Controlling of Spokes in ExB Plasmas

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Acknowledgment

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Theory:

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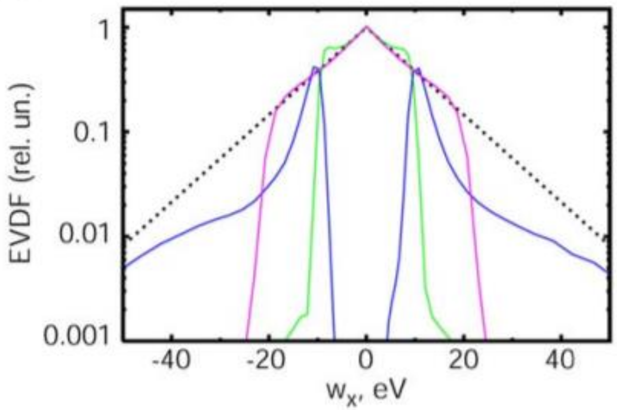
Outline

- **JP's question on transport: wall vs fluctuations**
- **Controlling spoke (CHT's case)**
  - **Suppression**
  - **Mode transition**
  - **Driving**
- **Gas effect on spoke (Penning's case)**

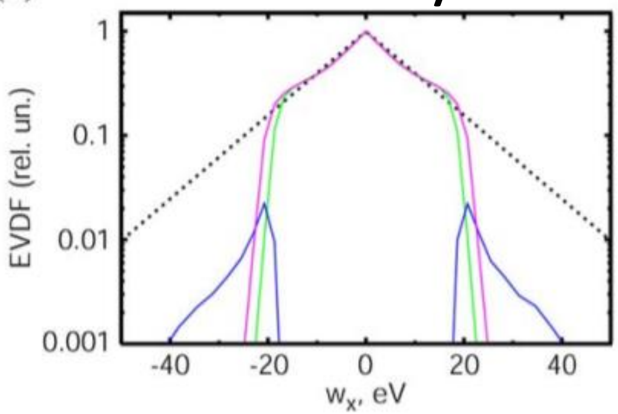
Conditions for near-wall conductivity in simulations

EVDF towards the wall

(a) **E=200 V/cm**



(c) **E=100 V/cm**



EVDF of bulk without SEE

EVDF of bulk with SEE

EVDF of beams

Maxwellian EVDF

- **From 1-D PIC simulations:**
  - **Electron-induced SEE (unlike magnetrons)**
  - **Depleted EVDF due to wall losses**
  - **Counter streaming electron beams gaining net energy due to ExB motion from the applied electric field:**

$$\varepsilon_B = mV_{\mathrm{dr}}^2(1 - \cos\varphi) \quad (4)$$

where $V_{\mathrm{dr}} = E/B$ is the drift velocity in the crossed electric and magnetic fields, and $\varphi = \omega_{\mathrm{ce}}\tau$ is the final phase of cyclotron rotation before the electron collides with the wall. Here, $\omega_{\mathrm{ce}} = eB/m$ is the electron gyrofrequency, and τ is the electron time of flight between the wall.

Note that the maximum of the additional electron energy on a scale of the gyroradius (see Fig. 5) is

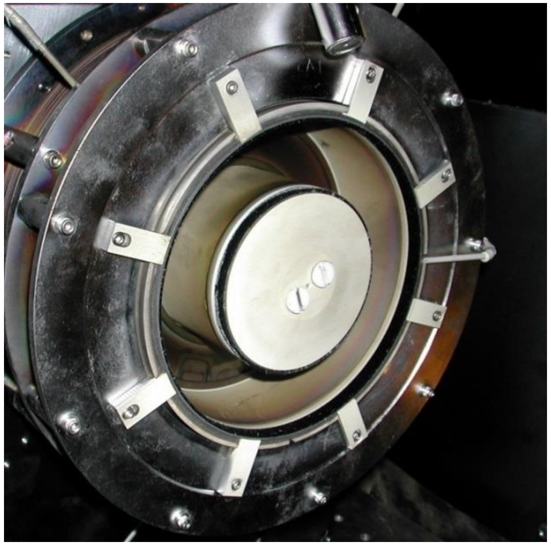
$$\varepsilon_{B\,\max} = 2eE\rho_e. \quad (5)$$

If this energy is insufficient to induce a strong SEE, counter-streaming beams of emitted electrons will have a weak effect on the plasma.

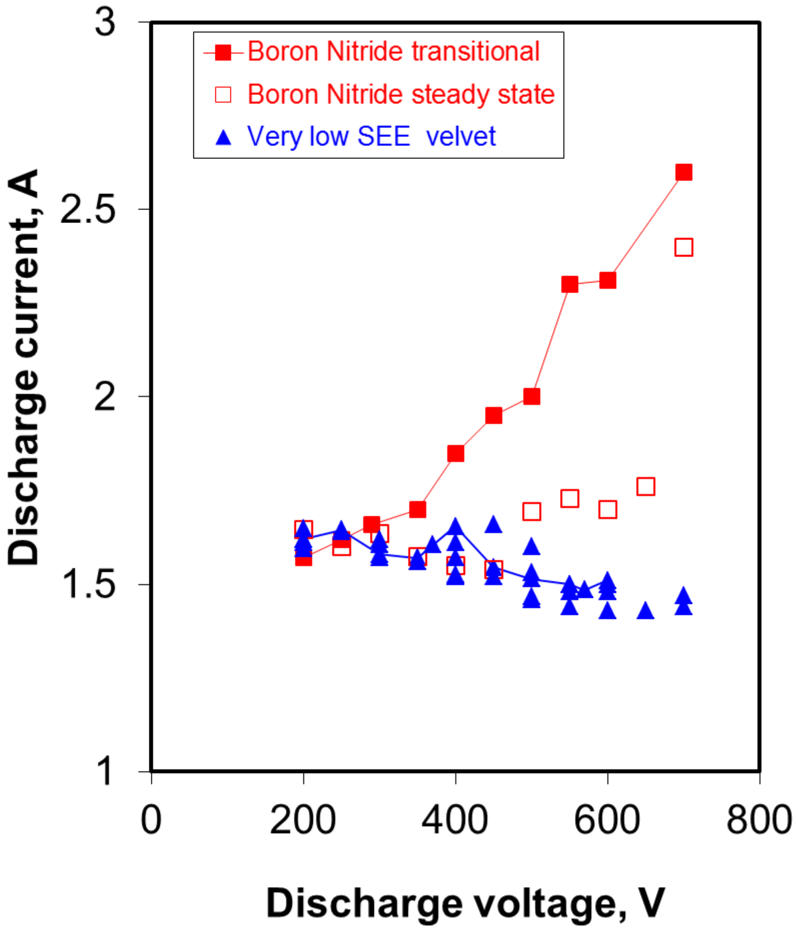
No strong E-field - No strong SEE beams, No "Near-Wall" conductivity!

Raitses et al., IEEE Trans. Plasma Sci., 39, 995 (2011)

Wall material effect in PPPL experiments



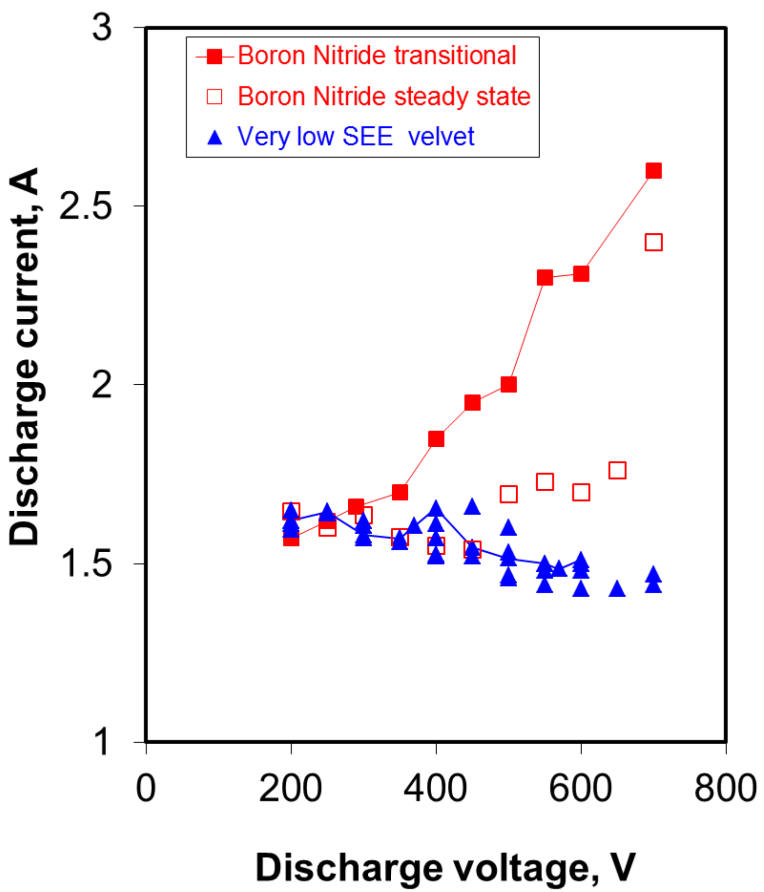
- Thruster V-I characteristics with different segmented wall materials



