ID: P1-2634

Impurity Accumulation and Radiation Dynamics in Advanced Scenarios in W7-X

D. Zhang*[1], B. Buttenschön[1], J. Baldzuhn[1], S.A. Bozhenkov[1], K.J. Brunner[1], O. Ford[1], T. Gonda[2], C. Johnson[3], A. Langenberg[1], N. Pablant[3]
T. Romba[1], H.M. Smith[1], M. Wappl[1], C.D. Beidler[1], J.-P. Bähner[1], G. Fuchert[1], M. Hirsch[1], J. Knauer[1], H.P. Laqua[1], E. Pasch[1], K. Rahbarnia[1],
F. Reimold[1], T. Stange[1], A. von Stechow[1], Th. Wegner[1], and the W7-X team

[1]Max-Planck-Institut für Plasmaphysik, Greifswald, Germany [2]Auburn University, Auburn, AL, US [3] Princeton Plasma Physics Laboratory, Princeton, NJ, US

Wendelstein 7-X

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ABSTRACT

This study reports on the recent experimental observations on impurity accumulation and radiation dynamics in advanced scenarios with improved energy confinement time ($\tau_E/\tau_{ISS04} \geq 1$; defined as high-performance (HP) phase) in the stellarator Wendelstein 7-X [Grulke, O., this conference].

The HP scenarios investigated include

- low-power ECRH plasmas fueled (only) with recycled neutral gas
- plasmas with pellet injections, and
- combined ECRH+NBI heating.

Bolometer tomography reveals significant plasma radiation in the inner plasma region (ρ≤0.5), for which VUV spectroscopy identifies traces of low-Z elements (mainly C from graphite divertor units) as well as metallic impurities (such as Fe, Cu, and W from plasma facing components (PFCs)). This pronounced core impurity radiation appears under plasma conditions with a steeper density gradient, which suppresses turbulence in the W7-X plasmas. It is suggested that this behavior of impurities is related to neoclassical impurity convection in ion-root regimes, which thereby gains in importance. An increased electric field strength in the ion-root has been demonstrated experimentally and theoretically. The investigations conducted so far on impurity transport confirm the role of neoclassical impurity convection.

INTRODUCTION

I. Plasma confinement in most gas-fueled, ECRH plasmas is strongly influenced by turbulence transport with the following characteristics:

- Edge-localized impurity radiation, which promotes highly radiative plasma detachment.
  [Zhang, D., et al., PRL, 2019] [Jakubowski, M., et al., NF, 2021] [Feng, Y., et al., NF, 2021]
- The neoclassically predicted impurity accumulation in the ion root region is not visible;. Impurity transport time << neoclassical predictions (~s)
  [Geiger, B., et al., NF, 2019] [Langenberg, A., et al., PoP, 2020] [Wegner, T., et al., JoPP, 2023]
- Energy confinement time lower than ISS04 scaling ($\tau_E/\tau_{ISS04} < 1$)
  [Yamada, H., et al., NF, 2005] [Fuchert, G., et al., NF, 2020]
- Ion temperature limits at T_i~1.5 keV
  [Beurskens, M.N., et al., NF, 2021] [Ford, O., et al., NF, 2024]

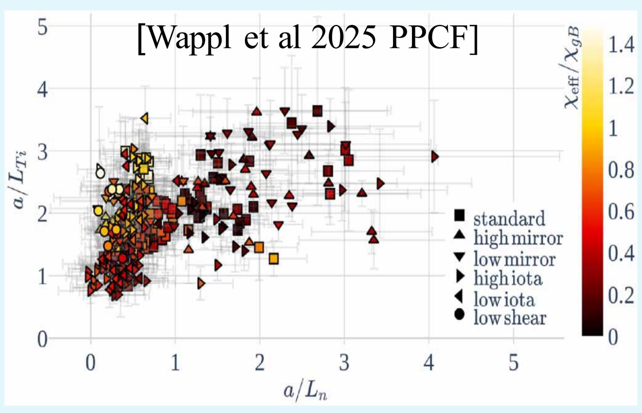
II. the normalized gradients of density and ion temperature

a/L_n = -a(dlnn_e/dr)

a/L_T = -a(dlnT_i/dr)

determine particle and heat transport in W7-X.

