Modélisation des décharges plasmas froids à basse pression

(Modeling of low pressure plasma discharges)

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Modelling of low-temperature plasmas

- Particles described separately per species
  - Electrons : energy absorption & ionization
  - Ions : influence electron motion, surface treatment
  - Excited neutrals : stepwize ionization, plasma chemistry
  - Gas neutrals

- Classical mechanics
  - Particle approach : Newton's equations + averaging
  - Macroscopic approach : fluid equations

- Electromagnetic interaction described via Maxwell equations
  - Electron-ion coupling : Poisson equation
  - Applied field : DC, RF, pulsed, microwave

- Collisions treated by input data from experiments & quantum-mechanics

  Cross sections, transport coefficients, rate coefficients

  Mainly with gas

  Many uncertainties / unknowns

Particle approach

- Sample individual particles from total population
- Simulate trajectories
- Take statistical averages

- Newton's equations of motion:

$$\frac{d\mathbf{x}}{dt} = \mathbf{v} \qquad \frac{d\mathbf{v}}{dt} = \frac{q}{m}\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

macroscopic fields due to collective particles (plasma + external)

Self-consistent description of plasma fields requires to follow a large number of particles simultaneously, e.g. PIC method

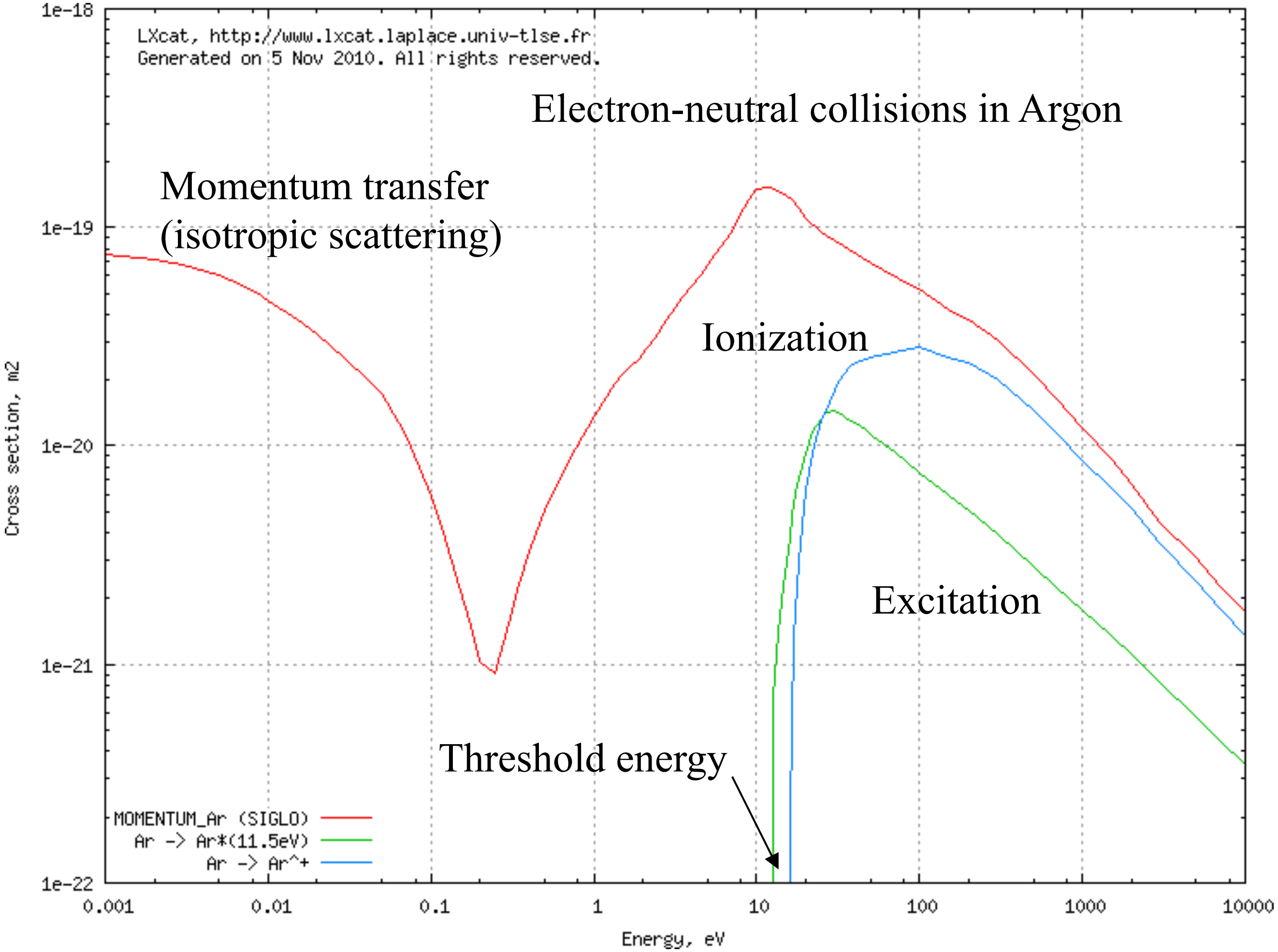
- Collision sampling from probability distributions (Monte Carlo)

collision probability per unit time:
(= collision frequency)

$$\nu = N\sigma(v_{\text{rel}})\,v_{\text{rel}}$$

target density — cross section — relative velocity

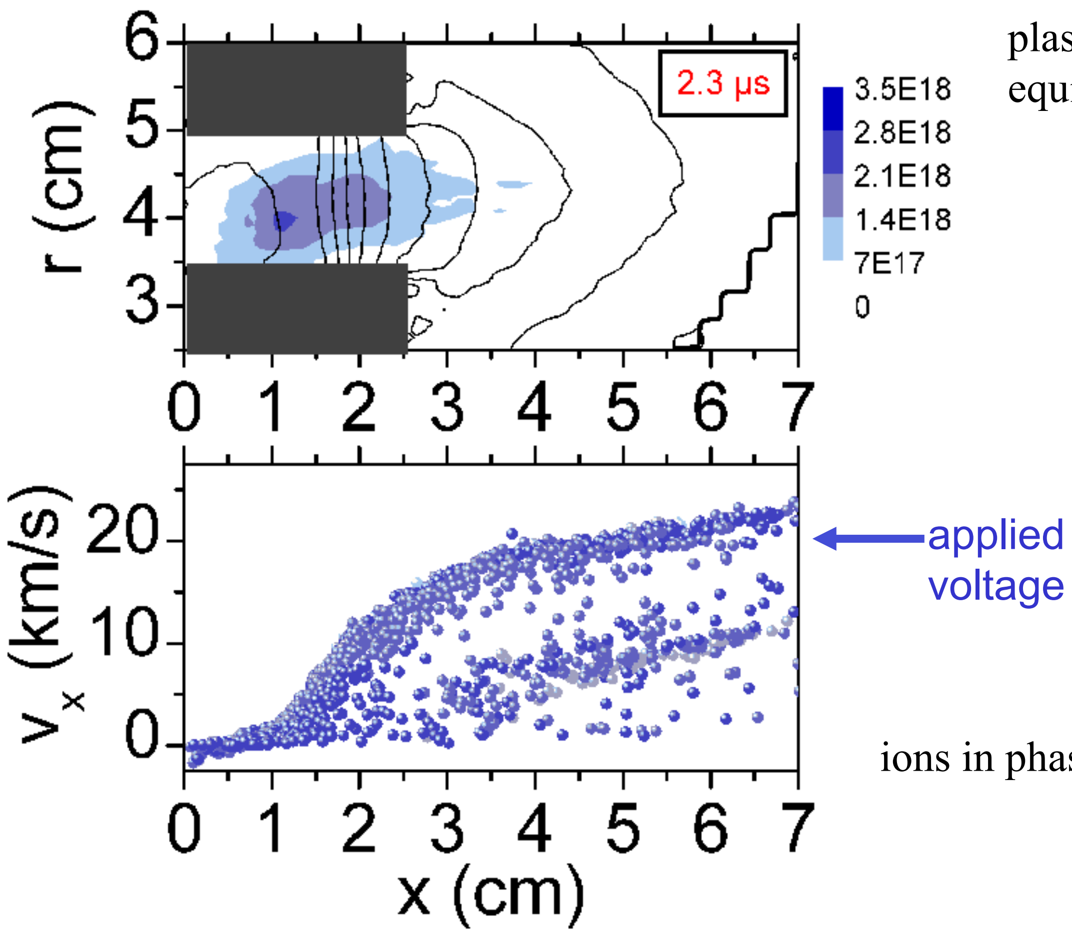
Cross sections



Electron laboratory energy ≅ relative energy $\varepsilon = \frac{1}{2} m_e v_e^2 \cong \frac{1}{2} m_{\text{red}} v_{\text{rel}}^2$

Hall-effect thuster simulation

Discharge shows instabilities, e.g. transit time oscillations:



plasma density &
equipotential lines

Ion energy can
exceed applied
voltage

ions in phase space

(thesis Jerome Barreilles)

Boltzmann equation

- Distribution function $f(t, \mathbf{x}, \mathbf{v})$ = density of particles in phase space

- Spatio-temporal evolution of f described by Boltzmann equation:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_{\mathrm{v}} f = C[f]$$

← collision operator

- Simplify by approximations:
  - Homogeneous approach
  - Nonlocal approach
  - Two-term velocity expansion
  - Velocity-moment approach (fluid equations)
  - …

Homogeneous Boltzmann equation

- Electrons in homogeneous field in state steady:

Spherical harmonics expansion

$$f(\mathbf{x}, \mathrm{v}, t) \cong f_0(v) + \cos\theta \, f_1(v) + \ldots$$

isotropic component (= EEDF) — $f_0(v)$; angle with E — θ; anisotropic component — $f_1(v)$

- Two-term homogeneous Boltzmann equation:

$$-\frac{e^2 (E/N)^2}{3 m_e^2} \frac{\partial}{\partial v}\left(\frac{v}{\sigma_m} \frac{\partial f_0}{\partial v}\right) = C_0[f_0] \qquad f_1 = \frac{e(E/N)}{m_e \sigma_m v} \frac{\partial f_0}{\partial v}$$

