Study of Plasma Detachment in a Simplified 2D Geometry using UEDGE

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Plasma detachment in fusion devices: How / Can we control the degree of detachment?

- Heat fluxes predicted for next-step fusion devices will cause ablation of divertor target plates $\Rightarrow$ reduction needed
- Detached plasma
  - » Cold (1eV) and dense ($n_{div} > 10^{20} m^{-3}$) divertor plasma
  - » Formation of an ionisation front, hot plasma well-separated from material surface
  - » Momentum and heat losses (plasma flow and temperature) synergetically linked

  $\Rightarrow$ advantageous operational regime
- Experimentally well-achievable regime; but, lack of detailed analytic description allowing active control

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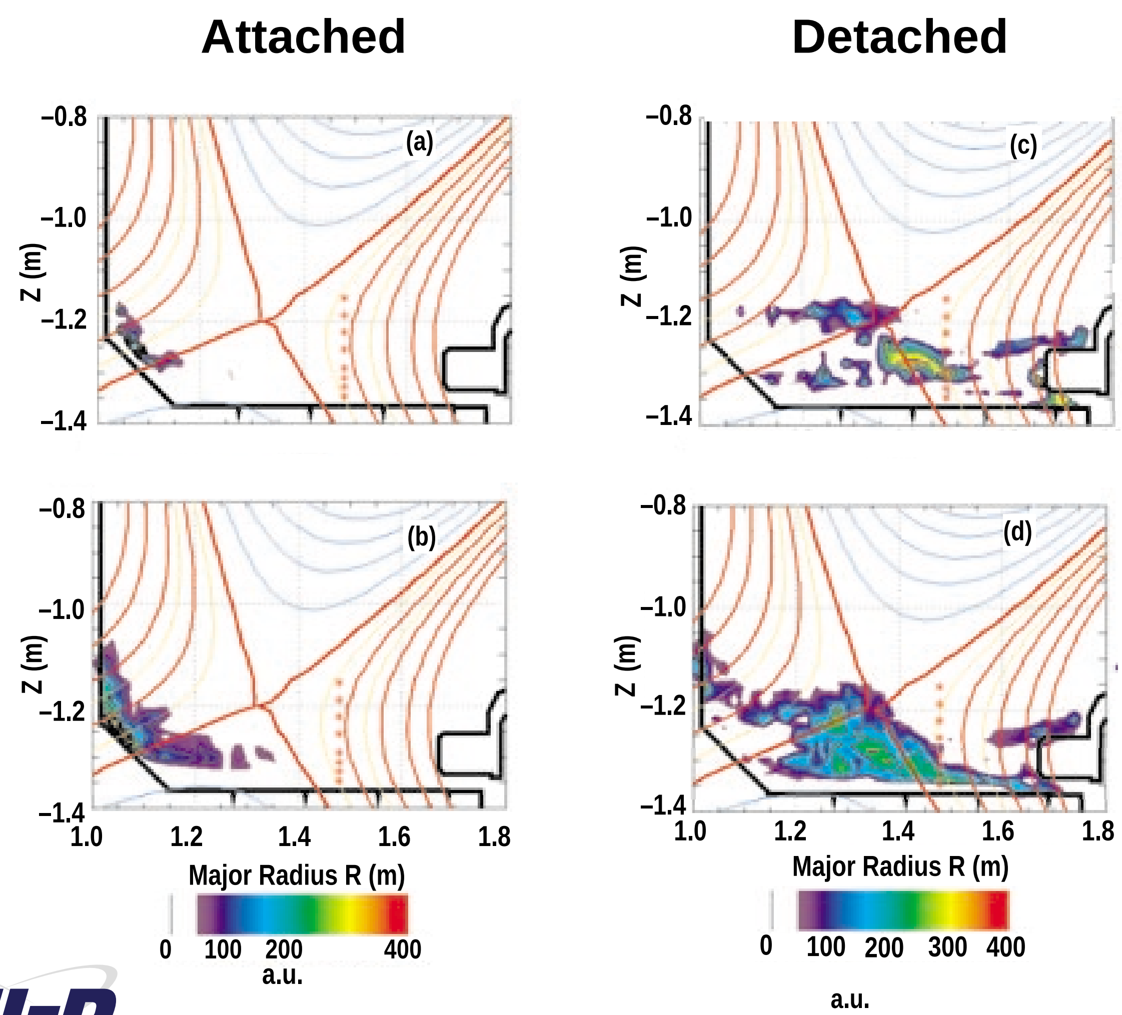
Detachment in experiment: formation of ionisation and recombination-dominated zones



DIII-D shot: 93993
(Fenstermacher, PSI1998)

Dalpha radiation from ionisation (ionisation front)

Dalpha radiation from recombination (recombining plasma)

Use UEDGE to simulate detached plasmas in 2D slab geometry to ...

- ... determine and describe the main processes that cause and affect plasma detachment
- ... study n_{core} and P_{heat} - dependence of the position of ionisation front (ionisation of hydrogen ~ 5eV), i.e. what is $\mathbf{L_{Te=5eV} \propto n^x_{core} P^y_{heat}}$?

$\Rightarrow$ **Active control of detachment in current and future fusion devices**

- ... study sensitivity of boundary conditions on UEDGE solutions
  - » How significant is wall pumping?
  - » What is the effect of the assumption for the ion speed at the target on the location of the ionisation front?

Highlights

UEDGE simulations of plasma detachment in 2D geometry reveal ...

