MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ASDEX Upgrade

SOLPS-ITER simulations of an X-point radiator in the single-null and snowflake divertor configurations in ASDEX Upgrade and EU-DEMO

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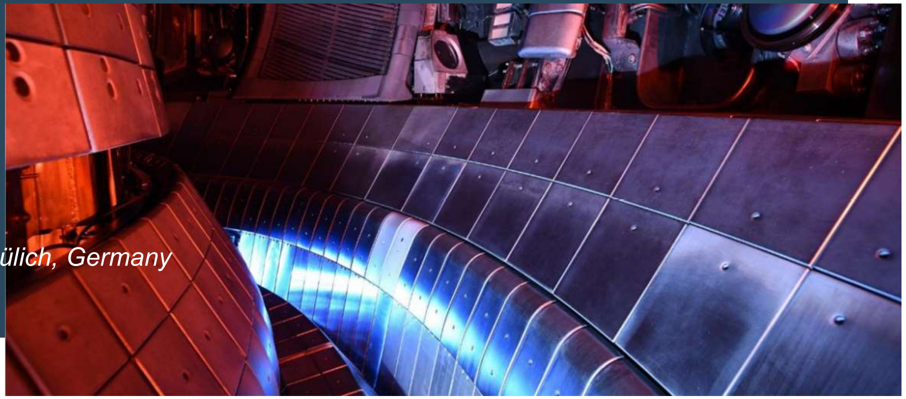

EUROfusion

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Outline

Motivation & Introduction

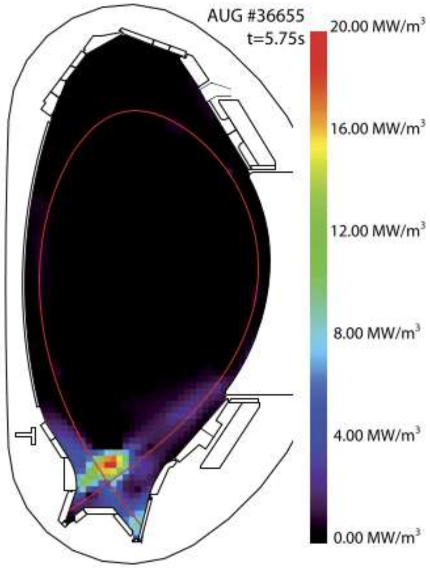
SOLPS-ITER modeling for an X-point radiator

The access condition of an XPR – comparison with the reduced model [Stroth, NF, 22]

Preliminary study on machine-size dependence

Summary

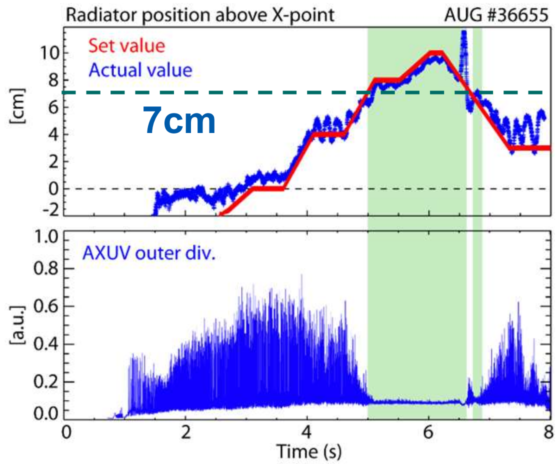
X-point radiator



[Bernert, NF, 2021]
[Bernert, PSI, 2022]

X-point radiator: a stable, localized and highly radiative region near the X-point inside the confined plasma in metallic machines AUG and JET.

ELM suppression with moderate confinement degradation when the XPR is deep enough inside the confined region.



Viable reactor scenario

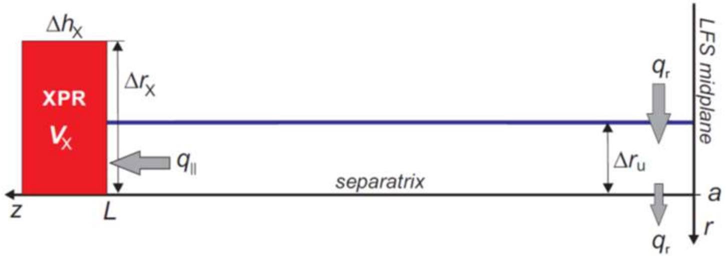
- Full detachment
- ≥90% radiation
- ELM suppression
- Acceptable confinement
- Easy control
- Compatible with power changes

