Study of detached H-modes in full tungsten ASDEX Upgrade with N seeding by SOLPS-ITER modeling

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Motivation

- Our current understanding of divertor physics indicates that at least partial detachment will be a necessary condition for operation of future fusion power devices such as ITER, DEMO and beyond.
- The transition to detachment is actively studied theoretically and experimentally.
- In recent years a divertor operation regime with complete detachment was achieved in ASDEX Upgrade with tungsten walls and nitrogen seeding [1-3], and a modeling with the SOLPS5.0 transport code reproduced the main features of these experiments [4].
- In the present work the modeling similar to [4] is performed by SOLPS-ITER code [5,6] with a focus on the analysis of the effect of drifts and currents on divertor cooling and on nitrogen distribution.

[1] S. Potzel *et al* Nucl. Fusion **54** (2014) 013001
[2] F. Reimold *et al* Nucl. Fusion **55** (2015) 033004
[3] A. Kallenbach *et al* Nucl. Fusion **55** (2015) 053026
[4] F. Reimold *et al* Journal of Nuclear Materials **463** (2015) 128–134
[5] S. Wiesen *et al* Journal of Nuclear Materials **463** (2015) 480–484
[6] X. Bonnin *et al* Plasma and Fusion Research **11** (2016) 1403102

Outline

- Description of the modeling scenario
- Modeling results: midplane and target profiles
- Discussion of nitrogen distribution
- Currents and E-field in the divertor region
- Conclusions

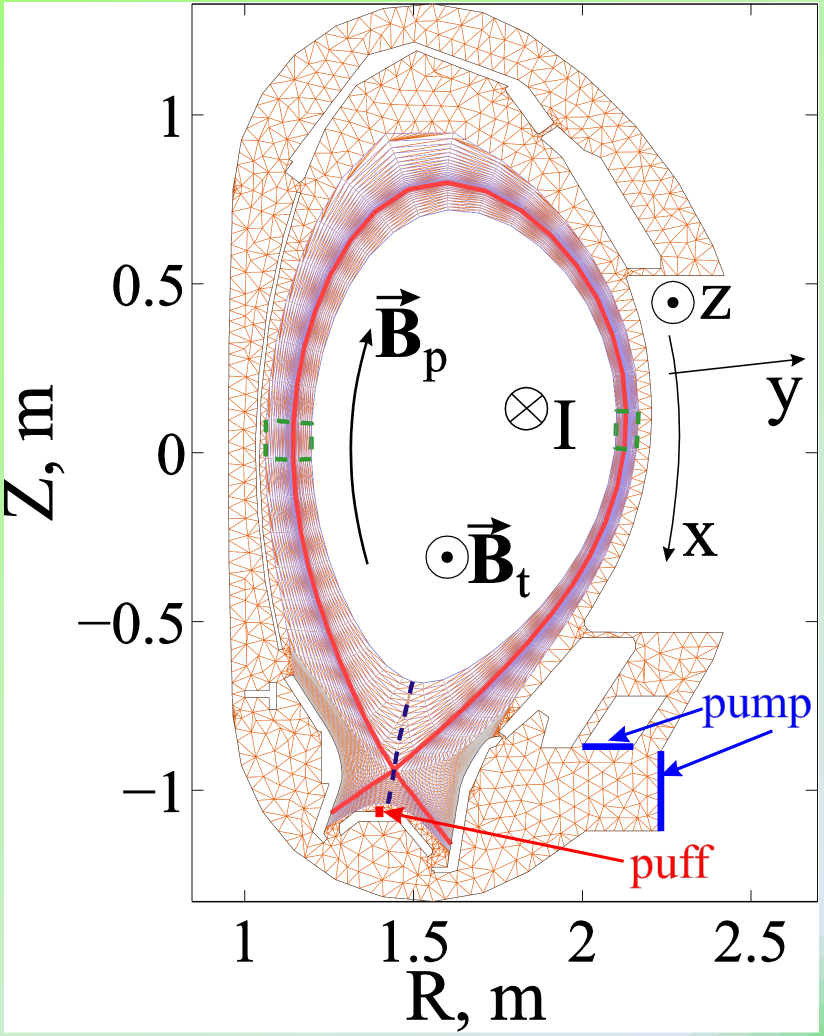
Modeling setup

Equations

- Braginski-like transport equations analytically rewritten for plasma species according to B2-5.2 concept [7];
- All drifts and currents are turned on;
- Unknown quantities are
  $$\{n_\alpha, u_{||\alpha}, T_e, T_i, \varphi\}$$
  $$\alpha = \{D^+, N^+, N^{++}, ..., N^{7+}\}$$
- Prescribed (not theory-based) anomalous transport coefficients;
- Monte-Carlo code EIRENE [8] is coupled returning sources and sinks due to collisions with neutral species;

[7] V. Rozhansky et al. Nucl. Fusion **49** (2009) 0250007
[8] R. Schneider et al 2006 Contrib. Plasma Phys. **46** 3–191

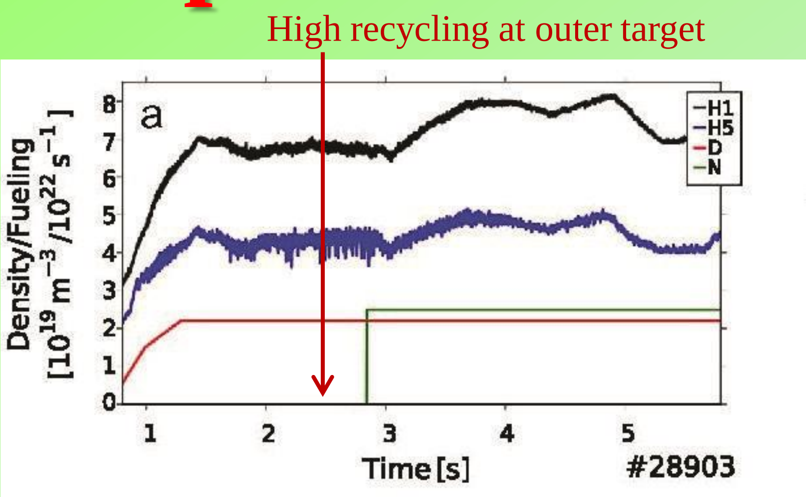
Computational domain



Modeling setup

Boundary conditions

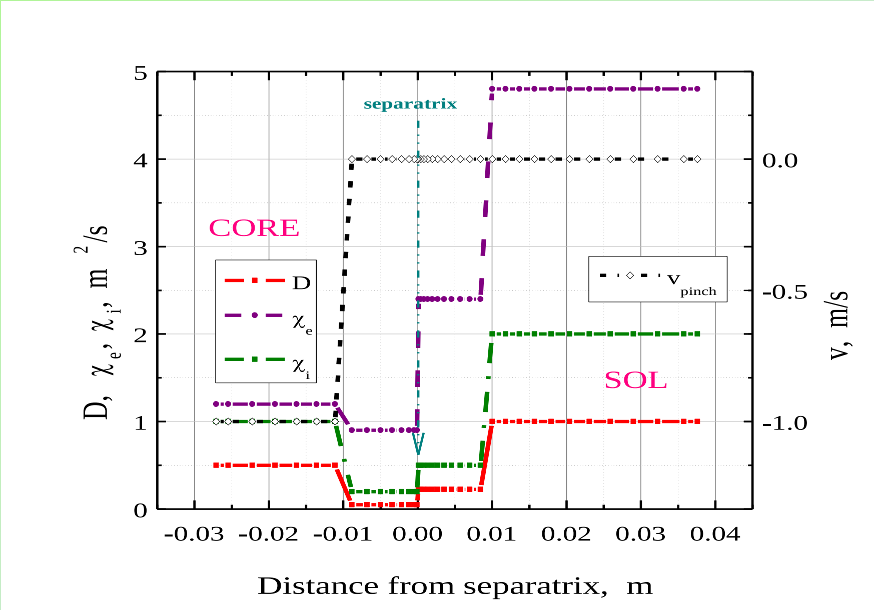
- Fueling rate $1{\cdot}10^{22}$ D_2 molecules per second;
- Seeding rate from $2{\cdot}10^{18}$ up to $5{\cdot}10^{20}$ N atoms/second;
- Sheath BC at targets;
- Prescribed n_α and $T_{e,i}$ decay lengths at SOL and PFR boundaries; $\partial u_{||\alpha}/\partial y=0$;
- Zero net current through core boundary;
- $< u_{||D+} > = -50$ km/s, $\partial u_{||N}/\partial y=0$ at the core;
- Zero net nitrogen flux at the core;



Fueling and seeding rates in AUG shot #28903 [4]

First task:

Prescribe n_D and $T_{e,i}$ at the core boundary and fit the anomalous transport coefficients to match the experimental profiles at 2.4 s (shown below): detached inner target, high-recycling outer target.