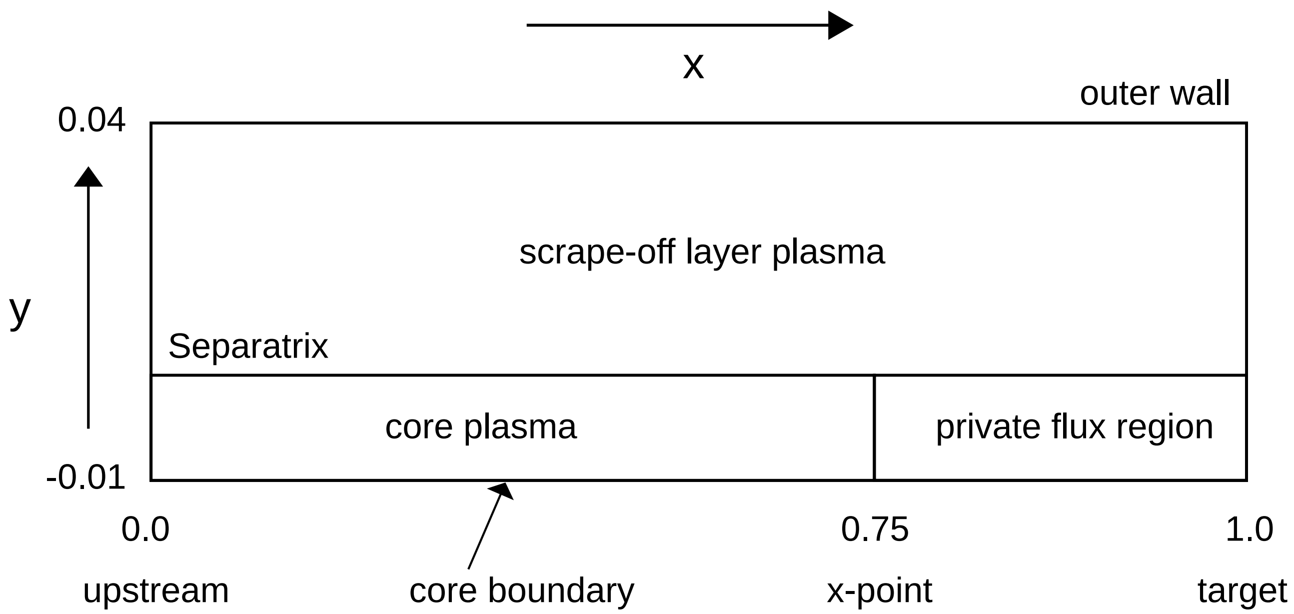
- Location of ionisation front is chiefly determined by
  - » parallel heat flux into divertor SOL
  - » radial heat transport from SOL into PFR below x-point
  - » radiation losses due to ionisation of recycling neutrals

- Highest separation of plasma - wall at high n_{core} (ionisation front close to x-point)

- High heating power permits highest degree of volumetric recombination and momentum flow reduction

- No further reduction of peak heat flux density once plasma detached

Computational domain: 2D slab geometry
Hydrogenic plasma - no impurities !



- $D_\perp$=0.5 m^2/s, $\chi_\perp$=0.7 m^2/s, spatially constant
- Ion removal at target (2%), neutral pumping outer wall (1%)
- n_{core} and P_{heat} defined at core boundary

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Braginskii Equations for momentum and power flow in UEDGE 2D slab geometry

- Momentum equation (plasma):

$$\frac{\partial}{\partial x}\left(m_i n_i u_{i\|} u_{ix} - \eta_{ix}\frac{\partial u_{i\|}}{\partial x} + \frac{B_x}{B}\frac{\partial P_p}{\partial x}\right) + \frac{\partial}{\partial y}\left(m_i n_i u_{i\|} u_{iy} - \eta_{iy}\frac{\partial u_{i\|}}{\partial y}\right) = S^{i}_{mom}$$

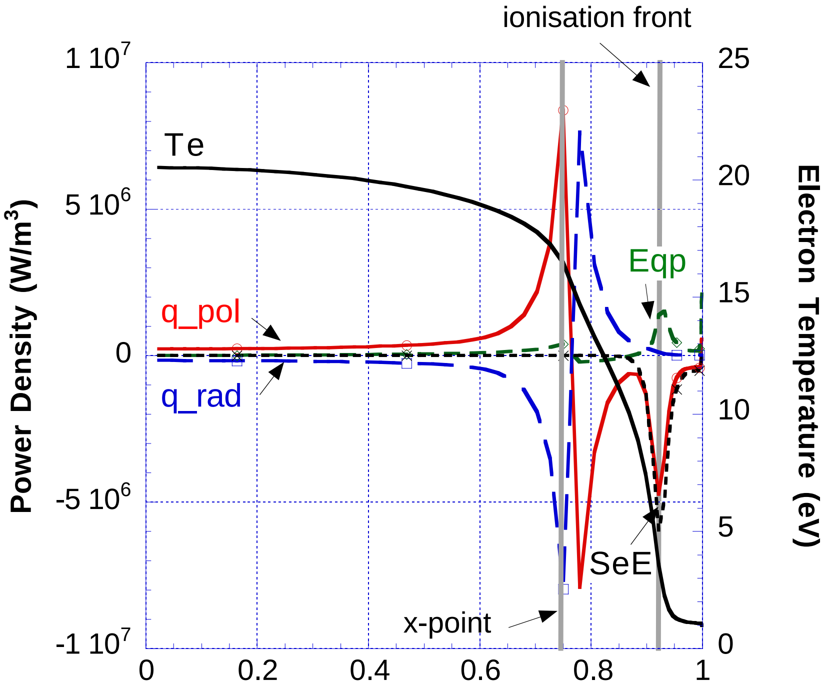
- Energy equation (electrons):

$$\frac{\partial}{\partial x}\left(\frac{5}{2} n_e u_{ex} T_e - k_{ex}\frac{\partial T_e}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{5}{2} n_e u_{ey} T_e - k_{ey}\frac{\partial T_e}{\partial y}\right)$$

$$= u_{ix}\frac{\partial P_e}{\partial x} - u_{iy}\frac{\partial P_e}{\partial y} - u_{i\|}\frac{B_x}{B}\frac{\partial P_p}{\partial x} + K_q\left(T_e - T_i\right) + S_{Ee}$$