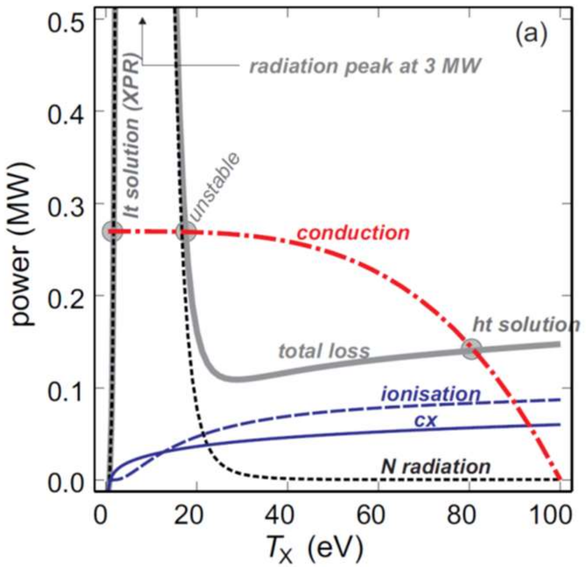
A reduced model for the initiation of an XPR

An XPR occurs when

$$X_A = \frac{P_I + P_{CX}}{P_{cond}} \approx \frac{(2\langle\sigma v\rangle_I + \langle\sigma v\rangle_{CX})}{(2/7)\hat{\kappa}_e} \cdot \boxed{\frac{L_c f_{exp} \Delta h_X B_{t,u}}{B_{\theta,u}}} \cdot \frac{n_{e,u}}{T_{e,u}^{2.5}} \cdot \boxed{n_{0,X}} > 1$$

[Stroth, NF, 2022]





Highlight the role of

- Neutrals
- Magnetic connection length & flux expansion

Neutral density at the X-point → hard to measure in experiments

Spatial distribution of particle and energy sources

Cross-field transport, drifts, HFS/LFS asymmetry

2D numerical simulations

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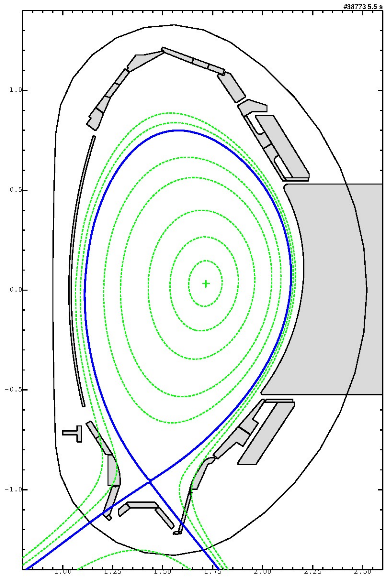
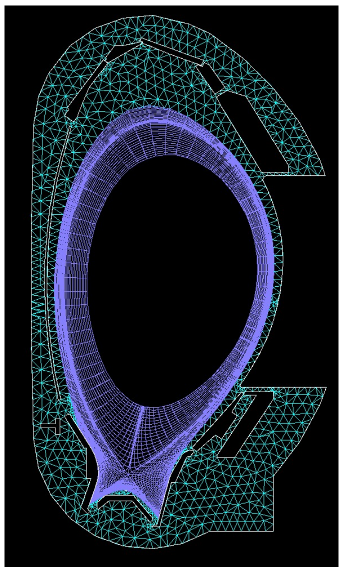
SOLPS-ITER simulation for an XPR

SOLPS-ITER code package:
- B2.5 (2D multi-fluid plasma transport code)
- EIRENE (kinetic Monte Carlo neutral particle transport code)