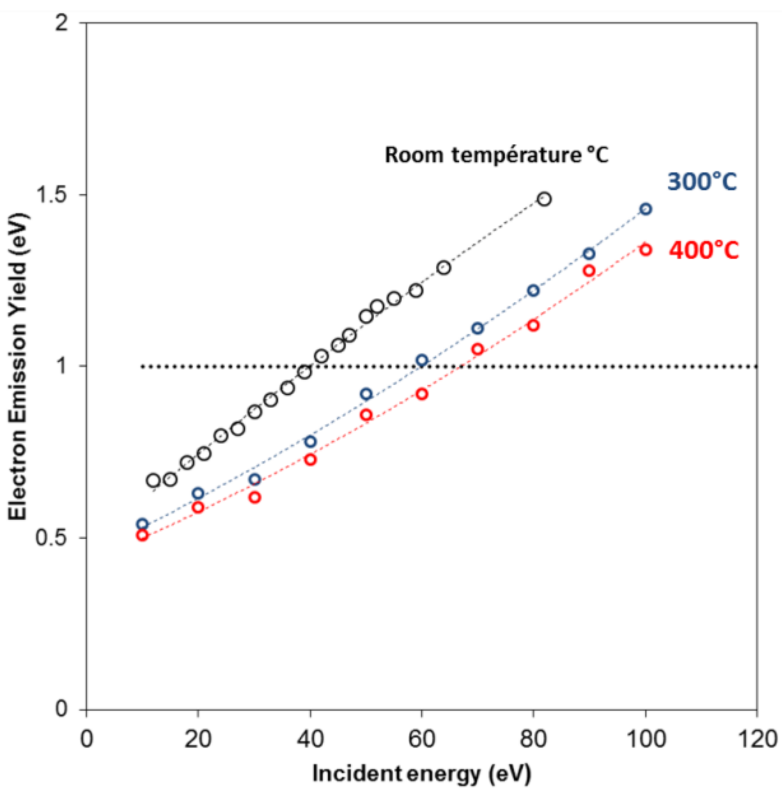
- Very low SEE velvet vs BN
- No significant wall effect up to V_d= 400 V, until E < 300 V/cm
- Significant differences above 400 V, when E ≥ 300 V/cm

Raitses, Staack, Dunaevsky, Fisch, J. App. Phys. ***99****, 036103 (2006)*

A possible explanation of different V-I's for BN case



- **Temperature effect on SEE from BN-SiO_2***



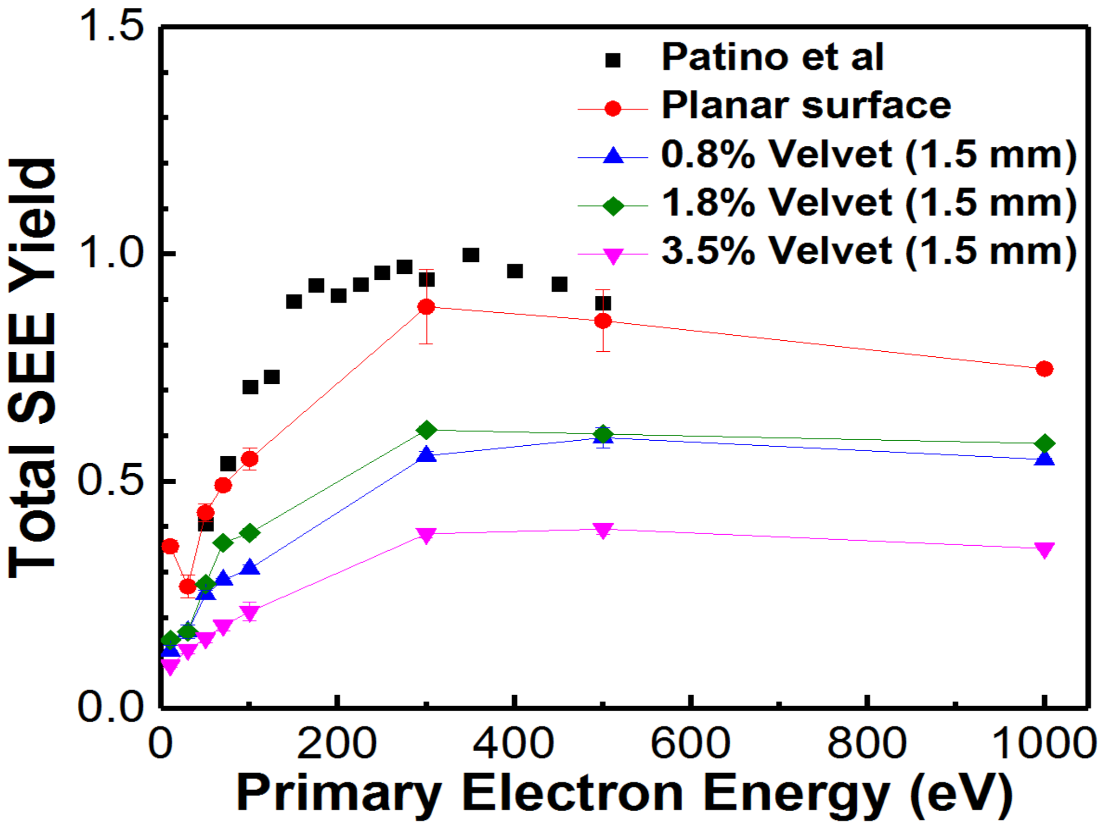
- **Heating of BN walls shifts SEE = 1 to much larger energies of primary electrons***
- **Do not expect to see wall material effect even at 400 V!!!!**

**M. Belhaj, N. Guibert, K. Guerch, P Sarrailh, N. Arcis, J. Phys. D: Appl. Phys. 2014*

Similar results in Raitses, Dourbal, Spector, IEPC-342-2015

Velvet: surface-architectured material with low SEE

- **Total SEE yield at normal incidence measured in vacuum**



- **SEE from velvet can be several times lower than SEE from BN at energies of primary electrons of < 100eV**

Jin, Ottaviano, Raitses (2017)

Wall material effect in CNRS-ICARE experiments

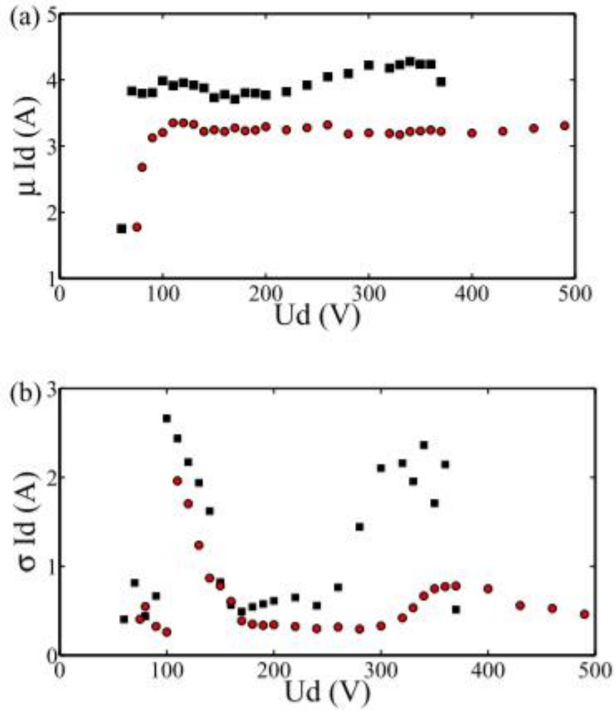


FIG. 4. Variations of (a) discharge current mean (μId) and (b) discharge current standard deviation (σId) with voltage for carbon velvet (squares) and $BNSiO_2$ (circles).

