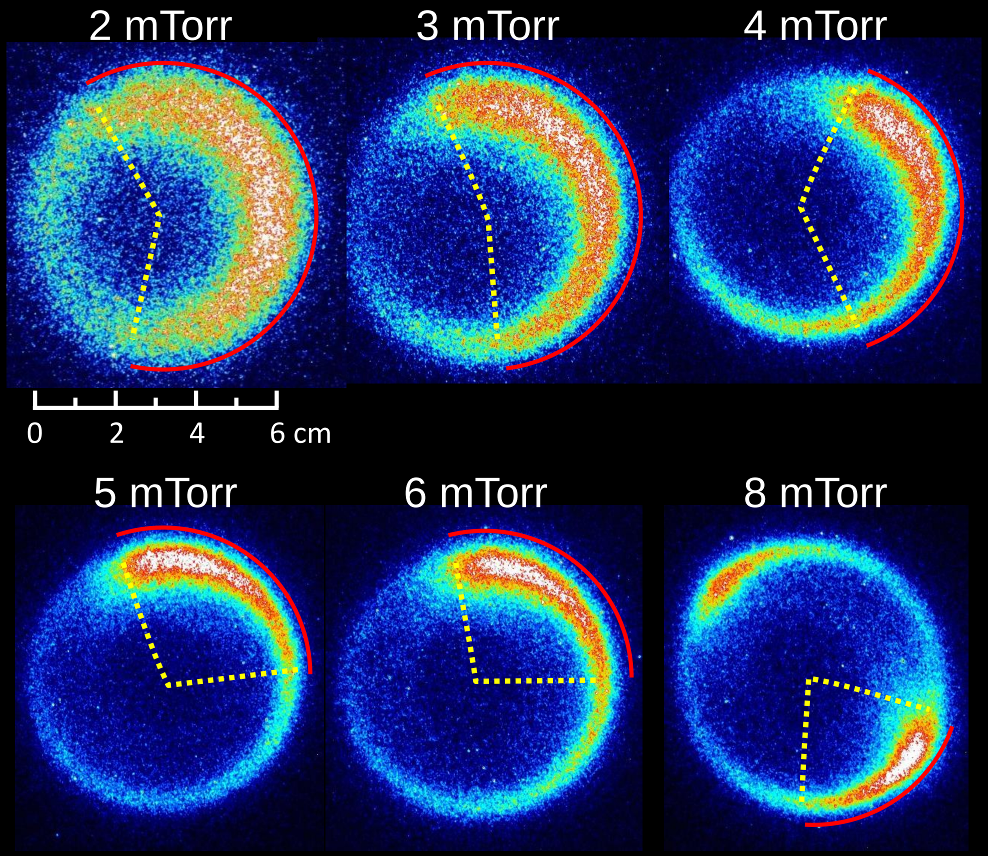


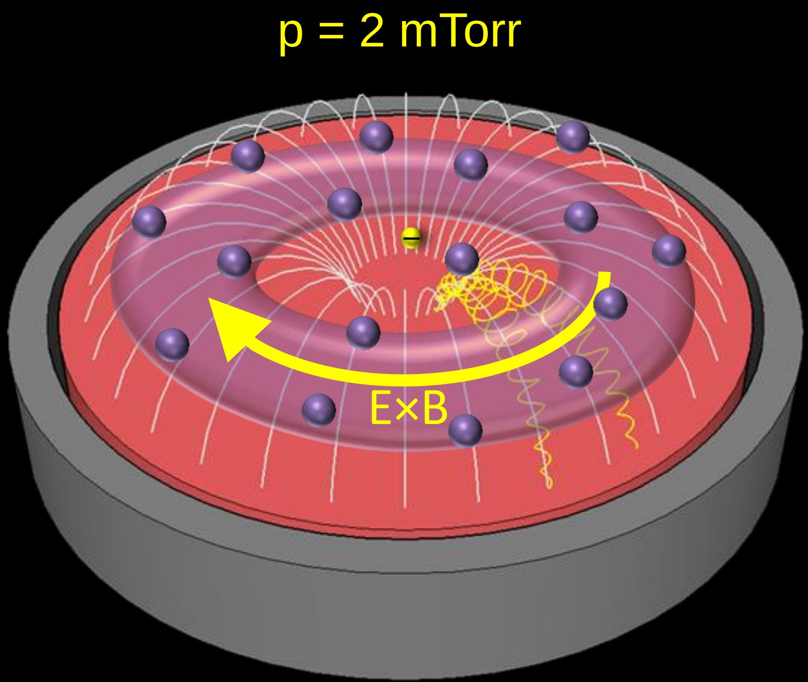
Azimuthal length of spokes is related to electron MFP

Collisions depend on the background ***pressure*** and ***electron energy***

Mean free path $$\lambda_{eAr} = \frac{1}{n_{Ar}\sigma_{eAr}}$$

MFP in ξ $$\lambda_{eAr}^{\xi} = \frac{kT_{Ar}v_{\mathrm{drift}}}{p_{Ar}\sigma_{eAr}v_e}$$





M. Panjan *et al., Plasma Sources Sci Technol* 24 065010 (2015)
M. Panjan, *J. Appl. Phys.*, 125 203303 (2019)

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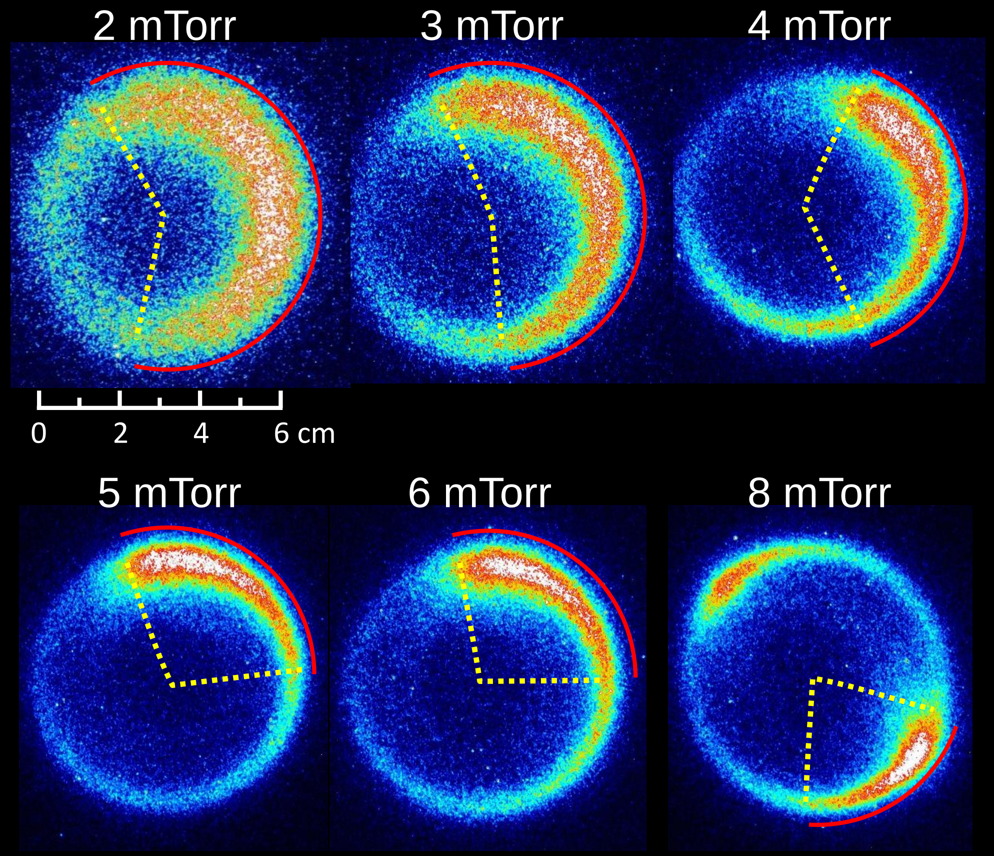
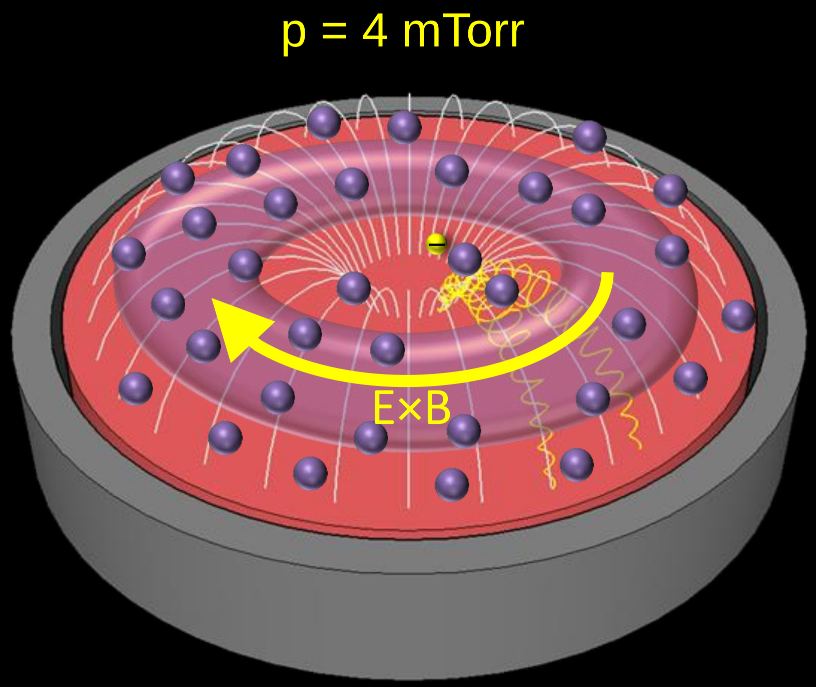
Mean free path $\boxed{\lambda_{eAr} = \frac{1}{n_{Ar}\sigma_{eAr}}}$

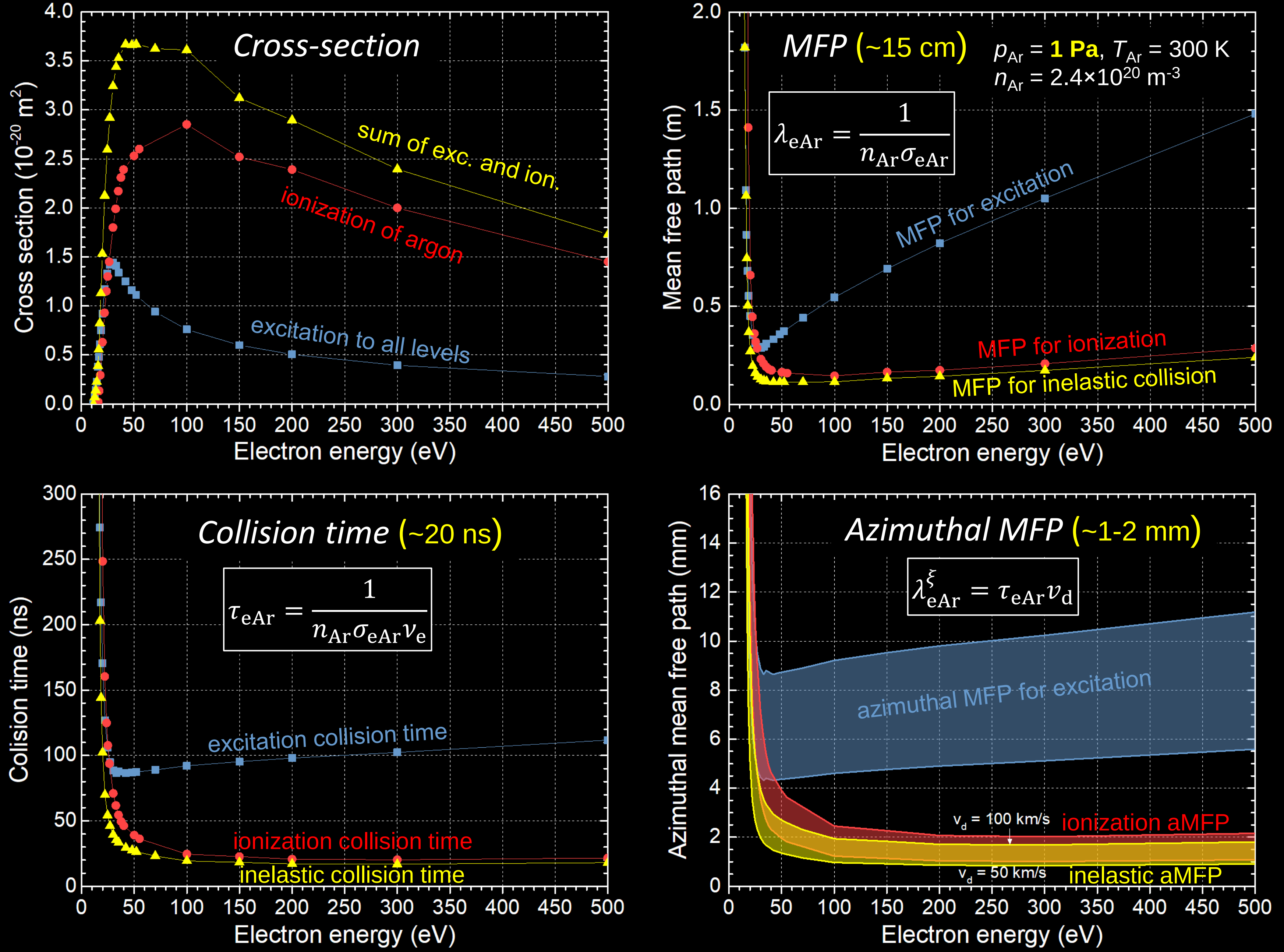
MFP in ξ $\boxed{\lambda^{\xi}_{eAr} = \frac{kT_{Ar}v_{\text{drift}}}{p_{Ar}\sigma_{eAr}v_e}}$