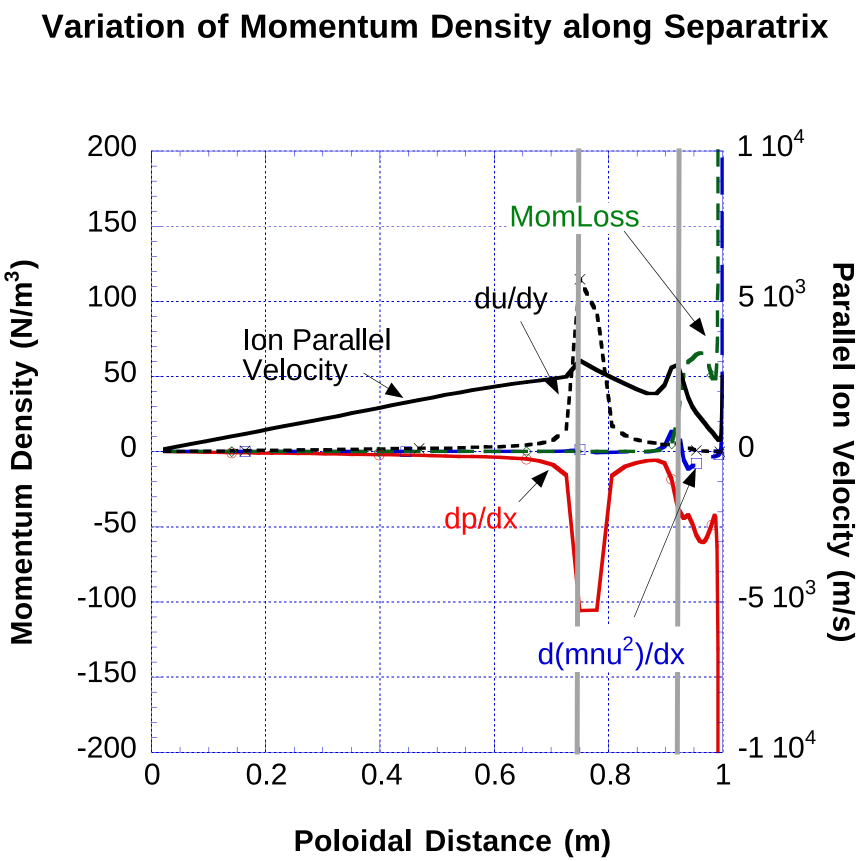
Base case results (energy equation)

Variation of Power Density along Separatrix



- Significant outflow of heat from SOL into PFR due to geometry $\Rightarrow$ plasma cooling $\Rightarrow$ spreading of heat over larger area
- Inside ionisation front: plasma cooling due to radiation, but also electron heating due to i-e temperature equipartition
- Recombining plasma zone: T_e ~ 1eV, but still significant radiation losses due to recombination / ionisation

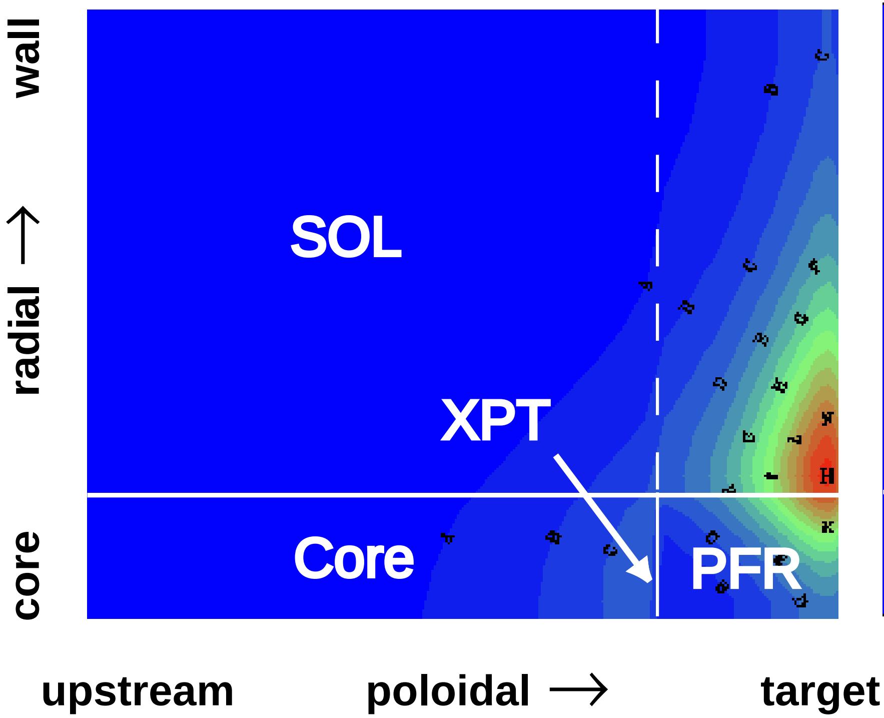
Base case results (momentum equation)



