Investigating radiated-power asymmetries in low aspect ratio fusion plasmas

NSTX-U meeting
19 May 2025

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with

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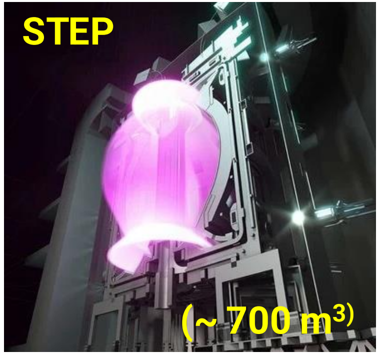
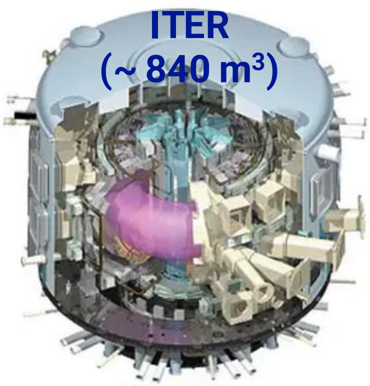
Handling high heat flux is a challenge for Fusion Pilot Plants (FPPs)

Examples:



P_{fus} ~1.5 - 1.8 GW
P_{aux} ~150 MW



P_{fus} ~ 0.5 GW
P_{aux} ~ 50 MW

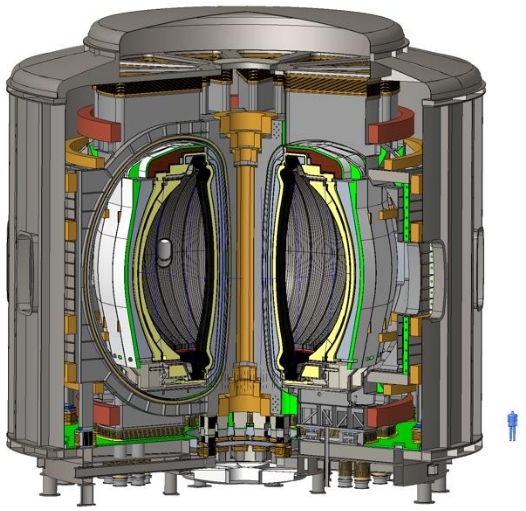
P_{fus} ~1.2 - 2 GW
P_{aux} ~ 50 MW

- Need to radiate as high as ~ 300 MW (P_{rad}) for STEP, DEMO i.e. 70% or more of radiation fraction to protect the divertor load (120 - 150 MW)
- More challenging for ST → compact size → less physical space for power distribution
- Impurity seeding using noble gases (Xe, Ar, Kr) is be a possible solution for desired core or edge radiation

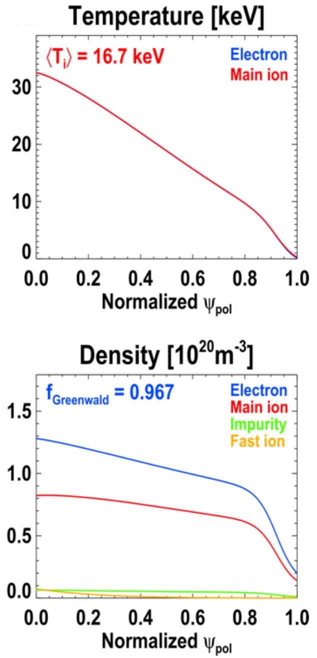
[Henderson et al., NF 2025]

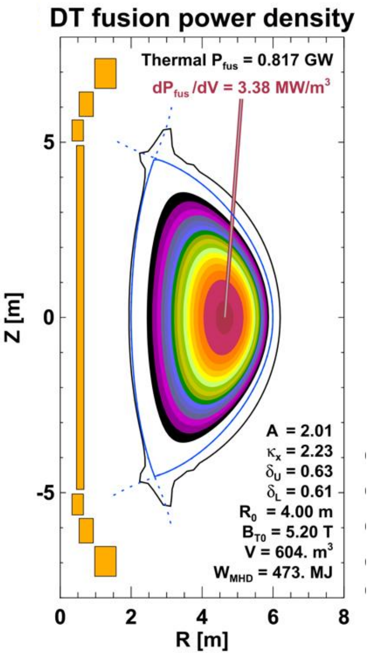
Spherical Tokamak Advanced Reactor (STAR) design project

