Collisional sheath, impact on ITER divertor plasma and power exhaust

Based on PSI presentation by D. Tskhakaya[1], R.A Pitts[2]

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Assumptions

[1] R. Chodura, Phys. Fluids (1982)

- Plasma sheath is collisionless[1]
- …

What can change for the collisional sheath?

$$\Gamma_i = M_{\parallel} n c_s \qquad \Gamma_e = \Gamma_0 \exp\left(-e\Delta\phi / T_e\right) \qquad e\Delta\phi \approx T_e \ln\left(\sqrt{m_i / m_e 4\pi} / M_{\parallel}\right)$$

$$M_{\parallel} = \frac{V_{\parallel,i}}{c_s} \geq 1$$

$$q_t = q_{t,plasma} + q_{t,recomb.} + q_{t,neutrals} + q_{t,rad.} \qquad q_{t,plasma} = \gamma_t T_e \Gamma_i \qquad q_{t,recomb.} = R\Gamma_i$$

$$q_{t,plasma} = q_{SE,plasma} + \Delta\phi J \neq q_{SE,plasma}$$

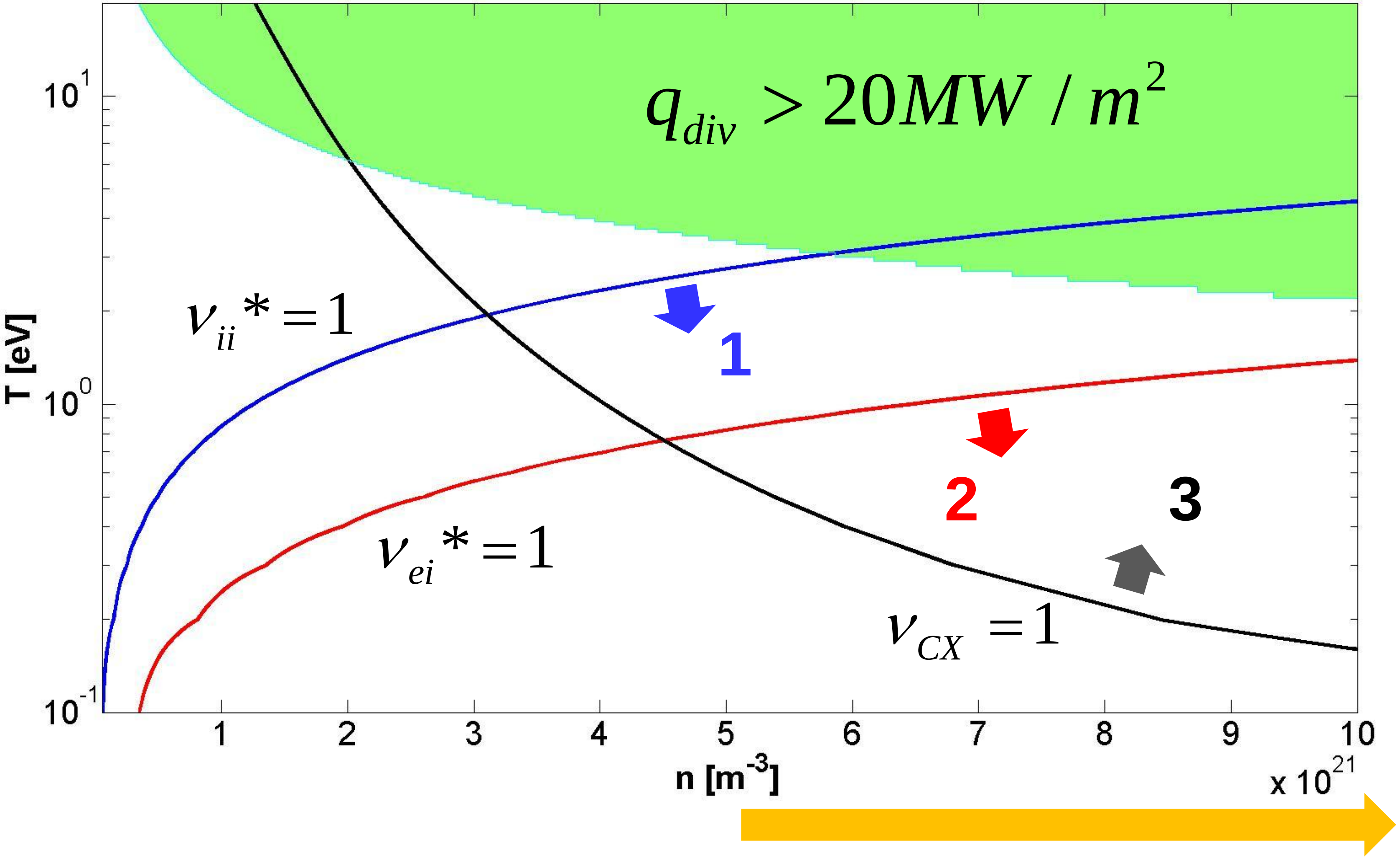
Surface recombination energy

$$R = 13.6 + R_{molecular}\ (3 \div 5 eV)$$

$$\gamma_t \neq \gamma_{SE} = q_{SE} / \Gamma_i T_e \qquad \gamma_t \approx 2.0\left(1 - \frac{J}{J_{i,sat}}\right) + 2.5 + e\Delta\phi / T_e + M_{\parallel}^2$$

Sheath collisionality

$B = 5\ [T],\ \theta = 3°,\ n_{neutr.} = 0.3 n_e$



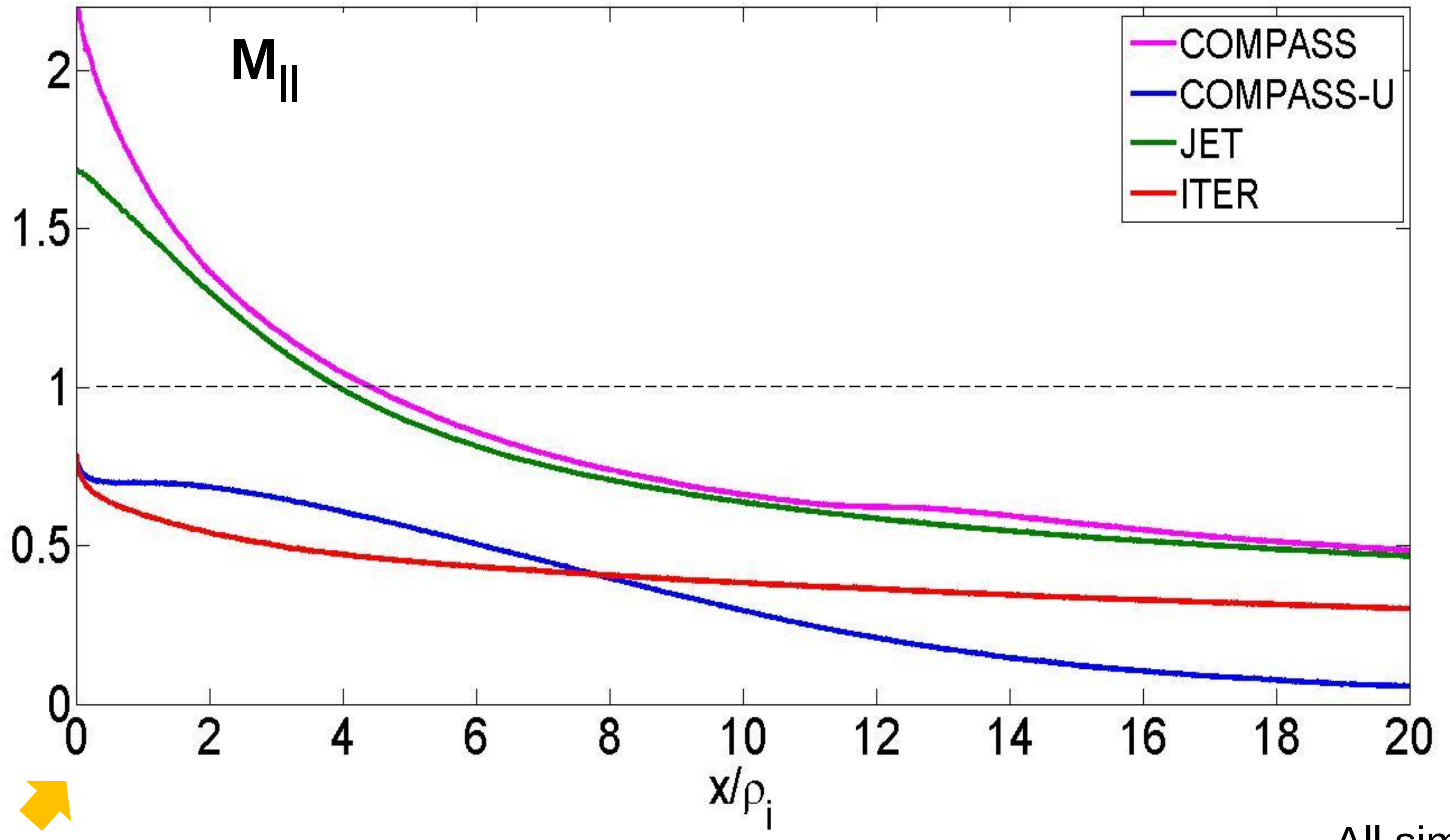
$$\nu_{ii}* = \frac{\nu_{ii}}{\Omega_i} \qquad \nu_{cx}* = \frac{\nu_{cx}}{\Omega_i \sin\theta}$$