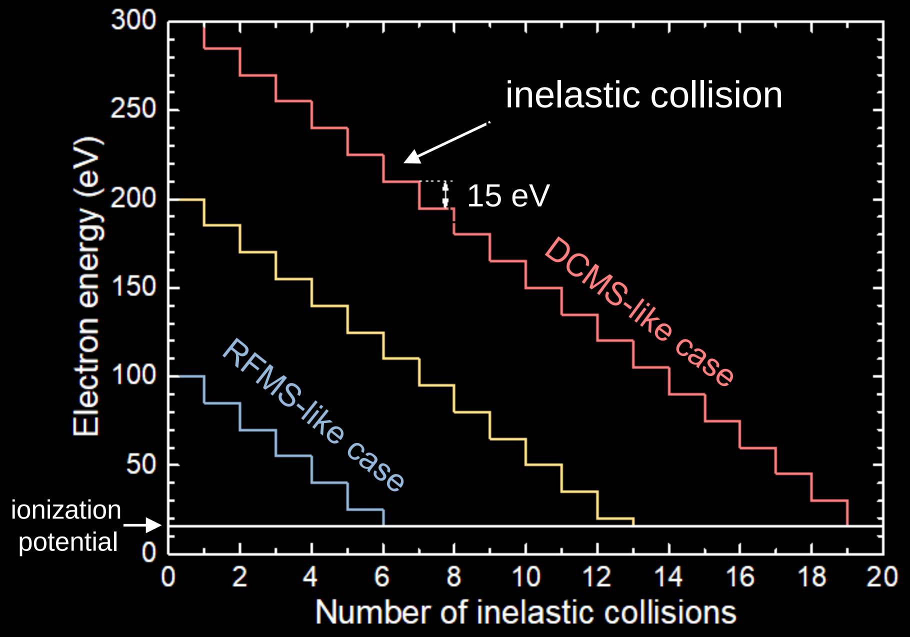


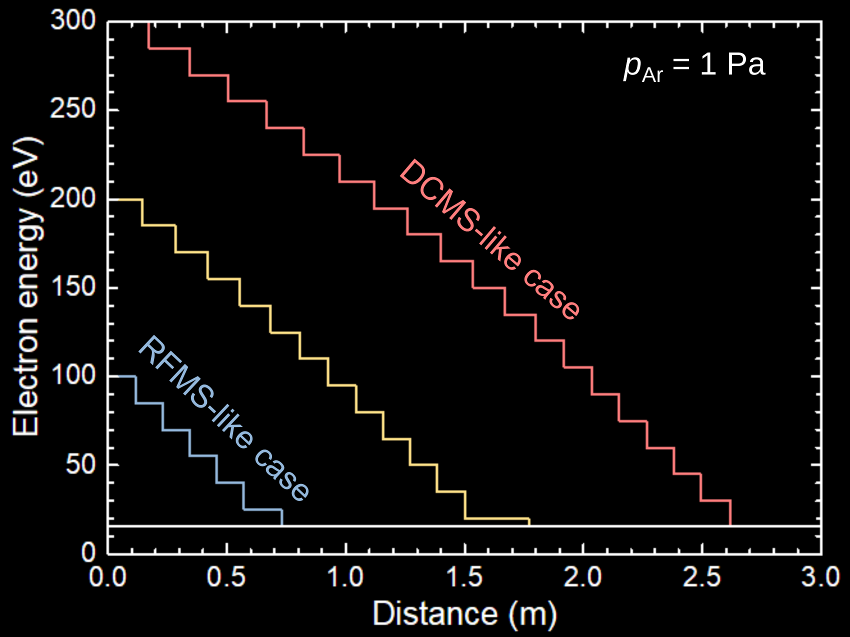
M. Panjan *et al.*, *Plasma Sources Sci Technol* 24 065010 (2015)
M. Panjan, *J. Appl. Phys.*, 125 203303 (2019)

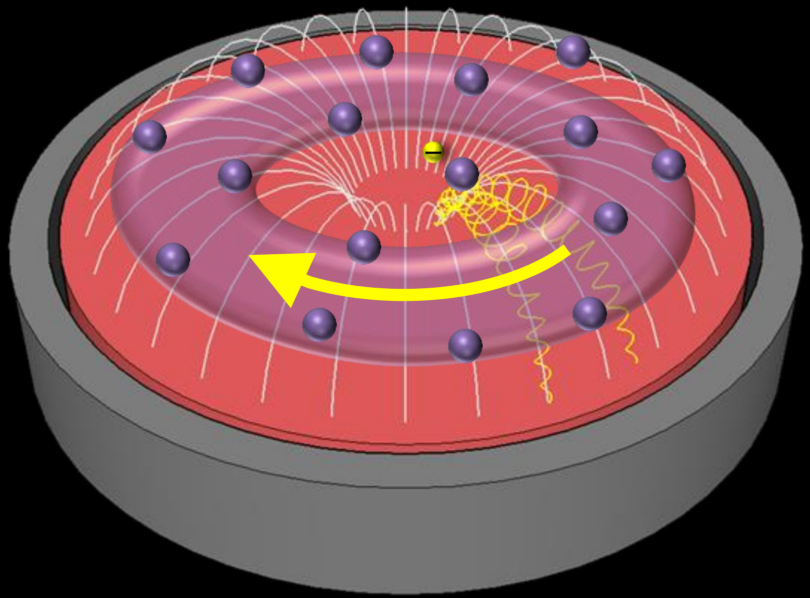
Interactions between electrons and argon atoms