- 'stability valley' conditions $\eta_i = (a/L_T)/(a/L_n) \approx 1$
  [Alcusón, J., et al., PPCF,2020]
- Higher a/Ln suppresses ITG turbulence, altering transport and improving plasma confinement.
  [Klinger, T., et al., NF, 2019] [Baldzuhn, J. 2020, PPCF] [Zhang, et al., 2023, PPCF]
  [Bozhenkov, S., NF, 2020] [Bähner, J.-P., et al., JoPP, 2021] [Romba, T., et al., NF, 2023]



Impurity transport study using STRAHL code

[Behringer, K., 1987] [Dux, R., 2006]

- Simulations of impurity radiation in the HP phase of low-power ECRH plasma (XP20180808.7)

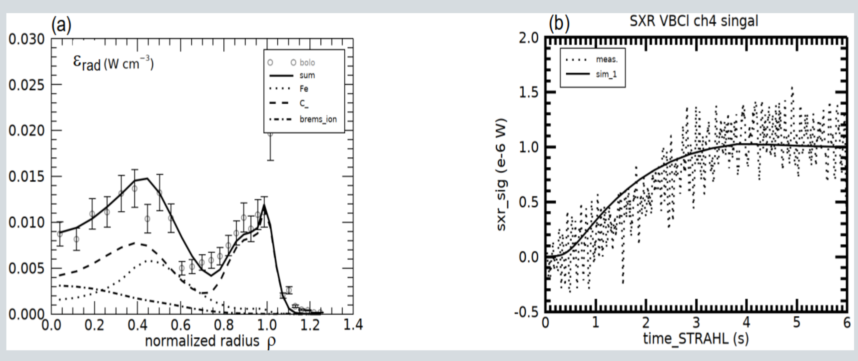
Impurity radiation profiles & SXR signal

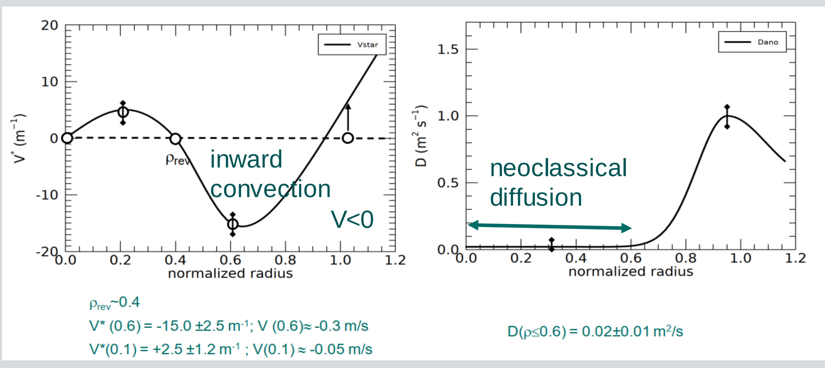
$$\varepsilon_{rad}(\mathrm{r}) = \mathrm{n}_e(r)\mathrm{n}_{Z,edge}L_Z(Z_0, T_e)e^{-\int_r^{r_{edge}} V^* d\tilde{r}}$$

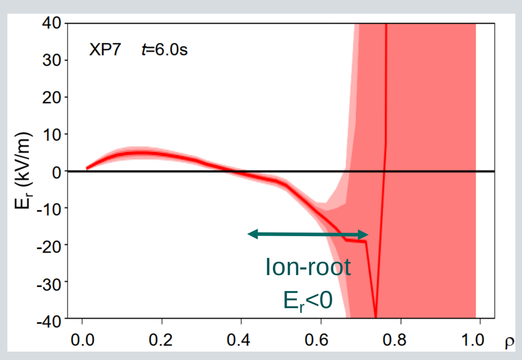
$$V^* = V/D$$

$$V^*_{neo} = \frac{q_Z E_r}{T_Z} - \left(\frac{D_2^Z}{D_1^Z} - \frac{3}{2}\right)\frac{1}{T_Z}\frac{dT_Z}{dr}$$