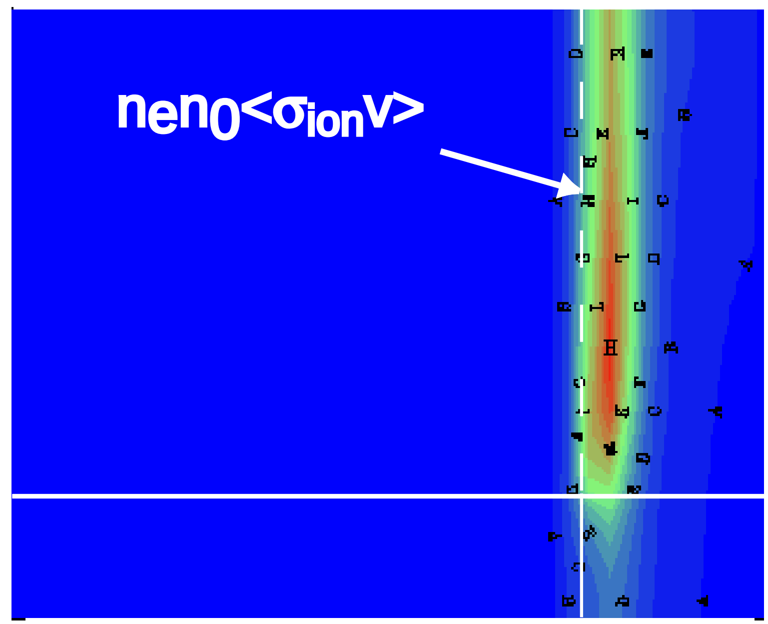
- Significant pressure drop along SOL:
  - » x-point: due to viscosity
  - » target region: CX momentum losses
- Ion speed responds to decrease in plasma temperature $\rightarrow$ shear around x-point
- CX momentum losses $\rightarrow$ reduces ion speed onto target plate

Ionisation zone moves toward x-point and spreads radially in strongly detached plasmas

Attached plasma: ionisation occurs nearby strikepoint



Detached plasma: ionisation front moves to x-point



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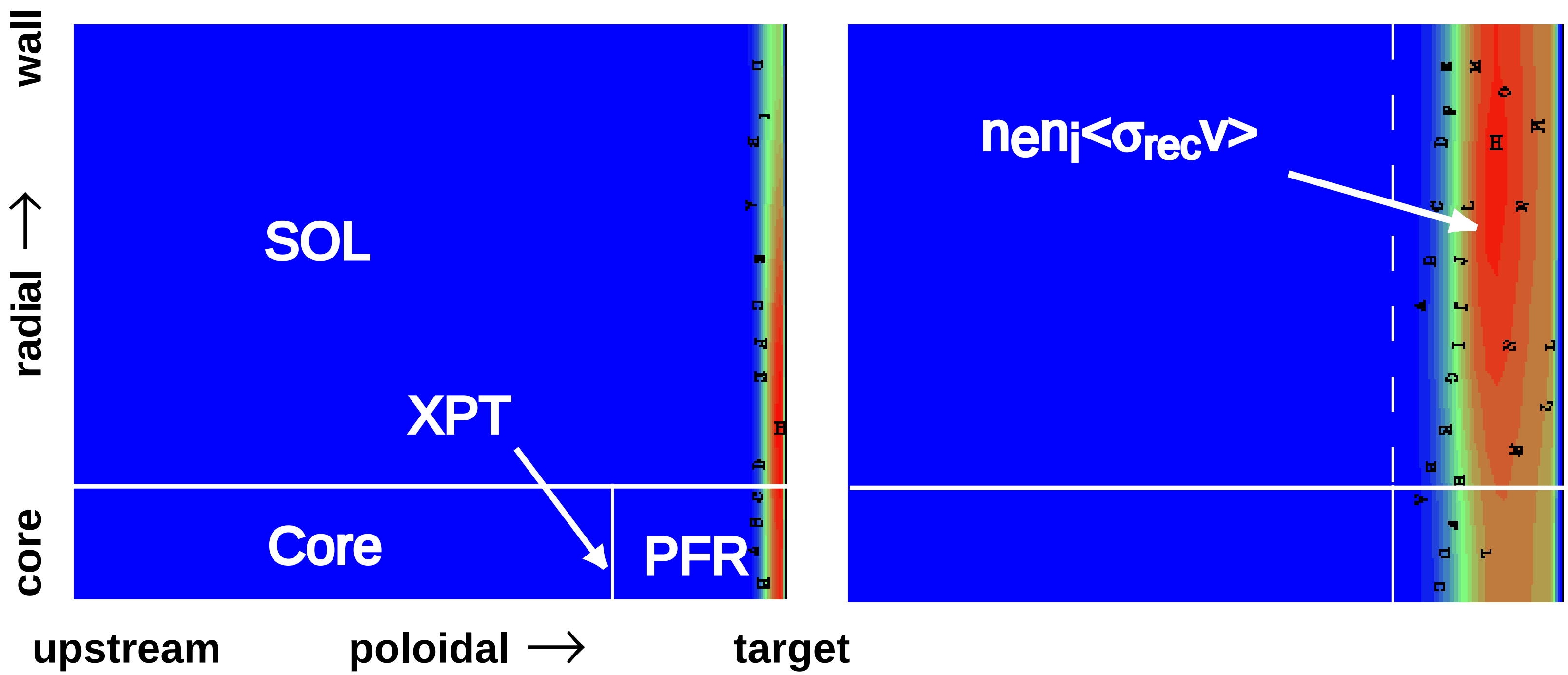
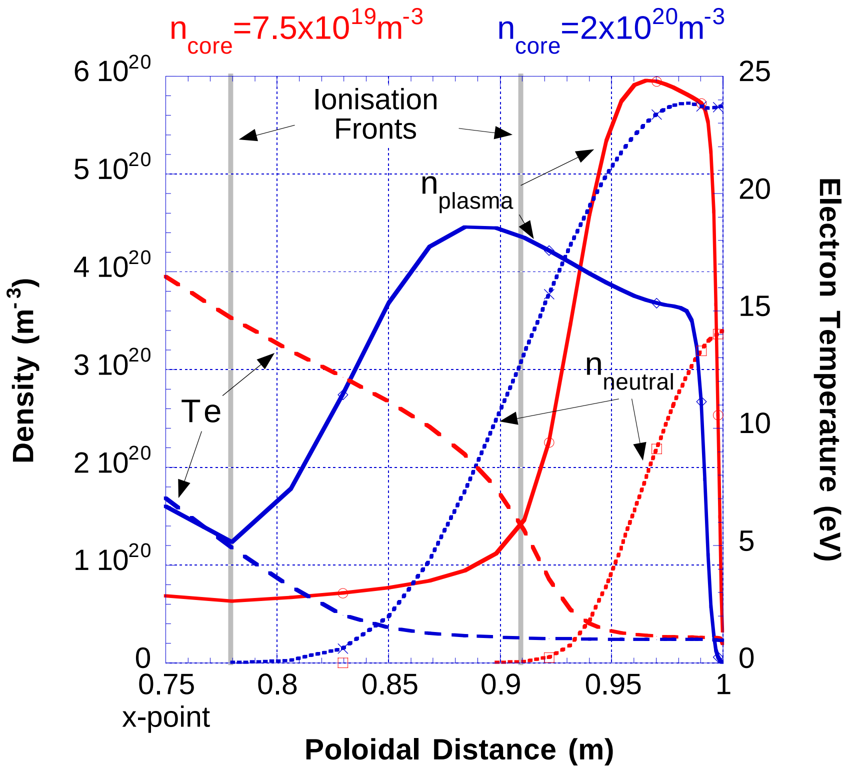
Recombination zone expands both poloidally and radially in strongly detached plasmas

