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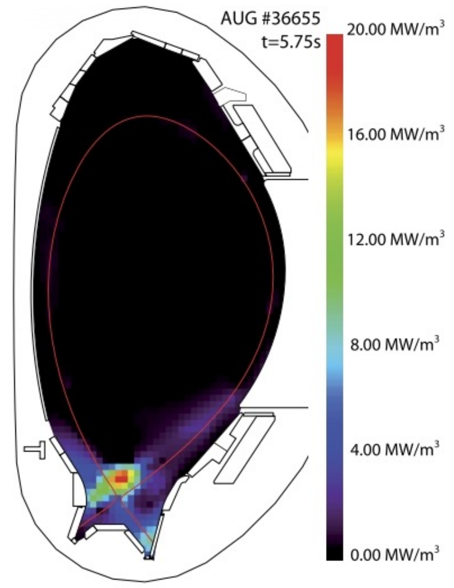
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

The formation of the X-point radiator (XPR)



PH1376 Seminar Plasma Physics

Yu-Chih Liang 23.01.2024

Outline

- Basic Tokamak Physics
- Experimental discovery of XPR
- Reduced model
- XPR control
- Advantages of XPR regime: Power exhaust & detachment
- Application: Compact radiative divertor
- Summary

Basis of a Tokamak

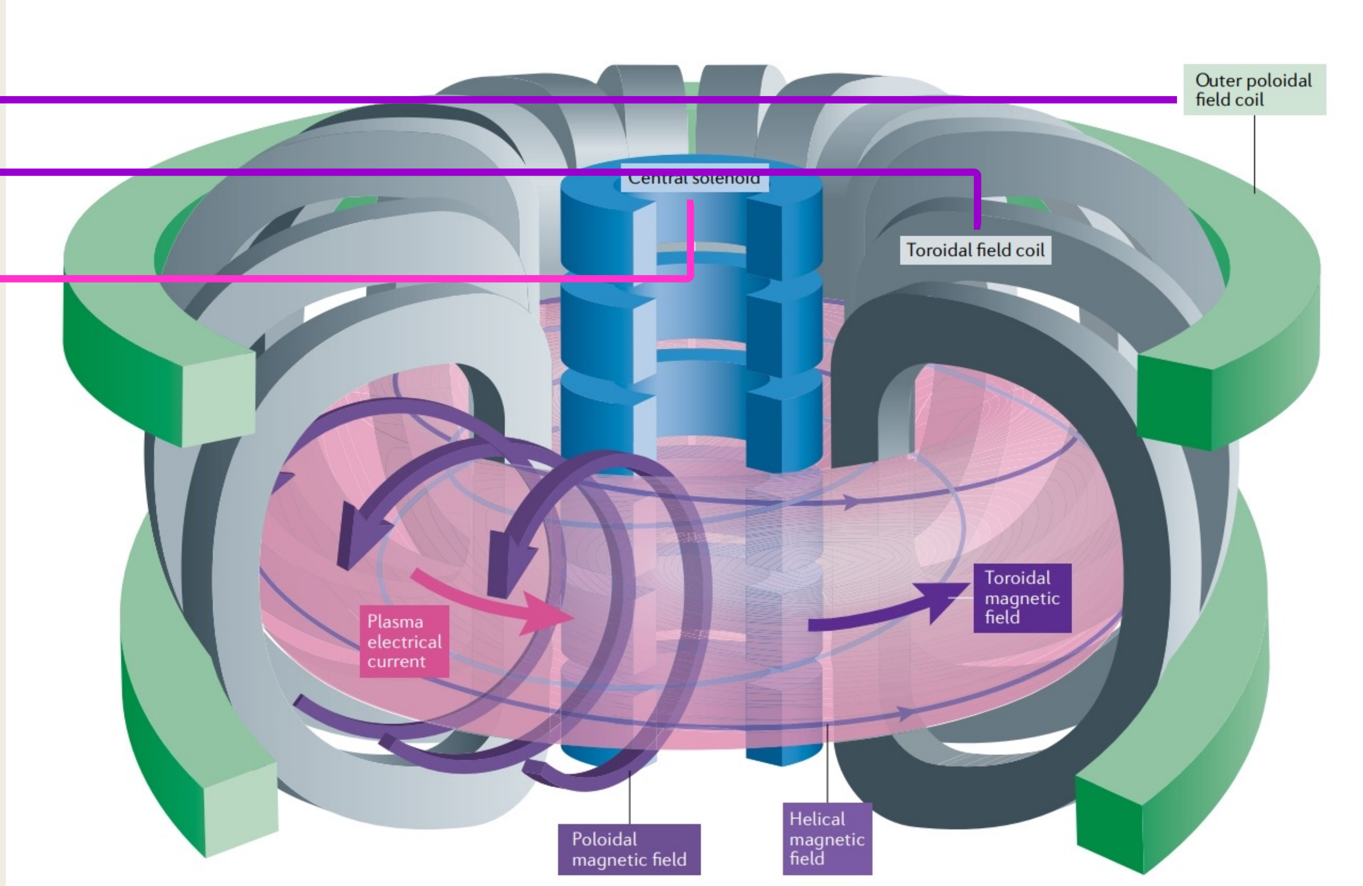
Essential elements for a Tokamak:

- Toroidal magnetic field (B_t)
- Toroidal plasma current (I_p)

↓

- Poloidal magnetic field (B_Θ)
- Vertical field

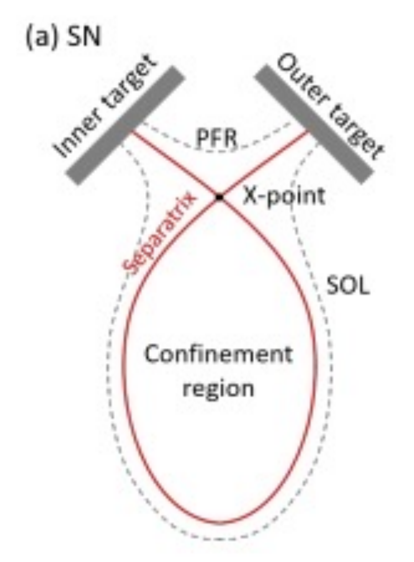
Toroidal confinement in a Tokamak



Ham C., et al. Nature Reviews Physics, 2(3):159–167, 2020

X-point configuration (single-null)

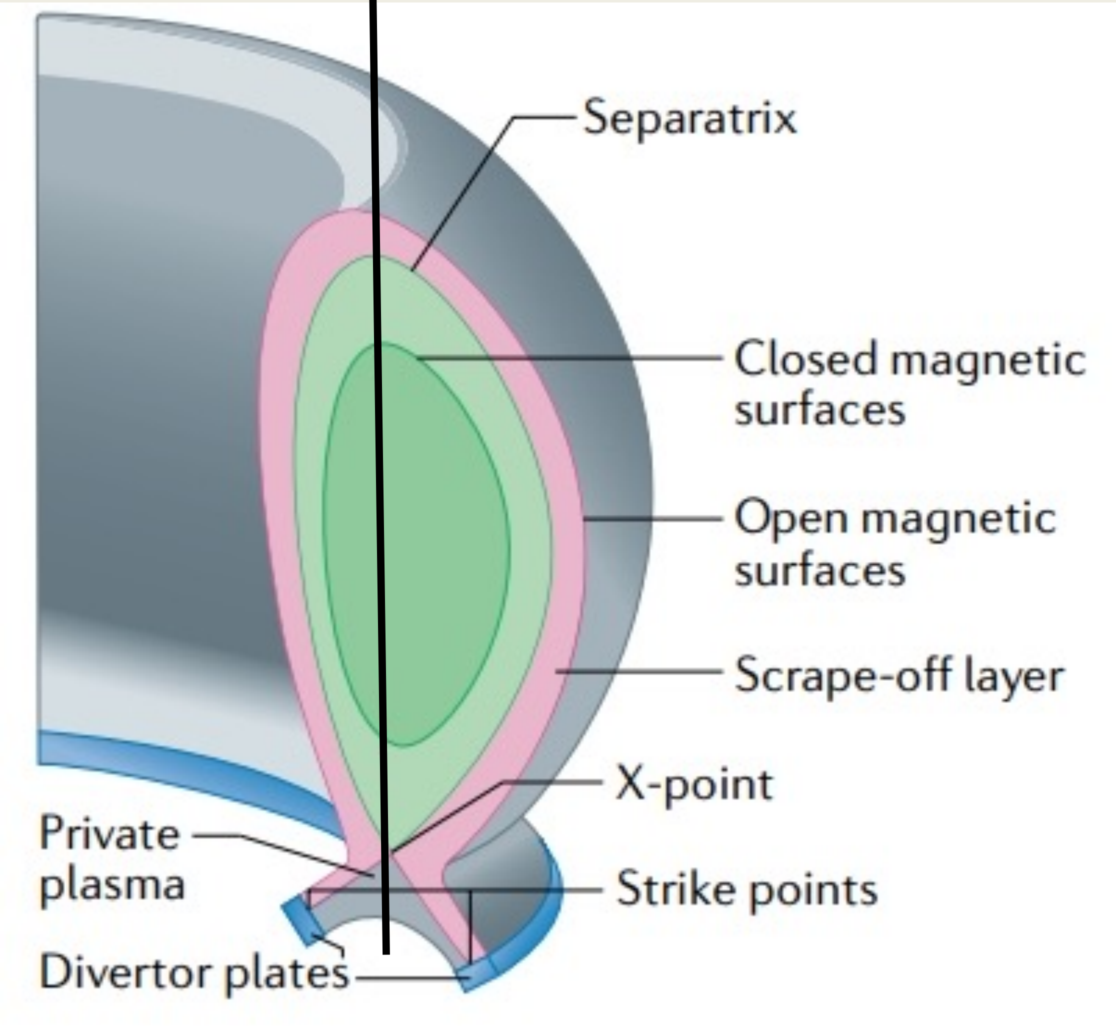
- Confined region
- Scrape-off layer (SOL)
- Separatrix
- X-point
- Private flux region (PFR)