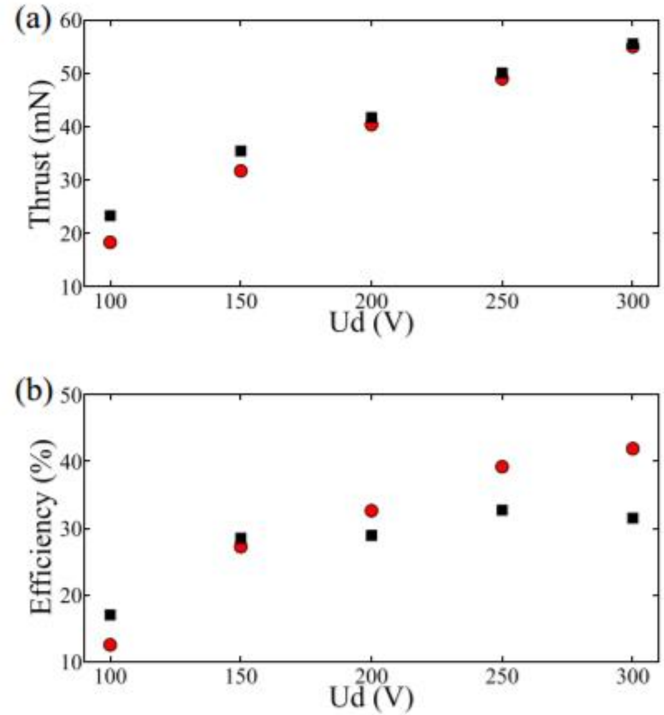
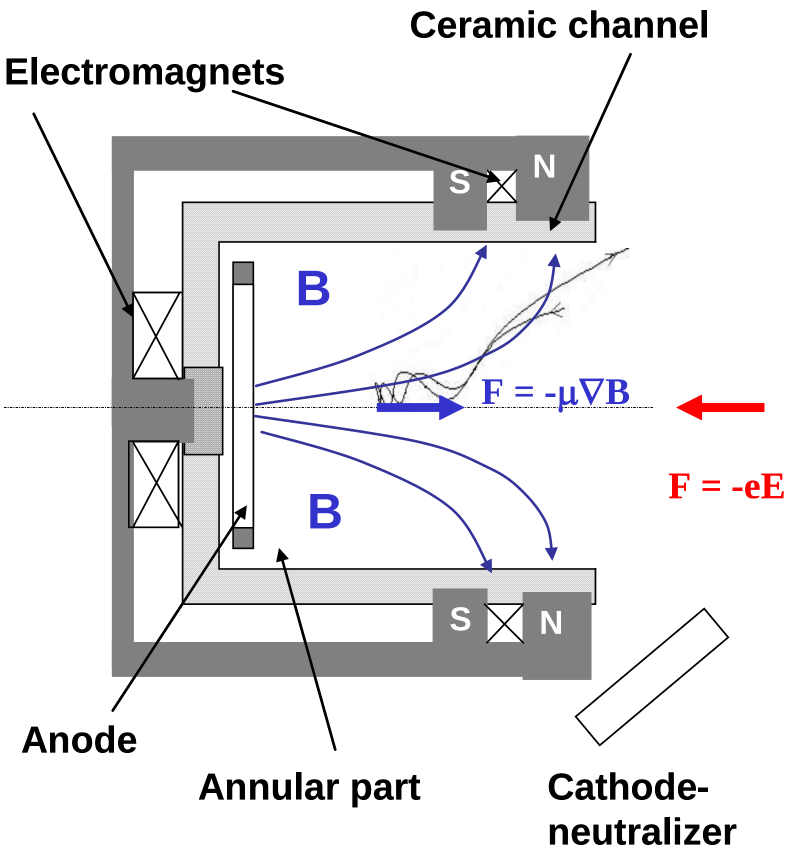


FIG. 5. Variations of (a) thrust and (b) total efficiency with voltage for carbon velvet (squares) and $BNSiO_2$ (circles).

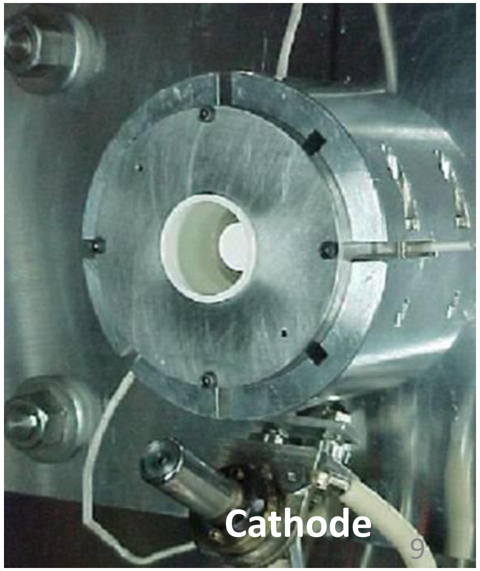
- **Wall material effect is stronger < 400 V than in PPPL experiments and opposite (increasing current for low SEE).**
- **No stable operation at > 400 V**
- **Sedina proposed enhanced ECDI but it could be a short circuit by velvet - ?**
- **wall effect is sensitive to thruster conditions and configuration!**

PPPL spoke studies in Cylindrical Hall thruster (CHT)



- Diverging magnetic field topology.
- Operation involves closed E×B drift.
- Electrons are confined in the hybrid magneto-electrostatic trap.
- Ions are accelerated in a large volume-to-surface area channel. (potentially lower erosion).

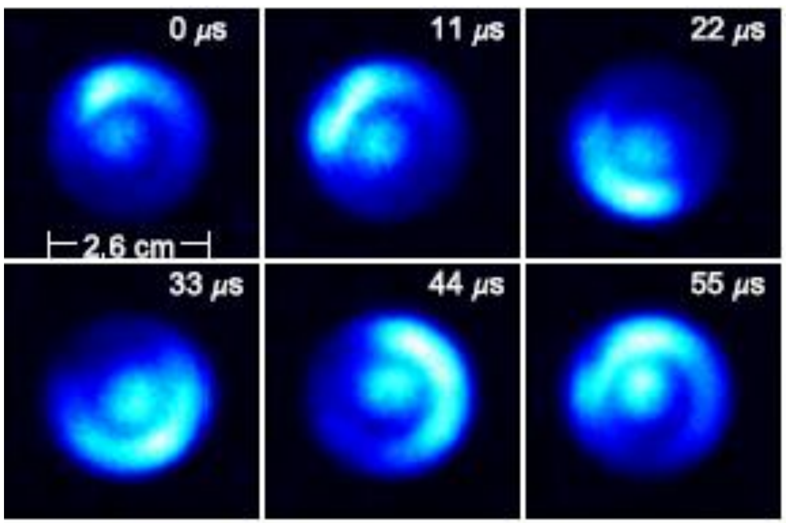
100 W 2.6 cm CHT



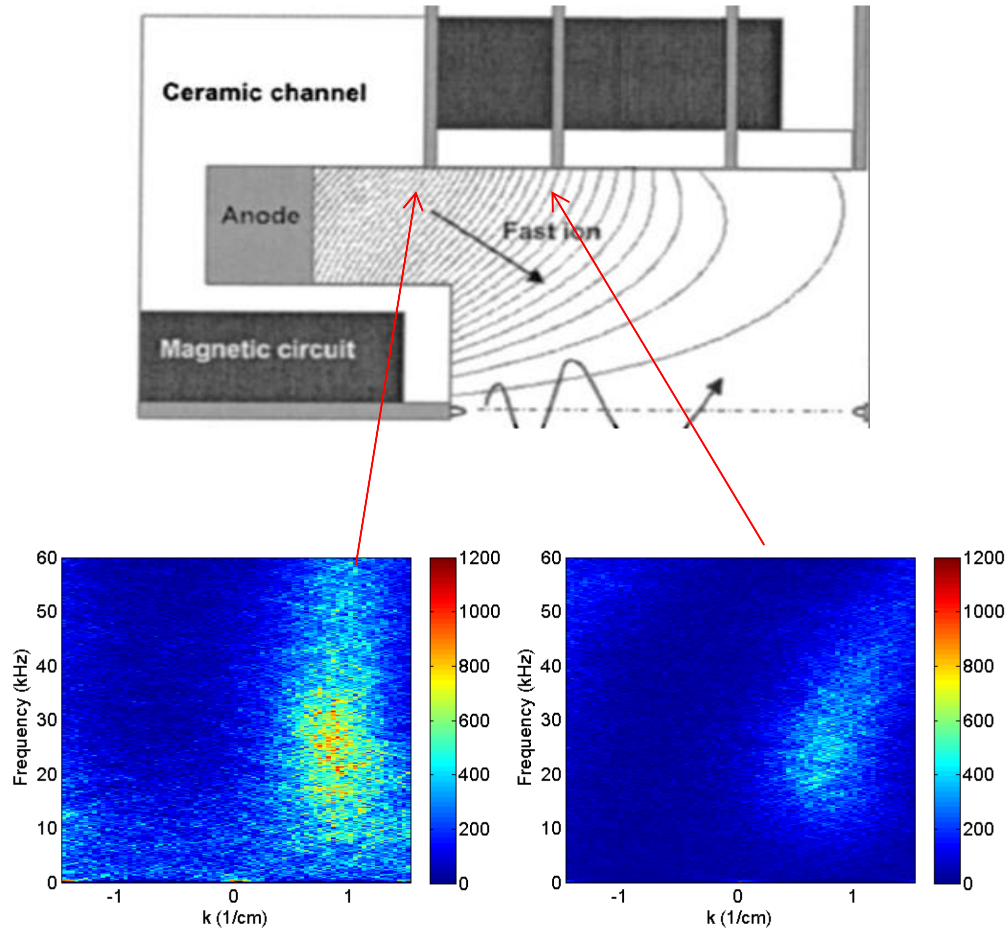
Raitses and Fisch, Phys. Plasmas 8, (2001)
Smirnov, Raitses, Fisch, J. Appl. Phys., 92 (2002)

