What LTP community needs to know about $E \times B$ discharges

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Online Low Temperature Plasma Seminar

International Online Plasma Seminar

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OUTLINE

1. **Basic physics of $E \times B$ plasmas**
   Classical, collisional cross-field transport
   Hall effect
   Closed drift devices
   Instabilities and anomalous transport – Dispersion relations

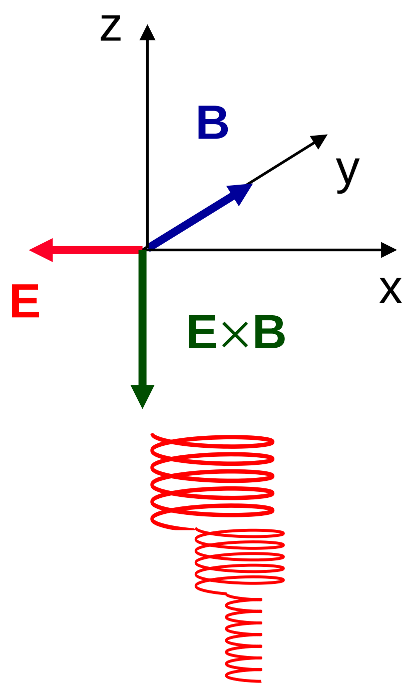
2. **ExB discharge devices**
   Magnetron discharges
   Hall thrusters

3. **Models of $E \times B$ plasmas – Instabilities and anomalous transport**
   Electron cyclotron drift instability (ECDI) in Hall thrusters
   Rotating spokes in magnetron discharges and Hall thrusters

4. **Conclusion**

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Electron trajectory in E×B fields



- **Electron drift in E×B direction** $u_{\boldsymbol{e}} = E/B$
- **Electrons are trapped in the E direction: no transport in the E direction without collisions**

cyclotron frequency $\Omega_{ce} = \dfrac{eB}{m}$

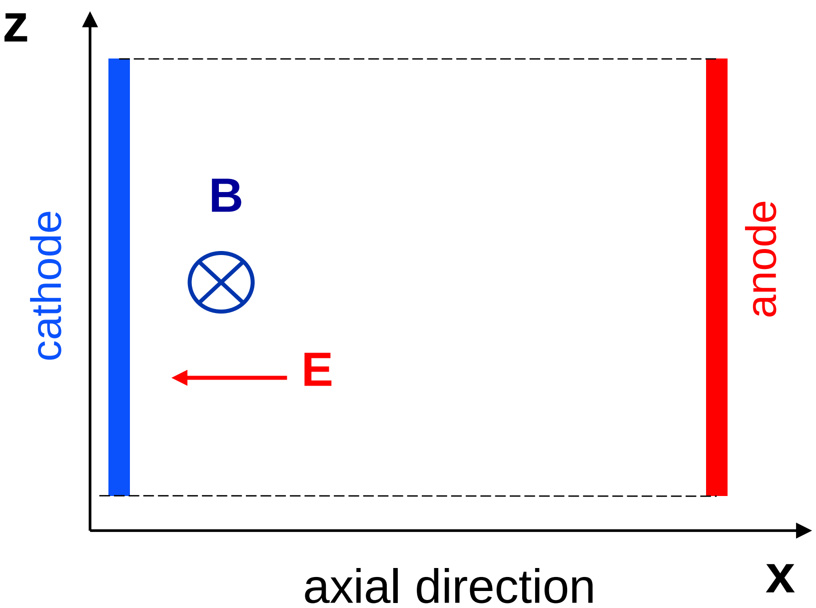
Larmor radius $\rho_e = \dfrac{v_\perp}{\Omega_{ce}}$

1. Basic physics of $E \times B$ plasmas

➢ **In low temperature $E \times B$ plasma sources**

- **Magnetic field ⊥ to anode-cathode current increases electron residence time and ionization allowing plasma sustainment at low pressure**
- **Electrons are strongly magnetized** $\rho_e << L$
- **Ions are weakly magnetized** $\rho_i > L$

« partially magnetized plasmas »



electrons trapped by B
→ collisional electrons

ions ~ not sensitive to B
→ weakly collisional ions

⇩

applications to ion sources
- Plasma processing sputtering / deposition
- Ion thrusters for space propulsion
- Generation of ion beam (ITER NBIS)

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Conditions and orders of magnitude

B	$10^2 – 10^3$ G
$\Omega_{ce} = eB/m$	$10^9 – 10^{10}$ s^{-1}
$\rho_e = v_e/\Omega_{ce}$	50 – 500 µm
$\Omega_{ci} = eB/M$	$10^4 – 10^5$ s^{-1}
$\rho_i = v_i/\Omega_{ci}$	5 – 50 mm

p	0.1 – 10 Pa
$\nu_{eN} \equiv \nu$	$10^6 – 10^8$ s^{-1}
ν_{iN}	$10^4 – 10^6$ s^{-1}

Hall parameter h characterizes electron confinement efficiency

$$\boldsymbol{h = \Omega_{ce} / \nu}$$

p=1 mtorr
B=100 G

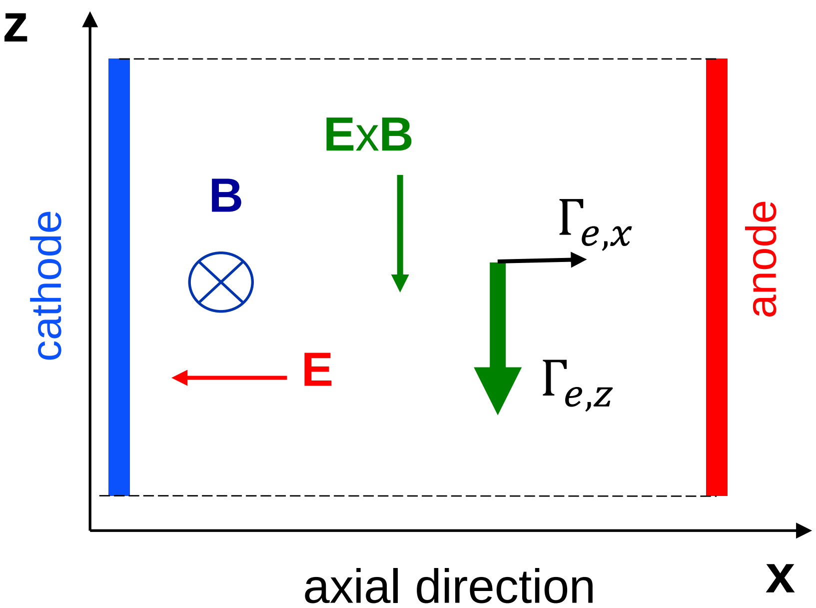
$$h \approx 2\ 10^9 / 2\ 10^6 = 10^3$$

- can be as large as or larger than 10^3
- can vary by several orders of magnitude in the same device

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Classical, collisional transport theory:

- Large electron drift (Hall current) in the $\boldsymbol{E} \times \boldsymbol{B}$ direction
- Electron mobility μ_e parallel to E and perpendicular to B is considerably reduced



➢ Simplified momentum equation

$$-\frac{e}{m}[\boldsymbol{E} + \boldsymbol{v_e} \times \boldsymbol{B}] - \nu \boldsymbol{v_e} = \boldsymbol{0}$$

$$\begin{cases} v_{ex} = -\dfrac{\mu_{e0}}{1+h^2} E_x \approx -\dfrac{\mu_{e0}}{h^2} E_x \\ v_{ez} = \mu_{e0} \dfrac{h}{1+h^2} E_x \approx \dfrac{E_x}{B} \end{cases}$$

$$\mu_{e0} = \frac{e}{m\nu}$$

$$\boldsymbol{h} = \frac{eB}{m\nu} = \frac{\Omega_{ce}}{\nu} \gg 1$$

$\boldsymbol{h}$ = Hall parameter can be 1000 or more

1. Basic physics of $E \times B$ plasmas

➢ Classical, collisional transport theory:

- Electron mobility parallel to the electric field $\mu_e \approx \frac{\mu_{e0}}{h^2}$ reduced by a factor h^2 with respect to mobility wthout magnetic field: h^2 as large as 10^4-10^6
- $\mu_e \approx \frac{\mu_{e0}}{h^2} = \frac{1}{B}\frac{\nu}{\Omega_{ce}}$ no transport in the x direction if $\nu = 0$,i.e. without collisions

→ Is the axial confinement of electrons as efficient as predicted by this theory ?

➢ Electron mobility parallel to E and perpendicular to B is actually much larger than predicted by classical theory

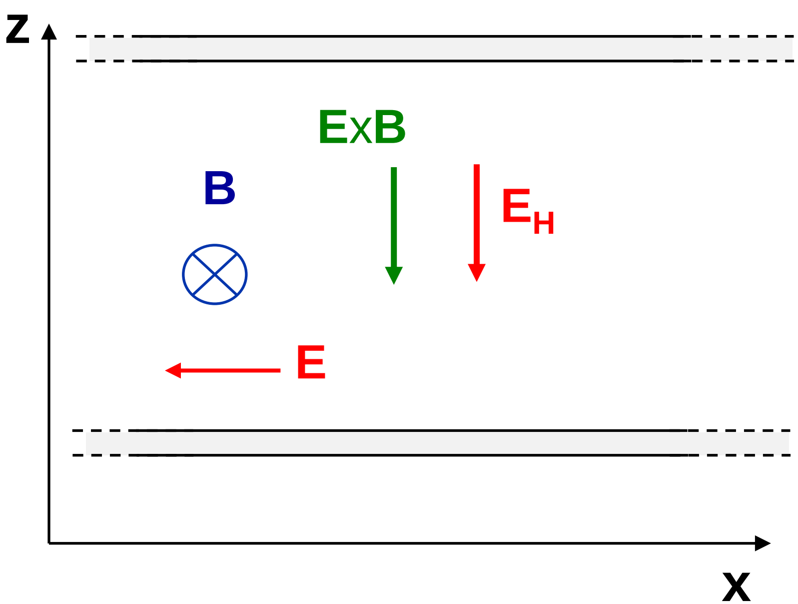
- Because of **Hall effect** in devices where Hall current goes to a wall
- Because of **instabilities** in devices where Hall current is closed on itself (closed drift devices)

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

Walls in the $\boldsymbol{E} \times \boldsymbol{B}$ direction: Hall effect

- Hall ($\boldsymbol{E} \times \boldsymbol{B}$) current to the walls
- Current to the walls must be zero