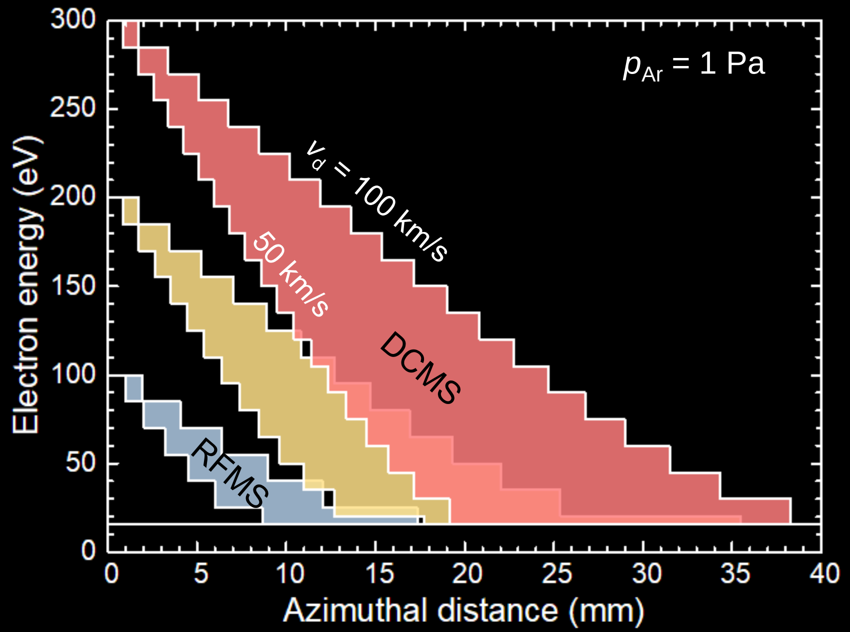


Electron energy dissipation in collisions with Ar

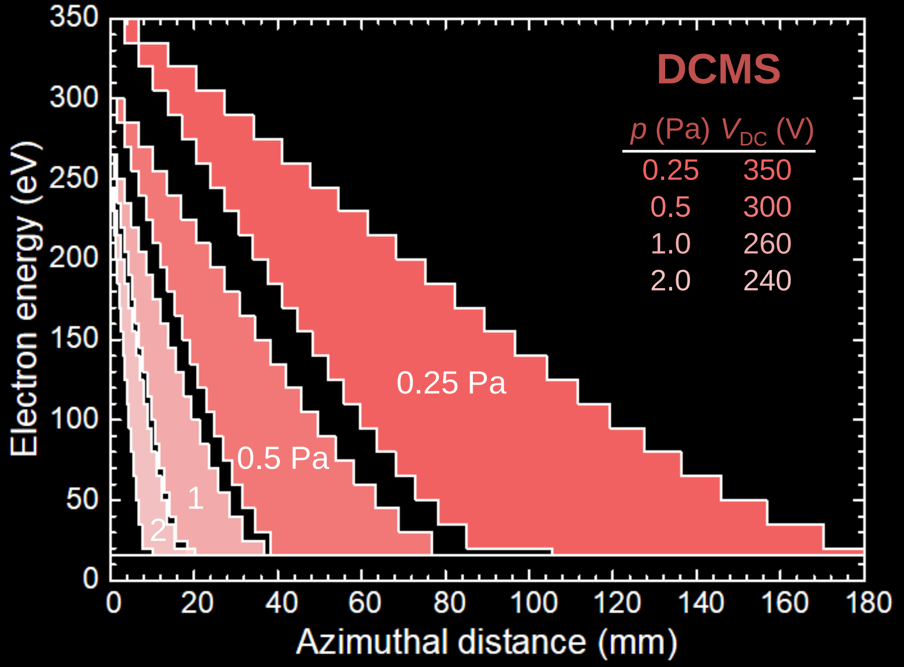


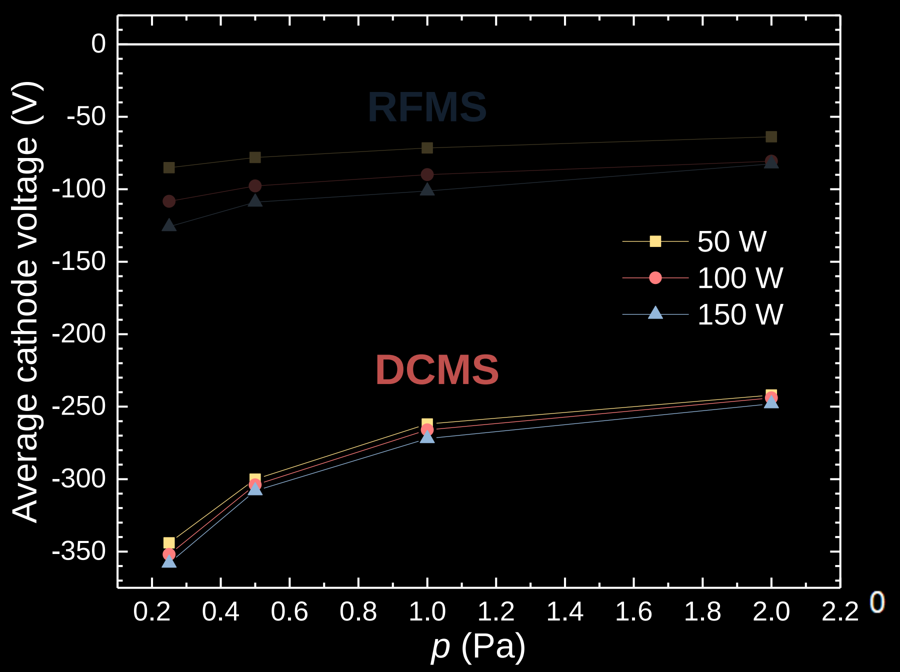


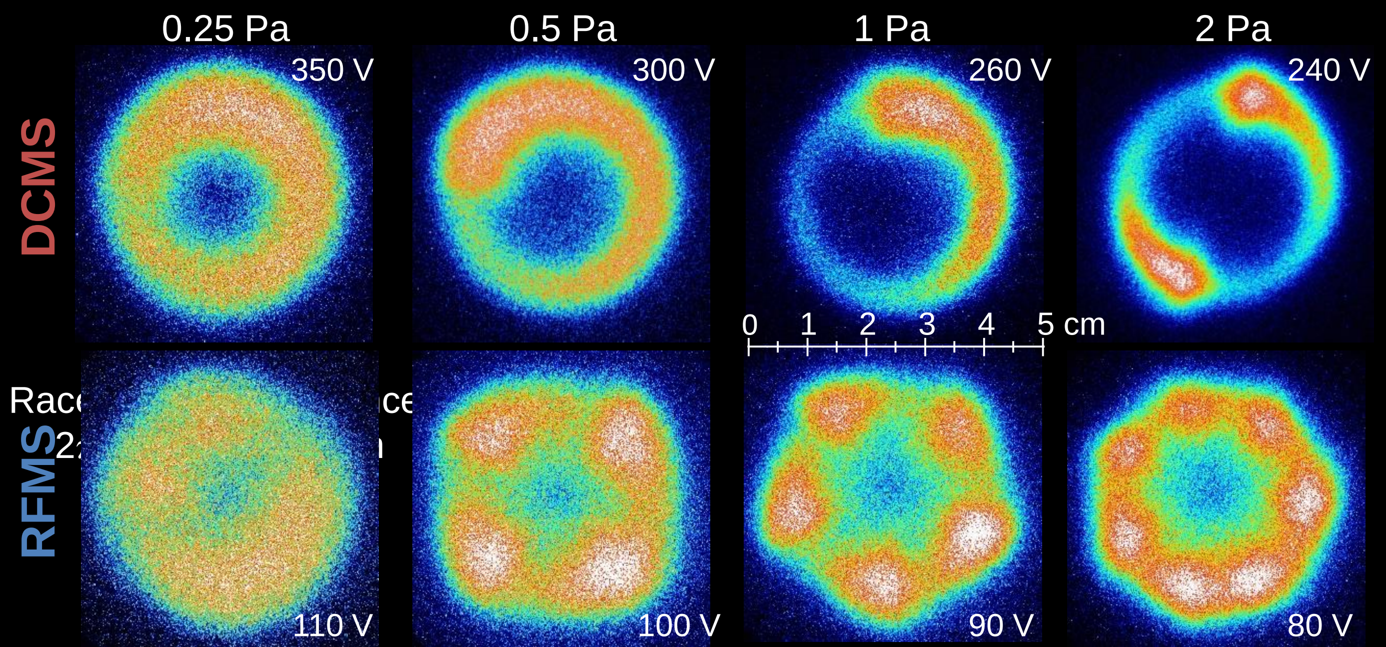




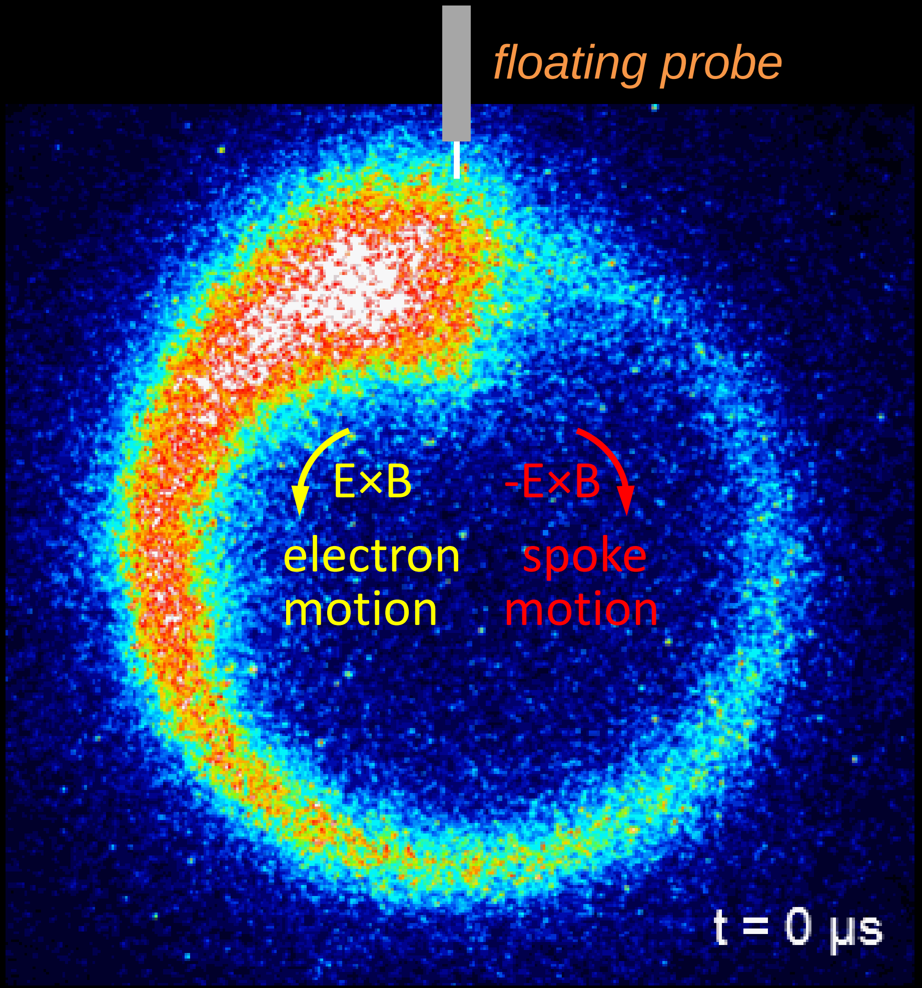
Azimuthal distance traveled by an electron

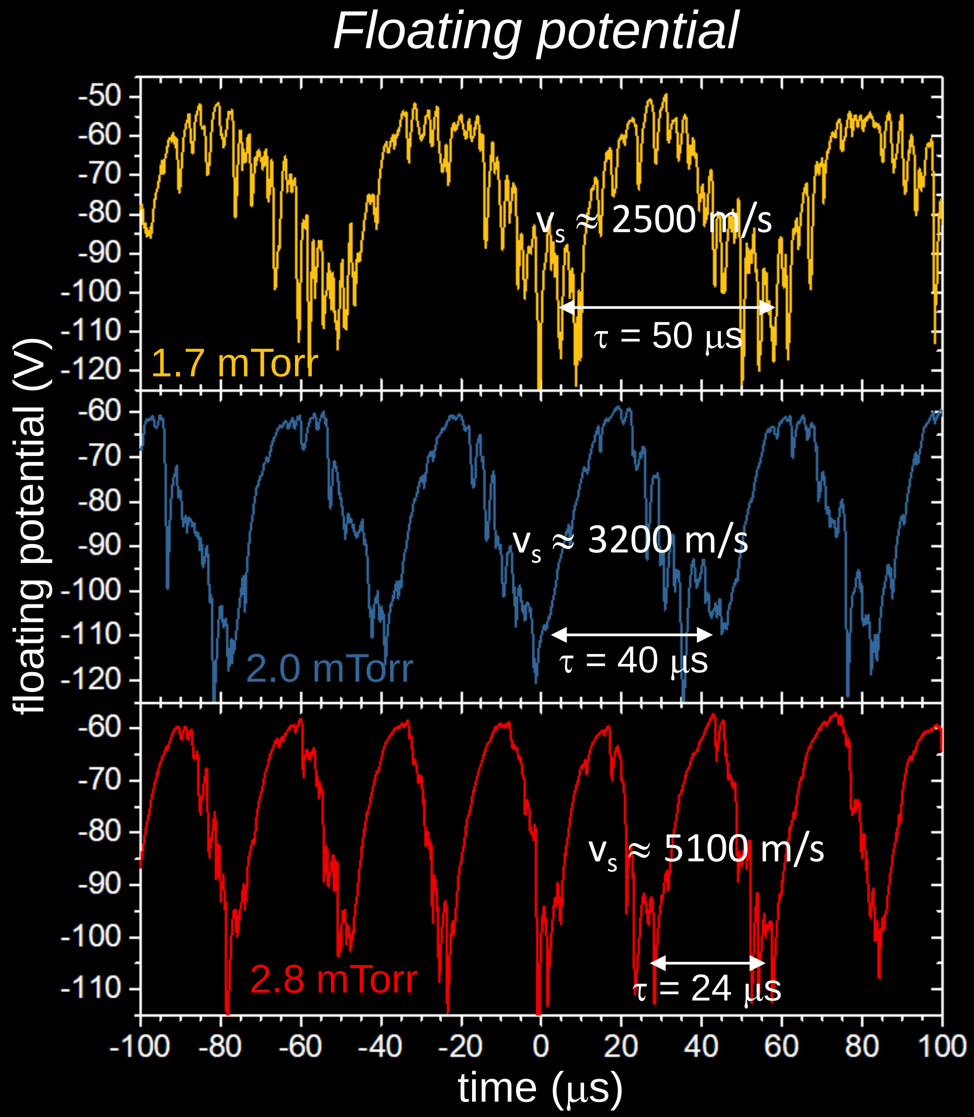






Low- and high-frequency oscillations in DC and RF regime





Spokes in DCMS and RFMS rotate opposite to the motion of electrons

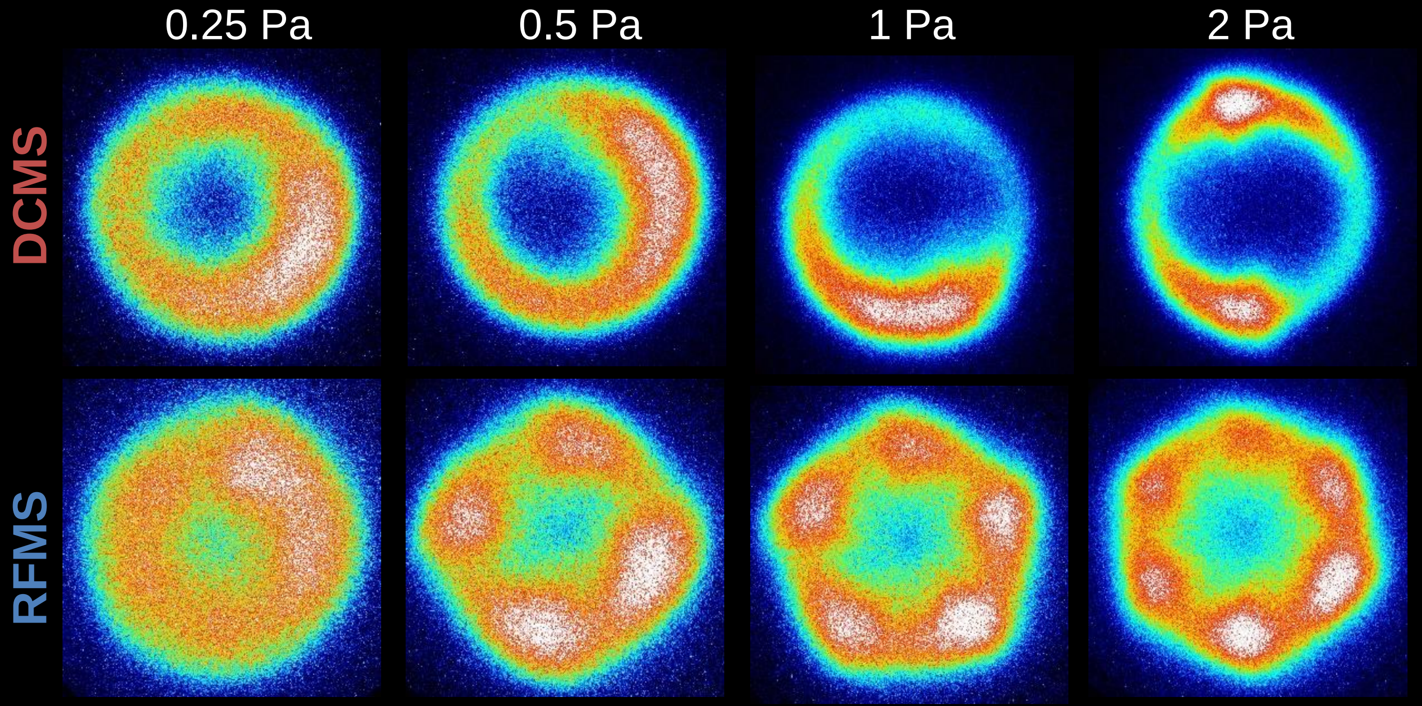
Low-frequency oscillations (10-100 kHz) are associated with rotation of spokes

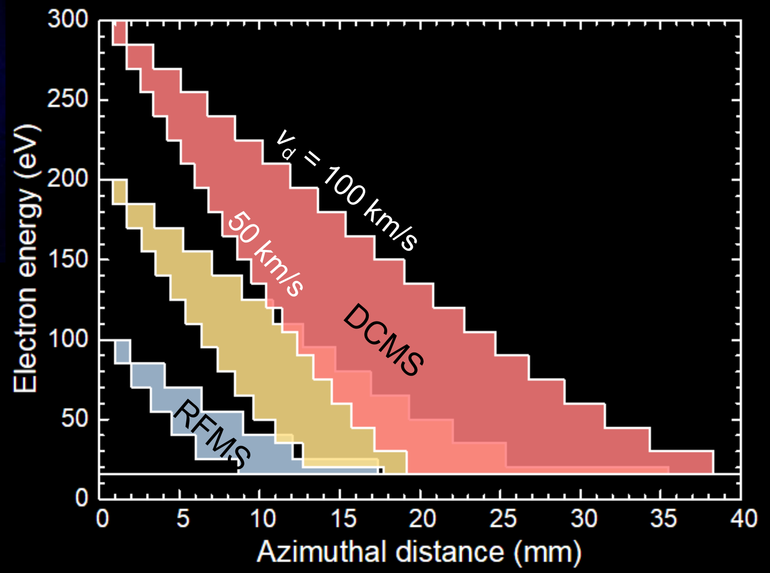
High-frequency oscillations (~10 MHz) are associated with electron cyclotron drift instability

S. Tsikata, T. Minea, *Phys. Rev. Lett.*, 114 (2015) 185001

Summary

- **Plasma self-organization** occurs in all types of magnetron sputtering regimes (DCMS, RFMS, HiPIMS)
- **Azimuthal length** and **number of spokes** depend on inelastic collisions of electrons with gas atoms – MFP (i.e., gas pressure and electron energy)
- **Calculations of electron energy dissipation** agree well with the observed azimuthal lengths of spokes