O. Pan 2020 Doctoral thesis, Technical University of Munich

High field side (HFS)

Low field side (LFS)

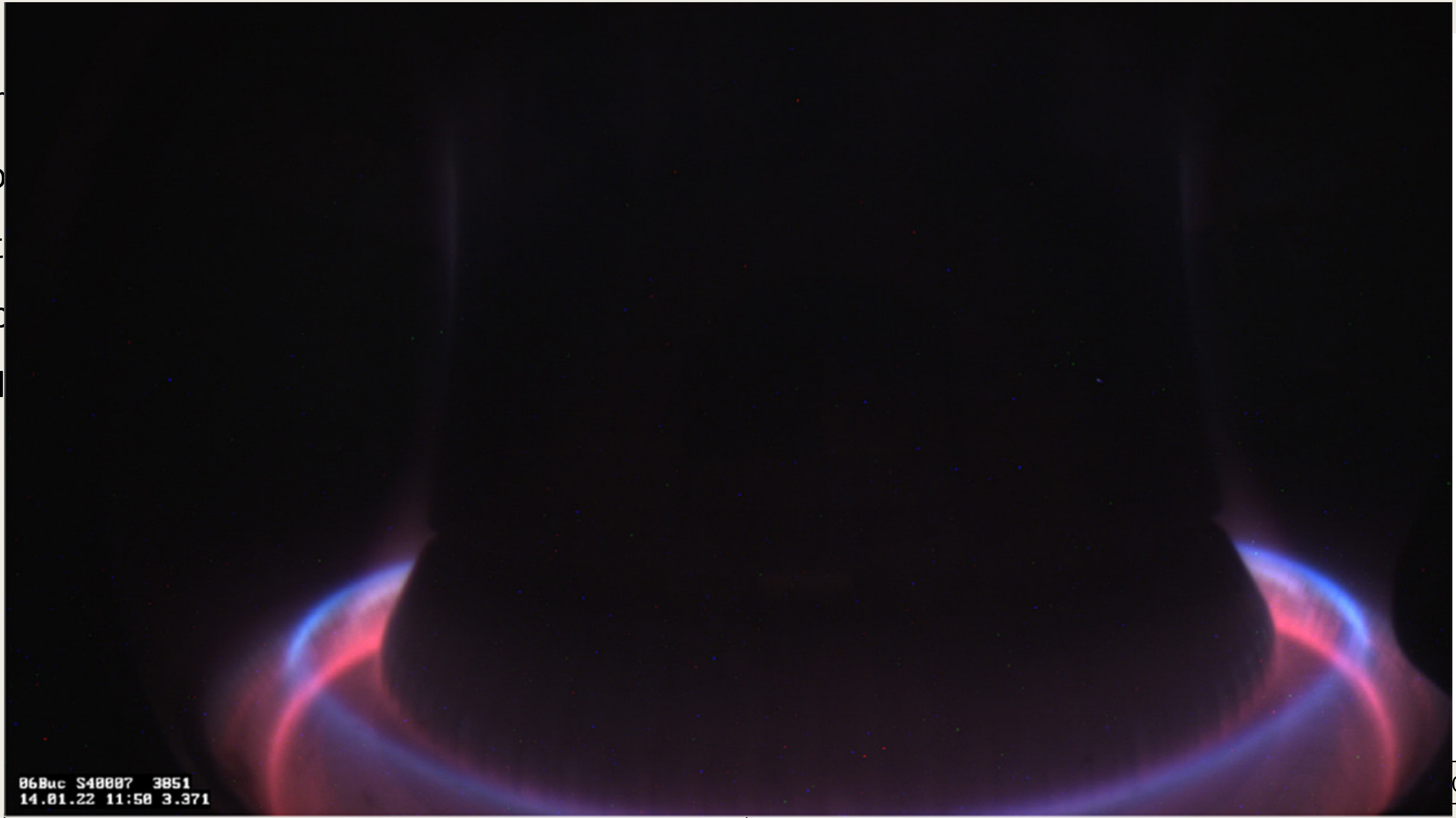


Ham C., et al. Nature Reviews Physics, 2(3):159–167, 2020

XPR : Experimental discovery

- High
- Stro
- Mot
- Imp

⇨ Col



M. Bernert et al 2023 Nuclear Materials and Energy Volume 34, 101376

024001

How does impurity enter the confined region?

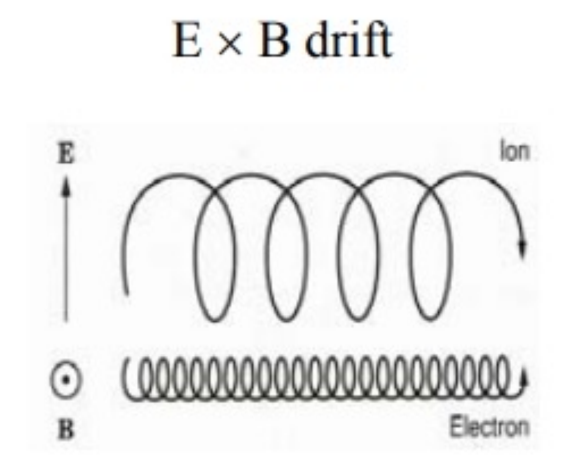
- Cross field transport around the x-point

⇨ Accumulation of impurities

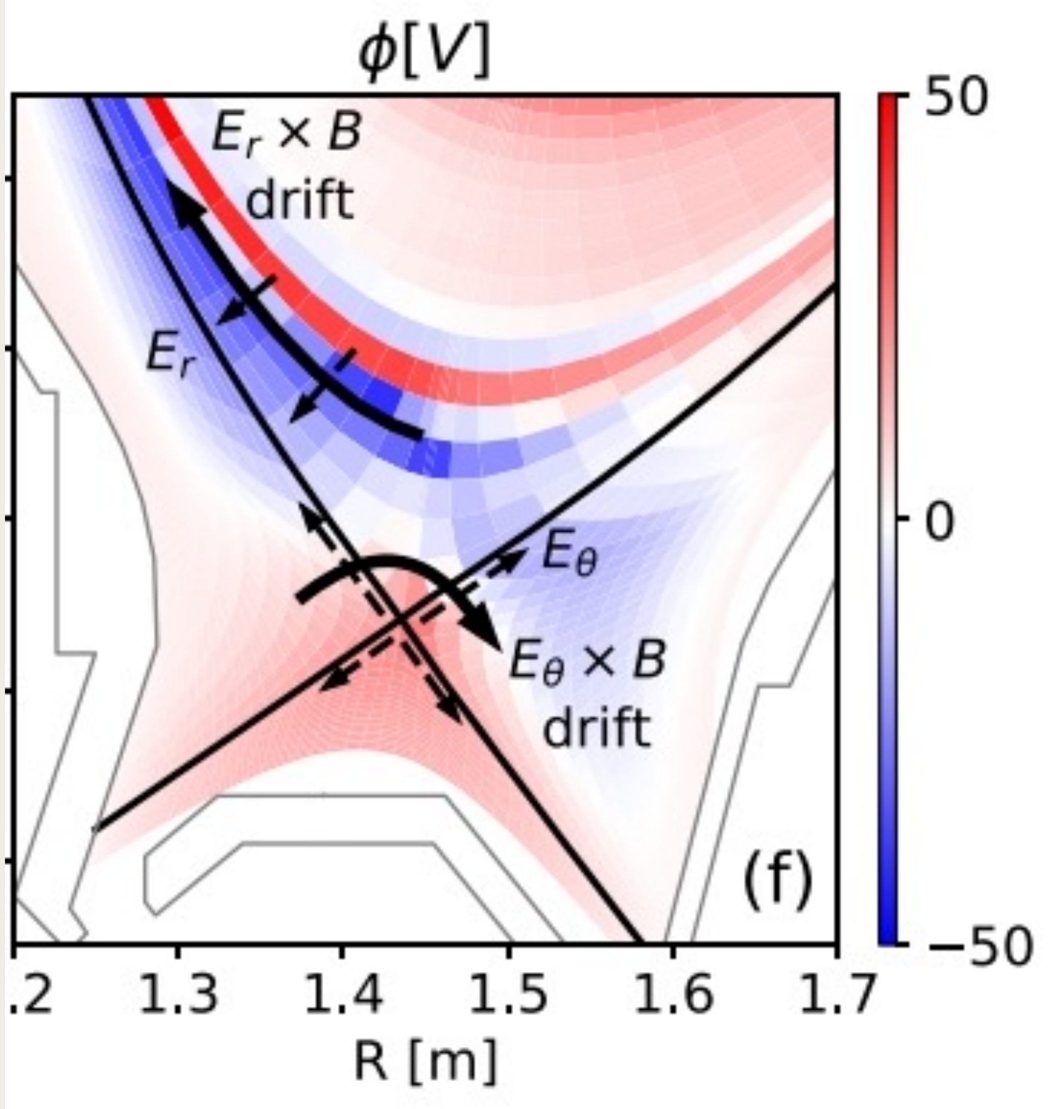
- Upstream transport towards HFS

⇨ Instability (Multifaceted Asymmetric Radiation From the Edge)

$$\vec{v}_D = \frac{\vec{E} \times \vec{B}}{B^2}$$



https://hesperia.gsfc.nasa.gov/summerschool/lectures/emslie/plasma_physics_handout.pdf