Detachment onset: recombination zone adjacent to target (also in PFR?)

Strongly Detached plasma: cold plasma fills space between ion.front and plate



Ionisation front moves toward x-point at higher core plasma density



Higher core plasma densities at constant heating power give rise to ...

- Lower T_e in upstream SOL
- Lower influxes of heat into divertor
- Heat is convected rather than conducted
- Lower divertor plasma densities, but higher divertor neutral densities

⇒ Shallower temperature gradients inside ionisation front

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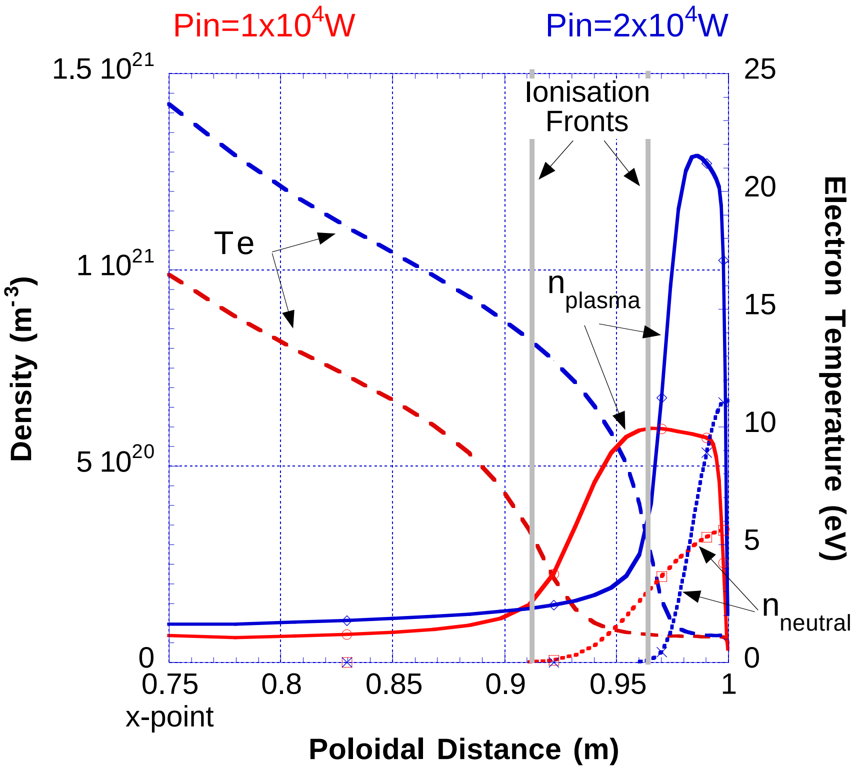
Ionisation front moves closer to the target at higher input power

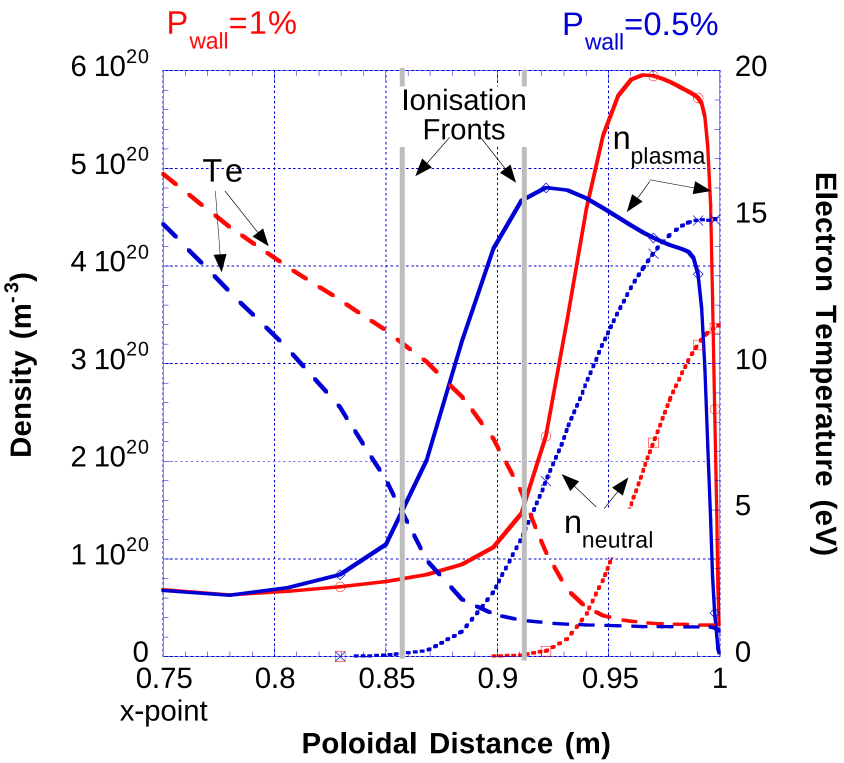


Higher input power at constant core plasma density give rise to ...

