第14回 若手によるプラズマ研究会
那珂核融合研究所，2011年3月8日

EROコードによるLHDダイバータモデリングと不純物輸送シミュレーション

G. Kawamura, Y. Tomita, M. Kobayashi, D. Kato
M. Tokitani, S. Masuzaki, A. Kirschner[†] and D. Tskhakaya[‡]

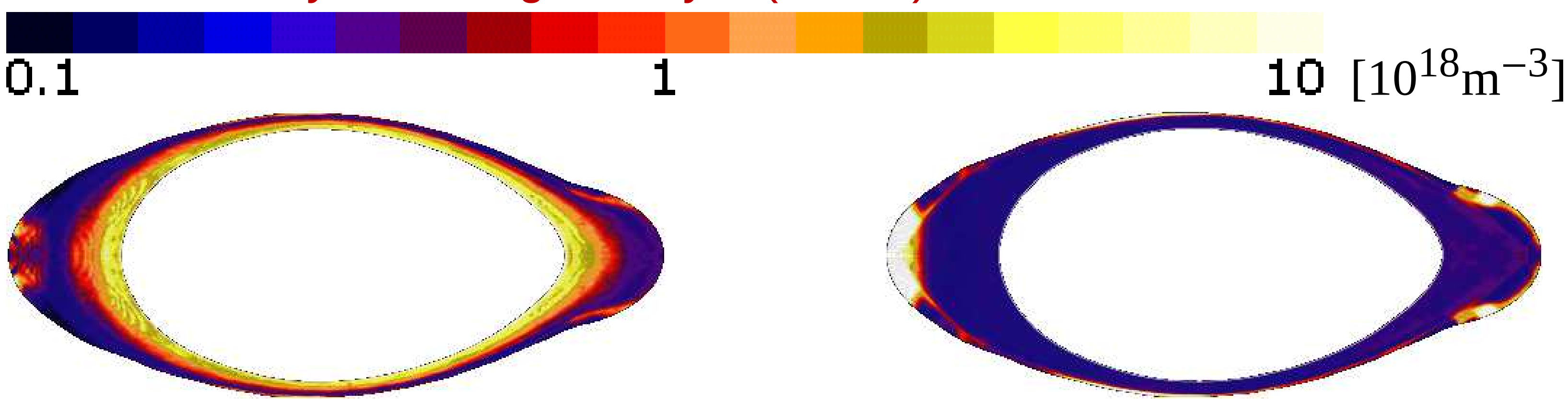
National Institute for Fusion Science, Japan
[†]Institut für Energieforschung-Plasmaphysik, Forschungszentrum Jülich GmbH, Germany
[‡]Institute of Theoretical Physics, University of Innsbruck, Austria

Outline

1. Introduction
2. Modeling of impurity transport simulation in LHD
   (a) Configuration of LHD divertor
   (b) Plasma modeling of LHD divertor
3. Impurity transport simulation in LHD diverter
   (a) Gas puffing simulation
4. Summary and future issues

1.Introduction
Impurity transport in the LHD edge plasma

§ Carbon density in the ergodic layer (EMC3)



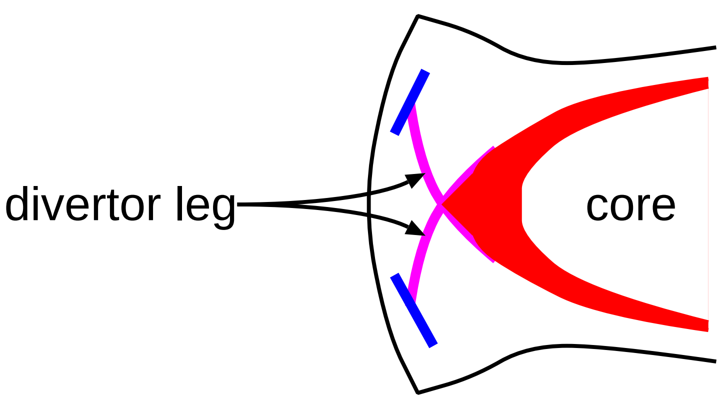
low density case: $n_{\mathrm{LCFS}} = 2 \times 10^{19}\mathrm{m}^{-3}$ high density case: $n_{\mathrm{LCFS}} = 4 \times 10^{19}\mathrm{m}^{-3}$

[M. Kobayashi]

† Impurity screening due to the parallel flow is found on high density discharges.

† It could reduce the accumulation of impurity in the core.

† However, ionization and transport effects of divertor plasmas are not involved yet.



LHD boundary plasma

§ Three characteristic regions in boundary plasma

- † Ergodic layer ⇒ $\boxed{\text{EMC3}}$

  M. Kobayashi et al., J. Nucl. Mater., 363–365, 294 (2007)

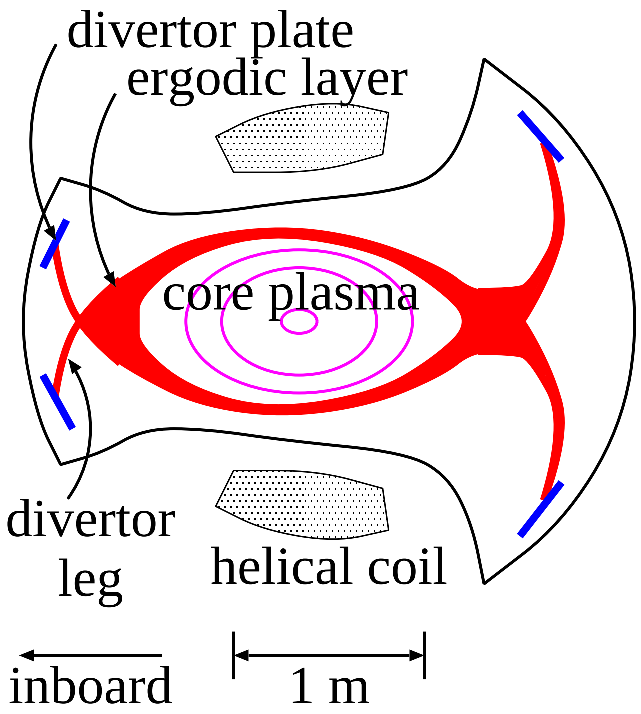
  - ‡ Stochastic magnetic fields
  - ‡ Cross-field diffusion and parallel transport
    - ⇕ Interactions
- † Divertor leg ⇒ $\boxed{\text{Fluid code}}$ (EMC3 in future)

  G. Kawamura et al., J. Plasma Fus. Res., 5 (2010) S1020

  - ‡ Parallel flow dynamics
  - ‡ Interactions with neutrals
  - ‡ Recycling
    - ⇕ Interactions
- † Impurity around divertor plates ⇒ $\boxed{\text{ERO}}$