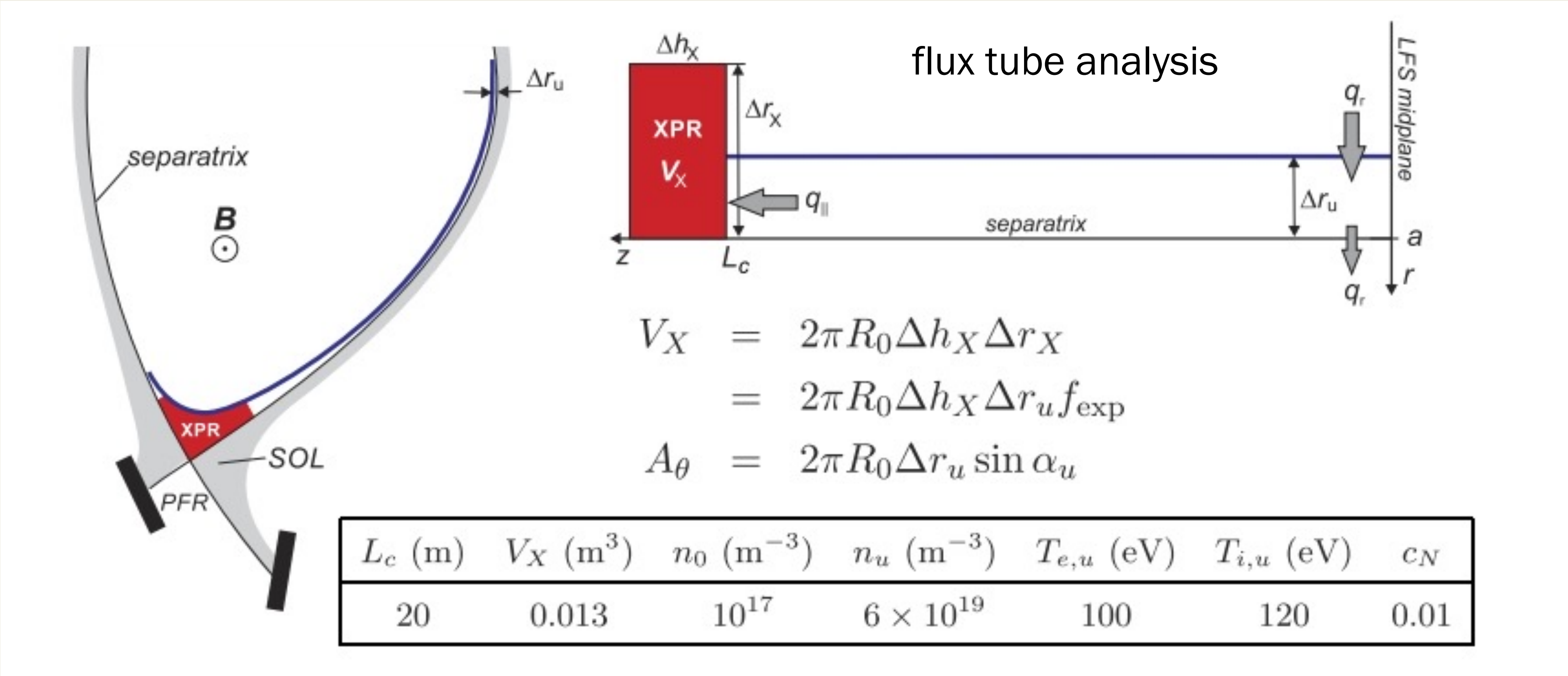
O. Pan et al 2023 Nucl. Fusion 63, 016001

XPR Reduced model

4 Processes for power sink:

Electron-impact ionization of neutral D + Charge exchange processes (cx) → ~20

eV Impurity radiation → ~10eV → Recombination



$$V_X = 2\pi R_0 \Delta h_X \Delta r_X$$

$$= 2\pi R_0 \Delta h_X \Delta r_u f_{\exp}$$

$$A_\theta = 2\pi R_0 \Delta r_u \sin \alpha_u$$

L_c (m)	V_X (m^3)	n_0 (m^{-3})	n_u (m^{-3})	$T_{e,u}$ (eV)	$T_{i,u}$ (eV)	c_N
20	0.013	10^{17}	6×10^{19}	100	120	0.01

U. Stroth et al 2022 Nucl. Fusion 62, 076008

Access condition & Stability criterium

From the flux tube analysis:

Power balance

➡ XPR parameter:

Geometric parameters

$$X_A \sim \frac{R_0^2 q_s^2 f_{exp}}{a} \frac{n_u n_0}{T_u^{\frac{5}{2}}}$$

upstream density, neutral D density

upstream temperature

Particle balance

➡ MARFE occurrence parameter:

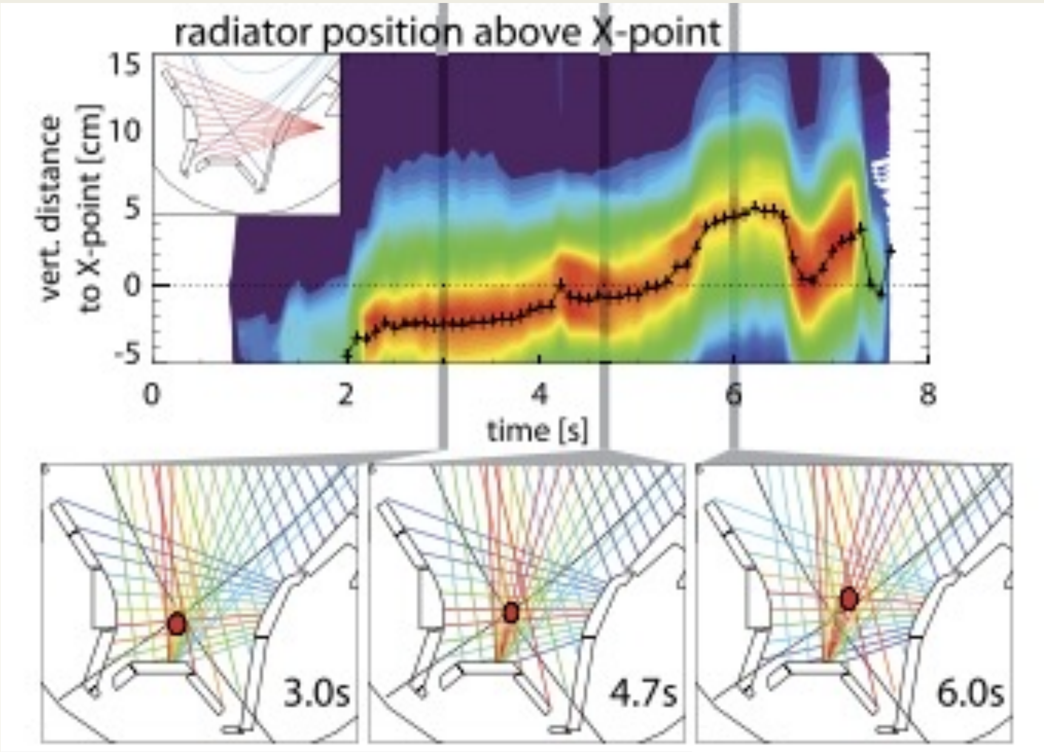
$$M_{\mathrm{A}} = \frac{R_0^3}{a^2} \sqrt{\frac{m_{\mathrm{i}}}{T_{\mathrm{u}}}} n_{\mathrm{u}}^3 q_{\mathrm{s}}^3 f_{\mathrm{exp}}^2 c_{\mathrm{imp}}$$

upstream density, impurity content

upstream temperature

XPR Control

- Typically extend to 5 cm above the X-point, up to 15 cm
- Extension and position depend on impurity puffing rate and heating power



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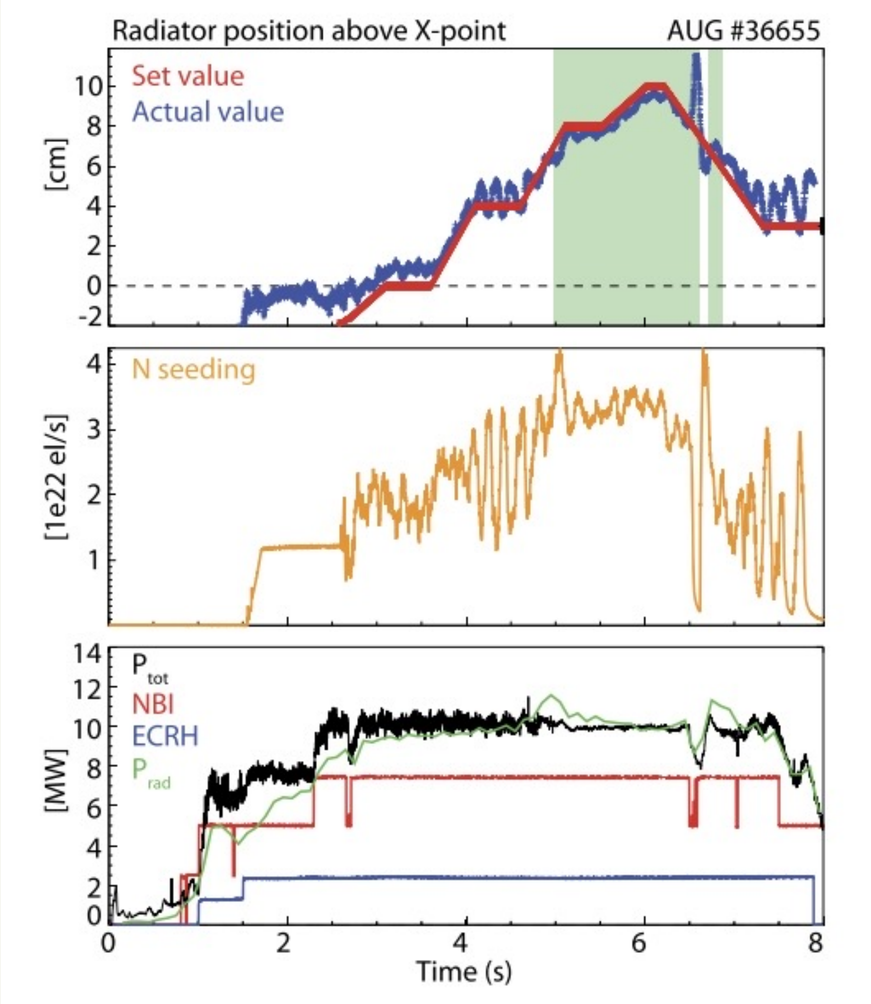