Project ongoing at PPPL to understand FPP related physics and engineering challenges, advantages/disadvantages for low-A/ST reactor & to complement advanced tokamak FPPs



[J. Menard et al., IAEA FEC 2023]





Motivation for this work

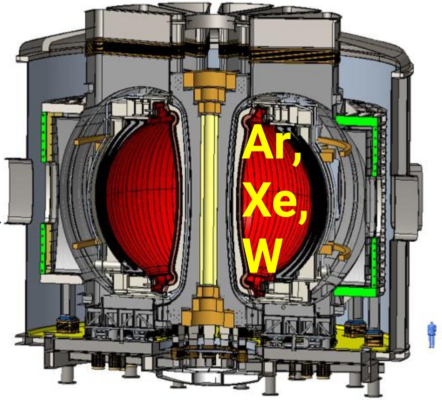
- Power radiation requirements for STAR
- Radiation asymmetries
- Centrifugal effects on radiation distribution

P_{fus} ~ 0.5 - 1.5 GW,
P_{heat} ~ 210 MW
(160 P_α, 50 P_{aux})

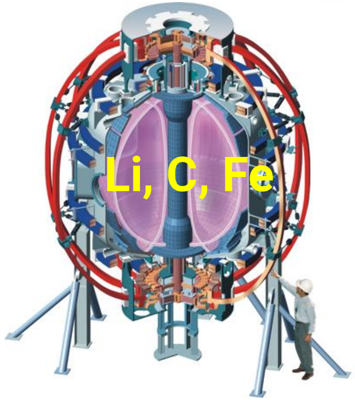
Range of impurities considered for the study: STAR & NSTX cases

- Both low- and high-Z materials used as PFCs or seeded impurities
  - Low Z: Li, C
  - High Z: Fe, W
  - Noble gases: Ne, Ar, Kr, Xe
- Important to understand the radiated power from both unwanted (metal) and desired (seeded) impurities

STAR
(FPP like device)
P_{aux}~ 50 MW



NSTX-U
(Present-day device)
P_{aux}~ 15 MW



[J. W. Berkery et al., Nuclear Fusion 2024]

Outline

- Impurities contribute differently to the radiated power for present devices and FPP
  - New Power Radiation Analysis Module (PRAM) calculates radiated power density (Prad) for STAR and NSTX
- Cooling rates affect the radiated power distribution due to temperature dependence
  - Radiation found to peak off-axis in certain cases
- Radiation asymmetries observed under the effect of rotation
  - Observed for both NSTX and STAR cases
  - High Z impurities are affected more compared to low Z
- Synchrotron radiation is considerable for FPP like plasma