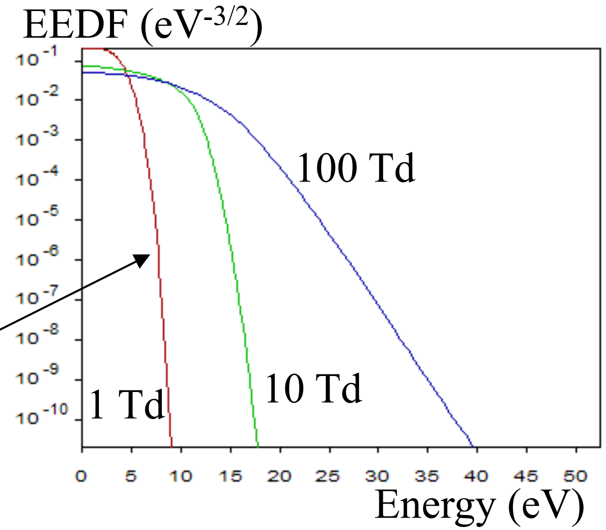
- Yields velocity distribution and all velocity-related quatities (EEDF, mean velocity, mean energy, rate coefficients) as a function of reduced field E/N

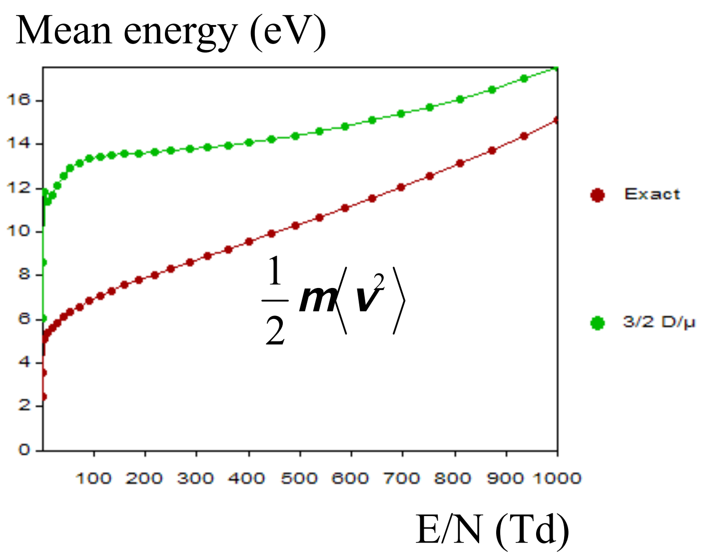
Homogeneous BE results in Argon

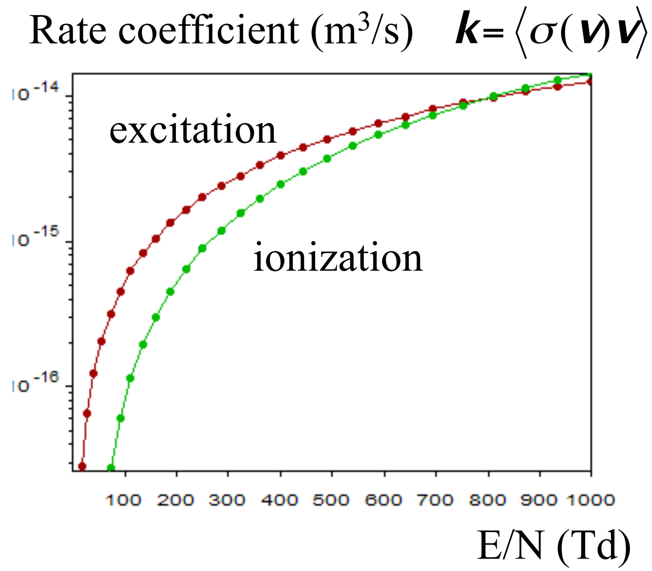
Freeware code BOLSIG+

www.bolsig.laplace.univ-tlse.fr

Non-Maxwellian EEDF!







Fluid approach

- Macroscopic quantities, averaged over velocity space

Particle density: $$n(\mathbf{x},t) = \iiint f(\mathbf{x},\mathbf{v},t)\, d^3\mathbf{v}$$

Mean velocity: $$\mathbf{w} = \langle \mathbf{v} \rangle = \frac{1}{n}\iiint \mathbf{v} f\, d^3\mathbf{v}$$

Mean energy: $$\varepsilon = \frac{m}{2e}\langle v^2 \rangle = \frac{m}{2en}\iiint v^2 f\, d^3\mathbf{v}$$

- Macroscopic transport equations = velocity moments of BE

$$\iiint \left(\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f + \frac{q}{m}(\mathbf{E} + \mathbf{v}\times\mathbf{B})\cdot\nabla_{\mathbf{v}} f \right) \mathbf{v}^m d^3\mathbf{v} = \iiint C[f]\,\mathbf{v}^m d^3\mathbf{v}$$

Fluid equations

- Continuity equation: particle conservation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{w}) = S \qquad S = \sum_i N_i n_{1i} n_{2i} k_i \qquad k_i = \langle \sigma_i(v) v \rangle$$

flux (↑ $n\mathbf{w}$), source (↑ S), rate coefficient (k_i)

- Momentum equation:

$$m\frac{\partial n\mathbf{w}}{\partial t} + m\nabla \cdot (n\mathbf{w} \otimes \mathbf{w}) + \nabla \cdot \mathbf{P} - qn(\mathbf{E} + \mathbf{w} \times \mathbf{B}) = -m\bar{\nu}_m n\mathbf{w}$$

collisions; momentum transfer frequency (↓ $\bar{\nu}_m$); inertia; pressure tensor: $\mathbf{P} = m\int (\mathbf{v} - \mathbf{w}) \otimes (\mathbf{v} - \mathbf{w})\, f\, d^3\mathbf{v}$

- Short mean free path: drift-diffusion approximation:

$$\text{flux} \quad n\mathbf{w} = \frac{q}{m\bar{\nu}_m} n\mathbf{E} - \frac{e}{m\bar{\nu}_m} \nabla(nT) \equiv \frac{q}{|q|} \mu n\mathbf{E} - \nabla(Dn)$$

mobility (↑ μ), diffusion coefficient (↑ D)

Minimal self-consistent model (high pressure)

- Electron & ion continuity:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{w}_e) = K N n_e \qquad \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{w}_i) = K N n_e$$

- Electron & ion drift-diffusion:

$$n_e \mathbf{w}_e \equiv -\mu_e n_e \mathbf{E} - D_e \nabla n_e \qquad n_i \mathbf{w}_i \equiv \mu_i n_i \mathbf{E} - D_i \nabla n_i$$

- Poisson (ambipolar + applied field):

$$\varepsilon_0 \nabla \cdot \mathbf{E} = -\varepsilon_0 \nabla^2 \Phi = e n_i - e n_e \qquad \mathbf{E} = -\nabla \Phi$$

- Local field approximation: transport coefficients and ionization rate are functions of reduced field E/N (from experiments are homogeneous BE)

- Boundary conditions for the particle fluxes

Boundary conditions

- Particle flux toward the wall

net flux → $nw_\perp = nw_w - \Gamma_w$ ← particles coming from wall due to reflection and creation (emission)

(nw_w: particles moving to the wall)

- Effective velocity of incident particles obtained from kinetic considerations

$$w_w = \frac{1}{4}\sqrt{\frac{8eT}{\pi m}} + \max\left(\mathrm{sgn}(q)\mu E_\perp, 0\right)$$

(↑ $\frac{1}{4}$: ¼ or ½ or ?)

- Flux coming from the wall obtained from incident fluxes

$$\Gamma_w = \sum_s \gamma_s n_s w_{w,s}$$

(γ_s: emission coefficient; $\sum_s$: sum over all species)

- Equating to drift-diffusion → mixed boundary condition, e.g.

$$\left(\mathrm{sgn}(q)\mu E_\perp - w_w\right)n - D\nabla_\perp n + \Gamma_w = 0$$

Numerics

- Integrate equations sequentially in time $t^{k+1} = t^{k} + \Delta t$
- Implicit update of drift-diffusion flux:

k = time index

$$\frac{n^{k+1} - n^{k}}{\Delta t} + \nabla \cdot \left(\pm \mu \mathrm{E} n^{k+1} - D \nabla n^{k+1} \right) = S$$

No CFL time step constraints $\Delta t < \left(W / \Delta x + 2D / \Delta x^2 \right)^{-1}$ (crossed out)

- Exponential scheme for drift-diffusion flux:

i = space index

$$\left(Wn - D \frac{\partial n}{\partial x} \right)_{i+1/2} = \frac{W_{i+1/2}}{1 - \exp(-z)} n_i + \frac{W_{i+1/2}}{1 - \exp(z)} n_{i+1}$$

$$z = \frac{W_{i+1/2} \Delta x}{D_{i+1/2}} = \frac{\pm \mu E_{i+1/2} \Delta x}{D_{i+1/2}}$$

For electrons in ambipolar sheath:
drift ≈ diffusion → Boltzmann relation: $\frac{n_{i+1}}{n_i} = \exp(z) \cong \exp\left(\frac{\Phi_{i+1} - \Phi_i}{T} \right)$

Semi-implicit Poisson method

- Charged particle transport strongly coupled with Poisson equation:

$$\nabla^2 \Phi^{k+1} = \frac{e}{\varepsilon_0}(n_e - n_i)$$

$$\frac{n^{k+1} - n^k}{\Delta t} + \nabla \cdot \left(\mp \mu n^{k+1} \nabla \Phi^{k+1} - D \nabla n^{k+1} \right) = S$$

Coupling time constant
(Maxwell relaxation time)

$$\tau_\mathrm{d} = \frac{\varepsilon_0}{e(\mu_e n_e + \mu_i n_i)} \cong \frac{\varepsilon_0}{e \mu_e n_e}$$

