

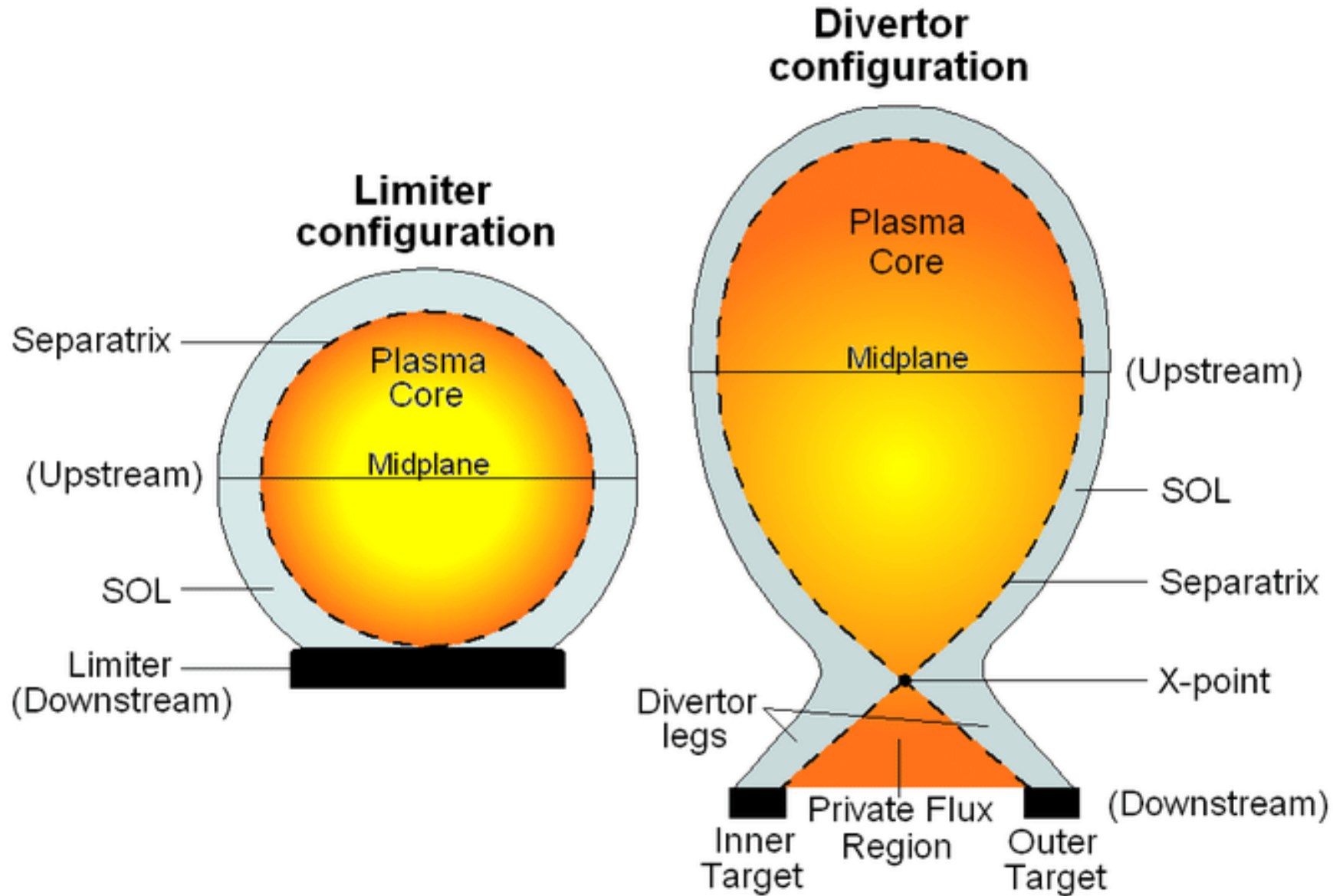
Plasma Boundary and Exhaust

Yasmin Andrew

Learning Outcomes I

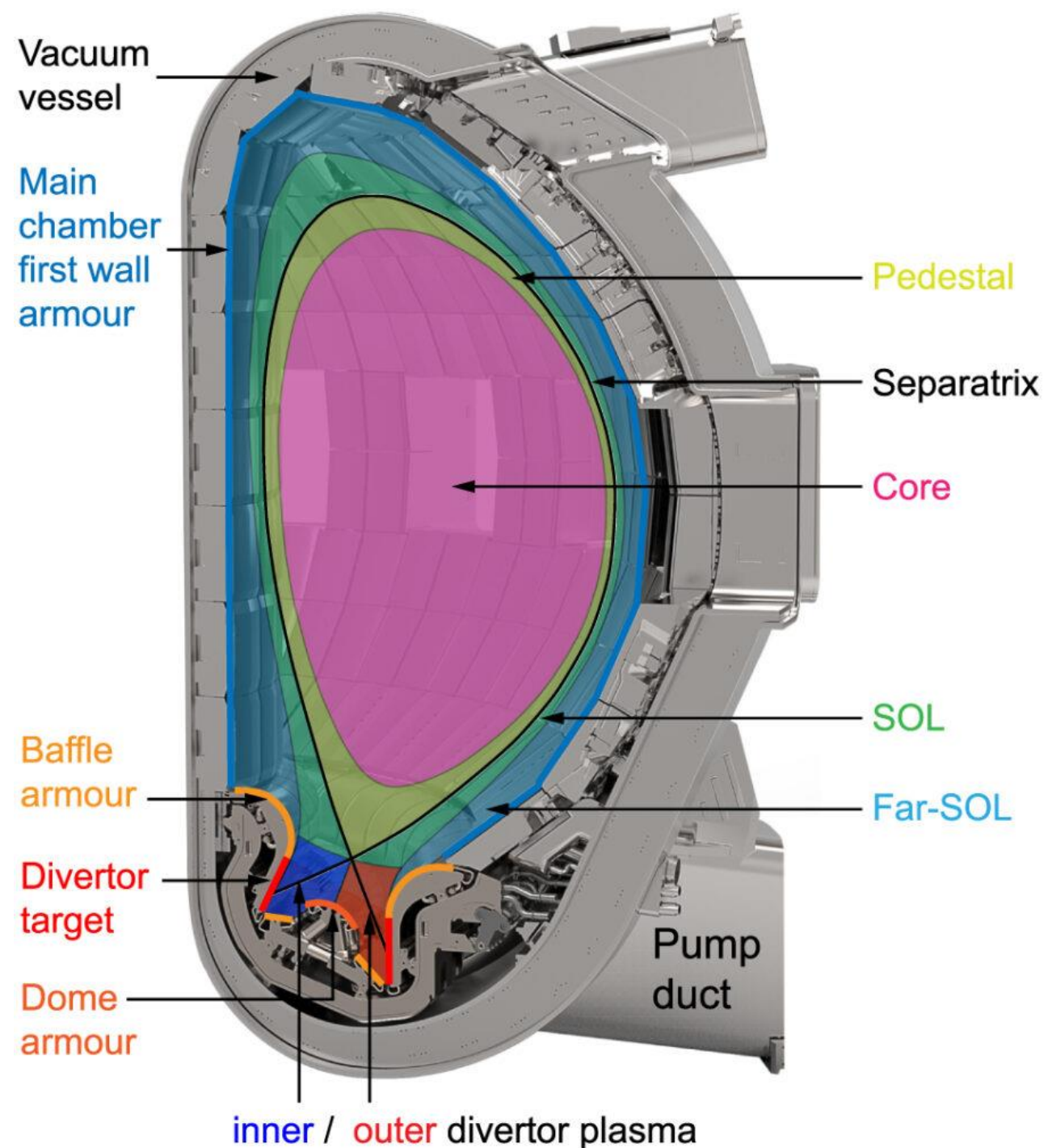
- Review expressions for sheath potential and plasma potential from the principles of ambipolar diffusion, demonstrating understanding of plasma–surface interactions.
- Explain the mechanisms of particle recycling in plasma-facing components and analyze their effects on local plasma properties.
- Describe and interpret the structure of plasma sheath and pre-sheath regions, including potential and density profiles, through annotated sketches.
- Calculate the power flux to a target and maximum plasma density in front of it, applying quantitative methods relevant to fusion devices.
- Evaluate SOL radial profiles of electron density and temperature, and infer perpendicular transport coefficients (D_{\perp}, χ_{\perp}) from SOL widths.