  G. Kawamura et al., Contrib. Plasma Phys., 50 (2010) 451

  - ‡ Impurity transport
  - ‡ Sputtering
  - ‡ Redeposition

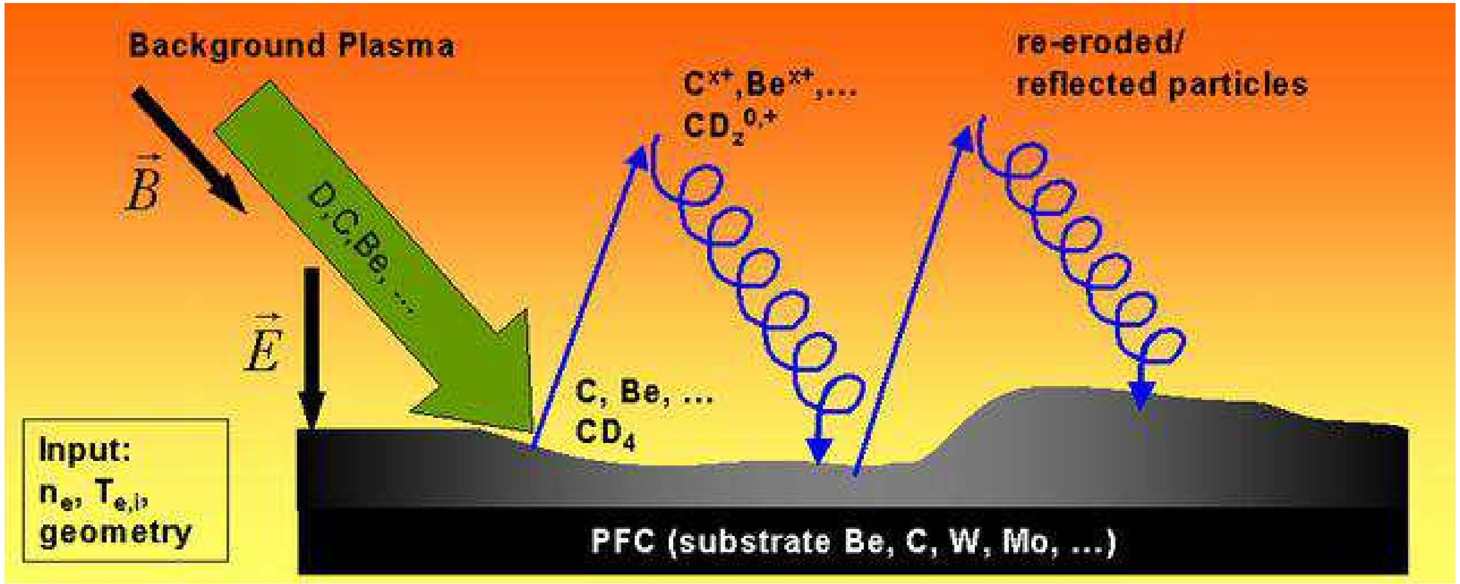


Polidal cross section of LHD

2. Impurity transport simulation in LHD diverter
ERO code (erosion and redeposition)

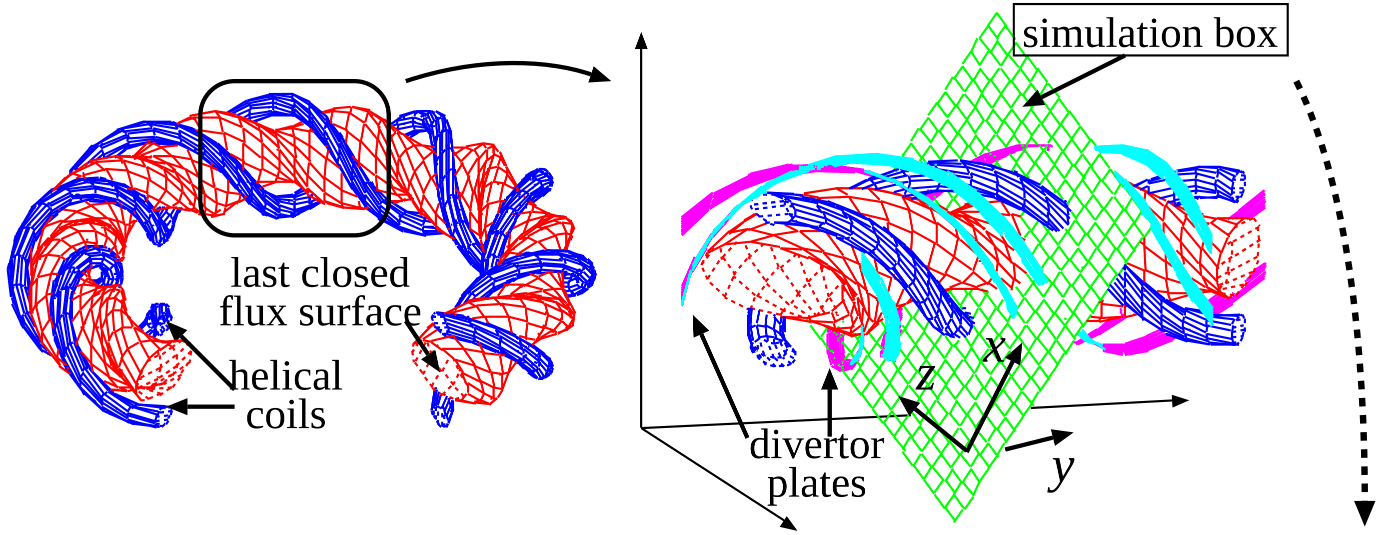
§ Monte Carlo simulation of impurity redeposition on the LHD first wall

- † We employed the ERO code to investigate impurity dynamics in LHD divertor.
  A. Kirschner et al., Nuclear Fusion, 40, 989 (2000)
- † Spatial distribution and deposition profile of impurities are available.
- † Impurity particles are sputtered from the plasma facing wall and traced in the simulation by using Newton's equation of motion with various forces; electromagnetic force, friction and thermal forces given by a fixed background plasma.
- † Atomic processes such as ionization and dissociative recombination yield various carbon species; C, C^+,C^{2+}, $\cdots$, CH, CH_2^+, $\cdots$.