Summary

- **Plasma self-organization** occurs in all types of magnetron sputtering regimes (DCMS, RFMS, HiPIMS)
- **Azimuthal length** and **number of spokes** depend on inelastic collisions of electrons with gas atoms – MFP (i.e., gas pressure and electron energy)
- **Calculations of electron energy dissipation** agree well with the observed azimuthal lengths of spokes

Open questions

- **What is the reason for plasma self-organization in magnetron discharges?**
- **Why spokes move in the opposite direction than electrons drift (-E×B)?**
- **Would magnetron discharge operate at such low voltages without the presence of spokes?**

Low-frequency oscillations and structures

Ivan Romadanov,

“Control of Coherent Structures via External Drive of the Breathing Mode”

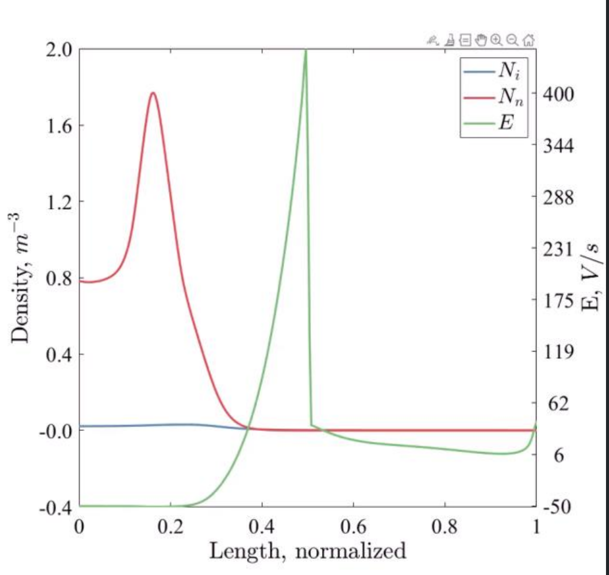
ExB Plasmas Workshop 2022

Madrid, online event

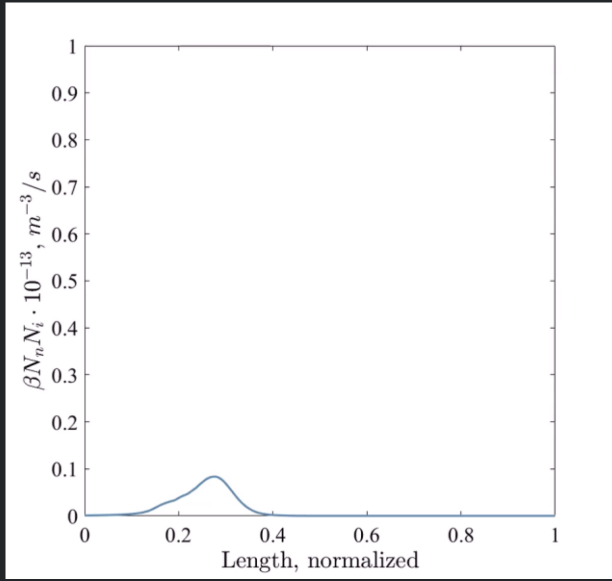
Mechanism for spoke and breathing modes coupling

Assumption: Spoke is an azimuthally propagating mode driven by axial gradients (N_i, T_e)[1] or by ionization processes[2]. Breathing mode modifies axial gradients (profiles) and ionization.

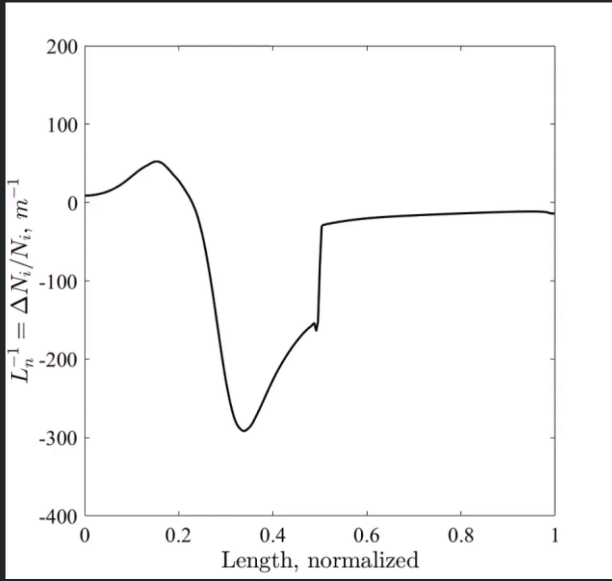
Neutral, ion densities and electric field



Ionization source term



Characteristic length of the density gradient



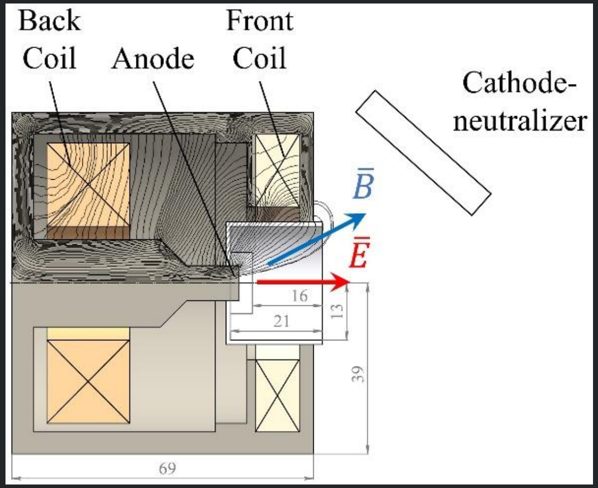
Example of oscillating profiles during the breathing mode in Hall thruster. BOUT++ simulations by O. Chapurin.

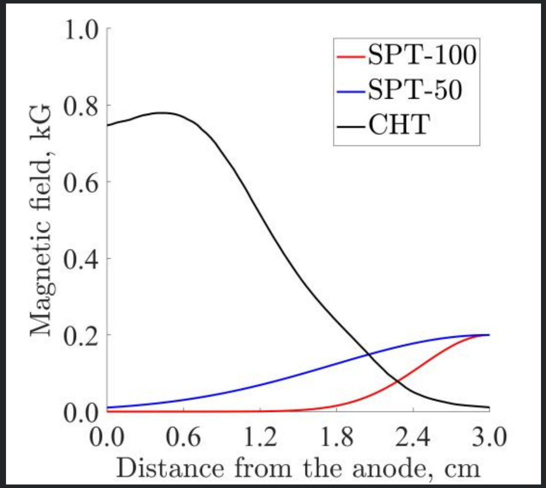
Can these modes interact?

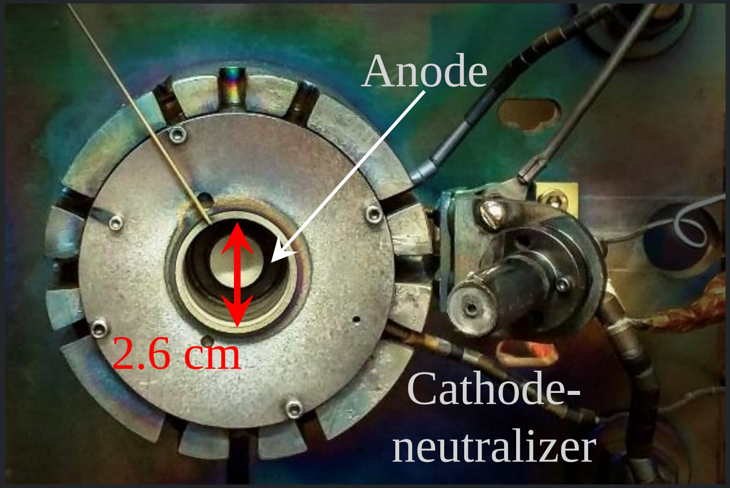
[1]*Powis, A.T., Carlsson, J.A., Kaganovich, I.D., Raitses, Y. and Smolyakov, A., 2018. Scaling of spoke rotation frequency within a Penning discharge. Physics of Plasmas, 25(7), p.072110.*
[2]*Boeuf, J.P. and Takahashi, M., 2020. Rotating spokes, ionization instability, and electron vortices in partially magnetized E× B plasmas. Physical review letters, 124(18), p.185005.*

Experimental setup

Cylindrical Hall Thruster (CHT)





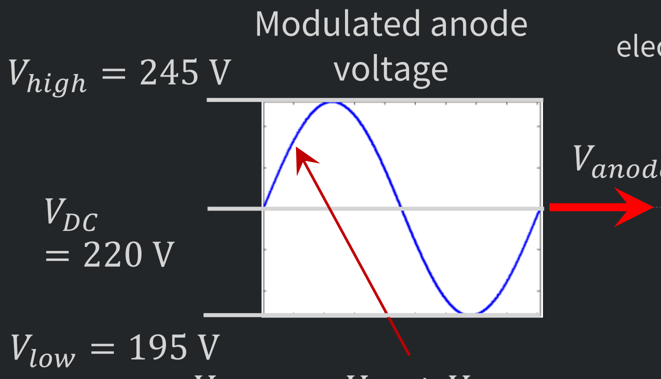


- $\phi = 220$ V
- I_d =0.8 A
- gas: Xenon
- mass flow: 3 sccm – anode, 2 sccm cathode
- Chamber pressure: $6 \cdot 10^{-5}$ Torr

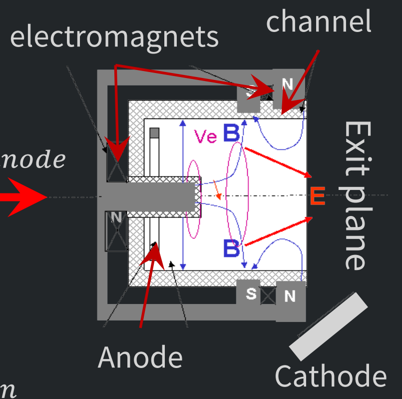
- Magnetic field is radial, electric field is axial
- Large magnitude of the magnetic field, as compared to annular hall thruster

Y. Raitses and N. Fisch, Phys. Plasmas 8 (2001),
A. Smirnov, Y. Raitses, Fisch, J. Appl. Phys. 92 (2002),
K. Diamant et al., IEEE TPS 38 (2010).

Modulation of the breathing mode

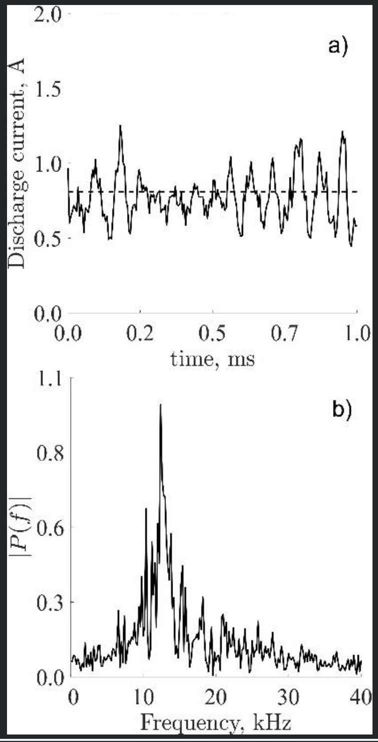


$V_{anode} = V_{DC} + V_{modulation}$



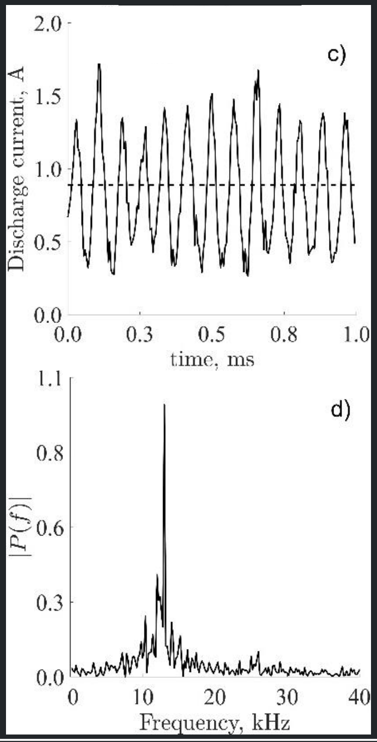
A. Diallo et al., Rev. Sci. Instr. 86 (2015)

Oscillations are **non-stationary** and **incoherent** in time



Applying modulation

$f_{natural}$ ~13 kHz



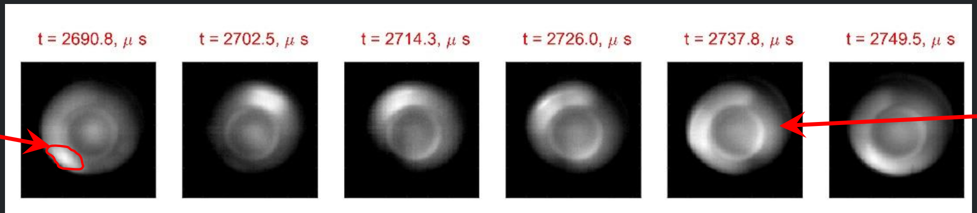
Oscillations are **coherent** in time.