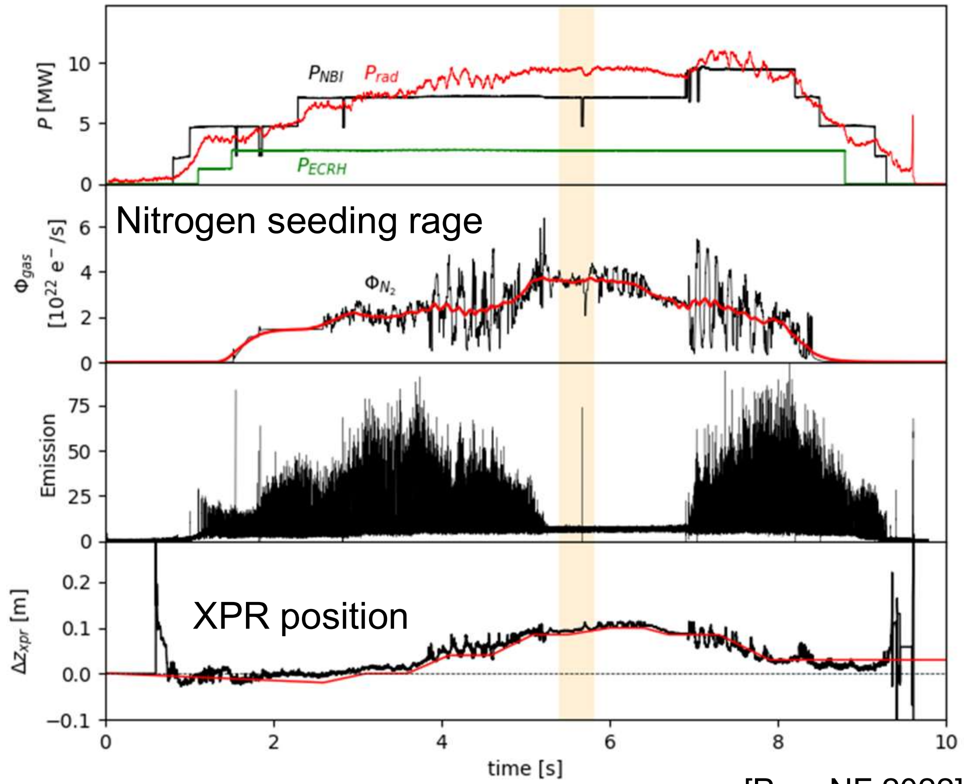
Equilibrium



SOLPS-ITER grids



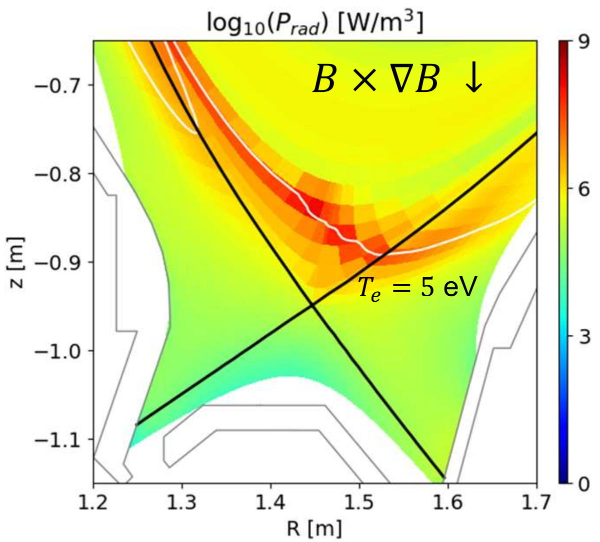
AUG #38773



[Pan, NF 2022]

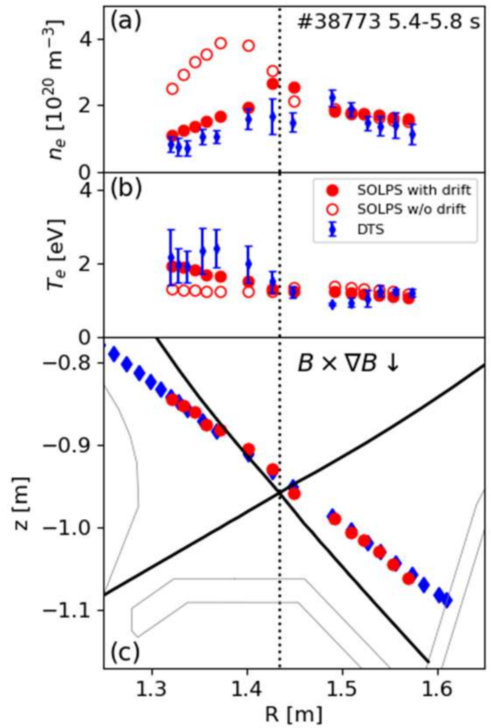
SOLPS-ITER simulation for an XPR

Line radiation



In the confined region near the X-point:

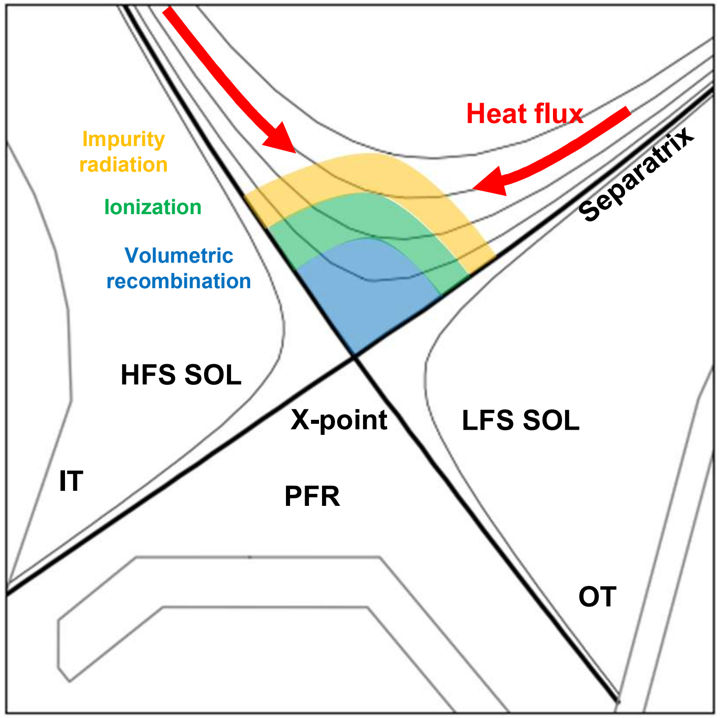
- A highly radiative band
- A cold XPR core ($T_e < 5$ eV)