Limiter versus Divertor

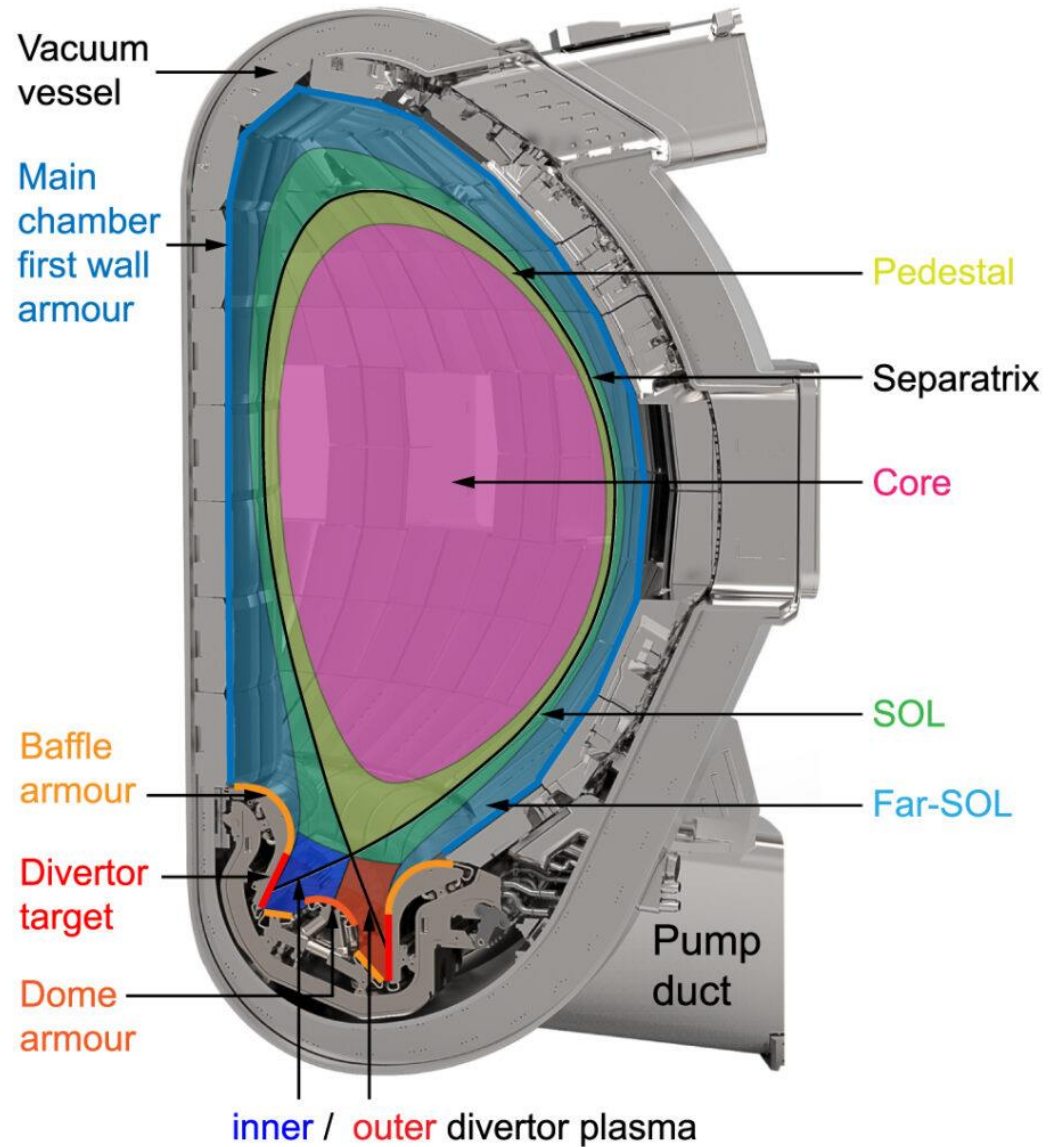


Magnetic Divertor

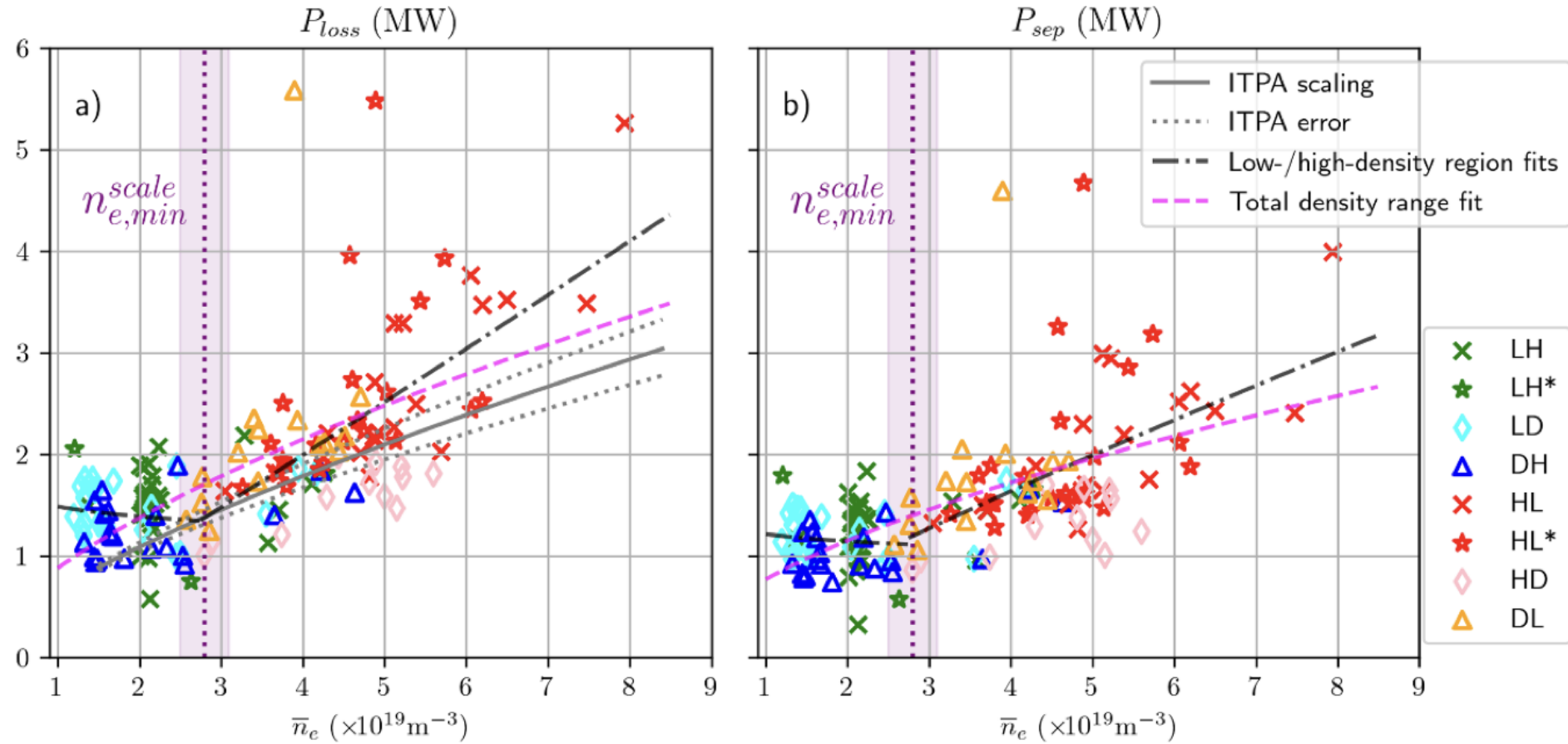
- Magnetic divertors were introduced in MCF devices to reduce and control impurities and improve target power handling capability.
- In the magnetic divertor configuration external coils are used to divert the magnetic field lines to a connected, separate chamber
- The plasma is neutralised and products of the plasma surface interactions are pumped away in the divertor chamber.
- The most successful divertor design utilises coils to create axisymmetric poloidal magnetic nulls.



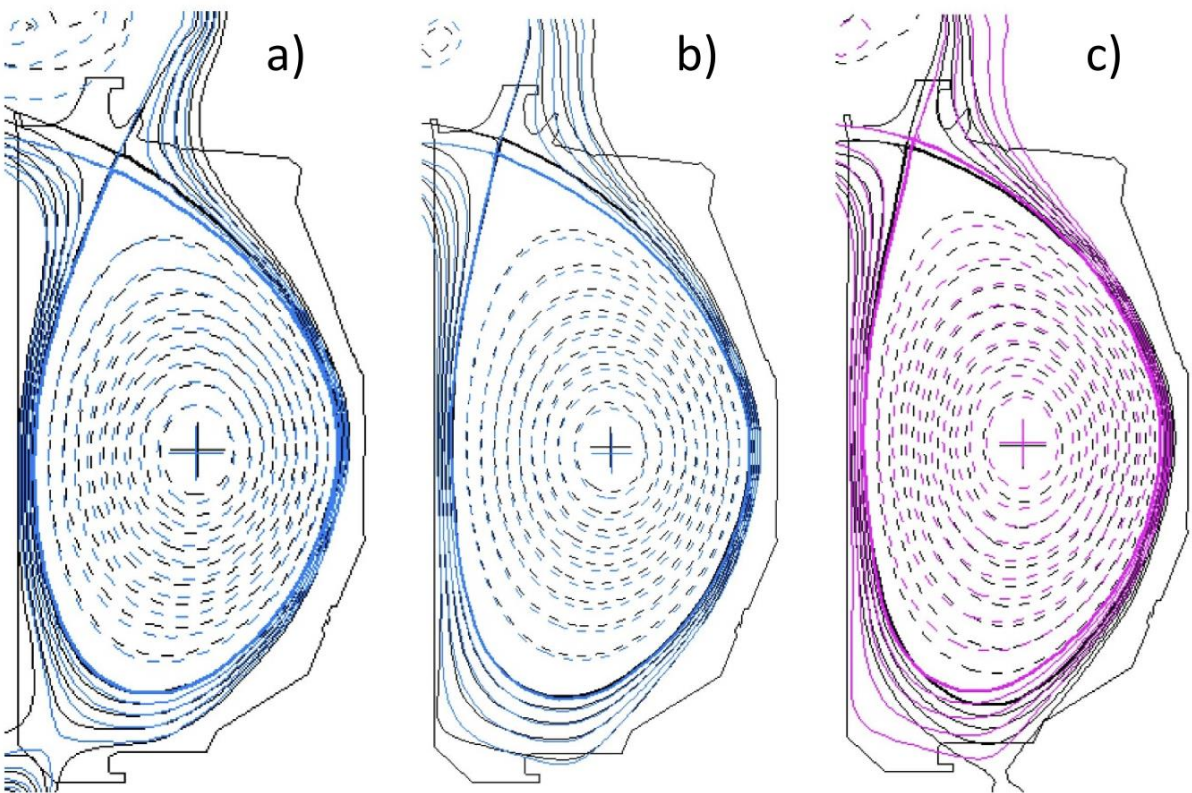
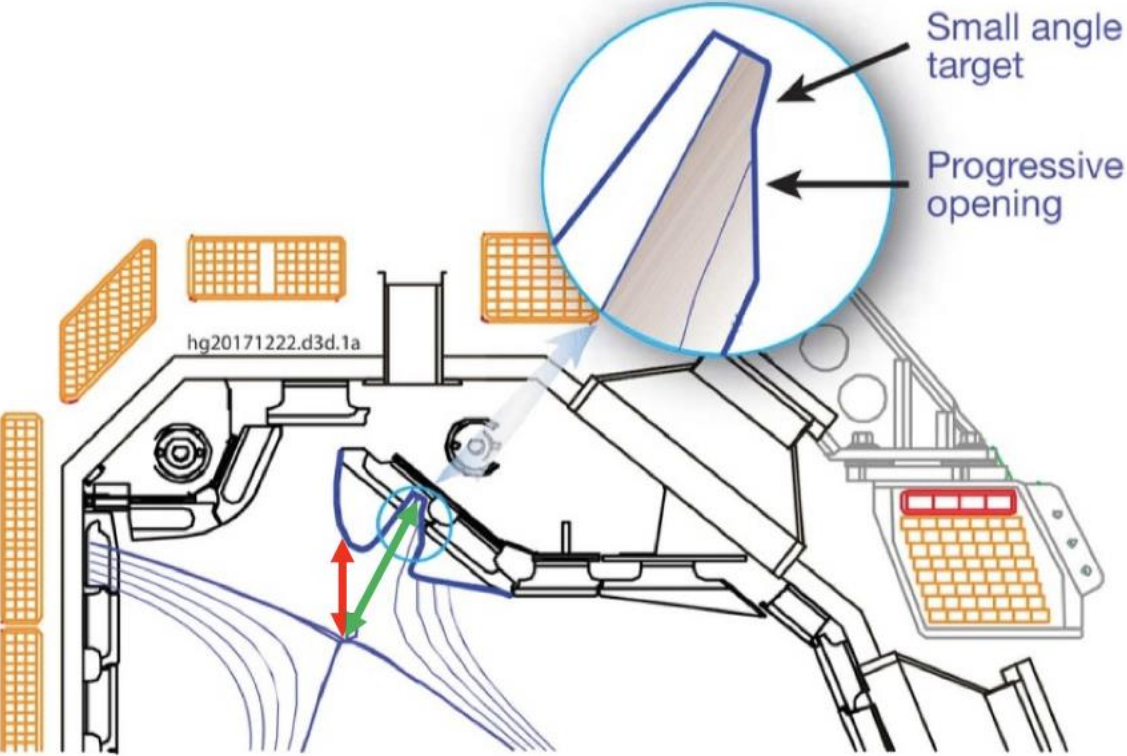
Core – Edge – SOL integration