- Higher T_e in upstream SOL
- Higher influxes of heat into divertor
- Larger divertor plasma and neutral densities

⇒ Steeper temperature gradients inside ionisation front

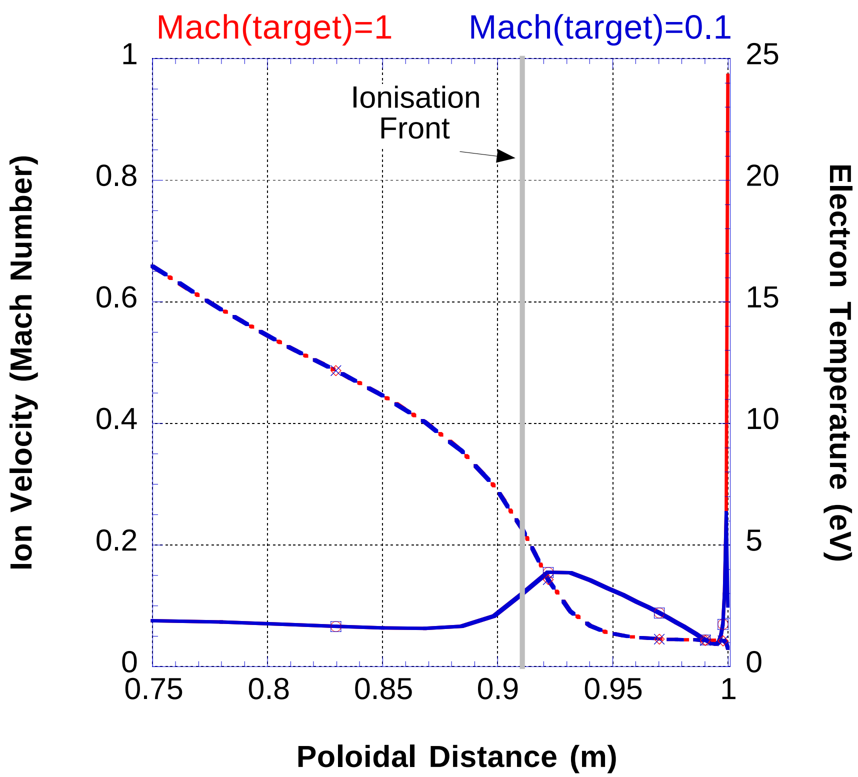
Ionisation front moves closer to target at lower wall pumping rates



Decreasing the wall pumping rate gives rise to ...

- Higher divertor neutral densities
- Similar divertor plasma densities
- Modest drop in upstream T_e at x-point
- Similar T_e gradients inside ionisation front

Location of ionisation front insensitive to ion speed setting at the target



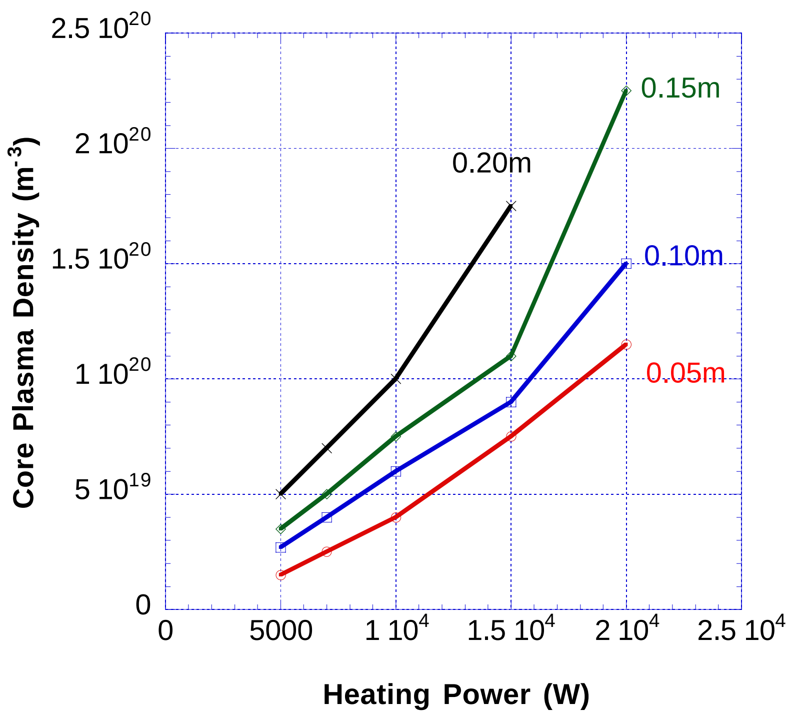
Reducing the Mach number at the target plate for detached plasmas gives rise to ...

- Identical temperature profile ⇒ no changes to ionisation front location

However, varying Mach number for attached plasmas ⇒ slight changes to temperature and density profiles

Result I: Location of the ionisation front in core density - heating power space

Contours of constant distance between ionisation front (T_e=5eV) and target plate



- Significant separation of plasma from wall require high core plasma densities
- Increasing heating drives plasma closer to target ⇒ even higher core densities needed
- Non-linear relationship between location of ionisation front and core density / heating power