→ **Generation of electric field $\boldsymbol{E_z}$ to oppose current**



Axially uniform plasma column
Axial electric field E_x

- electron momentum equation (with pressure gradient)

$$-\frac{e}{m}[\boldsymbol{E}^* + \boldsymbol{v_e} \times \boldsymbol{B}] - \nu \boldsymbol{v_e} = \boldsymbol{0}$$

$$E_x^* = E_x$$
$$E_z^* = E_z + T_e \frac{\partial_z n}{n}$$

- Ion velocity

$$\boldsymbol{v_i} = \mu_i \boldsymbol{E}$$

- Total current in the z direction must be 0

$$n v_{ez} = n v_{iz} = n \mu_i \, E_z$$

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Walls in the $\boldsymbol{E} \times \boldsymbol{B}$ direction: Hall effect

$$\begin{cases} nv_{ex} = -n\dfrac{\mu_{e0}}{\alpha}E_x - \dfrac{h}{\alpha}D_a\partial_z n \\ nv_{ez} = n\mu_i\dfrac{h}{\alpha}E_x - \dfrac{D_a}{\alpha}\partial_z n \end{cases}$$

axial mobility with Hall effect $\mu_e \approx \dfrac{\mu_{e0}}{\dfrac{\mu_i}{\mu_{e0}}h^2}$

$$\alpha = 1 + \frac{\mu_i}{\mu_{e0}}(1+h^2)$$

axial mobility without Hall effect $\mu_e \approx \dfrac{\mu_{e0}}{h^2}$

continuity equation

$$E_z = -\frac{1}{\alpha}T_e\frac{1}{n}\partial_z n + \frac{hE_x}{\alpha}$$

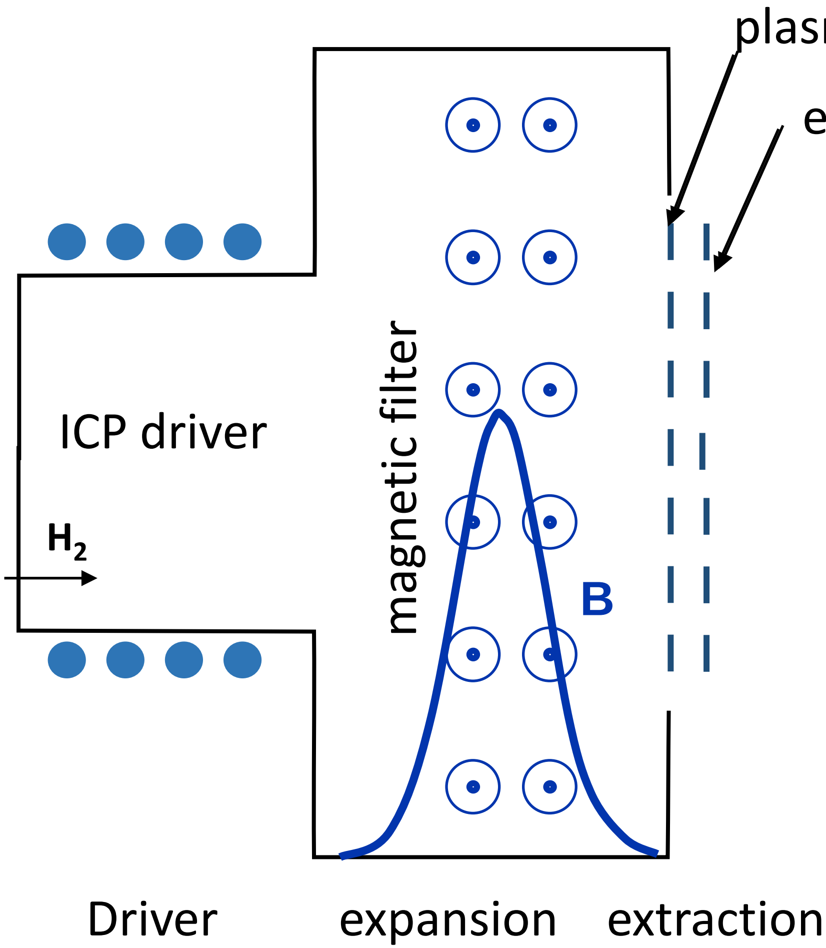
$$\partial_z\,(nv_{ez}) = n\nu_i \rightarrow D_a\partial_z^2 n + \beta\partial_z n + n\nu_i = 0$$

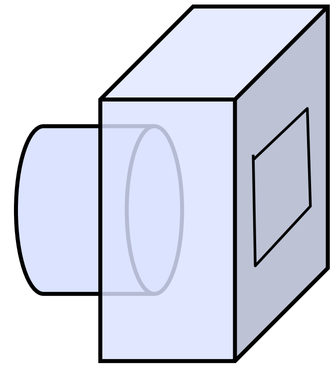
→ **consequences**
1. Mobility reduction much less important with Hall effect $\frac{\mu_i}{\mu_{e0}}h^2$ instead of h^2
2. Density profile in the z ($\boldsymbol{E} \times \boldsymbol{B}$) direction no longer symmetric

more complete treatment in:
Ecker and Kanne, Phys. Fluids 7, 1834 (1964); Kunkel, Am. J. Phys. 49, 733 (1981)

1. Basic physics of $E \times B$ plasmas

➢ Hall effect in ITER Negative ion source



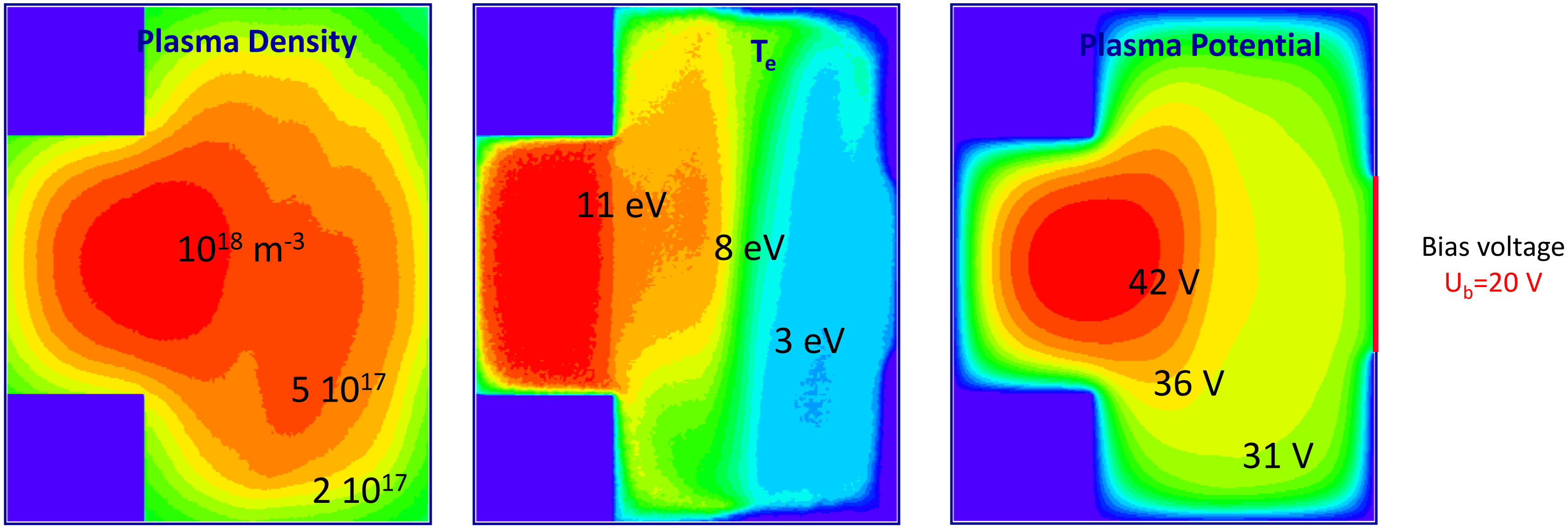


- Production of negative ions H^-/D^- in an inductive RF plasma source with magnetic filter in expansion region
- Electron temperature in RF driver ~ 10 eV
- High energy electrons detach negative ions
- Magnetic filter used to lower electron temperature (and flux to extraction region ?) and reduce negative ion detachment in extraction region
- High plasma density and electron temperature in RF driver. Electron current driven by pressure gradient and biased grid
- **Presence of walls → Hall effect**

E Speth et al. Nucl. Fusion 46 S220 (2006)

1. Basic physics of $E \times B$ plasmas

➢ Hall effect in ITER Negative Ion Source – PIC-MCC simulation



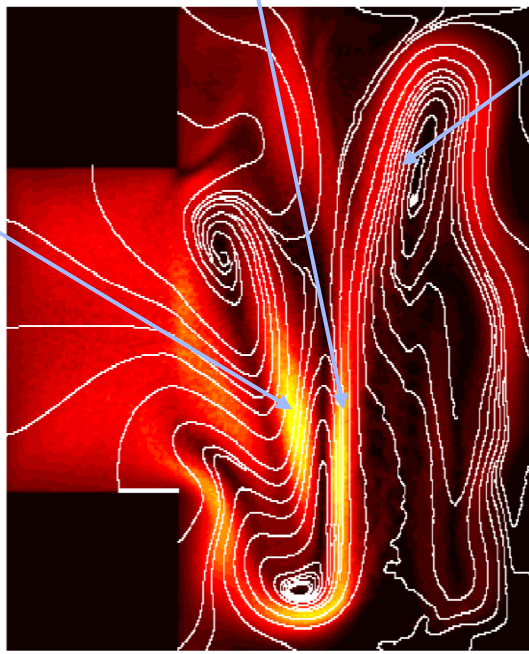
- Polarization due to Hall effect creates electric field E_H perpendicular to B and is responsible for plasma asymmetry.
- **Problem for uniformity of negative ion beam extraction ?**

PIC simulations
JP Boeuf et al., Phys. Plasmas 19, 113510 (2012)
G Fubiani et al., New J. Phys. 19 015002 (2017)

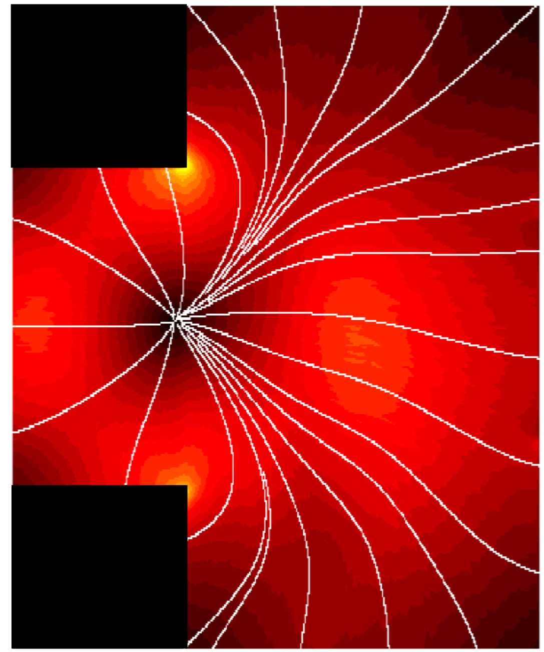
Experiments
L. Schiesko et al., Plasma Phys. Control. Fusion 54, 105002 (2012)
F. Gaboriau et al., Appl. Phys. Lett. 104 214107 (2014)

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Hall effect in ITER Negative Ion Source – PIC-MCC simulation



Electron Current Density



Positive ion Current Density

- Electron current driven by pressure gradient → diamagnetic drift ($\nabla P_e \times \boldsymbol{B}$ term)
- Hall effect due to diamagnetic drift plays an important role in electron transport across the magnetic filter
- Non ambipolar currents

