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Plasma-wall transition in magnetized plasmas: impact on wall sputtering and erosion

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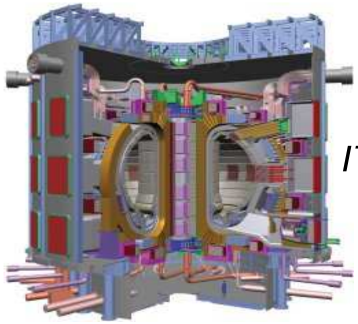
Motivations

- **Magnetically confined fusion plasmas**
  - Limiters and divertors in tokamaks
  - Problems: erosion, sputtering, recycling



ITER

- **Diagnostics in plasmas**
  - Langmuir probes, retarding field analyzers (RFA), …
  - Plasma-probe interaction can lead to significant errors in the measurements

Langmuir probe

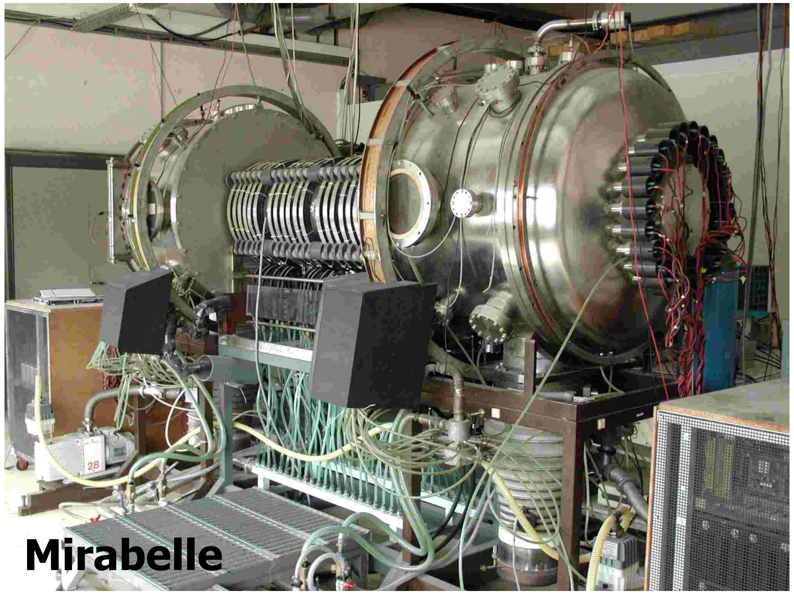
- **Plasma-assisted surface treatment**
  - Etching, thin-film deposition

- **Sound understanding of plasma-wall interactions is crucial to control the above effects**

Experimental conditions

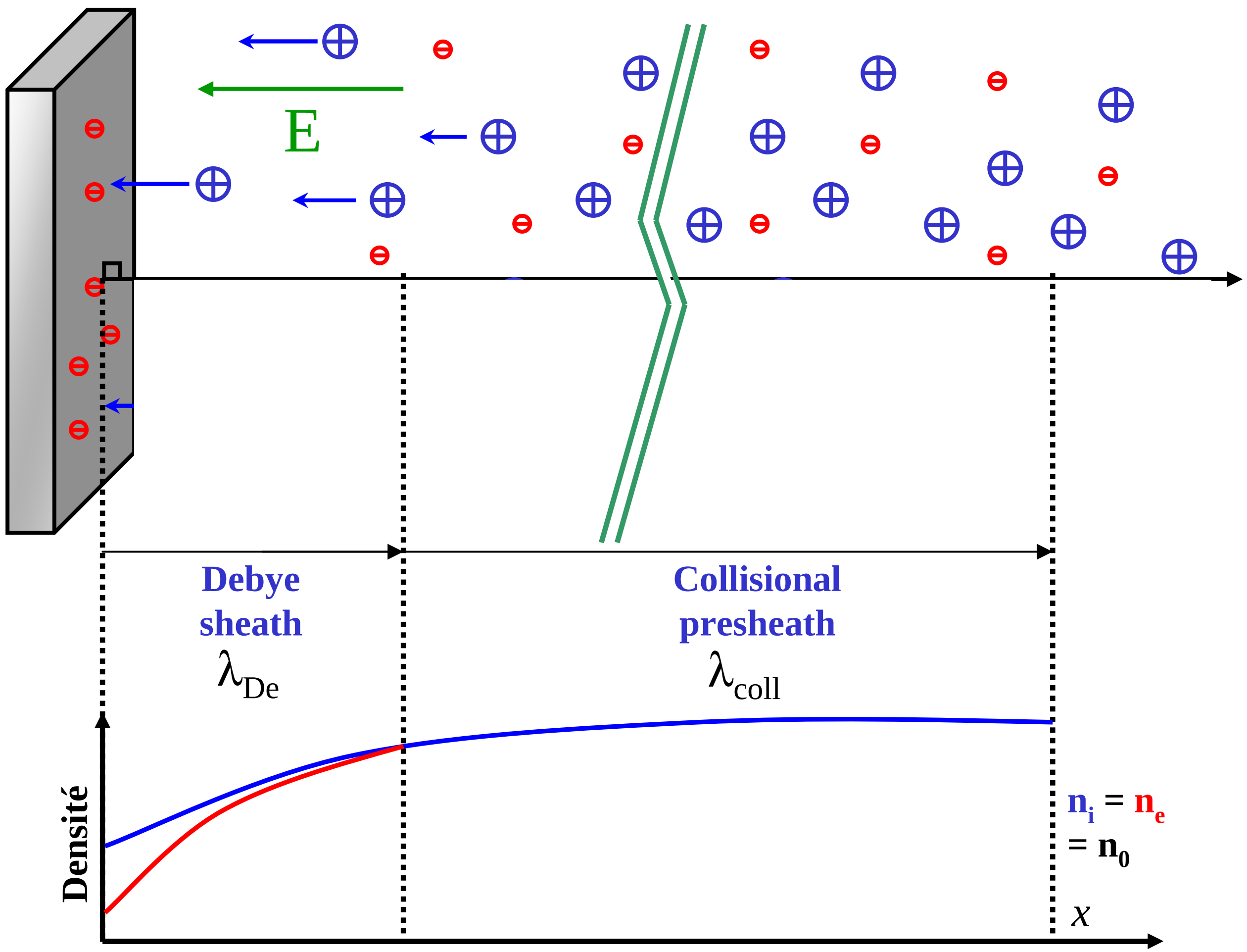
"Mirabelle" linear device (University of Nancy, France)

- ✓ Argon plasma
- ✓ Pressure : 10^{-4} torr
- ✓ Density (ions, electrons) : 5×10^{9} cm^{-3}
- ✓ Ion temperature: T_i~ 0.04 eV
- ✓ Electron temperature: T_e ~ 1 eV
- ✓ λ_{De} ~ 0.3 mm ; r_L ~ 6mm ; λ_{coll} ~ 9cm



Parameter	Value
T_e / T_i	$1 \leftrightarrow 35$
$\omega_{ci} / \omega_{pi}$	$0.1 \leftrightarrow 0.01$
ν / ω_{pi}	$10^{-3} \leftrightarrow 10^{-5}$

Sheath formation – unmagnetized case



Debye sheath (DS):

- nonneutral region
- width ~ λ_{De}
- Bohm criterion: ions velocity at DS edge > C_s

Collisional presheath (CP):

- quasi-neutral area
- width ~ λ_{coll}: mean free path
- ion acceleration towards the wall

Debye sheath — Bohm's criterion

- Criterion for the stability of the electrostatic Debye sheath (DS).
- **Q. : what is the minimum velocity at the entrance of the DS sheath?**
- Simple fluid model:

$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i u_i)}{\partial x} = 0 \qquad \frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x} = -\frac{e}{m_i}\frac{\partial \Phi}{\partial x}$$

$$\frac{\partial^2 \Phi}{\partial x^2} = -\frac{e}{\varepsilon_0}(n_i - n_e) \qquad n_e(x,t) = n_0 \exp\left(\frac{e\Phi}{k_B T_e}\right)$$

- We look for a stationary solution: $\partial/\partial t = 0$
- The ion Euler equation can be solved for n_i

$$\frac{n_i}{n_0} = \left(1 - \frac{2e\Phi}{m_i u_0^2}\right)^{-1/2}$$

- Substituting into Poisson's equation and linearizing , one obtains

$$\frac{d^2\Phi}{dx^2} = \frac{1}{\lambda_D^2}\left(1 - \frac{k_B T_e}{m_i u_0^2}\right)\Phi \quad \Longrightarrow \quad u_0 > \sqrt{\frac{k_B T_e}{m_i}} \equiv c_s$$

Collisional presheath

- Fluid equations for the ions with collision frequency W

$$\frac{d}{dx}(n_i u_i) = 0 \qquad\qquad u_i \frac{d\,u_i}{dx} = -\frac{e}{m_i}\frac{d\,\Phi}{dx} - W u_i$$

- Assuming quasineutrality: $\ln\frac{n_e}{n_0} = \frac{e\Phi}{k_B T_e} = \ln\frac{n_i}{n_0}$

- We obtain:

$$(u_i^2 - c_s^2)\frac{du_i}{dx} = -W u_i^2$$

- **Singularity at $u_i = c_s$,** which defines the Debye sheath edge (DSE)
- At the DSE, the assumption of quasineutrality breaks down
  - Need to use full Poisson's equation

Kinetic modelling I.