- Determined convective and diffusive transport coefficient (V and D) show neoclassical features (ρ<0.6)







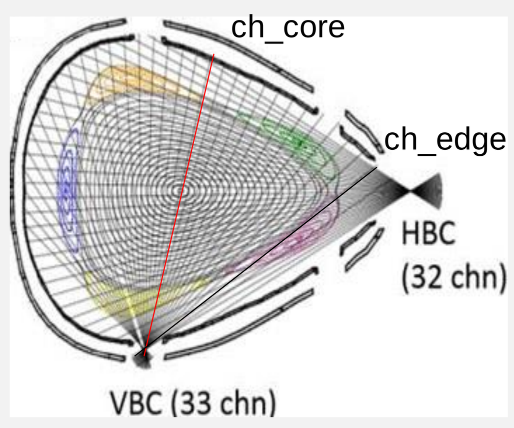
[Pablant, N., NF,2020]
[Langenberg, A, RSI, 2019]

CONCLUSION

- The compatibility of impurity accumulation with improved energy confinement has been observed in various W7-X scenarios. These HP phases are developed using different plasma fueling and heating methods; all exhibit a steepness of the n_e gradient (a/Ln >1) and a reduction in the η_i ratio (<1.5) compared to normal ECRH scenarios.
- The analysis shows that during these HP phases, the radiation fraction in the core (ρ<0.5) remains low ($f_{rad,core}$< 15%) and the emissivity reaches its maximum value 10–20 cm away from the plasma center. This suggests that limiting the edge impurity influx (especially metallic elements) and optimizing turbulence and neoclassical transport to achieve HP plasmas with tolerable impurity dynamics in W7-X remain key research topics.

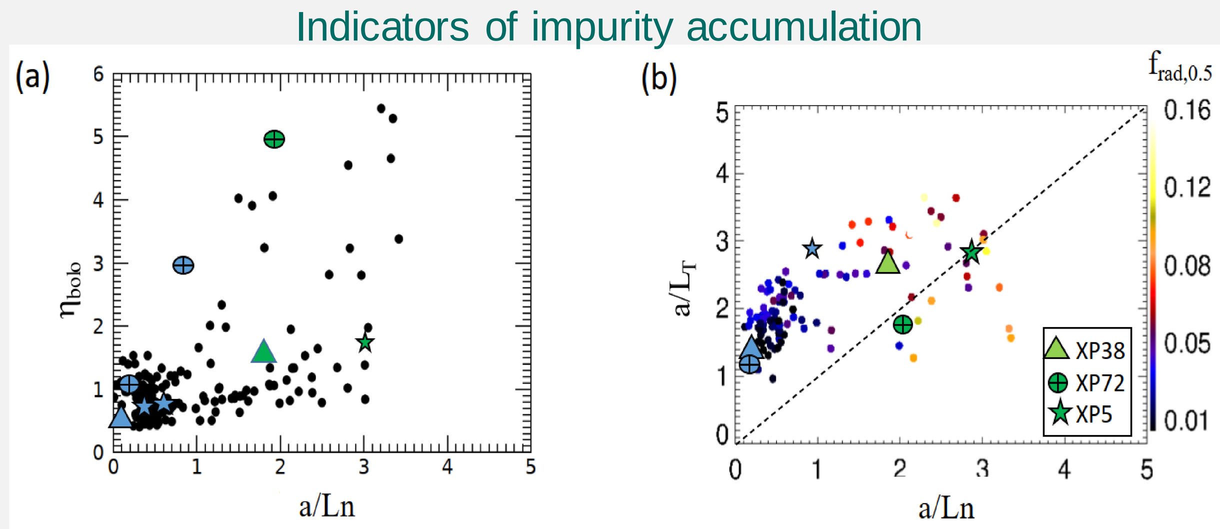
Observations of core plasma radiation enhancement with density gradient (ρ~0.5)