From probes and camera, spoke exists from the anode to exit, but strongest m=1 near the anode

- Spoke in high speed images



- Langmuir probes to measure spoke in CHT



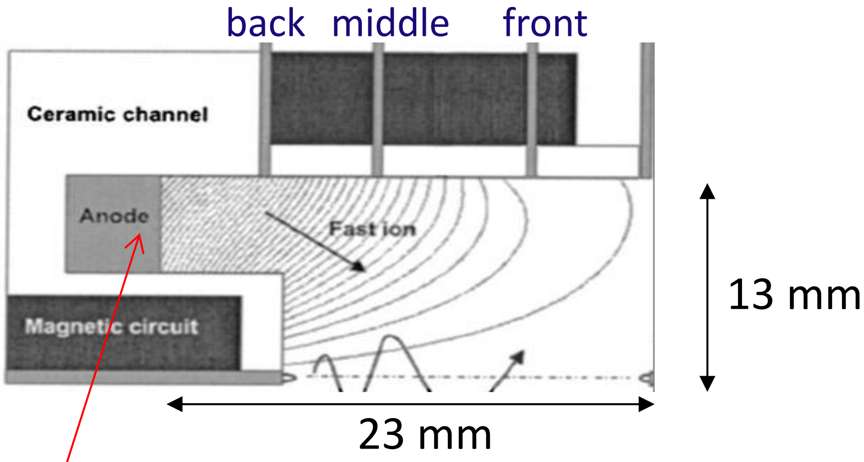
- Local wavenumber-frequency spectrum

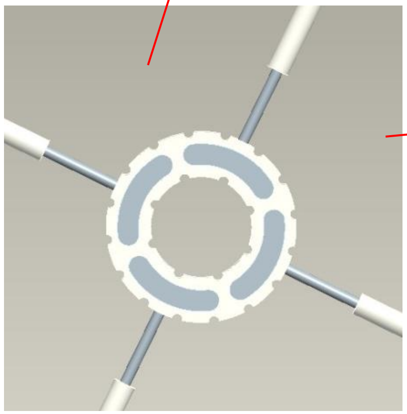
Direction: ExB
Velocity: 1.2-2.8 km/s
E/B: 30 km/s
V_{ia} 1-3 km/s
Size: 1.0-1.5 cm

J. Parker, Y. Raitses, N. J. Fisch, Appl. Phys. Lett., (2010)

Spoke conducts > 50% of the discharge current

3 azimuthal probes, 90 degrees apart, per axial location



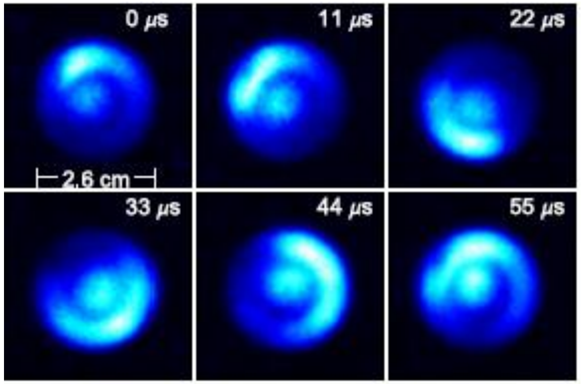


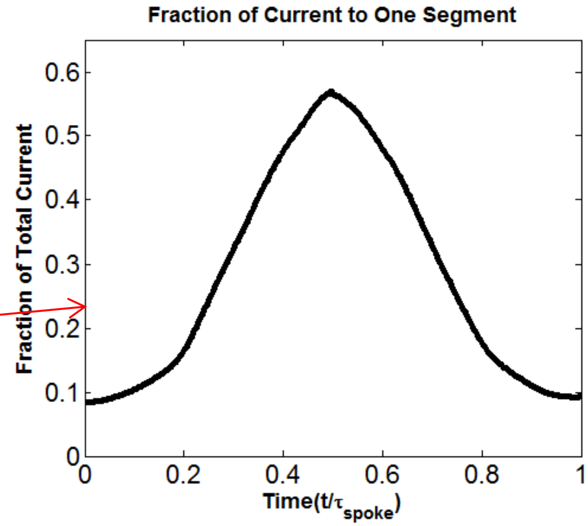
- **Segmented anode**

PPPL: Ellison et al., APS—DPP (2010), IEPC-173- (2011), Phys. Plasmas 19 (2012)

Michigan: Mcdonald et al., AIAA 5810, (2011)

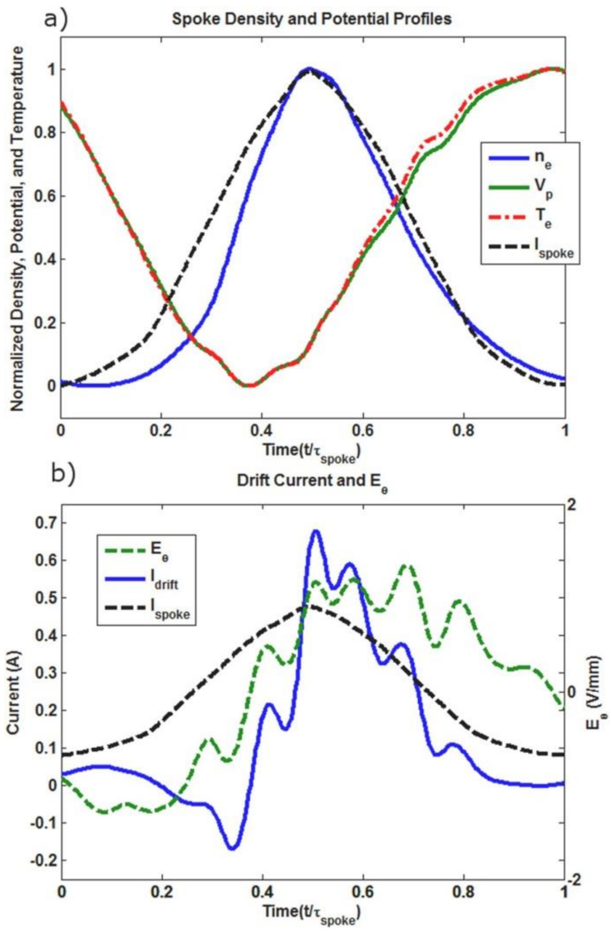
- **Spoke in CHT**





- **The evaluation of the segment current**

Measured electron-cross field current through the spoke to the anode at macro-time scale



- **Correlated segmented anode, interior probes, and high speed camera measurements:**

•The density oscillates in-phase with the spoke current.

•The potential is ~45° out of phase.