❖ Phase-space distribution function

$f(\vec{r},\vec{v},t).d\vec{r}d\vec{v}$ = Number of particles in the phase-space volume $d\vec{r}d\vec{v}$ centered on $(\vec{r},\vec{v})$

❖ Velocity moments of the distribution function

$$n(\vec{r},t) = \int f(\vec{r},\vec{v},t).d\vec{v}$$

Spatial density

$$\vec{u}(\vec{r},t) = \frac{1}{n}\int \vec{v} f(\vec{r},\vec{v},t).d\vec{v}$$

Mean velocity

$$nk_B T(\vec{r},t) = m_i \int w^2 f(\vec{r},\vec{v},t).d\vec{v}$$

$$\vec{w} = \vec{v} - \vec{u}$$

Temperature

Kinetic modelling II.

❖ Vlasov equation for the ions

$$\underbrace{\frac{\partial f_i}{\partial t} + \vec{v}\cdot\frac{\partial f_i}{\partial \vec{r}} + \frac{e}{m_i}\left(\vec{E} + \vec{v}\times\vec{B}\right)\cdot\frac{\partial f_i}{\partial \vec{v}}}_{\text{Conservation equation in the phase space}} = \underbrace{\left(\frac{\partial f_i}{\partial t}\right)_{coll} = -\nu\left(f_i - f_0\right)}_{\text{Collisions}}$$

Conservation equation
in the phase space

Collisions ⇒ relaxation to Maxwellian $f_0(v)$
ν^{-1} : typical relaxation time

1D space (x coordinate : normal to the wall) + **3D velocity**

❖ Boltzmann equilibrium for the electrons

$$n_e = n_0 \exp\left(\frac{e\phi}{k_B T_e}\right)$$

⇔ the electrons thermalize much faster than the ions

❖ Poisson's equation

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{e}{\epsilon_0}\left(\int f_i . dv - n_e(\phi)\right)$$

Self-consistent system closed by
Poisson's equation ⇒ nonlinearity

Kinetic modelling III.

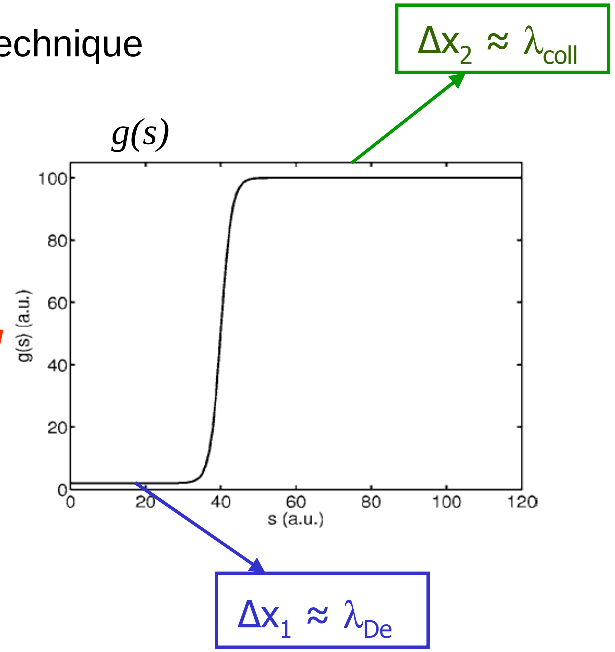
- ***Numerical method:* Vlasov Eulerian code**
  - Meshing of the full phase space
  - Low level of numerical noise

- ***Strategy***
  - Initialize homogeneous Maxwellian distribution for ions: $f_i = f_M(v)$
  - Let it evolve self-consistently until stationary state appears
    - ➢ Check that spatial profiles do not vary anymore
  - Corollary : no need for very accurate time-stepping technique

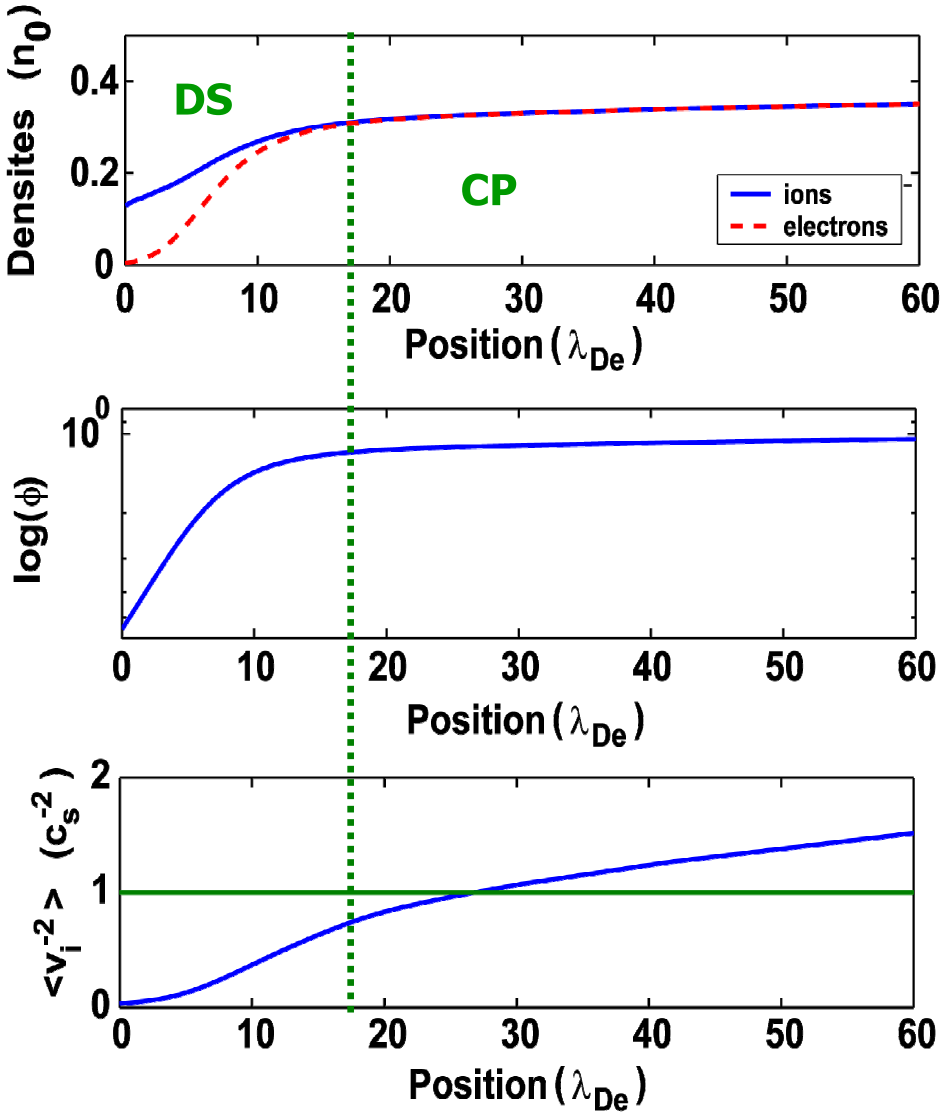
- ***Disparate spatial scales***
  - $\lambda_{De} << \lambda_{coll}$
  - Use inhomogeneous grid:

$$dx = g(s)ds\,,$$

$$g(s) = \Delta x_1 + \frac{\Delta x_2 - \Delta x_1}{2}\{1 + \tanh[c(s - s_0)]\},$$



Unmagnetized plasma-wall transition



Typical case : $T_e/T_i = 25$; $\nu / \omega_{pi} = 10^{-4}$

$\lambda_{coll} \approx 10^3 \lambda_{De}$

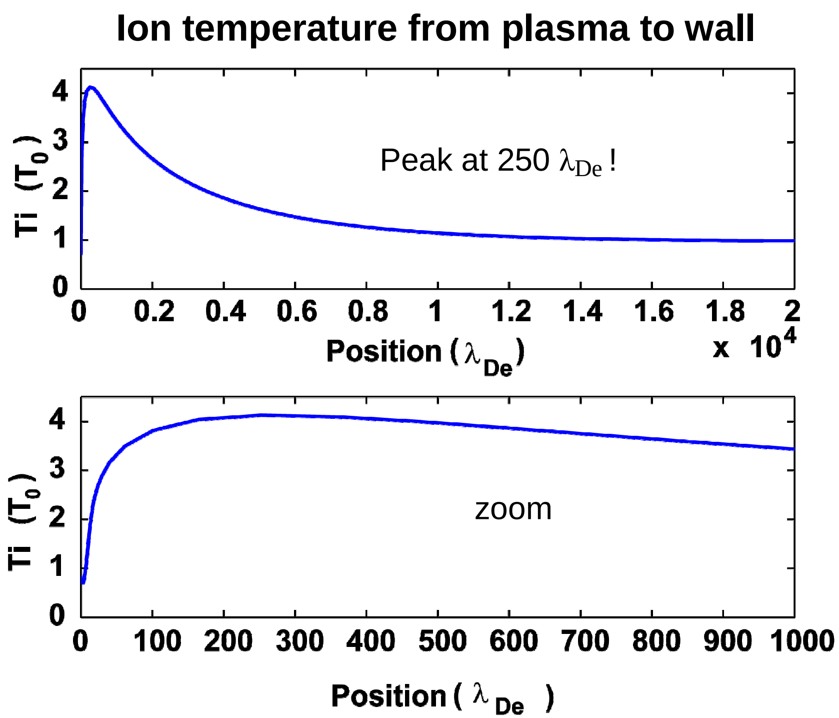
Fluid Bohm's criterion:

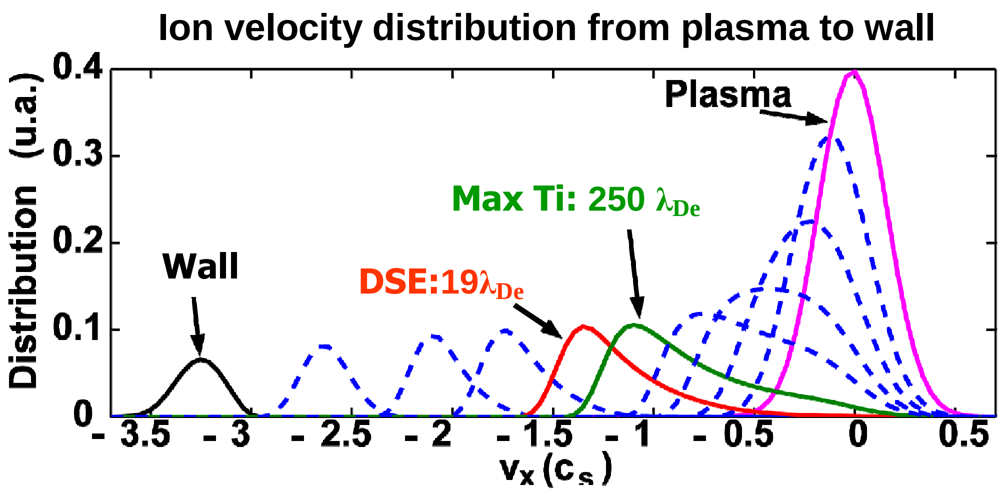
$$\langle v \rangle |_{x_0} \geq \left(\frac{k_B T_e}{m_i} \right)^{1/2}$$

Kinetic Bohm's criterion:

$$\langle v^{-2} \rangle |_{x_0} = \int \frac{1}{v^2} f.dv \leq \frac{m_i}{k_B T_e}$$

Ion temperature profile





Competition between two effects:

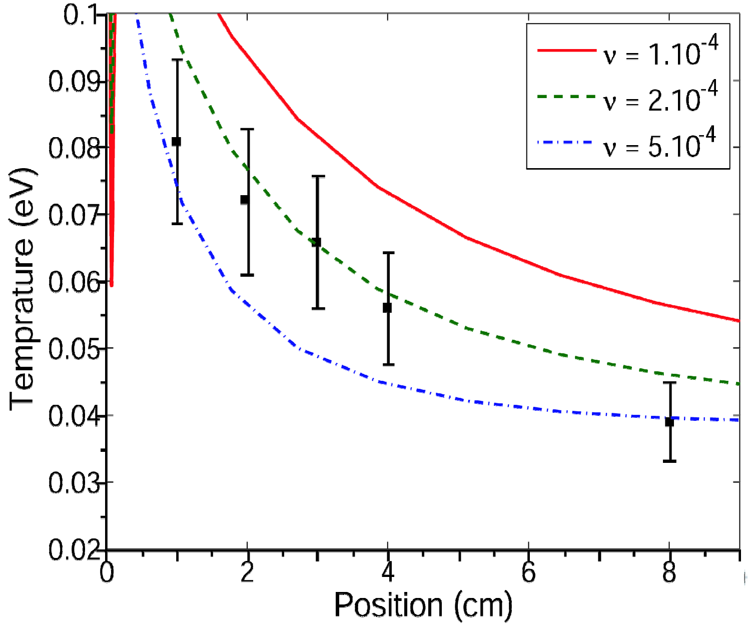
- Electric field : acceleration towards the wall
- Collisions : back to distribution f_0

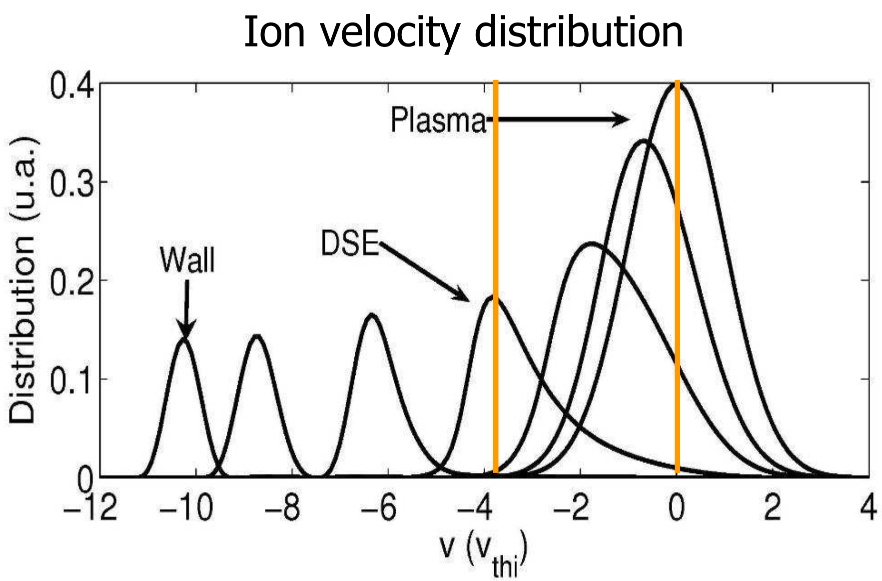
Comparison to experimental results

- Series of temperature measurements in the presheath

  Oksuz and Hershkowitz, Plasma Sources Sci. Technol. ***14****, 201 (2003)*
- Experimental conditions: $T_e/T_i = 25$; $\phi_{wall} = -30V$; $\nu / \omega_{pi} = 10^{-4}$

Ion temperature profile



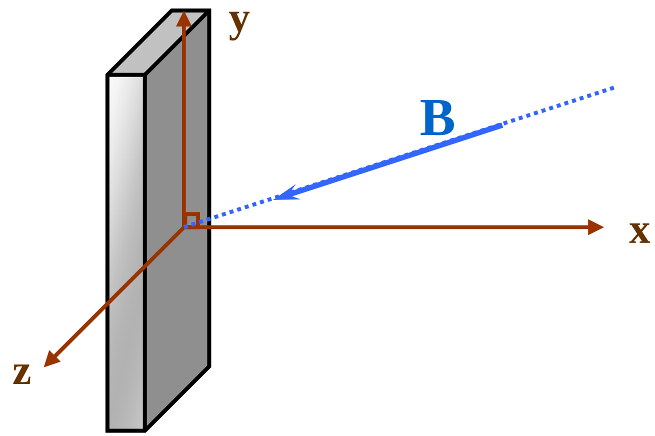


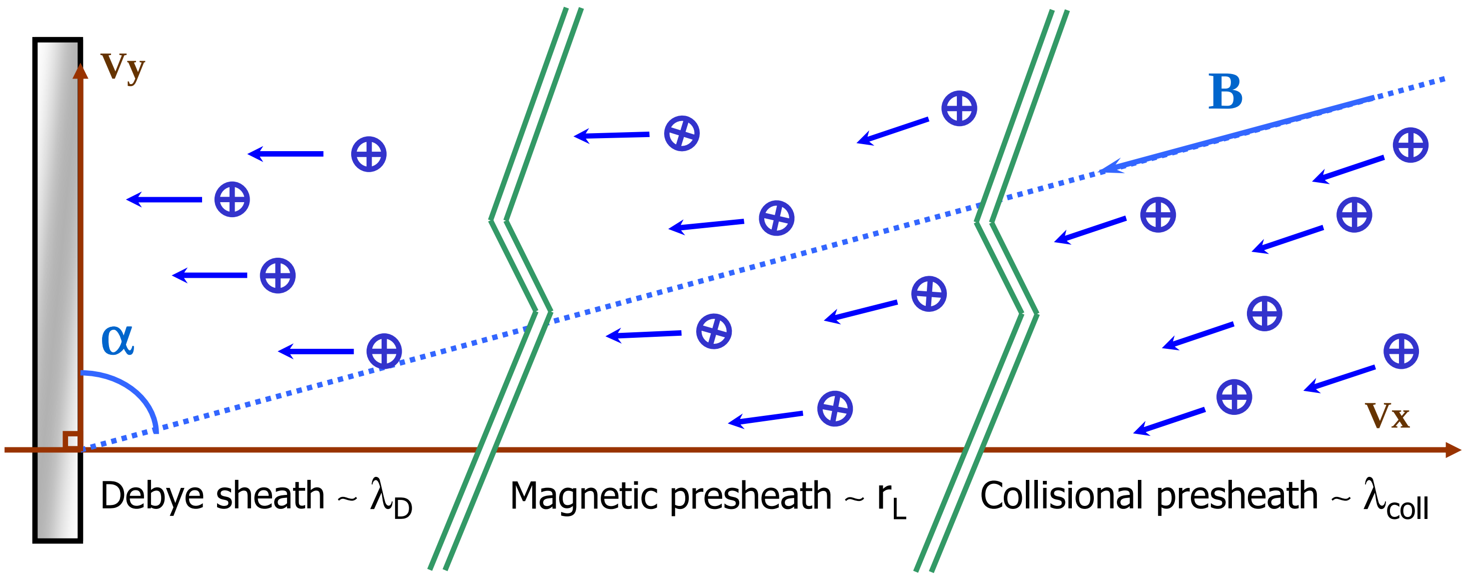
Sheath formation in a magnetized plasma

Ordering :