Power threshold dependence on core plasma n_e

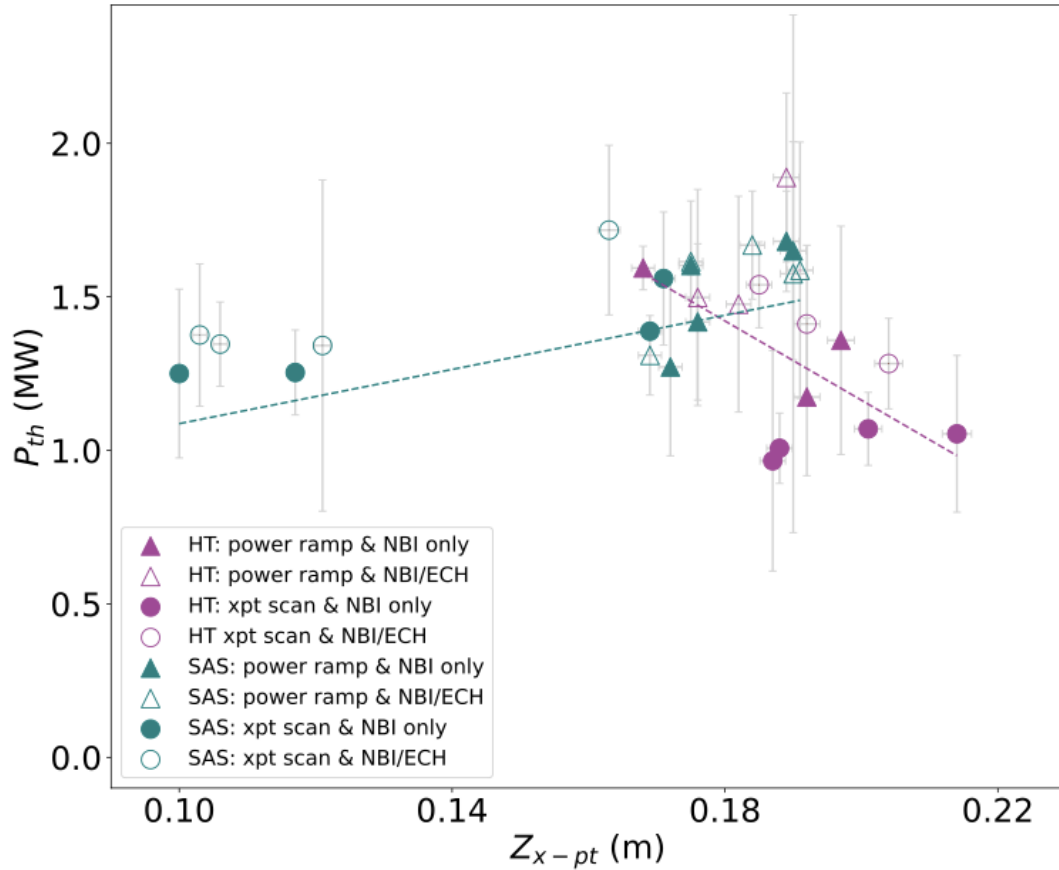


Power threshold dependence magnetic divertor configuration

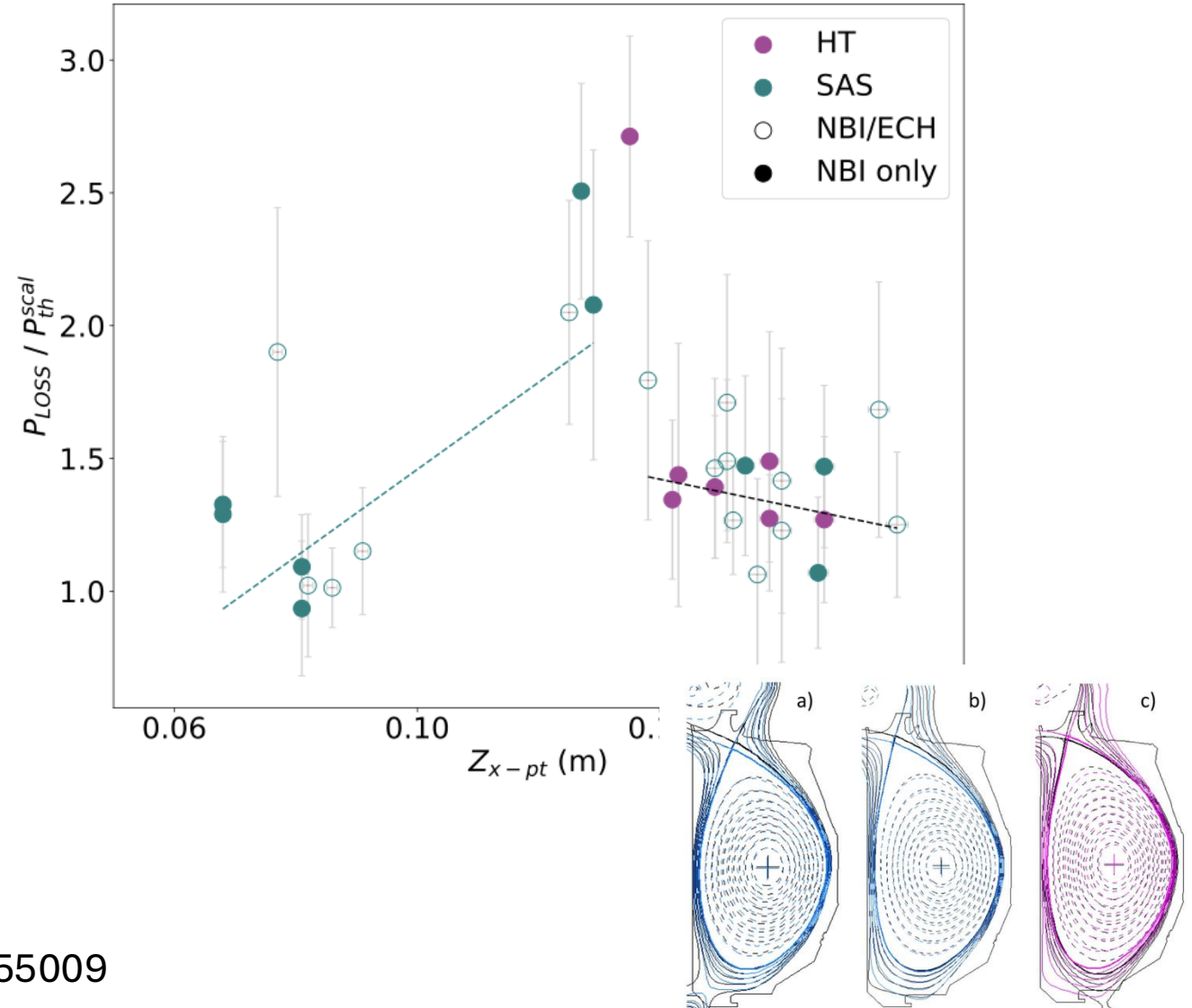


Power threshold dependence magnetic divertor configuration

a) LH Transition



b) HL Transition



Plasma sheath

- When a solid surface is introduced into a plasma with electrons and ions in thermal equilibrium, there will initially be a greater flux of electrons to the surface,
- This is due to the higher velocity of the electrons compared with the ions.
- The electron flux to the surface, results in the build up of a potential difference between the solid surface and the plasma until the current densities of electrons and ions to the surface are equal,

$$J^+ = en_e C_s = J^- = \frac{1}{4} en_e v_e (1 - \delta) \exp\left(-\frac{\Phi_s}{T_e}\right)$$

where T_e is plasma temperature in eV, Φ_s is the equilibrium potential of the surface, δ is the secondary electron yield from the surface due to the ion and electron flux, v_e is the mean electron velocity and C_s is the ion sound speed.