• The azimuthal electric field.

$$E = -\frac{dV}{dx} = -\frac{dV}{dt}\left(\frac{dx}{dt}\right)^{-1} = -\frac{1}{v_{spoke}}\frac{dV}{dt}$$

• The current to the anode:

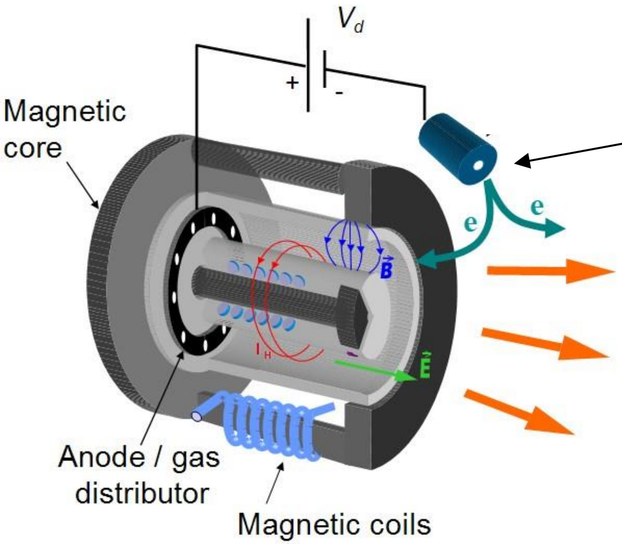
$$J_e = \langle \tilde{n}_e \, \tilde{E}_{e\,\theta} / B_r \rangle$$

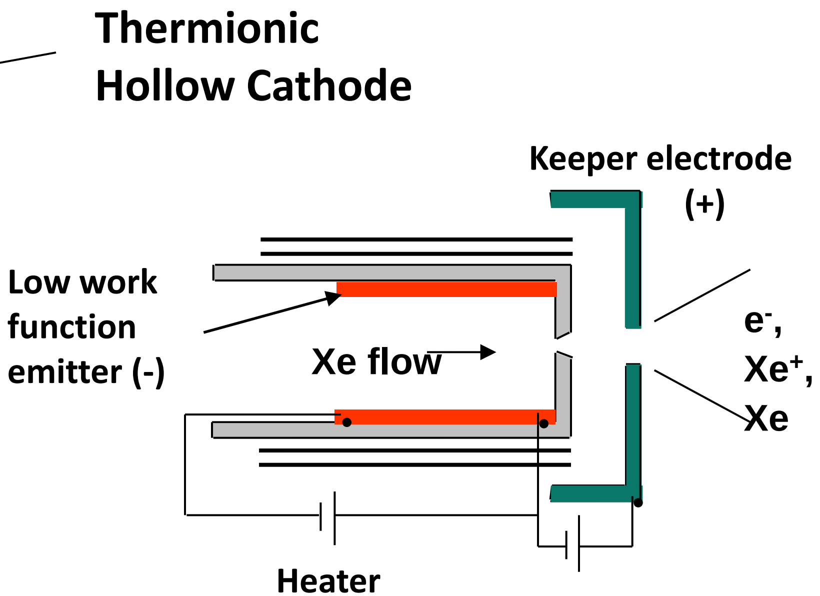
where υ_d =E/B.

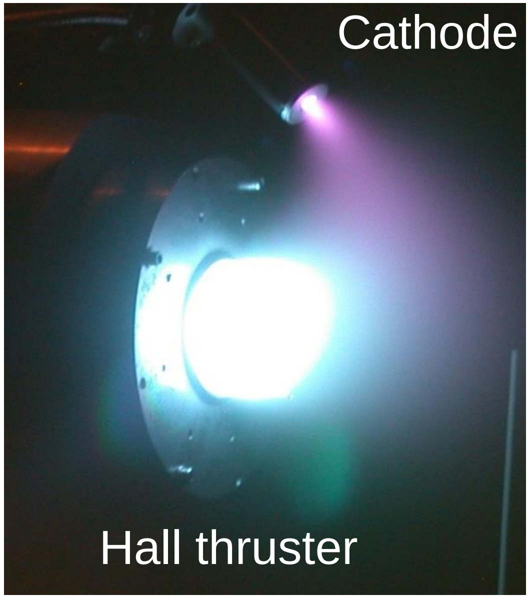
• The drift current is at least ~ 25% of the discharge current, explaining a large fraction ~ 50% of the anode current.

Ellison, Raitses, Fisch, Phys. Plasmas 19 (2012)

Controlling ExB transport from the cathode side



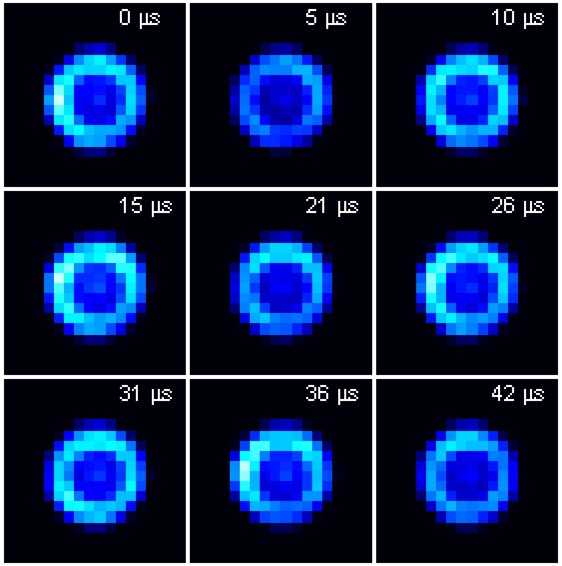




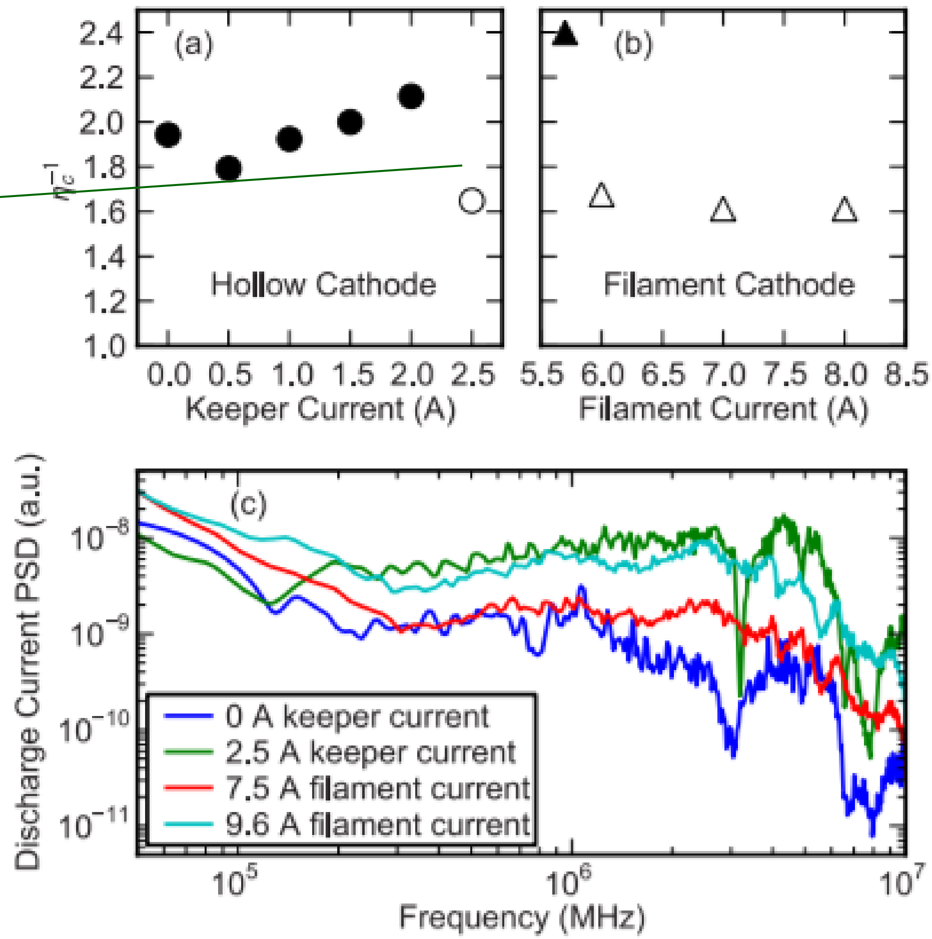
- **Control of the cathode electron emission by driving auxiliary (keeper-emitter) discharge.**
- **Overrunning the discharge current above a normal (self-sustained) steady-state value.**

Raitses, Smirnov, Fisch, Physics of Plasmas ***16****, 057106 (2009)*

Spoke suppression and transport mode transition: 1. Cathode effect



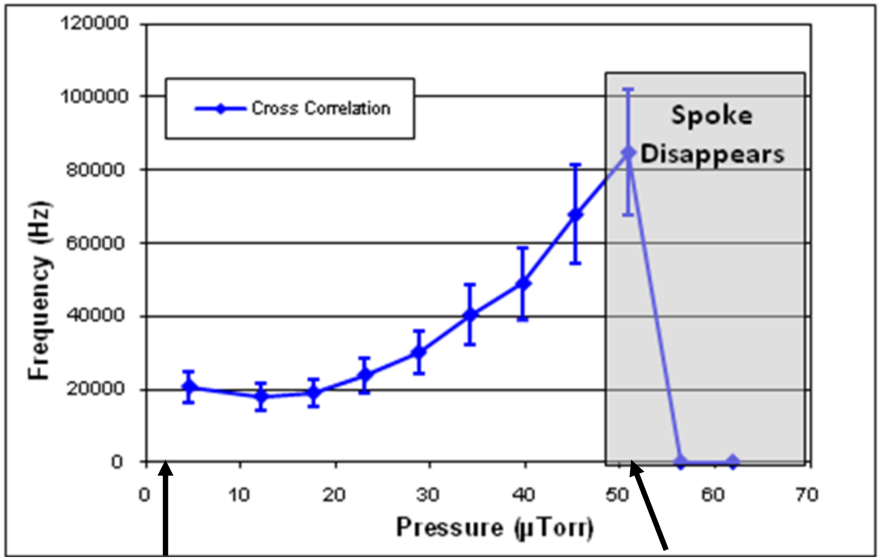
- **Hollow cathode and filament cathode effect on spoke**