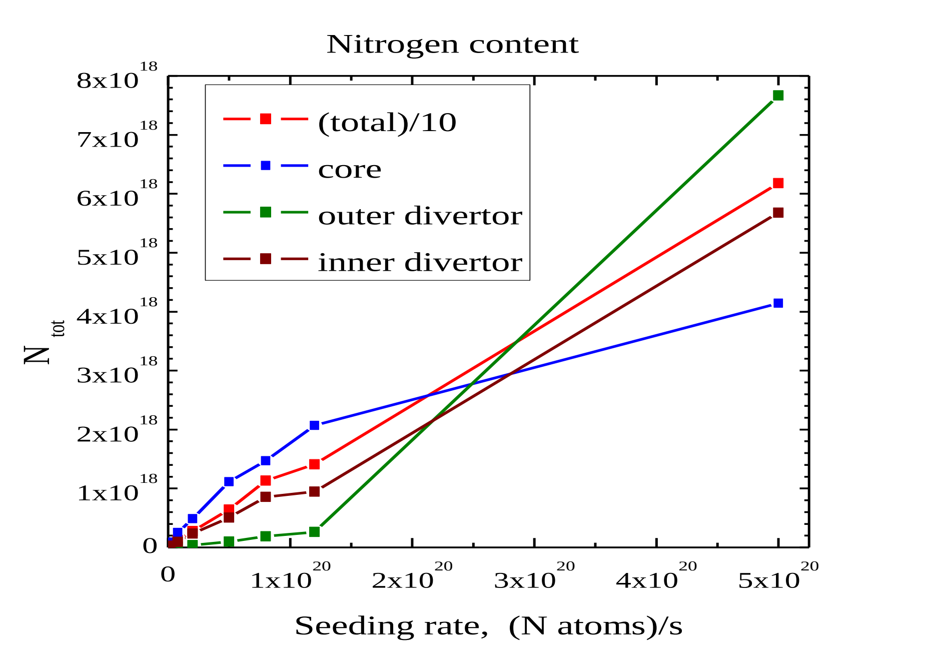
Modeling setup

Then

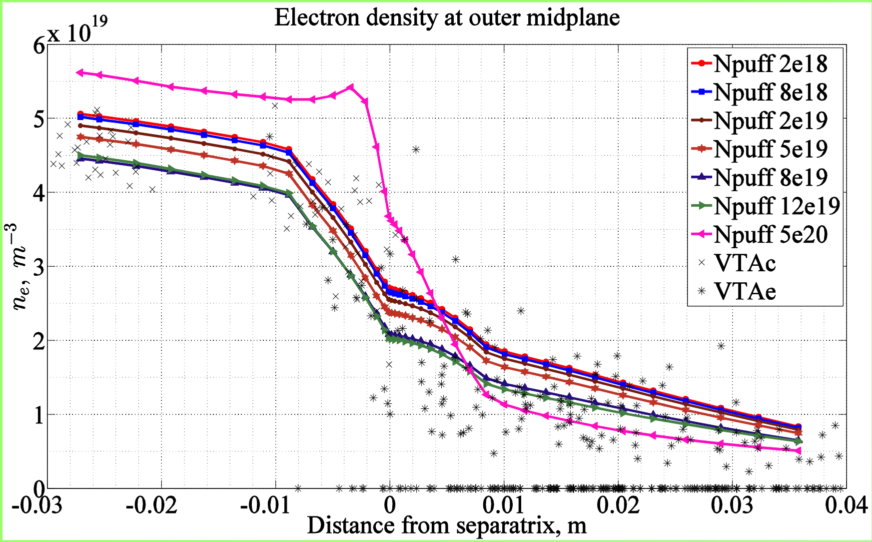
- Change boundary condition

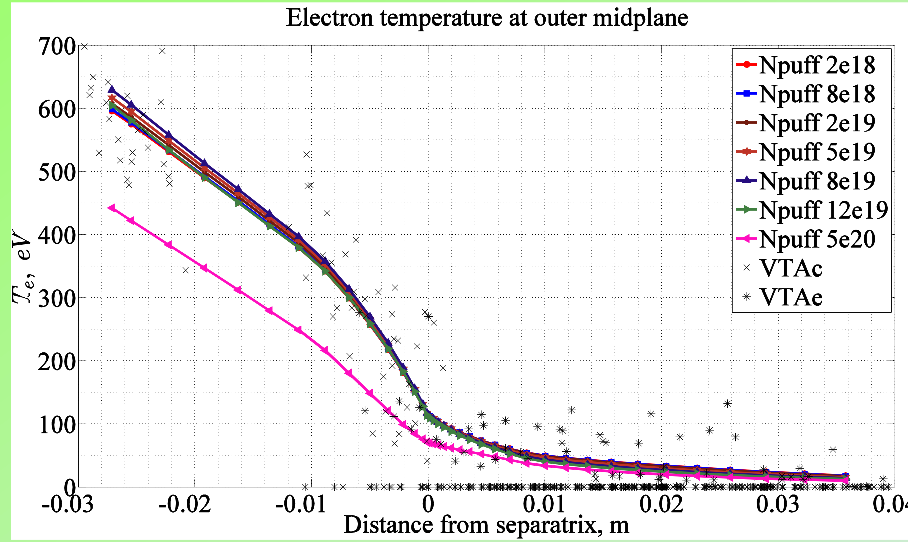
  prescribed n_D and $T_{e,i}$ → prescribed net D flux ($8 \cdot 10^{20}$ s^{-1}) and heat fluxes (Q_e=3.2 MW, Q_i=1.8 MW)
- Perform series of steady state runs which differs from each other by seeding rate only

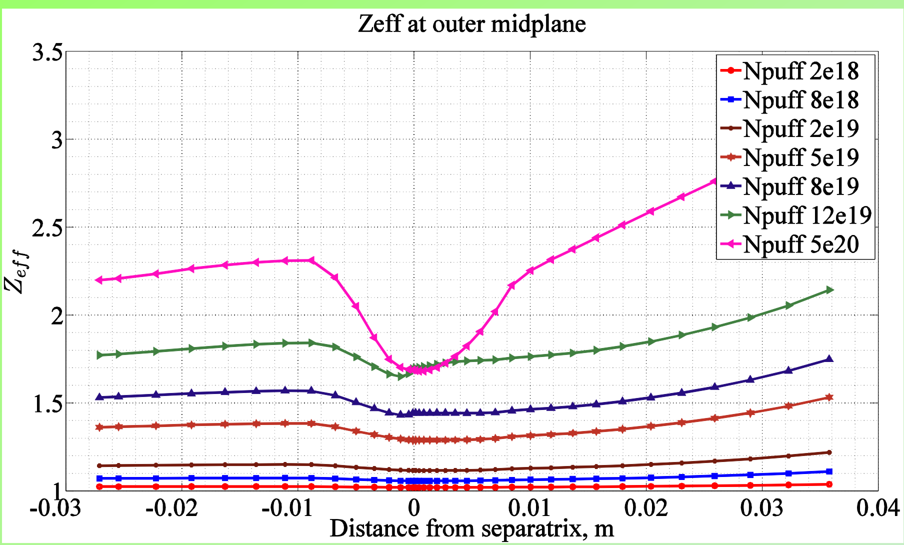
  (keep anomalous transport coefficients unchanged)
- Focus on the analysis of nitrogen transport and currents distribution near targets rather than on perfect reproducing the experiment.