1. Basic physics of $E \times B$ plasmas

➢ Closed drift devices

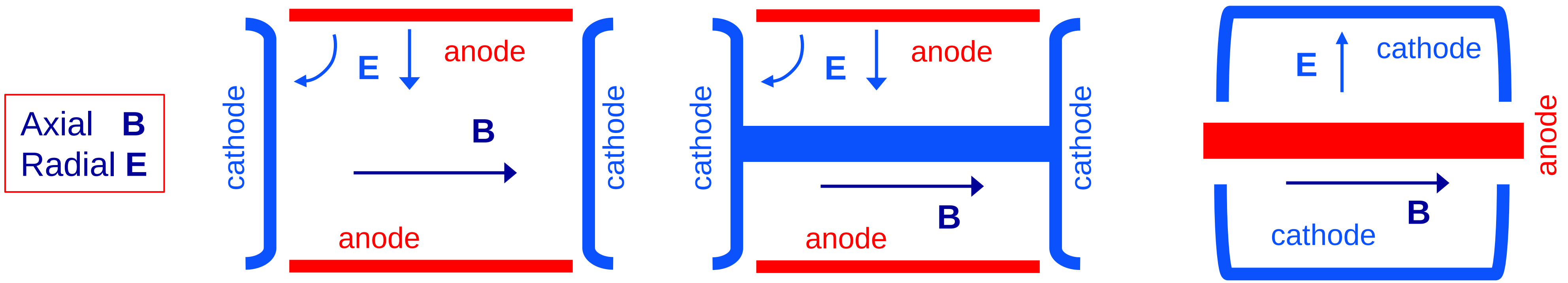
- **To avoid Hall effect and allow efficient electron confinement, the Hall current must be closed on itself (not directed toward a wall)**

- **This is possible in a cylindrical geometry where the $E \times B$ direction is the azimuthal direction : CLOSED DRIFT DEVICE**

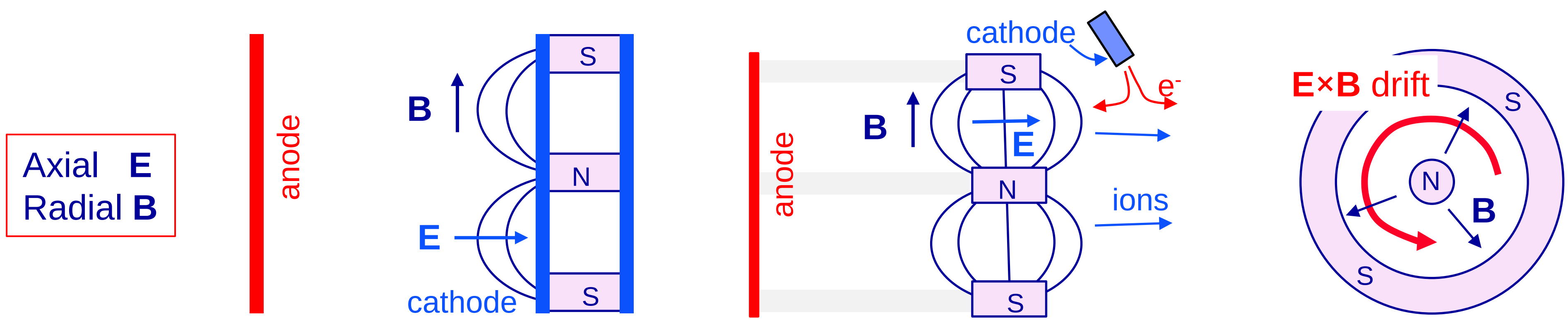
- **→ (axial E, radial B) or (axial B, radial E)**

1. Basic physics of $E \times B$ plasmas

➢ Closed drift devices



(a) Penning cell (b) Cylindrical magnetron (c) Inverted magnetron



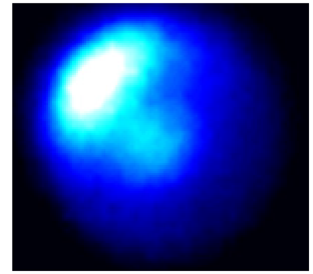
(d) Planar magnetron (e) Hall ion source (f) Hall current

1. Cross-field transport in low temperature $E \times B$ plasmas

➢ Efficiency of confinement in closed drift devices ?

- Electron mobility // to electric field is reduced but is much larger than predicted by classical, collisional theory
- Instabilities are ubiquitous in ExB plasmas used in applications → « anomalous » cross-field transport
- Unstable fluctuations in a large range of frequencies and wavelengths: kHz to 10's MHz, fraction of mm to cms
- Self-organization into coherent structures (spokes) typically occur in HiPIMS and Hall plasma devices.

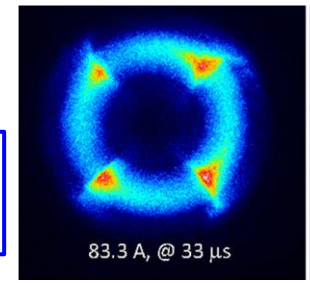
I. Kaganovich et al., Phys.Plasmas 27, 120601 (2020)



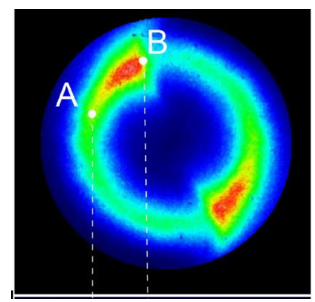
Hall thruster

Ellisson, Raitses & Fisch, POP (2012)

dc magnetrons
HiPIMS



Anders, JAP 2017



Hecimovic et al.
Jphys D (2016)

1. Basic physics of $E \times B$ plasmas

➢ Possible causes of anomalous electron transport in $E \times B$ devices

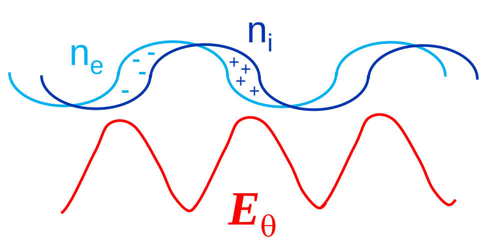
- **Axial electric field E_x tends to increase in the plasma because of the reduced electron mobility**

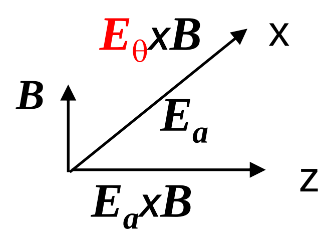
- **The axial electric field generates an azimuthal, $E \times B$ drift**
  - Large difference in electron and ion ExB drift velocities → charge separation

  → Formation of an azimuthal electric field E_θ

- **Azimuthal electric field and plasma density oscillations generate axial transport**
  - E_θ xB is in the axial direction

$$\overline{J_{ex}} = -e \int n_e \frac{E_\theta}{B} dA/A$$





1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Instabilities and anomalous transport – Dispersion relations

Fluid or kinetic nature of instabilities

Linearization of fluid or kinetic equations coupled with Poisson's equation

Fluid equations:
Inject small perturbations of the form $(\tilde{n}, \tilde{\phi}) \sim \exp(-i\omega t + \boldsymbol{k}.\boldsymbol{r})$ and linearize fluid equations
→ Dispersion relation = relation between frequency ω and wave number $\boldsymbol{k}$
→ Growth of the instability if imaginary part of ω is positive: $\mathrm{Im}(\omega) > 0$

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

$$\omega_0 = k\frac{E}{B}, \omega_* = k\frac{T_e}{BL_n}, \rho_e, \nu_{en}, c_s = \sqrt{\frac{eT_e}{m}}$$

ω_0: $\boldsymbol{E} \times \boldsymbol{B}$ drift

ω_*: Diamagnetic drift

See A. Smolyakov et al., Plasma Phys. Control. Fusion 59 01404041 (2017)

J.P. Boeuf, Phys. Plasmas 26 072113 (2019)

1. Basic physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas

➢ Instabilities and anomalous transport – Dispersion relations

- Example: Simon-Hoh instability

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

Long wavelength ($k\rho_e \ll 1$) solutions

$$\frac{\omega_*}{\omega - \omega_0} = \frac{k^2 c_s^2}{\omega^2}$$

$$\omega_0 = k\frac{E}{B}, \omega_* = k\frac{T_e}{BL_n}$$

Collisionless **Simon-Hoh instability**

Low frequency solutions $-\frac{\omega_*}{\omega_0} \approx \frac{k^2 c_s^2}{\omega^2}$ are unstable if $\frac{\omega_*}{\omega_0} > 0$

i.e. if electric field and plasma density gradient are in the same direction $\boldsymbol{E}.\boldsymbol{\nabla n} > \boldsymbol{0}$

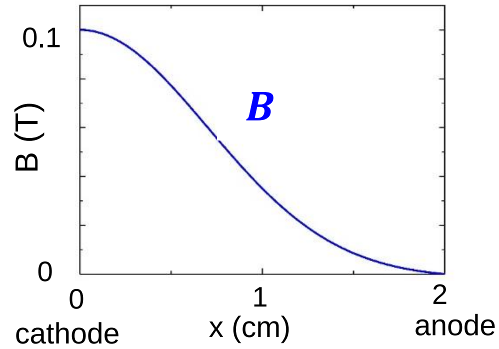
See A. Smolyakov et al., Plasma Phys. Control. Fusion 59 01404041 (2017)

1. Basic physics of $E \times B$ plasmas

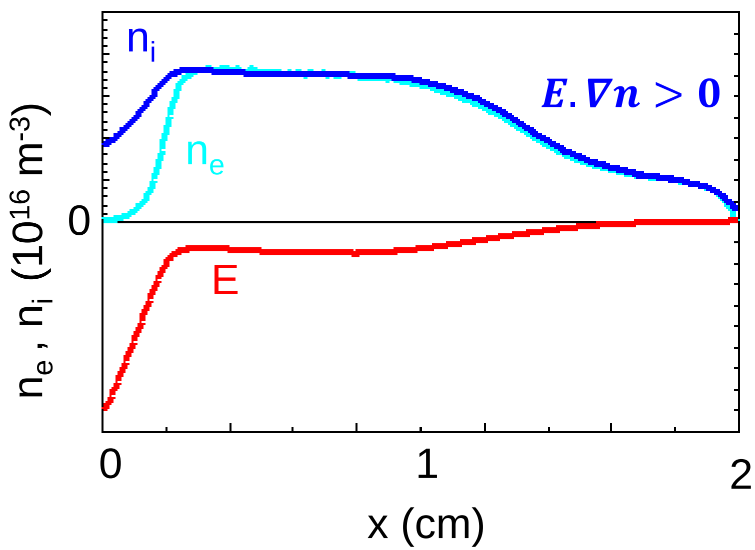
➢ Instabilities and anomalous transport – Dispersion relations

- Example of conditions for Simon-Hoh instability – magnetron discharge

argon – 15 mtorr
2 cm gap
B_{max} = 0.1 T
J_{e0} = 25 mA/m^2
V_a = 260 V (dc)