$$\nu_{ei}* = \frac{\nu_{ei}}{\Omega_i \sin\theta}$$

1	Ion de-magnetization
2	Electron-ion collisional sheath
3	CX collisional sheath

ITER, BEST, DTT, SPARC, STEP, COMPASS-U, …

Profiles of Mach number



Divertor surface

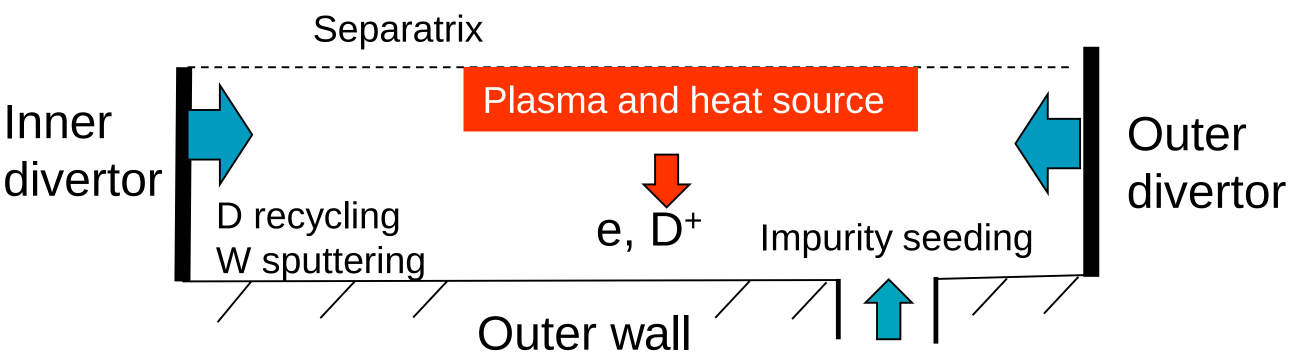
For $n_{SE} > 10^{21}$ m^{-3}

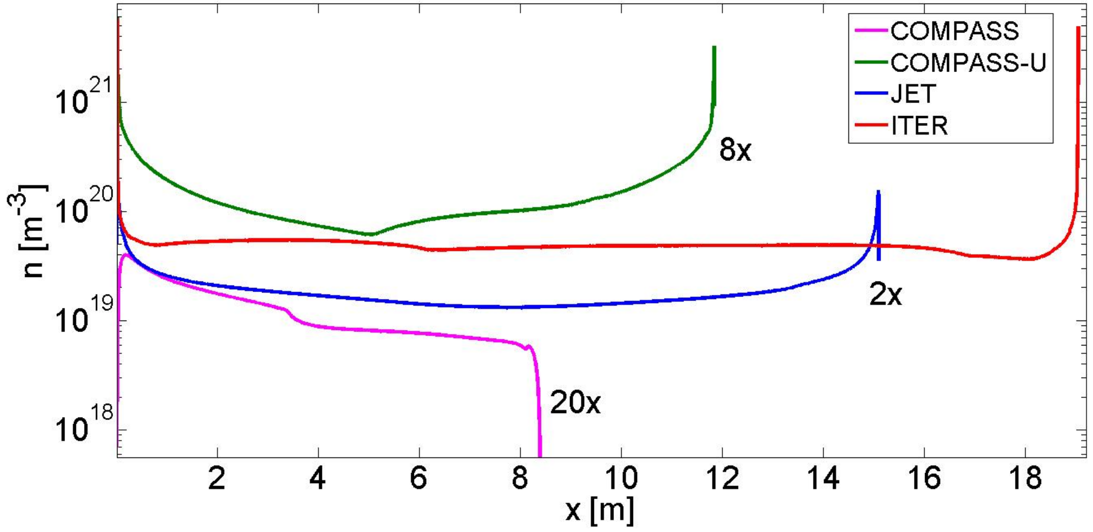
$M_{||} < 1$

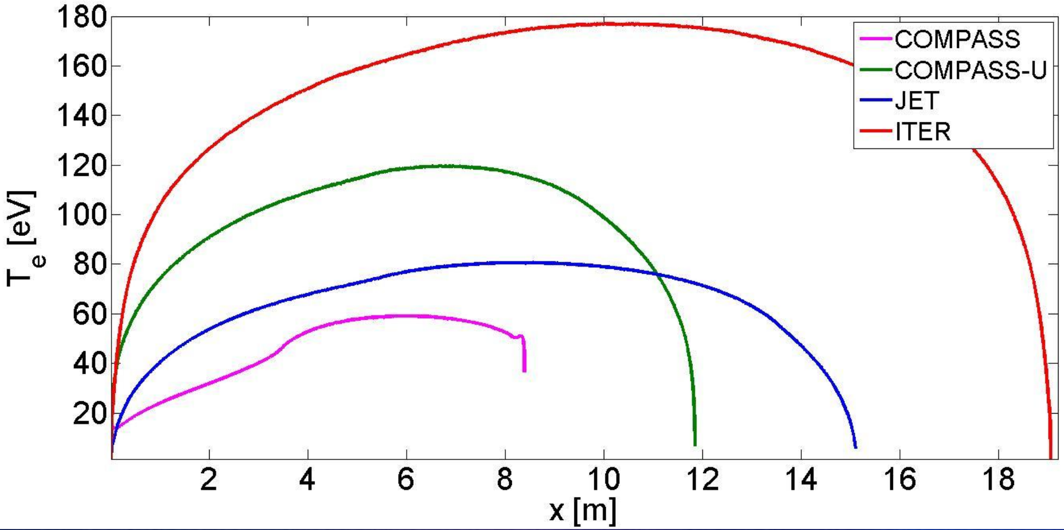
- How can these results be explained?
- How should the SE be defined?
- Do other sheath parameters also change?

All simulations discussed in this work were performed via **PIC MC code BIT1**

PIC model: BIT1







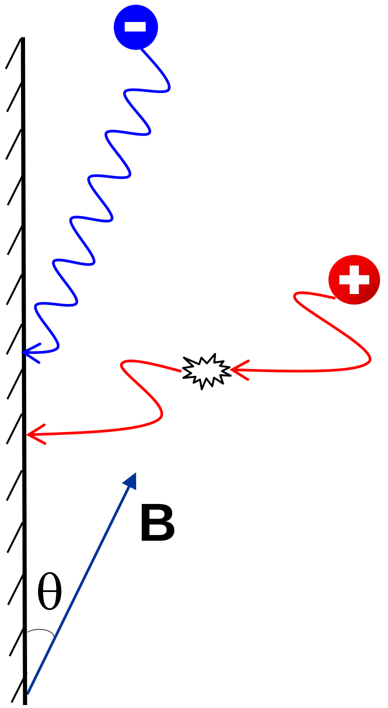
- ✓ 1D3V nonlinear transport of plasma, impurity and neutral particles
- ✓ Atomic processes: exact cross-sections and rate coefficients; DCSM model – millions of transition channels (no-coronal model). Nonlinear operators conserving particles, momentum and energy.
- ✓ Energy and angular dependent PSI processes
- ✓ More than 10^9 time steps per run
- ✓ Validated at JET, TCV, ASDEX, COMPASS (e.g. [1-4])

1. D. Tskhakaya, et al., J. of Nucl. Materials, 415, (2011)
2. D. Tskhakaya, et al., Nucl. Mater. and Energy, 26, (2021)
3. J. Horacek, et al., Nucl. Fusion 63 (2023)
4. I. Borodkina, et al., Nucl. Fusion, 64 (2024)

Why subsonic?