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Power exhaust & Detachment

- A potential solution to the power exhaust problem in power plants (DEMO)
- Lea ation

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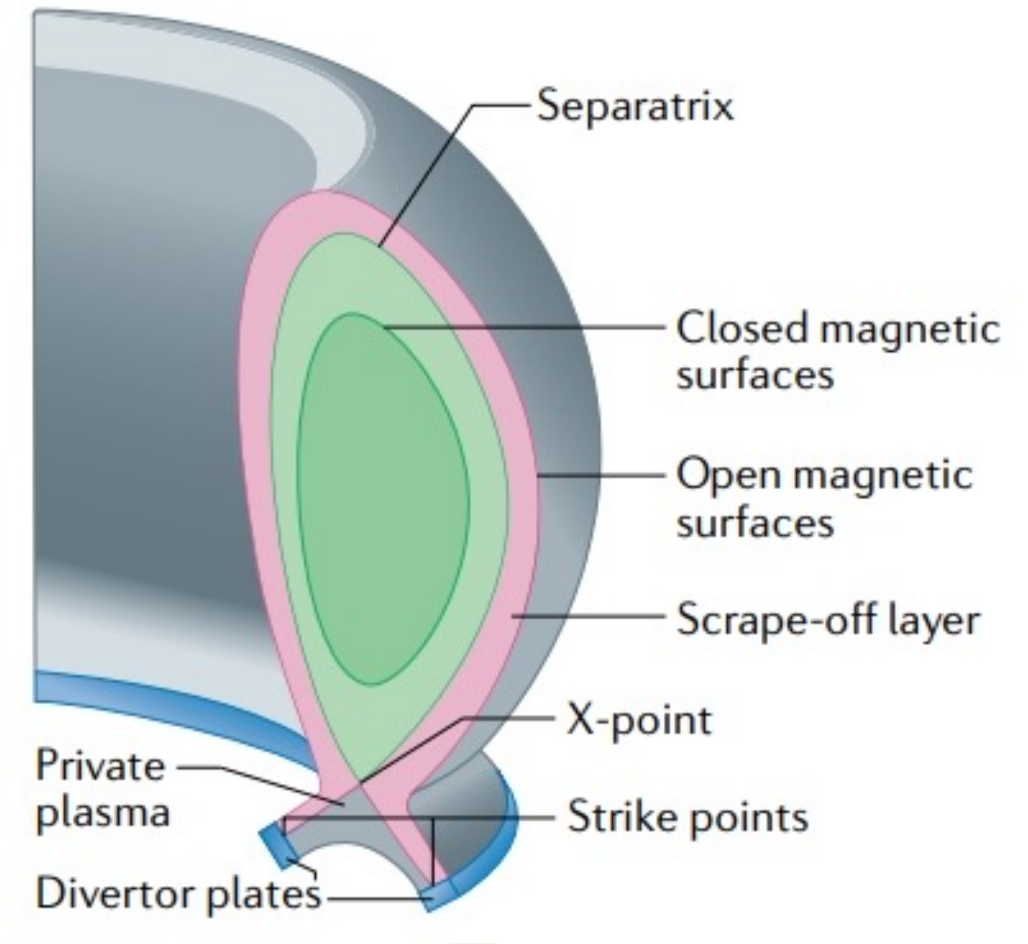
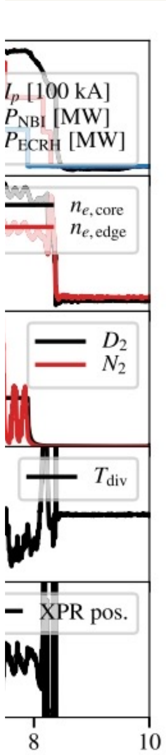
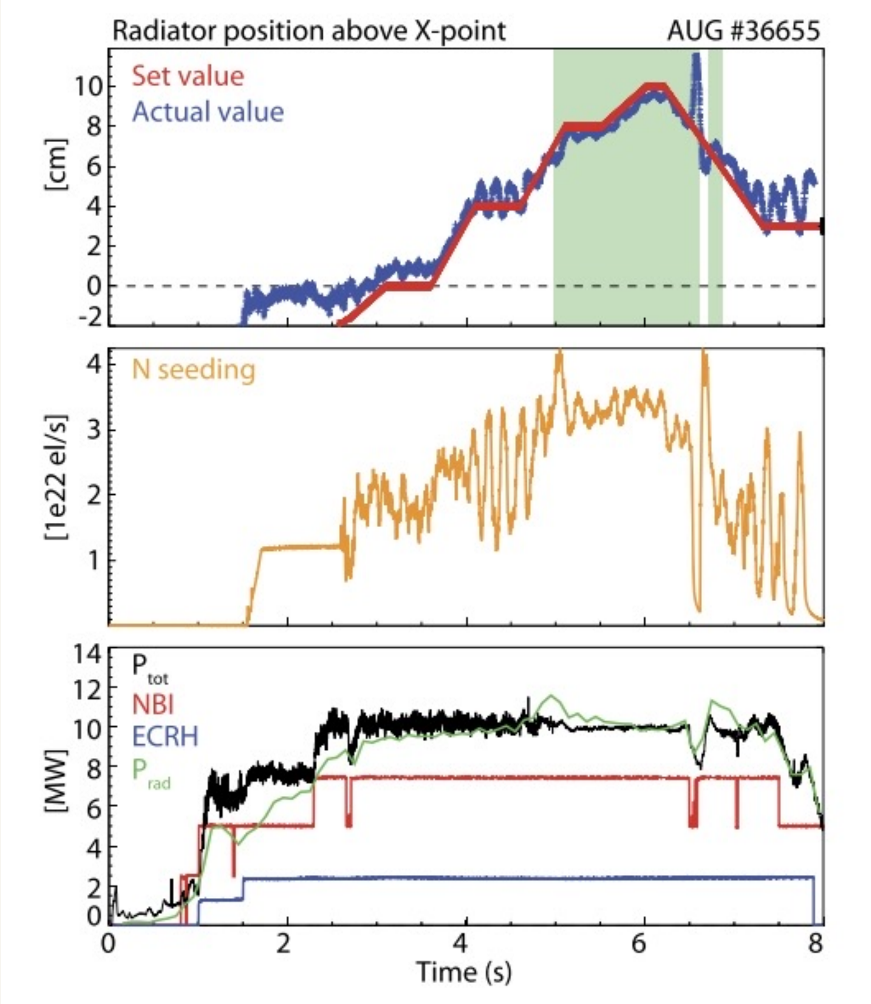






M. Bernert et al 2021 Nucl. Fusion 61, 024001

Ham C., et al. Nature Reviews Physics, 2(3):159–167, 2020.