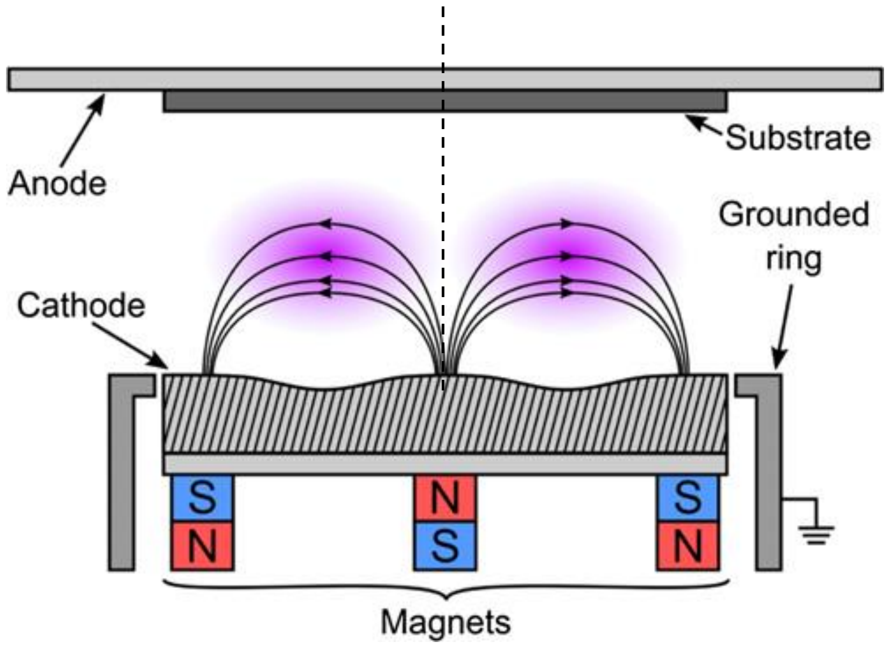
- 1D PIC-MCC model of dc magnetron



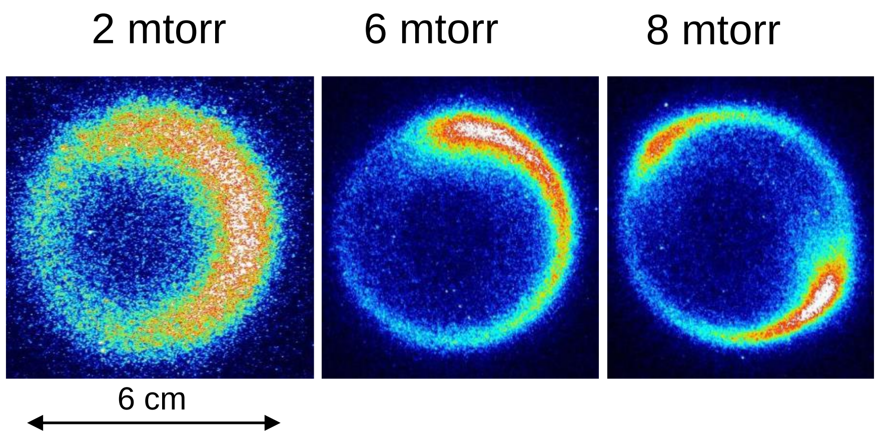
- The 1D solution is stable
- Electric field penetrates in the plasma because of low electron mobility
- A 2D solution including the azimuthal direction is not stable because of Simon-Hoh instability $E.\nabla n > 0$ in the plasma (illustrated below)

2. Closed drift devices

➢ Magnetron discharges



JT Gudmundsson, PSST 29 113001 (2020)

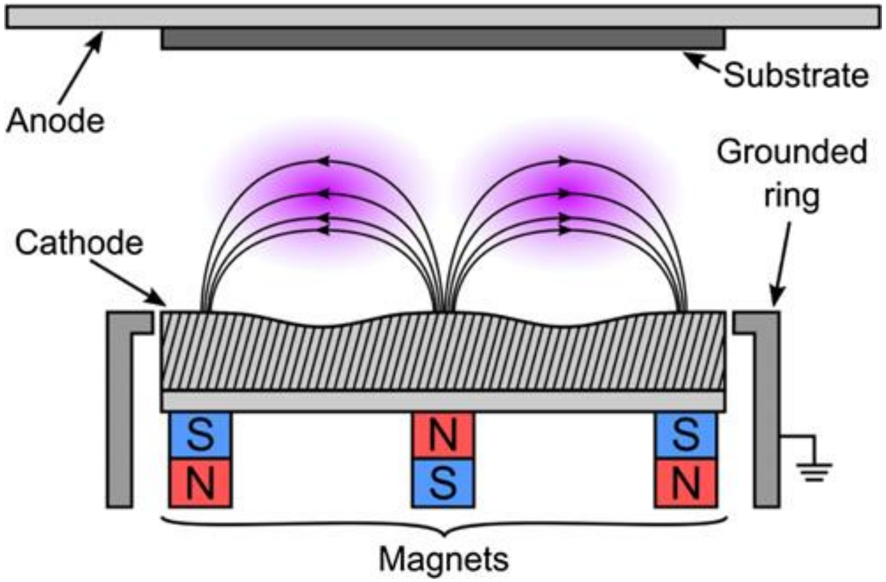


M. Panjan et al., PSST 24 065010 (2015)
M. Panjan, J. Appl. Phys., 125 203303 (2019)

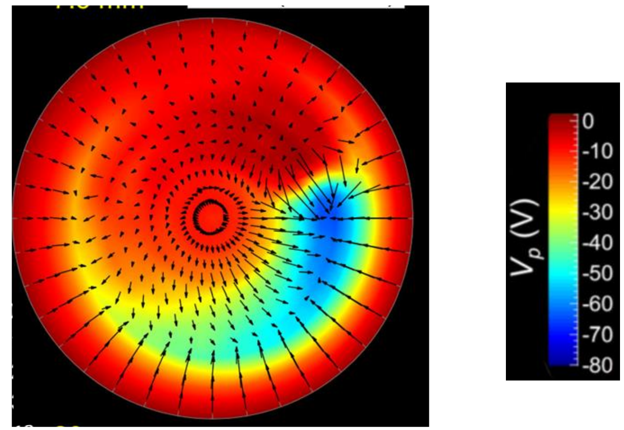
- Discharge is not azimuthally uniform
- Rotating structure (spoke), azimuthal, $-\boldsymbol{E} \times \boldsymbol{B}$ direction, velocity several km/s
- Number of modes increases with pressure

2. Closed drift devices

➢ Magnetron discharges



JT Gudmundsson, PSST 29 113001 (2020)

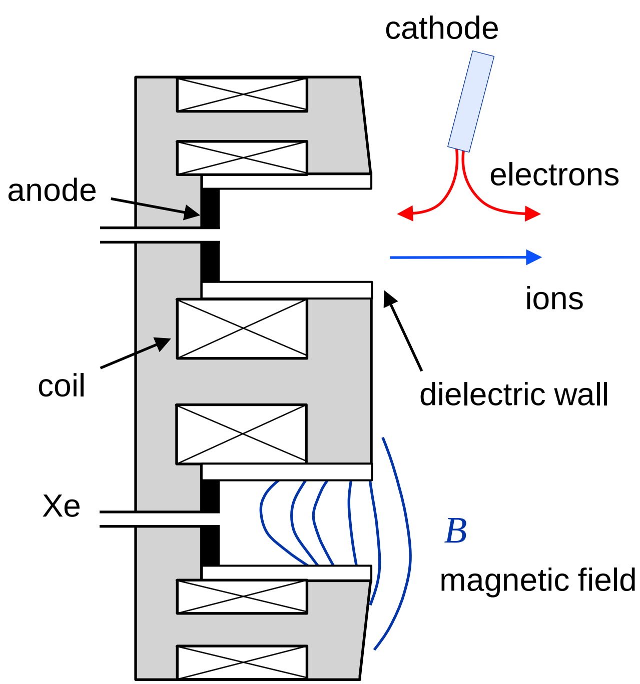


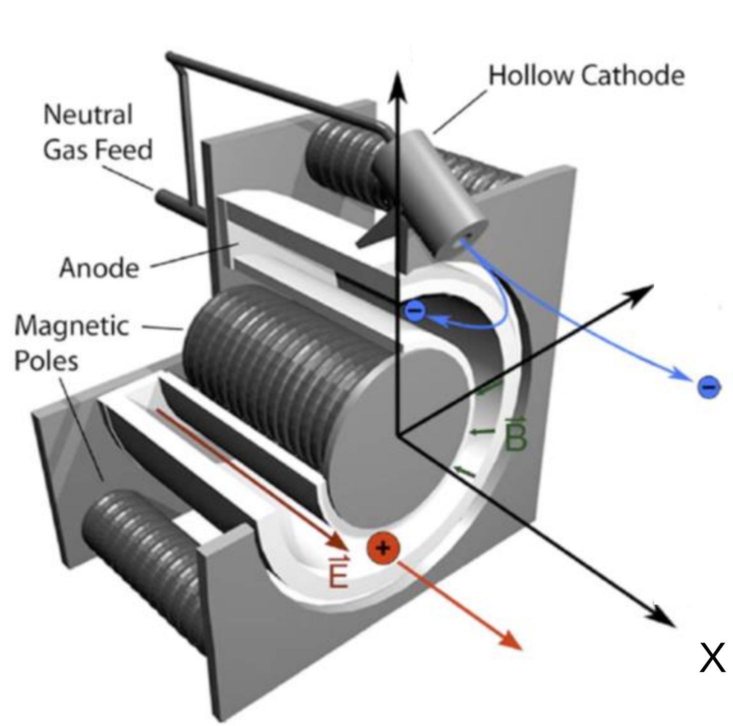
M. Panjan and A. Anders
J. Appl. Phys. 121 063302 (2017)

- Abrupt potential drop at the front of the spoke (several 10s of Volts)
- Attributed to tne formation of a double layer

2. Closed drift devices

➢ Hall thruster

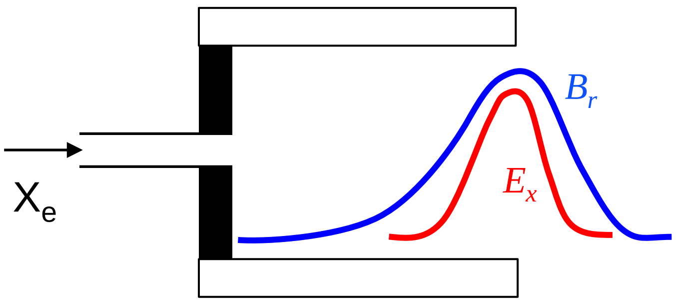




kW thruster: ~ 300 V, 4 A, 5 mg/s Xenon

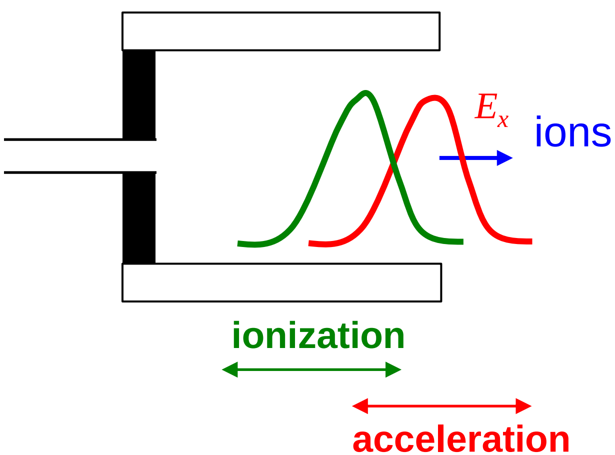
2. Closed drift devices

➢ Hall thruster



$$E_x = \frac{J_e}{\sigma_e} = \frac{J_e}{e^2 n \mu_e}$$

- **Various types of instabilities**
  - Inside channel $\boldsymbol{E}.\boldsymbol{\nabla n} > \mathbf{0}$ → Simon-Hoh, Rotating spoke
  - Outside channel → Electron Cyclotron Drift Instabilty, ECDI, $\boldsymbol{E}.\boldsymbol{\nabla n} < \mathbf{0}$
  - Neutral depletion → « breathing mode »
  - Ion transit time instability
- **Role of dielectric walls**
  - Dielectric walls contribute to cross field transport because of secondary electron emission