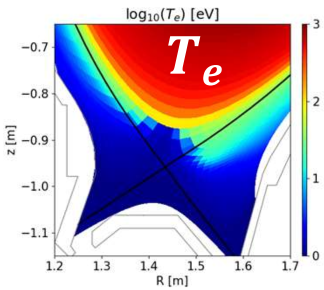


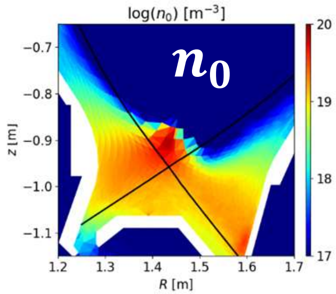
[Pan, NF 2022]

Good agreements with the divertor Thomson scattering measurements

A simple sketch of XPR in SOLPS-ITER simulations





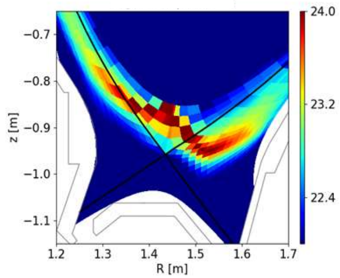


Increased neutral density at the X-point

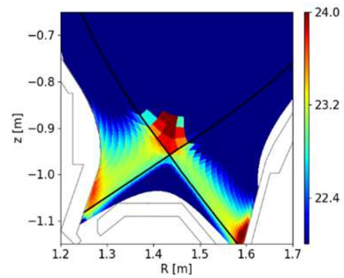
Ionizing region with $T_e \sim 10$ eV

Recombining region with $T_e \sim 1$ eV

Ionization rate



Volumetric recombination rate



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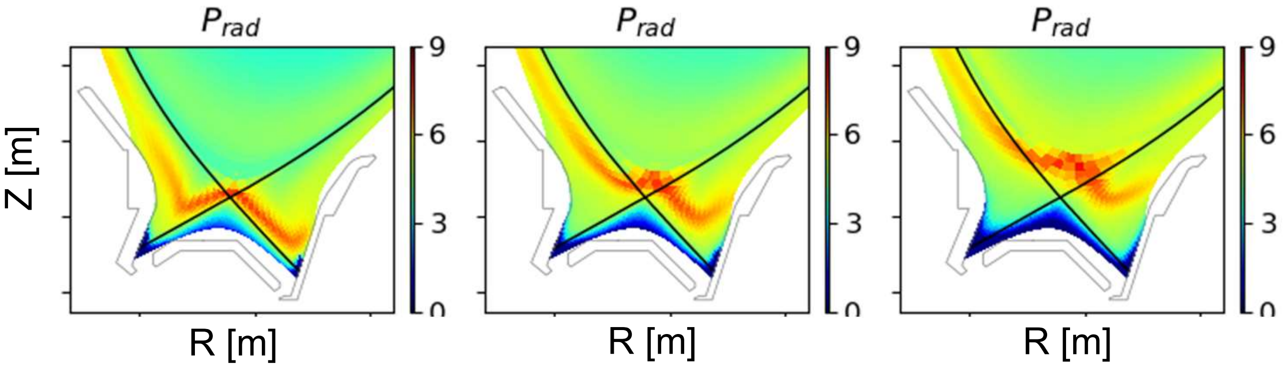
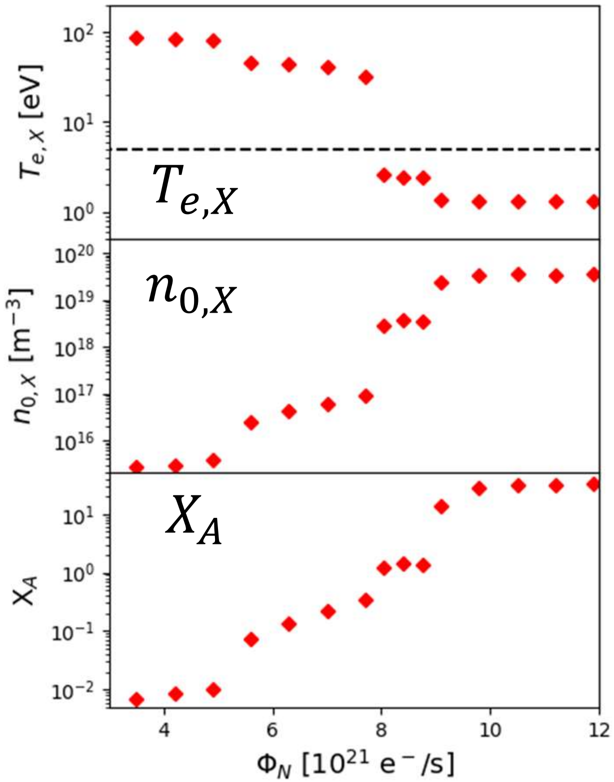
The formation of an XPR in SOLPS-ITER simualtions