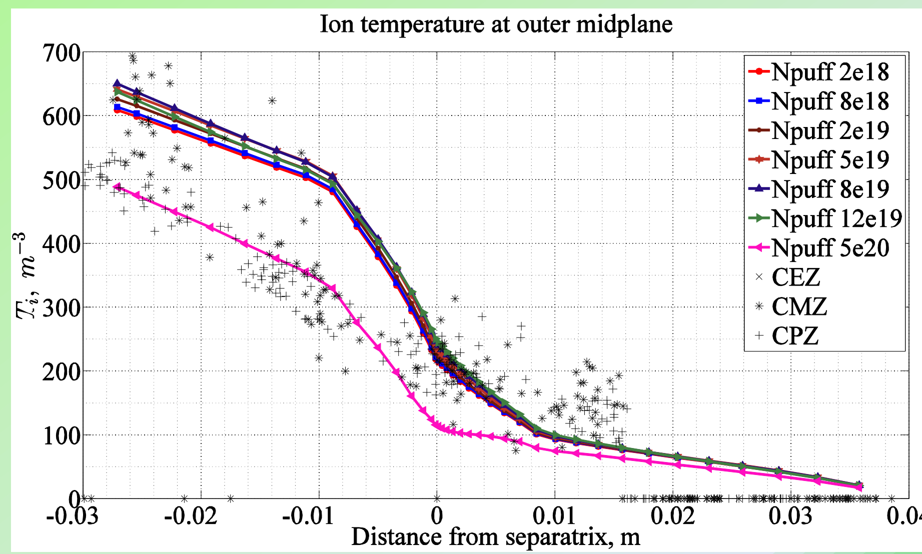


Modeling results. Outer midplane

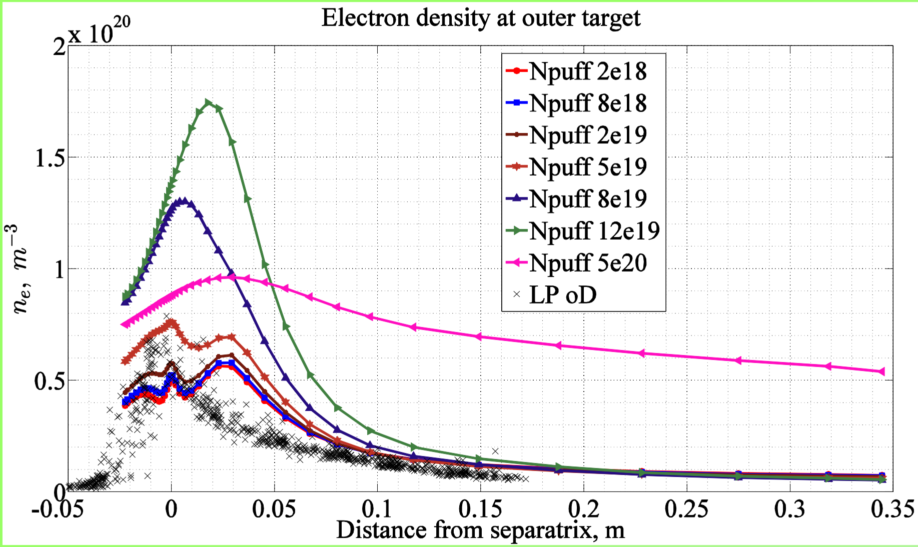


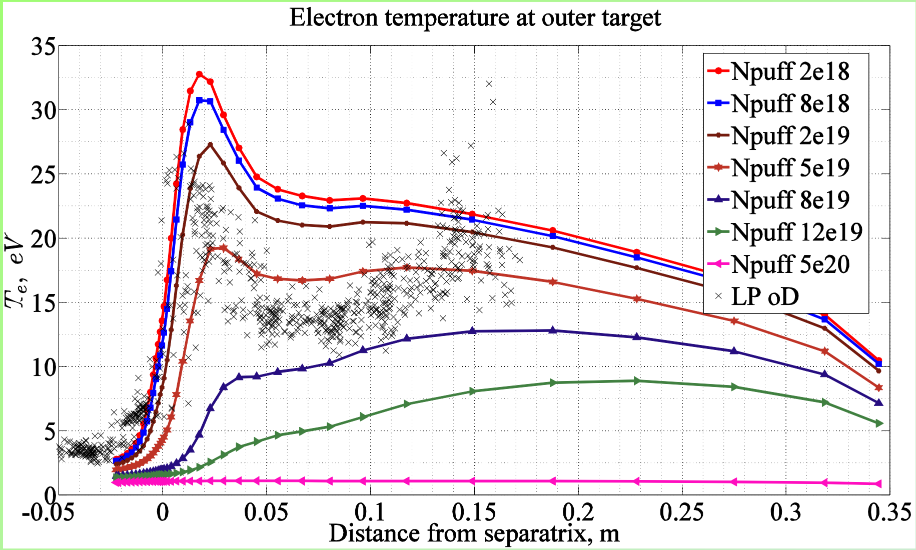


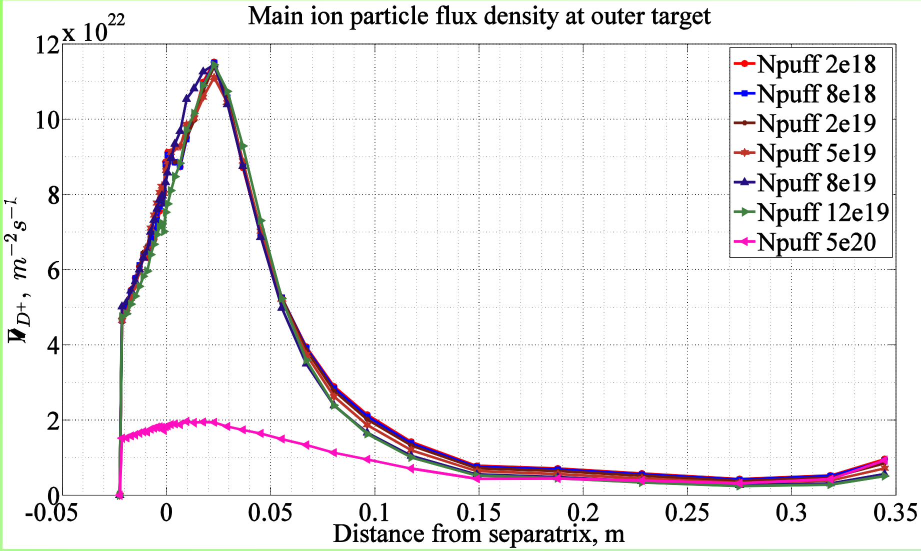


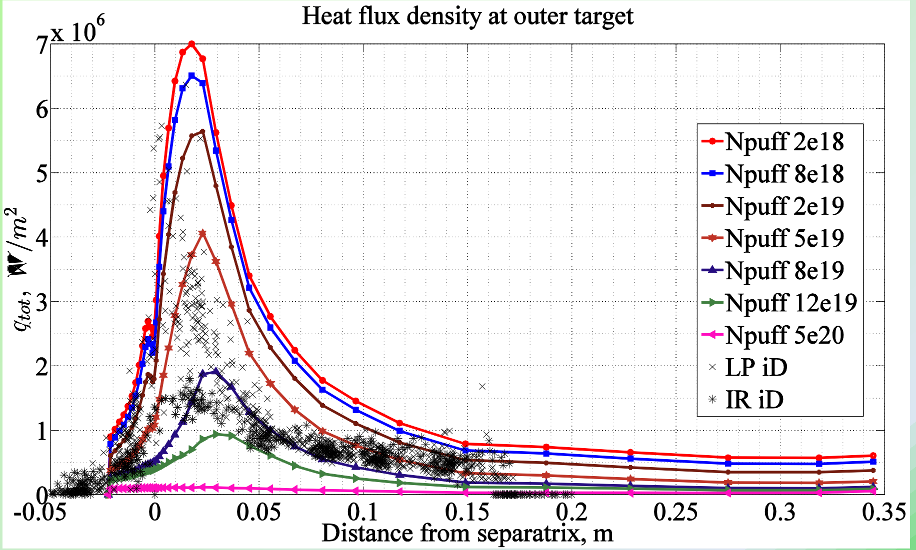


Modeling results. Outer target

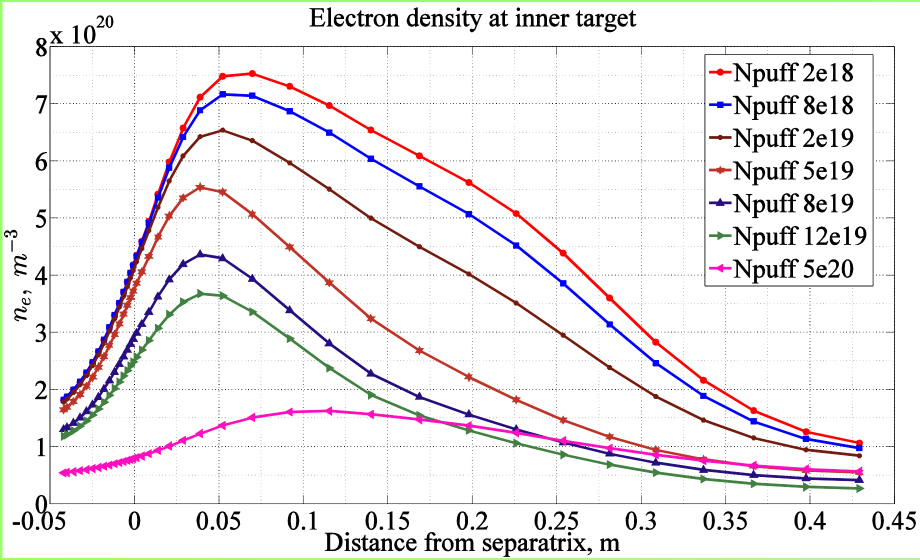


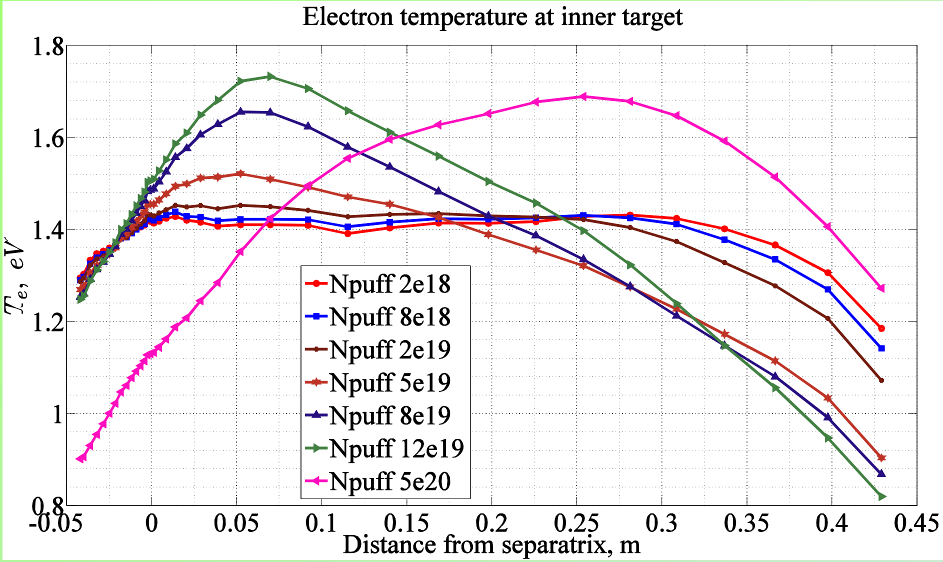


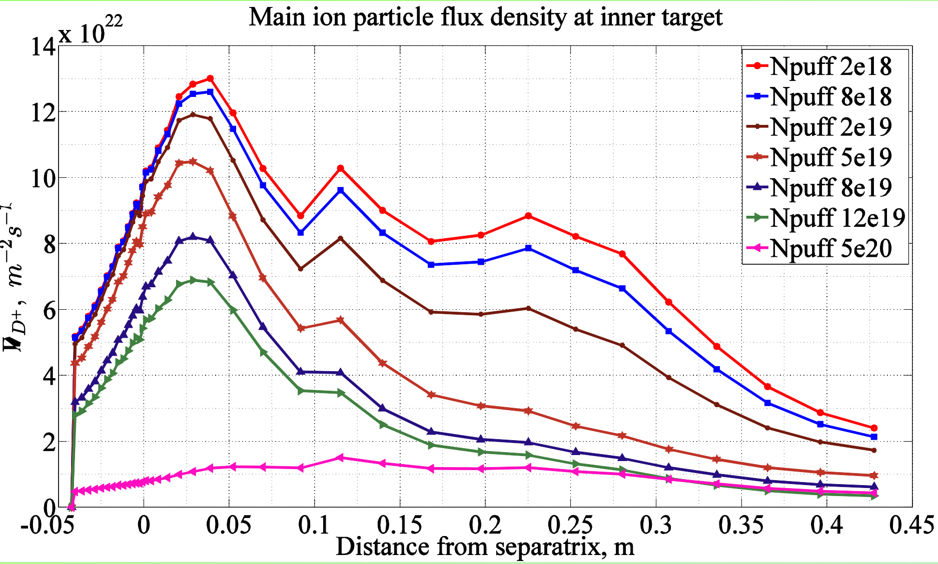


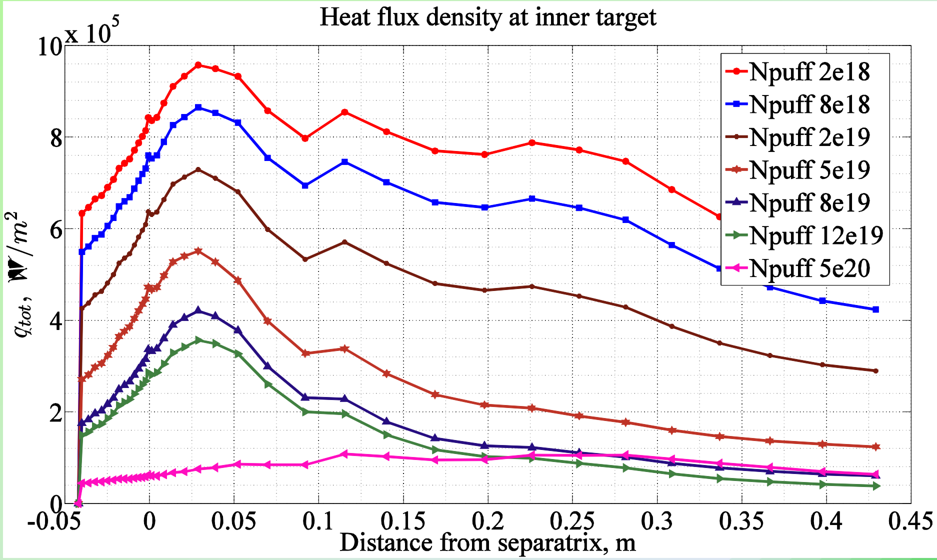


Modeling results. Inner target

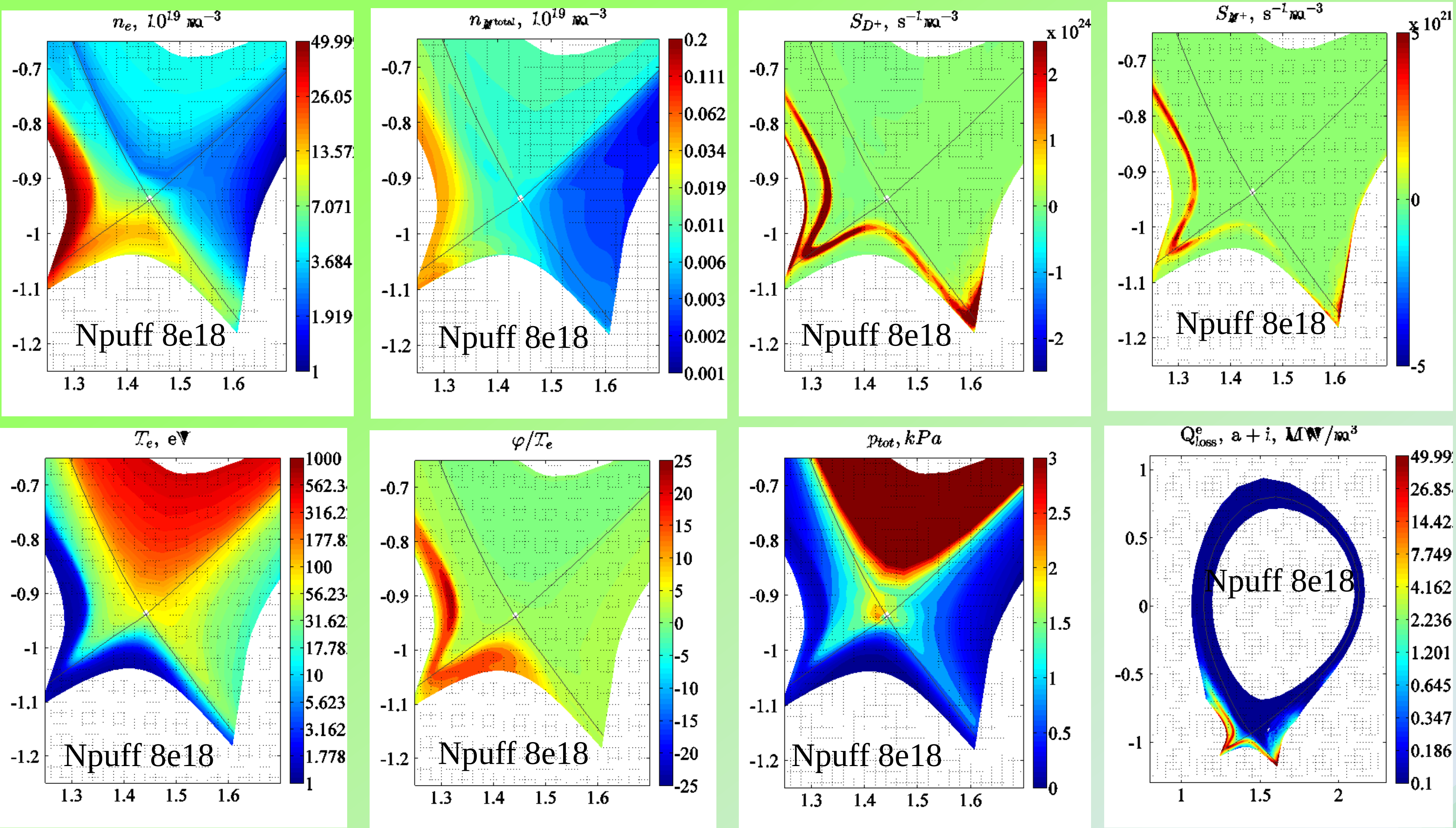






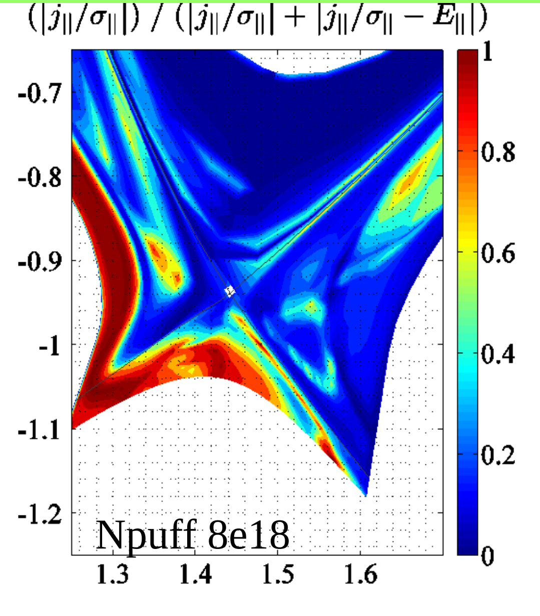