Radiated power density is estimated in PRAM

- Self consistent calculation following Quasi-neutrality condition

$$n_e = n_D + n_T + \sum n_Z \langle Z \rangle (T_e)$$

$\langle Z \rangle (T_e)$: average charge state

- Radiated power density estimation, P_{rad}

$$P_{rad} = n_e^2 \left(C_D L_D + \sum C_Z L_Z \right)$$

$C_Z = n_z/n_e$ (impurity fraction), L_Z : cooling rates (W m^3),

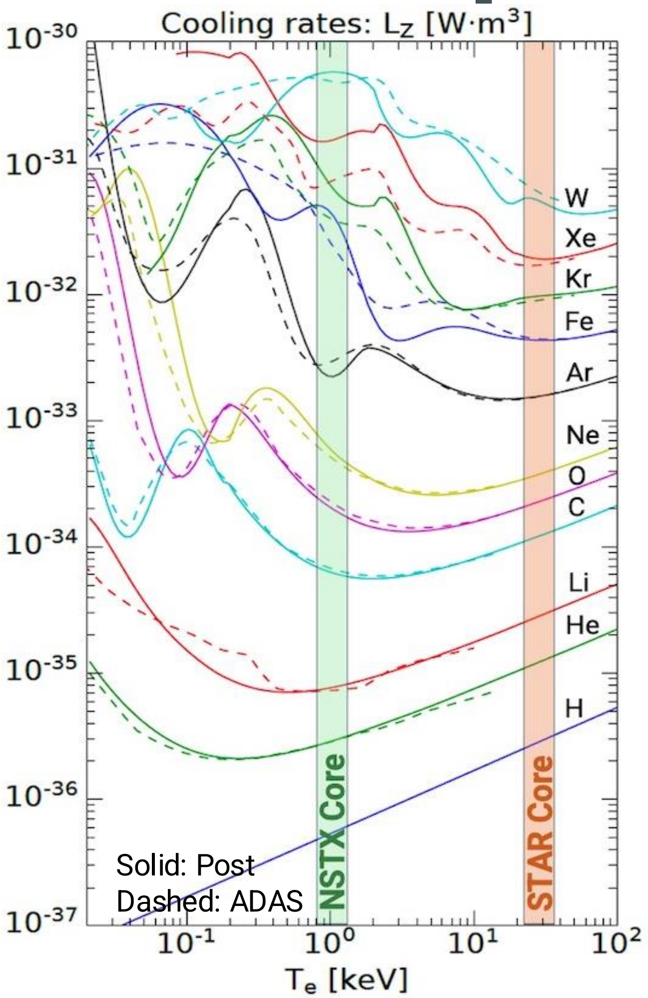
$L_D = 5.35 \times 10^{-37}\, T_e^{1/2}$ [keV] W m^3 (Hydrogenic)

- Atomic data included from ADAS database[1] and Post[2] for a range of impurities
- 2D distribution using n_e, T_e, n_Z profiles & equilibrium files
- Calculates effect of toroidal rotation on P_{rad} based on the centrifugal force induced charge separation
- Developed in OMFIT[3], for easy use and application to range of devices

[[1]Henderson PPCF 2017] , [[2]Post D et al. 1977 Atomic Data and Nuclear Data Tables 20 397– 439], [[3]Meneghini et al., NF 2015]

Cooling rates (L_Z) play important role to estimate radiated power density profiles

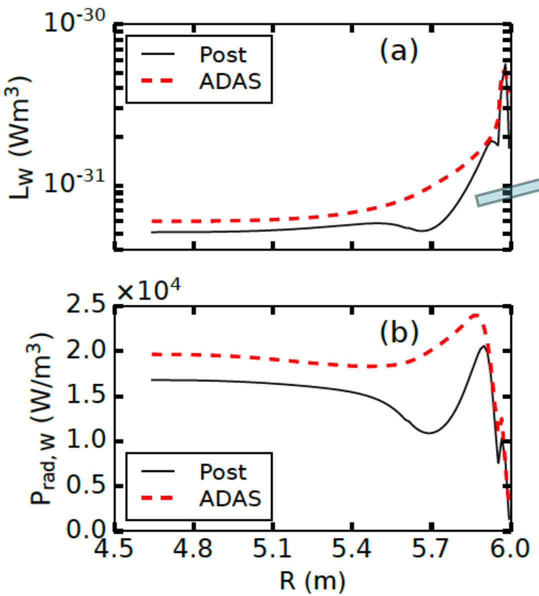
- PRAM can estimate P_{rad} using two sets of cooling rates:
  - ADAS database and Post
  - Cooling rates include contributions from
    - Bremsstrahlung
    - Radiative recombination
    - Impurity line radiation
- Coronal approximation is considered
  →balance between electron impact ionization and radiative recombination → L_Z are functions of T_e only
- Cooling rates from Post and ADAS are similar for low Z but differ for high Z