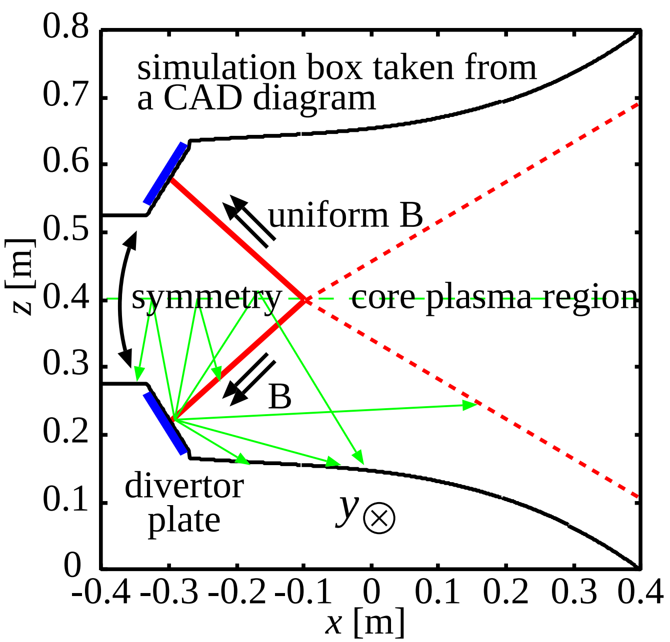
Configuration of the LHD divertor

§ 3D illustrations of the LHD core plasma



§ 2D simulation box

- † The simulation box is chosen to be normal to the divertor plate.
- † With the aid of the up-down symmetry, the lower half of the plane is employed as the simulation box.
- † The impurity particles are reflected at the upper boundary, z = 0.4.



Physical models

§ Major components of ERO

† Transport of impurity particles in the plasma

‡ Newton's equation of motion

‡ collisional effects with the background plasma

‡ database of ionization and recombination rates (ADAS)

$\Longrightarrow$ These core components are available for any devices.

† Sputtering model

‡ Bohdansky-Yamamura model and SDTimSP code for physical sputtering

‡ Roth model or externaly given constant yield for chemical sputtering

$\Longrightarrow$ Device-independent, but many uncertainties such as incident-angle effect.

† Background plasma and surface geometry

‡ magnetic field

‡ plasma profiles of n, T_{e}, T_{i}, v and gradients of n, T_{e} and T_{i}
Parallel electric field is calculated from these gradients.

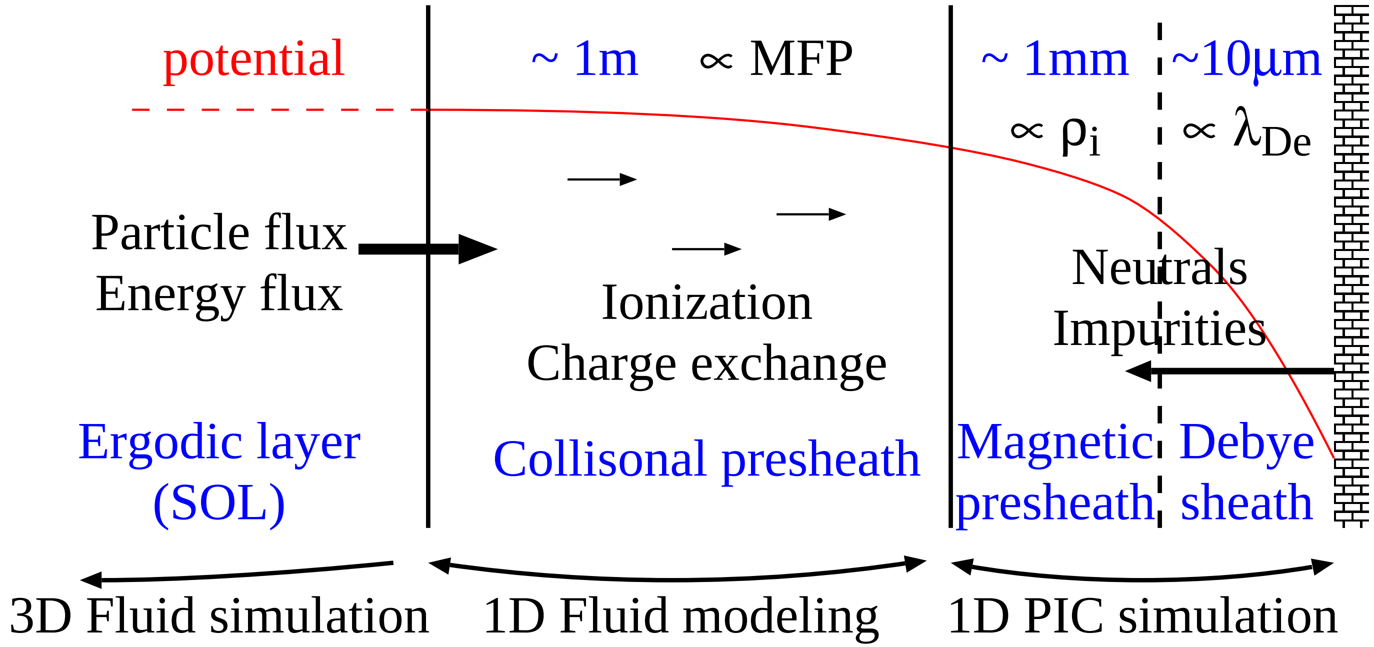
‡ wall configuration and grid generation

$\Longrightarrow$ Modeling is necessary to apply the code to a new device.

Plasma modeling of the divertor leg*

§ Modeling and simulation of the divertor plasma

- † Parallel dynamics is dominant on the diverter plasma.
- † Braginskii equations along a flux tube is good approximation.
- † Interaction between plasma and neutral particles determines plasma profile.



*G. Kawamura et al., J. Plasma Fus. Res., 5 (2010) S1020

1D fluid equations of divertor plasma

§ Equilibrium equations solved numerically

$$
\begin{aligned}
\frac{d}{ds}[nv] &= S_{\mathrm{n}}, \\
\frac{d}{ds}\left[m_{\mathrm{i}}nv^2 + n(T_{\mathrm{e}} + T_{\mathrm{i}})\right] &= S_{\mathrm{p}}, \\
en\frac{d\phi}{ds} &= \frac{dnT_{\mathrm{e}}}{ds} + 0.71n\frac{dT_{\mathrm{e}}}{ds} - \frac{j}{\sigma_{||}}, \\
\frac{d}{ds}\left[\frac{m_{\mathrm{i}}nv^3}{2} + \frac{5}{2}nvT_{\mathrm{i}} - \kappa_{||\mathrm{i}}\frac{dT_{\mathrm{i}}}{ds}\right] &= -env\frac{d\phi}{ds} + \frac{3m_{\mathrm{e}}n}{m_{\mathrm{i}}\tau_{\mathrm{e}}}(T_{\mathrm{e}} - T_{\mathrm{i}}) + S_{\mathrm{Ei}}, \\
\frac{d}{ds}\left[\frac{5}{2}nvT_{\mathrm{e}} + q_{\mathrm{lim}}\right] &= env\frac{d\phi}{ds} - \frac{3m_{\mathrm{e}}n}{m_{\mathrm{i}}\tau_{\mathrm{e}}}(T_{\mathrm{e}} - T_{\mathrm{i}}) - Lr_{\mathrm{imp}}n^2 + S_{\mathrm{Ee}}, \\
\frac{1}{q_{\mathrm{lim}}} &= \frac{1}{-\kappa_{||\mathrm{e}}\frac{dT_{\mathrm{e}}}{ds}} + \frac{1}{\alpha n v_{\mathrm{t}} T_{\mathrm{e}}}. \quad \underline{\text{electron heat flux limit } (\alpha = 0.15)}
\end{aligned}
$$