- Avoid time step constraint $\Delta t < \tau_\mathrm{d}$ by space charge prediction:

$$\nabla^2 \Phi^{k+1} = \frac{e}{\varepsilon_0}(\tilde{n}_e^{k+1} - \tilde{n}_i^{k+1}) \qquad \tilde{n}^{k+1} = n^k + \Delta t \left(S - \nabla \cdot \left(\mp \mu n^k \nabla \Phi^{k+1} - D \nabla n^k \right) \right)$$

Modified Poisson equation:

$$\nabla \cdot \left((1+\chi) \nabla \Phi^{k+1} \right) = \nabla \cdot \left(\chi \nabla \Phi^k \right) + \frac{e}{\varepsilon_0}\left(2 n_e^k - n_e^{k-1} - 2 n_i^k + n_i^{k-1} \right)$$

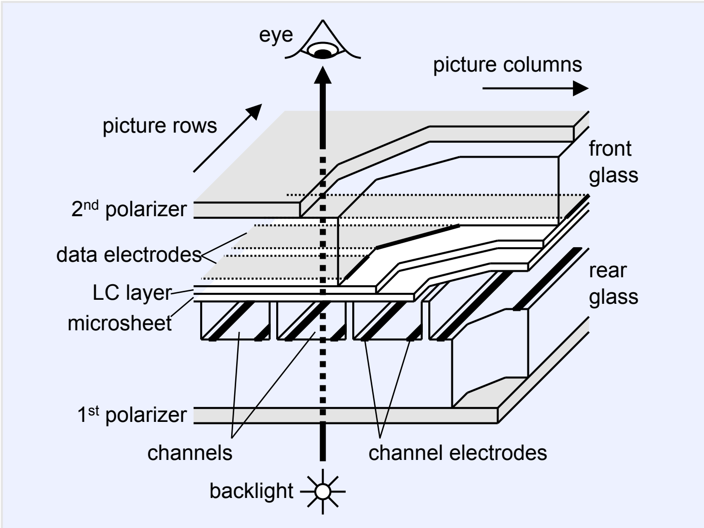
Extrapolated space charge density

Semi-implicit susceptibility: $\chi = \frac{e \Delta t}{\varepsilon_0}(\mu_e n_e + \mu_i n_i) = \frac{\Delta t}{\tau_\mathrm{d}}$

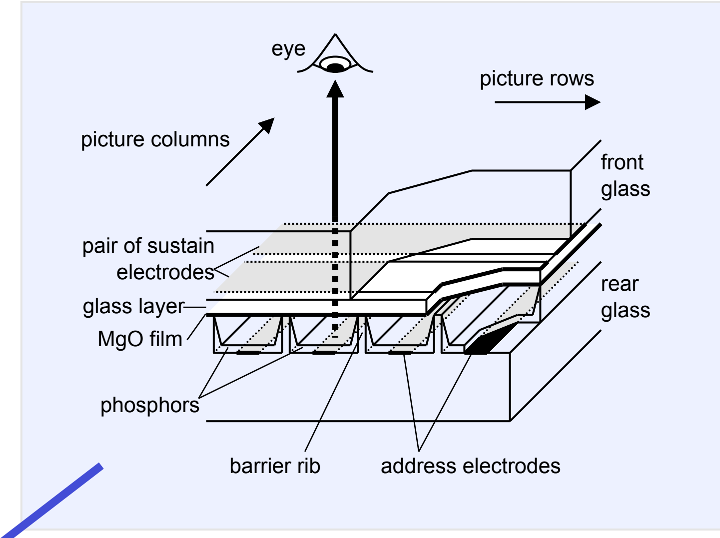
Semi-implicit terms cancel in steady state!

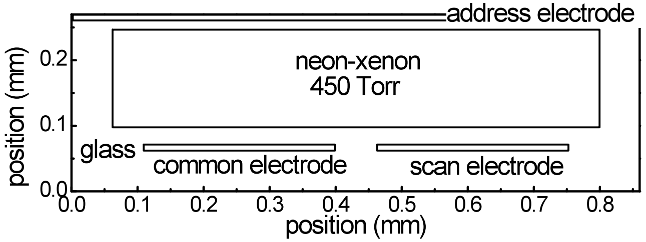
Microdischarges for display technology

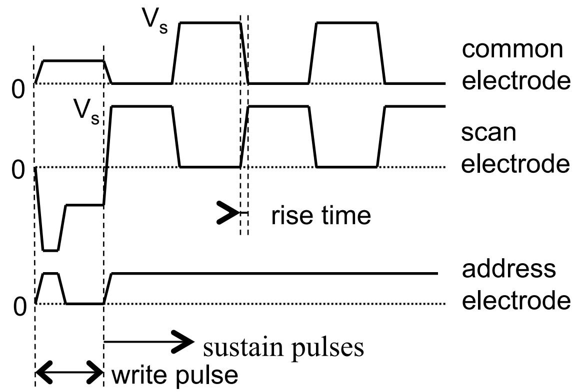
Plasma Adressed Liquid Crystal
(Philips Eindhoven 1995-1998)



Plasma Display Panel (PDP)
(Philips Aachen 1998-2001)





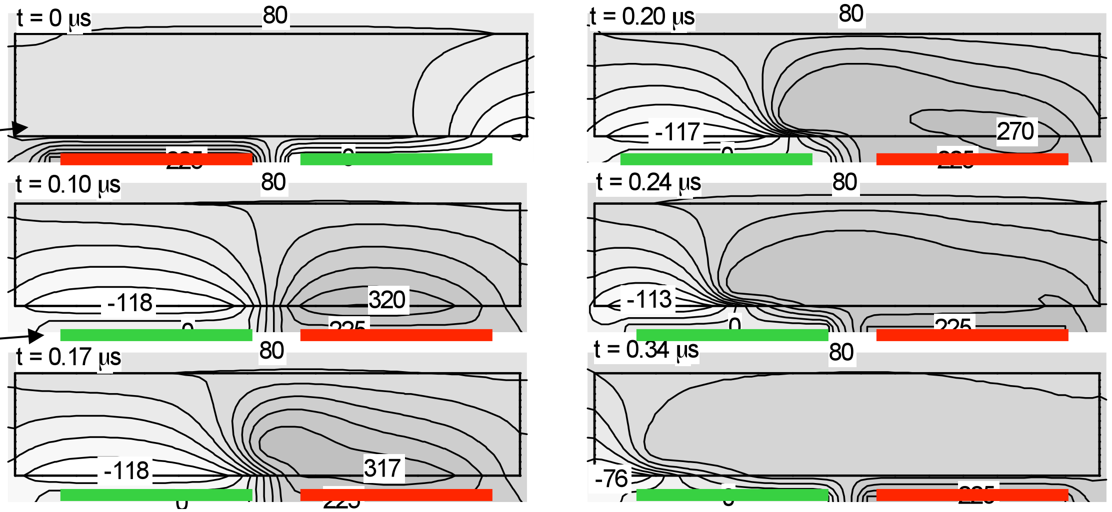


Coplanar PDP simulation

Electric potential

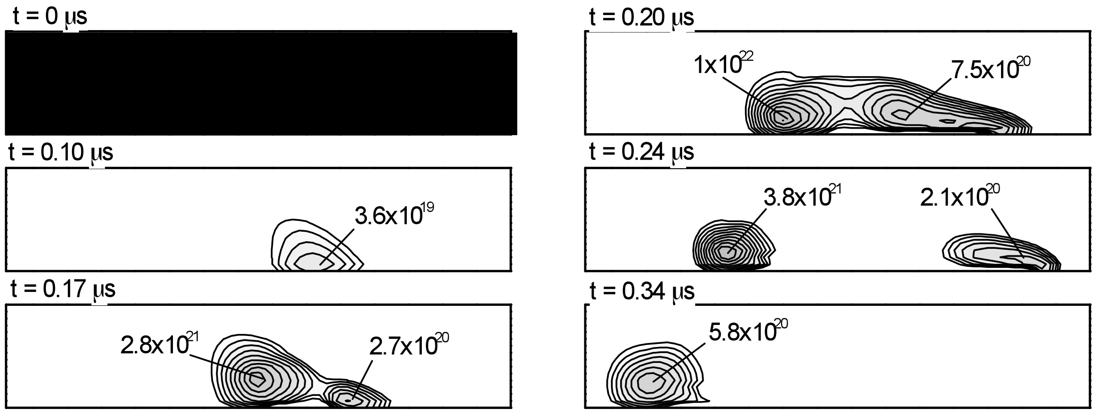
Field screened by surface charges from previous discharge

Polarity change creates new discharge



Discharge stopped by surface charges

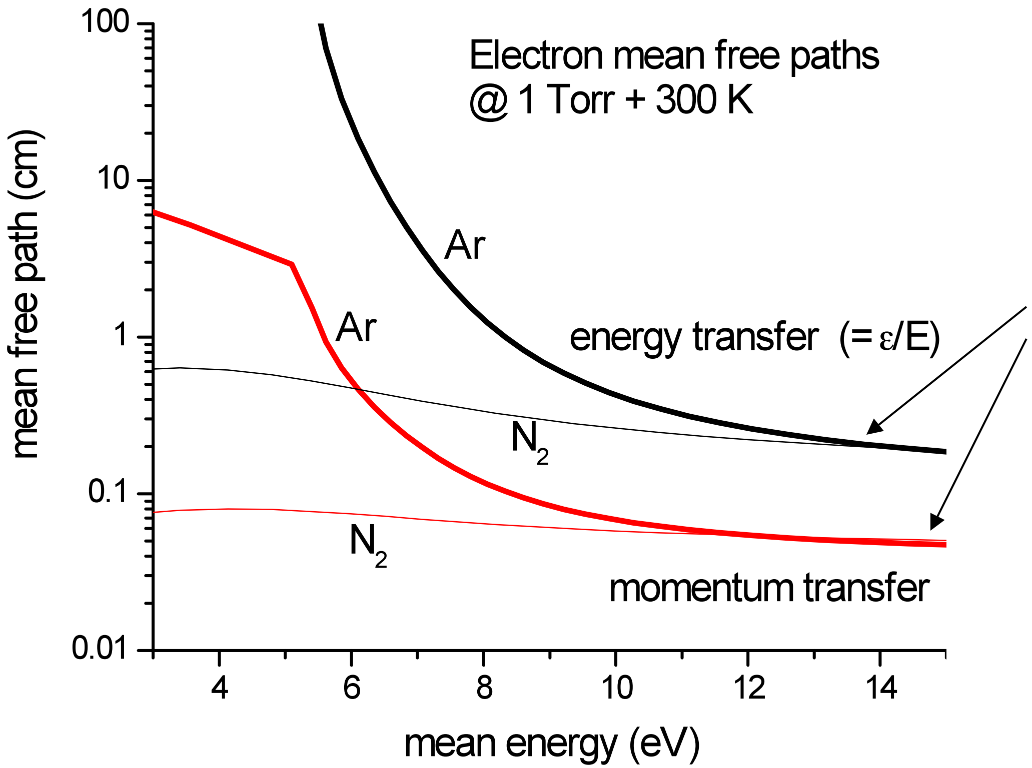
UV emission rate



Low pressure

Compare mean free path with macroscopic length scales (plasma size etc)