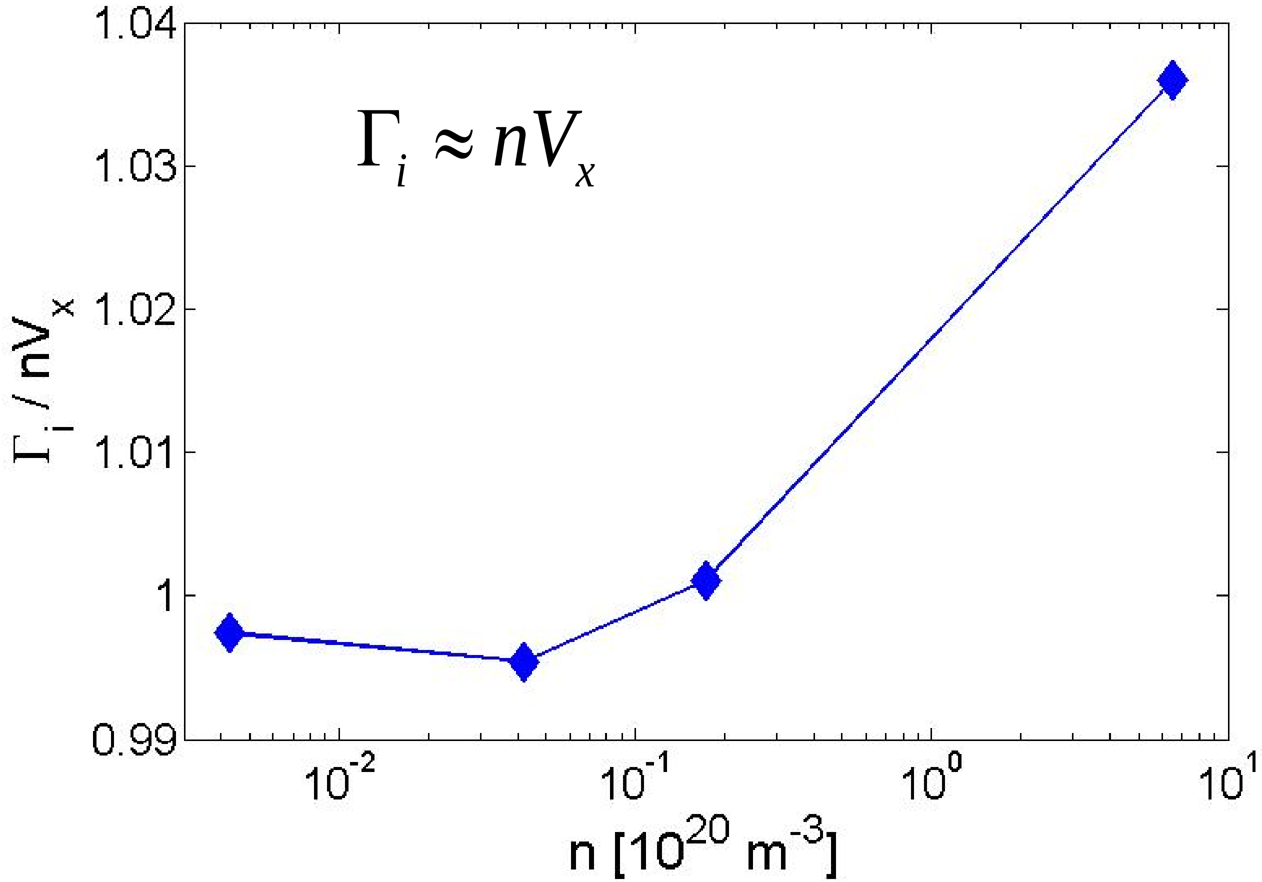
Diffusive sheath? $\Gamma_i = nV_x + \Gamma_{diff}$?

[D. Tskhakaya, PSI 2018]

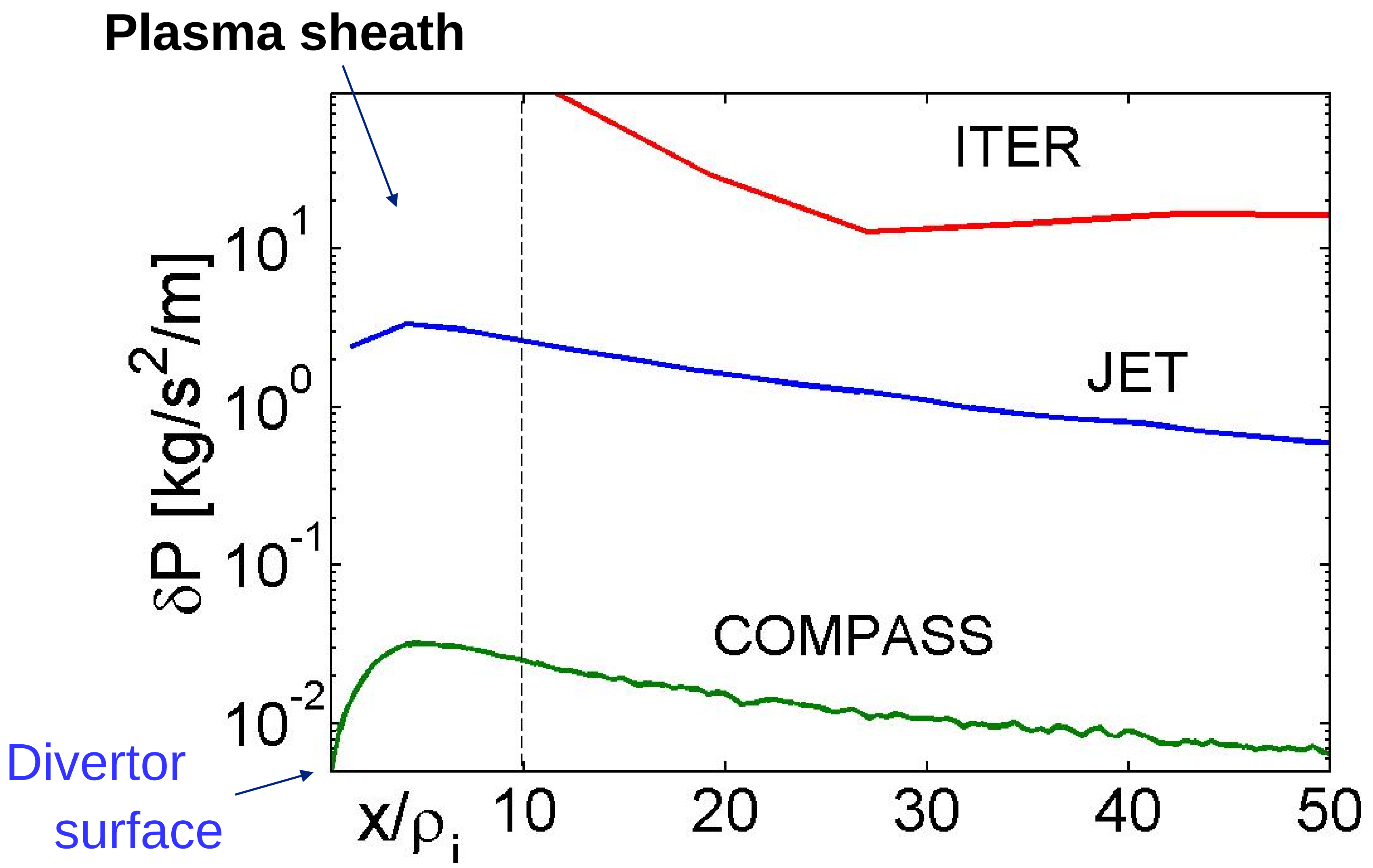


Collisional sheath!