$\Phi_N = 5.6 \times 10^{20}\ e^-/s$ $\Phi_N = 8.4 \times 10^{20}\ e^-/s$ $\Phi_N = 1.1 \times 10^{21}\ e^-/s$

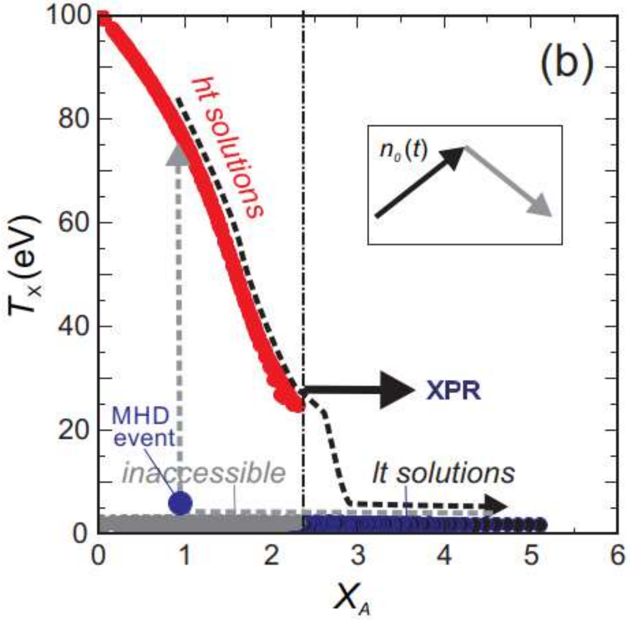


With increasing nitrogen impurity seeding rate:

- Electron temperature decreases at the X-point
- Neutral density increases at the X-point
- X_A increases

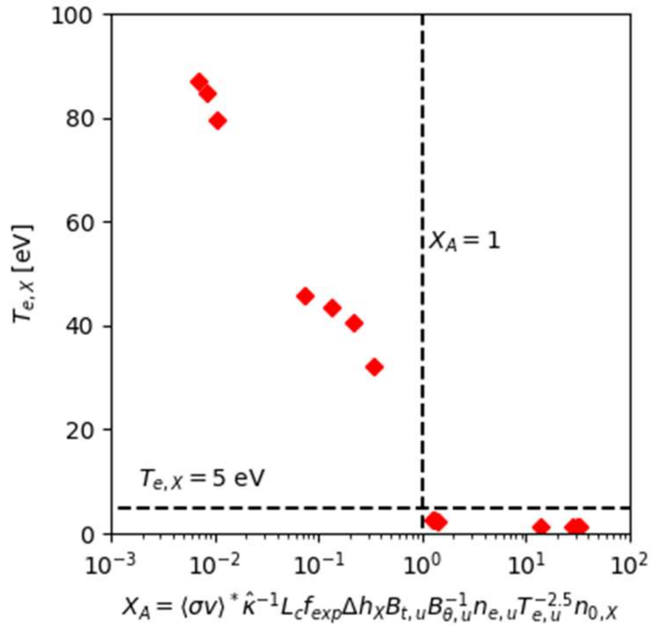
XPR access condition – comparison with the reduced model

Reduced model



[Stroth, NF, 2022]

SOLPS-ITER simulation



$\langle\sigma v\rangle^* = 2\langle\sigma v\rangle_I + \langle\sigma v\rangle_{CX}$, $\hat{\kappa} = \frac{2}{7}\hat{\kappa}_e$

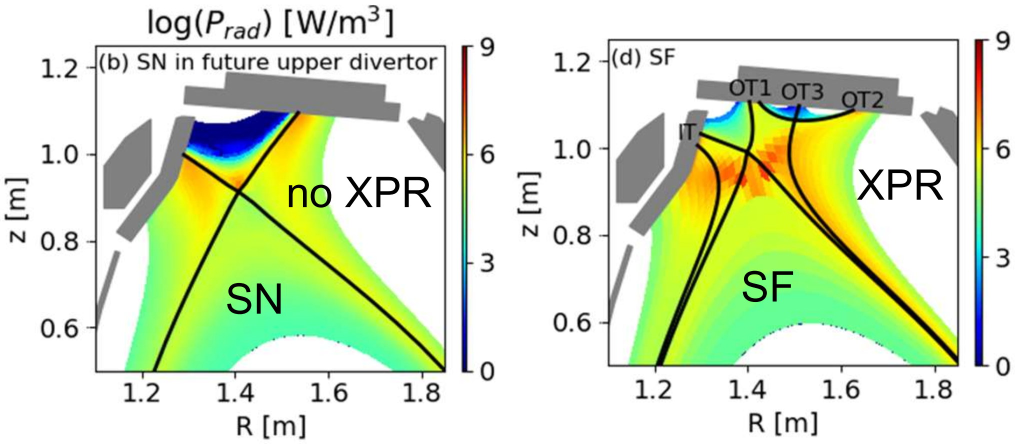
An XPR ($T_{e,X} < 5$ eV) occurs with $X_{A,threshold} \sim 1$