Mfp inversely proportional to pressure



Electron energy-transfer less efficient than momentum-transfer

Electron energy equation

- Long energy-transfer mean-free-path: local field approximation not valid

$$E/N \rightarrow \not{f_0, \bar{\varepsilon}}, \mu_e, D_e, K$$

- Solve mean energy from energy equation:

$$\frac{\partial n_e \bar{\varepsilon}}{\partial t} + \frac{5}{3}\nabla \cdot \left(n_e \mathbf{w}_e \bar{\varepsilon} - n_e D_e \nabla \bar{\varepsilon}\right) = -e n_e \mathbf{w}_e \cdot \mathbf{E} + P_{\text{ext}} - n_e N \kappa$$

thermal conduction (the $-n_e D_e \nabla \bar{\varepsilon}$ term); work of electrostatic field ($-e n_e \mathbf{w}_e \cdot \mathbf{E}$); inductive / MW power (P_{ext}); collisional losses ($n_e N \kappa$)

- Parametrise electron transport coefficients & rates as a function of electron mean energy

$$\bar{\varepsilon} \rightarrow \mu_e, D_e, K, \kappa$$

- Maxwellian EEDF: $\bar{\varepsilon} = \frac{3}{2} T_e$ $\quad D_e = \mu_e T_e$

Einstein relation

Momentum equation

- Long momentum-transfer mean-free-path: drift-diffusion not valid, reconsider momentum equation:

$$m\frac{\partial n\mathbf{w}}{\partial t} + m\nabla\cdot(n\mathbf{w}\otimes\mathbf{w}) + \nabla\cdot\mathbf{P} - qn(\mathbf{E}+\mathbf{w}\times\mathbf{B}) = -m\bar{\nu}_m n\mathbf{w}$$

- Electrons: isotropic due to ambipolar trapping → neglect **w** terms

Boltzmann equilibrium: $T_e\nabla n_e \approx -en_e\mathbf{E}$ → $n_e = n_0 \exp\left(\frac{\Phi-\Phi_0}{T_e}\right)$

Drift-diffusion equilibrium: $D_e\nabla n_e \approx -\mu_e n_e\mathbf{E}$ →

Boltzmann relation

- Ions: very anisotropic → neglect pressure (& substitute continuity equation)

$$\frac{\partial\mathbf{w}_i}{\partial t} + (\mathbf{w}_i\cdot\nabla)\mathbf{w}_i + \left(\bar{\nu}_i + \frac{S_i}{n_i}\right)\mathbf{w}_i = \frac{e}{m_i}\mathbf{E}$$

inertia: memory in time & space

ion creation at zero velocity [arrow to the S_i/n_i term]

If **w** // **E**:

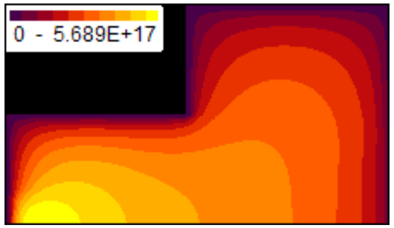
$$\nabla\left(\frac{1}{2}m_i w_i^2 + e\Phi\right) + \left(\bar{\nu}_i + \frac{S_i}{n_i}\right)m_i\mathbf{w}_i = 0$$

Low pressure ambipolar plasma transport

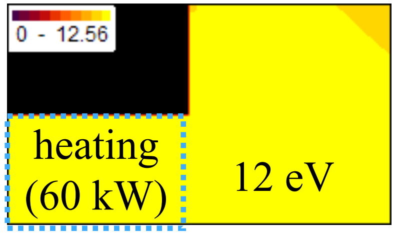
Self-consistent description of sheath & presheath: Poisson equation

Example without magnetic field:

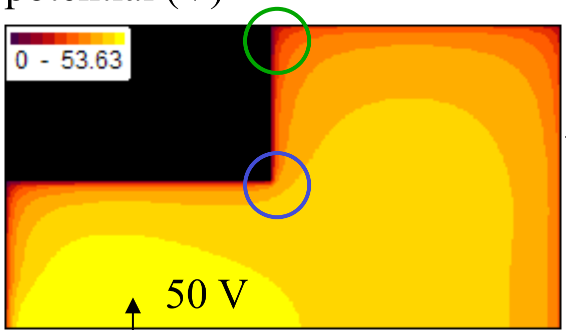
plasma density



e temperature (eV)

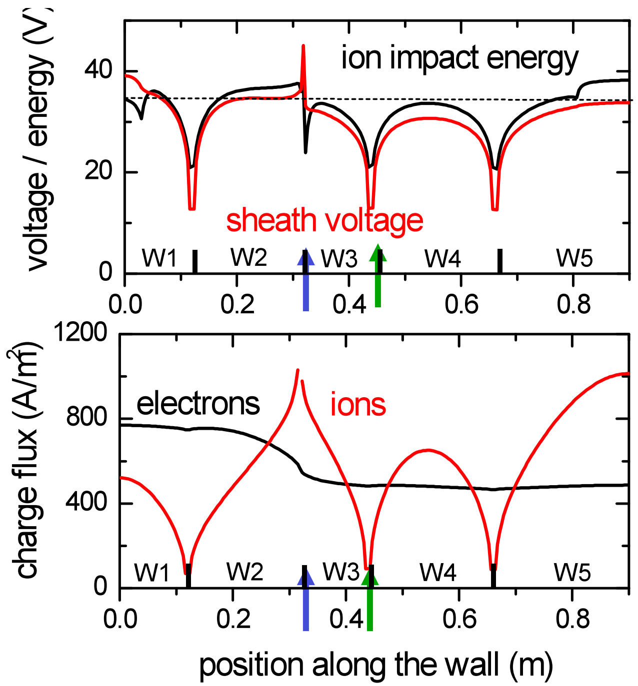


potential (V)



plasma potential

sheath voltage & ion energy vary along the walls!



$$\Phi_p \simeq T_e\left(1+\frac{1}{2}\ln\left(\frac{m_i}{2\pi m_e}\right)\right) \approx 4T_e$$

Dense plasmas: quasineutral approach

- Compare sheath size (Debye length) with plasma size $\lambda_D = \sqrt{\frac{\varepsilon_0 T_e}{e n_e}}$

- Thin sheath → eliminate Poisson's equation using quasineutrality:

$$n_e = n_i$$

Solve electric field from electron conservation / current conservation:

$$\nabla \cdot \left(-\mu_e n_e \mathbf{E} - D_e \nabla n_e\right) = S_e - \frac{\partial n_e}{\partial t} = \nabla \cdot (n_i \mathbf{w}_i)$$

- Drift-diffusion ions: ambipolar diffusion:

Separate ambipolar / external field:

$$\mathbf{E} = \mathbf{E}_{\mathrm{amb}} + \mathbf{E}_{\mathrm{ext}}$$

$$(\mu_e + \mu_i) n_e \mathbf{E}_{\mathrm{amb}} = -(D_e - D_i) \nabla n_e$$

→

ambipolar diffusion coefficient

$$\frac{\partial n_e}{\partial t} - \nabla \cdot \left(\frac{\mu_i D_e + \mu_e D_i}{\mu_e + \mu_i} \nabla n_e \right) = S_e$$

$$\nabla \cdot \left((\mu_e + \mu_i) n_e \mathbf{E}_{\mathrm{ext}} \right) = 0$$

- Complications at low pressure due to inertia & boundary conditions
  But: semi-implicit Poisson method also works!