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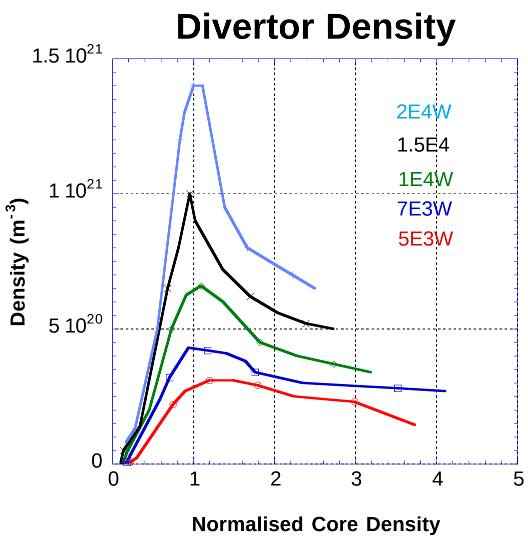
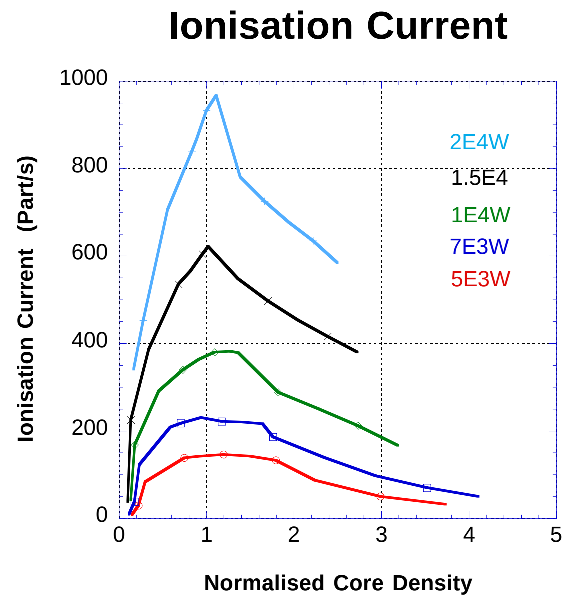
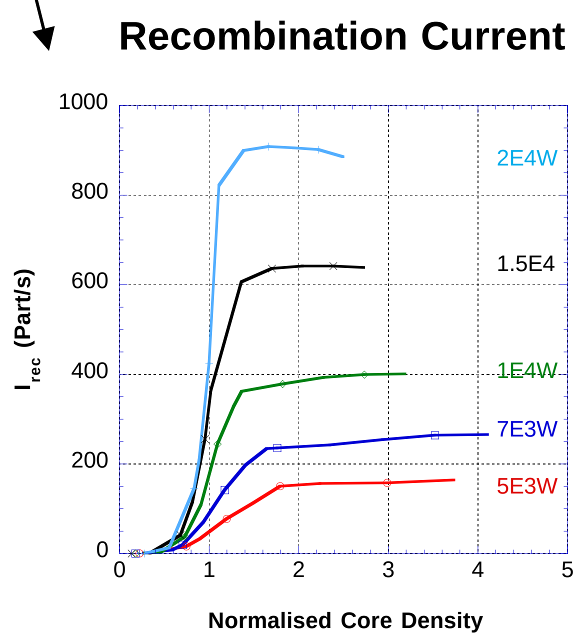
Result II: Roll-over of ionisation current with n_{div}, threshold for vol. recombination at high P_{heat} ?

$$I_{ion} \propto n_{i,div}$$







$$I_{rec} \propto n_{i,div}^2 \Delta V_{RDR}$$

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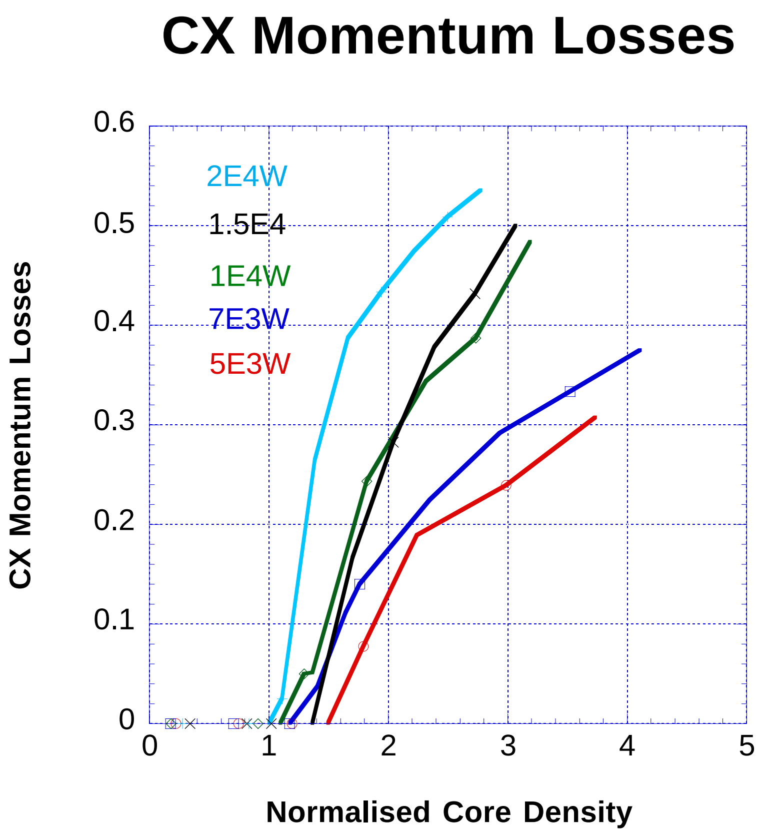
UEDGE density normalised to predicted upstream density by 2-Point Model

- Use Two-Point Model (1D Model) to predict upstream SOL density (detachment onset, $T_t = 1\text{eV}$) :

$$n_{up-2PM} = \sqrt{2\frac{m_i}{e} q_{\|}^2 \frac{\left(\frac{7}{2}\frac{q_{\|}L}{\kappa_{0e}}\right)^{-4/7}}{\gamma^2 e^2 T_t}}$$

- Estimate width of parallel heat flux density: $q_{\|} \approx \frac{P_{in}}{\lambda_{q_{\|}}}\frac{B_T}{B_P}$