Ham C., et al. Nature Reviews Physics 2(3):159–167, 2020

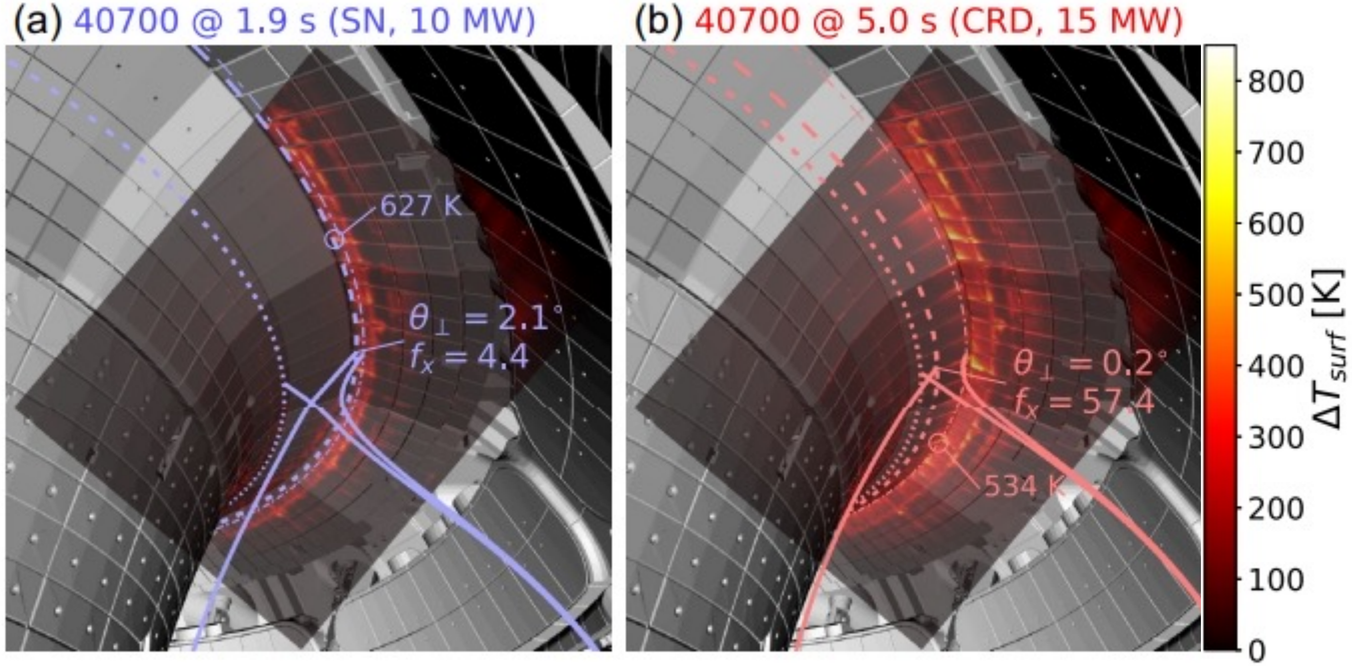
M. Cavedon et al 2022 Nucl. Fusion 62 066027

Compact radiative divertor

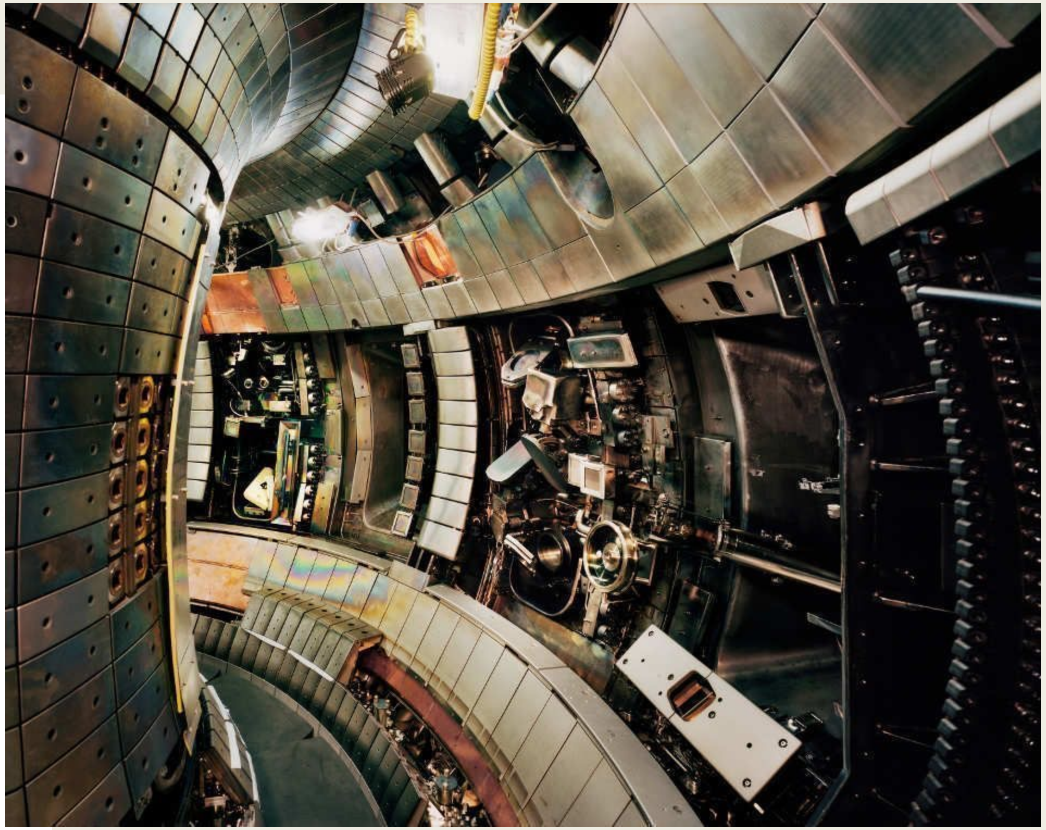
- Benefits: Simpler divertor structure, lower material loads, larger plasma volume
- Concerns: Radiation power, reattachment, different transport in DEMO (modelling)

SN (single-null) → CRD

Magnetic reconstruction + IR thermography

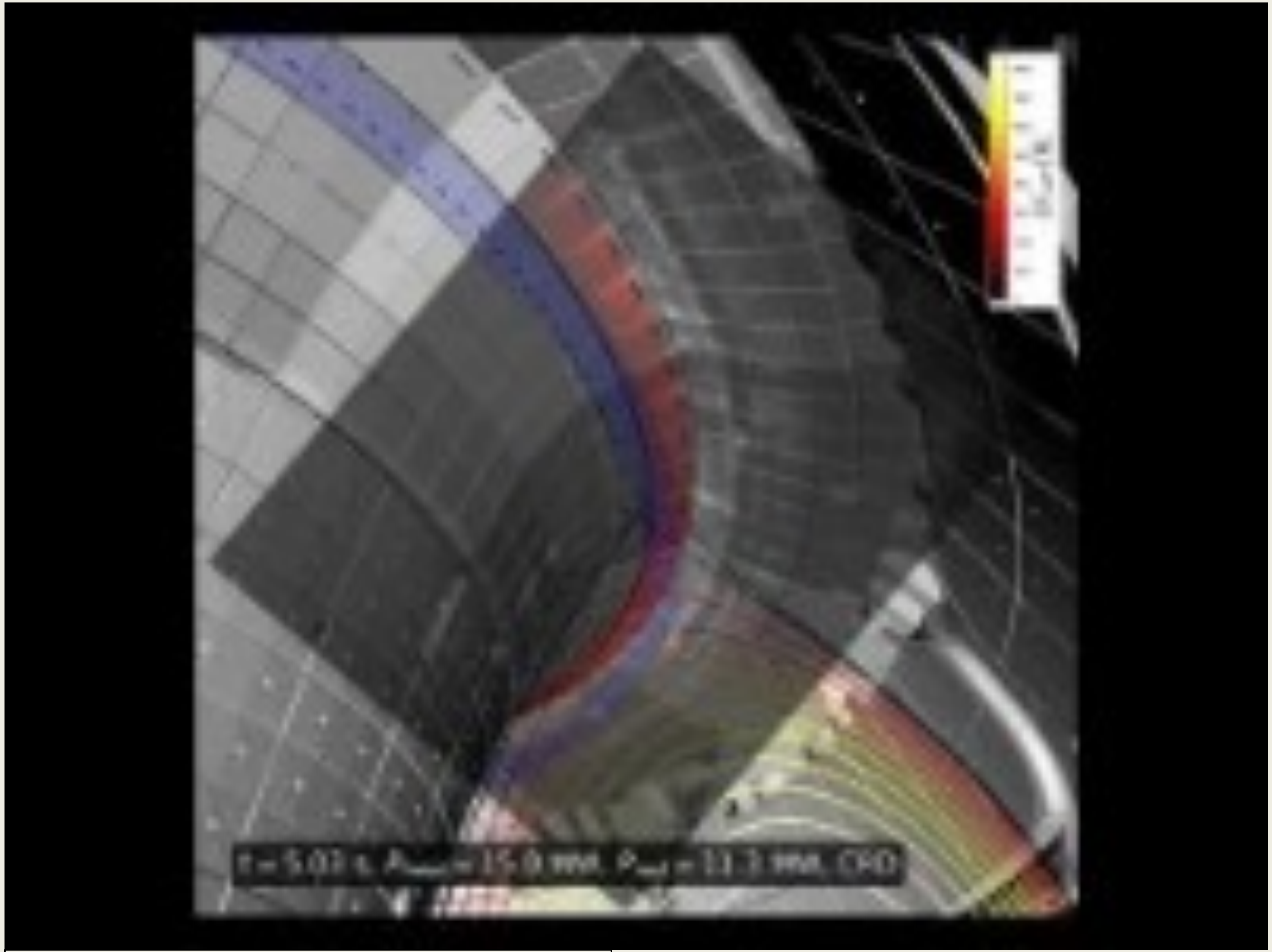


T. Lunt et al 2023 Phys. Rev. Lett. 130, 145102



https://artinwords.de/thomas-struth/thomas-struth-tokamak-asdex-upgrade-interior-2-2009/

Compact radiative divertor



https://www.youtube.com/watch?v=o9G6cAR5rCs

Summary

- Impurity gas puffing leads to XPR.
- Position of XPR can be controlled by heating power and puffing rate.
- Unstable XPR moves upstream towards HFS and turns into a MARFE.
- XPR is a potential solution to power exhaust problem in a tokamak.
- XPR leads to full detachment and 100% power dissipation.
- Compact radiative divertor is an attractive divertor configuration.
- More detailed study on XPR and its interaction with other plasma edge phenomena requires dedicated modelling and more experiments.