Good agreements with the reduced model

Only a rough estimate, while parameter dependencies are more robust

$$X_A = \frac{P_I + P_{CX}}{P_{cond}} \approx \frac{(2\langle\sigma v\rangle_I + \langle\sigma v\rangle_{CX})}{(2/7)\hat{\kappa}_e} \cdot \frac{L_c f_{exp} \Delta h_X B_{t,u}}{B_{\theta,u}} \cdot \frac{n_{e,u}}{T_{e,u}^{2.5}} \cdot n_{0,X}$$

SOLPS-ITER modeling for the future upper divertor of AUG



With similar upstream profiles and N seeding rate:

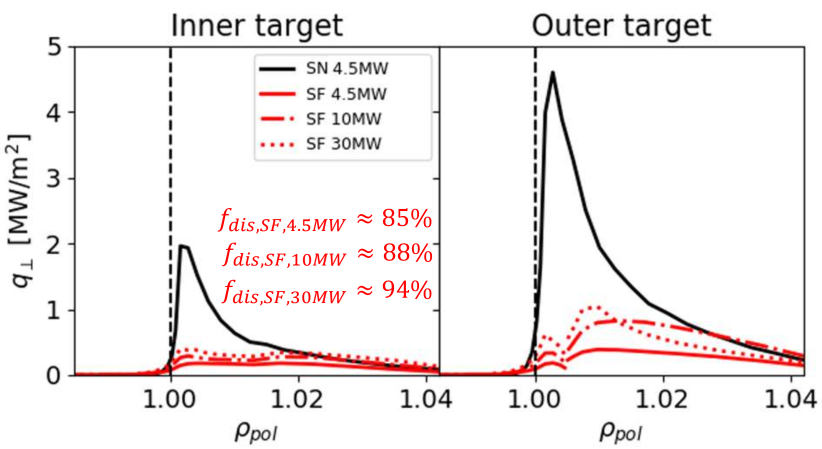
SN: $X_A = 0.004, \quad n_{0,X} = 7 \times 10^{15} m^{-3}$

SF: $X_A = 1.2, \quad n_{0,X} = 5 \times 10^{17} m^{-3}$

Easier access of an XPR in a snowflake divertor

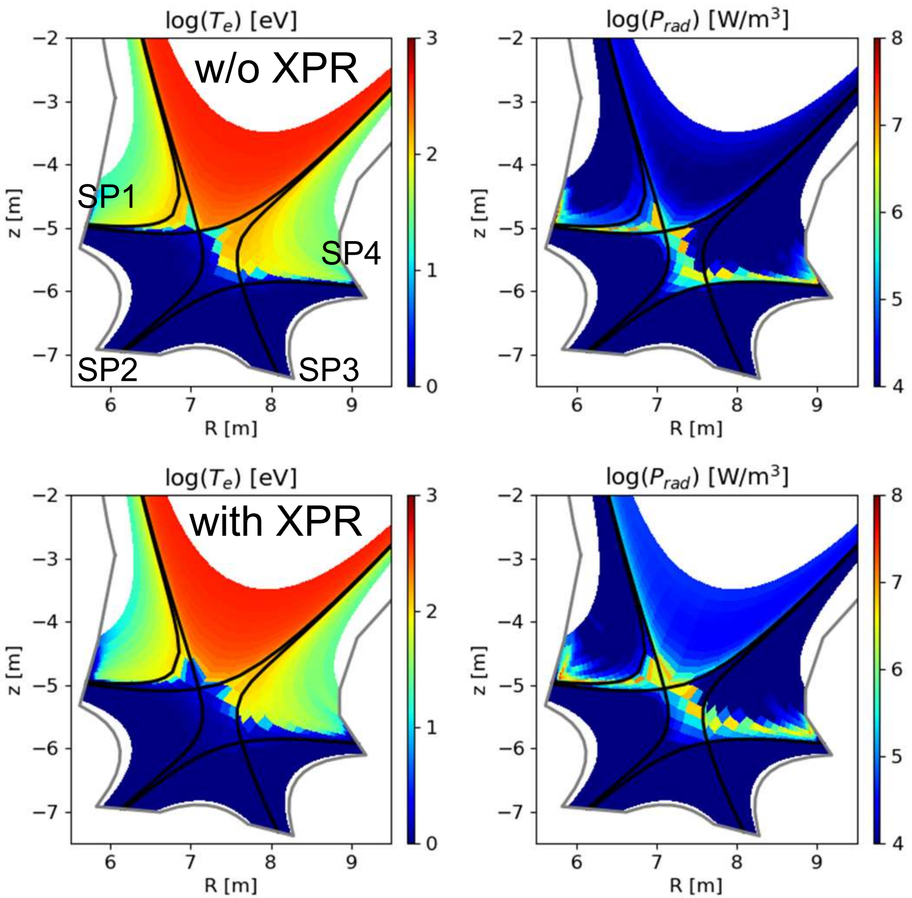
(larger connection length and larger flux expansion)