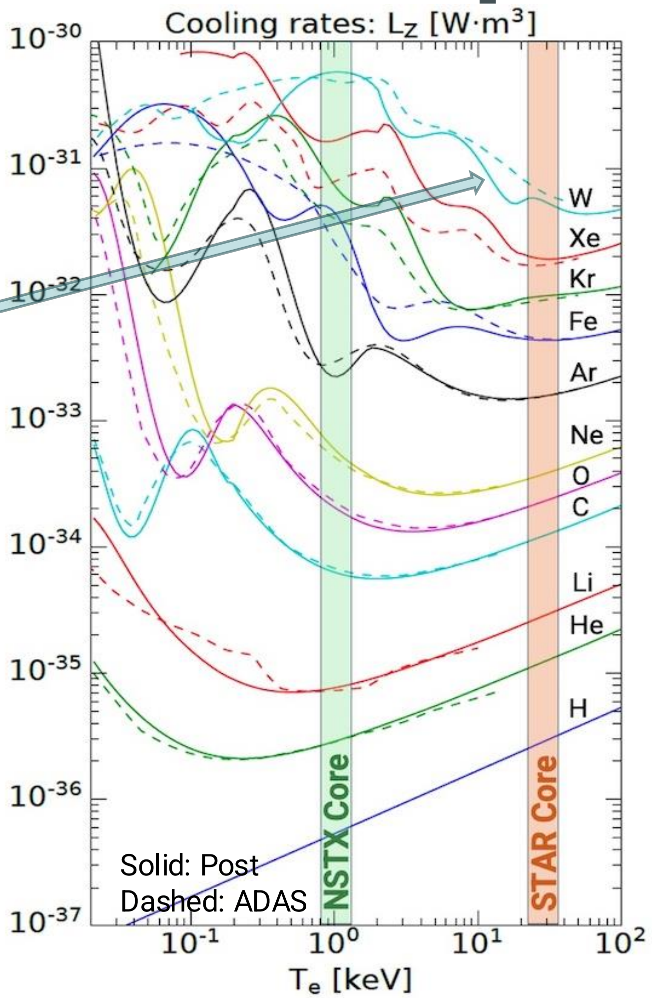


[*Henderson PPCF 2017]
[**Post D et al. 1977 Atomic Data and Nuclear Data Tables 20 397– 439]

Cooling rates (L_Z) play important role to estimate radiated power density profiles

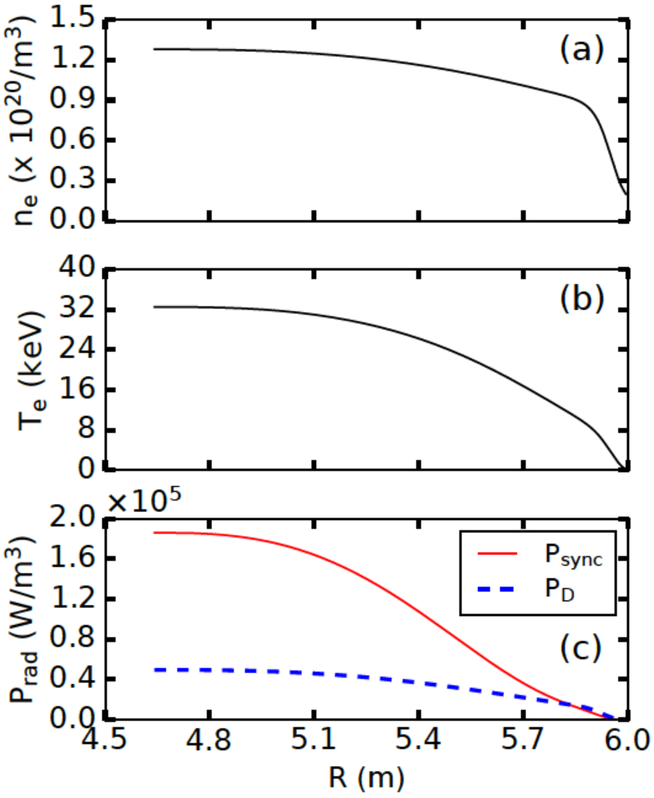
W radiated power density distribution for STAR





$P_{rad,W}$ is higher for ADAS than for Post, also it peaks in the edge

Synchrotron radiation is considerable for STAR



$$P_{sync} = \int C(R_w)(n_e/a)^{1/2}\,(\boldsymbol{T_e B})^{\boldsymbol{5/2}} M(T_e)\left(1+\frac{18}{A\sqrt{T_e}}\right)^{1/2} dV^*$$