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$$C_s = \left(\frac{k_B(T_e + T_i)}{m_i}\right)^{1/2} \leq v_e$$

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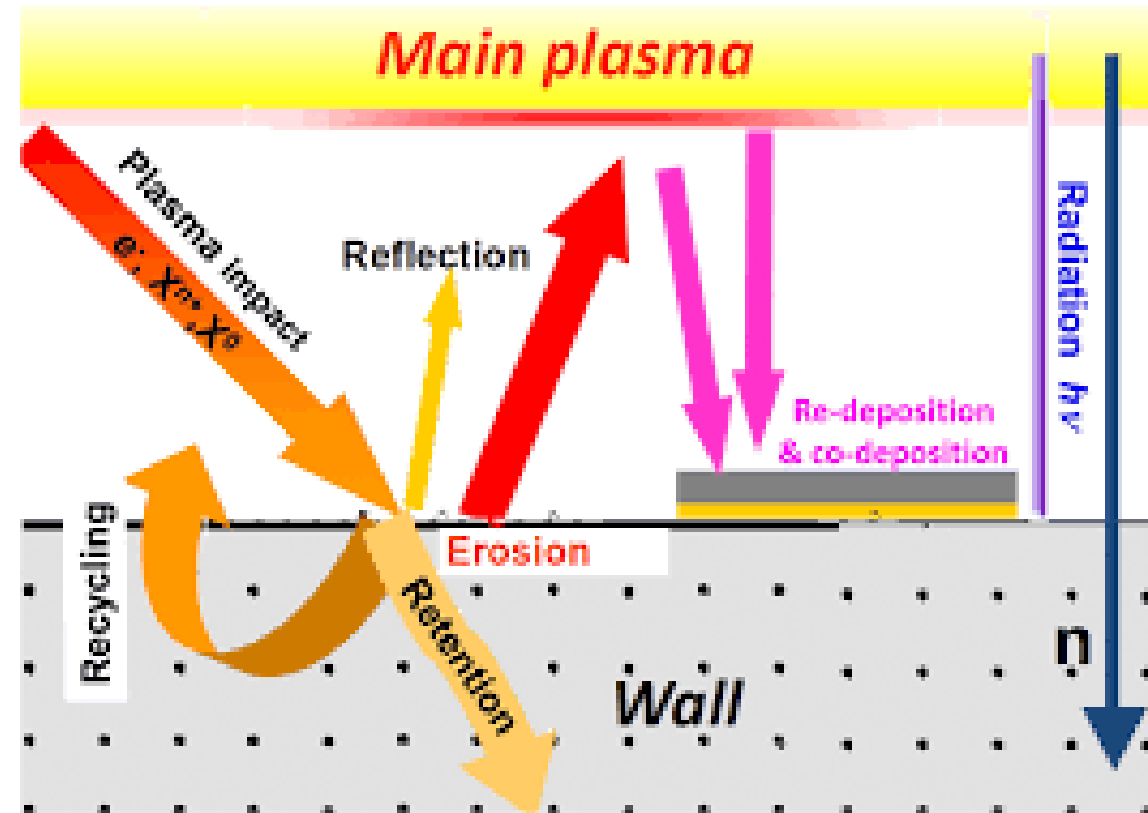
- The surface or **sheath potential** is given by the expression,

$$\Phi_s = -\frac{1}{2} k_B T_e \ln \left[\frac{2\pi m_e (1 + T_i/T_e)}{m_i (1 - \delta)^2} \right],$$

which reduces to $\Phi_s = 2.5k_B T_e$ for a hydrogen plasma with secondary electron emission coefficient, $\delta = 0$ and $T_i = T_e$.

Plasma surface interaction - recycling

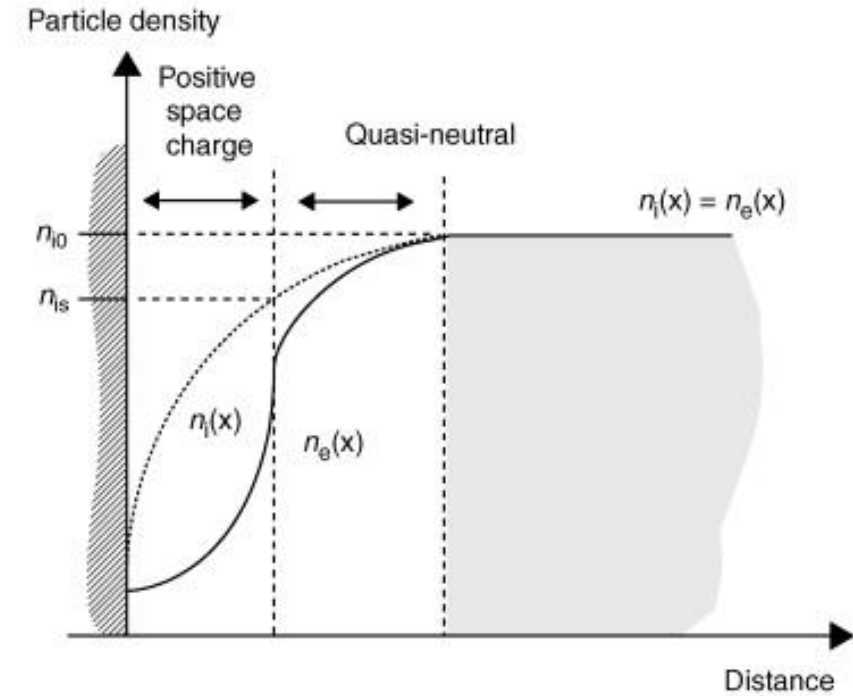
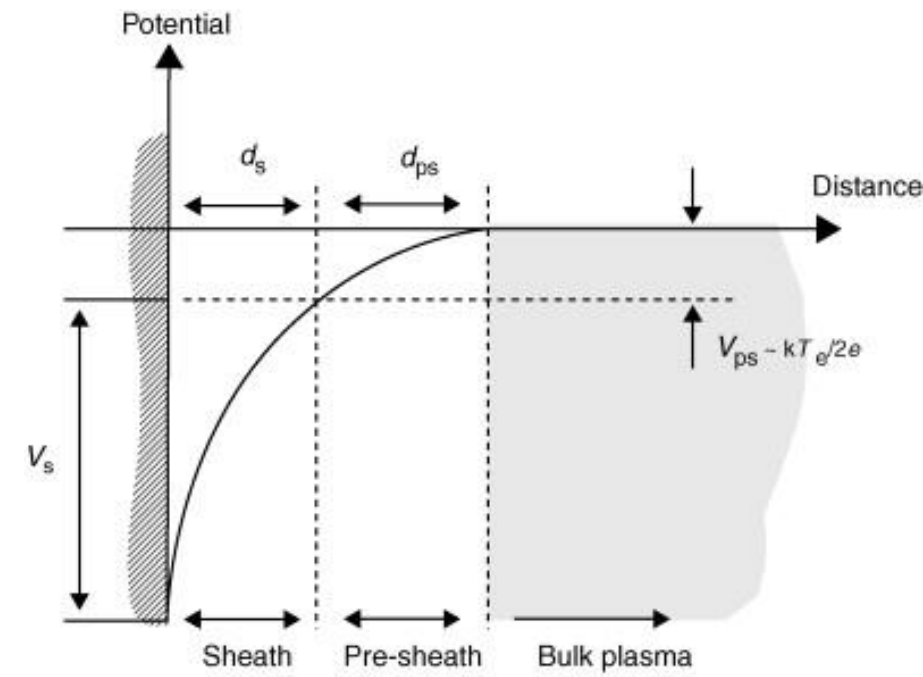
- A solid surface in a plasma acts as a sink for both electrons and ions.
- When an ion arrives at a surface it has a high possibility of recombining with an electron and becoming a neutral.
- Therefore, there needs to be a method to continue to ionise the neutral gas in the vessel to generate the main plasma.
- Atoms or molecules that are emitted or return from the plasma wall are ionised through collisions with plasma electrons and this process is called recycling.
- A source of heat is required to maintain the plasma temperature and keep the electrons hot, since the continuous flux of particles to the solid surface is a channel for loss of energy.





Plasma sheath and pre-sheath

- The sheath potential means that the plasma in contact with it also has a fixed potential, the plasma potential, Φ_{ps}
- The electric field that develops due to ambipolar diffusion and Φ_s and Φ_{ps} , has a significant effect on plasma transport.
- The plasma ions are accelerated to the solid surface by the potential difference across the plasma sheath.
- Hence the ion energy distribution is approximately an accelerated Maxwellian, with the velocity of each ion increased by a constant value compare with the bulk and pre-sheath plasma.
- The electrons are decelerated by the sheath, again due to ambipolar diffusion.
- The electron distribution at the solid surface is therefore still a Maxwellian but the electron flux is reduced.