High recycling regime at outer target



- Nitrogen and Deuterium retain near the cold detached inner target;
- Shape of ionization source profile repeats the shape of the cold-hot plasma boundary;
- **Strong E-field (above 1 kV/m) and high electric potential develop in the cold plasma region**

Electric field and current



$$j_{\|} = j_{PS} + j_{th}$$

$$\frac{j_{\|}}{\sigma_{\|}} = E_{\|} + \frac{1}{en_e}\nabla_{\|}(n_e T_e) + \frac{1}{e}0.71\nabla_{\|}T_e$$

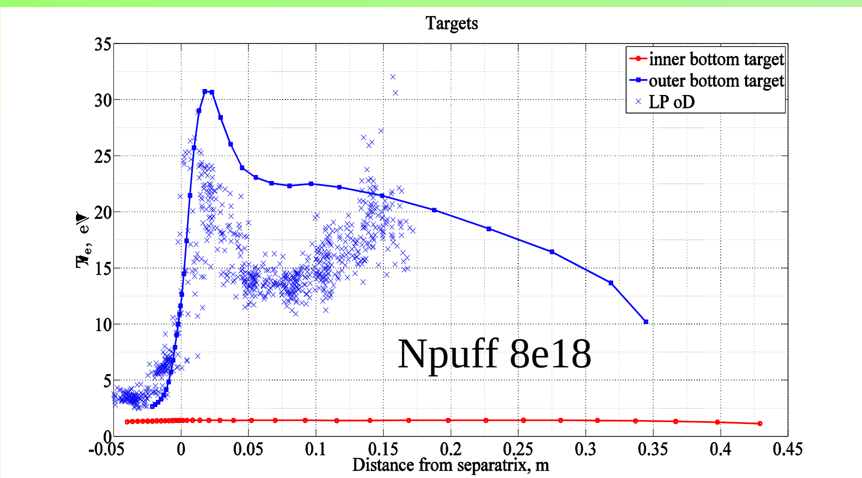
$$\left|\frac{j_{\|}}{\sigma_{\|}}\right| << |E_{\|}|, \quad \text{high } T_e$$