- **Spoke is suppressed by increasing cathode emission.**
  - **Independent on cathode type**
- **When spoke disappears, fast oscillations (~MHz) are excited.**
  - **Inverse cascade?**

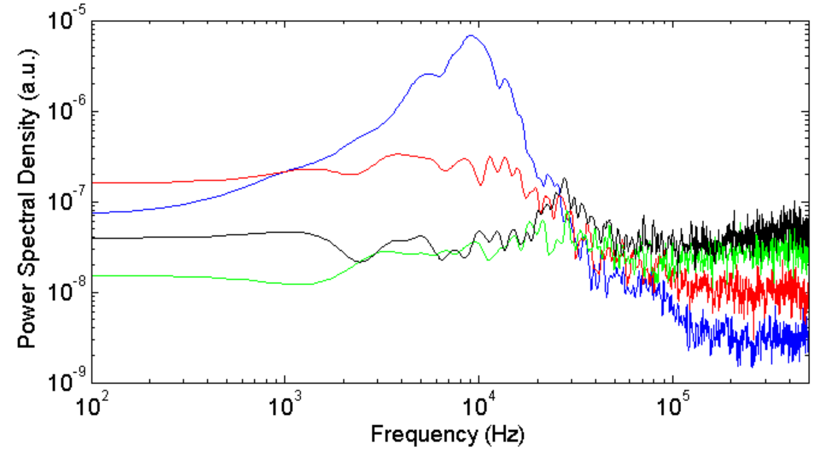
Parker, Raitses, Fisch, Appl. Phys. Lett., 97 (2010)

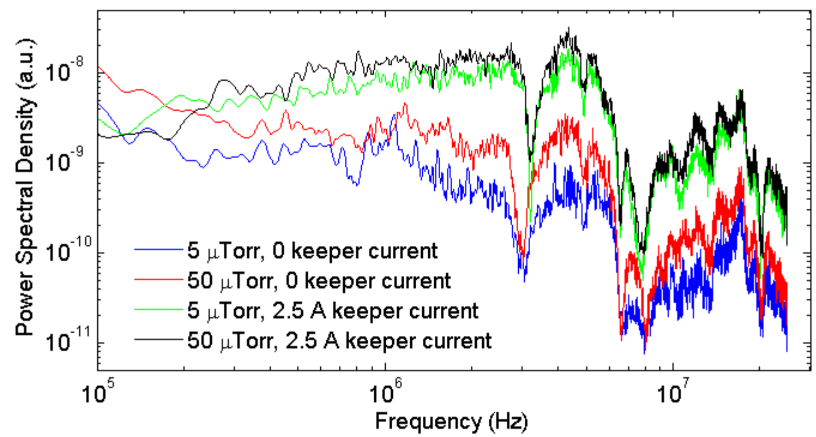
Spoke suppression and transport mode transition: 1. Background pressure effect



$\upsilon_{en} \sim 10^5 s^{-1}$ $\upsilon_{anom} \sim 10^8 s^{-1}$ $\upsilon_{en} \sim 10^6 s^{-1}$

Discharge Current Spectrum (low and high frequency)



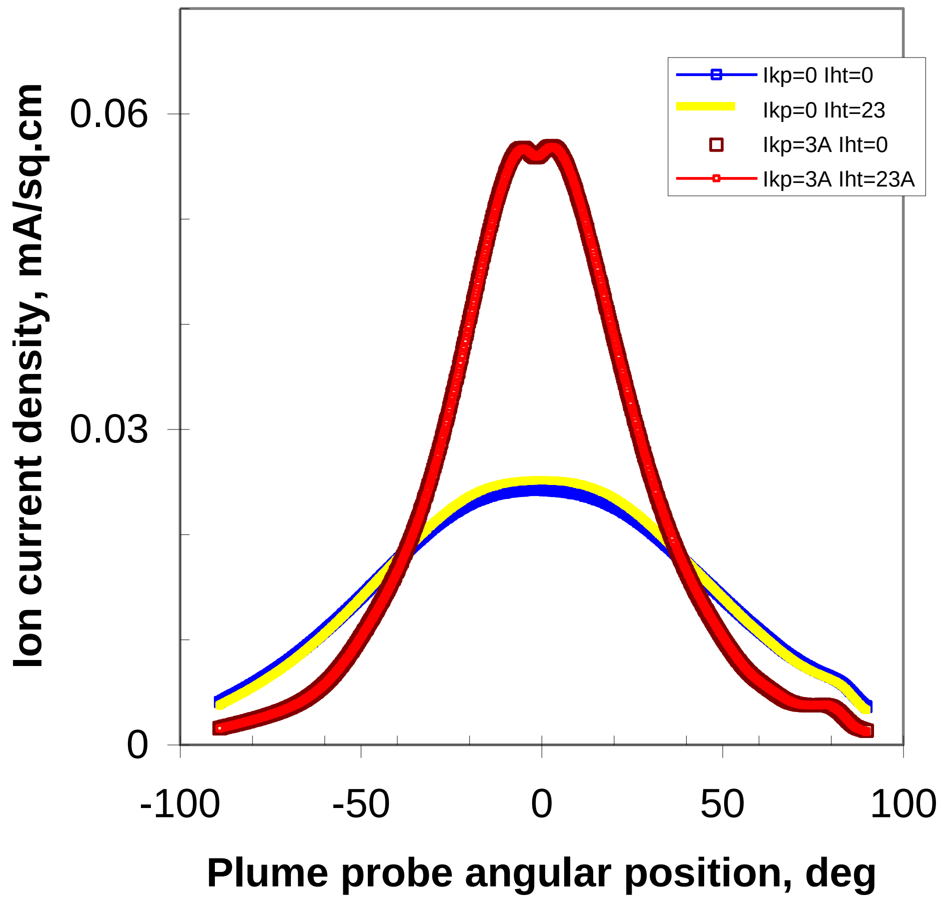


- **Suppression of spoke, similar to cathode electron emission effect**
- **Excitation of fast oscillations in discharge current (at ~MHz, see below right)**
- **Suppression of breathing mode (at ~10 kHz, see above right)**

Raitses, Parker, Davis, and Fisch, AIAA 2010-6775 (2010)

Cathode mode effect on performance

Angular ion current distribution in the plume from CHT



Correlation or cause?

Enhanced mode, without spoke

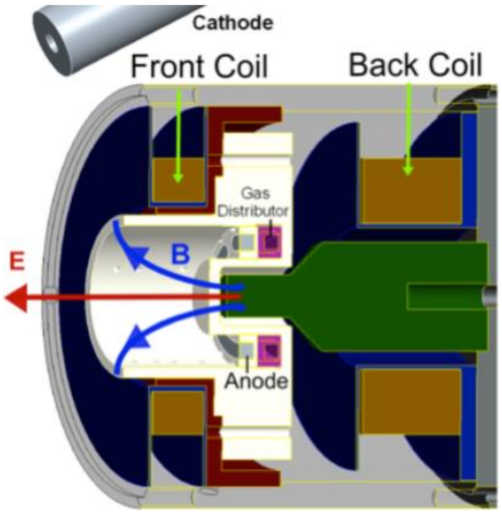
Normal mode, with spoke

- **20-30% plume narrowing**
- **50% increase of the anode efficiency**
- **No spoke, no breathing modes**

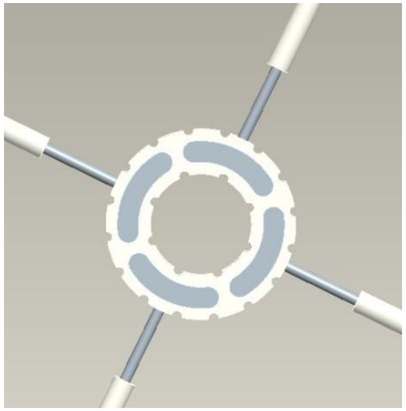
Raitses, Smirnov and Fisch, Appl. Phys. Lett. 2007