Bolometer LoS arrangement



chord brightness
$<\varepsilon_{ch}>=S_{ch}/(L_{LoS}$*Etendue)

Indicators of impurity accumulation



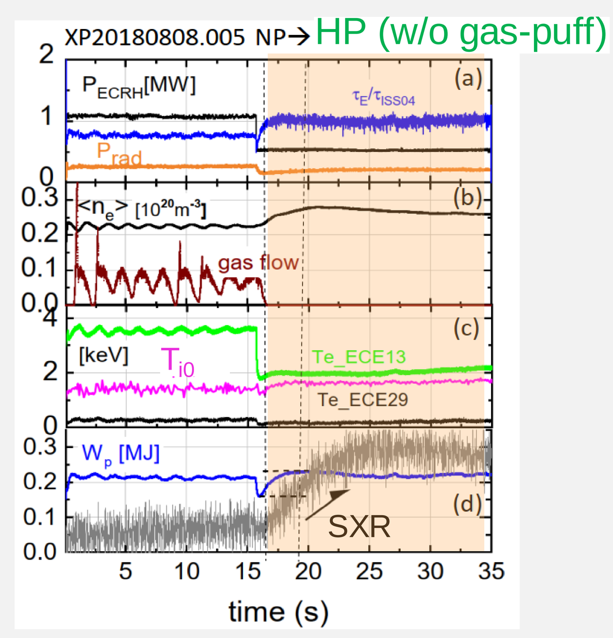
η_{bolo} $=<\varepsilon_{ch\_core}>/<\varepsilon_{ch\_edge}> \geq 1.5$

$f_{rad,0.5}$ $=P_{rad,0.5}(\rho<0.5)/P_{heat}>$ 5%

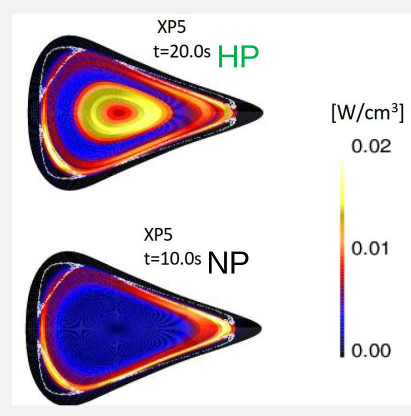
Impurity accumulation in plasma scenarios with improved confinement

Scenario 1: Low-power ECRH w/o gas-puff (XP5)

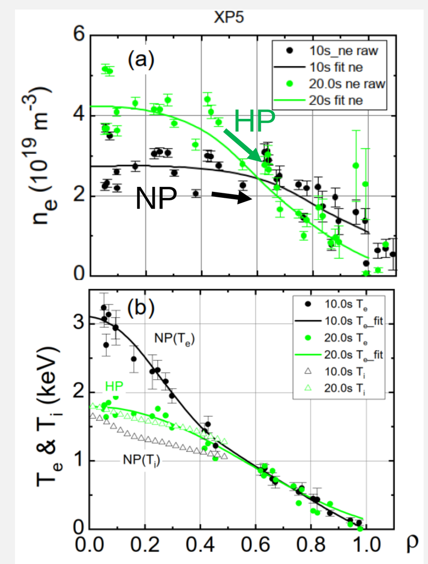
[Zhang, et al., 2023, PPCF]