s: spatial coordinate along B, n: plasma density ($n_{\mathrm{e}} = n_{\mathrm{i}} = n$), v: parallel flow velocity, S_{n}: particle source, T_{e} and T_{i}: electron and ion temperatures, S_{p}: momentum source, $\kappa_{||\mathrm{i}}$: ion heat conduction coefficient, S_{Ei}: ion energy source, $\kappa_{||\mathrm{e}}$: electron parallel heat conduction coefficient, τ_{e}: e-e collision time, $L = L(T_{\mathrm{e}})$: radiation cooling efficient, S_{Ee}: electron energy source.

Neutral model

§ Recycling and cascade processes of hydrogen

Wall surface

$\Downarrow$ release

H_2 molecules

$\Downarrow$ dissociation

H atoms

$\Updownarrow$ IZ, CX, recombination

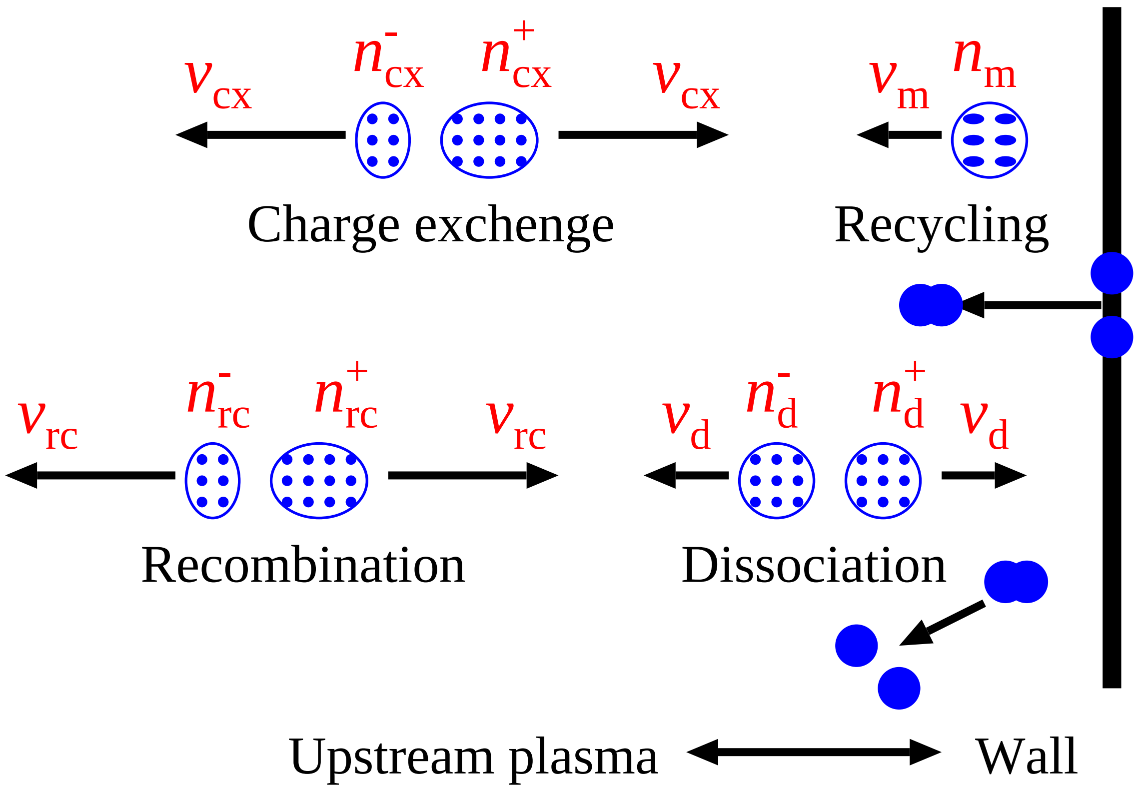
H^+ ions

$\Downarrow$ surface recombination

Wall surface

n^+ : downstream particle.

n^- : upstream particle.



§ Equilibrium equations

$$-v_m \frac{dn_m}{ds} = -(\langle \sigma_{d1} v \rangle + \langle \sigma_{d2} v \rangle) n_m n,$$

$$\pm v_d \frac{dn_d^\pm}{ds} = \ldots, \quad \pm v_{cx} \frac{dn_{cx}^\pm}{ds} = \ldots, \quad \pm v_{rc} \frac{dn_{rc}^\pm}{ds} = \ldots.$$

Plasma profile — an example

§ Plasma and neutral profiles

- † Used parameters:

  $l_\mathrm{p} = 3$ [m], $\varphi = 80°$,

  $T_\mathrm{m} = 600$ K,

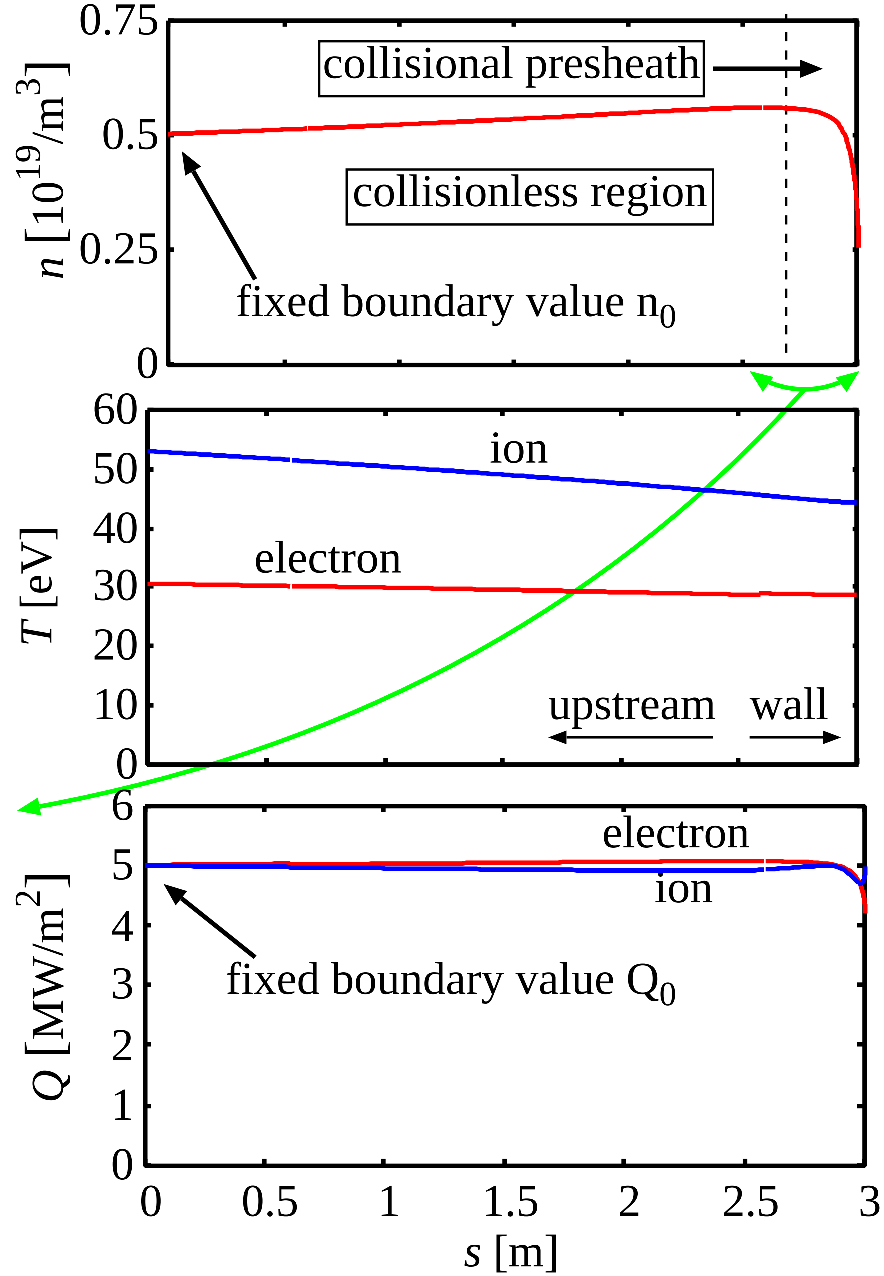
  $r_\mathrm{pl} = 0.5$, $r_\mathrm{imp} = 0.03$,

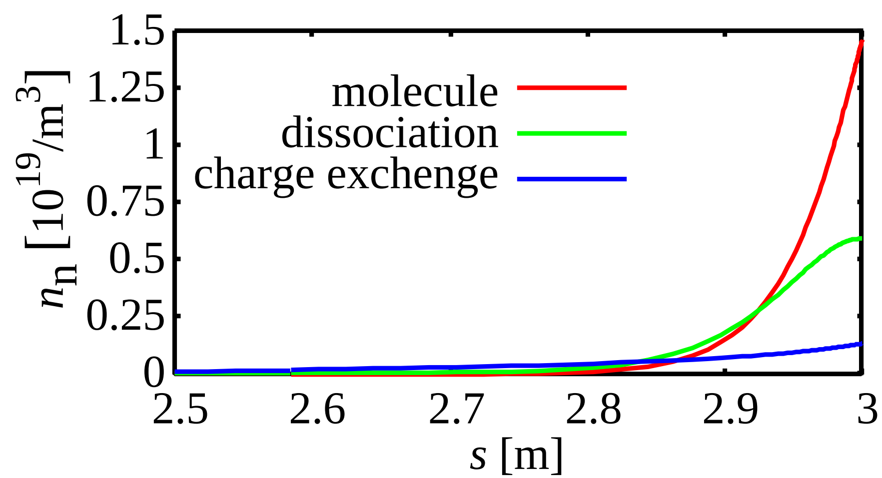
  $n_0 = 0.5 \times 10^{19}$ [m^{-3}],

  $Q_0 = 10$ [MW/m^2].

- † Calculation time:

  0.2~0.5 seconds on Core2Quad machine (Q9300 2.5GHz).





Plasma profile in ERO simulation

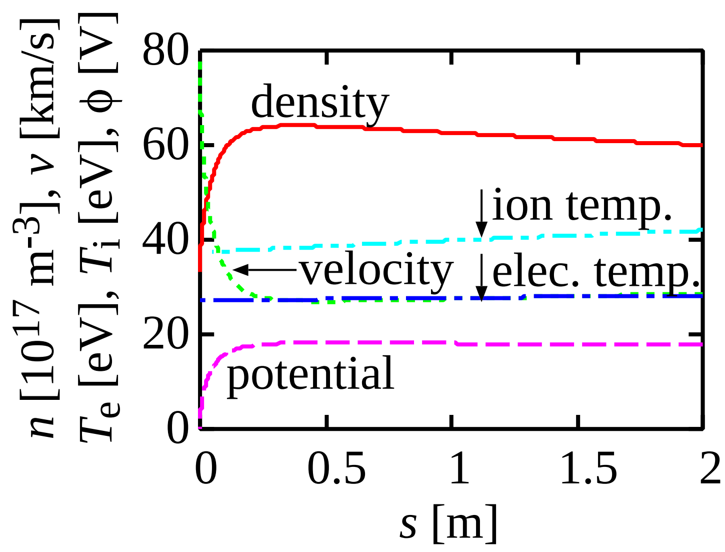
§ Background plasma

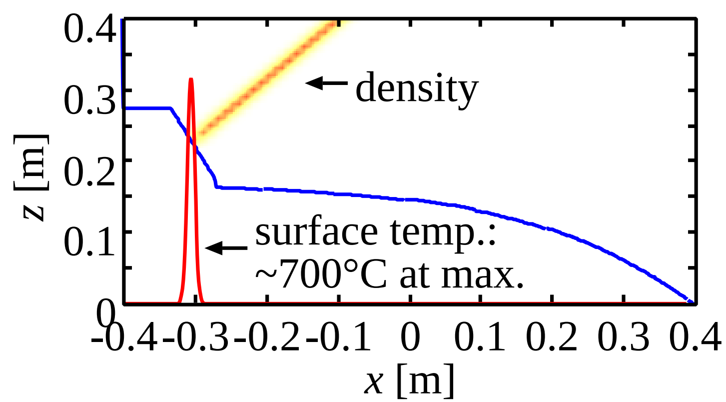
- The divertor leg plasma is given by a 1D profile of a two-fluid model including interactions with neutral particles.
- The perpendicular profiles to the center line of the divertor leg is given by a Gaussian shape,

$$T(l) \propto \exp(-l^2/\lambda^2),$$

  where characteristic length $\lambda = 1$cm.
- Surface temperature is calculated from the power load on the surface,

$$Q_{\mathrm{wall}} \propto nvT \propto n(T_e + T_i)^{3/2}.$$





§ Surface geometry

- Surface is defined by a fuction $z(x)$.
- Only one surface is avialable in the current version.