Strongly depends on T_e and B

$B_{T,0}$ ~5.2 T for STAR

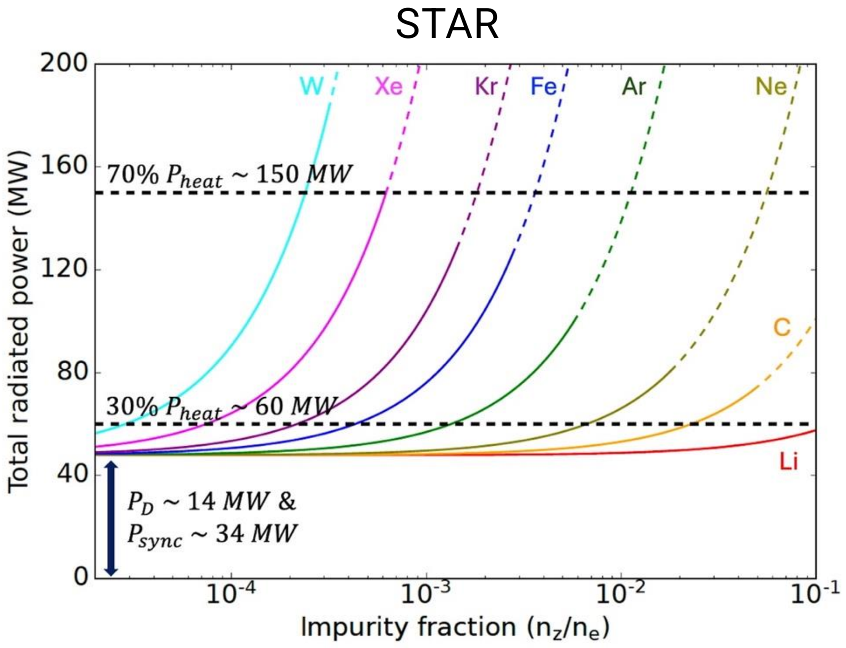
$C(R_w)$= 2.1 x $10^{-7}(1-R_W)^{1/2}$, R_w (wall reflection coef.) assumed to be 0.

$M(T_e) = (1 + 1.930/\mu)/\ (1 - 0.581/\mu)$, $\mu = mc^2/\ T_e$

P_{sync}~ 34 MW for STAR

[*F. Albajar et al., NF 2009]

Tolerable concentration levels of impurities for STAR determined by radiation and fuel depletion



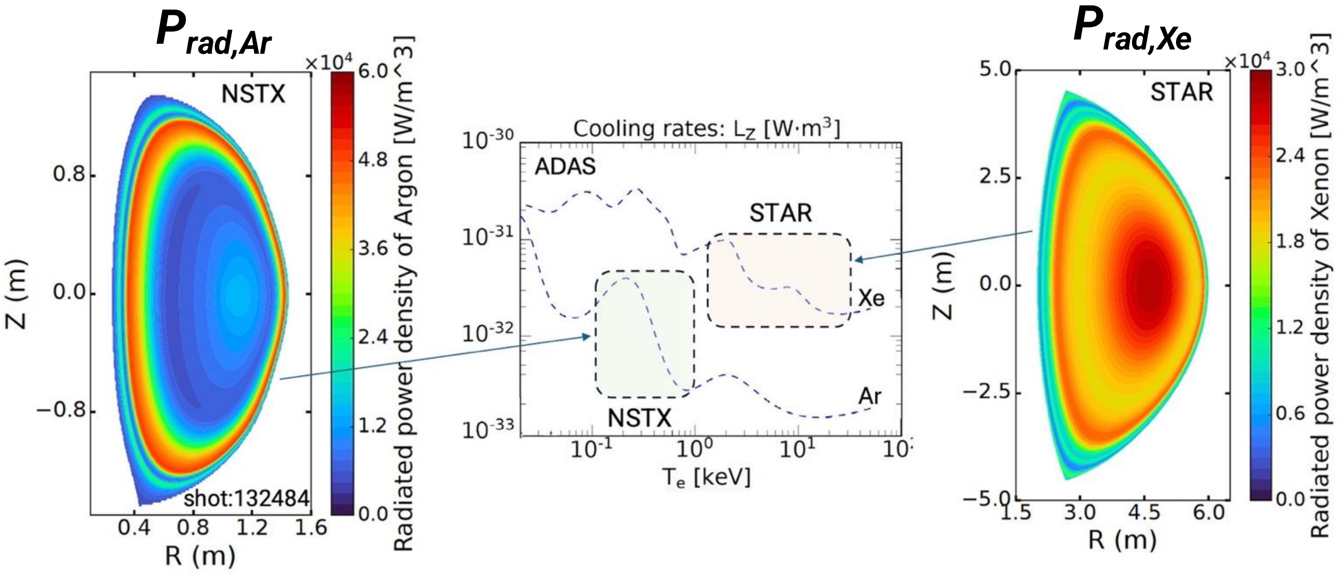
- f_{rad} ~ 30 % for STAR (P_{heat}~210 MW)
- Lithium divertor design exploited to handle 120 - 150 MW of heat flux
- Desired noble gases:
  c_{Xe}~ 1x 10^{-4}, c_{Kr}~ 2.3×10^{-4}, c_{Ar}~ 1.3×10^{-3}
- Undesired metal:
  c_W~ 2×10^{-5}
- Impurity conc. chosen based on 0D model of fuel depletion*