Hybrid models of magnetized discharge plasmas: fluid electrons + particle ions

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Introduction

Magnetic fields used in low-pressure discharges:

- magnetron
- electron-cyclotron resonance (ECR)
- helicon
- Hall-effect thruster
- etc… (magnetized discharges)

Magnetic field → complex physics

Insight from simple models

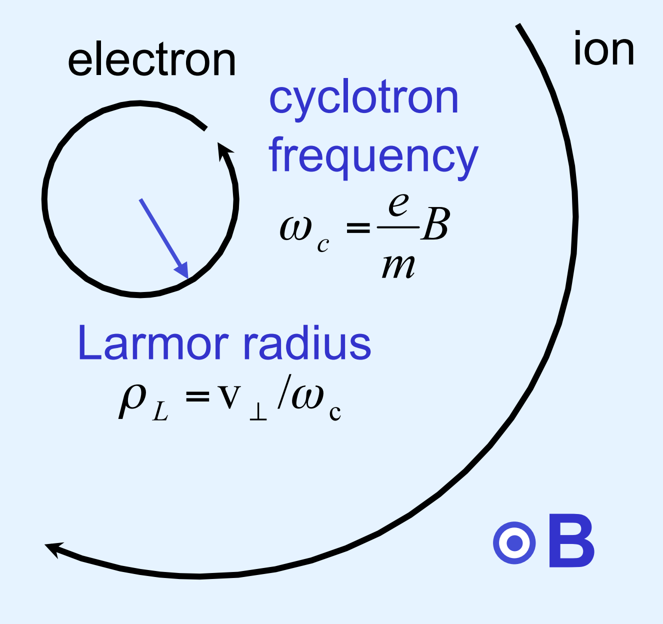
Plan

- Elementary physics
- Modelling
- Limits of modelling
- Illustrative model results:
  - ECR reactor
  - Hall thruster
  - Galathea trap

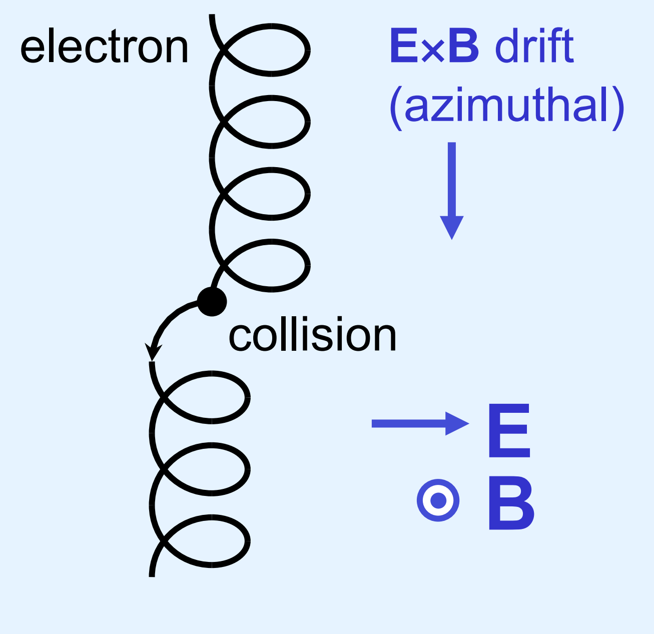
Elementary effects of the magnetic field

- Cyclotron motion → confinement
- Perpendicular electric field → **E×B** drift
- Collisions destroy magnetic confinement

$$-e\mathbf{v}\times\mathbf{B} = m_e \frac{d\mathbf{v}}{dt}$$



$$-e\mathbf{E} - e\mathbf{v}\times\mathbf{B} = m_e \frac{d\mathbf{v}}{dt}$$



Typical conditions

plasma	pressure	0.1 – 10 mTorr
	plasma density	$10^{15} – 10^{19}$ m^{-3}
	magnetic field	0.001 – 0.1 T
	electron temperature	2 – 20 eV
lengths	Debye length	$10^{-5} – 10^{-3}$ m
	electron Larmor radius	10^{-4} – 0.01 m
	ion Larmor radius	0.02 – 5 m
	mean free path	0.01 – 1 m
	plasma size	0.02 – 1 m
frequencies	electron cyclotron	$3\times10^{8} – 2\times10^{10}$ s^{-1}
	electron collision	$3\times10^{5} – 10^{8}$ s^{-1}

Long mean free path

Electrons are magnetized → collisions + ionization

Ions have only few collisions

Magnetic field not influenced by plasma

Modelling

Low pressure → particle-in-cell (PIC):

- electron and ion trajectories
- space charge electric fields

K. A. Ashtiani *et al*, J. Appl. Phys. 78 (4), 2270-2278 (1995).
S. Kondo and K. Nanbu, J. Phys. D: Appl. Phys. **32**, 1142-1152 (1999).
J. C. Adam *et al*, Phys. Plasmas **11** (1), 295-305 (2004).

Magnetized PIC models cumbersome:

- high plasma density → small time steps, small cells
- important 2D effects

→ interest in simpler faster models
→ describe electrons by collisional fluid equations

Electron fluid equations

- Electron conservation

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = S$$

ionisation source

density flux

- Anisotropic flux

$$\Gamma_e = \mu n_e \nabla \Phi - \mu \nabla (n_e T_e)$$

drift diffusion

- Mobility tensor (classical theory)

$$\mu_\perp = \frac{\nu^2}{\nu^2 + \omega_c^2} \mu_{//} = \frac{e\nu / m_e}{\nu^2 + \omega_c^2}$$

collision frequency

cyclotron frequency

perpendicular mobility << parallel mobility

Magnetized drift-diffusion equation

Hall parameter ↓   drift   diffusion

$$\boldsymbol{n}_e \mathbf{w}_e - \mu \mathbf{B} \times (\boldsymbol{n}_e \mathbf{w}_e) = \mu \boldsymbol{n}_e \nabla \Phi - \mu \nabla (\boldsymbol{n}_e \boldsymbol{T}_e) \equiv \mathbf{G}$$

Take cross product and dot product with **B** and combine

$$\boldsymbol{n}_e \mathbf{w}_e = \frac{1}{1 + (\mu \boldsymbol{B})^2} \left(\mathbf{G} - \mu \mathbf{B} \times \mathbf{G} + \mu^2 (\mathbf{B} \cdot \mathbf{G}) \mathbf{B} \right) \equiv (\mu / \mu) \cdot \mathbf{G}$$

↑ mobility tensor

Mobility tensor components:

$$\mu_{//} = \mu \qquad \mu_{\perp} = \frac{1}{1 + (\mu \boldsymbol{B})^2} \mu \qquad \mu_{\times} = \pm \frac{\mu \boldsymbol{B}}{1 + (\mu \boldsymbol{B})^2} \mu$$

Parallel transport unaffected

Perpendicular confinement

Magnetic drifts

Hybrid models

Non-quasineutral scheme:

- ion particles → n_i
- electron fluid → n_e
- Poisson → Φ

$$\varepsilon_0 \nabla^2 \Phi = e(n_e - n_i)$$

no plasma oscillations
→large time steps

Quasineutral scheme:

- ion particles → $n_i = n_e$
- electron fluid → Φ

$$\nabla \cdot (\mu n_e \nabla \Phi - \mu \nabla (n_e T_e)) = \nabla \cdot \Gamma_i$$ (Ohm's law)

no sheaths → large cells

R. K. Porteous *et al*, Plasma Sources Sci. Technol. **3**, 25-39 (1994).
J. M. Fife, Ph. D. thesis, MIT, 1998.
G. J. M. Hagelaar *et al*, J. Appl. Phys. **91** (9), 5592-5598 (2002).

Limits of the electron equations

- Anomalous transport ⊥**B** → empirical parameters

$$e\nu / m_e(\nu^2 + \omega_c^2) < \mu_\perp < 1/16B$$

classical mobility ? Bohm mobility

- Non-local effects //**B**: inertia, mirror confinement

But: flux //**B** limited by boundaries

$$\mu_{//} n_e \nabla_{//} \Phi \approx \mu_{//} \nabla_{//} (n_e T_e)$$

drift diffusion

$$\rightarrow \quad \Phi(\mathbf{r}) = \Phi^*(\lambda) + T_e(\lambda) \ln\left(n_e(\mathbf{r})/n_0\right) \qquad \text{(Boltzmann)}$$

potential = constant + diffusion term

Magnetic field lines approximately equipotential

Numerical issues (1)

Extreme anisotropy → numerical errors tend to destroy the magnetic confinement

drift diffusion drift diffusion

electron flux

$$\Gamma_{e,x} = \frac{1+\Omega_x^{\ 2}}{1+\Omega^2}\left[\mu_0 n_e \frac{\partial \Phi}{\partial x} - \mu_0 \frac{\partial n_e T_e}{\partial x}\right] + \frac{\Omega_x \Omega_y}{1+\Omega^2}\left[\mu_0 n_e \frac{\partial \Phi}{\partial y} - \mu_0 \frac{\partial n_e T_e}{\partial y}\right]$$

Hall vector

$$\Omega = \frac{e\mathbf{B}}{m_e \nu}$$

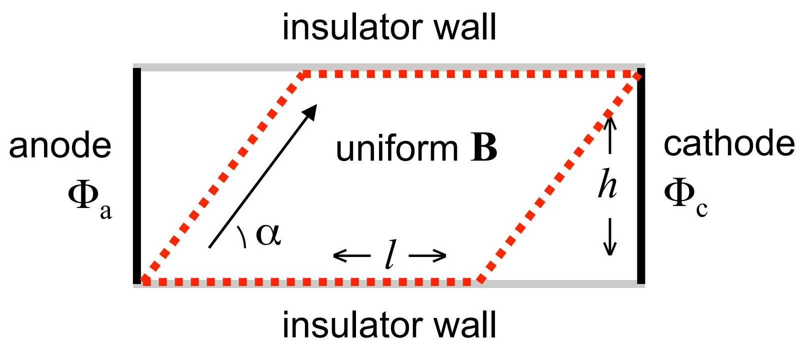
longitudinal term and transverse term very large and opposite in sign