Result III: Fractions of plasma momentum lost to neutrals larger at high heating power



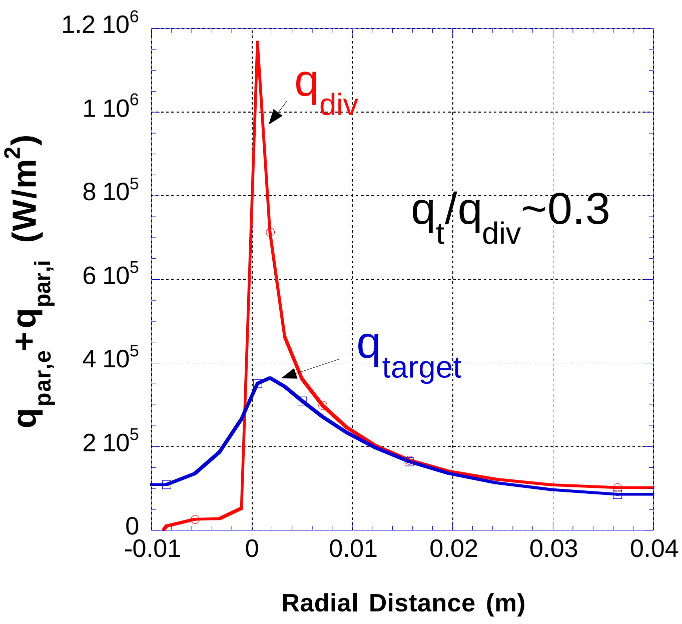
$$S_{mom} \propto n_{i,RDR} \cdot n_{0,RDR} \cdot \Delta V_{RDR}$$

- Plasma momentum integrated over PRF and SOL domain in divertor, over SOL upstream
- Higher heating power ⇒ higher ion densities in divertor ⇒ larger momentum removal
- Drop in ion density as ionisation front moves off target compensated by increase in neutral density and RDR width

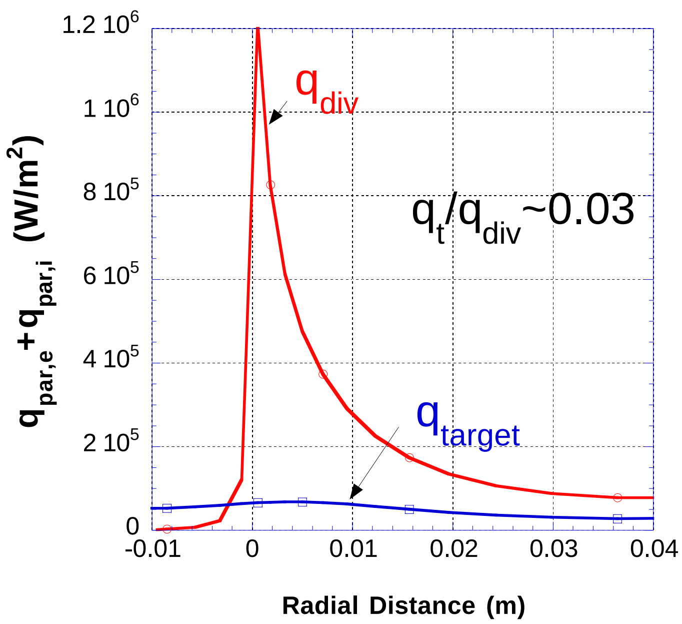
Result IV: Peak heat flux is reduced and shifted radially outward in transition to detachment

Electron + ion heat flux density measured at divertor entrance (x-point) and target

attached plasma



plasma at detachment onset



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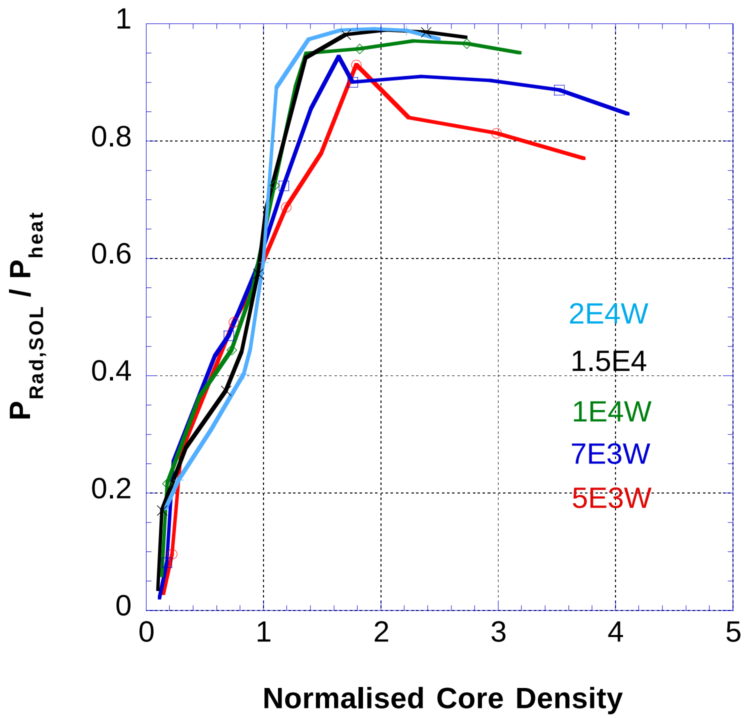
Peak heat flux is reduced until onset of detachment, no further reduction once detached

Radiation Heat Losses



$$\frac{q_{\|,RDR}}{q_{\|,up}} \propto P_{rad} \propto n_{div}^2$$

- Radiated power integrated over PRF and divertor SOL domain
- Sharp increase in power losses when plasma is attached ($0.1 \le n_{core,norm} \le 1.5$)
- P_{rad} approaches unity and then decreases as entire SOL plasma becomes cold (T_e~5-10eV)
- High fraction of P_{rad} are sustained at high heating power

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