Bolometer tomography



Thomson scattering

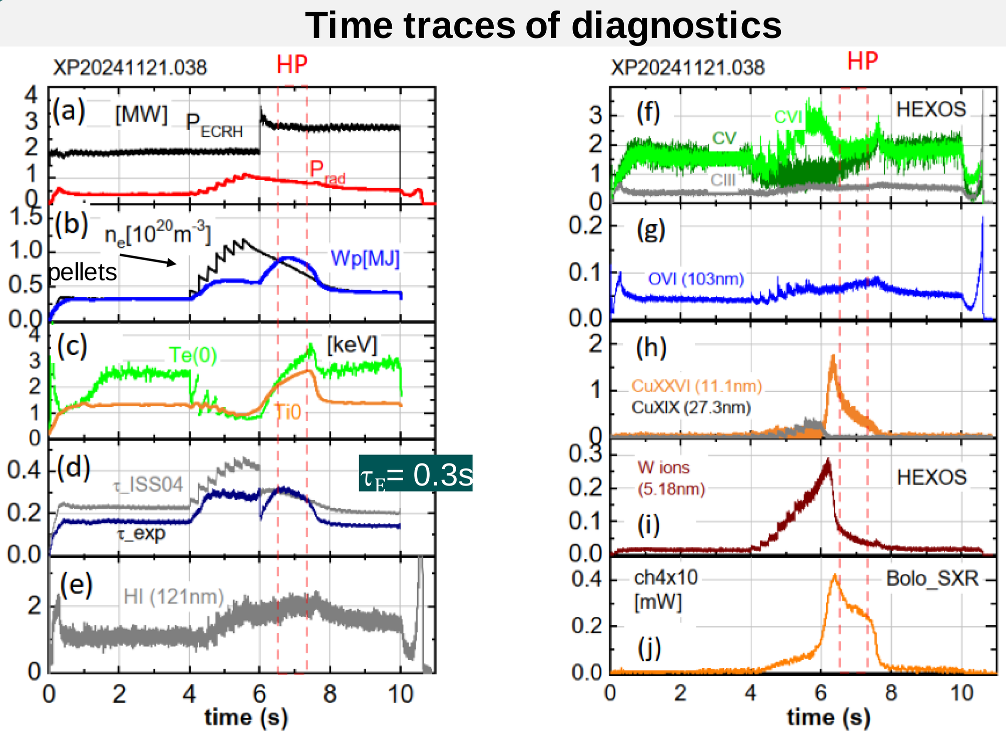


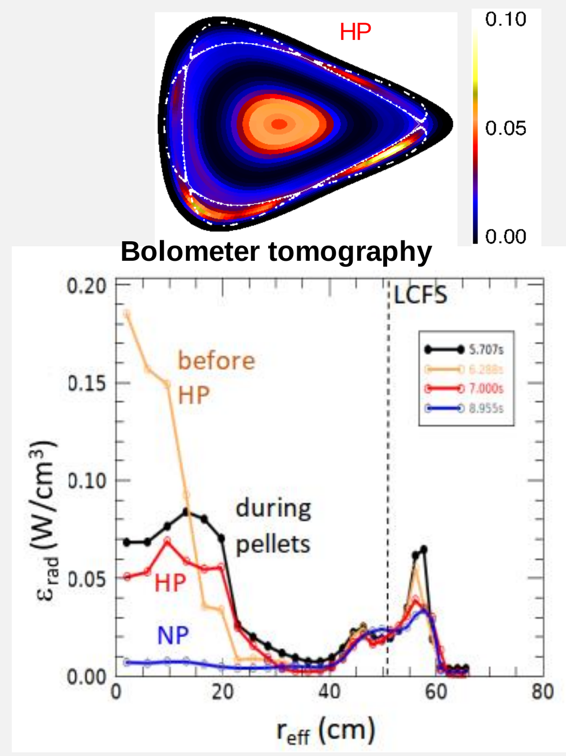
η_i (HP)~1
τ_E= 0.4s

η_i (NP)~3
τ_E= 0.2s

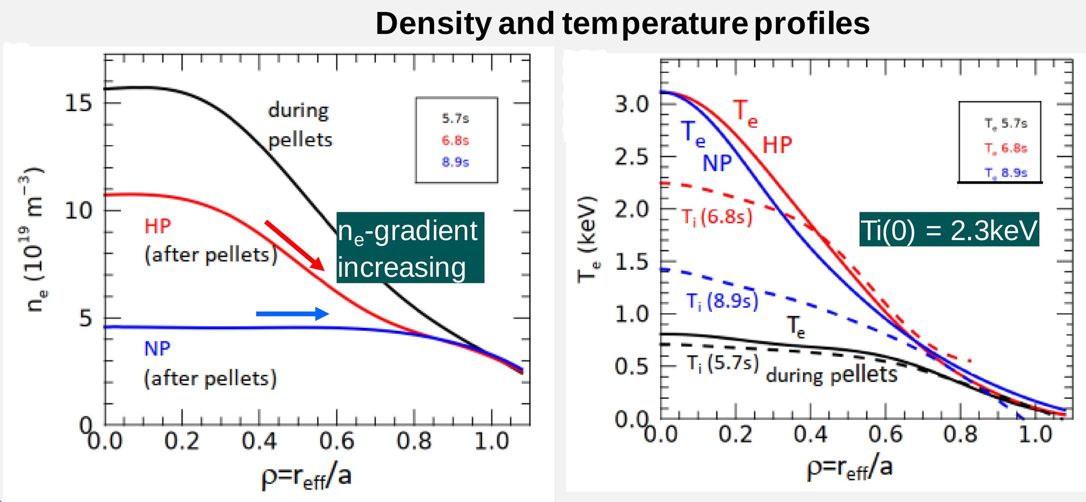
Scenario 2: Pellet injection fueled ECRH plasma (e.g. XP38)