3. Modeling of $\boldsymbol{E} \times \boldsymbol{B}$ discharges – Anomalous transport

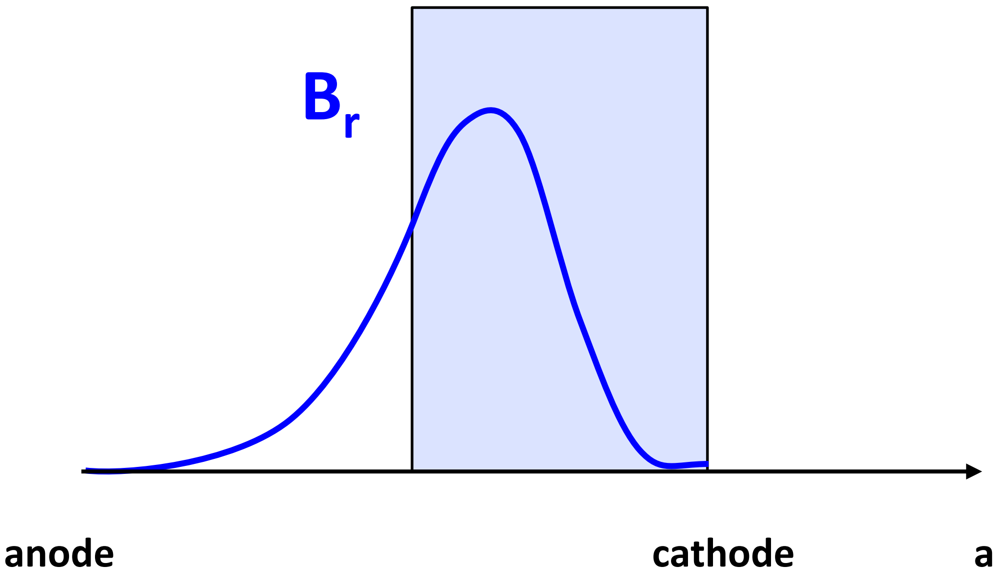
Modeling approaches

- The physics of $\boldsymbol{E} \times \boldsymbol{B}$ plasmas is complex and not completely understood (mainly because of « anomalous electron transport » and strong non-linearity) . Still no predictive models of $\boldsymbol{E} \times \boldsymbol{B}$ devices
- 3D Particle models still extremely expensive → 2D models
- 2D models must contain azimuthal direction to describe $\boldsymbol{E} \times \boldsymbol{B}$ instabilities
- To understand the physics: simplified, or reduced models to study specific types of instabilities: separate different mechanisms, different time scales etc…

3. Modeling of $\boldsymbol{E} \times \boldsymbol{B}$ discharges – Anomalous transport

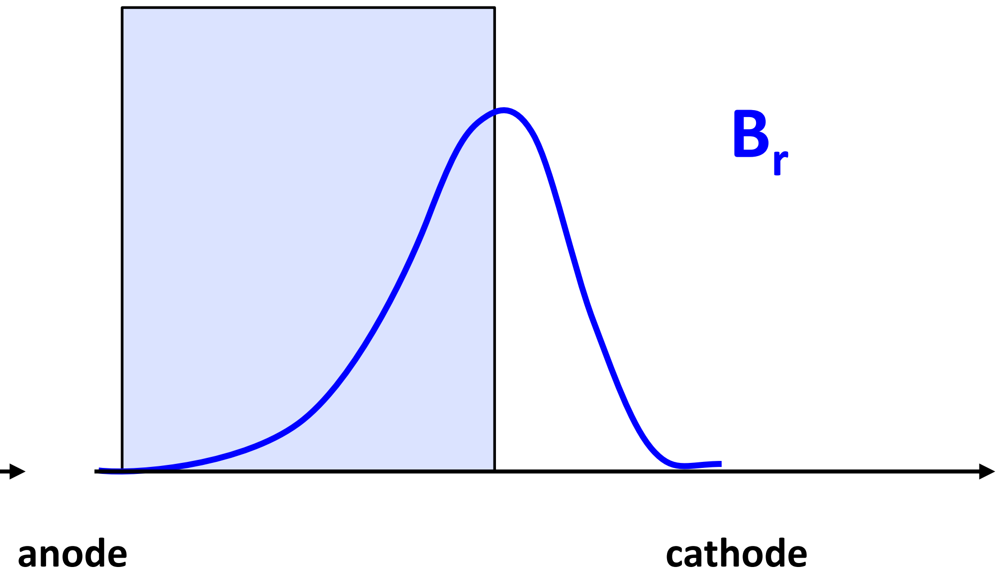
➢ Example 2: 2D PIC MCC axial-azimuthal model of $\boldsymbol{E} \times \boldsymbol{B}$ discharges

Example 1



- Simplied model of exhaust region of Hall thruster
- Collisionless
- Given ionization profile

Example 2

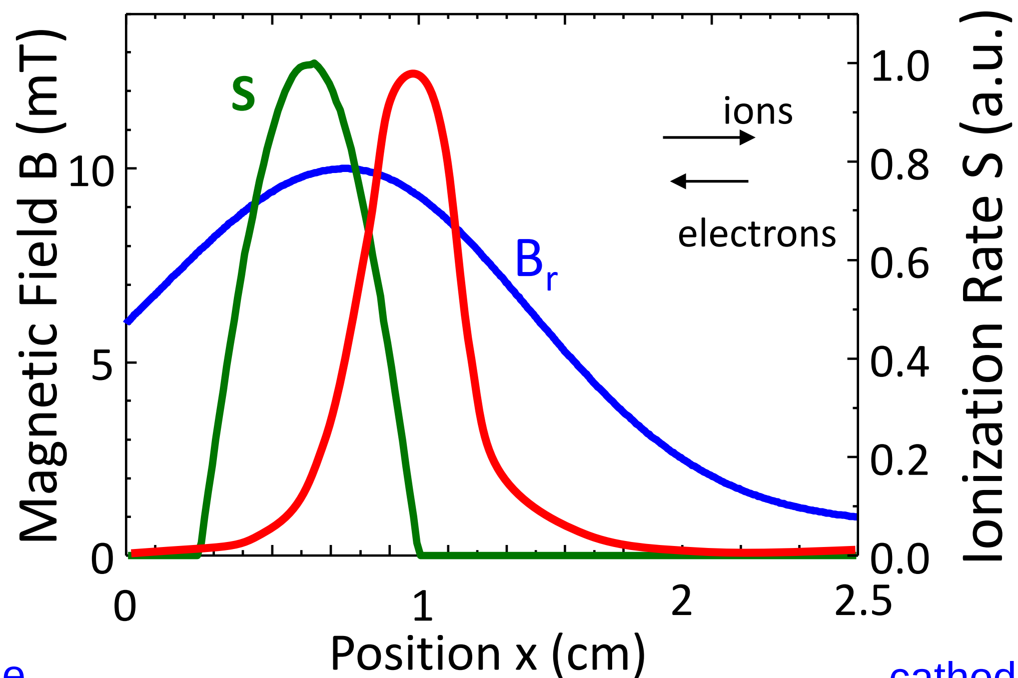


- Simplied model of magnetron or inside channel of Hall thruster
- Collsional
- Self-consistent ionization

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 1: Simplified 2D PIC MCC axial-azimuthal model of Hall thruster

- (x,z) **collisionless** PIC simulation with given source term (ionization rate) and given electron current injected on the cathode side
- Given magnetic field profile and applied voltage (200 V)
- Goal: study cross-field transport between cathode and ionization region



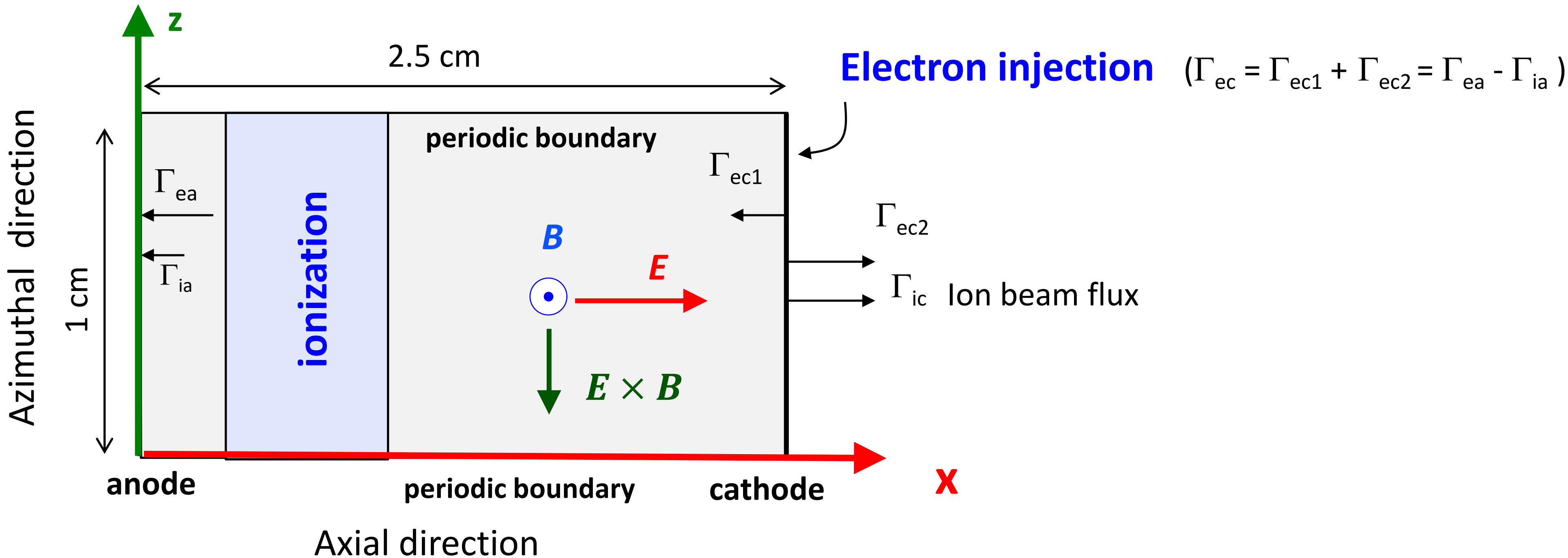
anode side

cathode side

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 1: 2D PIC MCC axial-azimuthal model of Hall thruster

- Rectangular domain with periodic boundary conditions (azimuthal direction)