[K. Shah et al., under review PPCF]

[*T. Putterich et al., Nucl. Fusion 2019]

Effect of cooling rates on impurity radiation for STAR and NSTX

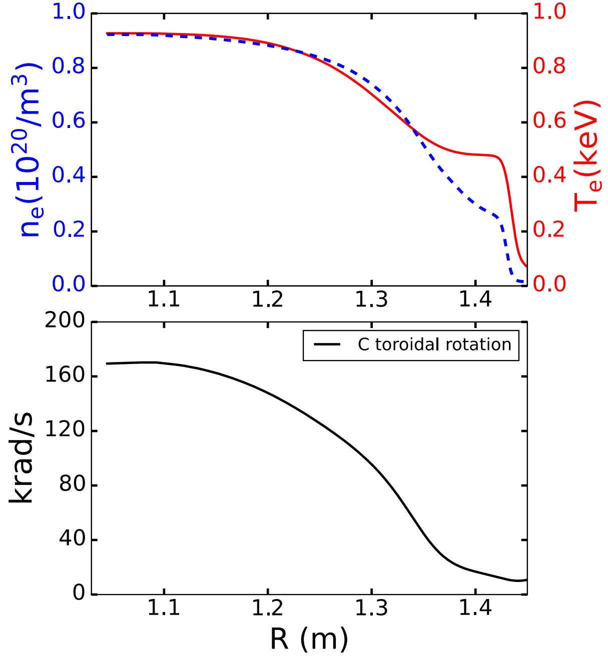
- Xe in the core for STAR with off axis radiation in the edge
- Ar radiated in the edge for NSTX
- Impurity transport is not included which can significantly change the distribution



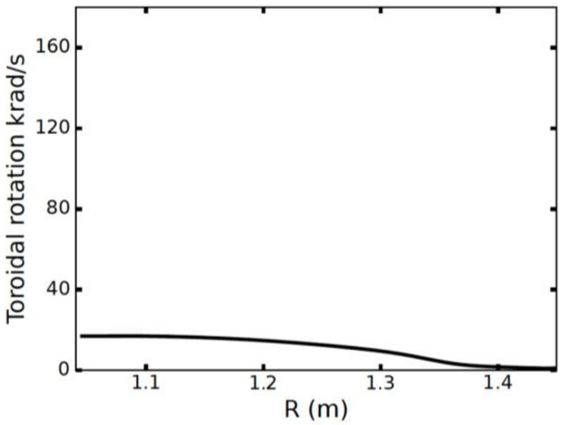
[K. Shah et al., under review PPCF]