[D. Tskhakaya, 47th EPS, 2021]



Main ion momentum losses in the sheath



Strong electron–ion and ion–neutral frictions **prevent** ions from reaching the sound speed

Re-definition of the sheath edge

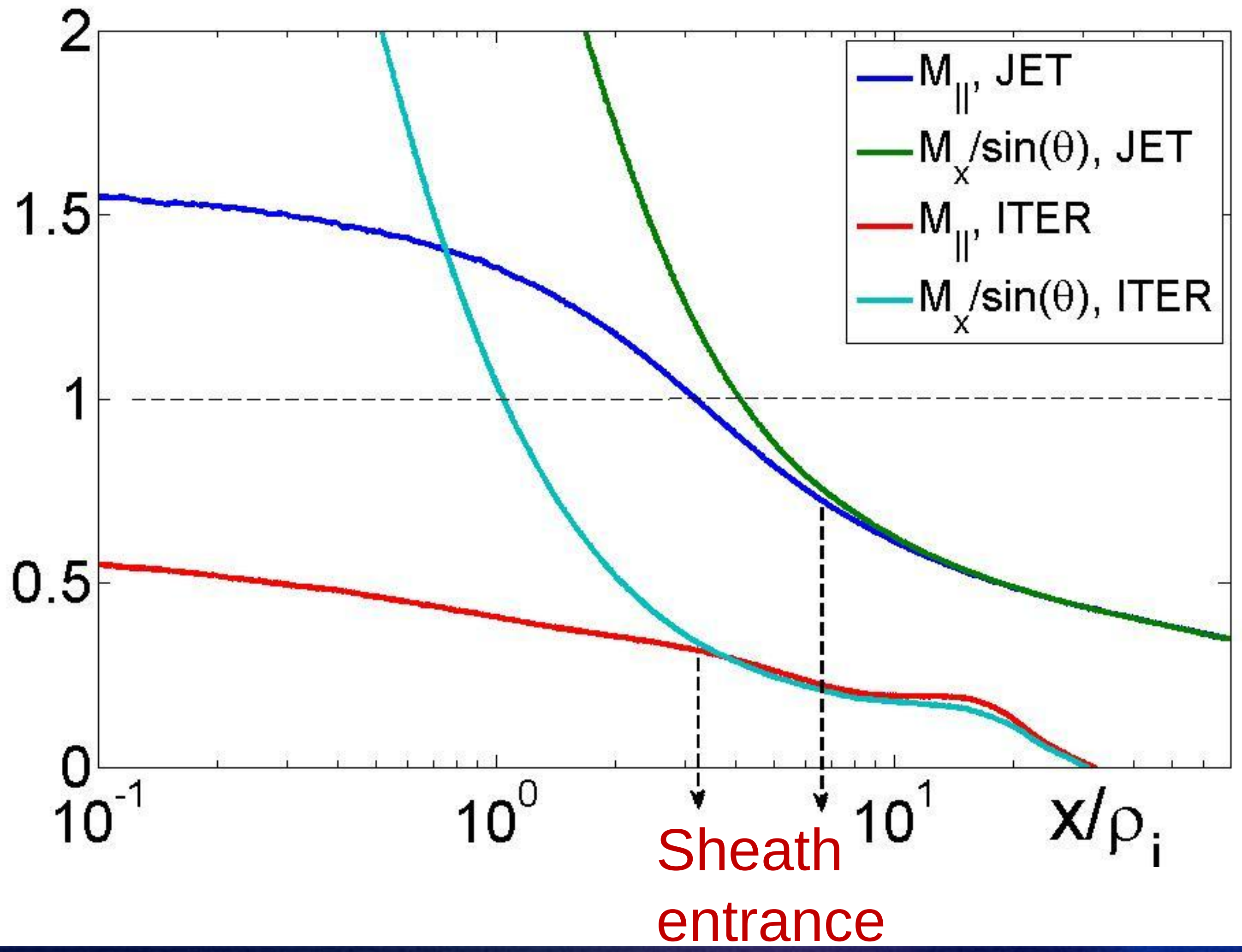
Classical sheath

- $M_{\parallel} = 1$
- Plasma (1D) is magnetized when

$$M_{\parallel} = \frac{M_x}{\sin(\theta)}$$

Collisional sheath (proposal)

We define the magnetic sheath entrance (SE) as **a point nearest to the wall surface, where ions are still magnetized**



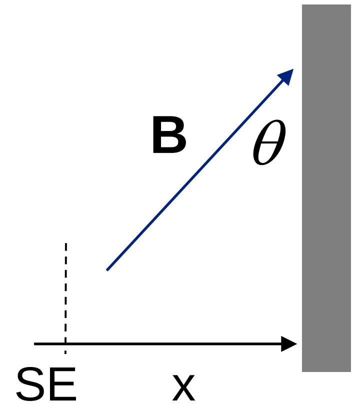
Analytic model of the collisional sheath

Particle and momentum conservation equations

$$\vec{\nabla} n \vec{V} = 0, \qquad |\nabla \ln T| << |\nabla \ln n|, \qquad |\vec{\nabla} \vec{\vec{\pi}}| \sim \tau_{col}, \ \upsilon_i \ (T_e < 10\, eV)$$

$$m_i \vec{V} \vec{\nabla} \vec{V} = e\vec{E} + e\vec{V} \times \vec{B} - T \vec{\nabla} n / n - m_i \upsilon_{mt} \left(\vec{V} - \vec{V}^n \right) - m_i \upsilon_{ei} \vec{J} / en$$

$$eE_x = -T_e \partial_x n / n$$



$$\left(\left(1 + \nu_{ei}^{*2} \right) / M_{\parallel}^2 - 1 \right) \partial_x M_{\parallel} = \upsilon_{CX}^* A + \nu_{ei}^* B$$