f_{mod}=13 kHz

Image processing for spoke and breathing modes

Spoke and breathing mode can be observed on fast frame camera signal due to changes in intensity

Spoke,
Local intensity increase

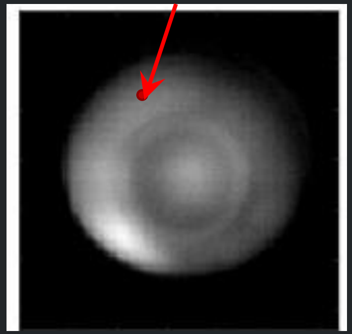


Breathing,
Global intensity increase

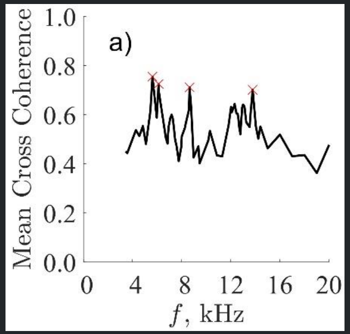
Image processing technique allows to identify both modes

1. Select reference point, randomly located
2. Calculate cross-coherence for each pixel on processed signal and average over all pixels
3. For frequencies with highest average coherence plot phase maps
4. Smooth variation of phase $0 - 2\pi$ indicates rotation mode (spoke)
5. In phase changes of all pixel indicate global mode (breathing)

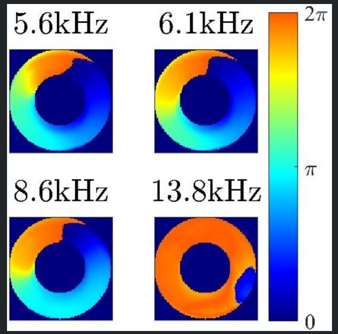
Reference point



Cross-coherence



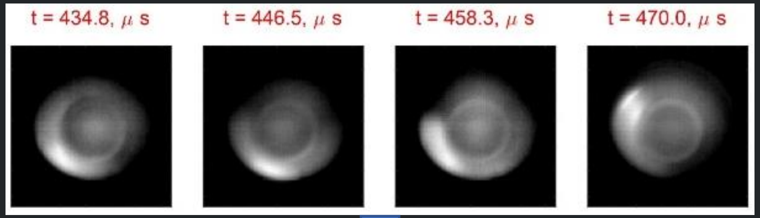
Phase maps



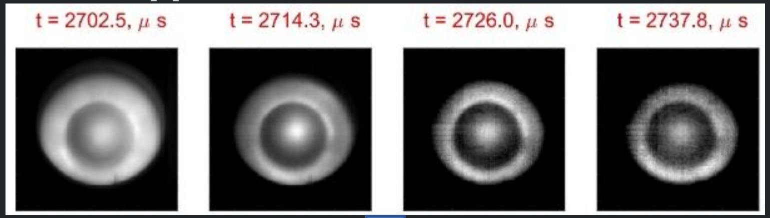
Spoke suppression via coupling with the breathing mode

Several experiments with different modulation regimes were conducted, results were analyzed with developed imaging processing technique.

No modulations



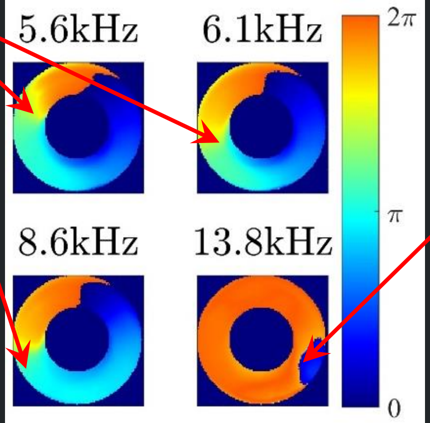
30 V_{pp} modulation at 10-15 kHz



Spoke (phase $0 - 2\pi$)

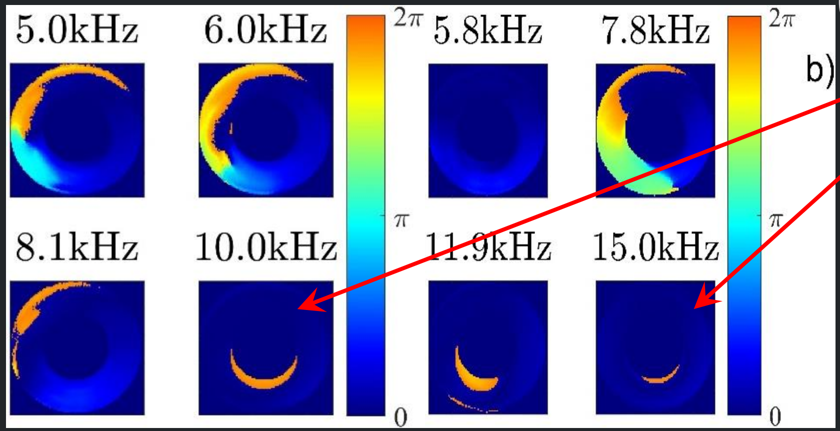
Phase maps

Natural breathing (phase 0 or 2π)



Phase maps

Modulation (global mode)



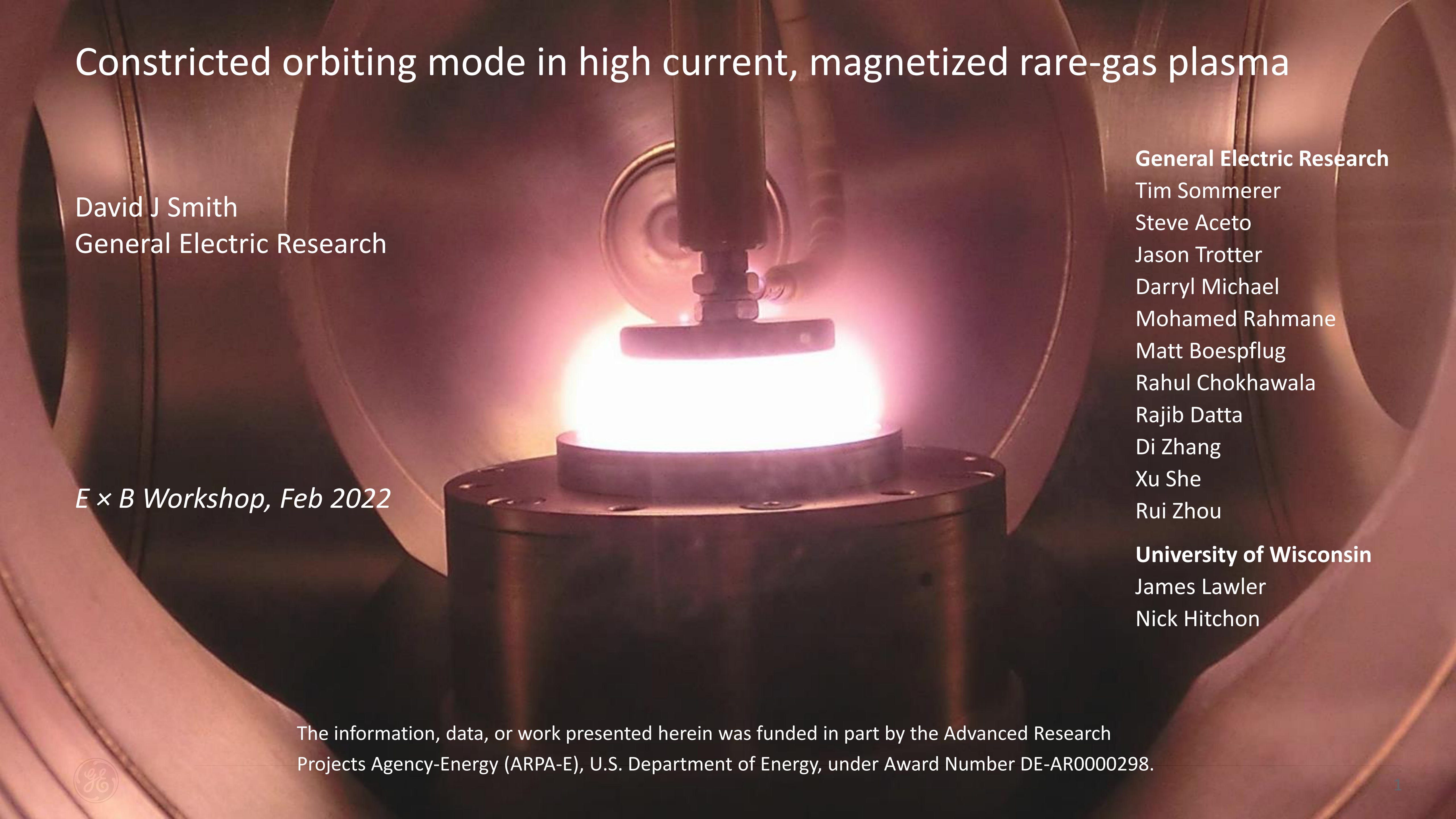
Breathing and spoke modes coexist

Only mode from modulation

Modulation of the breathing mode can lead to suppression of the spoke mode

Key results on mode coupling

- It was shown that modulations of the breathing mode can be used to suppress spoke appearance.
- This suggests the interaction between two modes:
  - either through changes of gradients
  - or thought changes in ionization processes
- Is it possible to control spoke mode with breathing e.g., change spoke direction with modulation?
- Such experiments can be used to verify simulations, confirming underlaying mechanisms.
- Image processing technique for identification of spoke and breathing modes was developed.



Constricted orbiting mode in high current, magnetized rare-gas plasma

David J Smith
General Electric Research

E × B Workshop, Feb 2022

General Electric Research
Tim Sommerer
Steve Aceto
Jason Trotter
Darryl Michael
Mohamed Rahmane
Matt Boespflug
Rahul Chokhawala
Rajib Datta
Di Zhang
Xu She
Rui Zhou

University of Wisconsin
James Lawler
Nick Hitchon

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

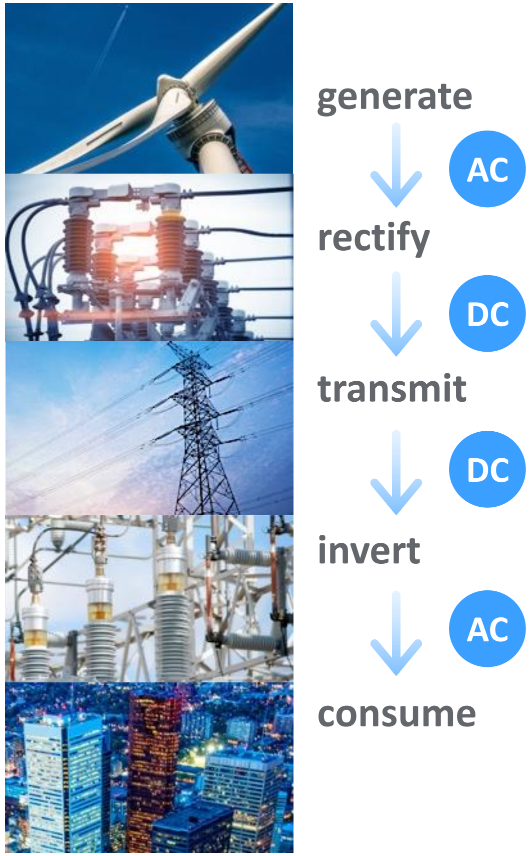
Application: high voltage direct current (HVDC) transmission

Grid HVDC transmission versus HVAC

- Lower cost per unit distance than AC transmission but higher terminal costs
- HVDC only cost competitive for long haul (≥ 500 miles)

Why return to gas tubes?