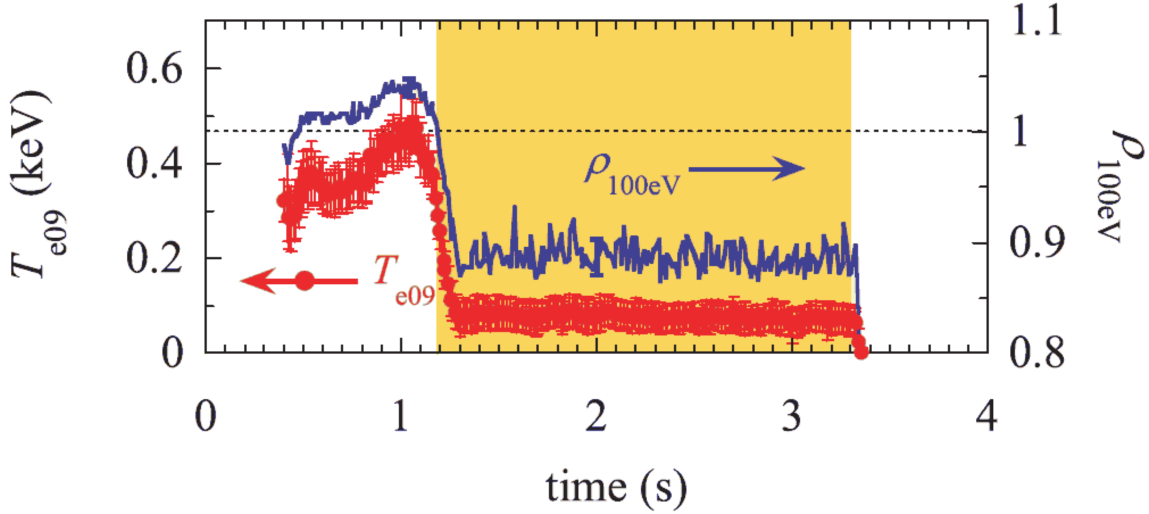
3. Gas puffing simulation

§ Background

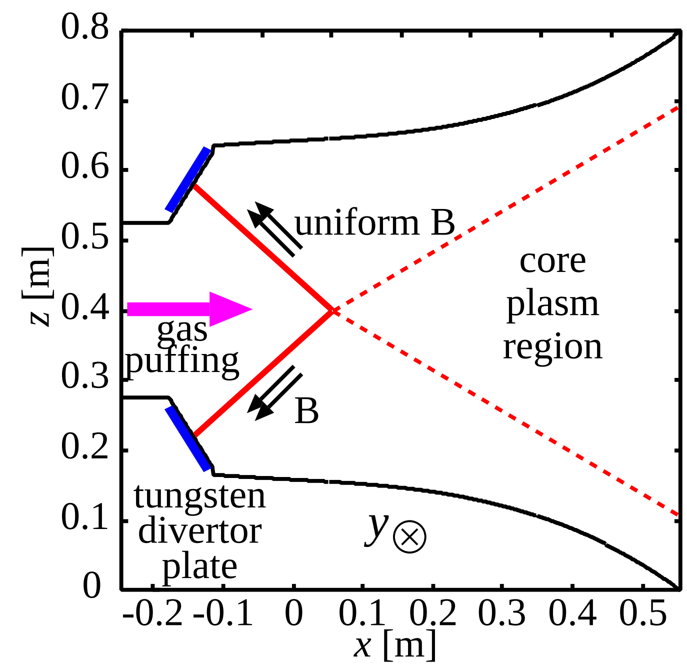
- † Sustained detachment has been achieved with the aid of strong H gas puffing. The core plasma, however, becomes low temperature due to the excess source.
- † Neon and argon gas puffing is planed to expect larger radiation cooling and a preliminary test has been carried out successfully.

§ Objectives

- † Heavy ion causes large erosion of the divertor tiles even on tungsten.
- † Understanding of transport of the ions and estimation of the erosion are necessary task for advanced LHD discharges in future.



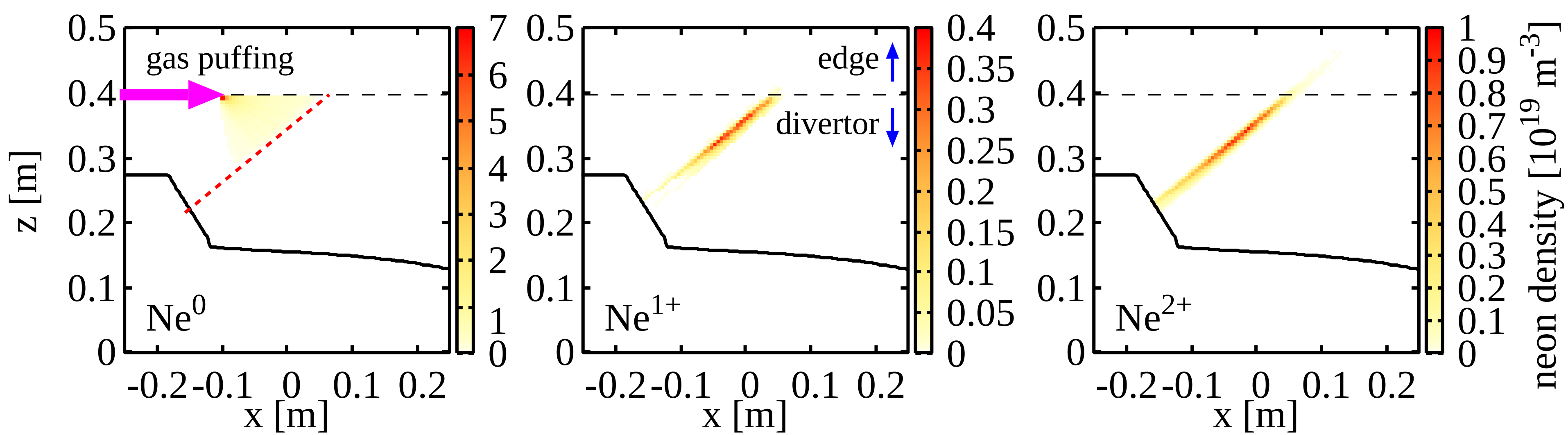
Detachment by strong hydrogen gas puffing



Neon transport

§ Spatial distributions of neon atom and ions

- † Flow rate of the neon gas: 1Pam^3/s = 2.7×10^{20} atoms/s in 300 K.
- † The neon atoms are ionized immidiately and flow toward the divertor tile.
- † The friction force is dominant.
- † Significant fluxes of Ne^{2+} and Ne^{3+} are observed on the surface.