Classical model

$$\partial_x \to \infty \Rightarrow \left(1 / M_{\parallel}^2 - 1 \right) = 0$$

Generalized model

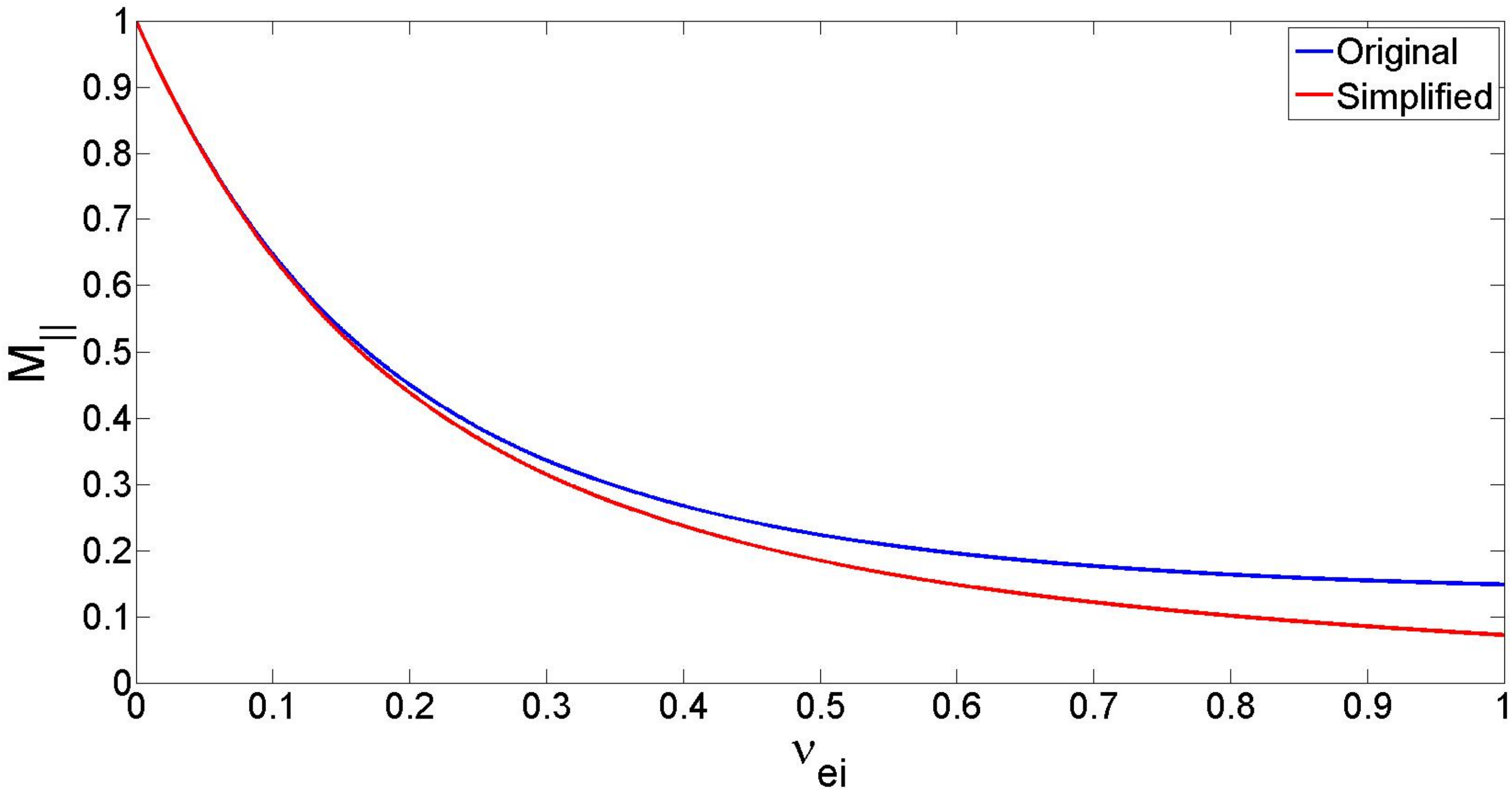
$$M_{\parallel} = 1 + \nu_{ei}^{*2} / 2 + \chi - \sqrt{\chi^2 + \left(2 + \nu_{ei}^{*2} \right) \chi + \nu_{ei}^{*4} / 4}$$

$$\delta \sim 1$$

$$\chi = \frac{1}{2} \left(\delta \sin^2 (\vartheta) \nu_{CX}^* + \nu_{ei}^* \right) x_{SE}$$

Independent to the current

Analytic model of the collisional sheath (ii)



- ✓ **The boundary value of the Mach number decreases rapidly with increasing collisionality**
- ✓ **The simplified expression of the Mach number well-reproduces the original one**

If we neglect nonlinear terms

$$M_{||} = 1 + \chi - \sqrt{\chi^2 + 2\chi}$$

$$\chi = \frac{1}{2}\left(\delta \sin^2(\vartheta)\nu_{CX}^* + \nu_{ei}^*\right)x_{SE}$$

Sheath parameters (from PIC model)

	COMPASS ID / OD	COMPASS-U ID / OD	JET ID / OD	ITER ID / OD	Classical
ν_{ei}^*	$2.0\mathrm{x}10^{-3}$ / $5\mathrm{x}10^{-5}$	0.094 / 0.026	$5.5\mathrm{x}10^{-3}$ / $2.2\mathrm{x}10^{-3}$	0.28 / 0.22	0.0
$e\Delta\phi/T_e$	7.21 / 1.94	1.83 / 2.92	3.25 / 3.63	2.33 / 2.31	2.8
$M_{\|\|}$	1.0	0.40 / 0.49	1.0	0.30 / 0.37	1.0
E_i	15.0/ 6.05	2.67 / 4.69	8.27 / 10.2	3.50 / 3.58	6.3
γ_{pl}	11.7 / 13.2	4.84 / 7.63	19.8 / 19.0	4.90 / 5.0	8.3

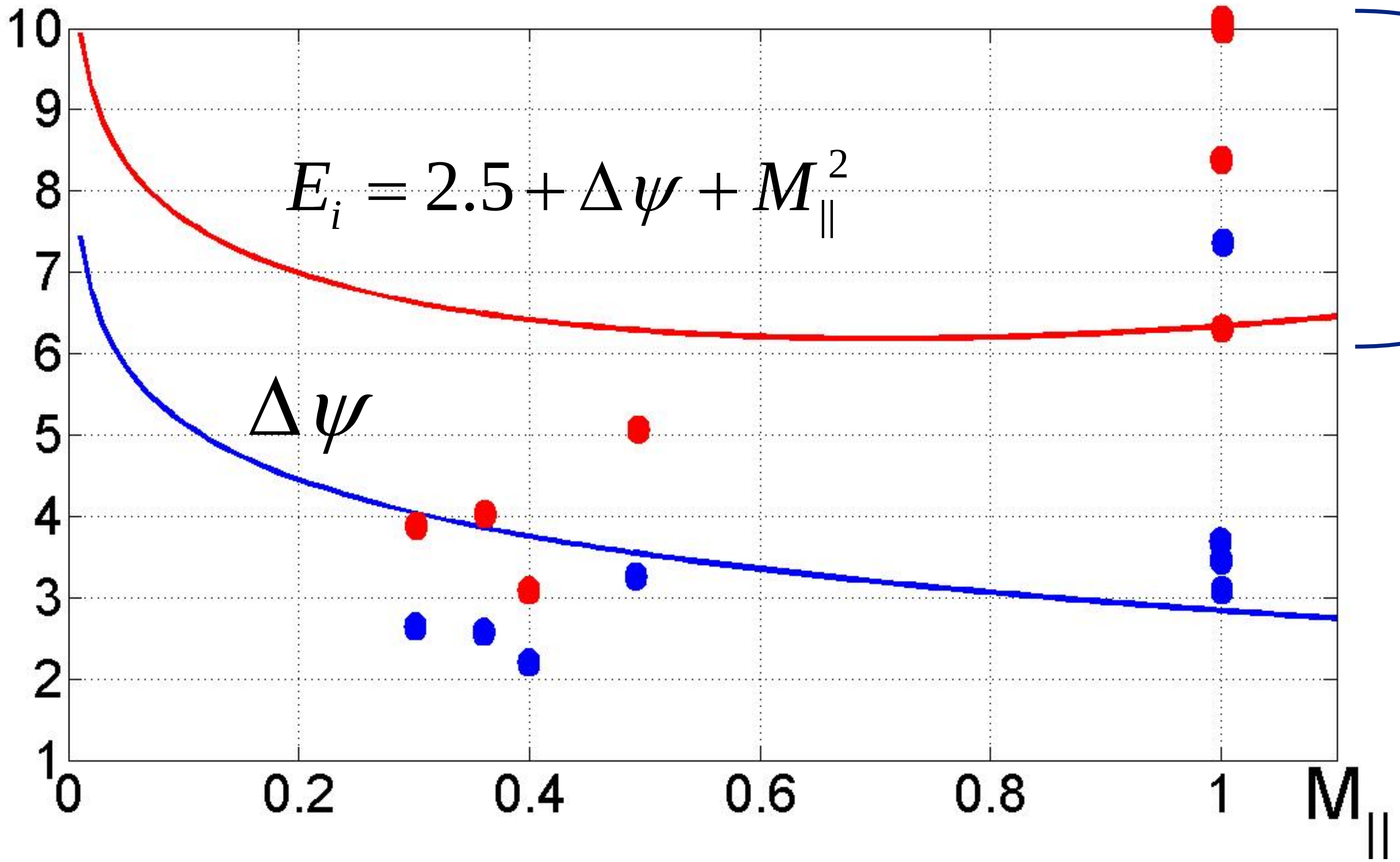
- Collision effects
- Super-thermal particle effects

$$E_i = \langle q_{i,div} \rangle / F_i T_i \,, \qquad \gamma_{pl} = 2.0 + E_i$$

$$J = 0, \quad T_e = T_i \quad \leftarrow \text{ assumptions}$$

$$\nu_{ei}{}^* = \nu_{ei} / \Omega_i \sin\theta$$

PIC results vs classical model



Super-thermal electrons[1]

$$\Delta\psi = \frac{e\Delta\varphi}{T_e} \approx \Delta\psi_0 - \ln\left(M_{||}\right)$$