Spoke suppression from the anode side

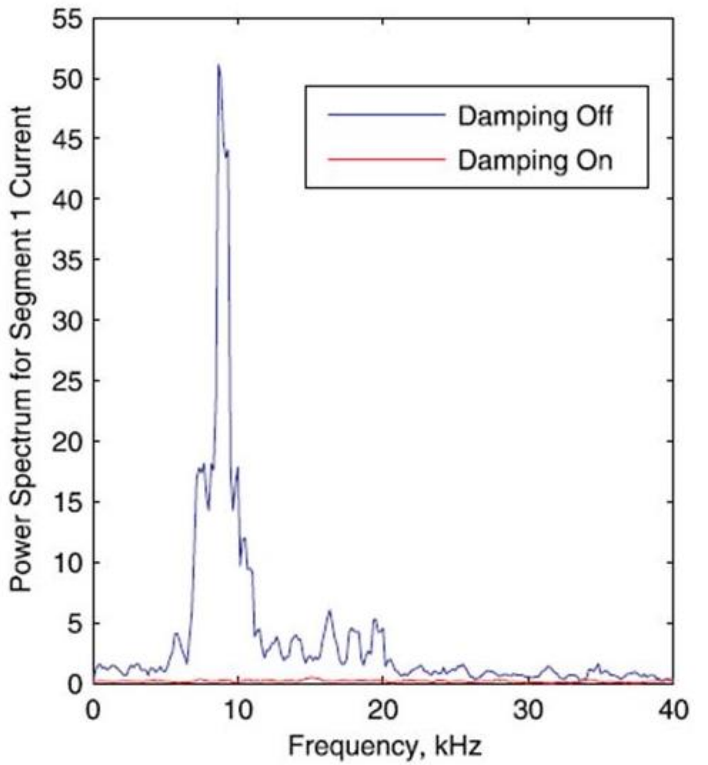
- **Damping spoke with a low frequency negative feedback:**



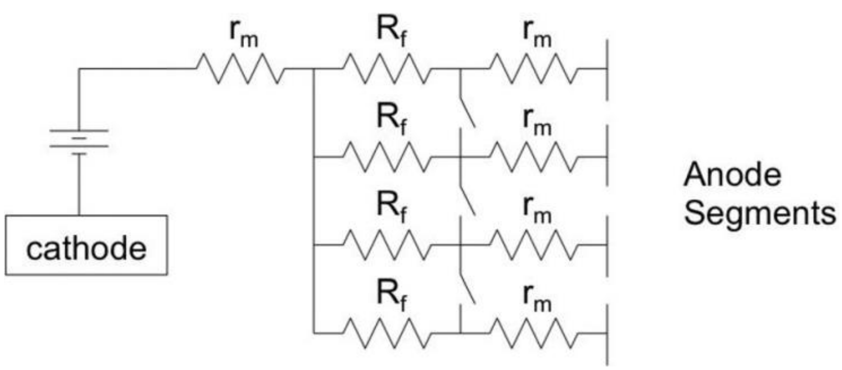
Segmented anode



- **FFT of segment current**

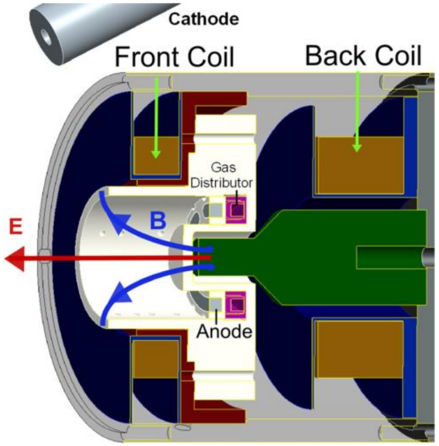


- **Dumping circuitry**

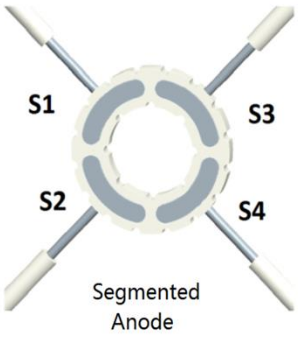


Griswold, Ellison, Raitses, Fisch,
Phys. Plasmas 19, 053506 (2012)

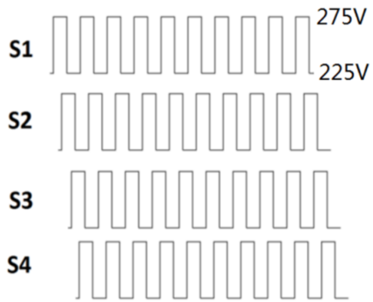
Linear drive of m=1 mode coherent structures in CHT