Erosion and redeposition of tungsten

§ Erosion distribution of W tile along *x*-axis

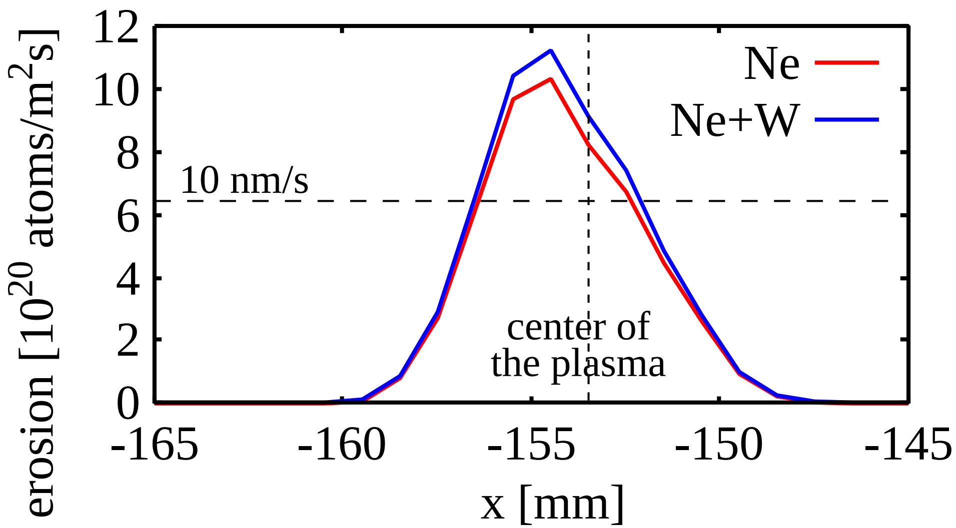
† Erosion by Ne bombardment ~ 15nm/s for 1 Pam^3/s.

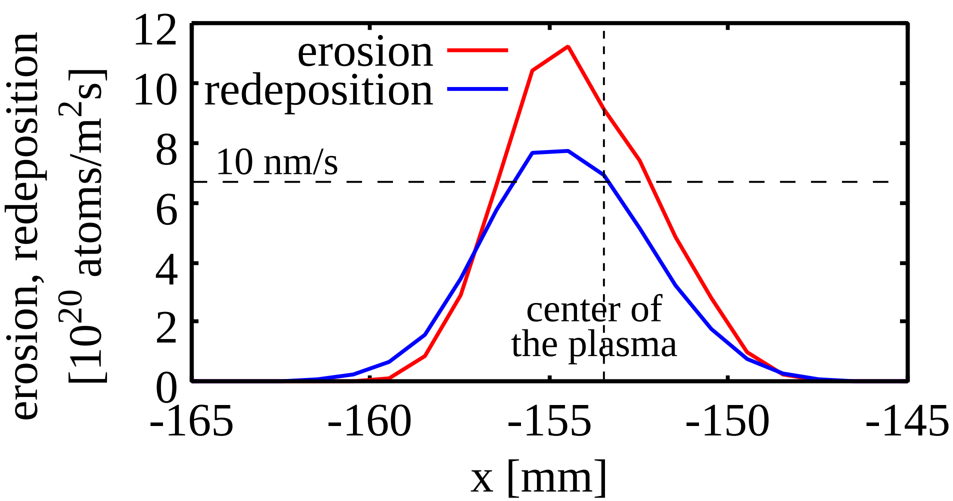
† Erosion by W bombardment, i.e. self-sputtering, is not significant in this case.

§ Redeposition distribution of W tile along *x*-axis

† The effective erosion rate is around 1/3 of the pure erosion rate.

† Deposition region is observed outside the erosion region.





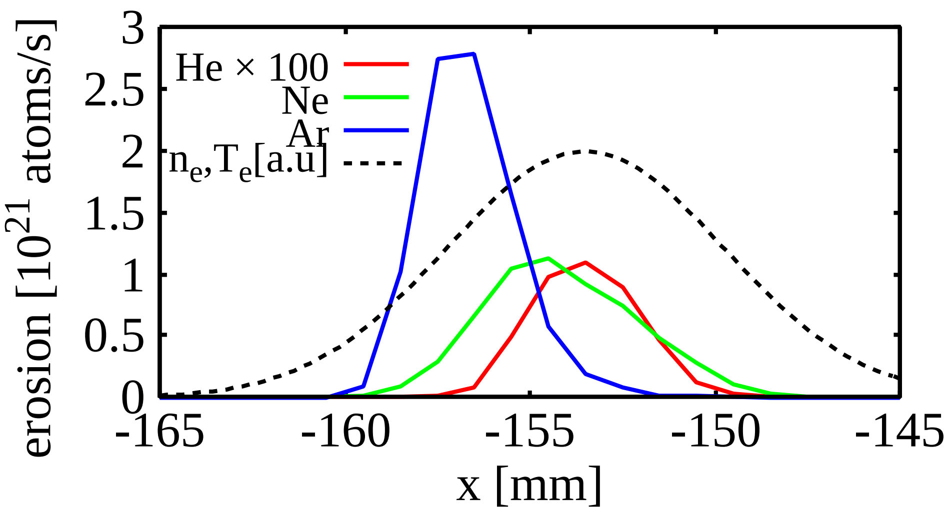
We note that the distribution can change for different cross-field diffusion coefficient.