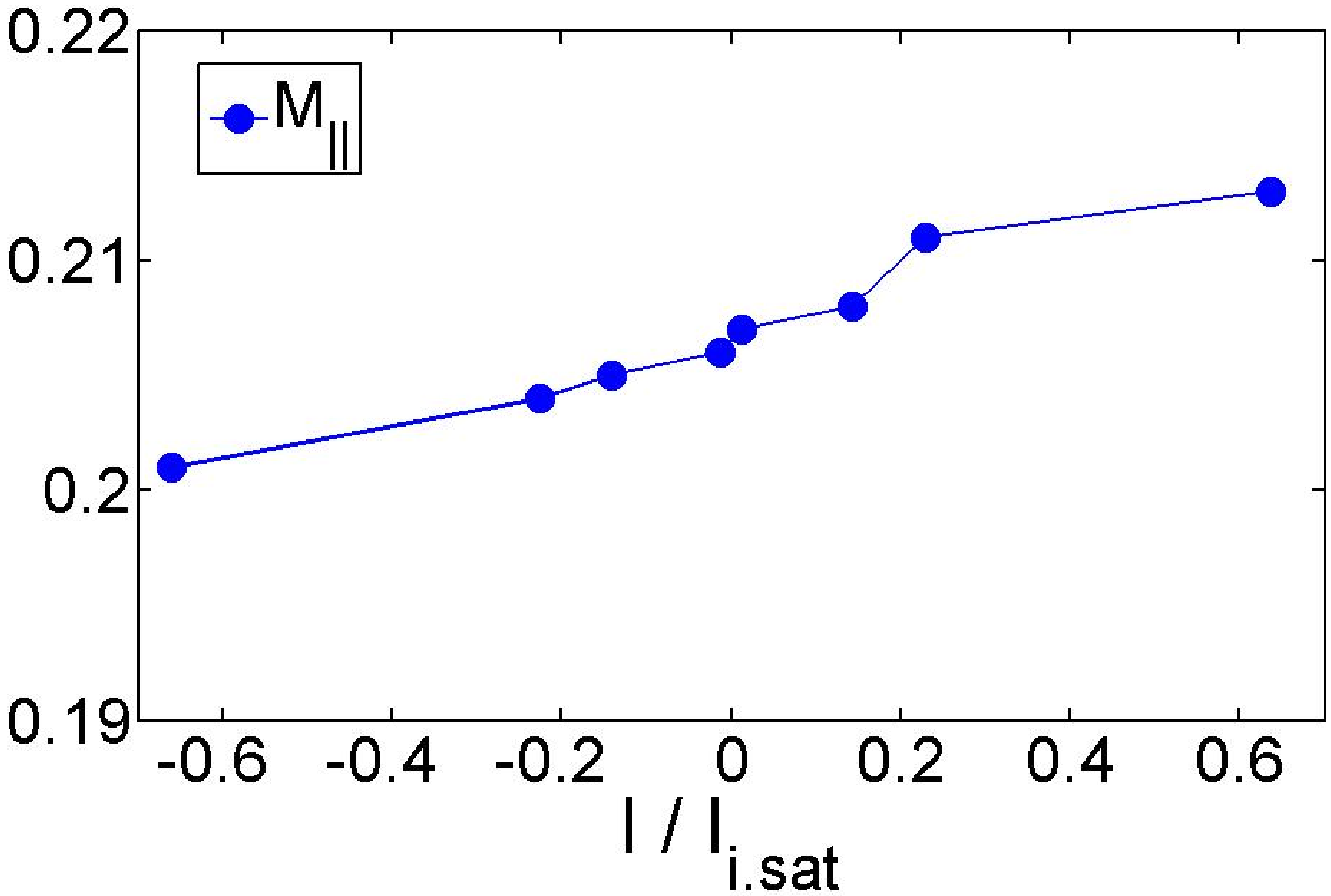
✓ The sheath potential drop is **lower** than the classical value

$$E_i = \frac{\langle q_{i,div} \rangle}{F_i T_i} \approx E_{i,0} - \ln\left(M_{||}\right) + \left(M_{||}^2 - 1\right)$$

✓ Energy of ions absorbed at the surface is **lower** than the classical one

[1] Tskhakaya, PPCF, 2017

PIC results vs classical model (ii)



Collisional sheath simulations for different current regimes

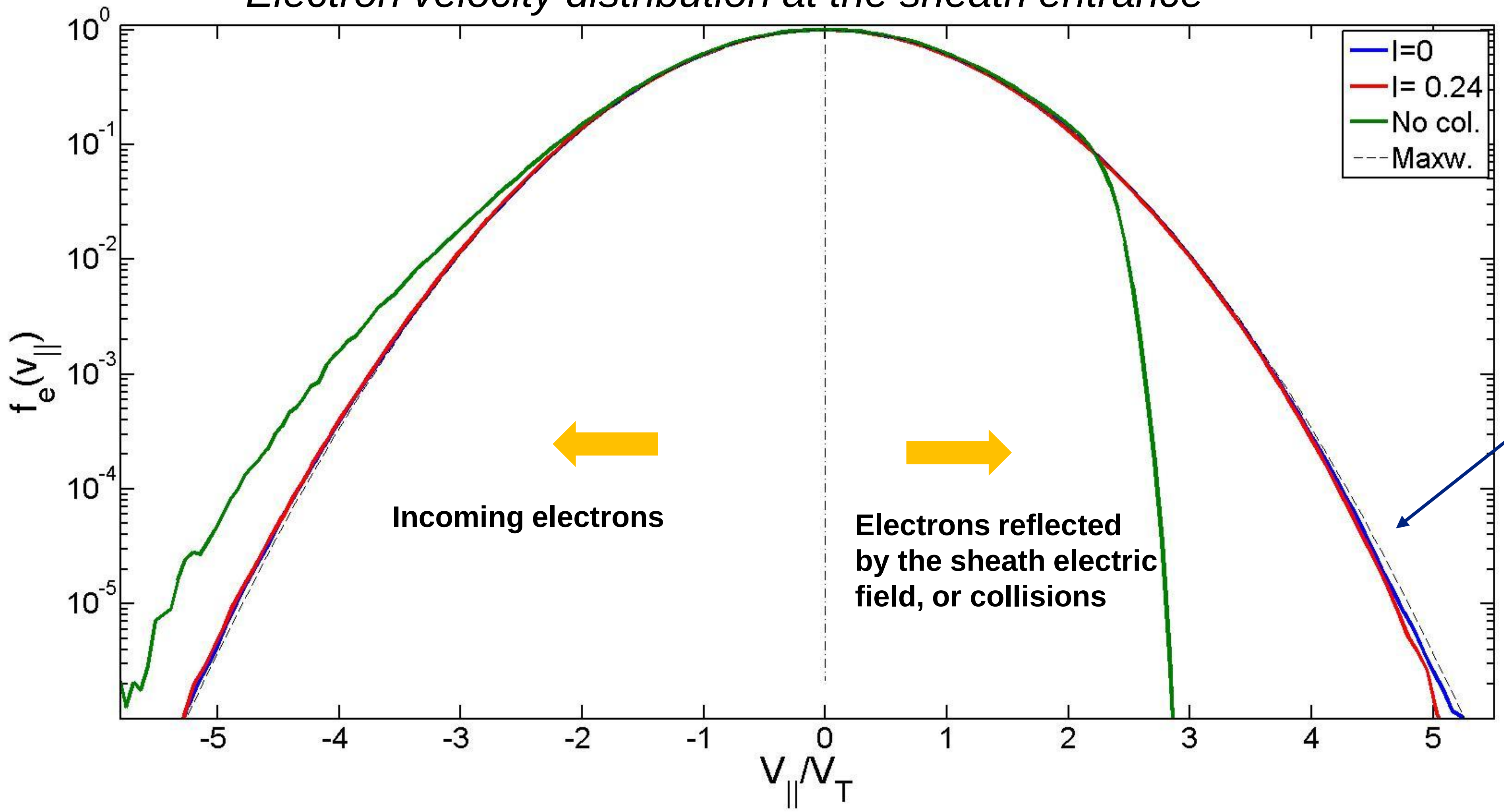
✓ Mach number is independent of the current to the wall