$\lambda_{De} << r_L << \lambda_{coll}$

Debye length | Ion Larmor radius | Ion–neutral mean free path



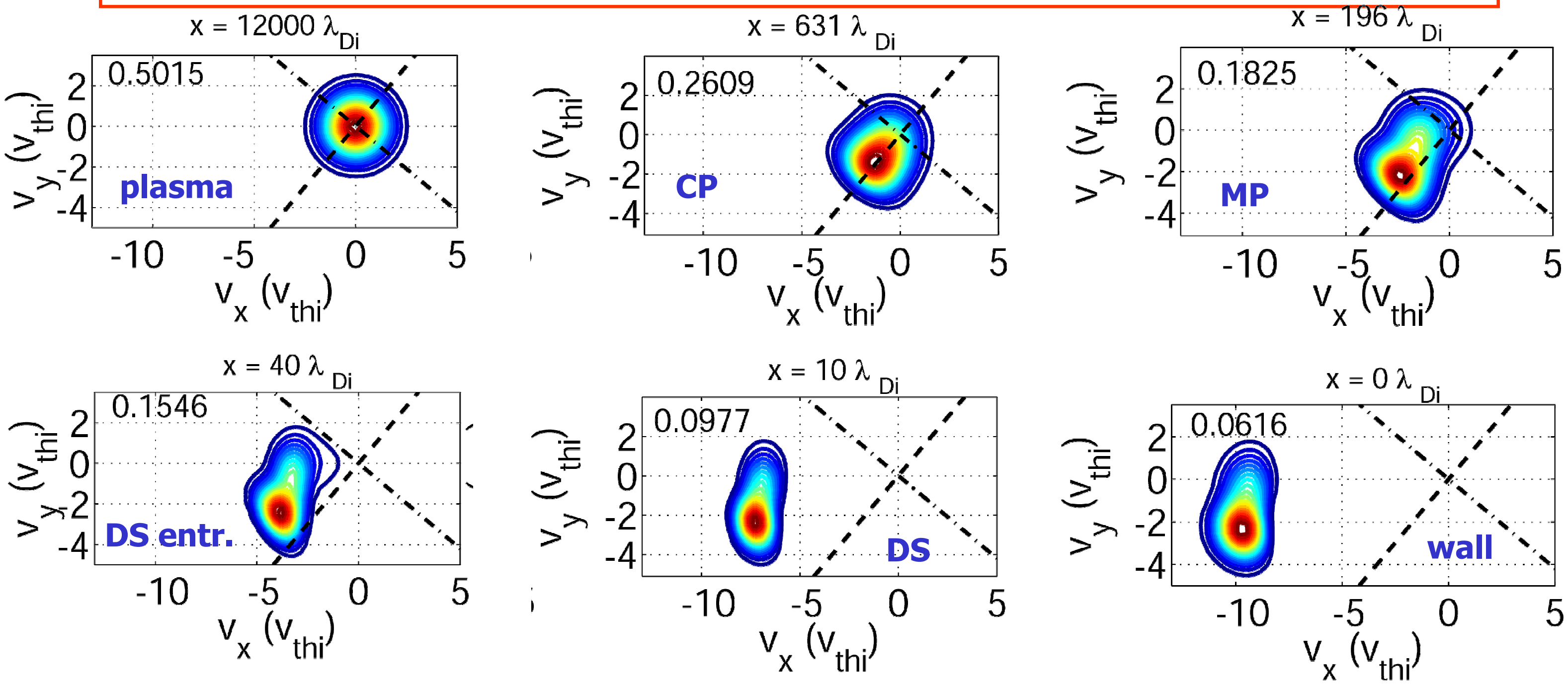


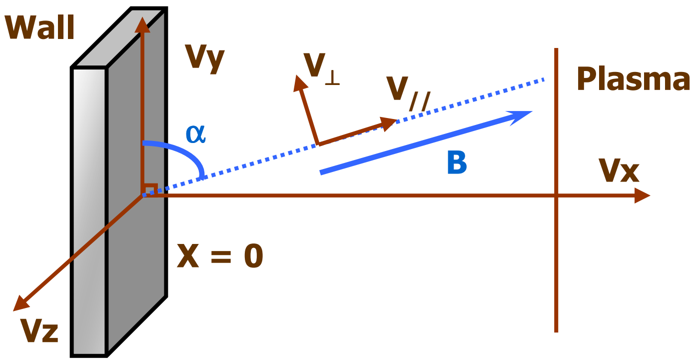
Magnetic presheath (MP):
- quasi-neutral
- width ~ r_L
- ion redirection toward the wall

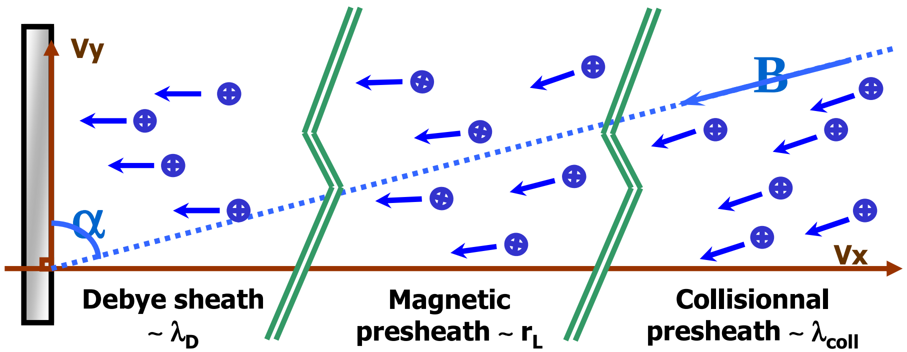
Collisional presheath (CP):
- quasi-neutral
- width ~ λ_{coll}
- ion acceleration along magnetic lines

Magnetized plasma-wall transition: phase-space

$\alpha = 40°$ $\omega_{ci} / \omega_{pi} = 0.01$ $T_e / T_i = 10$ $\nu / \omega_{pi} = 10^{-3}$



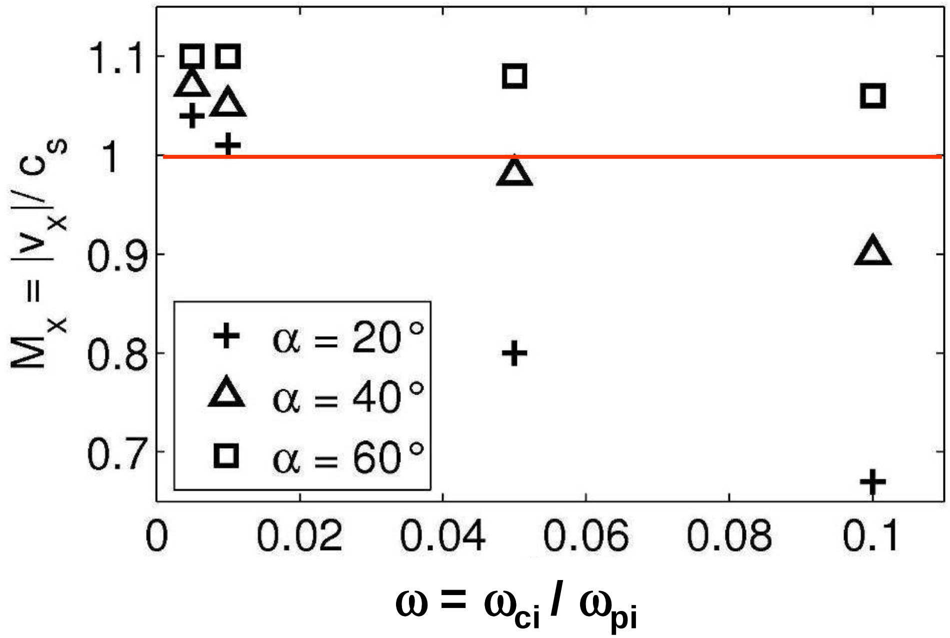




Magnetized Bohm's criterion

$$\langle v_x \rangle > \sqrt{\frac{k_B T_e}{m_i}} \equiv c_s$$ **at DS edge**

Mach number Debye sheath edge



Bohm's criterion **not** satisfied for:

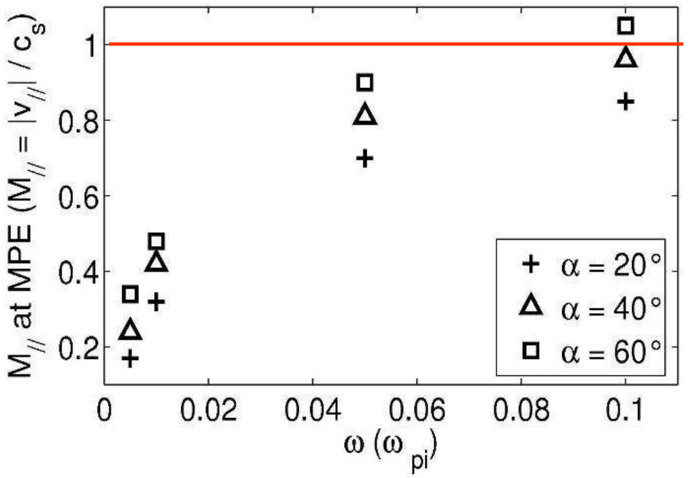
- Large magnetic fields
- Grazing incidence (α small)

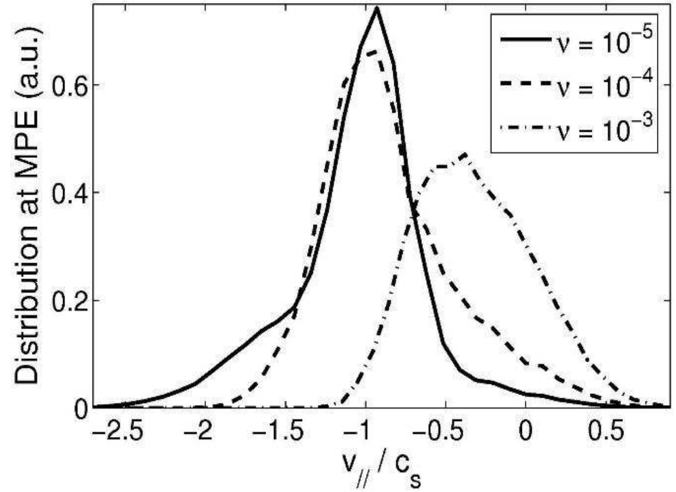
Magnetic presheath (MP) edge: Chodura's criterion

$$\langle v_{//} \rangle > \sqrt{\frac{k_B T_e}{m_i}} \equiv c_s$$ **at MP edge**

- Chodura's criterion **not** satisfied for:
  - Weak magnetic fields ($\omega << \omega_{pi}$)
  - Large collision rate ($\upsilon >> \omega_{pi}$)
- Not very reliable to estimate the MP width

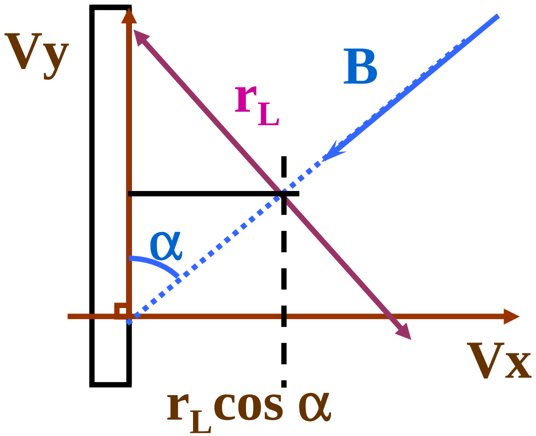
Parallel Mach number

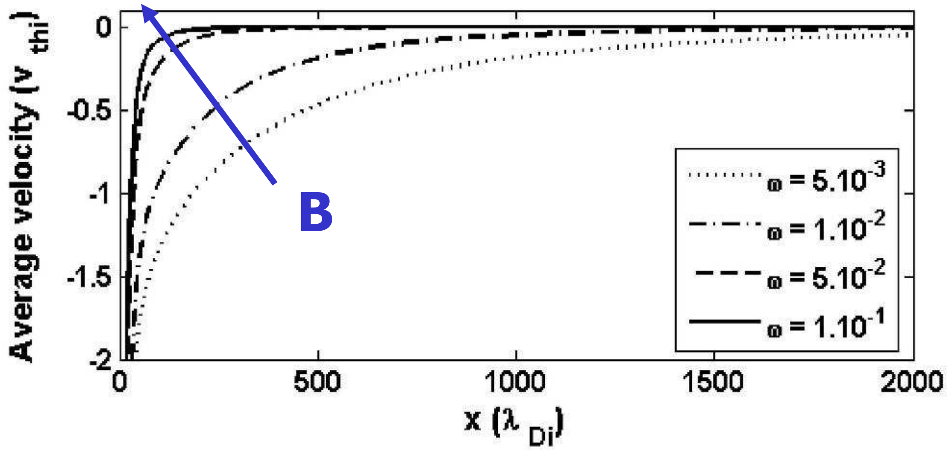




Magnetic presheath width I.

- Magnetic presheath width ∝ ion Larmor radius ∝ **1/B**
- Criterion for the magnetic presheath edge
  - MP edge: ions start being collected at the wall
  - Therefore, velocity perpendicular to B becomes nonnegligible

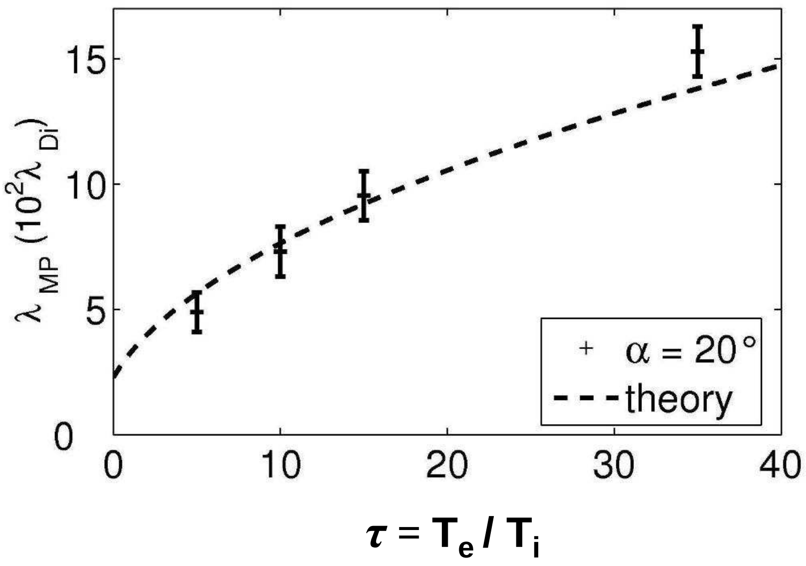




MP width decreases with increasing B

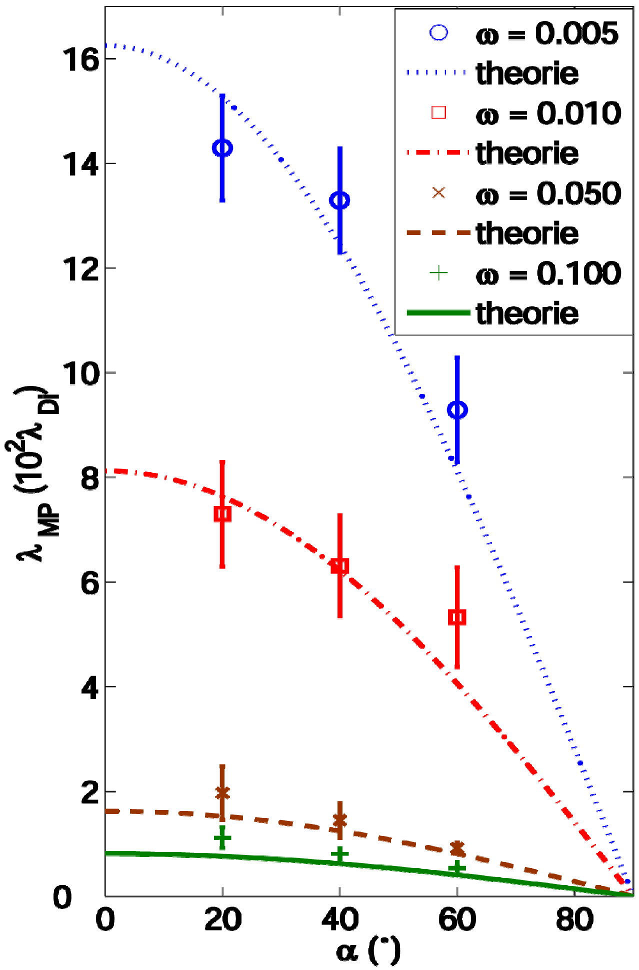
Magnetic presheath width II.