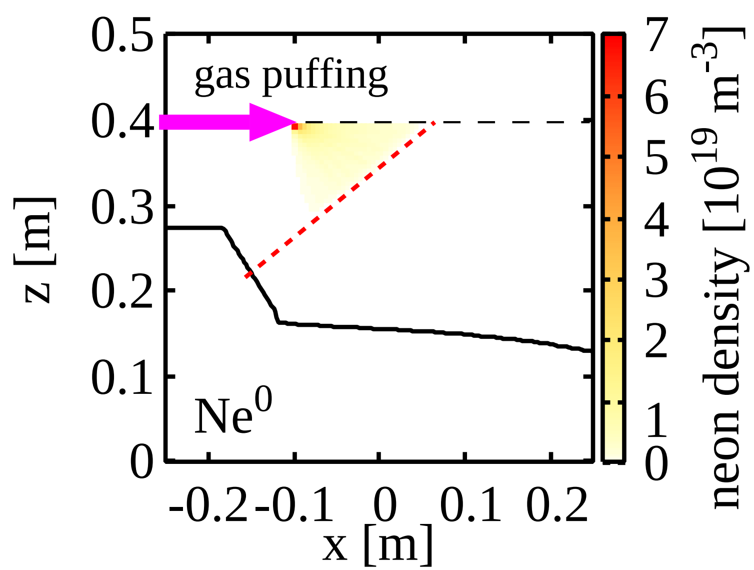
No diffusion in this simulation.

Influence of different gas species

§ Helium, neon and argon puffing simulation

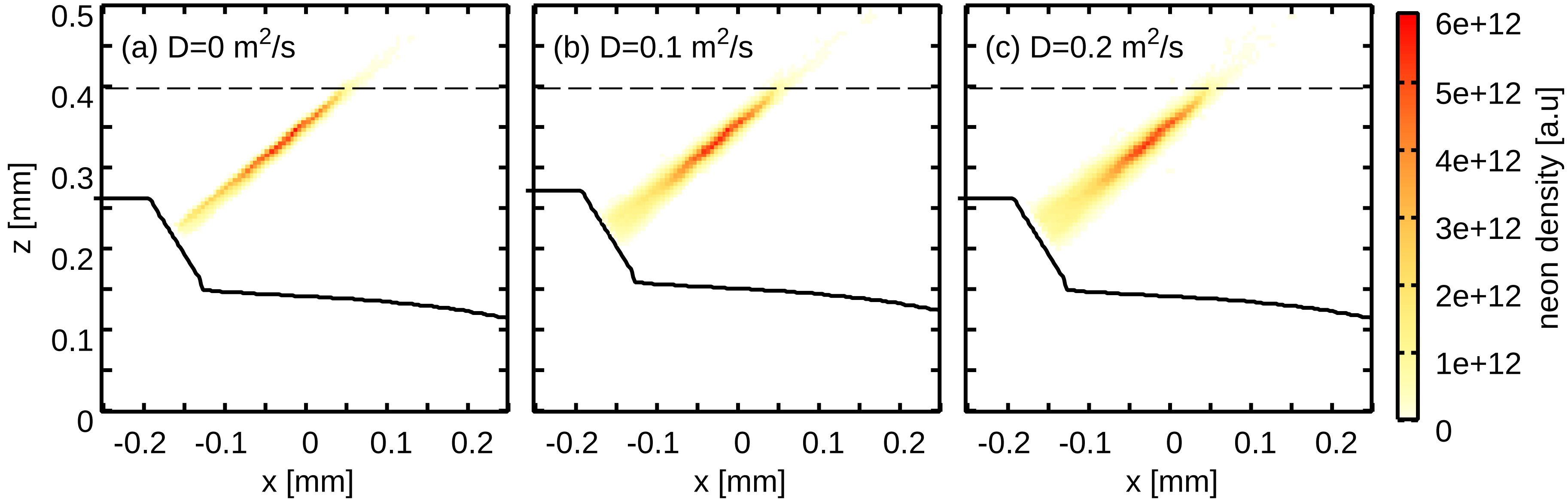
- † Erosion due to helium is negligibly small for the plasma of $T_e \sim 30$eV because of the higher energy threshold.
- † Argon erodes tungsten two times more than neon.
- † The peak shift is caused by the higher ionization rate which makes ionizations in shallow position in the leg.
- † Ionization energy
  He: 24.6eV, Ne: 21.6eV, Ar: 15.8eV.





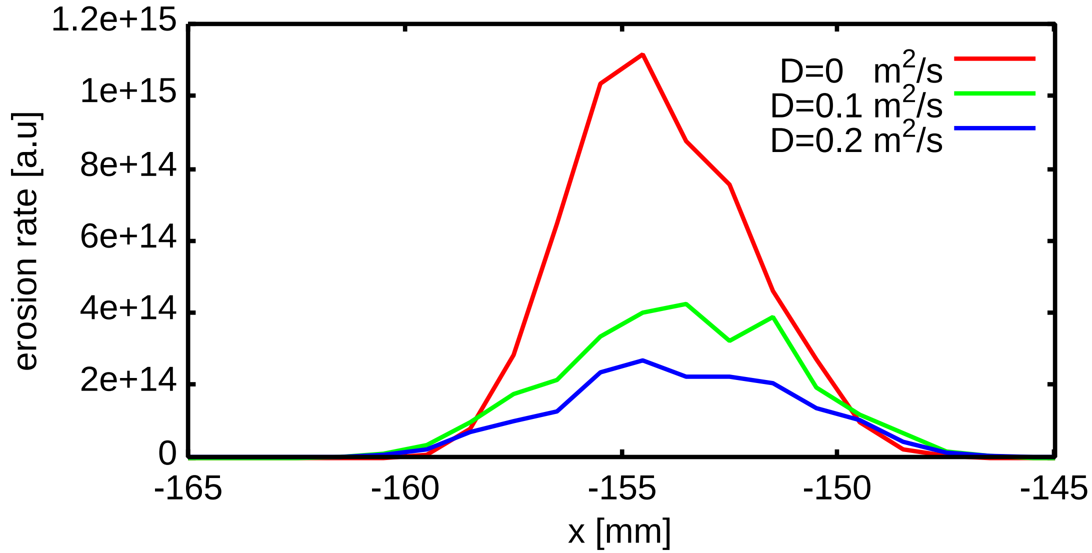
Perpendicular diffusion of impurity

§ Impurity distribution with constant diffusion coefficient



§ Erosion distribution

- † Large diffusion causes less erosion.
- † Diffusion model for the divertor leg is necessary.
- † Plasma modeling with diffusion is also important.



4.Summary

§ LHD divertor modeling for ERO

† Plasma and wall cofigurations

† 1D plasma modeling by two fluid equations

§ Gas puffing simulation

† Upper limit of erosion and redeposition rate were estimated.

† Effect of impurity diffusion was studied.

§ Future issues

† Diffusion coefficient model of impurity in the divertor leg.

† Advanced plasma modeling with EMC3.

⇒ extension of the simulation grids to the legs

† Integration of ERO and EMC3

impurity source

ERO (local) ⇄ EMC3-EIRENE (global)

plasma profile
SOL and leg