Target power flux

- The electron flux is limited by ambipolarity to the same value as the ion flux.
- The power flux at the target is given by the expression,

$$P = J_s T_e \left[\frac{2T_i}{T_e} + \frac{2}{1 - \delta} - \frac{1}{2} \ln \left\{ \frac{2\pi m_e (1 + T_i/T_e)}{m_i (1 - \delta)^2} \right\} \right]$$

where J_s is the ion current density in $A\ m^{-2}$ and T_e is in eV.

- For the assumed conditions of $T_i = T_e$ and $\delta = 0$, and the sheath heat transmission coefficient, $\gamma = P/J_s T_e$, in a deuterium plasma, **$P = 7.8 \times 10^{-16} \gamma n_e T_e^{3/2}$** ,.
- In fusion plasmas $\delta \simeq 1$; γ is significantly higher for values of $\delta \geq 0.8$.

Power flux to the Target

- The surface or **sheath potential** is given by the expression,

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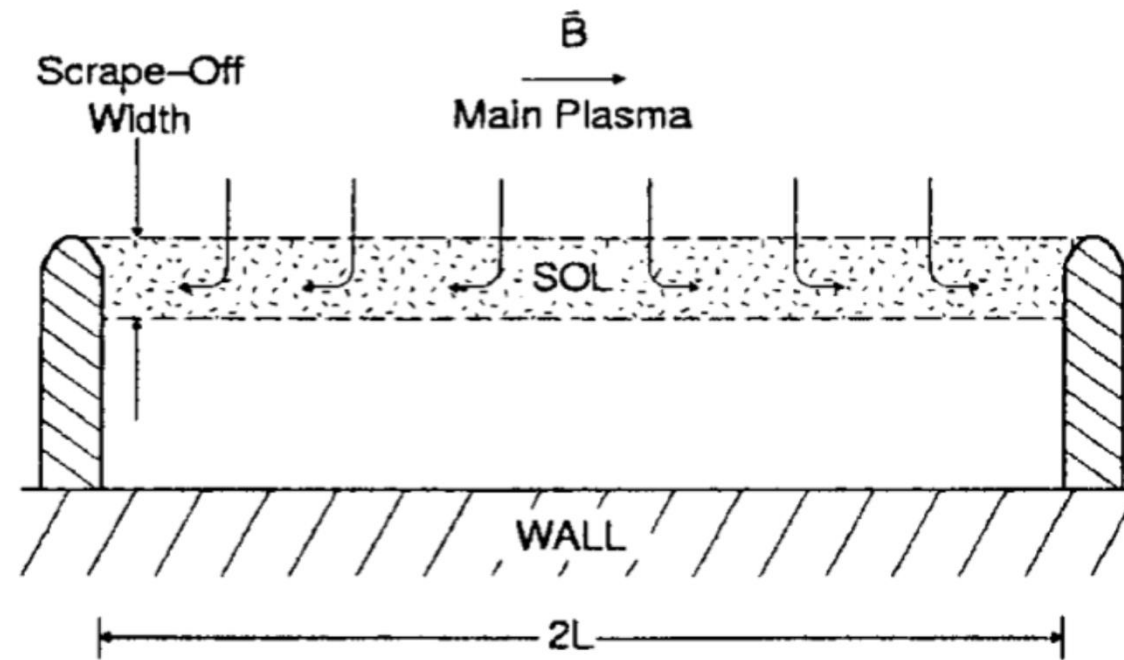
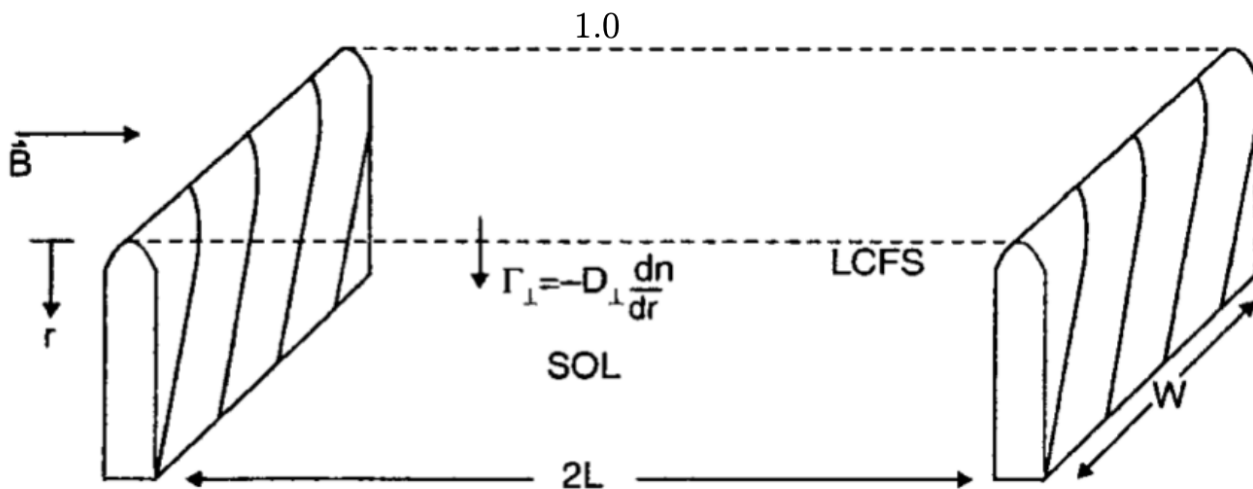
- As shown by the equation the sheath potential becomes more negative (its magnitude increases as more electrons are emitted through secondary electron emission
- The surface potential becomes more negative to suppress electron current to the surface and maintain current balance and ambipolarity.
- The number of secondary electrons that can be emitted from the surface saturates due to space charge effects in the sheath region
- For any cooled divertor target plate material, the maximum tolerable power flux, P_{max} , is determined by the material properties.
- This allows a maximum plasma density at the material surface to be expressed from equation

$$P = 7.8 \times 10^{-16} \gamma n_e T_e^{3/2},$$

$$n_e^{max} = 1.3 \times 10^{15} \frac{P_{max}}{\gamma T_e^{3/2}}$$

SOL radial profiles

- Outside the confined plasma's separatrix the plasma flows parallel to the magnetic field lines of the scrape-off layer (SOL), and perpendicularly to them at a much slower rate.
- These directions are illustrated in the 2D schematic diagram of the straightened-out tokamak core and SOL plasma
- In a steady-state, provided that there are no additional plasma sources, such as ionisation, or sinks, such as a solid surface recombination site,
- The particle losses along the magnetic field lines in a flux tube, must be balanced by the net flow of particles across the field lines into the flux tube.

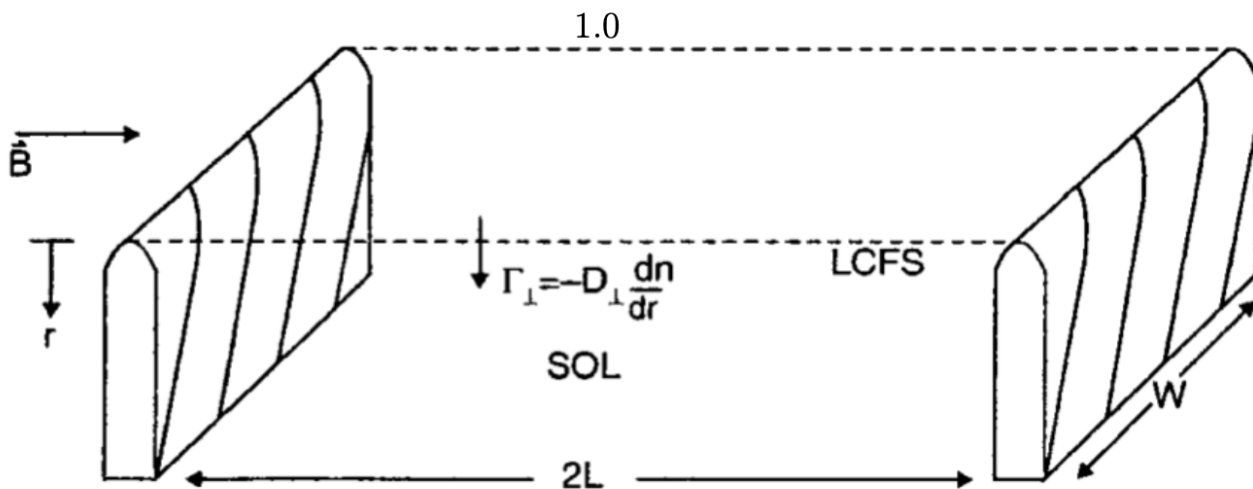


SOL n_e radial profile

Derivation!

- The e-folding or decay length of density radially across the SOL is given by,

$$\lambda_n = \sqrt{\frac{D_{\perp} L_c}{V_S}}$$



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SOL n_e radial profile

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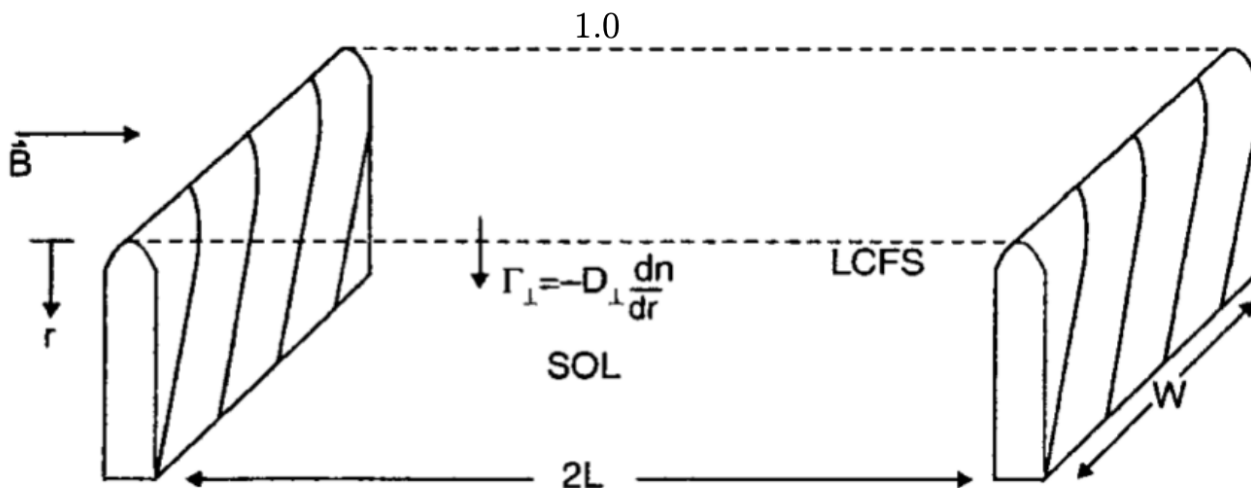
- The e-folding or decay length of density radially across the SOL is given by,

$$\lambda_n = \sqrt{\frac{D_{\perp} L_c}{V_S}}$$

which is a key measure of SOL width.