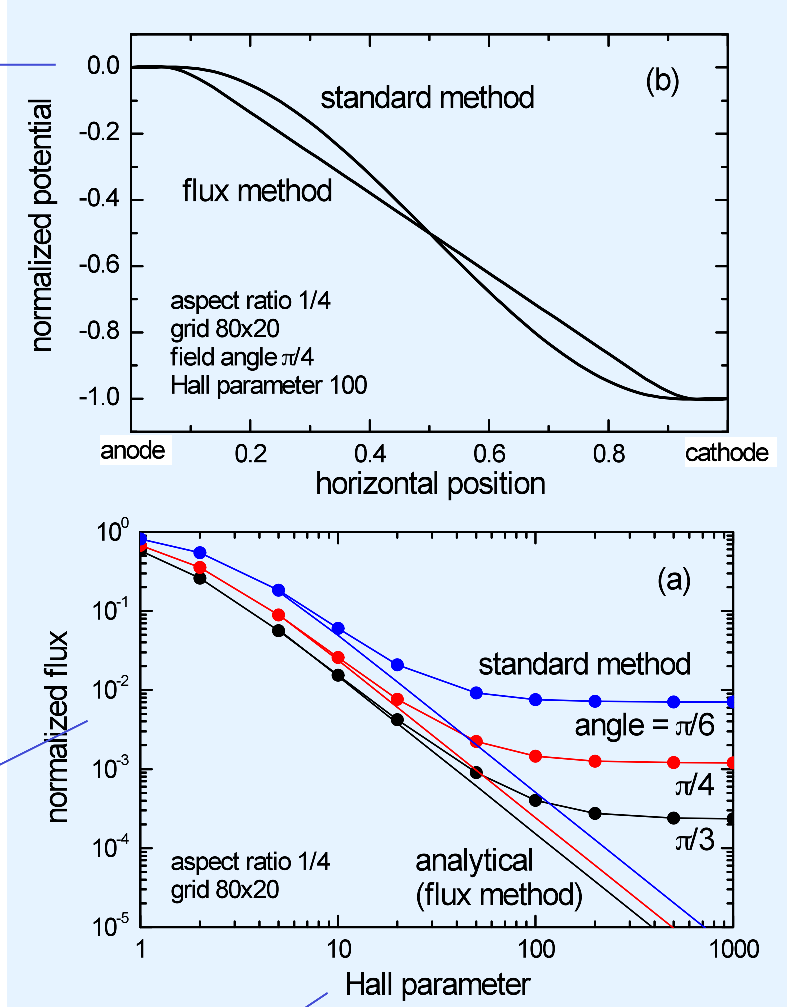
$|\Omega| = \omega_c/\nu >> 1$

Numerical issues (2)

potential profile at mid height

$$\nabla\cdot(\mu n_e \nabla\Phi) = 0$$





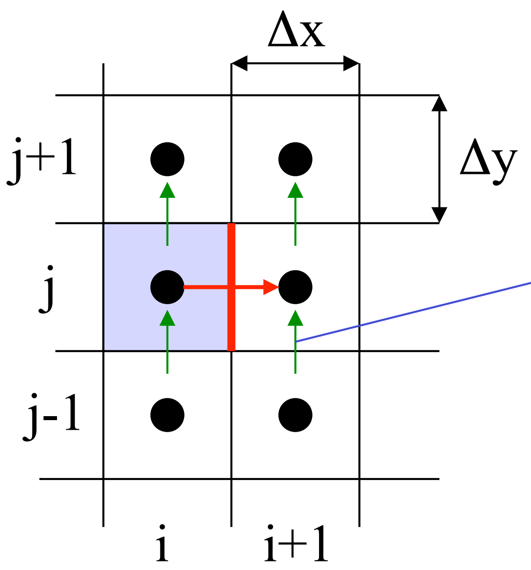
electron flux in the middle of the channel

$|\Omega|$ = [cyclotron frequency] / [collision frequency]

Numerical issues (3)

Iterative flux scheme:
interpolate transverse flux rather than transverse field

$$\Gamma_{e,x}^{k+1} = \frac{1}{1+\Omega_y^2}\left[\mu_0 n_e \frac{\partial \Phi}{\partial x} - \mu_0 \frac{\partial n_e T_e}{\partial x}\right]^{k+1} + \frac{\Omega_x \Omega_y}{1+\Omega_y^2}\overline{\Gamma}_{e,y}^{k}$$



average of 4 surrounding transverse fluxes

Numerical issues (4)

Coupling with Poisson's equation:
severe time step constraint for explicit scheme

$$\Delta t < \frac{\varepsilon_0}{e n_e \mu_{//}} = \frac{\nu}{\omega_{pe}^{2}}$$

$< 10^{-11}$ s
(vs. ion CFL-time $10^{-8} – 10^{-6}$ s)

Semi-implicit scheme:
Poisson's equation includes prediction of space charge

$$\nabla \cdot \left((\varepsilon_0 + e \Delta t \mu n_e) \nabla \Phi - e \Delta t \mu \nabla (n_e T_e) \right) = e(n_e - n_i)$$

implicit
space charge
prediction

Examples of model results

Non-quasineutral hybrid model → sheaths resolved

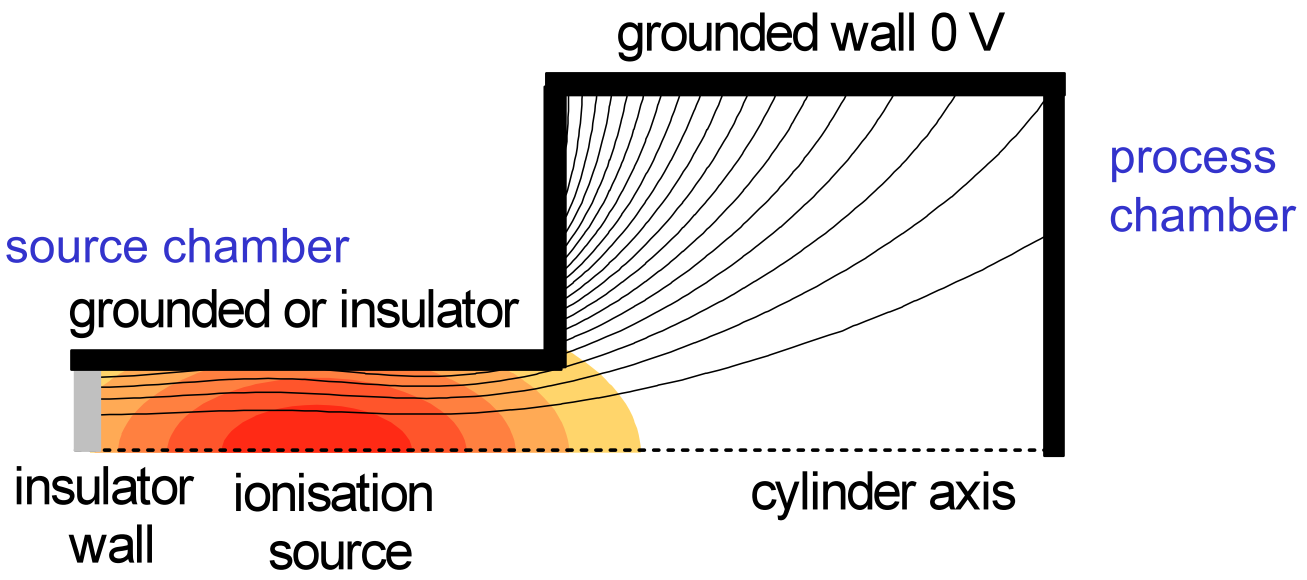
Fixed:

- Gaussian ionisation source
- uniform electron temperature (diffusion)
- electron collision frequency

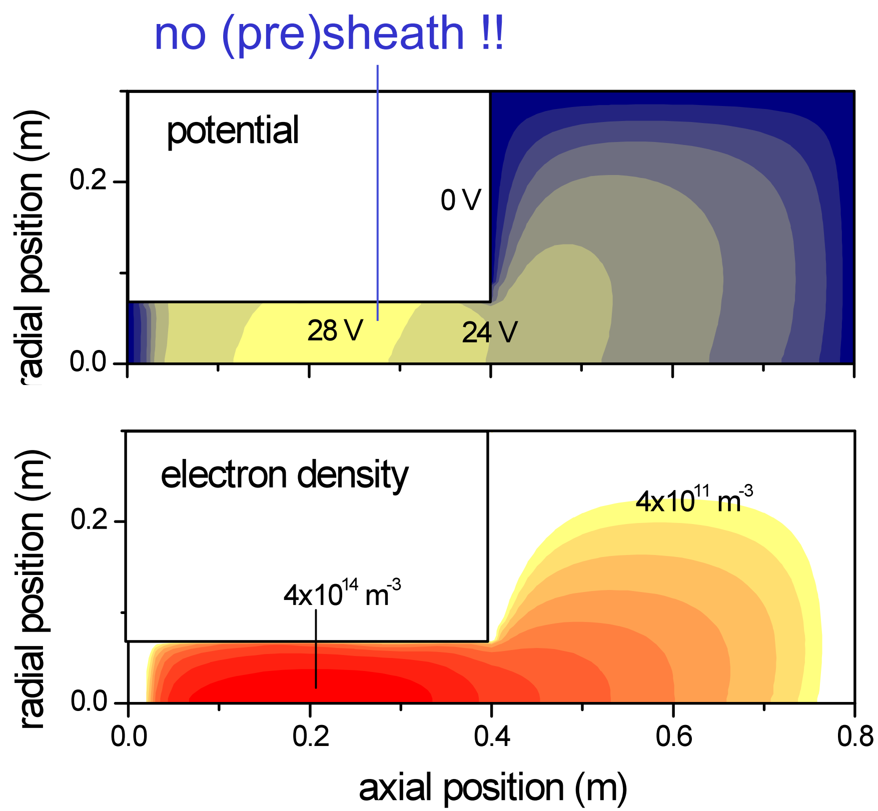
Calculated:

- electron/ion densities
- electron/ion fluxes, currents
- self-consistent potential