References

- Ham C., et al. Nature Reviews Physics, 2(3):159–167, 2020
- O. Pan 2020 Doctoral thesis, Technical University of Munich
- M. Bernert et al 2021 Nucl. Fusion 61, 024001
- M. Bernert et al 2023 Nuclear Materials and Energy Volume 34, 101376
- U. Stroth et al 2022 Nucl. Fusion 62, 076008
- T. Lunt et al 2023 Phys. Rev. Lett. 130, 145102
- O. Pan et al 2023 Nucl. Fusion 63, 016001
- M. Cavedon et al 2022 Nucl. Fusion 62 066027
- https://hesperia.gsfc.nasa.gov/summerschool/lectures/emslie/plasma_physics_handout.

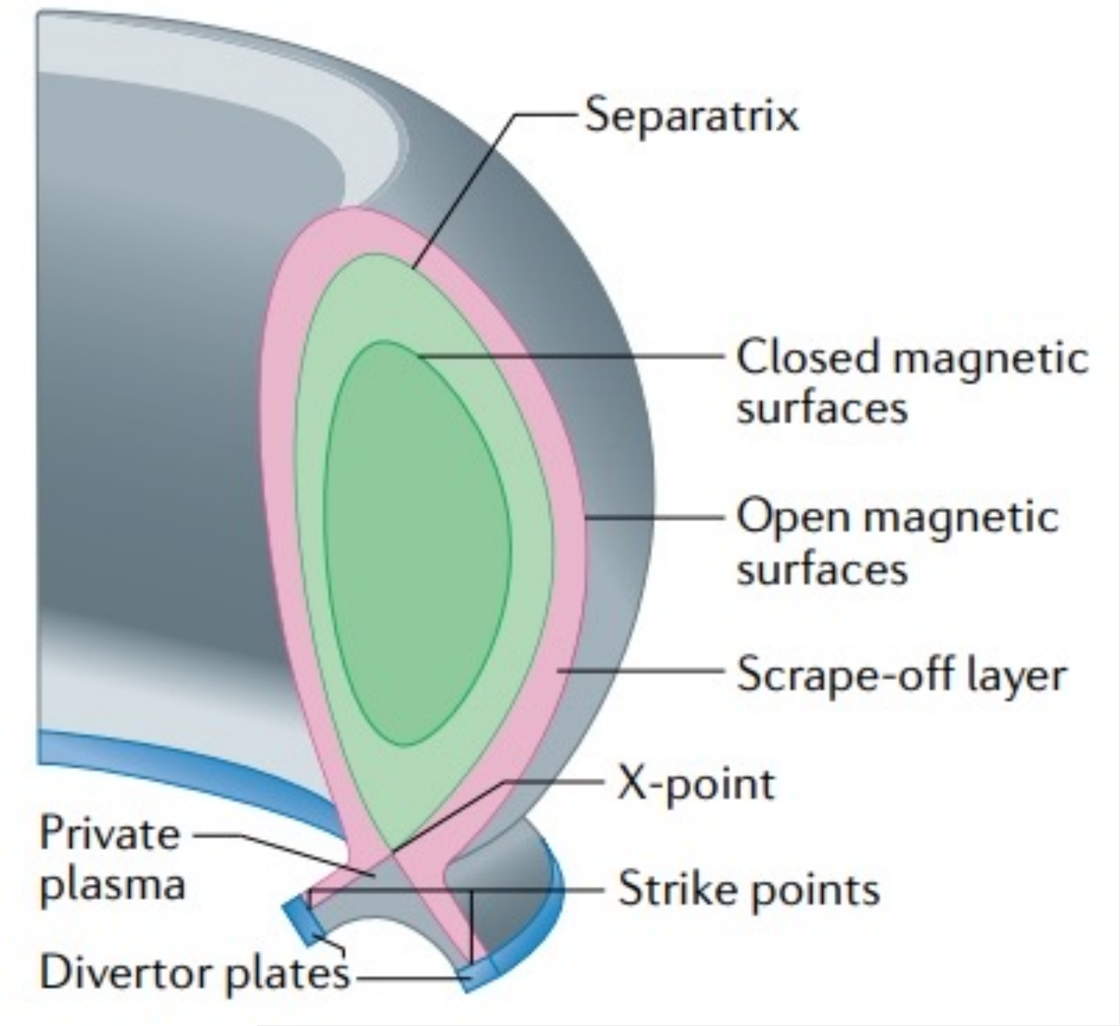
Magnetic flux surfaces

In an equilibrium ($\vec{j} \times \vec{B} = \nabla p$)

- Magnetic field lines stay parallel to the magnetic flux surfaces.
- Plasma pressure stays constant on each magnetic flux surface.

⇓

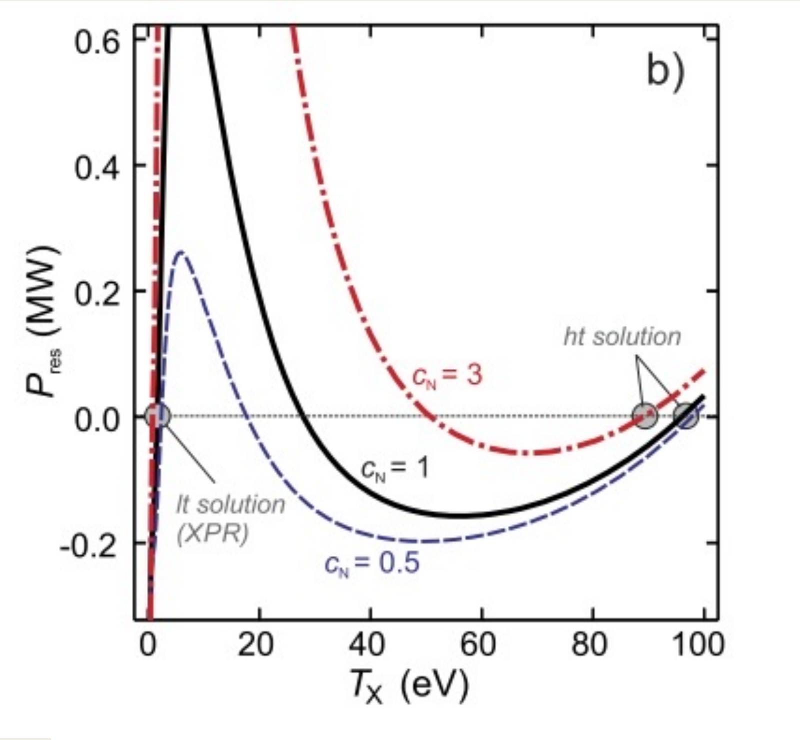
- No pressure gradient along the field lines



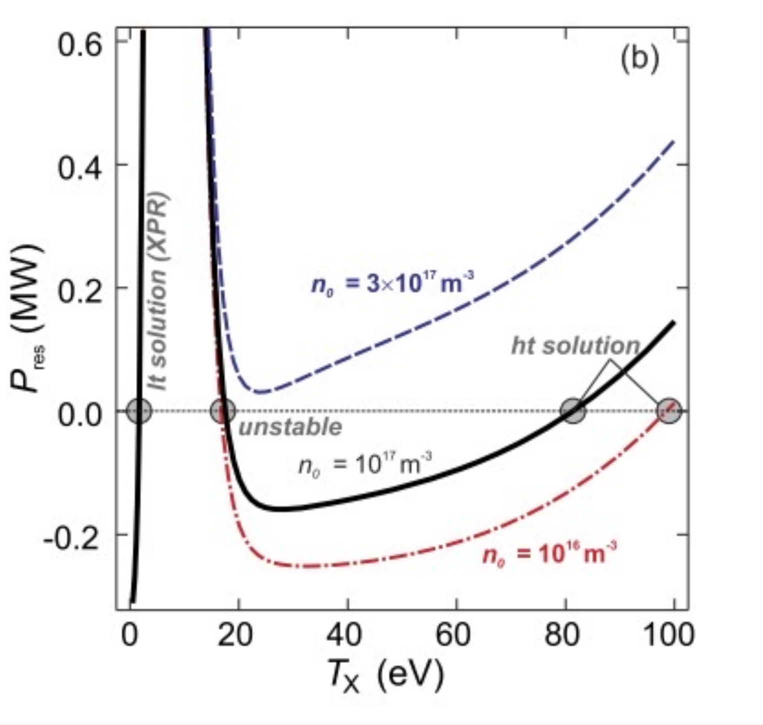
Ham C., et al. Nature Reviews Physics, 2(3):159–167, 2020

XPR : The XPR parameter

- Power balance between up/down- stream ➡ High-T solution + Low-T solution
- High-T solution vanishes with increased upstream neutral density (n_0) ➡ XPR (C_N>0.1%)
- Increased impurity content (C_N) ➡ Also helps to form XPR



From figure 5 of [Stroth_NF_2022]