- A longer connection length and higher perpendicular diffusion coefficient (for example, due to enhanced plasma turbulence levels in the L-mode) lead to a wider SOL.
- Higher plasma temperatures, leading to a higher parallel plasma speed along the SOL leads to a narrower SOL.

- The e-folding or decay length of density radially across the SOL is given by,



$$\lambda_n = \sqrt{\frac{D_{\perp} L_c}{V_S}}$$

SOL T_e radial profile

- An electron heat balance equation can be considered in an analogous way to equation,

$$\lambda_n = \sqrt{\frac{D_{\perp} L_c}{C_S}} \qquad \lambda_T = \sqrt{\frac{X_{\perp} L_c}{C_S}}$$

where, X_{\perp} is the perpendicular thermal diffusion coefficient in $\text{m}^2 \text{s}^{-1}$, and C_S is the sound speed.

- The two expressions for decay length in the SOL in terms of cross-field particle and thermal diffusion coefficients.
- Since dominant transport is anomalous, measured values of λ_n and λ_T are used to deduce values of D_{\perp} and X_{\perp} .
- Typical values in fusion plasmas are around $\lambda_n \sim 10 \text{ mm}$ in tokamak SOLs and $D_{\perp} \cong 1 \text{ m}^2 \text{ s}^{-1}$.

Learning Outcomes II

- Review parallel transport in the scrape-off layer (SOL) and apply force balance to derive relationships between plasma temperature and density at the divertor target and mid-plane.
- Apply energy balance arguments in the SOL to derive relationships between plasma temperature at the divertor surface and upstream (mid-plane) conditions.
- Examine expressions for the power flux to the divertor target using ion and electron particle fluxes.
- Integrate particle, momentum, and energy balance relations to explain and apply the two-point model of scrape-off layer transport.
- Describe and discuss the principal mechanisms by which impurities are introduced into magnetically confined fusion plasmas.

Parallel SOL transport

- An isothermal fluid model is the simplest method to describe the main features of transport along the open magnetic field lines of the SOL.
- Steady-state, inviscid, isothermal, 1D flow is determined by the conservation of particles and momentum along the SOL, z ,

$$\frac{d(nv)}{dz} = S,$$

$$nm_i v \frac{dv}{dz} = - \frac{dp}{dz} + enE - mvS,$$

where, $\Gamma_{\parallel} = nv$, is the parallel particle flux density, $p = nkT_i$, $E = -d\Phi/dz$, S is the source rate of particles due to cross-field transport or ionization, and the ion charge is assumed to be $Z_{\text{eff}} = 1$ (no impurities).

- The first term on the RHS of the force balance equation is the pressure gradient along the field lines, the second term is the force due to the electric field, the third term is the drag due to the acceleration of cold ions from the source.

Parallel SOL transport

- Using the Boltzman relation, $n = n_0 \exp(e\Phi/kT_e)$, along with,

$$nm_i v \frac{dv}{dz} = - \frac{dp}{dz} + enE - mvS,$$

$$\Gamma = nv = \mu nE - D\nabla n$$

to give the expression,

$$\frac{dM}{dz} = \frac{S}{nC_S} \frac{1+M^2}{1-M^2},$$

where M is the Mach number of the plasma flow parallel to the magnetic field lines, $M = v/C_s$.

- It can be seen that as $M \rightarrow 1$, $dM/dz \rightarrow \infty$, and the solution breaks down.
- The condition of $M = 1$ indicates the boundary between the plasma and the sheath.
- This is known as the **Bohm Criterion**, the plasma must reach the sound speed at the entrance to the plasma sheath.

Parallel SOL transport

$$\frac{dM}{dz} = \frac{S}{nC_S} \frac{1+M^2}{1-M^2},$$

- If the further assumption $S \propto n$ is made and then as $M \rightarrow 1$,

$$\frac{n(M)}{n(0)} = \frac{1}{1+M^2} \rightarrow 0.5,$$

$$\Phi(M) = T_e \ln(1 - M^2) \rightarrow 0.69T_e,$$

where $n(0)$ is the plasma density at the stagnation point halfway between the two targets.

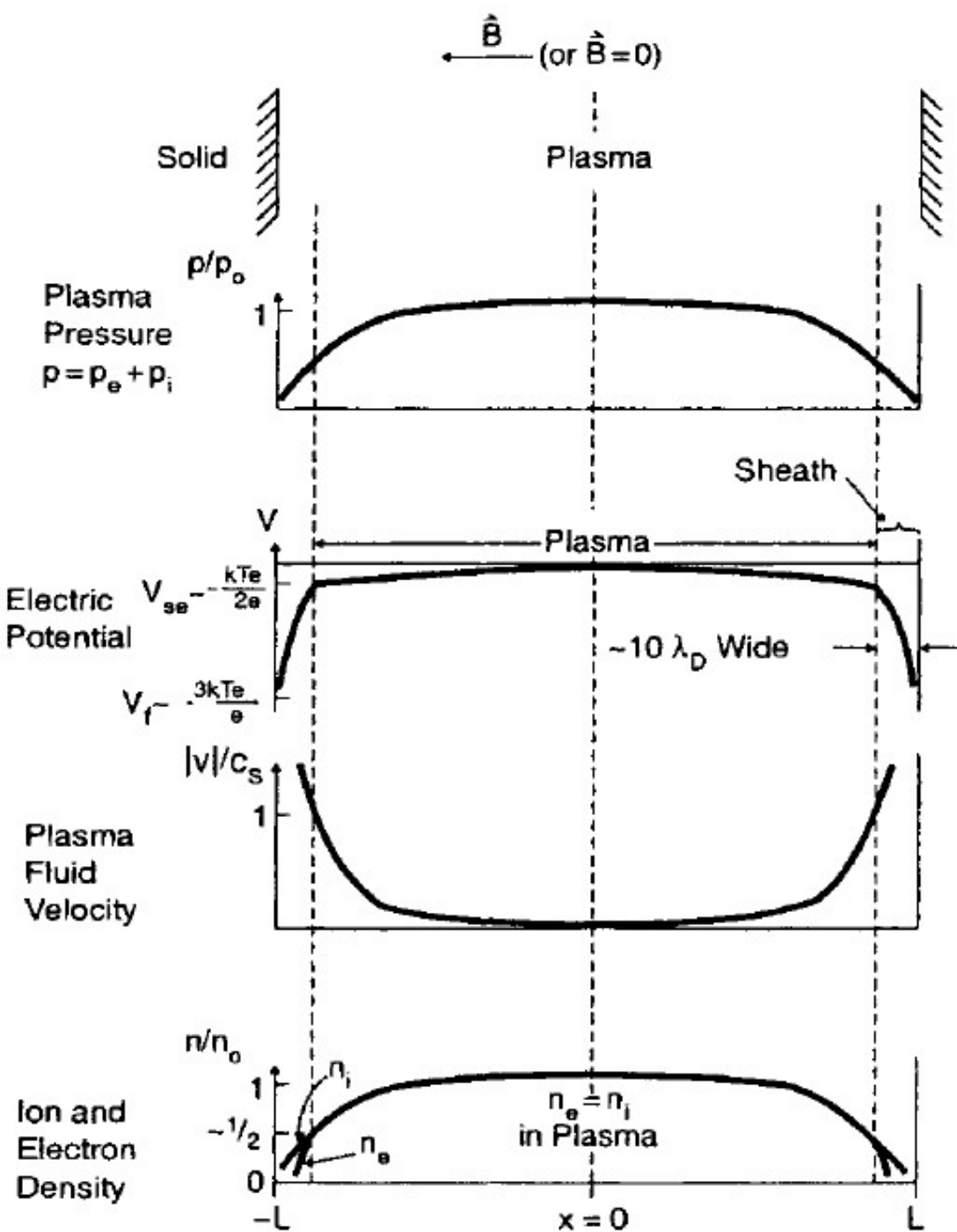
Parallel SOL transport

Schematic plots of

- (a) plasma pressure,
- (b) electric potential,
- (c) fluid velocity and
- (d) density

as a function of distance along the SOL between two divertor target plates, for a fluid model description of magnetised flow along the field lines.

The thickness of the plasma sheath has been exaggerated for clarification.



Parallel SOL transport

- There are many other more sophisticated and complete models for parallel SOL transport, including both fluid and kinetic treatments.
- For the most important variables, the predictions by these models are fairly similar and the the fluid descriptions provides a good starting point.
- The simplified model presented here neglects plasma impurities and considers only the hydrogenic species.
- Impurities that are released from the solid surfaces and flow into the SOL plasma are also subject to the electric field, and their own pressure gradient.
- The impurity ions also experience frictional force due to ion flow towards the target plates.