Theoretical estimate: $\lambda_{MP}^{th} \approx \sqrt{6}\cos\alpha \frac{\tau^{1/2}}{\omega}\lambda_{Di}.$



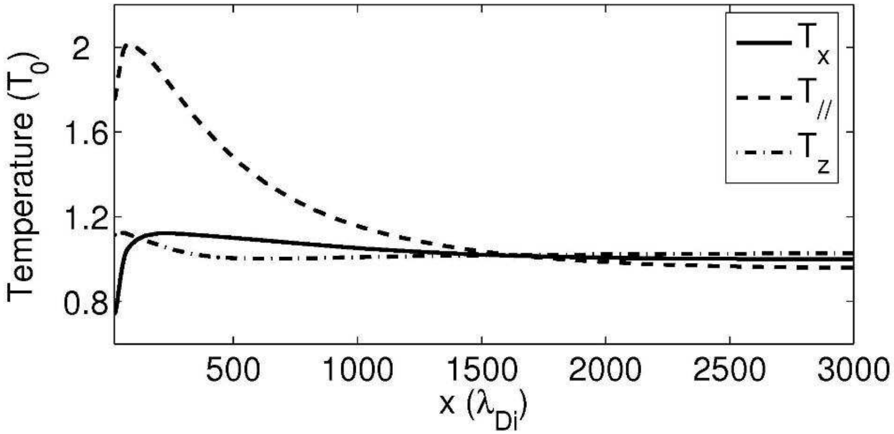
Good agreement between numerical, theoretical, and exp. results

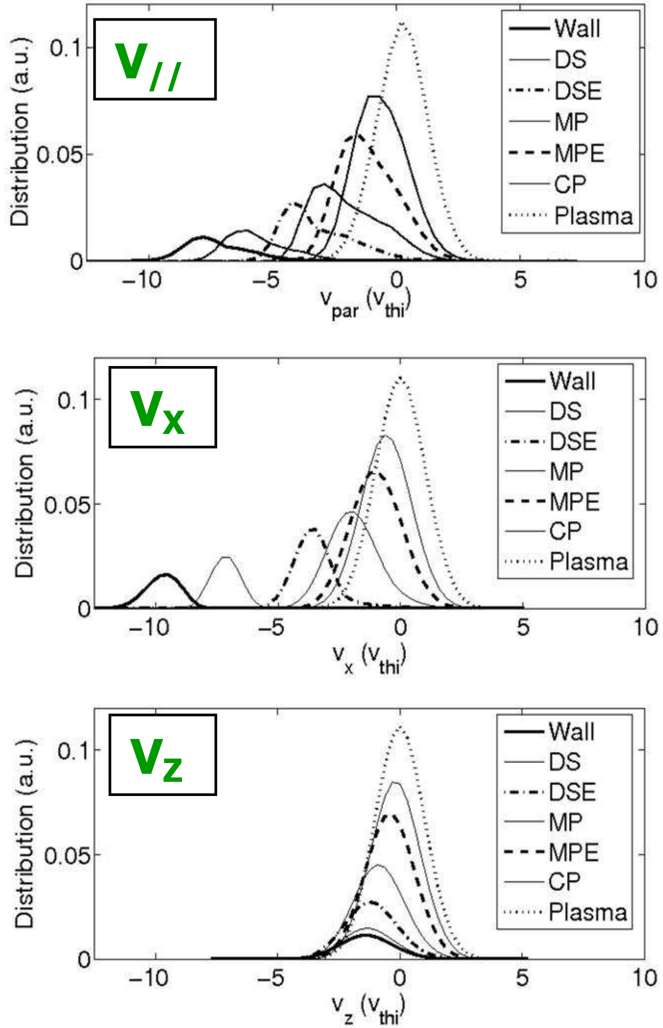
$\omega = \omega_{ci} / \omega_{pi}$



Magnetic presheath: temperature profiles

- Temperature increases near the wall
- Same mechanism as in unmagnetized plasma



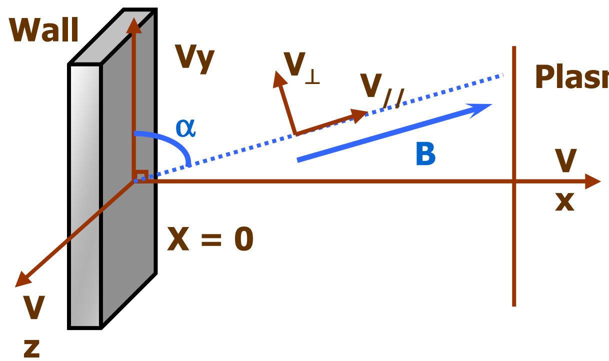


E X B drift

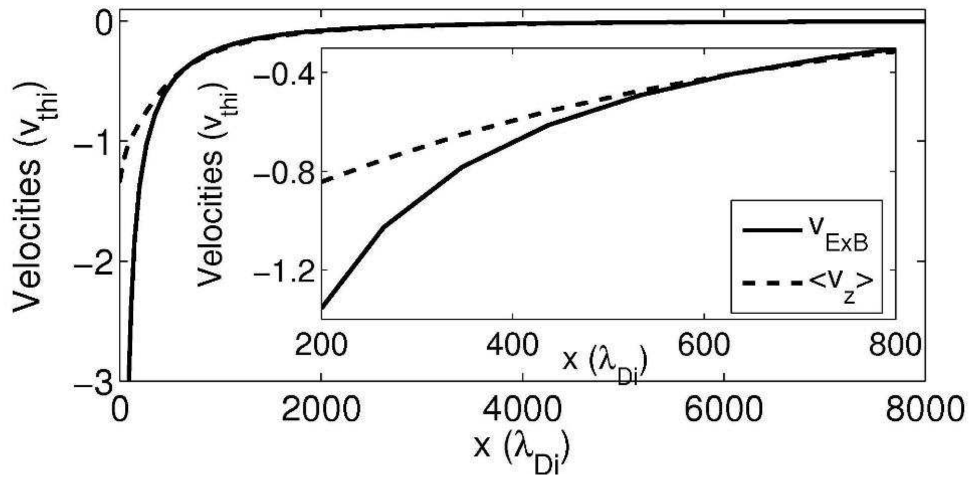
- The E X B drift is directed along the z direction

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2} = \frac{E_x(x)\cos\alpha}{B}\hat{z}.$$

- V_z and V_E coincide in the collisional presheath, but start diverging in the magnetic presheath
- Guiding-center approach invalid in the MP and DS



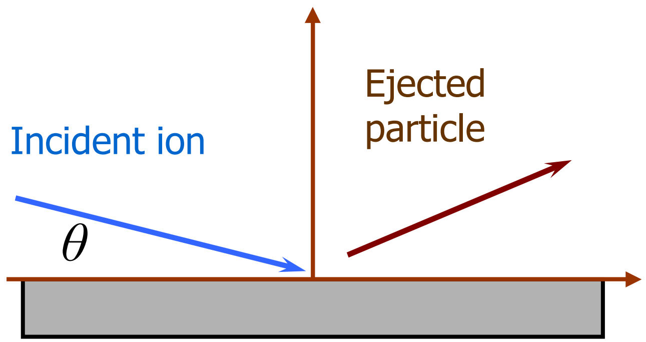
Profile of the velocities Vz and V_E



Wall sputtering and erosion

Sputtering yield Y depends on :