- Higher voltage per device… significantly fewer devices, lower terminal cost
- Recent advances in microwave power tubes and x-ray tube performance and reliability… more compact solution

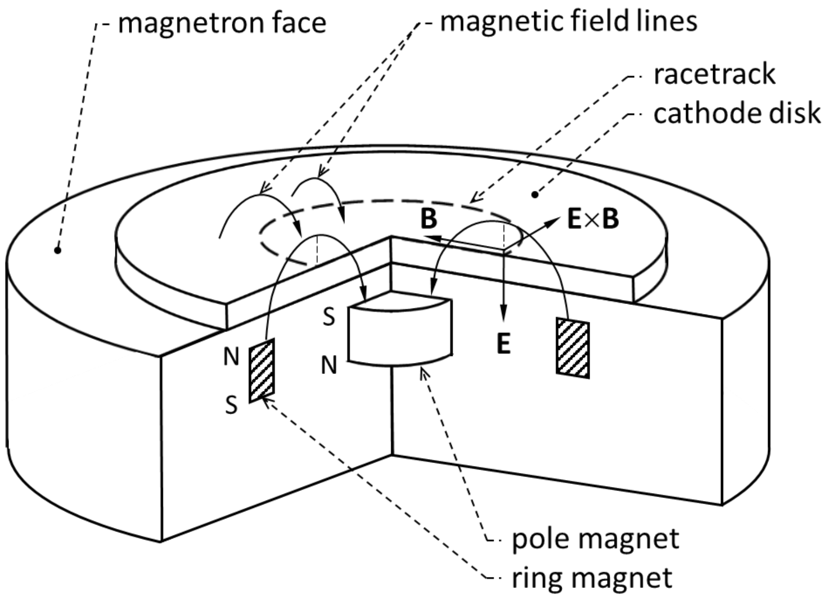


Reduced terminal cost… HVDC viable for less than 250 miles

Experimental configuration

Experimental features

- Pulsed operation, OCV up to 1.4 kV, current ~ 5-30 A, 3-10 ms pulse
- Modified commercial magnetron using custom cathode plate and external anode
- Range of gas type (Ar, H_2, He), pressure (0.05-6.4 Torr)
- Various cathode materials (Al, Ga, Cu, Mo, W, Ta)
- Magnetic field on cathode surface on order 1000 Gauss



Christopher A Allen et al 2019 J. Phys. D: Appl. Phys. **52** 435203
Timothy J Sommerer et al 2019 J. Phys. D: Appl. Phys. **52** 435202

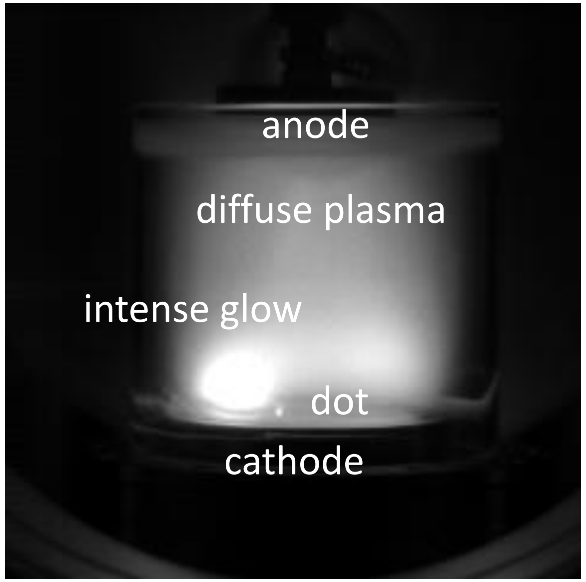
Key observations

Three distinct operating modes

- Diffuse, stationary (typical magnetron mode, >200 V)
- **Constricted, orbiting mode** (40-120 V)
- Constricted 'stationary' (40-60 V)

Diffuse, stationary

Constricted, orbiting



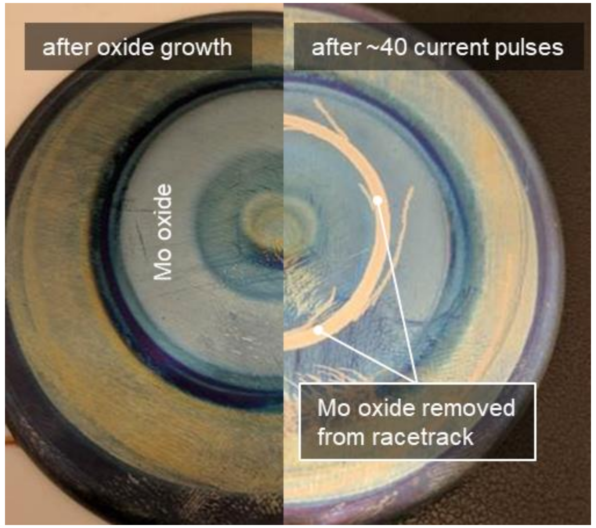
Constricted, 'stationary'

Christopher A Allen et al 2019 J. Phys. D: Appl. Phys. **52** 435203
Timothy J Sommerer et al 2019 J. Phys. D: Appl. Phys. **52** 435202

Constricted orbiting mode in magnetized plasmas: key features

Key characteristics of CO mode

- Unexpectedly **low operating voltage (40-120 V)** compared with typical magnetron operation (> 200 V)
- Observed for various gases (H_2, He) and over wide pressure range (0.05-6.4 Torr)
- Observed for all cathode materials tested, but transiently in some cases
- Requires **presence of oxide layer**



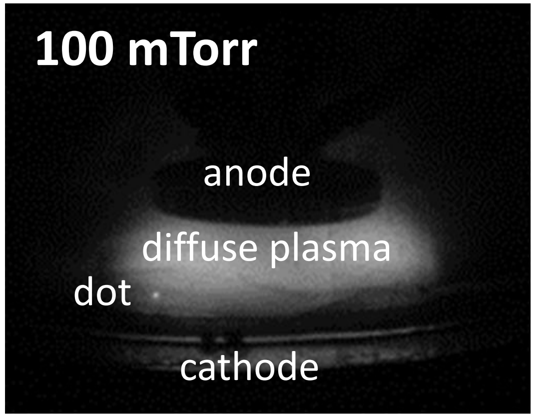
CO mode: low operating voltage (40-120 V), requires oxide layer on cathode

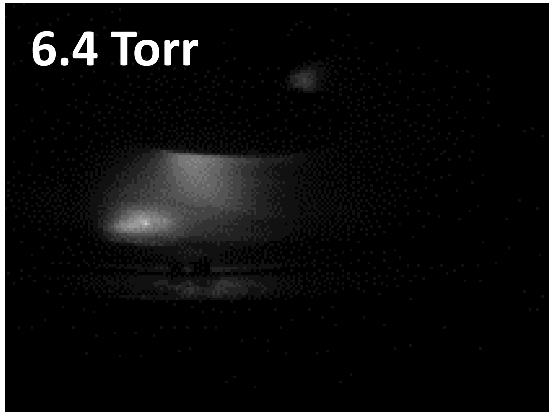
Timothy J Sommerer et al 2019 J. Phys. D: Appl. Phys. **52** 435202

Constricted orbiting mode in magnetized plasmas: key features

Key characteristics of CO mode

- **Plasma rotation in opposite direction to $\underline{E} \times \underline{B}$ force** (verified by switching polarity of magnets)
- Rotation frequency typically 2-3 kHz for 10 cm circumference (2-5 x 10^4 cm s^{-1}), independent of pressure
- **Demonstrated over wide range of pressures (0.05-6.4 Torr)**
- No obvious difference in appearance of ‘dot’ on cathode as pressure is varied over wide range
- Significant change in appearance of other plasma regions above the dot





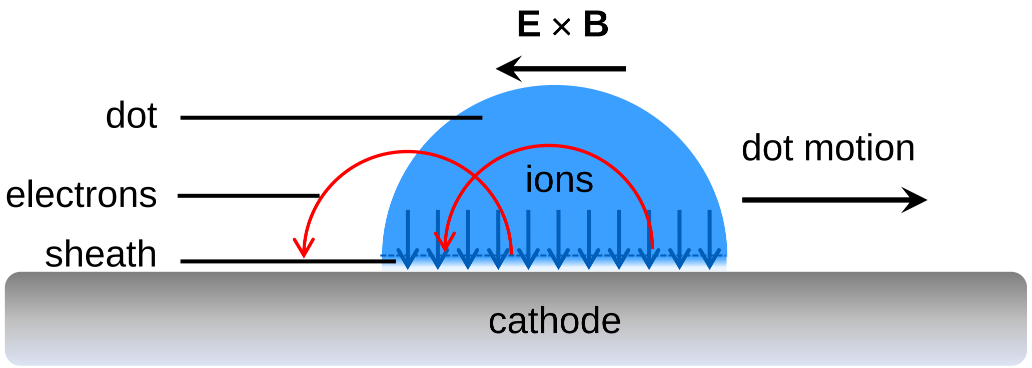
CO mode: plasma rotation in -$\underline{E} \times \underline{B}$ direction, approx. 2-5 x 10^4 cm s^{-1}

Timothy J Sommerer et al 2019 J. Phys. D: Appl. Phys. **52** 435202

Proposed explanation for direction of rotation

Role of oxide layer

- Critical role of presence of oxide layer for field emission
- Localized charging and discharging of oxide layer drives plasma dot motion
- See paper for details: David J Smith et al 2021 J. Phys. D: Appl. Phys. **54** 295201



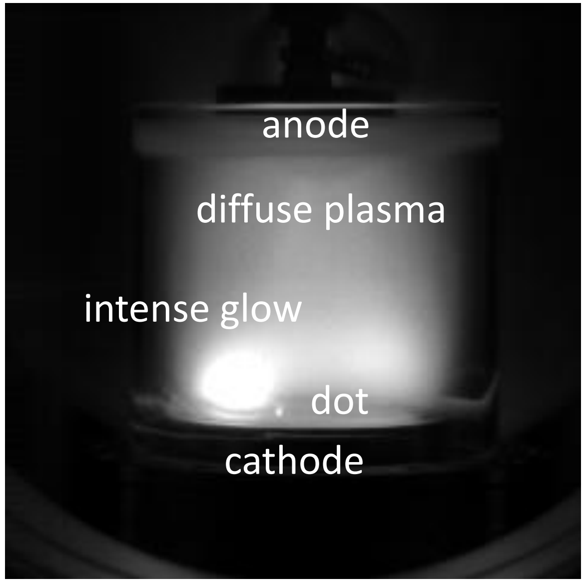
Conclusions

Key features of constricted orbiting mode

- **Low voltage** (40-120 V) with demonstrated pressure dependence
- **Plasma rotation in opposite direction to E × B force**, frequency of 2-3 kHz (3-5 x 10^4 cm s^{-1})
- Three distinct regions: 'dot' on cathode surface, intense glow, diffuse region
- CO mode only occurs in **presence of cathode oxide layer**
- Effect occurs for range of gases, cathode materials and over a wide range of pressures

Proposed explanation for dot motion

- Charging of thin oxide layer sufficient for field emission
- Localized charging and discharging of oxide layer as plasma interacts with surface

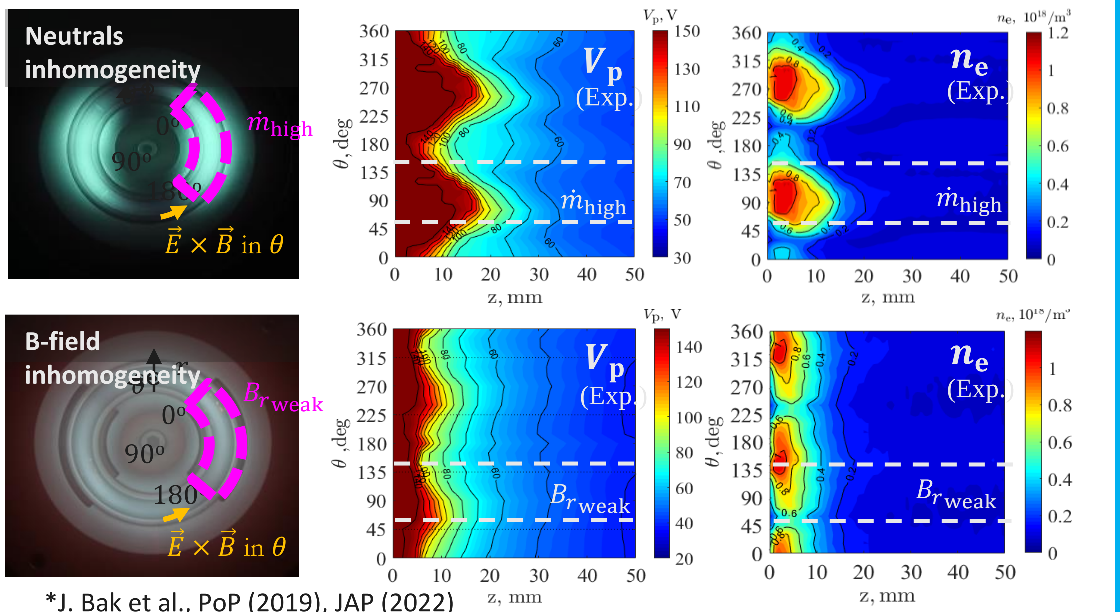


David J Smith et al 2021 J. Phys. D: Appl. Phys. **54** 295201

J. Bak, ExB Plasma control by artificial azimuthal modulation

- Control of static (confined) structure or dynamic structure on the cross-field plane
- Enable active localized control of plasma structure and electron cross-field transport

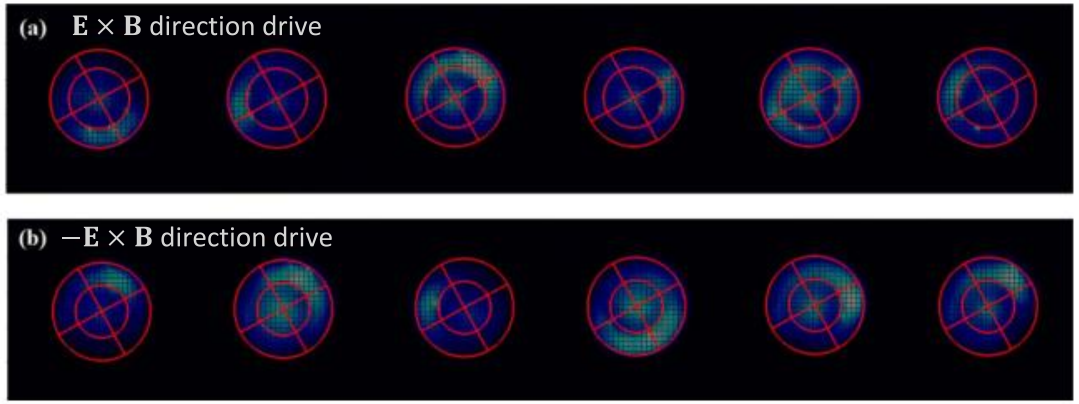
❑ Plasma control with $\dot{m}$ and B_r modulation [1,2]



*J. Bak et al., PoP (2019), JAP (2022)

- Locally modulated V_p and n_e structures
- Induce $1/B$ proportional cross-field transport

❑ Control of the spoke using a segmented anode [3]



* Y. Shi et al., PSST (2018)

- By varying the voltage and the relative phases of the anode segments, properties of the azimuthal mode can be altered substantially
- Rotating direction of the spoke can be driven in both $\mathrm{E} \times \mathrm{B}$ and $-\mathrm{E} \times \mathrm{B}$

Q. Do we need these controls? Where can these controls be useful?

- Characteristic $z - \theta$ plasma structure can be used for code validation
- Can distinguish influences of a specific controlled parameter
- Performance/operation control? Etc… what else?