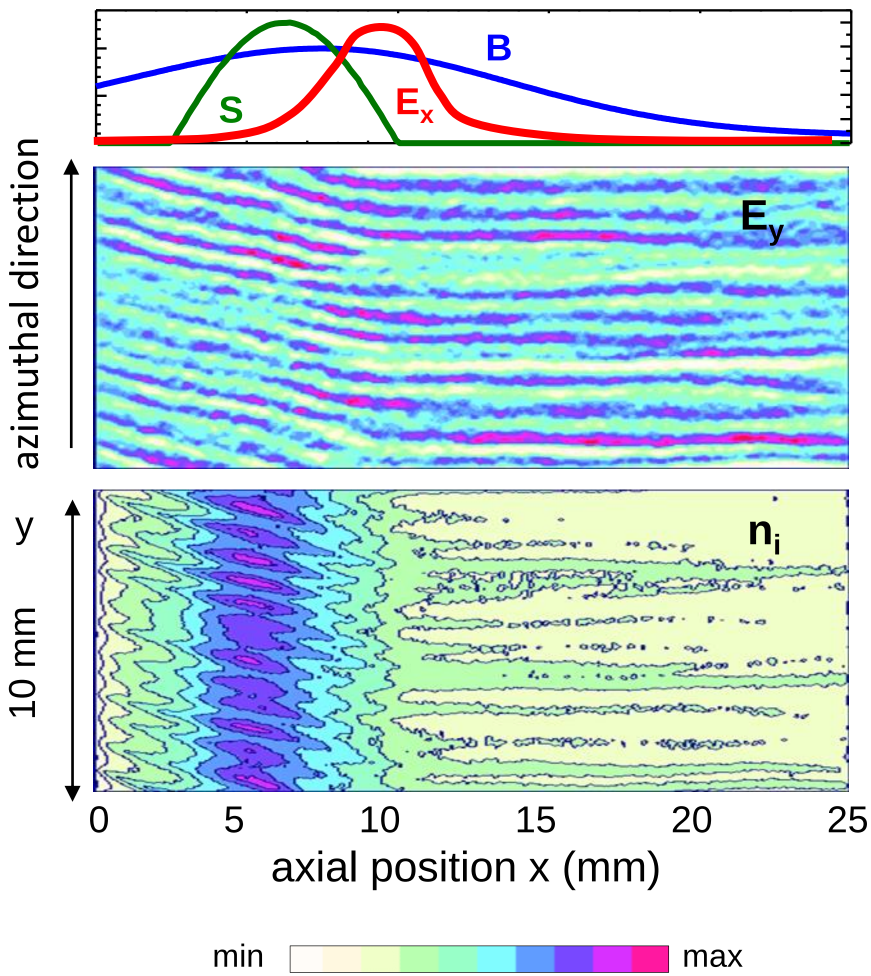


- Typical dimensions (x, y): 2.5 cm x 1 cm

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 1: 2D PIC MCC axial-azimuthal model of Hall thruster

Electron Cyclotron Drift Instability: ECDI



- Collisionless electron transport across B field
- Effective (anomalous) collision frequency: several 10^6 s^{-1}, increases with plasma density
- Effective Hall parameter: several 100

← Azimuthal field E_y [-5×10^4, $+5 \times 10^4$] V/m

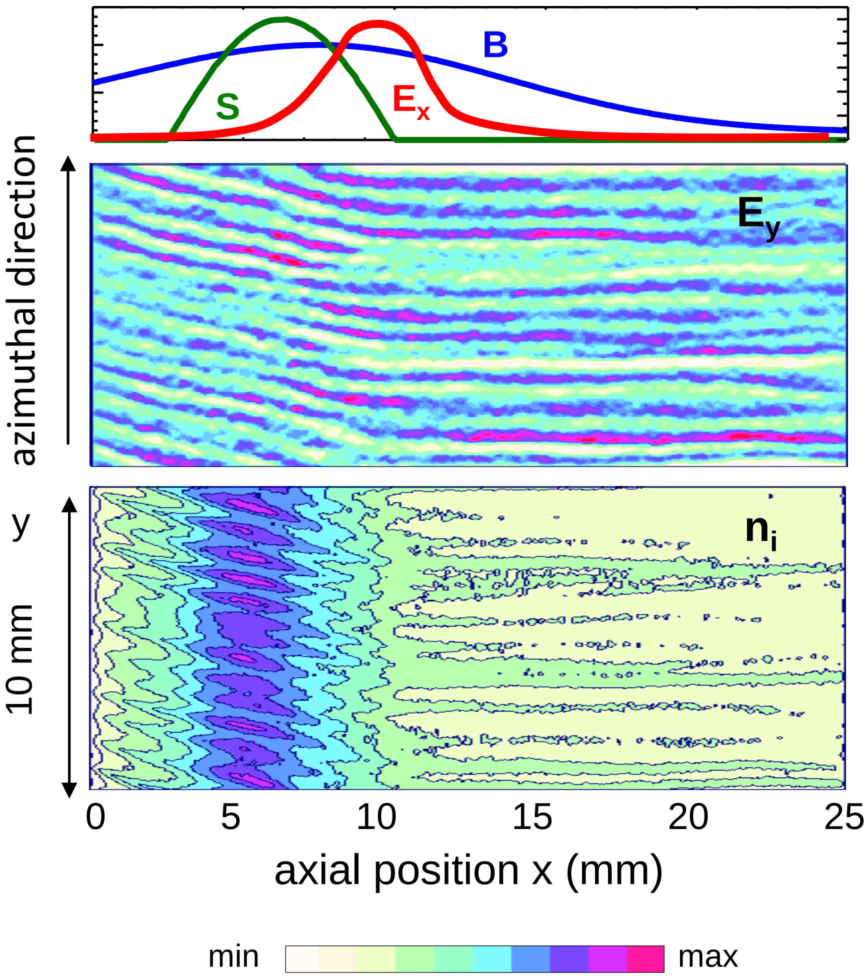
← Positive ion density n_i [0 – 5×10^{17}] m^{-3}

JP Boeuf & L Garrigues, Phys. Plasmas 25 061204 (2018)
T Charoy et al., PSST 28 105010 (2019) (benchmarks)
First evidence of ECDI in Hall thrusters in PIC MCC models:
JC Adam, A Heron, G Laval, Phys. Plasmas 11 295 (2004)
Experiments:
Tsikata et al., Phys. Plasmas 16 033506 (2009)

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ **Example 1: 2D PIC MCC axial-azimuthal model of Hall thruster**

Electron Cyclotron Drift Instability: ECDI

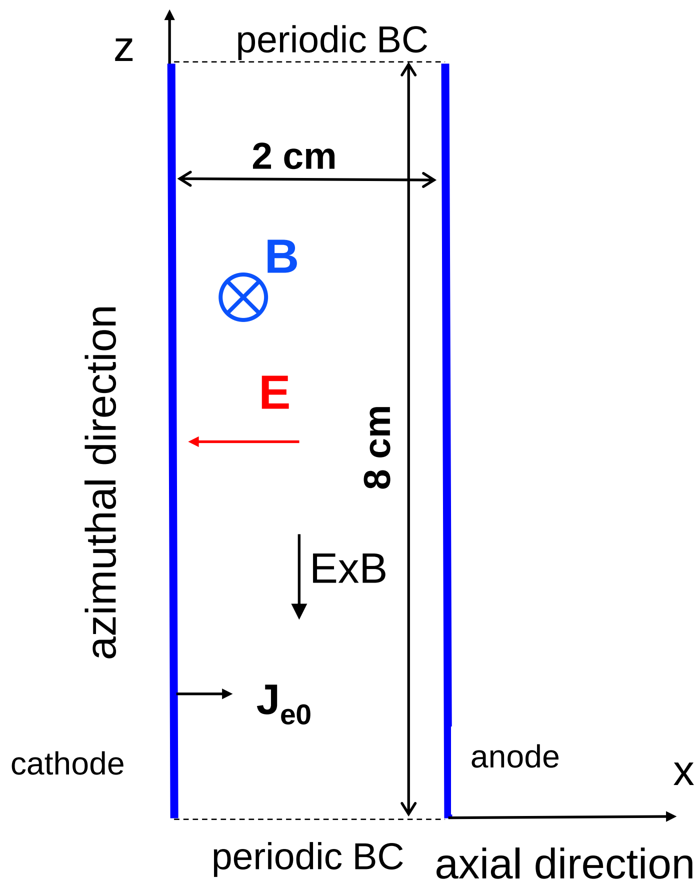


- Wavelength of the instability ~1 mm
- Wave velocity ~ 5×10^3 m/s
- Wave angular frequency ~ 3×10^7 rd/s

3. Modeling of $E \times B$ discharges – Anomalous transport

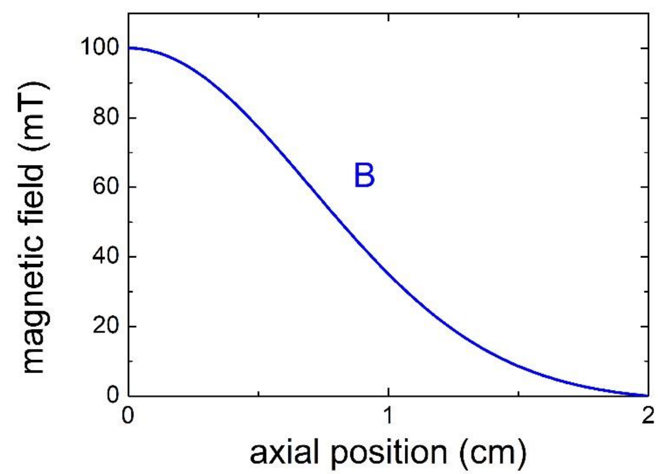
➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron

- 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 ($n_e=n_i=5\times10^{14}$ m^{-3})

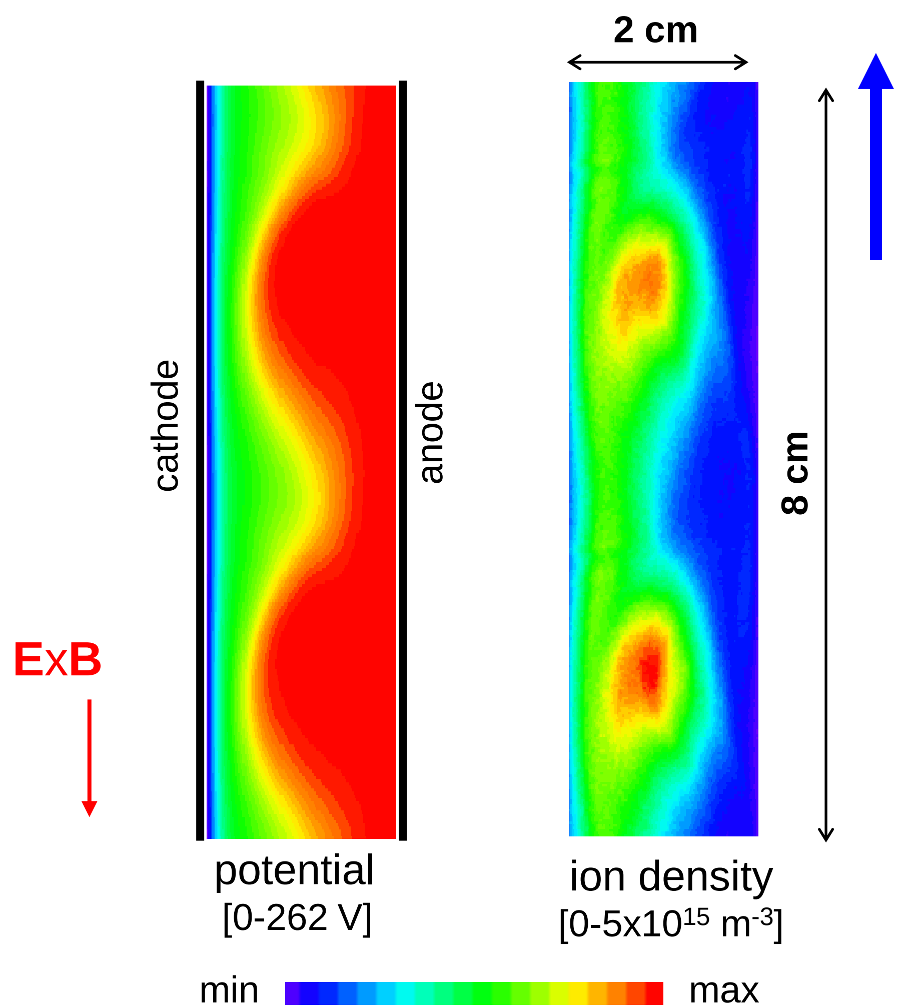
Conditions similar to experiment of T Ito, CV Young, & MA Cappelli, Appl. Phys. Lett. 106, 254104 (2015)