Time traces of diagnostics

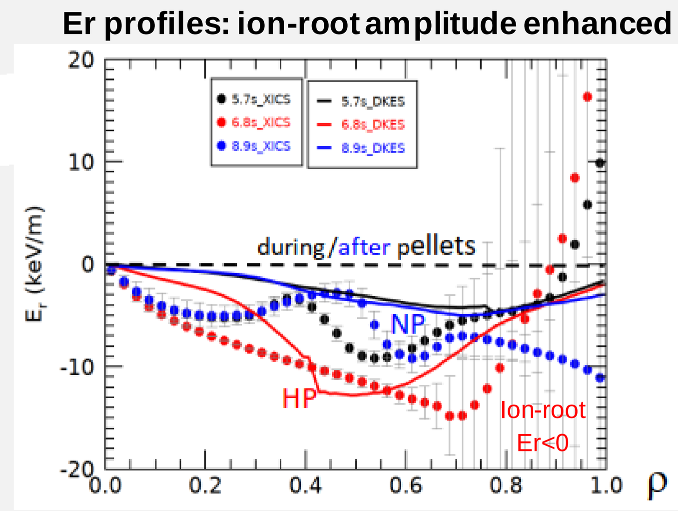




Density and temperature profiles

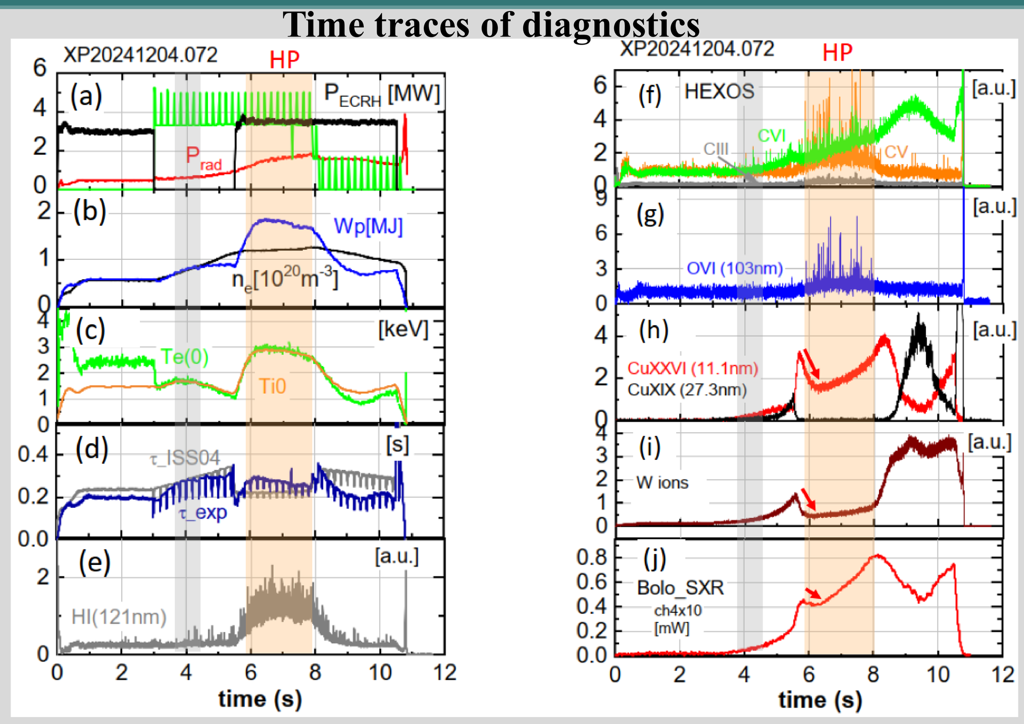


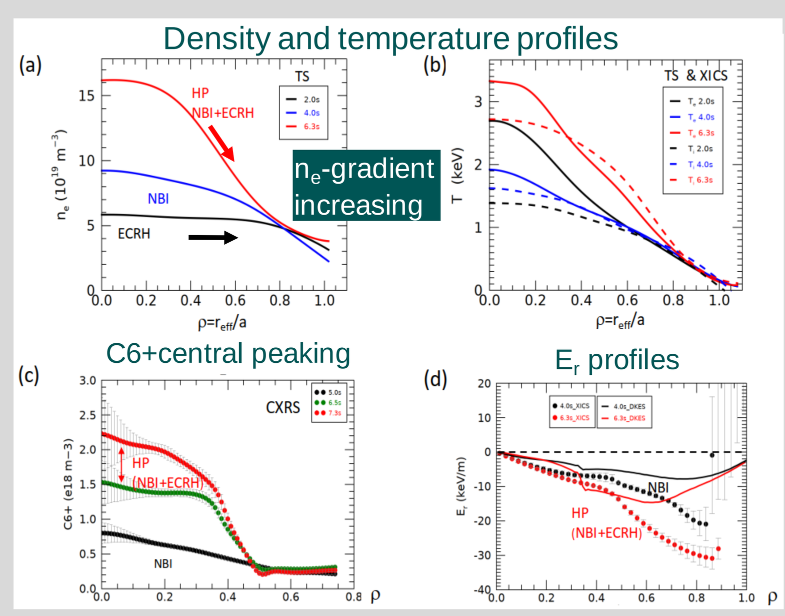
Er profiles: ion-root amplitude enhanced



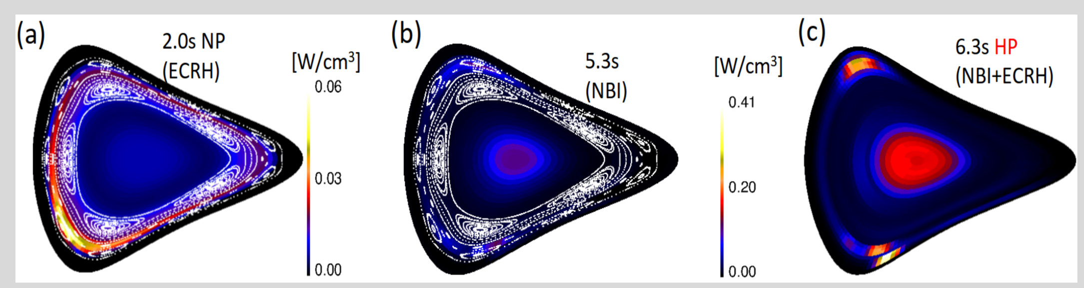
Scenario 3: Plasmas with combined NBI+ECRH(XP72)

Time traces of diagnostics





Bolometer tomography



Observations:

- Enhanced radiation in the inner plasma region mainly contributed by line emissions of metallic impurity ions such as Cu and W.
- C6+ central peaking confirms neoclassical impurity accumulation, but does not contribute significantly to P_{rad}.
- E_r profiles show an increased ion-root amplitude with qualitative agreement between experimental results and neoclassical predictions.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.