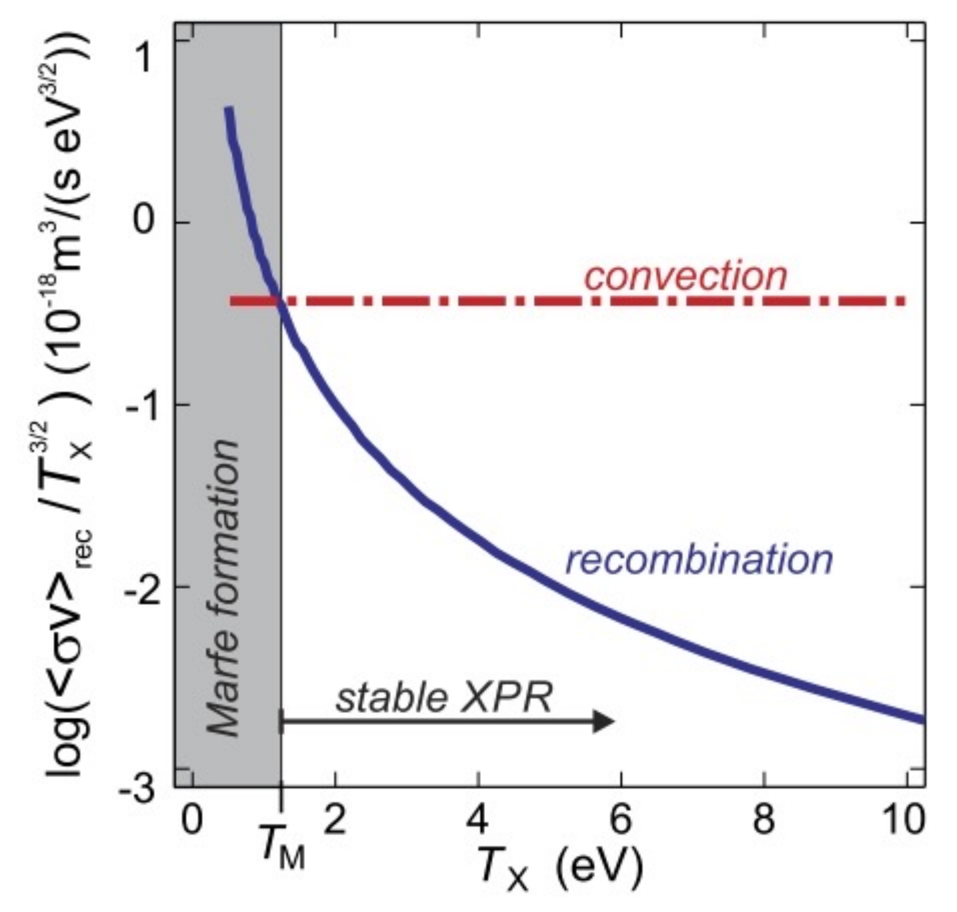
XPR parameter:

$$X_A \sim \frac{R_0^2 q_s^2 f_{exp}}{a} \frac{n_u n_0}{T_u^{\frac{5}{2}}}$$

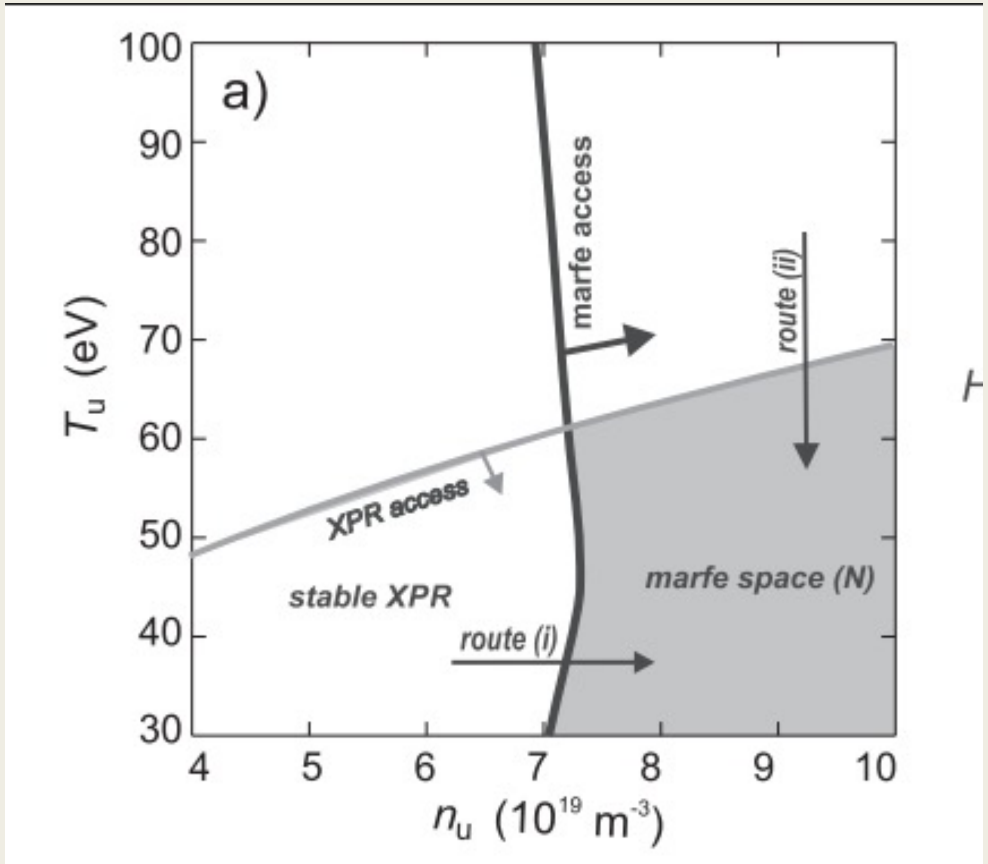
From figure 3 of [Stroth_NF_2022]

XPR : Stability

- Particle balance ➡ MARFE occurrence parameter: $M_\mathrm{A} = \frac{R_0^3}{a^2}\sqrt{\frac{m_\mathrm{i}}{T_\mathrm{u}}}n_\mathrm{u}^3 q_\mathrm{s}^3 f_\mathrm{exp}^2 c_\mathrm{imp}$



From figure 7 of [Stroth_NF_2022]

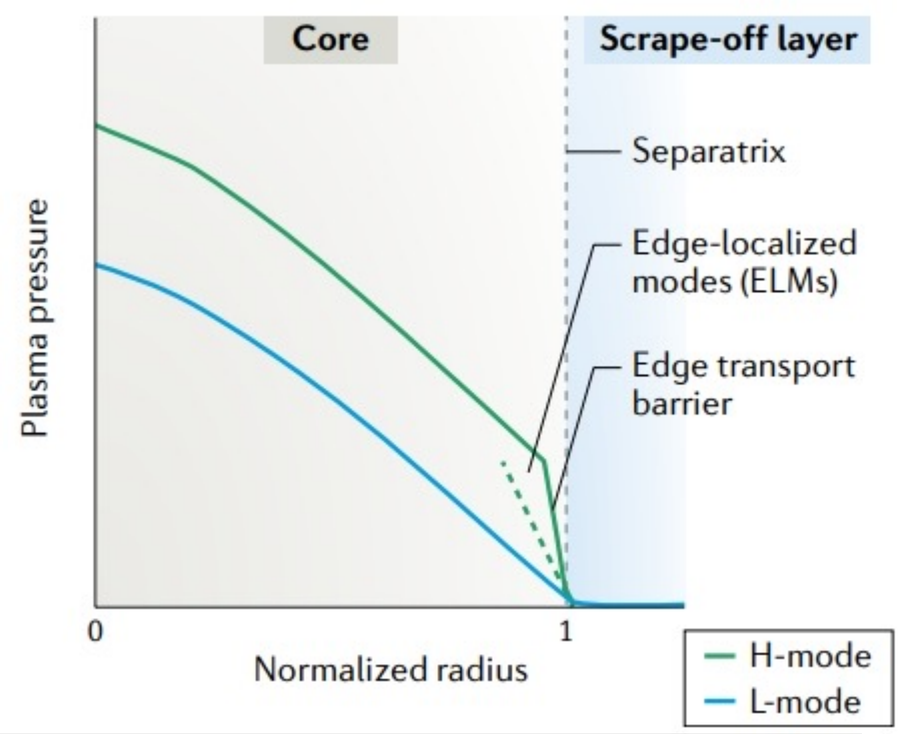


From figure 11 of [Stroth_NF_2022]

ELM suppression (?)

- Edge localized mode: Pedestal relaxation in H-mode
- At a position of 7 cm, an ELM suppressed regime was found experimentally with power dissipation ≈ 100% !

  (Though not exactly in H-mode: weak pedestal)