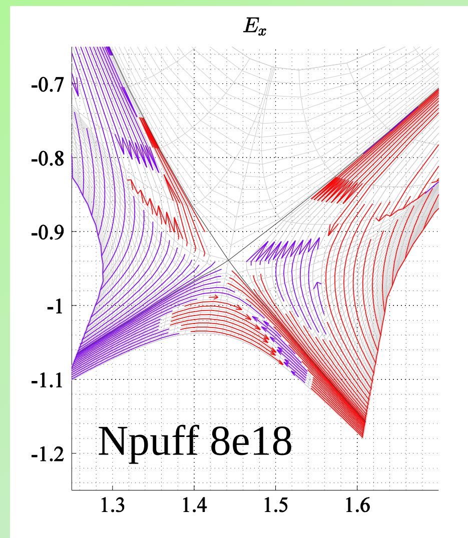
$$E_{\|} \approx -\frac{1}{en_e}\nabla_{\|}(n_e T_e) - \frac{1}{e}0.71\nabla_{\|}T_e$$

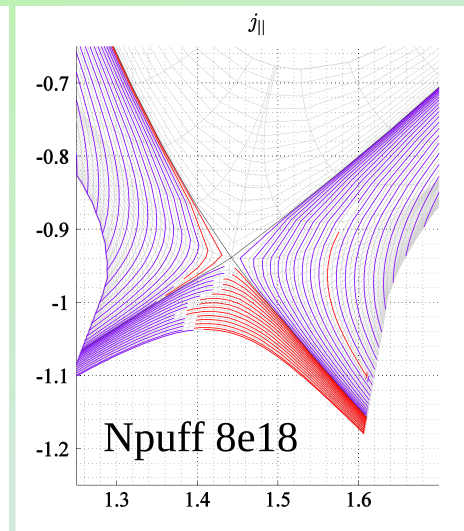
$$\frac{j_{\|}}{\sigma_{\|}} \approx E_{\|}, \quad \text{low } T_e$$

$$|E_{\|}| >> \left|\frac{1}{en_e}\nabla_{\|}(n_e T_e) + \frac{1}{e}0.71\nabla_{\|}T_e\right|,$$

PS current dominates in the PFR; thermoelectric one is important in the SOL







positive (towards outer target)

negative (towards inner target)

Nitrogen distribution

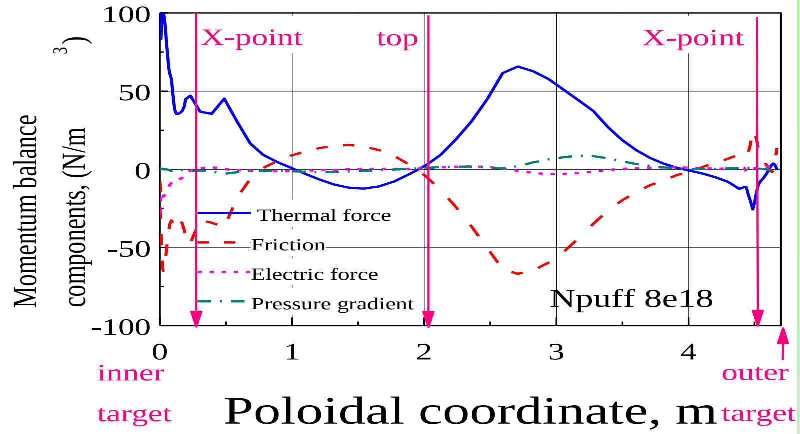
$$R_{\|N} \approx n_N \mu_{DN} \left(u_{\|D} - u_{\|N}\right) \tau_{ND}^{-1}$$

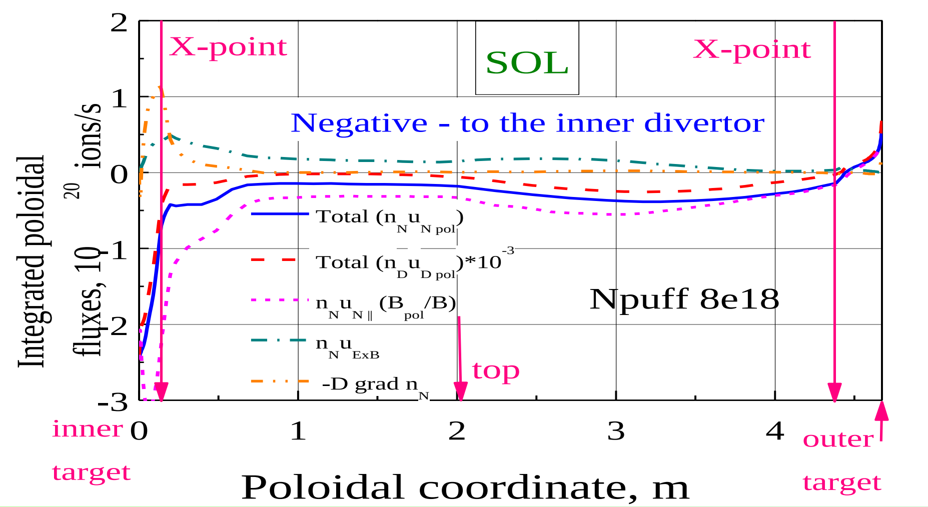
$$R_{\|N}^T \approx 1.56 Z^2 n_N \nabla_\| T_i$$

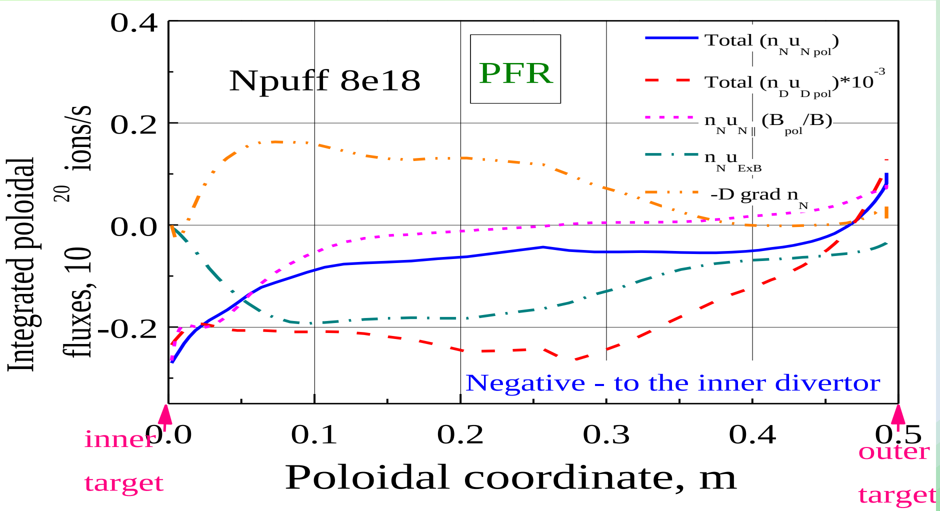
$$R_{\|N}^T \approx R_{\|N}$$

$$u_{\|N} \approx u_{\|D} + 1.56 \tau_{ND} \mu_{DN}^{-1} \nabla_\| T_i$$

$$\tau_{\alpha\beta}^{-1} = \frac{8\sqrt{\pi} n_\beta}{3} \frac{Z_\alpha^2 Z_\beta^2 \Lambda}{T_i^{3/2} \mu_{\alpha\beta}^{1/2}} \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2$$