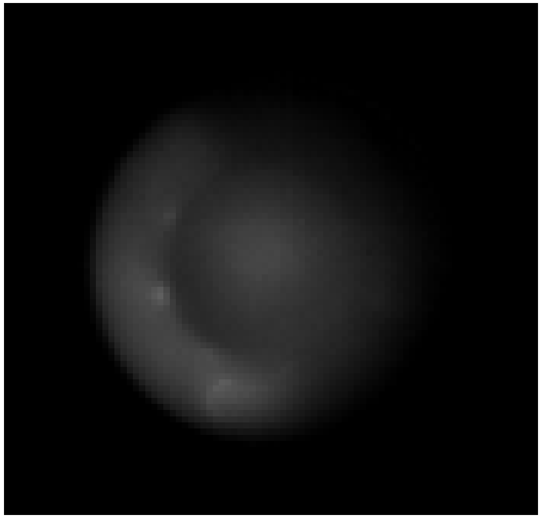
Segmented anode

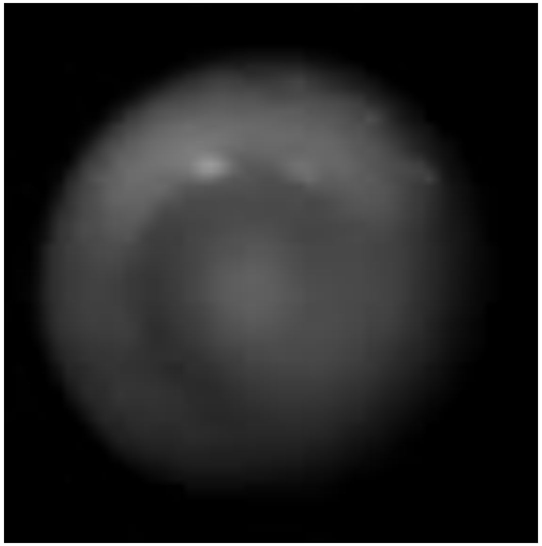


Driving anode Segments signal



ExB

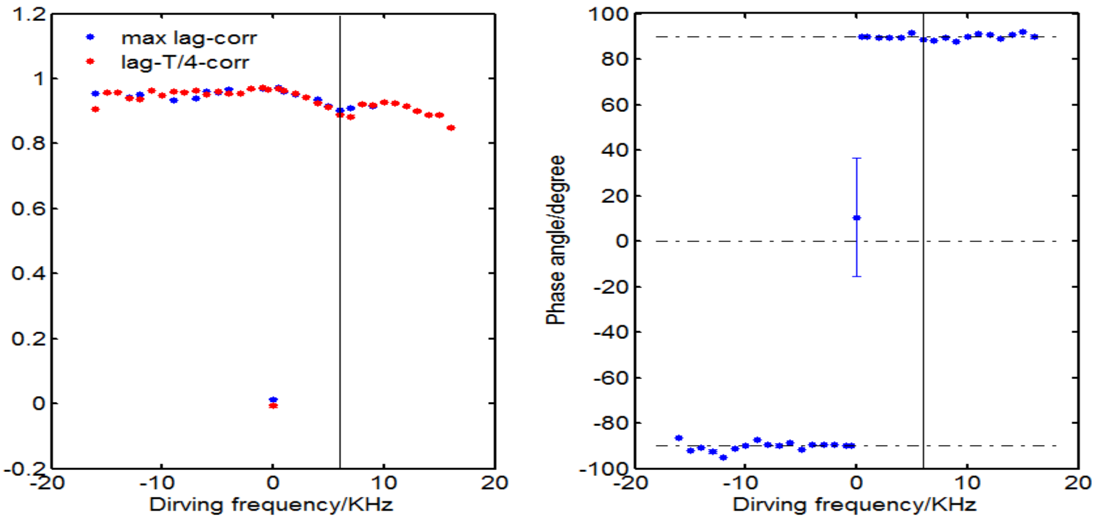




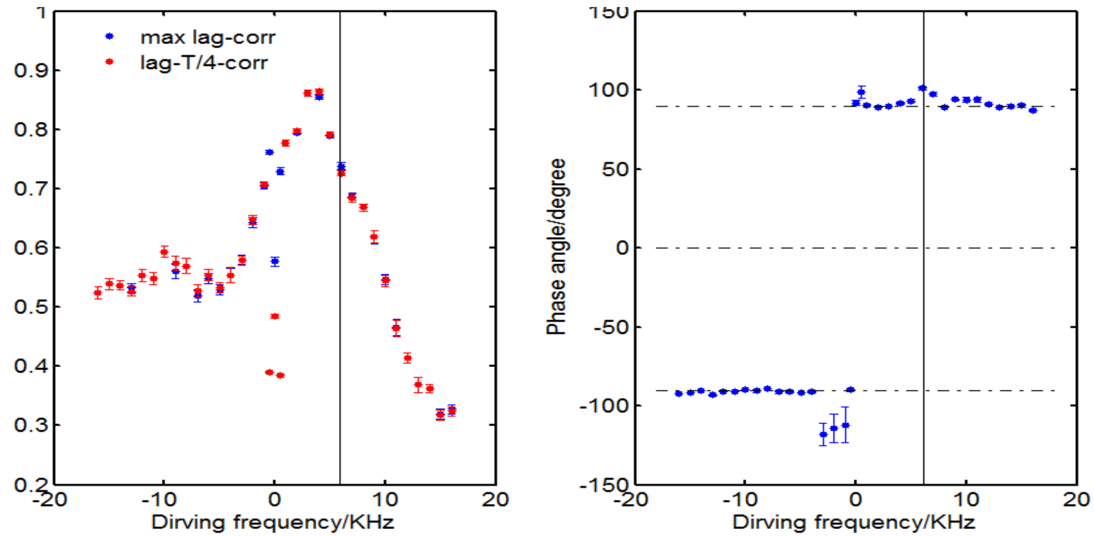
-ExB

- **Applied a voltage modulation to segmented anode in CHT**
- **Spoke is driven in both +/- ExB directions**

Linear drive of m=1 mode coherent structures in CHT



Cross correlation between voltage on two adjacent anode segments. Deviate from 1 because 1Ω resistors are in series with segments to measure current.



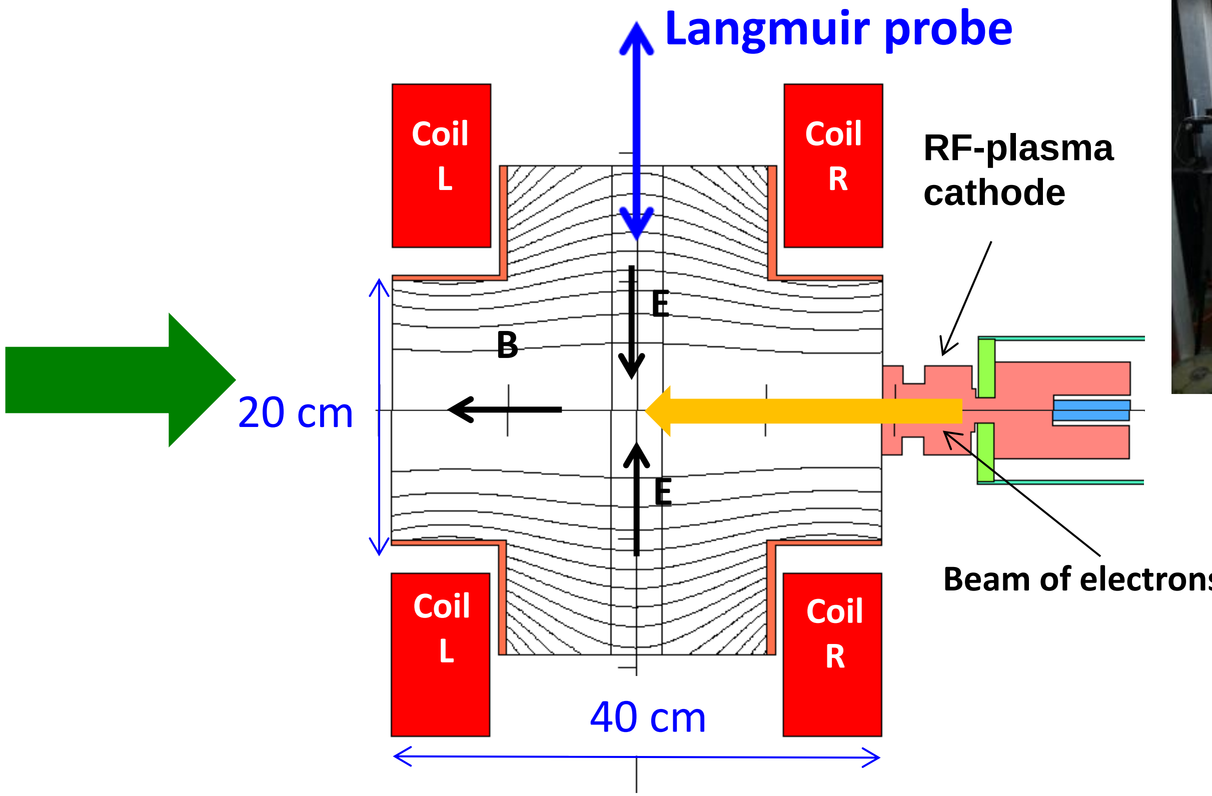
Cross correlation between Current though two adjacent anode segments. Maximum coherence when driving near natural frequency 6 KHz

Summarizing remarks on spoke in CHT

- **Anomalously high cross-field current**
- **Spoke is everywhere in the channel**
- **Spoke control from the cathode side or anode side (in spite of magnetic insulation)**
- **Better performance without spoke – accidental correlation or cause?**
- **Mode transition of electron transport: when there is no spoke, there are high frequency oscillations**
    - **Could it be that spoke dissipate energy to small scale turbulence?**
- **If spoke is needed, it can be excited.**

Beam-plasma Penning system

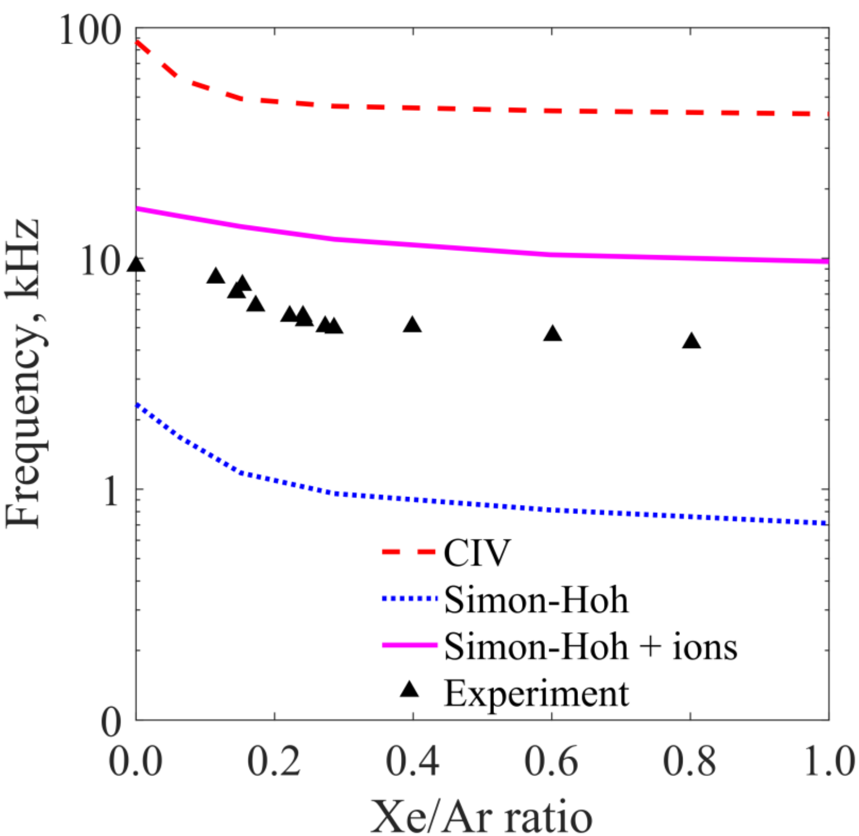
- Easier diagnostic access than in Hall thrusters
- A broad pressure range (10^{-4}-10^{2} mtorr) –Hall thruster level to higher pressures than in previous studies.



- Emissive and fast-sweeping biased probes, filtered high speed imaging, time-resolving Laser Induced Fluorescence, OES

Varying the gas mixture composition to study and control coherent plasma structures – ExB spoke rotation

- Spoke rotating frequency: Experiment vs Linear Theory



- Measurements of spoke frequency with probes, and filtered fast frame imaging
- Independ on gases (Xe, Ar, H_2), and gas mixtures always single frequency of rotation, m=1 mode
- Significant differences between experiment and linear theory of MSHI and critical ionization velocity (CIV)
- Accounting for the ion rotation seems gives a better agreement with the experiment
    - But linear analysis predicts more unstable higher m>1 modes.