3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge

○ Time evolution of electric potential and ion density



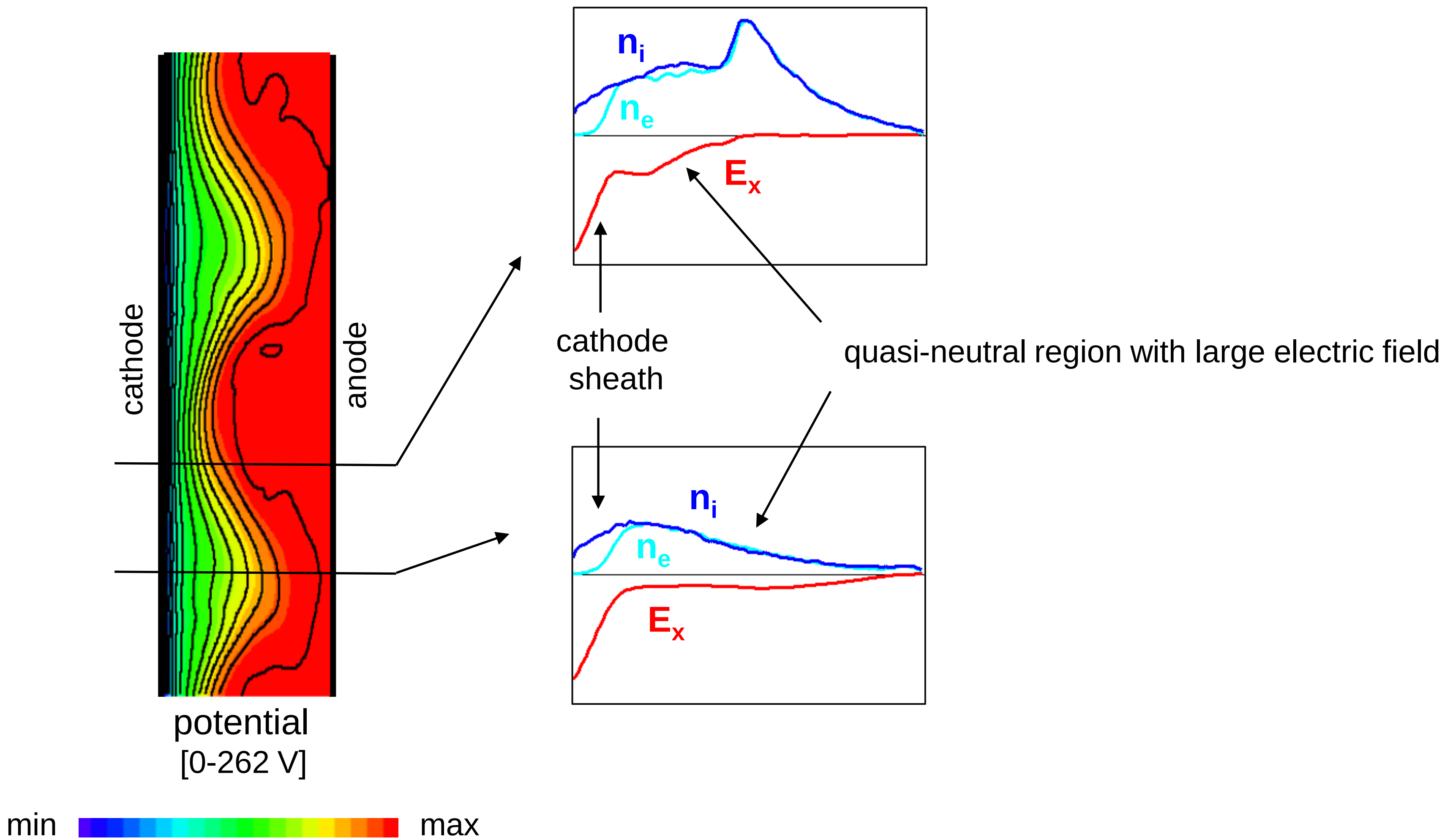
- Formation of azimuthal non-uniformities
- Wave moving in the azimuthal, -ExB direction
- Velocity v ~ 10 km/s consistent with exp,
- Long wavelength, ~3 cm

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

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ **Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge**

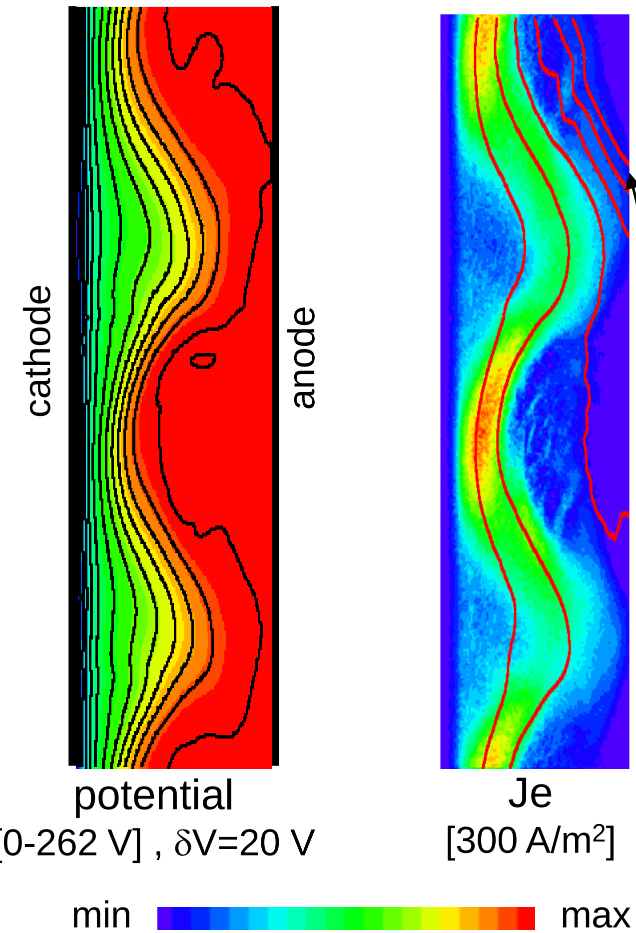
○ Electric potential – E field penetration in quasineutral plasma



3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge

○ 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 <u>interface</u> between low field region and larger field region

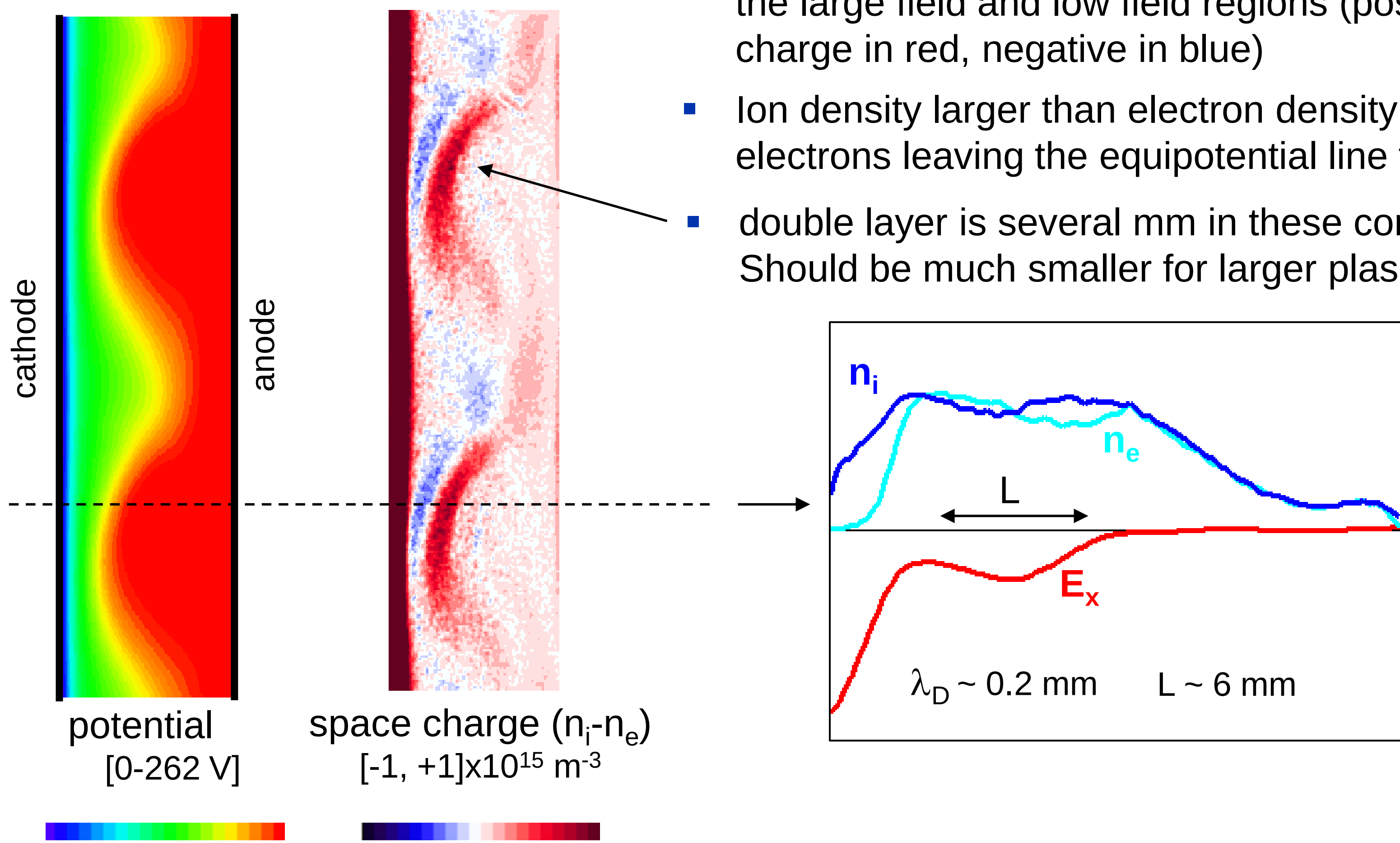
- The electric potential distribution creates a kind of « short-circuit » allowing electrons to reach the anode in spite of the strongly reduced axial mobility