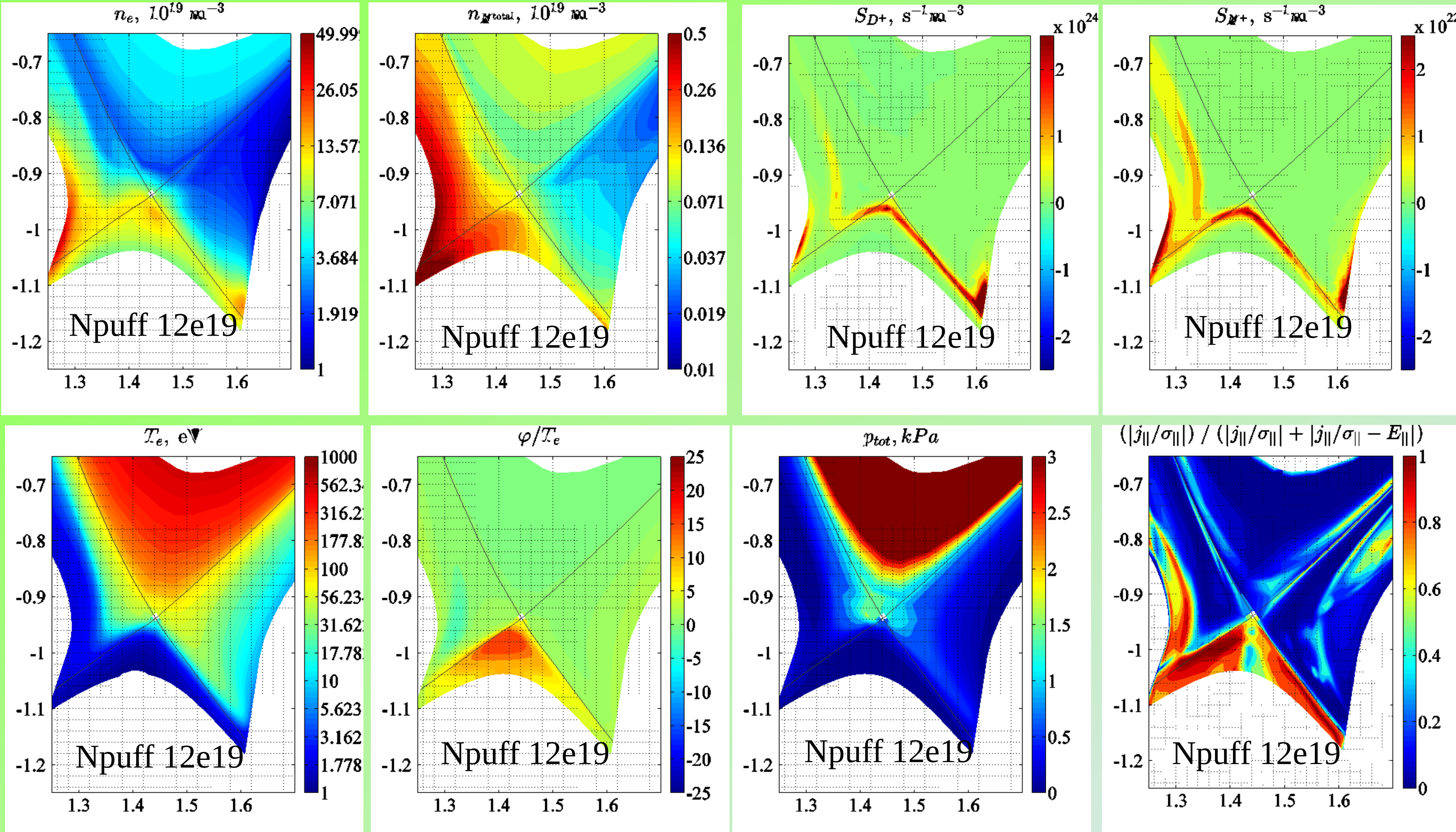






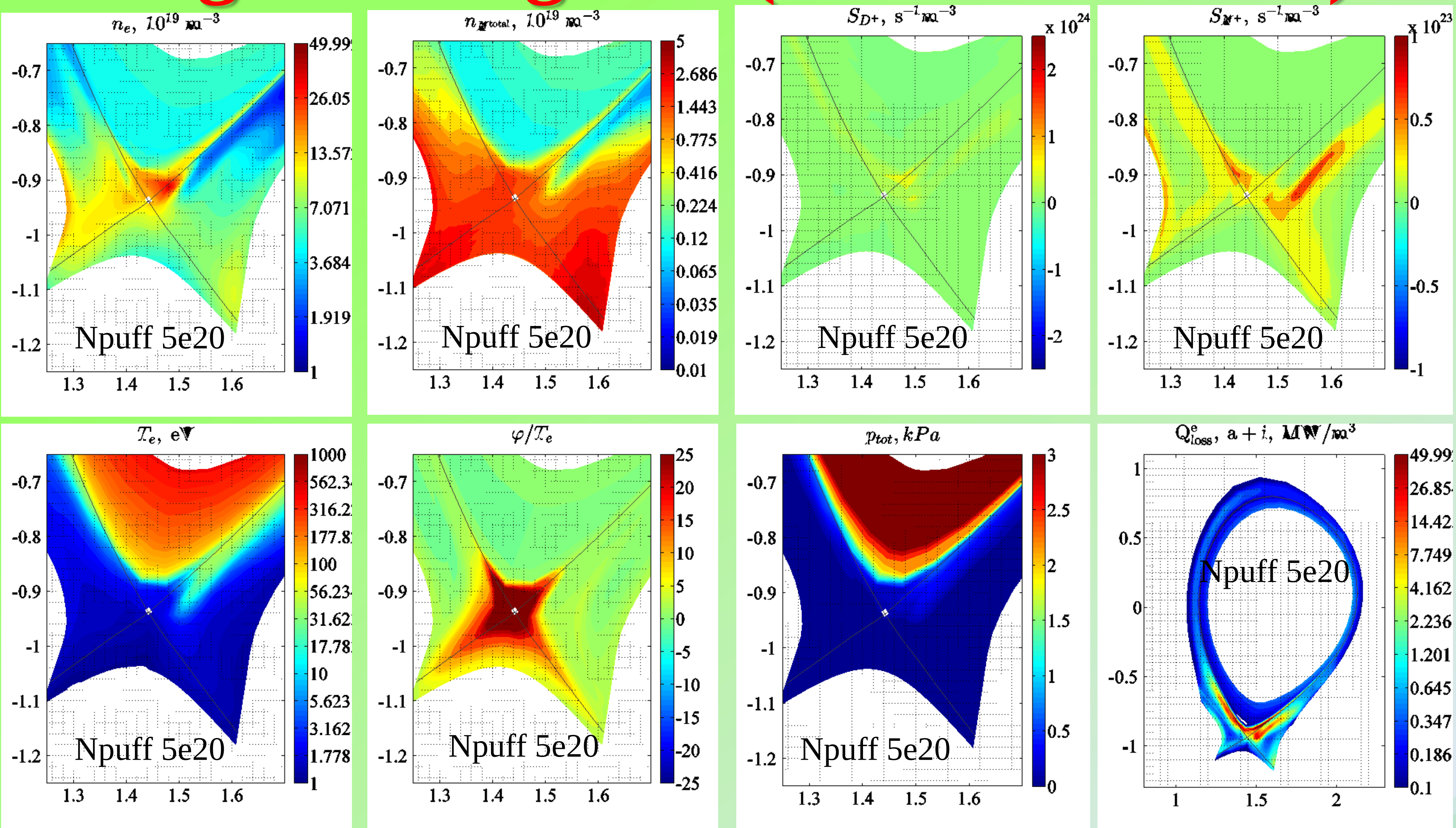
As a result, nitrogen retains at inner target and leaks at outer target

Intermediate seeding rate



- Outer divertor cools with increasing seeding rate, the region of cold plasma broadens, while nitrogen still accumulates near inner target;
- **Electric potential maximum starts to develop near the X-point;**

High seeding rate (full detachment)



- Cooling of the confinement region occurs
- Electric potential peak develops at the X-point
- Nitrogen starts to accumulate near the outer target

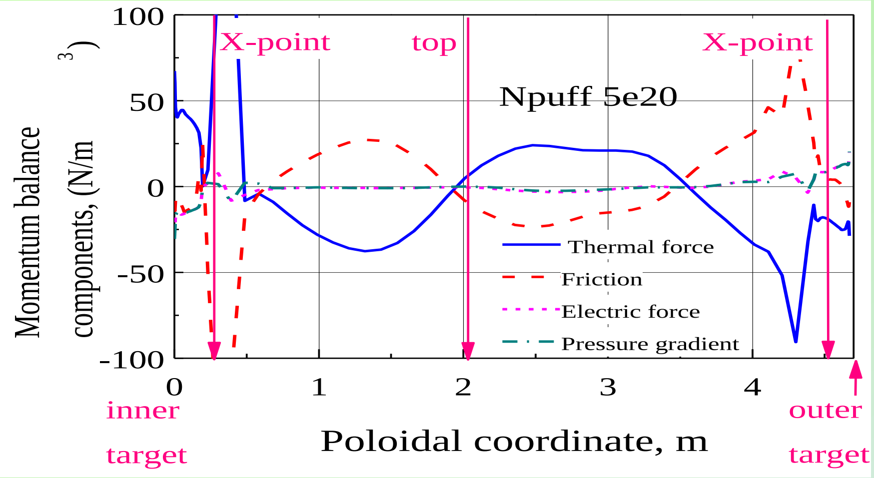
Nitrogen distribution (high seeding rate)

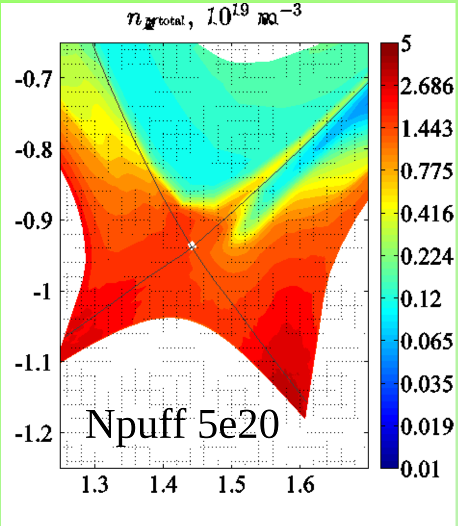
Friction force still balances the thermal force, and nitrogen velocity may be estimated as

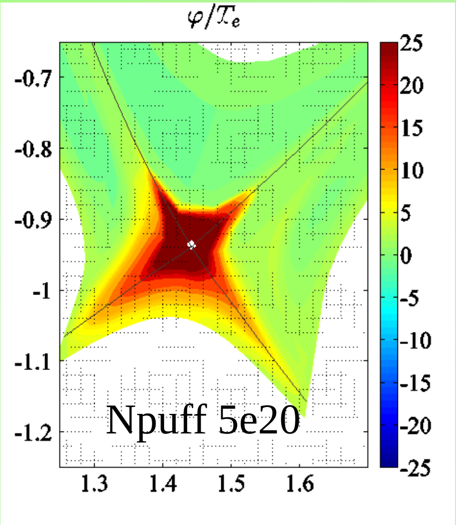
$$u_{\parallel N} \approx u_{\parallel D} + 1.56\tau_{ND}\mu_{DN}^{-1}\nabla_{\parallel}T_i$$