$$X_A \approx \frac{(2\langle \sigma v \rangle_I + \langle \sigma v \rangle_{CX})}{(2/7)\hat{\kappa}_e} \cdot \frac{L_c f_{exp} \Delta h_X B_{t,u}}{B_{\theta,u}} \cdot \frac{n_{e,u}}{T_{e,u}^{2.5}} \cdot n_{0,X}$$

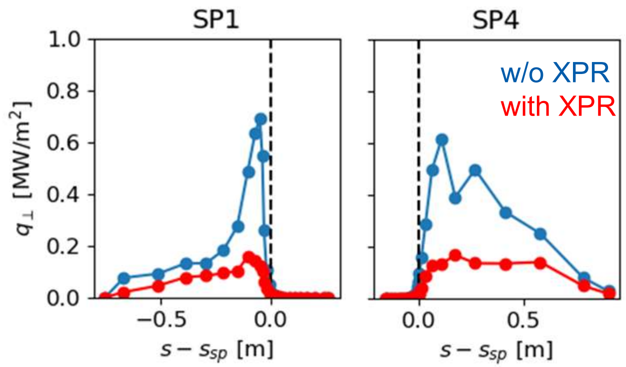


Withstanding a power increase by a factor of 6

SOLPS-ITER modeling for DEMO SFD



Reduced target heat fluxes with an XPR



Without XPR:

$T_{e,u} = 209\ eV, n_{e,u} = 3.0 \times 10^{19}\ m^{-3}, Z_{eff,ompsep} = 1.03$

$T_{e,X} = 97\ eV, n_{0,X} = 1.9 \times 10^{15}\ m^{-3}, X_A = 0.37$

With XPR:

$T_{e,u} = 183\ eV, n_{e,u} = 2.5 \times 10^{19}\ m^{-3}, Z_{eff,ompsep} = 1.08$

$T_{e,X} = 2.7\ eV, n_{0,X} = 2.3 \times 10^{17}\ m^{-3}, X_A = 4.7$

The X_A threshold also roughly works for DEMO SFD

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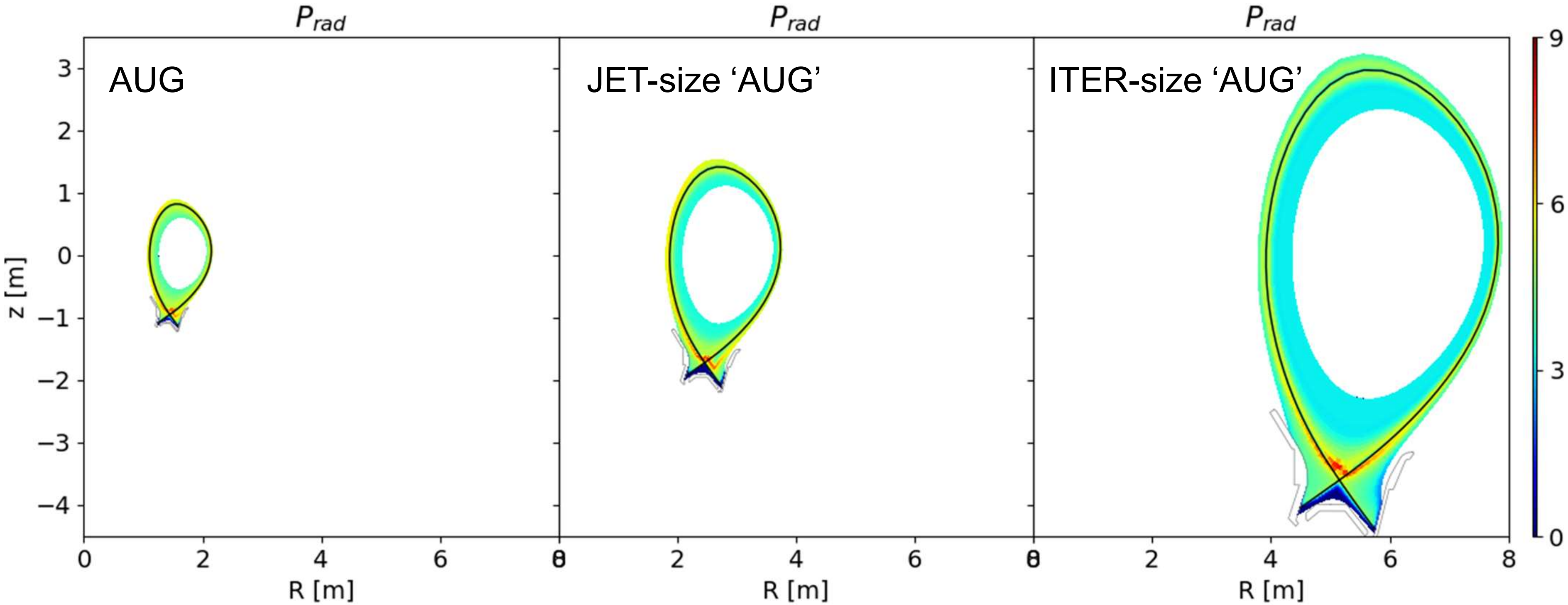
Keeping the same separatrix and divertor shapes