- Angle of incidence on the wall: θ
- Kinetic energy: E_{kin}

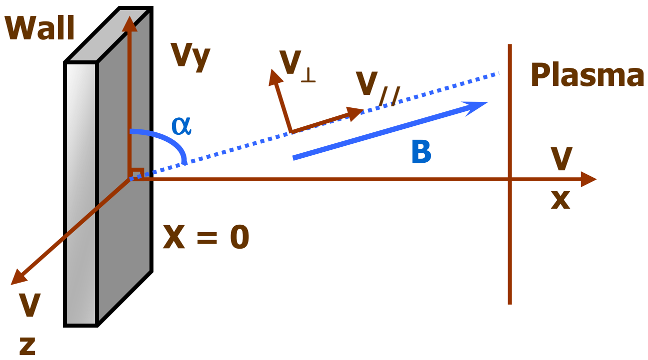


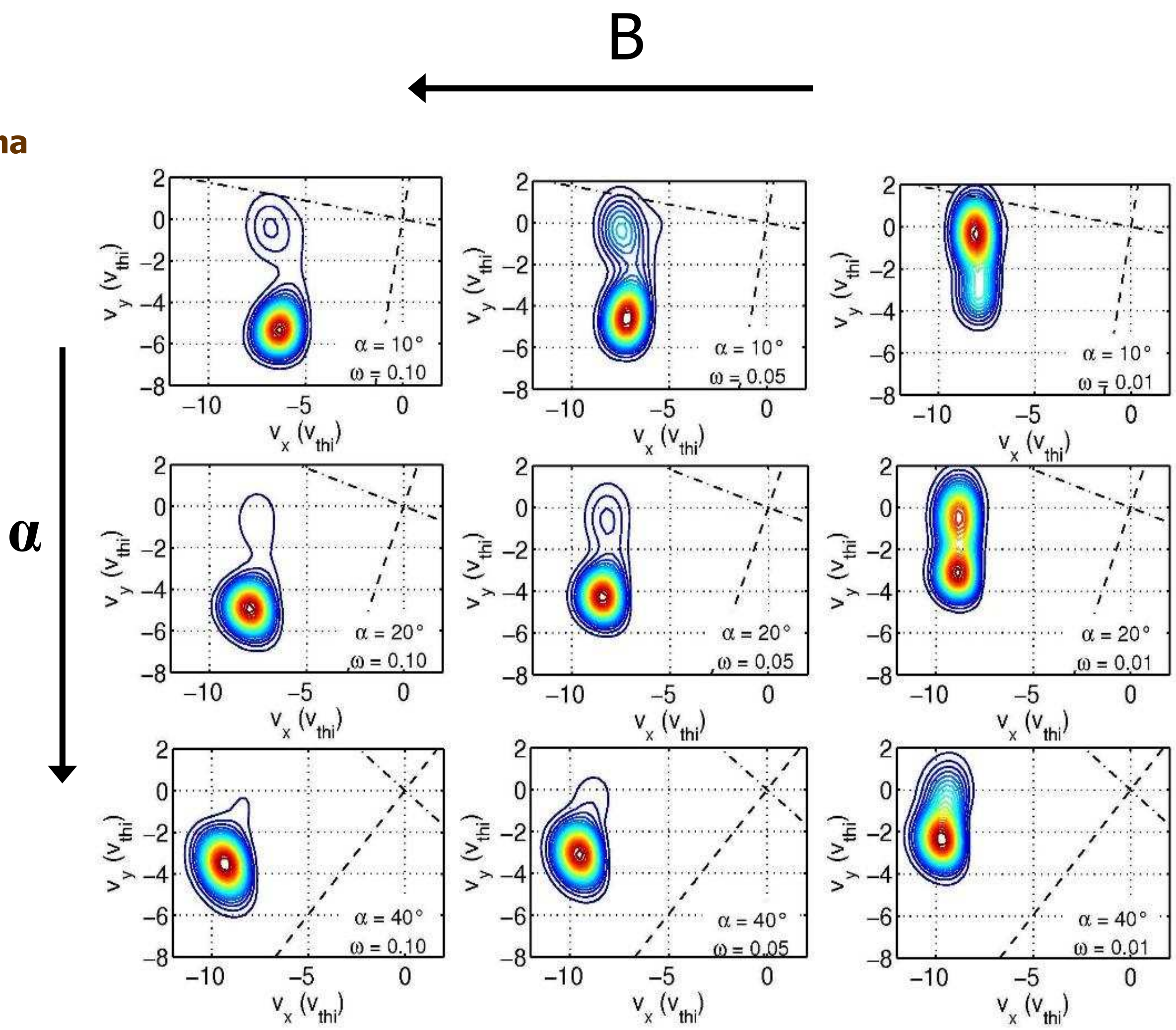
$$Y(\alpha, \omega) \propto \int_0^\infty \int_0^{\pi/2} \frac{E_{\text{kin}}}{\sin\theta} F(\theta, E_{\text{kin}}) \mathrm{d}\theta \, \mathrm{d}E_{\text{kin}}$$

α = angle of incidence of the magnetic field

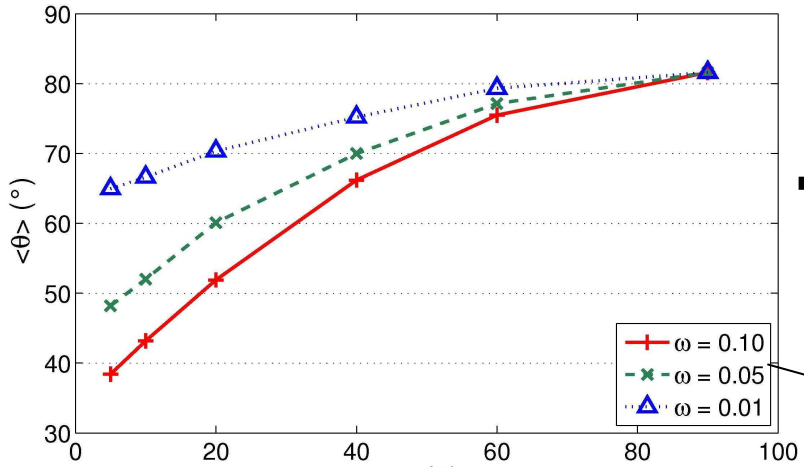
$F(\theta, E_{kin})$ = distribution function in angle/energy variables

$\omega = \omega_{ci} / \omega_{pi}$


Wall
Vy
V⊥
V//
Plasma
α
B
V
x
X = 0
V
z


B
α
α = 10°
ω = 0.10
α = 10°
ω = 0.05
α = 10°
ω = 0.01
α = 20°
ω = 0.10
α = 20°
ω = 0.05
α = 20°
ω = 0.01
α = 40°
ω = 0.10
α = 40°
ω = 0.05
α = 40°
ω = 0.01
vx (vthi)
vy (vthi)

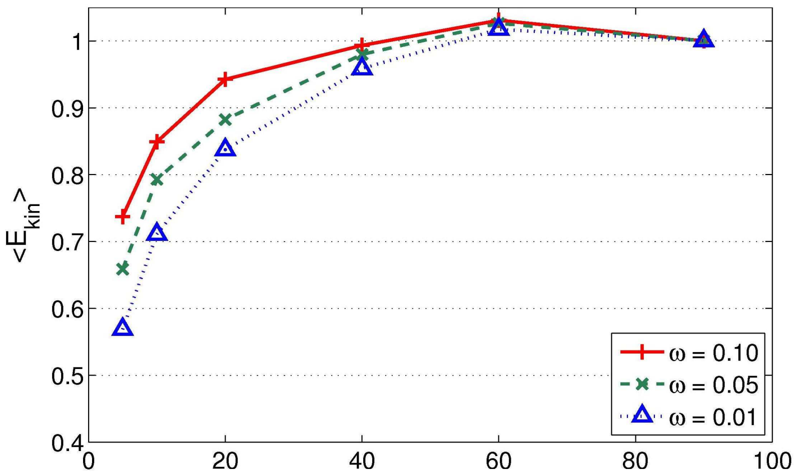
Results: angle of incidence and kinetic energy on the wall



α = angle of incidence of magnetic field

Average angle of incidence on the wall, $<\theta>$

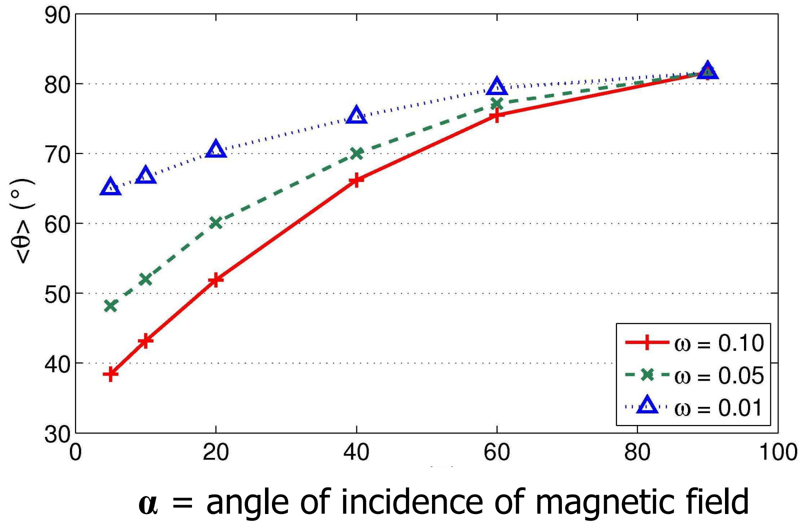
$\omega = \omega_{ci} / \omega_{pi}$

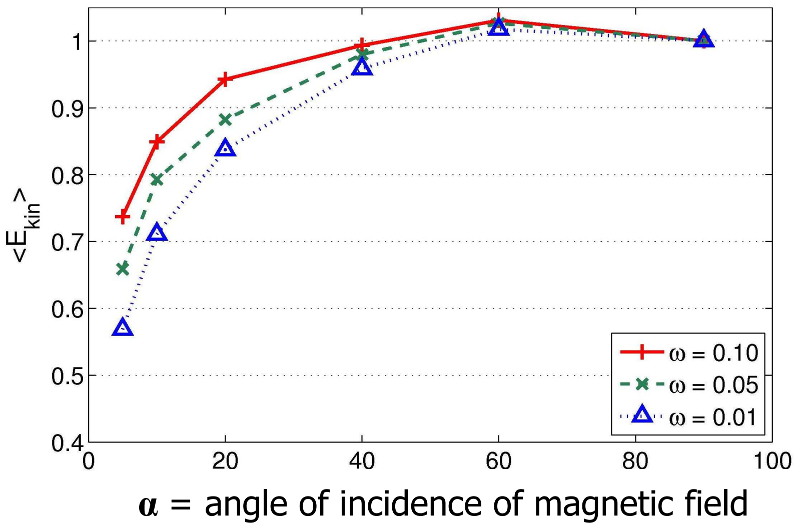


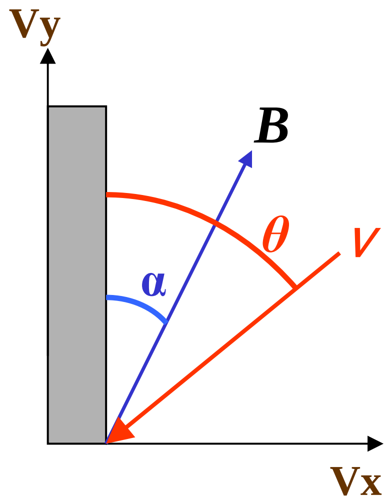
α = angle of incidence of magnetic field