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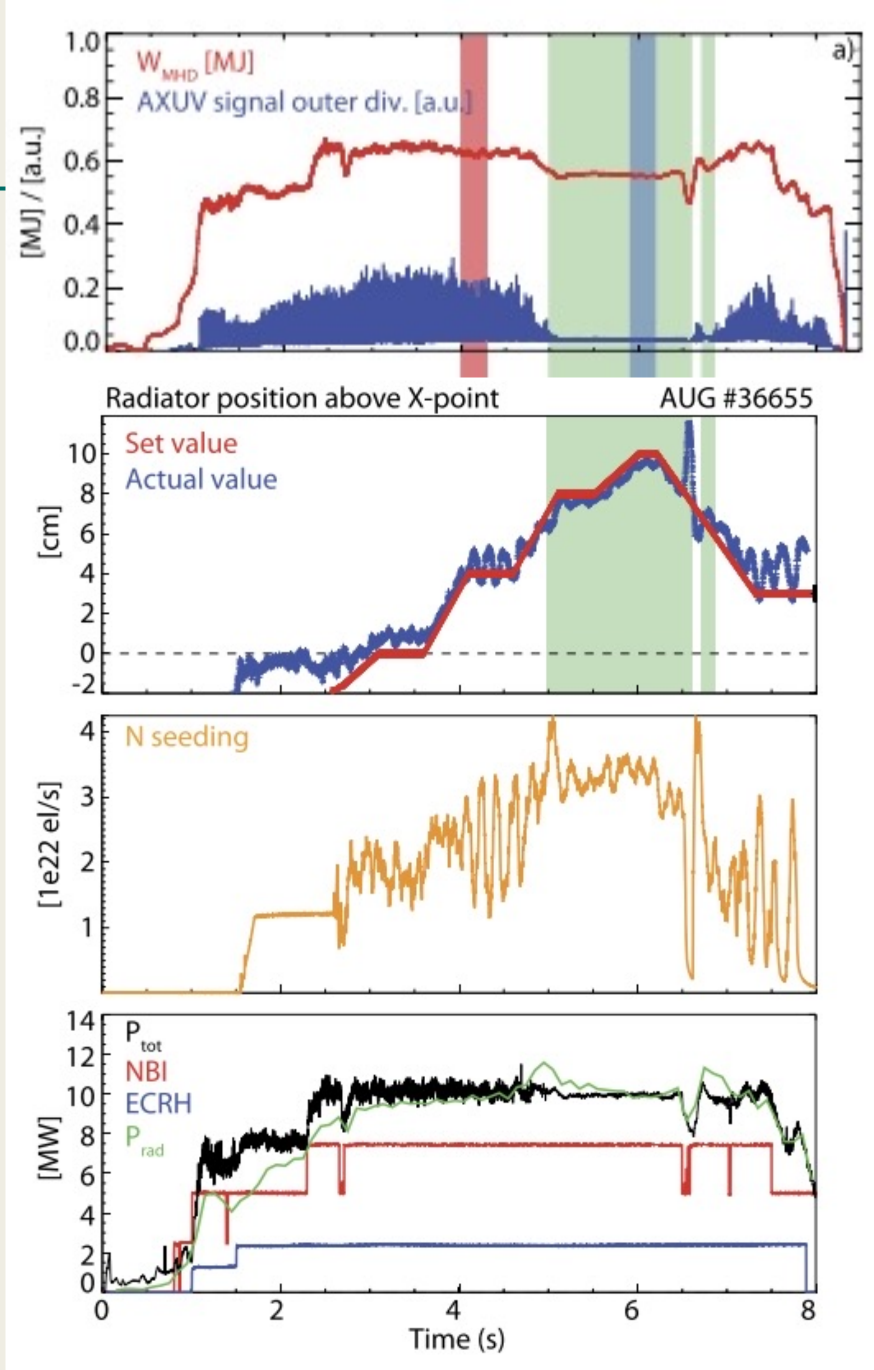
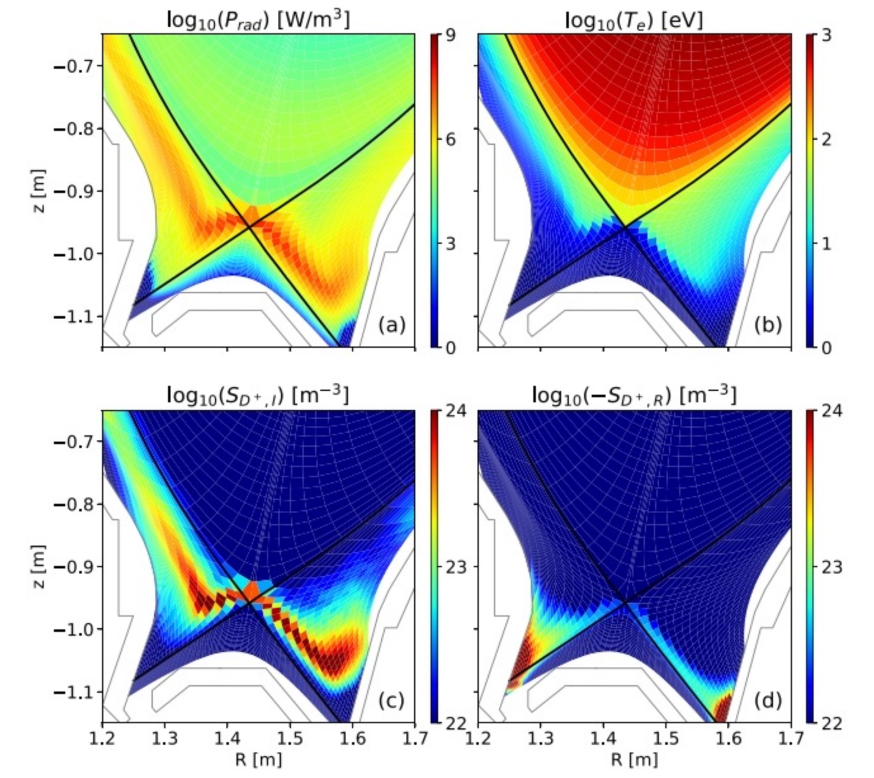


M. Bernert et al 2021 Nucl. Fusion 61 024001

https://www.youtube.com/shorts/qbqmWLeRqq

SOLPS – ITER simulation

- Low Φ_N = 9.8 x E20 [e/s]
- Detached
- Radiative/ ionizing region at SOL



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- High Φ_N = 2.1 x E21 [e/s]
- Colder divertor region
- Radiative region at up stream SOL

  and above x-point

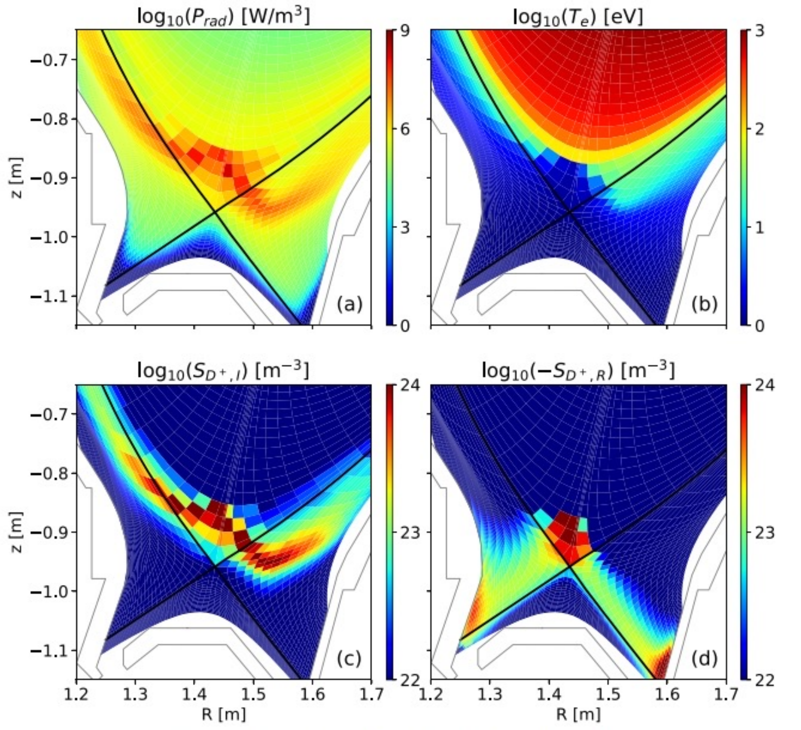

Figure 4. Same as figure 3 but for $\Phi_N = 2.1 \times 10^{21}$ e$^-$ s^{-1}.

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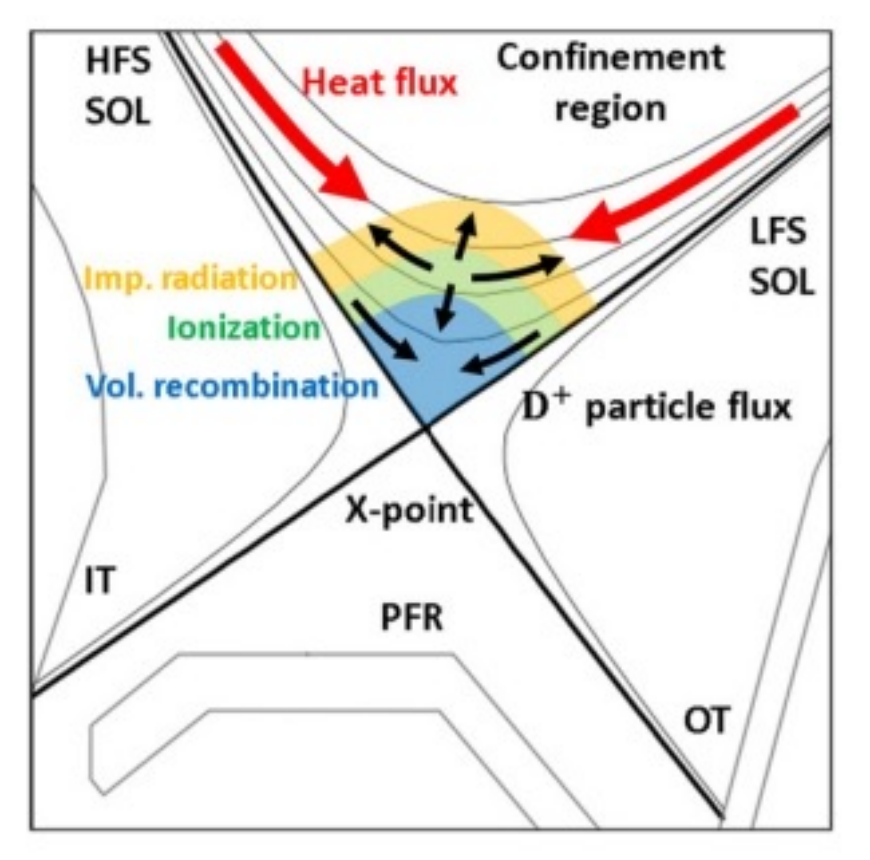
SOLPS – ITER simulation

- Confirm the access condition from the reduced model
- Sketch of XPR
- Tests with absorbing/ reflecting baffle

⇨ Neutrals are important for initiating XPR but not necessarily for maintaining it



O. Pan et al 2023 Nucl. Fusion 63, 016001