This appears to be inconsistent with the effects of electron–ion friction in a collisional sheath.

$$\vec{R}_{ei} = -m_i \upsilon_{ei} \vec{J}$$

Explanation of results: potential drop

Electron velocity distribution at the sheath entrance



$$F_e \sim F_i$$

Collisions fill up the electron and reduce their flux

Electron reflection by a strong sheath field is no longer required

Explanation of results: low energy of absorbed ions

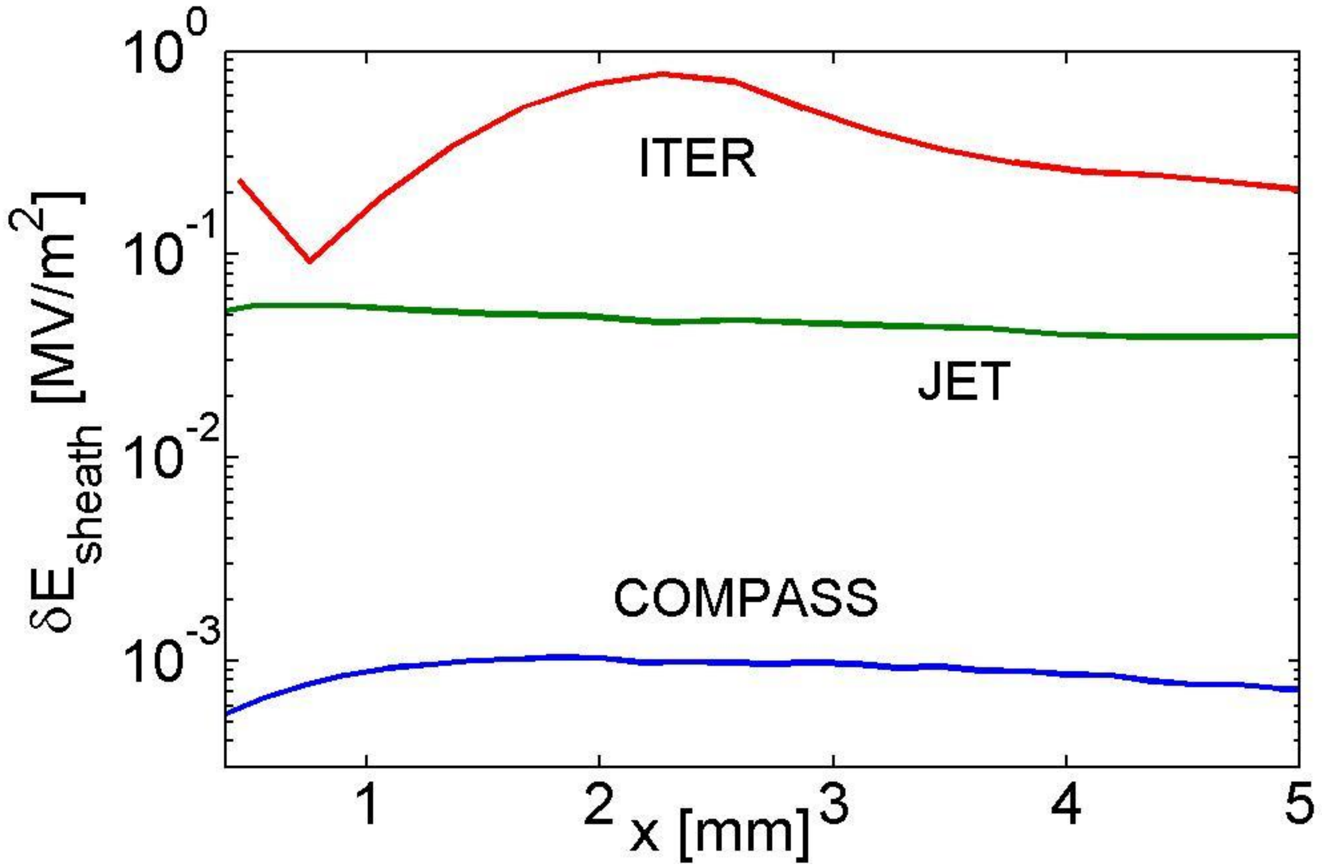
$$E_i = \left\langle q_{i,wall} \right\rangle / F_i T_i \approx 2.5 + \Delta\psi_{sheath} + M_{\|}^2 - \delta E_{sheath}$$

← Losses inside the collisional sheath

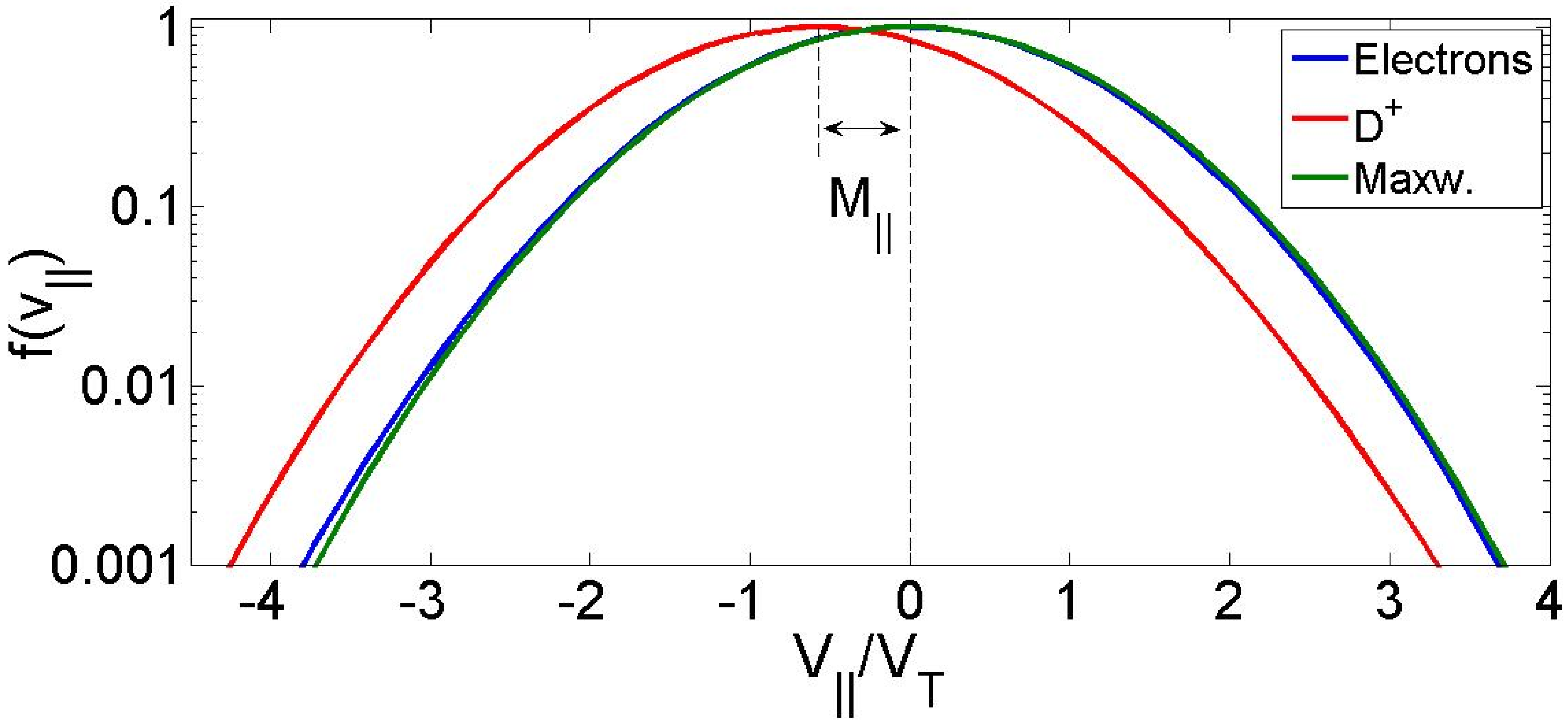
$$\Delta\psi_{sheath} < \Delta\psi_0 \approx 2.8$$