Average kinetic energy on the wall, $<E_{kin}>$

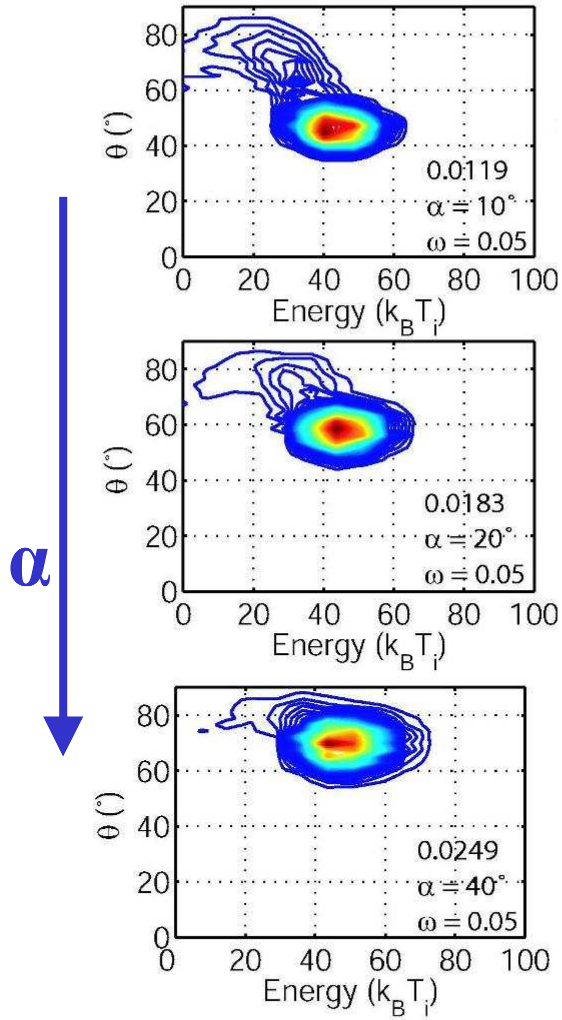
Results: angle of incidence and kinetic energy on the wall





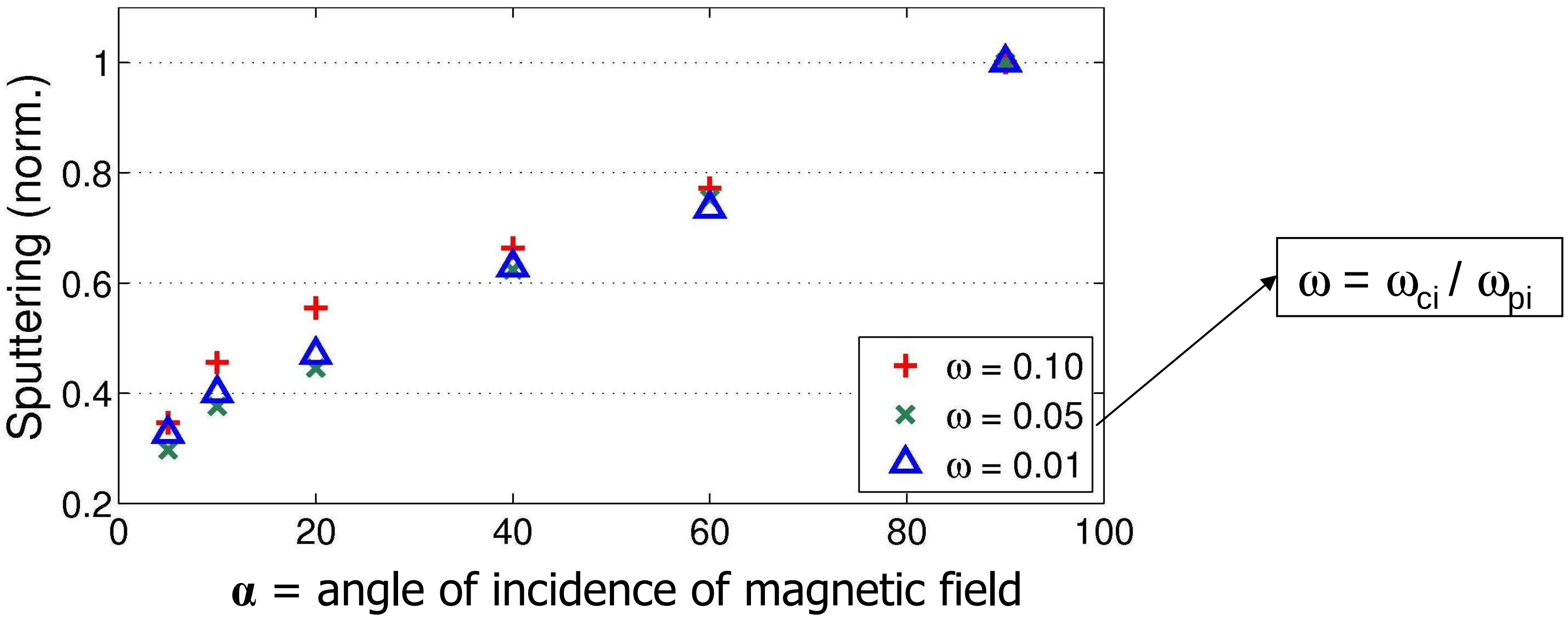


θ > α !



Sputtering yield on the wall

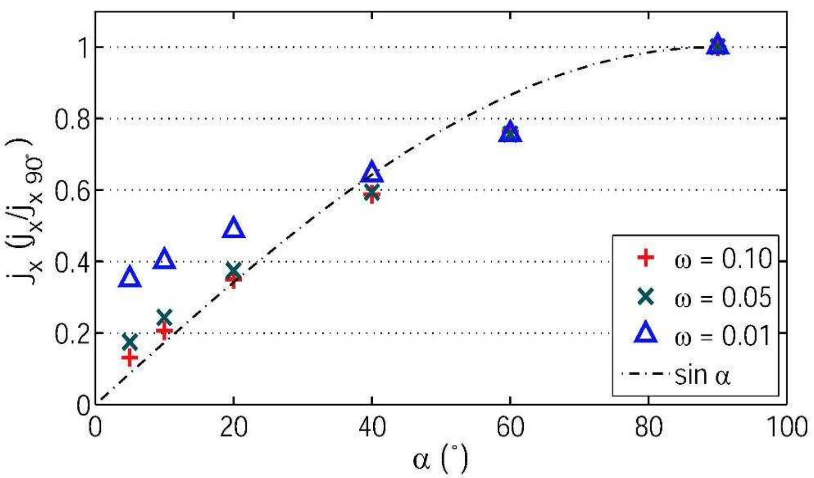
$$Y(\alpha, \omega) \propto \int_0^{\infty} \int_0^{\pi/2} \frac{E_{\text{kin}}}{\sin\theta} F(\theta, E_{\text{kin}}) \mathrm{d}\theta \, \mathrm{d}E_{\text{kin}}$$



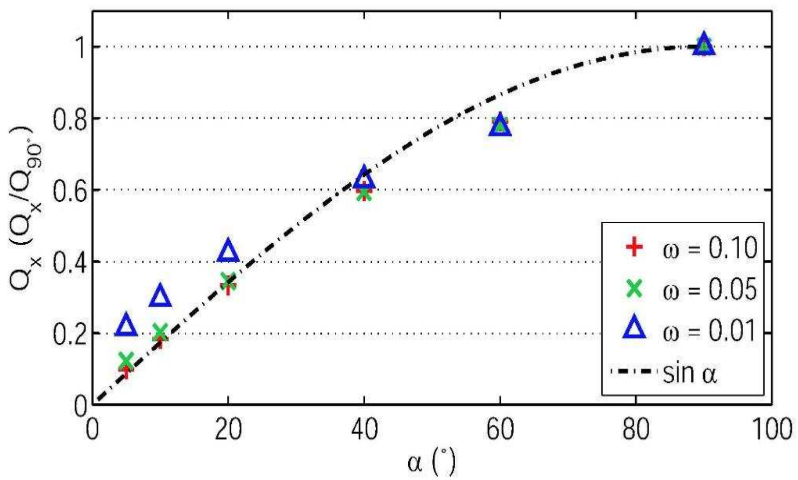
Heat and particles fluxes on the wall

- For large enough magnetic field, the fluxes follow a ‘sin α’ law

Particles flux



Heat flux



Conclusions

- Kinetic model for ion population – Vlasov code
- Full description of the magnetized plasma-wall transition
  - Colllisional presheath, magnetic presheath, Debye sheath
- Experimental validation
- Applications: computed distributions allow calculation of:
  - Energy and angle of incidence of ions on wall
  - Sputtering yield
  - Particles and heat fluxes on wall
- Perspectives
  - Dynamical formation of sheaths
  - Two-species plasmas (DT, impurities, …)

- S. Devaux, G. Manfredi, Phys. Plasmas **13**, 083504 (2006).
- S. Devaux, G. Manfredi, Plasma Phys. Control. Fusion **50**, 025009 (2008).