Pressure balance

For a steady-state, 1D plasma along a SOL field line, the parallel pressure balance can be written as,

$$\frac{d}{ds} (p_e + p_i + m_i n u_{\parallel}^2) = -R_{\parallel}$$

where s is the distance along the magnetic field line in m, $p_e = nT_e$ and $p_i = nT_i$ are the electron and ion thermal pressures in Pa, n is in m^{-3} , T is in J, u_{\parallel} is the parallel ion velocity in the dynamic pressure term.

- The left side of the equation represents the derivative of the total parallel momentum flux in Pa m^{-1} .
- The left-hand side of the equation, $-R_{\parallel}$ is the volumetric parallel momentum loss term in Pa m^{-1} , due to ion-neutral charge exchange losses, ion - neutral friction and ion recombination.

Pressure balance

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Derivation!

- A simple model to describe the SOL and divertor plasma assumes $T_i = T_e$ everywhere and assuming pressure balance,

$$n_d T_d = \frac{1}{2} n_u T_u.$$

- The upstream plasma pressure is purely thermal due to relatively low ion parallel flow speed.
- At the same time, the downstream pressure at the target supports both thermal pressure and dynamic pressure from the parallel ion momentum flux into the sheath due to sonic flow at the sheath entrance.
- Plasma energy at the target is 'lost' to acceleration of the ions at the sheath entrance and to the target.
- So, the thermal pressure at the target is only about half the upstream SOL thermal pressure.

This model breaks down when charge exchange losses, recombination and neutral friction effects become significant, so that $R_{\parallel} \neq 0$. High levels of recycling and detached divertor plasma conditions also invalidate the model since the sheath conditions change significantly.

Energy balance

- Under steady-state conditions, in 1D, the heat flux along a magnetic field line is constant if volumetric losses are neglected,

$$\frac{dq_{\parallel}}{ds} = 0$$

- An expression can be derived that describes relates the upstream temperature to the divertor temperature as heat is conducted along a field magnetic field length,

$$T_u^{7/2} - T_d^{7/2} = \frac{7 PL_c}{2 A \kappa_0}.$$

Derivation!

where κ_0 is the Spitzer thermal conductivity coefficient.

- Greater power, P , into the SOL leads to a steeper parallel temperature gradient.

Power transmission to the target

- The power transmitted from the SOL plasma must equal the power transmitted across the sheath to the target. This provides an important boundary condition for the SOL **Two Point Model**.

Ion Energy Flux

- The ion energy flux to the target in W m^{-2} is described by,

$$q_i = \Gamma_i E_i = n_d C_S T_d.$$

Electron Energy Flux

- The electron energy flux at the sheath entrance is described by,

$$q_e = \Gamma_e E_e = 4.8 n_d C_S T_d.$$

Derivations!

Total power to the target

- The total heat flux into the sheath is the sum of the ion and electron heat flux contributions,

$$q_{sheath} \cong 7.3n_d C_S T_d.$$

If $\gamma = 7$, then the power to the target can be expressed as,

$$P = \gamma n_d C_S T_d A$$

Electron Energy Flux

- The electron energy flux at the sheath entrance is described by,

$$q_e = \Gamma_e E_e = 4.8n_d C_S T_d.$$

- This equation describes the power flowing into the SOL plasma to the divertor target.
- It is evaluated at the entrance to the plasma sheath.

Two-point model

- The SOL Two Point Model is described by the three expressions and is valid for an attached, conduction-limited SOL plasma,

Momentum balance

$$n_d T_d = \frac{1}{2} n_u T_u$$

Energy balance

$$T_u^{7/2} - T_d^{7/2} = \frac{7 P L_c}{2 A \kappa_0}.$$

Sheath boundary condition

$$P = \gamma n_d C_S T_d A$$

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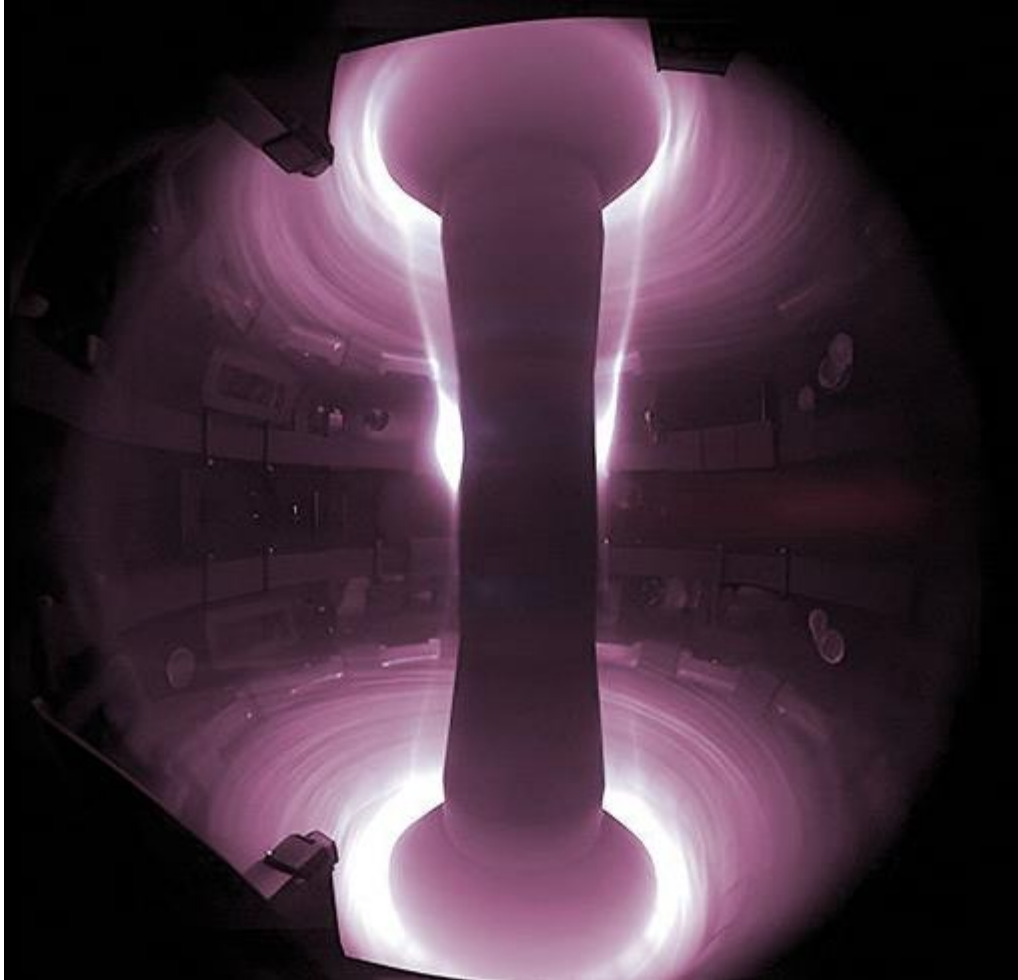
Momentum balance $n_d T_d = \frac{1}{2} n_u T_u$

Energy balance $T_u^{7/2} - T_d^{7/2} = \frac{7 PL_c}{2 A \kappa_0}$

Sheath boundary condition $P = \gamma n_d C_S T_d A$

- The Two Point Model is simple analytical model of the scrape-off layer (SOL) plasma in a tokamak.
- The model allows the estimation of the plasma temperature, density and heat flux at the target based on the upstream values and power entering the SOL through the separatrix from the confined plasma.
- It is called "two-point" because it relates upstream and downstream.
- It can be used to estimate the divertor heat flux, critical for plasma facing materials design and selection.
- It can be used as a foundation for more complicated conditions of radiation, high recycling, detachment, cross-field transport and significant levels of impurities.

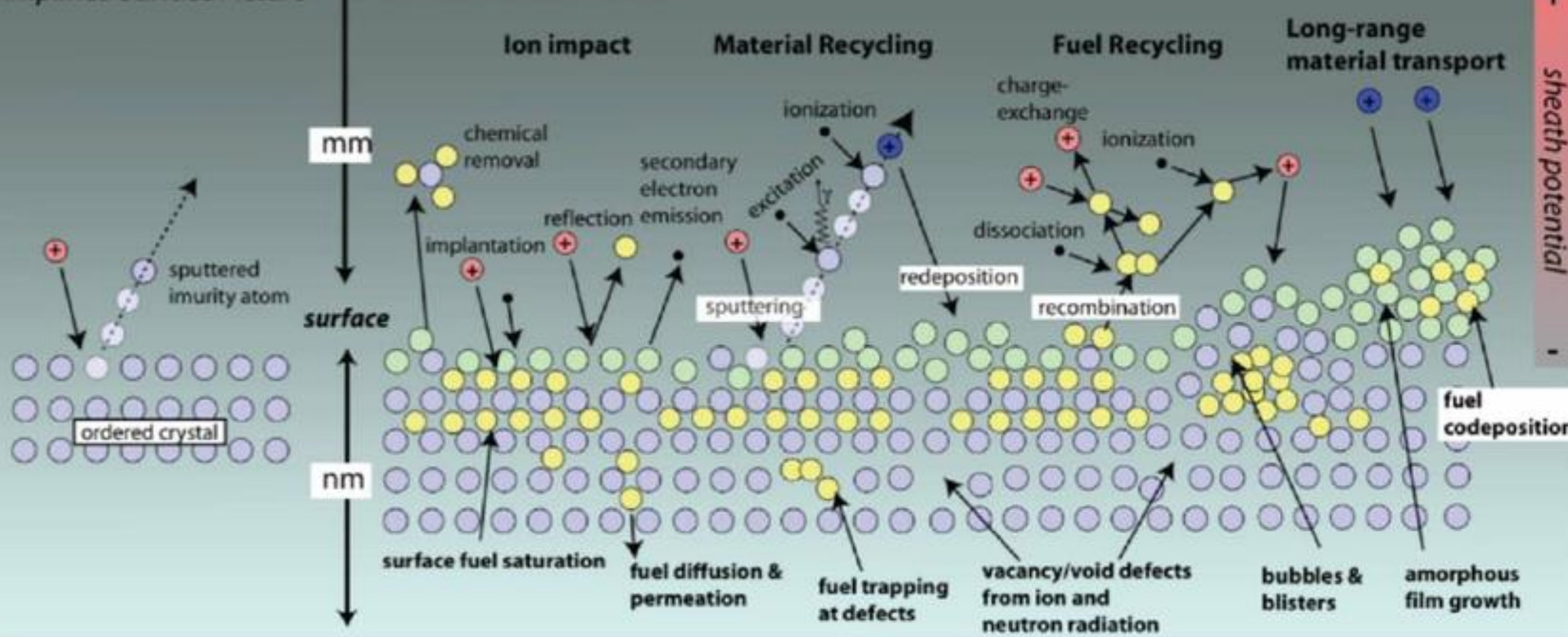
MAST-U SOL and Divertor Filaments



Plasma Surface Interactions

Simplified Surface Picture

Realistic Surface Picture



- Electron
- ⊕ H/D/T fuel ion
- ⊕ PFC material ion
- H/D/T fuel neutral atom
- PFC material atom
- Redepleted PFC material atom