Three reasons for energy reduction

- ✓ $M_{\|} < 1$
- ✓ Reduced acceleration in the sheath
- ✓ Collision losses inside the sheath and the pre-sheath



Explanation of results:
independence from the current



Electron and ion (D^+) normalized DFs at the sheath edge (PIC simulation of ITER SOL)

There is a “constant” **shift** between the electron and the ion VDFs at the sheath edge

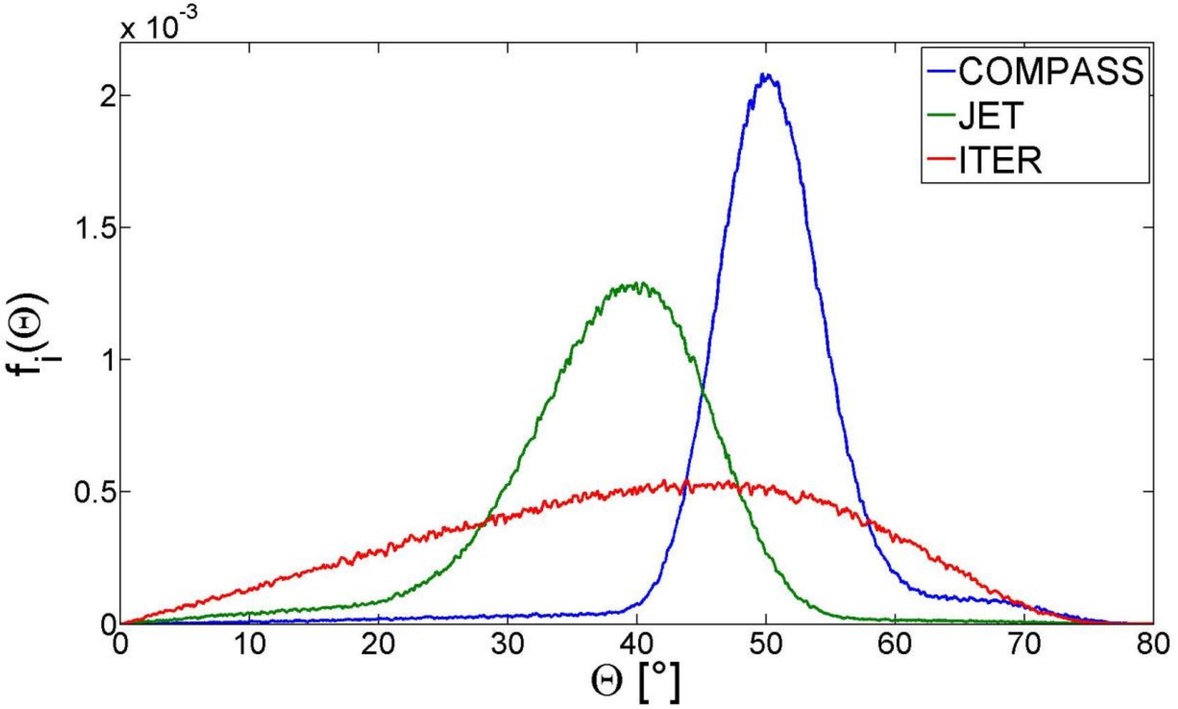
$$R_{\parallel}^{ei} = -m\upsilon_{ei}\left(V_{\parallel}^{i} - V_{\parallel}^{e}\right)$$

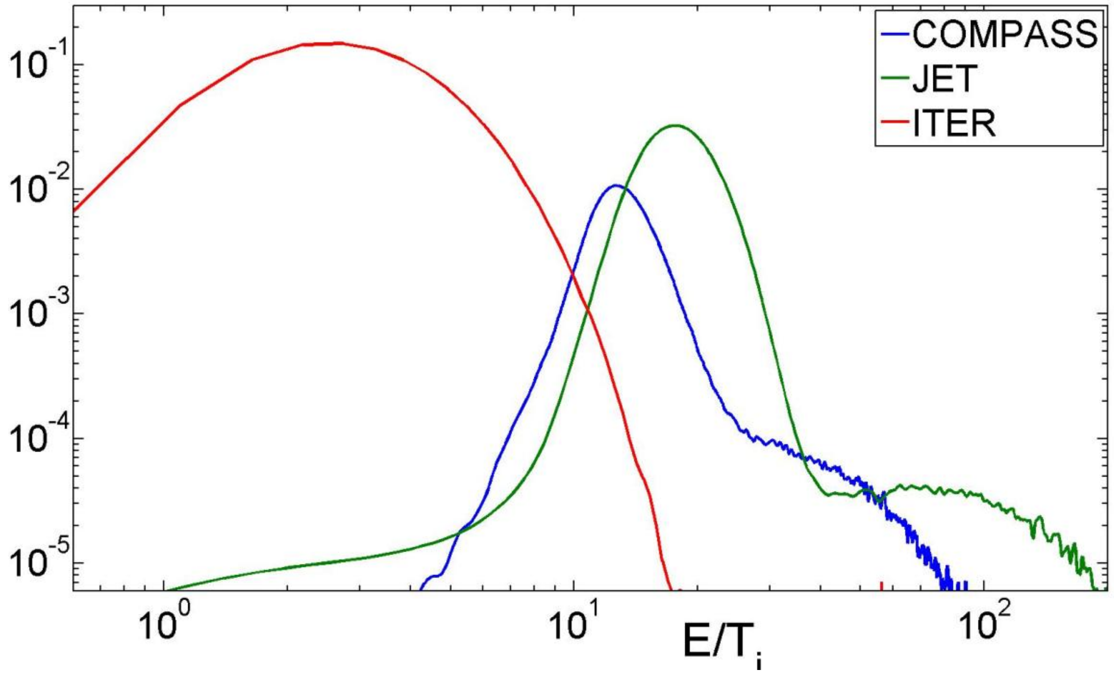
$$R_{\parallel}^{ei} \approx -m\upsilon_{ei}V_{\parallel}^{i} = m\upsilon_{ei}I_{\parallel,sat}/e$$

Electron-ion friction at the sheath edge is **independent** of the current regime

[D. Tskhakaya, PET 9, 2003]

Distribution functions of absorbed ions (D^+)





- ✓ **ADFs flatten with increasing collisionality**

Physical sputtering yields

$$\gamma(E,\vartheta) \sim E^{\alpha>1} / \sin(\vartheta)$$

- ✓ **EDFs: non-Maxwellian super-thermal ions disappear in the collisional sheath.**
- ✓ **Peaking values of D^+ ion EDF absorbed at the ITER divertor surface: $E_{i,peak} \sim 2.5\ T_i$**

Conclusions

- In high-density discharges in **next-generation fusion devices**, the divertor plasma sheath will operates in a **collisional regime**, where its parameters differ significantly from those of the classical sheath.
- The plasma flow remains subsonic. The parallel Mach number at the sheath edge (SE) is independent of the current regime and, under ITER-relevant conditions, satisfies $M_{\|} < 0.4$. Good agreement is observed between the PIC results and the new analytical model.

$$M_{\|} = 1 + \chi - \sqrt{\chi^2 + 2\chi} \qquad \chi = A\nu^*_{CX} + B\nu^*_{ei}$$

- Sheath **potential drop** is below the classical value (~3T_e); for **ITER** - $\Delta\psi \approx 2.3$ (I=0)
- Plasma and ion divertor heat loads are **significantly lower** than the classical ones. For **ITER**-relevant conditions the divertor power loads are up to **2 times lower** than the classical values.
- Angular DFs of absorbed ions are **flat**.
- **Take-home message for ITER SOL modellers:** use **updated values** for $M_{\|}$ (~0.4), γ_{pl} = 5 and **flat angular distribution** functions of absorbed ions
- **Other results not discussed above** - modified impurity and neutral particle exhaust, exotic IV characteristic