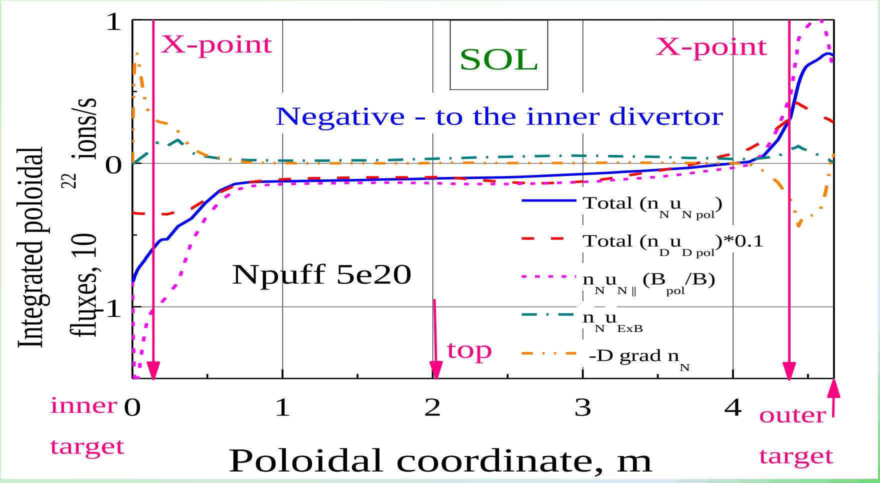
- However, in a cold plasma collisional time becomes smaller, and D and N velocities become closer to each other.
- ExB drift vortex flux around the X-point equalizes nitrogen density between inner and outer divertor regions.

As a result, nitrogen retains at outer target too.

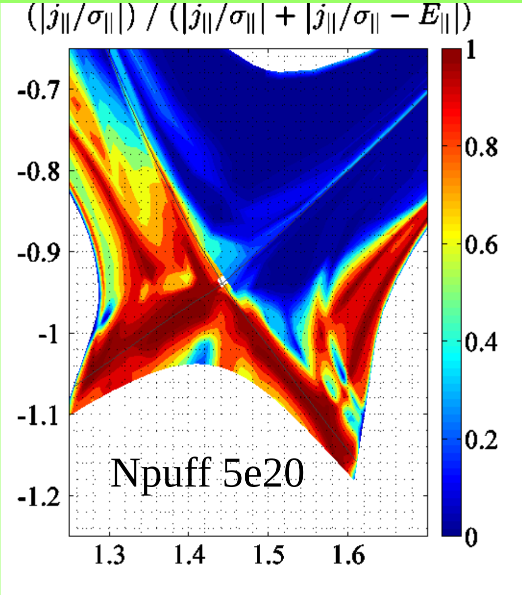






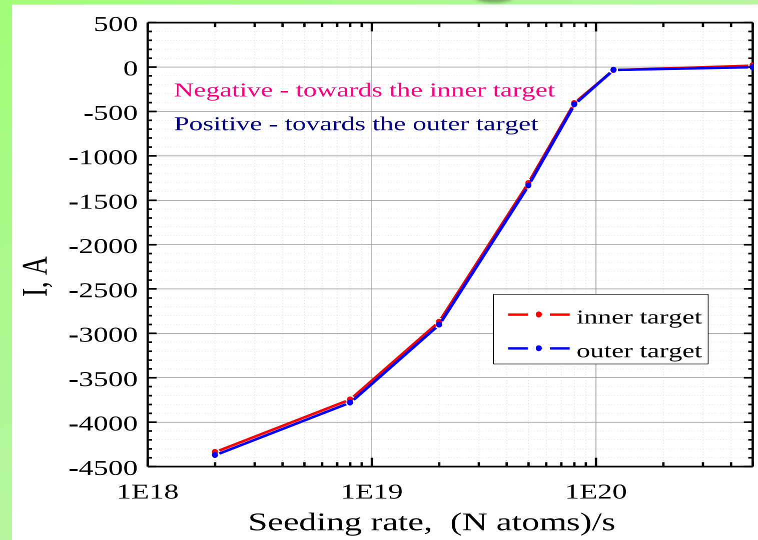


Current through divertor targets

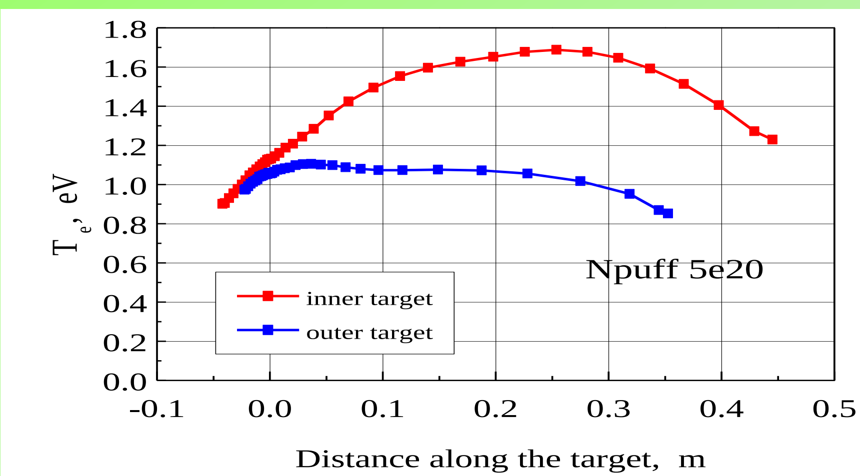


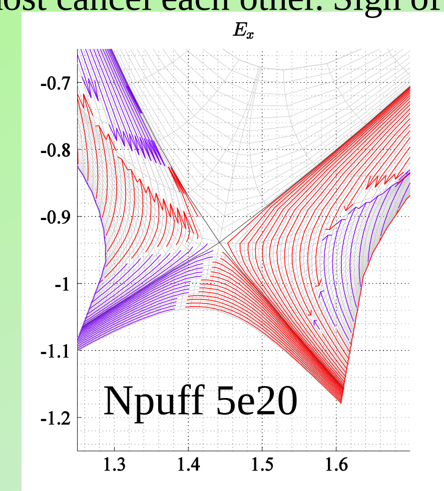
$$j_{\parallel} = j_{PS} + j_{th}$$

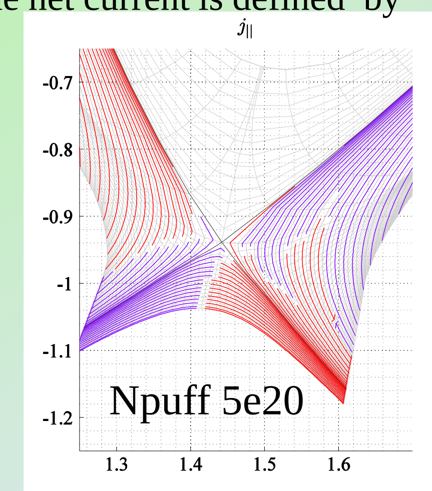
As the plasma near the outer target cools, thermoelectric current reduces, and changes its sign if outer divertor plasma becomes colder than inner one.



PS current dominates in the SOL and in PFR, however, directions are opposite, and SOL and PFR parts almost cancel each other. Sign of the net current is defined by thermoelectric current.







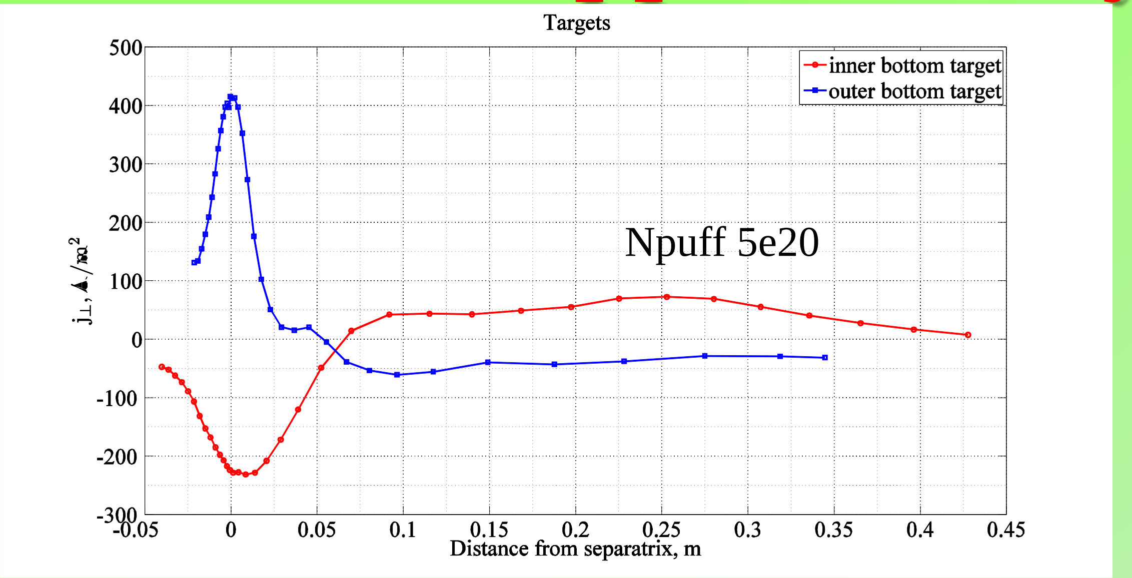
positive (towards outer target)