Impurity introduction methods

- There are five main mechanisms through which impurities are introduced into the plasma:

(a) Sputtering of the wall material by energetic ions

(b) Desorption of surface impurities

(c) Evaporation or sublimation of material

(d) Arcing

(e) Chemical reactions or chemical sputtering

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(e) Chemical reactions or chemical sputtering

- The contribution of these different processes is dependent on the power flux to the surfaces being considered and along with incident particle energy distribution.
- Impurity production is mostly dominated by ion induced process, in particular physical and chemical sputtering.

Sputtering

- An energetic incident ion transfers energy to the wall material atoms on collision, causing a collision cascade.
- When the surface atom receives sufficient energy to overcome the surface binding energy it is released into the plasma.
- There is a threshold energy of the incident ion below which the insufficient energy is transferred to the solid surface atom for sputtering to occur.
- If the incident atom's mass is much less than the solid surface atom's mass, $m_2/m_1 > 10$.
- The threshold energy for sputtering to occur can be calculated from the conservation of momentum,

$$E_T \approx \frac{m_s E_s}{4m_1},$$

where E_s is the surface binding energy of the target material.

- The sputter yield is dependent on the material surface conditions and the angle of incidence of the plasma ions.

Desorption

- The surface impurities in carbon or a metal such as tungsten are a result of bulk impurities in the solid.
- Surface impurities also arise from oxidation, adsorption and contamination from, for example, the experiment assembly or maintenance.
- These surface impurities can be desorbed by incident ions, electron or photons.
- As the surface layer of impurities are desorbed, an impurity density gradient can form from the surface to the depths of the material, allowing more impurities to diffuse to the surface.
- A range of physical processes that can contribute to desorption are thermal, electronic and momentum transfer to the surface adsorbed impurities.
- These processes occur more readily than sputtering because adsorbed impurities have very low binding energies.
- Hence a relatively small increase in surface temperature due to incident electrons, ions or photons, is enough to significantly increase thermal desorption of the impurities.

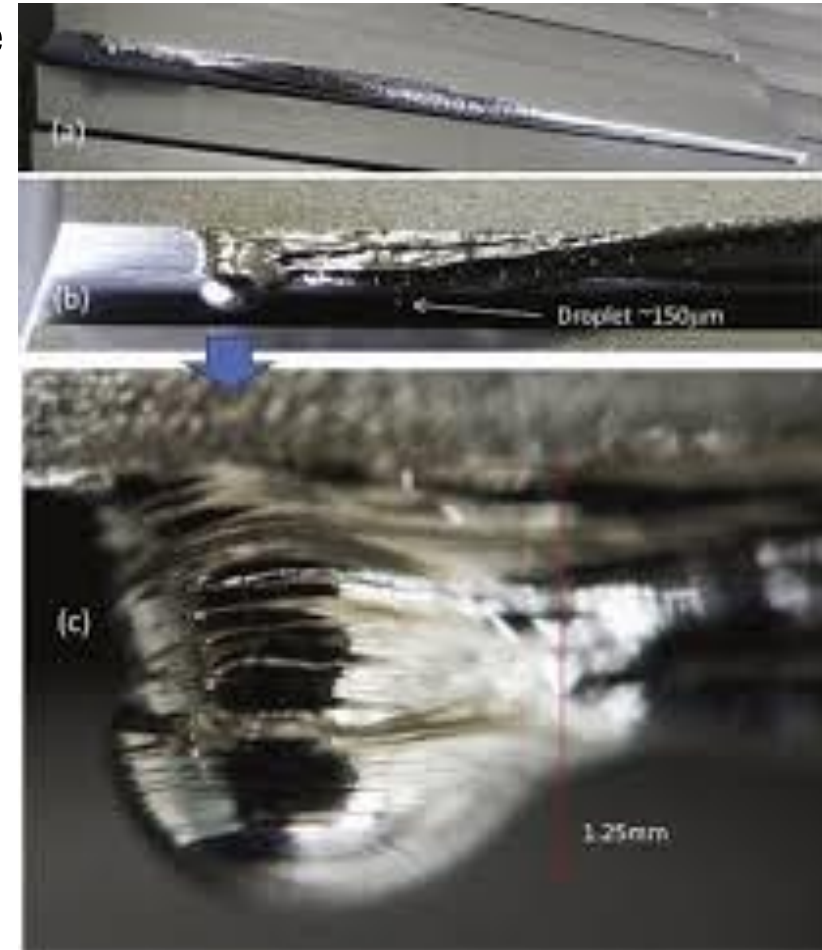
Evaporation

- Evaporation takes place when the target material's surface temperature rises to the melting point.
- The evaporation rate (in atoms $\text{m}^{-2} \text{s}^{-1}$) is directly proportional to the vapour pressure of the material as,

$$\frac{dn}{dt} = 4.6 \times 10^{26} \alpha (mT_s)^{1/2} p,$$

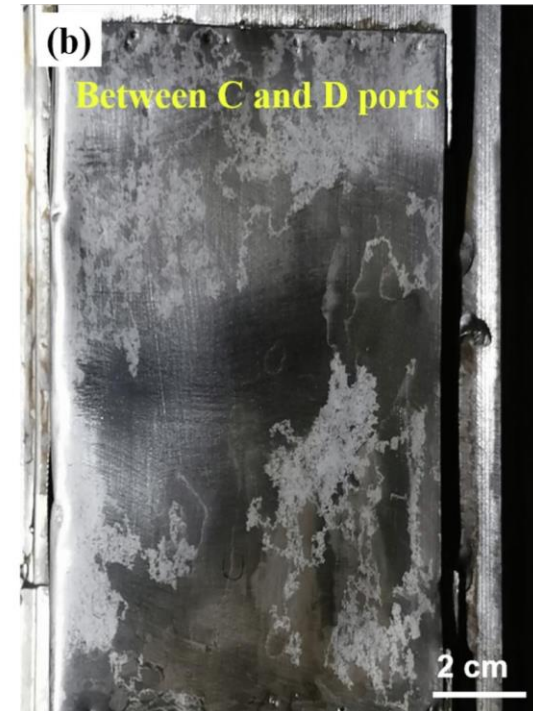
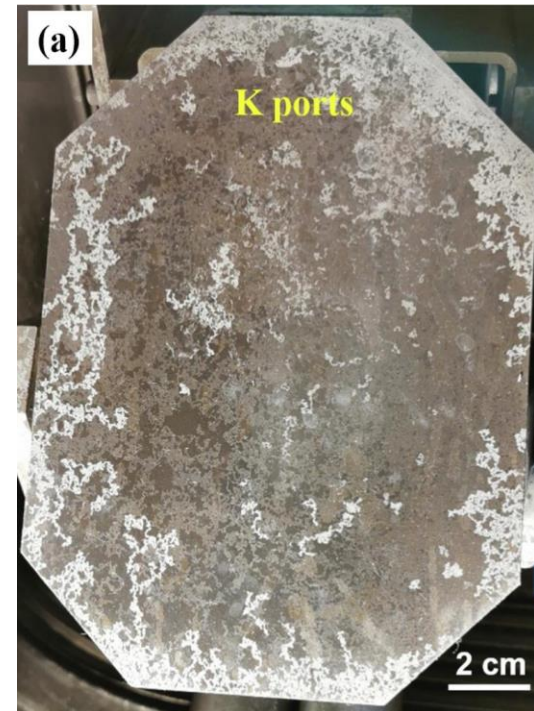
where α is the sticking co-efficient of the surface atom, m is the atomic mass of the evaporating atom in amu, T_s is the surface temperature in K, and p is the vapour pressure in mbar.

- The numerical pre-factor, 4.6×10^{26} incorporates all the conversion factors for unit consistency.
- The surface temperature of the target can be calculated from the power flux to the surface.



Arcing

- Arcing can take place between two surfaces when a large enough potential is applied across them.
- The plasma can create a unipolar arc in which the applied potential difference is applied by the plasma sheath.
- When the arc starts, the electrons from a local 'cathode spot' are accelerated by the sheath potential.
- Arcs leave signature tracks on the solid surface and are regularly observed on plasma facing components in MCF devices.
- Arcing does not contribute a significant level of impurities to the confined plasma.



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Chemical reactions

- Chemical reactions that lead to chemical sputtering of the plasma facing surfaces have been widely studied and yields are dependent on the incident ion energy.
- Chemical sputtering yields are also strongly dependent on the target surface temperature.

Q&A