Varying the major radius

Comparing simulations with a similar $T_{e,X}$

	R_0 [m]	P_{in} [MW]	I_p [MA]	B_T
AUG	1.65	5	0.8	2.5
JET-size	2.96	21	2.5	3.0
ITER-size	6.20	105	12	5.3



Preliminary study on machine-size dependence

Simulation results in the flux tube with $T_{e,X} \approx 1.4$ eV

	$B_{t,u}/B_{\theta,u}$	f_{exp}	$n_{e,u}$ $[10^{19}\mathrm{m}^{-3}]$	$T_{e,u}$ [eV]	$n_{0,X}$ $[10^{19}\mathrm{m}^{-3}]$	X_A
AUG	5.3	36	3.1	65	2.5	1.7
JET-size	4.0	36	3.2	106	3.4	1.3
ITER-size	3.1	36	2.4	112	1.8	1.2

Similar X_A value with different machine-size

Good agreement with the reduced model

$$X_A \approx \frac{(2\langle\sigma v\rangle_I + \langle\sigma v\rangle_{CX})}{(2/7)\hat{\kappa}_e} \cdot \frac{L_c f_{exp} \Delta h_X B_{t,u}}{B_{\theta,u}} \cdot \frac{n_{e,u}}{T_{e,u}^{2.5}} \cdot n_{0,X} \sim R_0^2 q_s^2 f_{exp} n_{e,u} T_{e,u}^{-5/2} n_{0,X}$$

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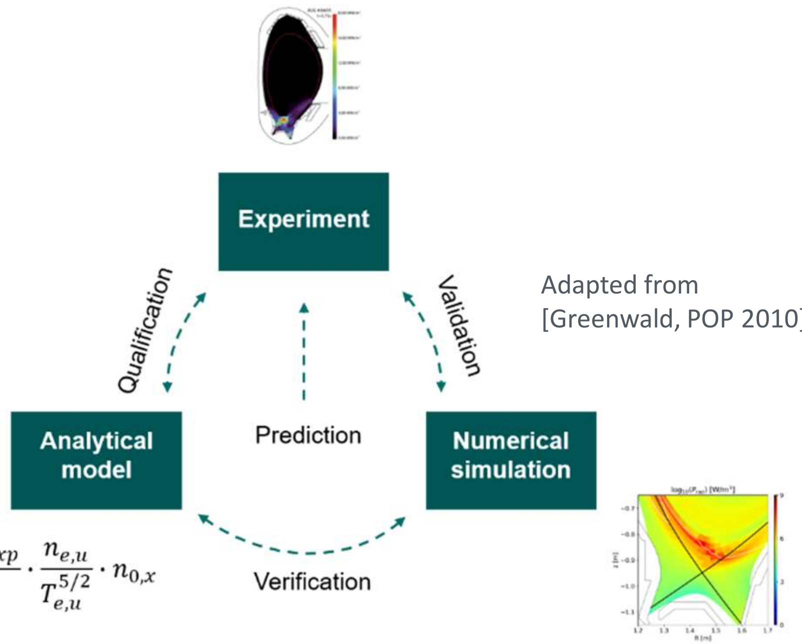
SOLPS-ITER modeling is able to reproduce the X-point radiator phenomenon in AUG and showed good agreements with experimental measurements.

The simulations also showed consistency with the reduced model for the initiation of an X-point radiator [Stroth, NF 2022].

The simulations highlight the important role of neutrals, magnetic connection length & flux expansion in the initiation of an XPR.



$$X_A \sim \frac{R^2 q_s^2 f_{exp}}{a} \cdot \frac{n_{e,u}}{T_{e,u}^{5/2}} \cdot n_{0,x}$$

Adapted from [Greenwald, POP 2010]