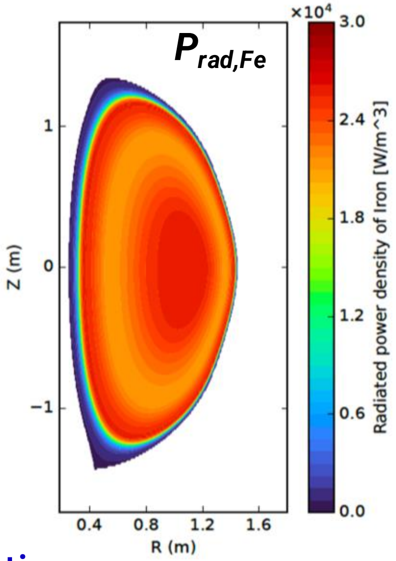
Centrifugal effect on radiated power density of Fe in NSTX

NSTX case: 132484 @ 0.695 s



Max. rotation : 170 krad/sec





High toroidal plasma rotation

⇩

Strong centrifugal effects

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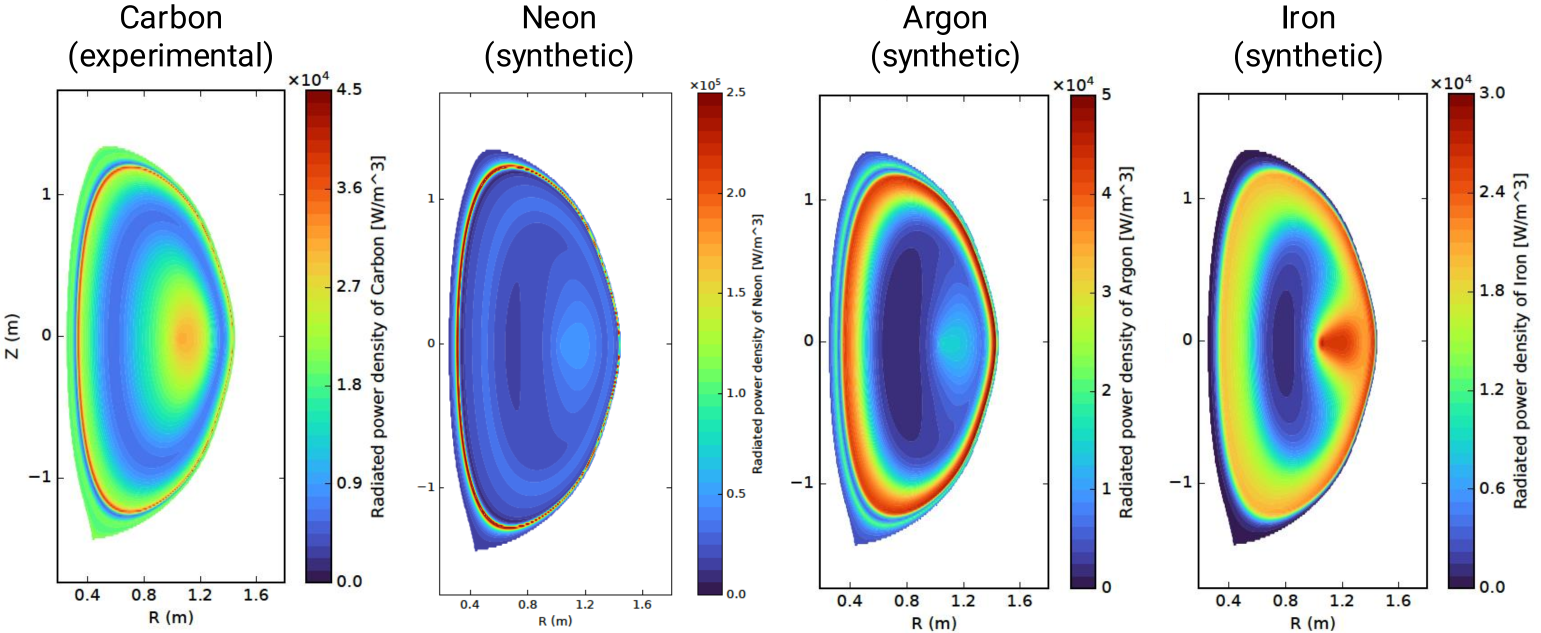
Density depletion on HFS with respect to LFS midplane