Example I : Diffusion in ECR reactor

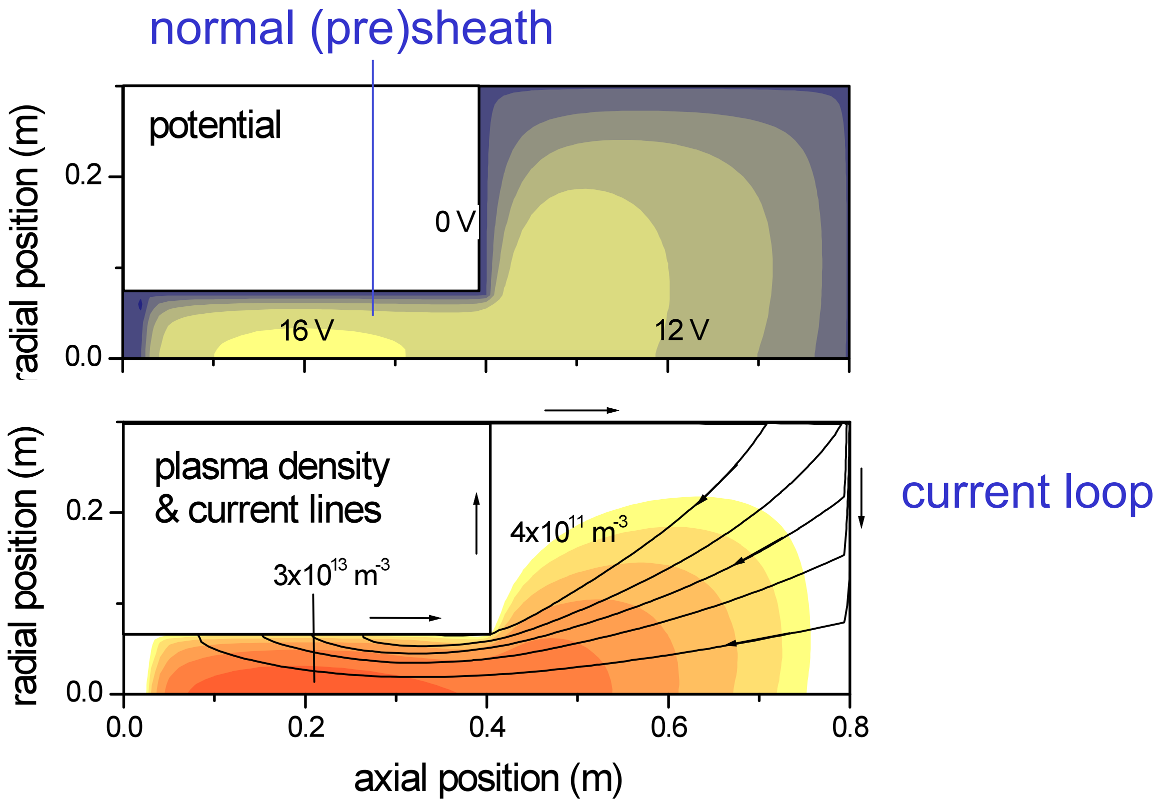


ECR reactor with dielectric wall



Magnetic confinement reduces loss to source wall

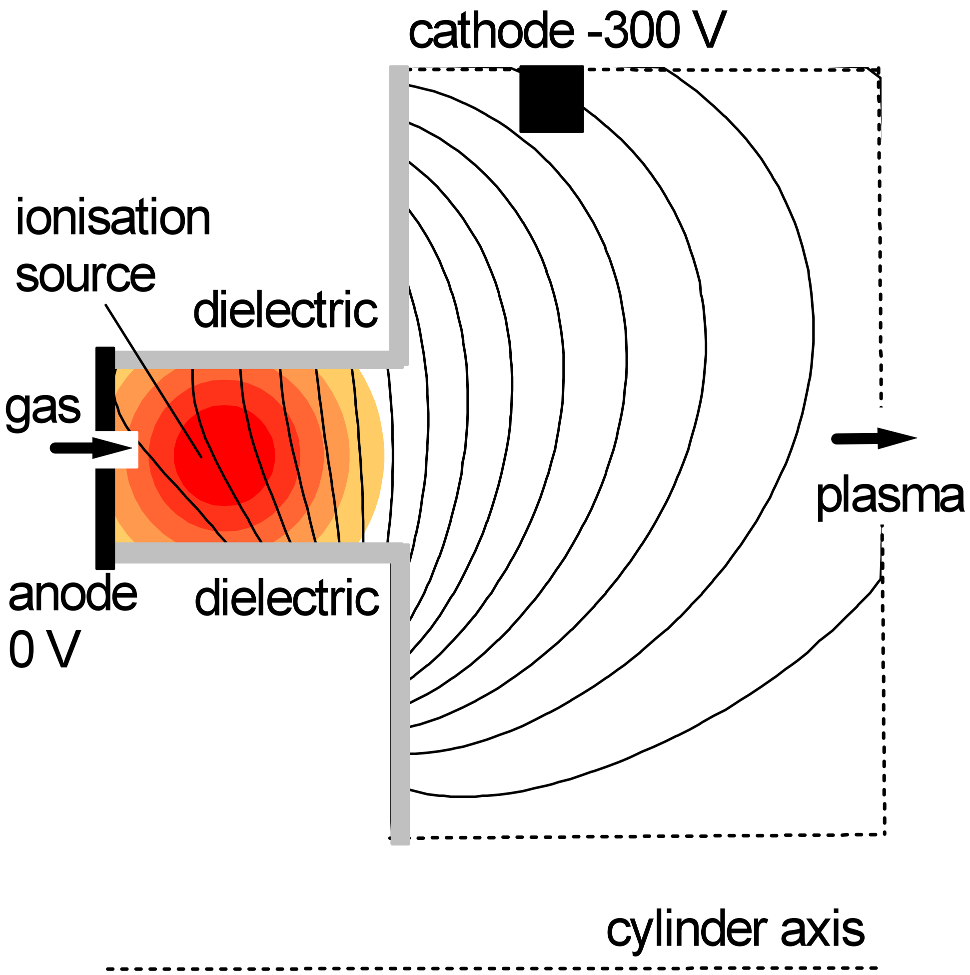
ECR reactor with grounded wall

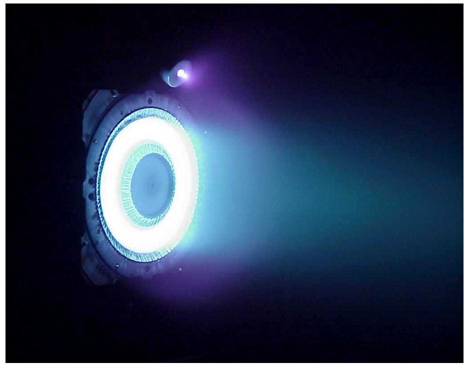


Magnetic confinement shortcircuited by walls

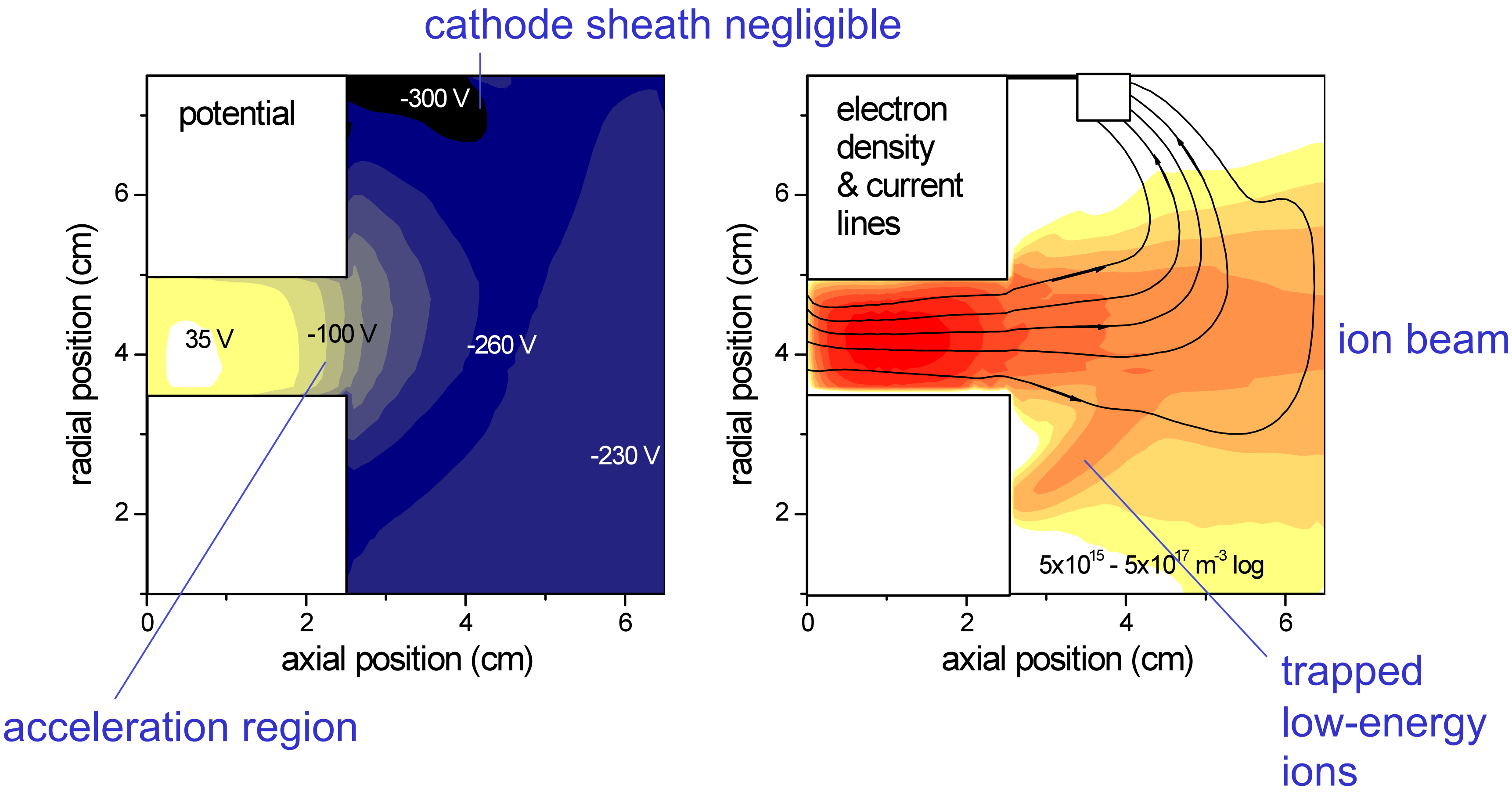
A. Simon, Phys. Rev. **98** (2), 317-318 (1955).