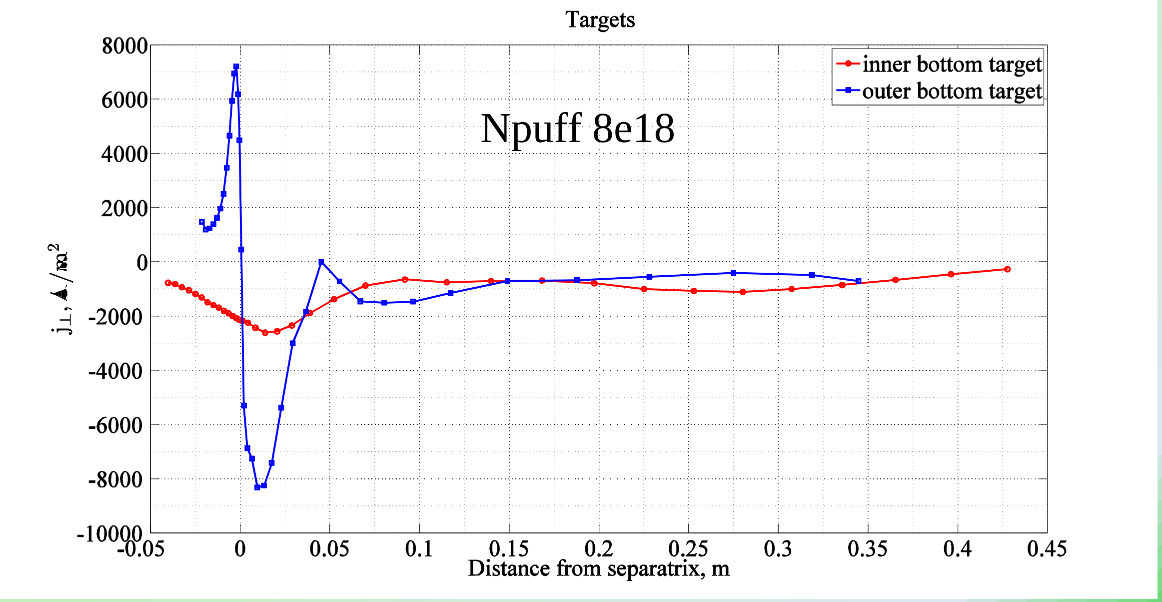
negative (towards inner target)

Conclusions

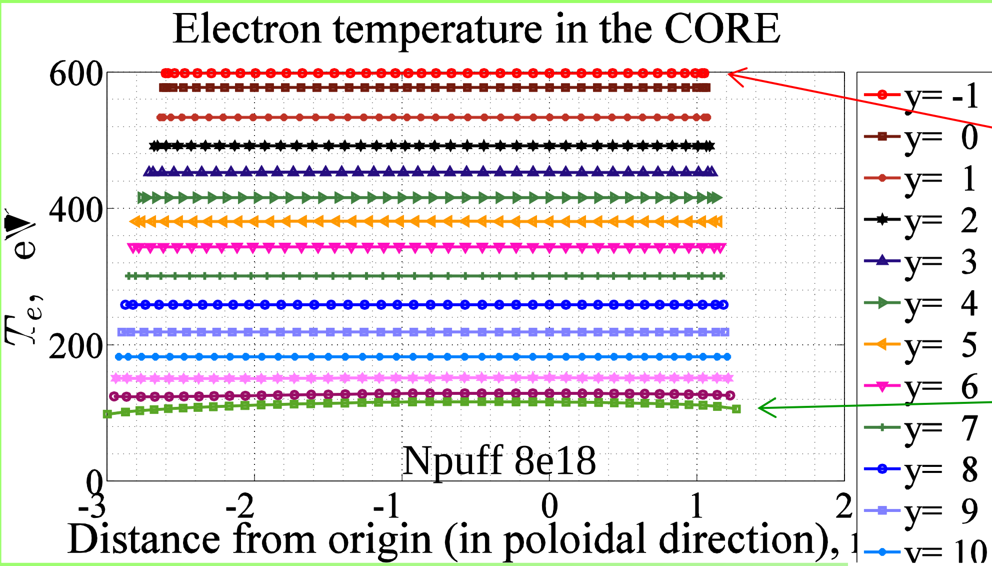
- Modeling of transition to the detachment in ASDEX Upgrade H-mode with N seeding is performed by SOLPS-ITER code with drifts and currents turned on.
- It is demonstrated that the B-parallel velocity of nitrogen is defined by the balance of thermal force and friction force.
- When the inner target is detached while outer is not, the nitrogen is concentrated near the detached inner target, and as the outer target detaches, the nitrogen accumulates near the outer target.
- As the amount of nitrogen increases and the divertor region cools, a strong electric field develops to drive the current through the zones of low electric conductivity.
- The ExB drift flux becomes comparable to diffusive flux.
- Thermoelectric current reduces with the outer divertor plasma cooling, and changes its sign as the outer divertor plasma becomes colder than the inner one, similarly behaves the net current through divertor plates.

Supplementary slide





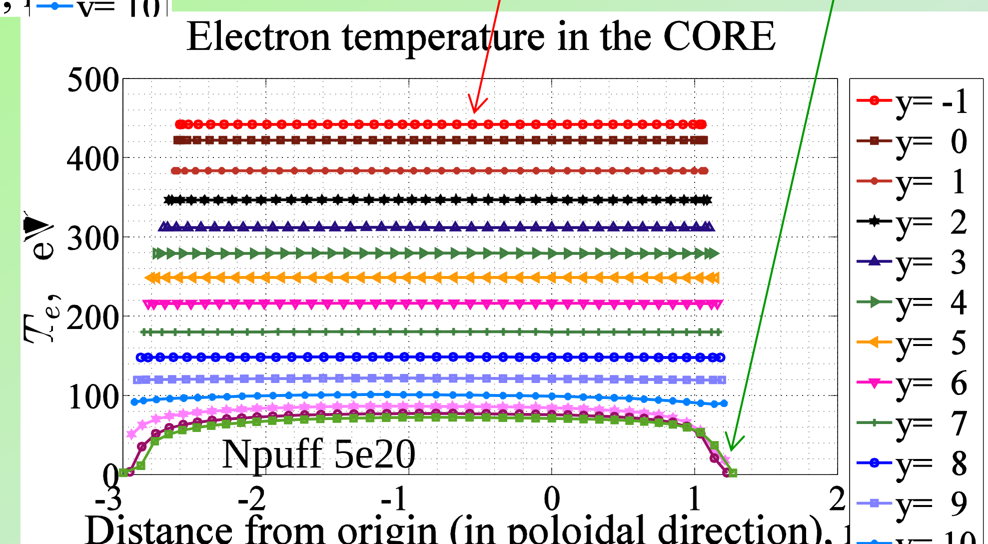
Supplementary slide



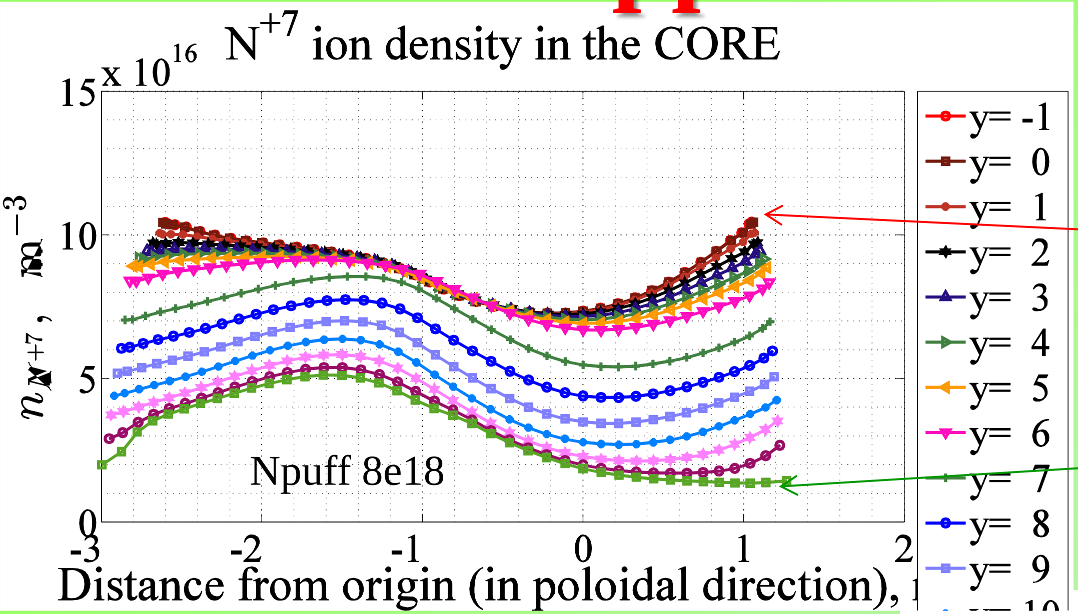
X-point
inner midplane
top
outer midplane
X-point

core

separatrix



Supplementary slide



X-point

inner midplane

top

outer midplane

X-point

core

separatrix