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge

○ Electric potential – Space charge

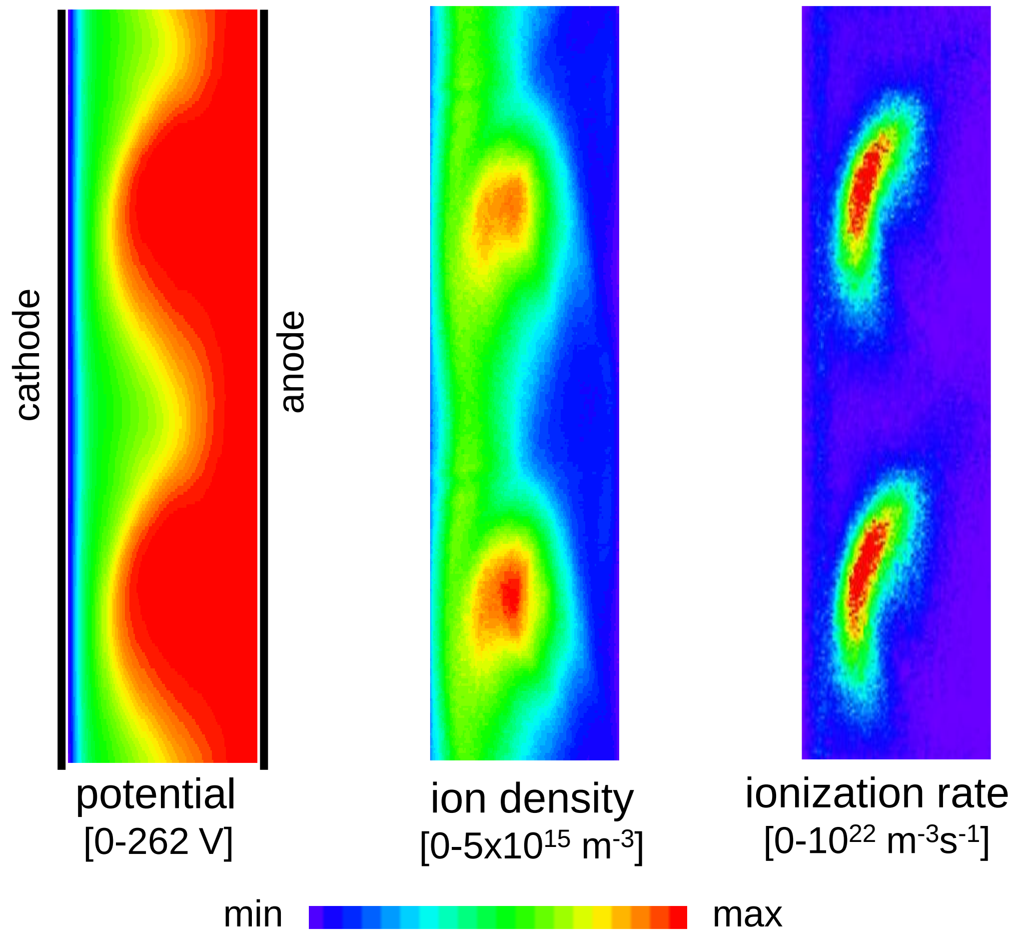
- Formation of a **double layer** at the interface between the large field and low field regions (positive space charge in red, negative in blue)
- Ion density larger than electron density because electrons leaving the equipotential line to anode region
- double layer is several mm in these conditions.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



3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge

○ Electric potential – Ion density – Ionization rate

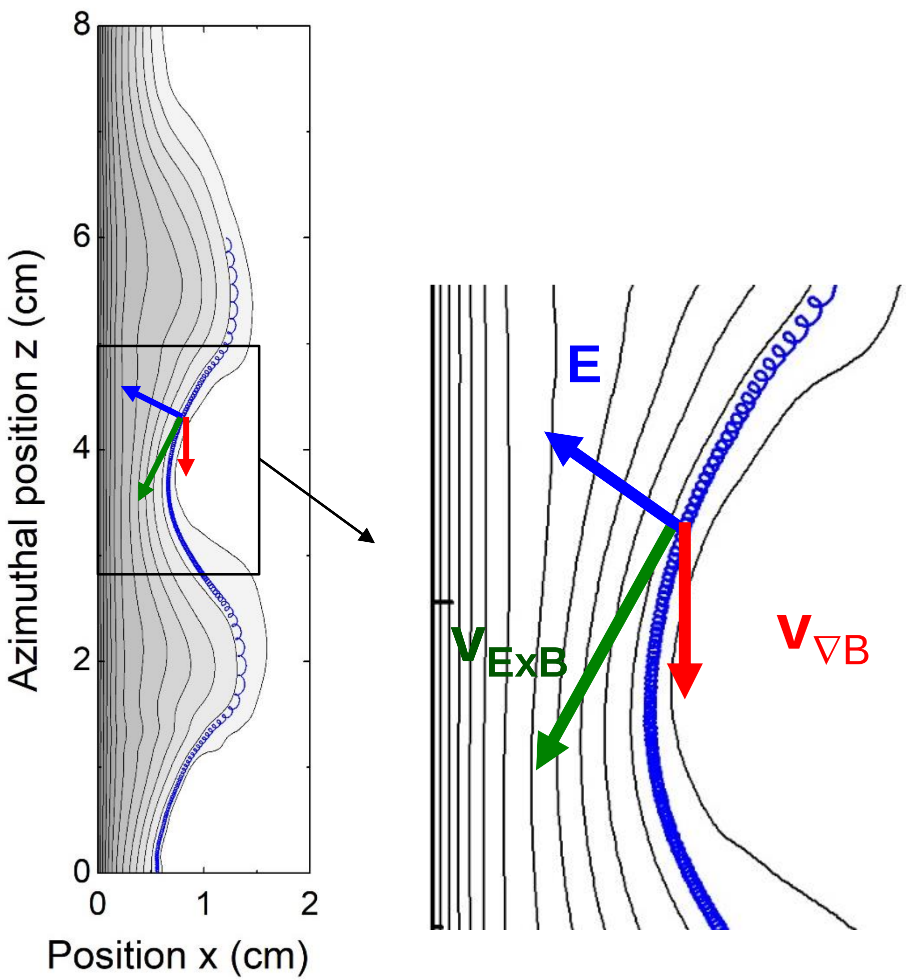


- Distribution of ionization rate close to distribution of emitted light → spoke is an ionization wave
- Spoke is located in the double layer, above the maximum plasma density → moves up, i.e. in the –ExB direction
- Ionization rate is much larger in the spoke than in the cathode sheath
- What are the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

3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge

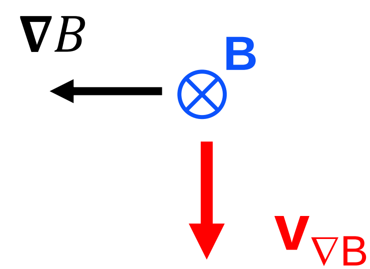
- Electron heating in the spoke



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

Grad B drift velocity $\boldsymbol{v_{\nabla B}}$

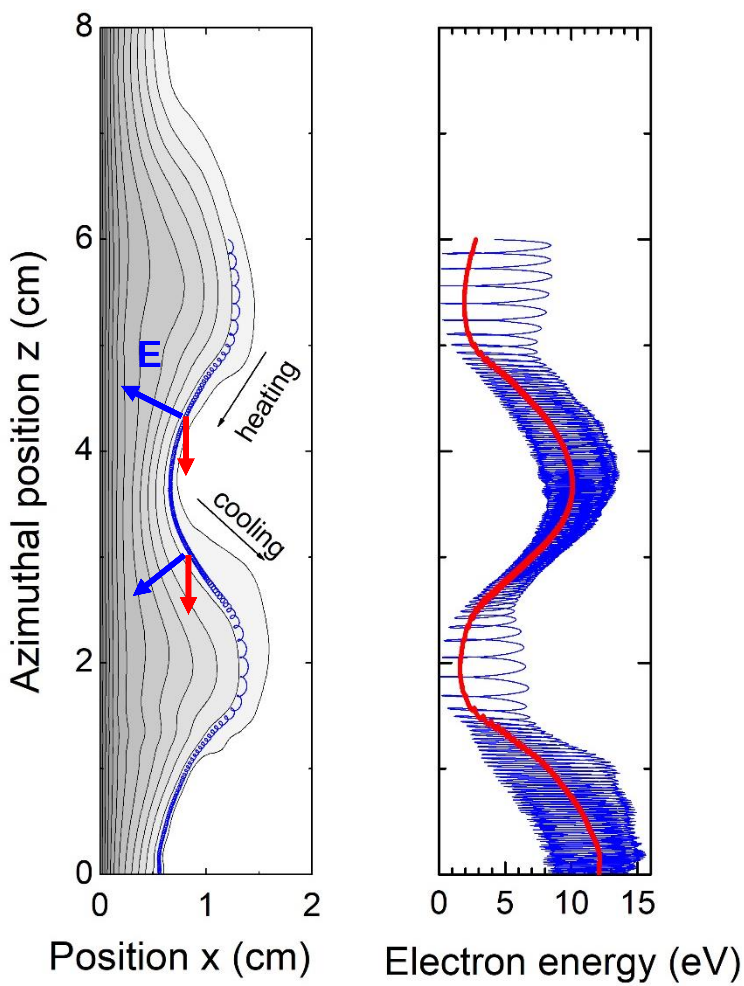
$$\boldsymbol{v}_{\nabla B} = 1/2\ \rho_e v_\perp \boldsymbol{B} \times \nabla B / B^2$$



3. Modeling of $E \times B$ discharges – Anomalous transport

➢ Example 2: 2D PIC MCC axial-azimuthal model of a magnetron discharge

○ 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

- $E \times B$ configurations are used to confine electrons and generate plasmas at low (mtorr) pressures e.g. in ion sources, ion thrusters for space propulsion, magnetron discharges for sputtering-deposition
- The physics of $E \times B$ discharges is rich and complex, and not fully understood
- Important recent progress in the understanding of $E \times B$ plasmas. Synergy between different approaches: theory, experiments, fluid models, kinetic models.
- Work is still needed to develop models with predicting capabilities
- LTP community is organizing itself to identify critical questions and suggest directions for future research

$\rightarrow$ ***Physics of $E \times B$ discharges relevant to plasma propulsion and similar technologies*, Phys.Plasmas 27, 120601 (2020)**

Igor D. Kaganovich, Andrei Smolyakov, Yevgeny Raitses, Eduardo Ahedo, Ioannis G. Mikellides, Benjamin Jorns, Francesco Taccogna, Renaud Gueroult, Sedina Tsikata, Anne Bourdon, Jean-Pierre Boeuf, Michael Keidar, Andrew Tasman Powis, Mario Merino, Mark Cappelli, Kentaro Hara, Johan A. Carlsson, Nathaniel J. Fisch, Pascal Chabert, Irina Schweigert, Trevor Lafleur, Konstantin Matyash, Alexander V. Khrabrov, Rod W. Boswell, and Amnon Fruchtman