Example II : Hall-effect thruster





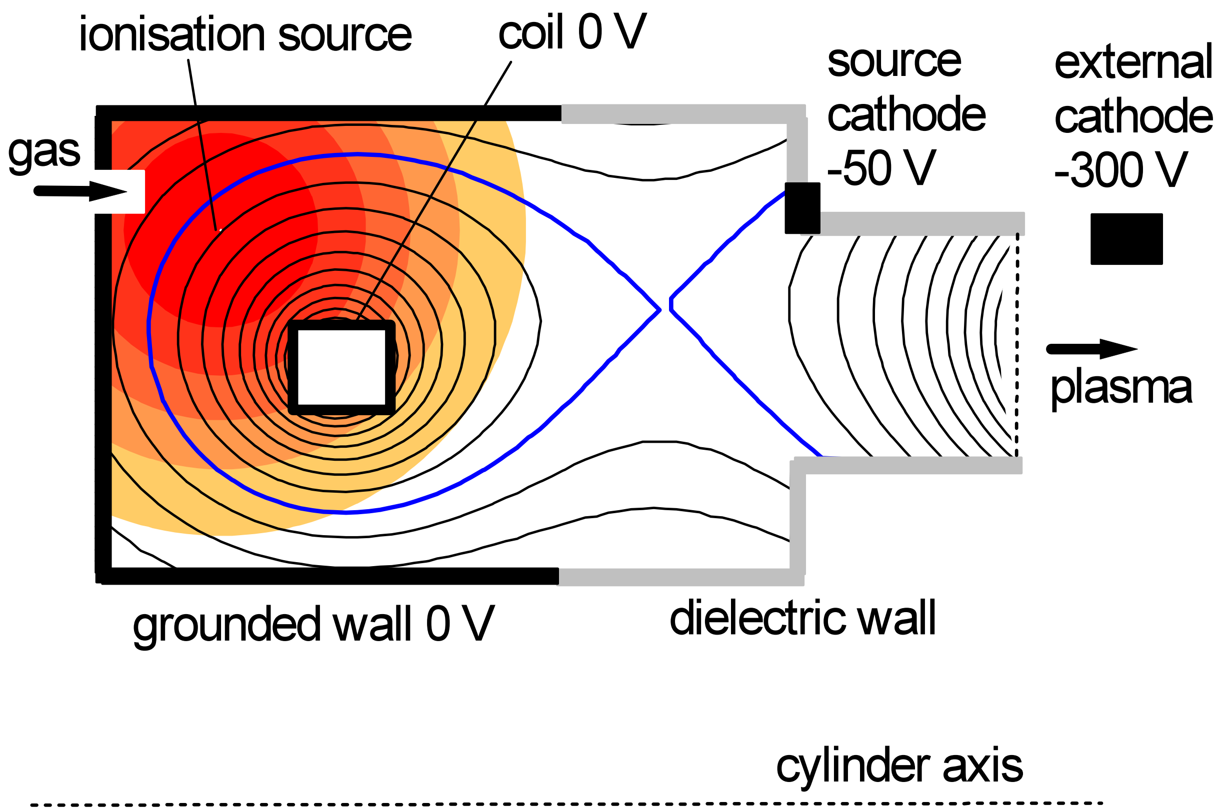
Hall-effect thruster



Equipotential lines ~ magnetic field lines

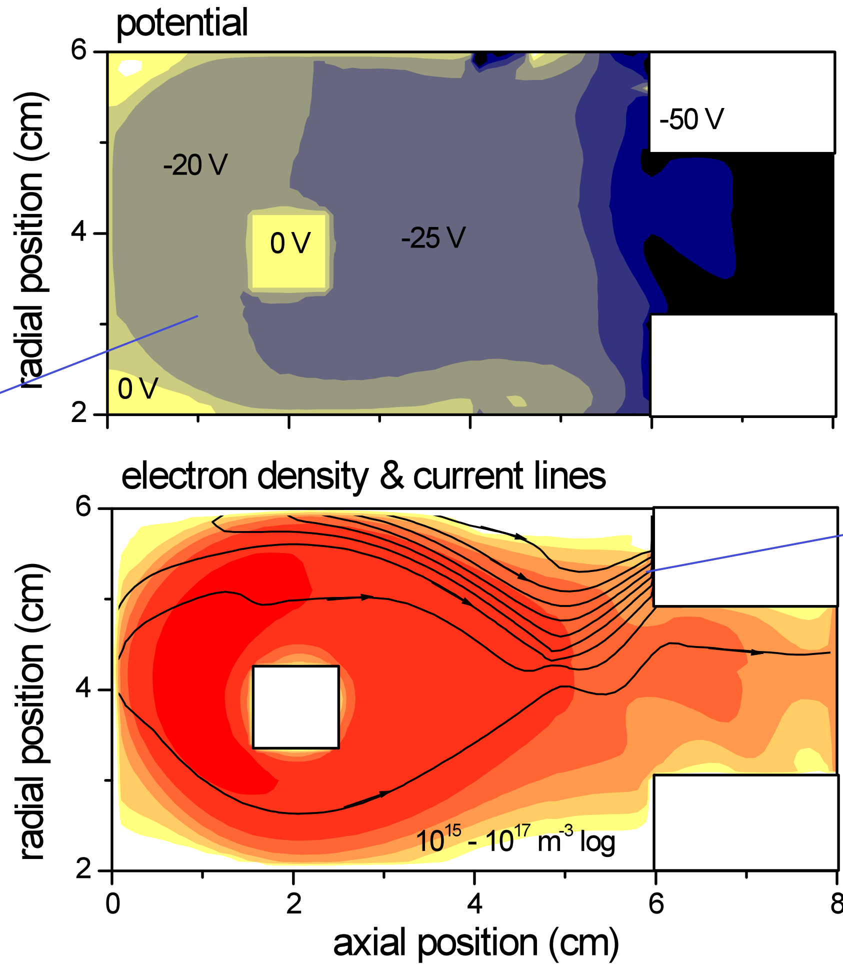
Applied voltage penetrates in plasma bulk

Example III : semi-Galathea trap



A. I. Morozov and V. V. Savel'ev, Physics – Uspekhi **41** (11), 1049-1089 (1998).

Semi-Galathea trap



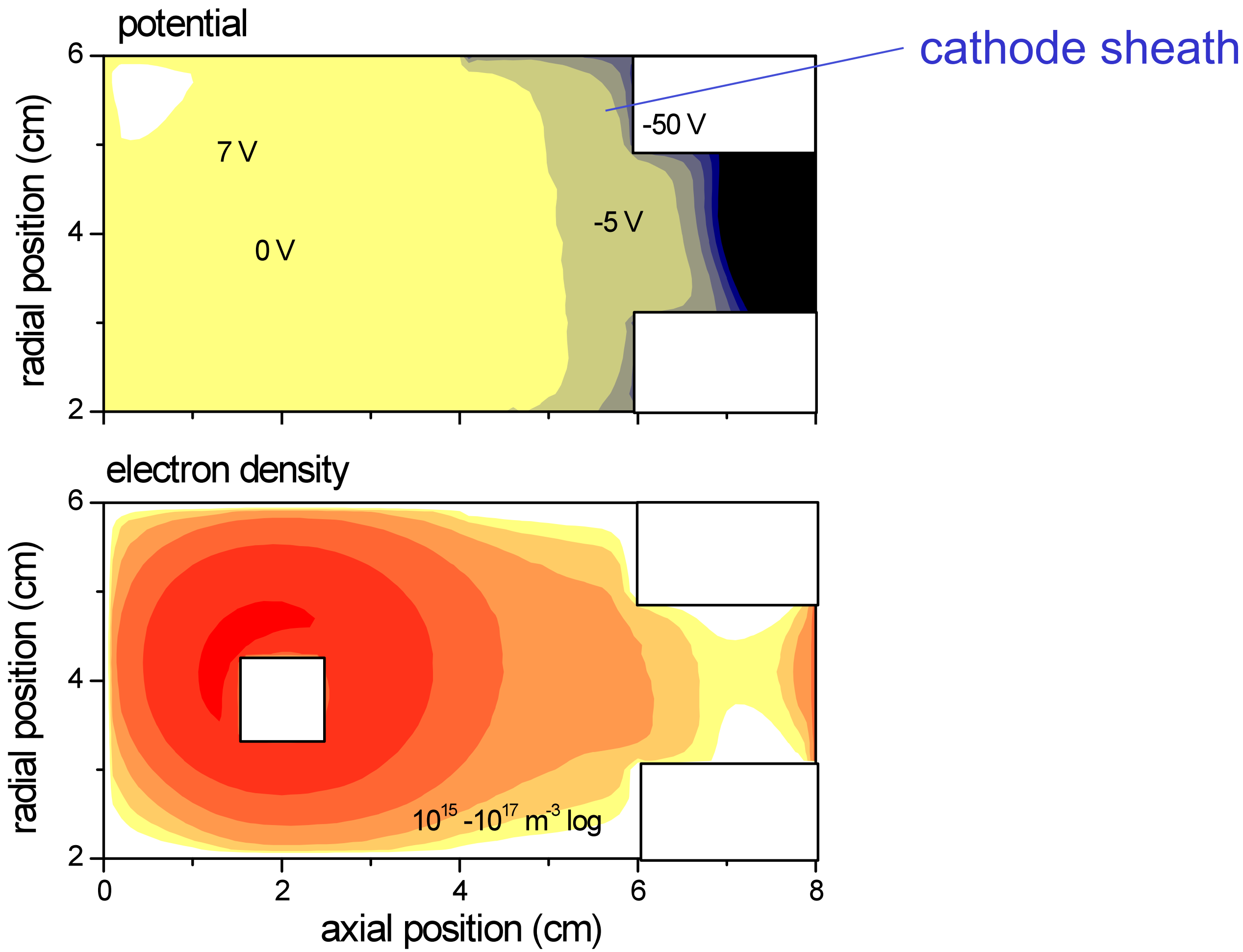
negative plasma potential ! (inverted presheath)

70 % of ions guided to exit

electron current from emissive cathode to walls

Potential well reduces ion wall loss and guides ions to exit

Semi-Galathea trap without emission



Potential well disappears because of cathode sheath

Conclusions

- In magnetized discharges, charged particle transport and space charge fields are different
- This can be studied in 2D by hybrid models
- No predictive simulations, but insight in physical principles