[1] J. Bak et al., PoP (2019) https://doi.org/10.1063/5.0067310
[2] J. Bak et al., JAP (2022) https://doi.org/10.1063/1.5090931
[3] Y. Shi et al., PSST (2018) https://doi.org/10.1088/1361-6595/aae42b

Session 2: Low-frequency oscillations and structures

Chairmen: Y. Raitses, I. Kaganovich

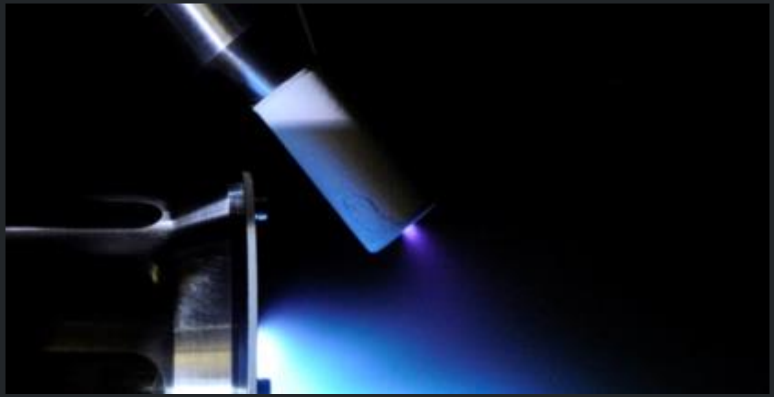
Panelist: J. Szabo, Chief Scientist for Hall Thrusters, Busek Co. Inc.
“Rationale for Three Dimensionional Hall Thruster Modeling”

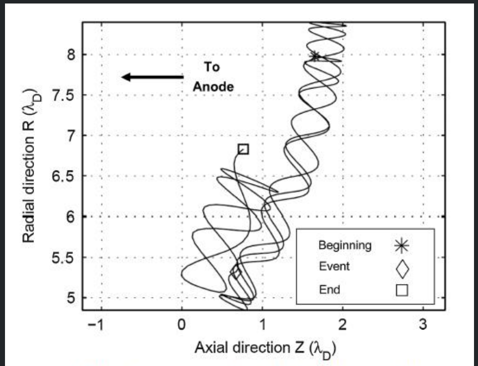
ExB Plasmas Workshop 2022

Madrid, online event

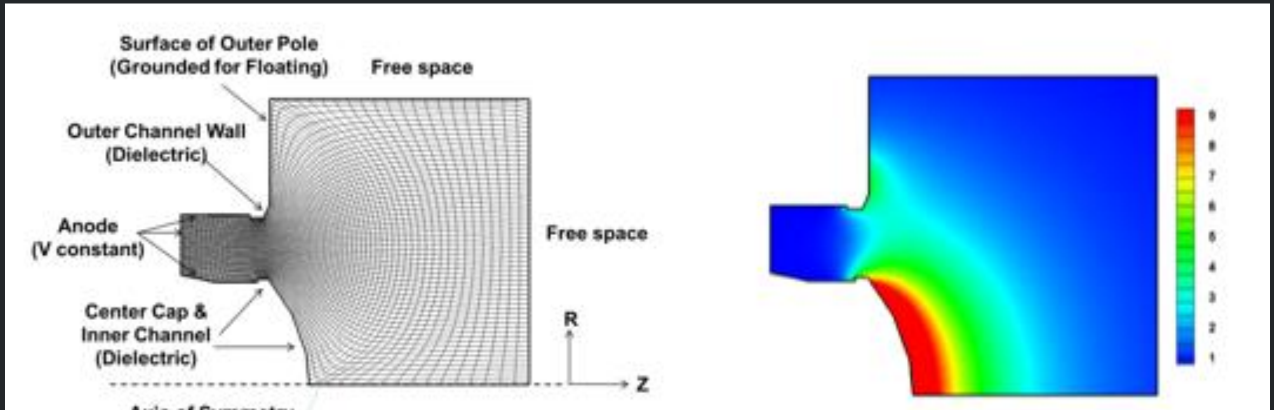
Radial-Axial Full PIC Modeling of Hall Thrusters

- For thruster design analysis, typically model axisymmetric geometry and B-field (2D/3V) w/no azimuthal variations
- 2D models include “anomalous” transport coefficients, where transport coefficients vary in space
- Physics based transport models are highly desired



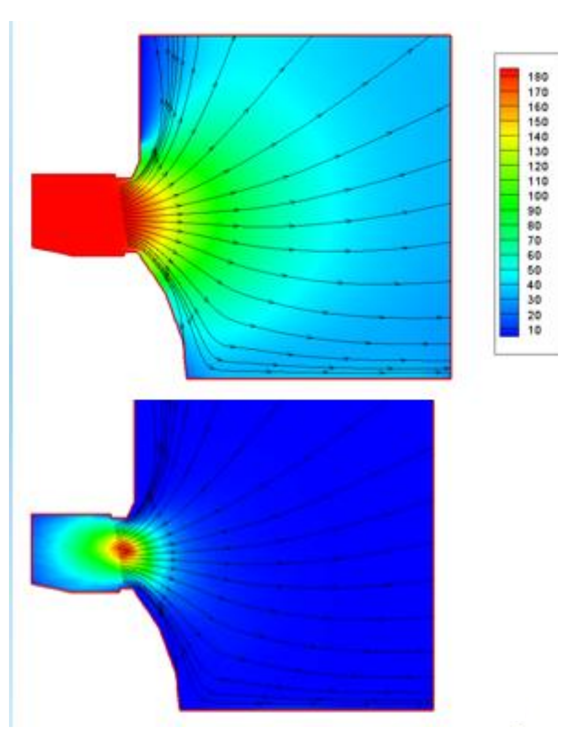


Electron trace produced by full PIC simulation.

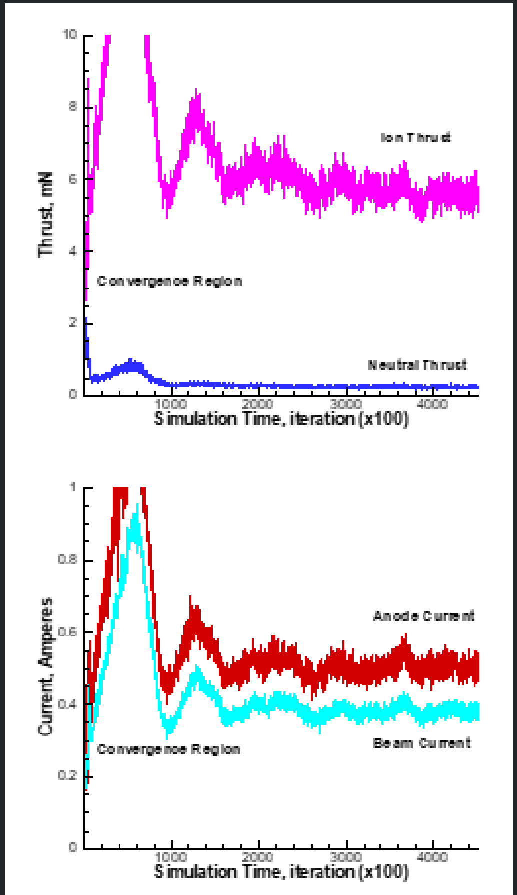


B-field magnitude

Electric Potential & Current Streamlines

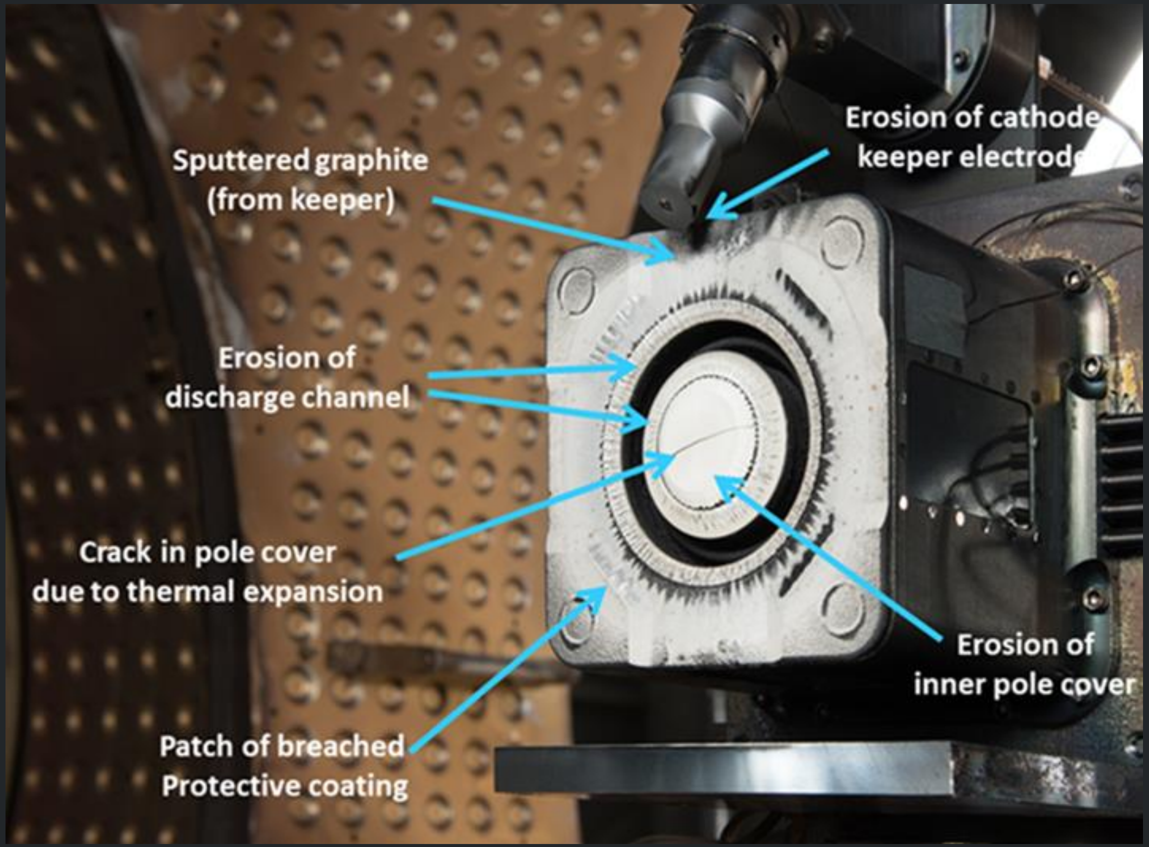


Ionization Rate & Current Streamlines



The Need for Three Dimensions

- Idealized axial-azimuthal models seem to capture the mechanisms responsible for anomalous transport in the channel
- 3D models are required to capture ExB transport due to azimuthal variations in a realistic geometry
- Model should include (at least) near channel region
  - Include non-symmetric features, such as external cathode
- How do azimuthal variations present at beginning of life affect electron transport?
  - What is the sensitivity to variations in gas density?
  - What is the sensitivity to variations in magnetic field?
  - How tightly does thruster need to be toleranced?