High Z impurities are more affected by the rotation in NSTX

NSTX case: 132484 @ 0.695 s



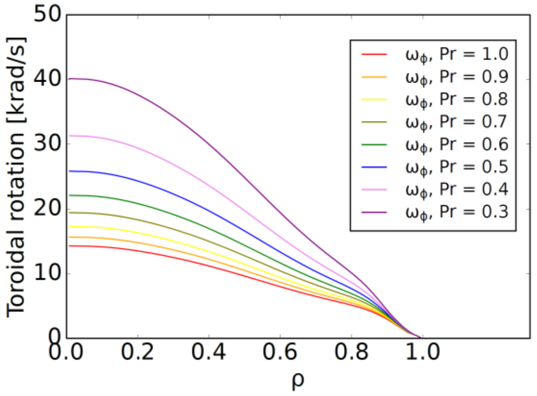
- Centrifugal effects due to rotation are significant for high Z impurities*
- Impurity density enhancement on the LFS and depletion in the core
- Further investigations are ongoing

[*L. Delgado et al., RSI 2014]

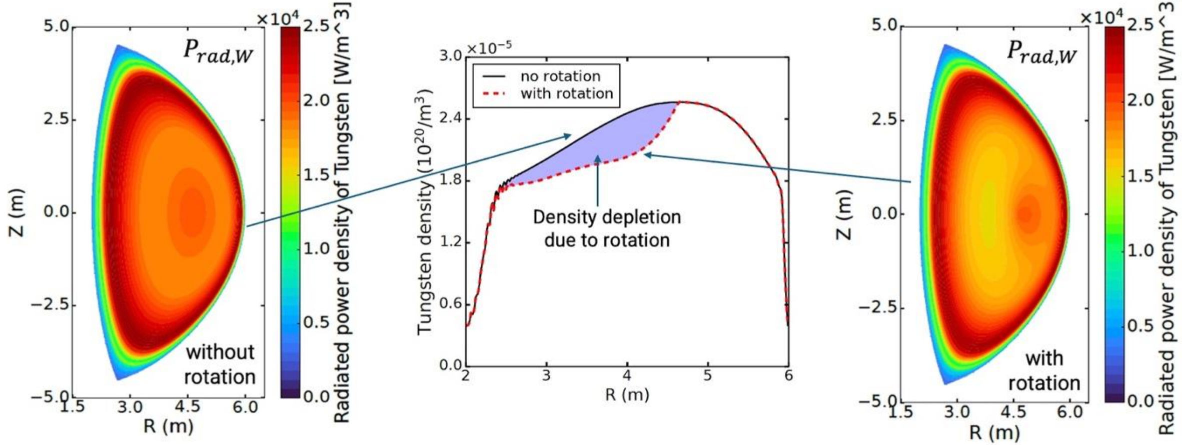
Centrifugal effect on radiated power density of W in STAR

Toroidal rotation estimated for STAR using TRANSP*

NBI with 50 MW of 0.7 MeV



Rotation causes around 10% depletion of W density in HFS in STAR



- Due to large plasma volume, rotation is much lower in STAR than in case of NSTX
- Radiation asymmetry seems to be low to cause major radiation asymmetry in STAR, however, impurity transport is yet to be included to get better understanding

[K. Shah et al., under review PPCF]

[*A. Pankin et al., CPC 2025]

Summary

Radiated power density distribution is

- Investigated for a range of impurities for STAR and NSTX plasma using PRAM
- Dependent on impurity cooling rates due to temperature,
  - Found to be off-axis in some cases
  - Differences seen between data from ADAS and Post
- Showing that Xenon can be a good candidates for STAR like FPP for core radiation
- Showing f_{rad} ~ 30% for STAR compared to much higher fractions in other FPPs
- Found to have asymmetries due to rotation:
  - Significant for NSTX, small but non-negligible for STAR

Future work

Continuing the efforts

- STAR has been good platform to investigate FPP related challenges in context to power exhaust issue
- Include effect of impurity transport together with rotation in STAR
- Investigate more data from NSTX especially with high rotation
- NSTX-U experiments will give further understanding of impurity radiated power distribution, off-axis effects and effect of rotation on radiation asymmetries.