Busek BHT-600 after 1 MN Duration Test (7200 h)
AIAA-2020-3651

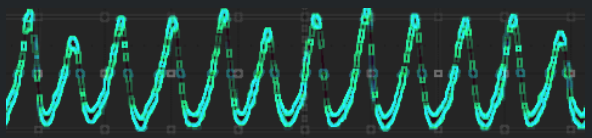
Erosion Creates Important 3D Variations

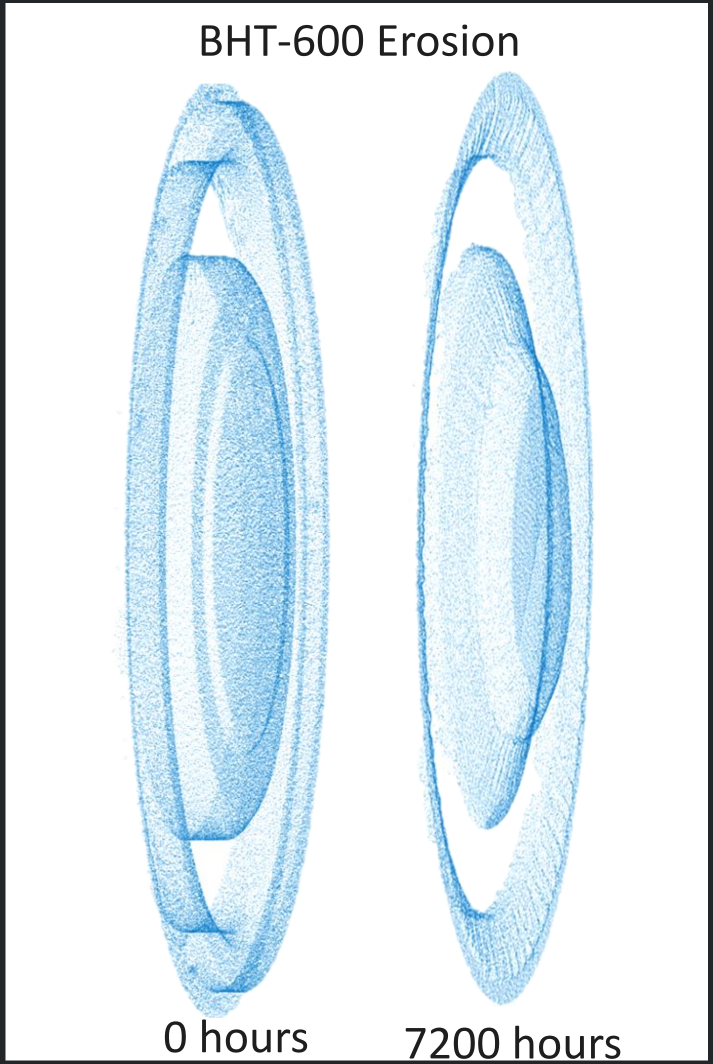
- Fact: Performance, oscillations, and plume properties change over time

- Effects of erosion:
  - Changes in wall profile, neutral density, plasma density, wall temperature…
  - Formation of non-symmetric striations
  - Sputtering and redeposition inside channel, on anode
    - Secondary emission
    - Surface conductivity
  - Magnetic field may change due to pole erosion

- Material from chamber is also ingested and deposited (e.g. carbon)

Ionization Oscillations



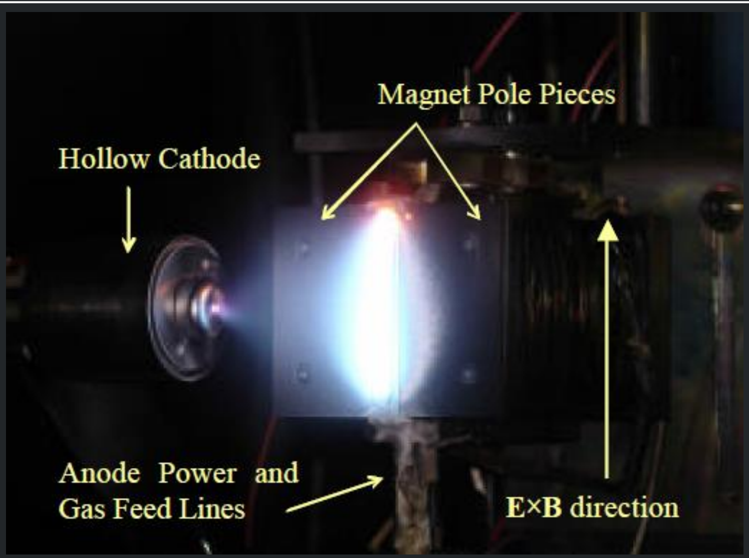


AIAA-2020-3651

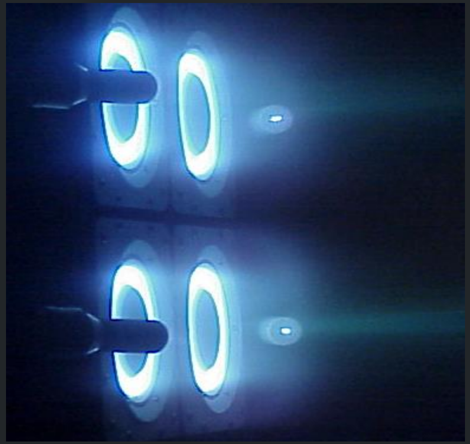
Many Important Features can be Captured by 3D Models

- 3D modeling needed for
  - Complex and non-axisymmetric shapes
  - Cathode coupling
  - Clustering & multiple channels
- Also need to consider
  - Different materials/wall interactions
  - Different propellants

Linear Hall Thruster
Gascon & Cappelli
AIAA-2005-4401

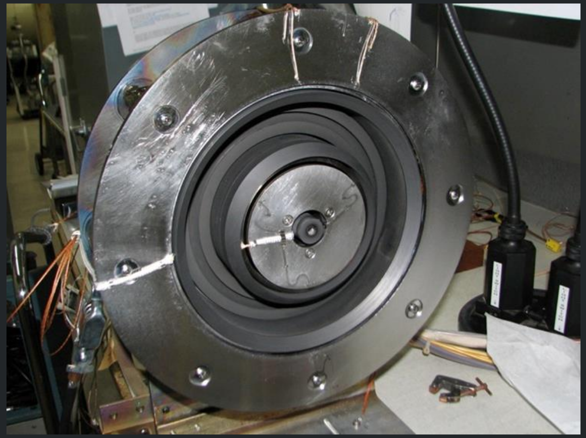


Iodine Fueled Hall Thruster
AIAA-2017-4728



Cluster of BHT-600's
AIAA-2011-6152

Busek Nested Thruster
AIAA-2011-6152

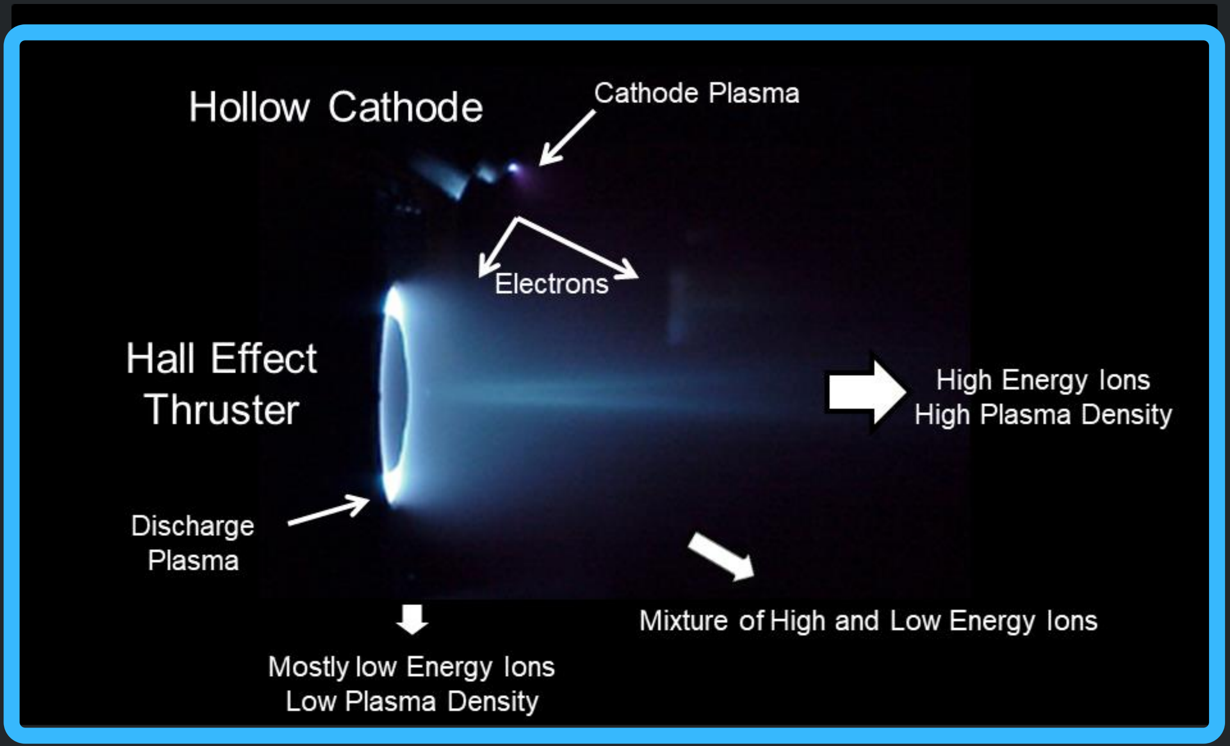


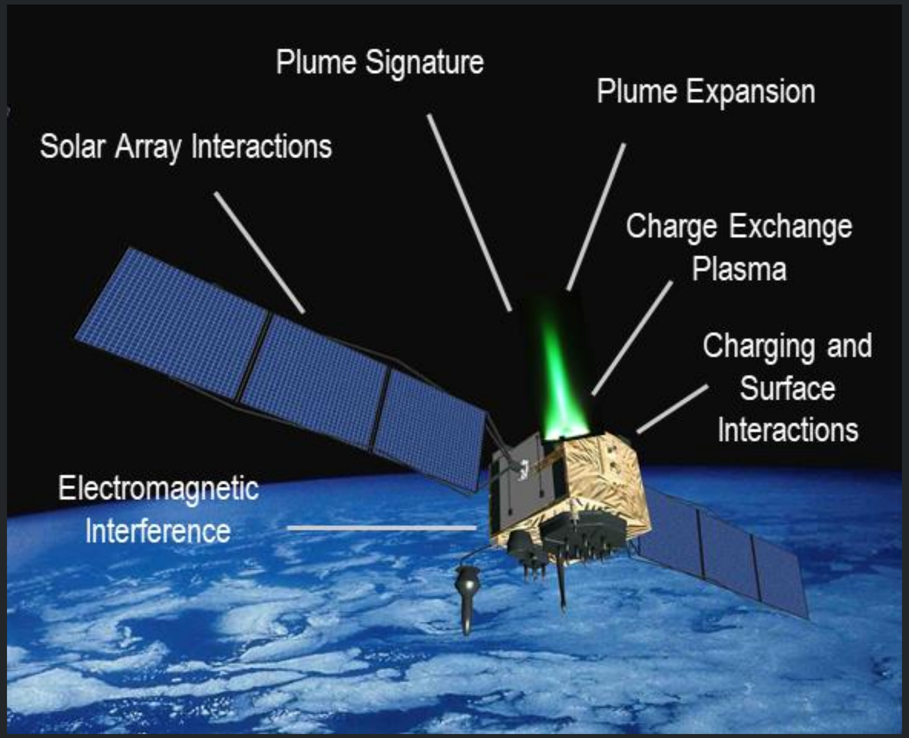
Carbon Channel Thruster
Hofer, 2013

Need for Integrated Models

- How does the thruster interact with the test chamber? What are the effects of background pressure? What happens in space, when the chamber disappears and the background pressure is much lower?
- What is anomalous transport <u>outside</u> the channel, in the near and far field plumes?
- For plume modeling, how accurate does the ion source model need to be?

Test Chamber





Figures from 2022 IEPC

Laplace’s Demon

"We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it - an intelligence sufficiently vast to submit these data to analysis – it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.”

-From "A Philosophical Essay on Probabilities" by Pierre Simon, Marquis de Laplace

A sufficiently detailed 3D PIC model should provide a complete view of the Hall thruster including ExB transport.

Some References

- Szabo, J., Gray, S., Sheehan, F., Hinckley, J., Sawyer, S., Costa, W., Yu, T., Taillefer, Z., “High Speed Plasma Probe and Electronics Suite,” to be presented at 2022 IEPC Conference in Boston.
- Szabo, J., Byrne, L., Strain, M., Paintal, S., Sawyer, S., Yu, T., Kolencik, G., Hruby, V., Gray, T., Petters, D., Haag, T., Mackey, J., Taillefer, Z., “One Million Newton-Second Duration Test of a 600 Watt Hall Effect Thruster Fueled By Xenon,” AIAA-2020-3651, Propulsion and Energy 2020, August 24 – 26, 2020.
- Szabo, J., Tedrake, R., Metivier, E., Paintal, S., Taillefer, Z., “Characterization of a One Hundred Watt, Long Lifetime Hall Effect Thruster for Small Spacecraft,” *AIAA Propulsion and Energy Forum*, AIAA 2017-4728, July 2017.
- Szabo, J., Warner, N., Martinez-Sanchez, M., Batishchev, O., “A Full Particle-In-Cell Simulation Methodology for Axisymmetric Hall Effect Thrusters,” Journal of Propulsion and Power, Vol. 30, No. 1, pp. 197-208 (2014).
- Hofer, R., “Magnetic Shielding in Hall Thrusters: Breakthrough Space Propulsion Technology for the 21 st Century,” Presented at the Michigan Institute for Plasma Science and Engineering (MIPSE) Seminar Series at the University of Michigan, Ann Arbor, MI March 20, 2013.
- Szabo, J., Pote, B., Hruby, V., Byrne, L., Tedrake, R., Kolencik, G., Kamhawi, H., Haag, T., “A Commercial One Newton Hall Effect Thruster for High Power In-Space Missions,” 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2011-6152, San Diego, CA, July 31 – Aug 3, 2011.
- Gascon, N., Cappelli, M., Hargus, W., “Ion Velocity Measurements in a Linear Hall Thruster,” u41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-2005-4401, July 2005.