NSTX-U

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Synthetic capability for the study of poloidal impurity asymmetries in NSTX-U

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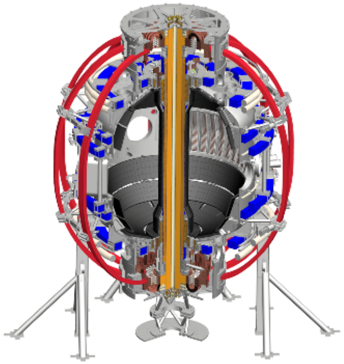


Abstract

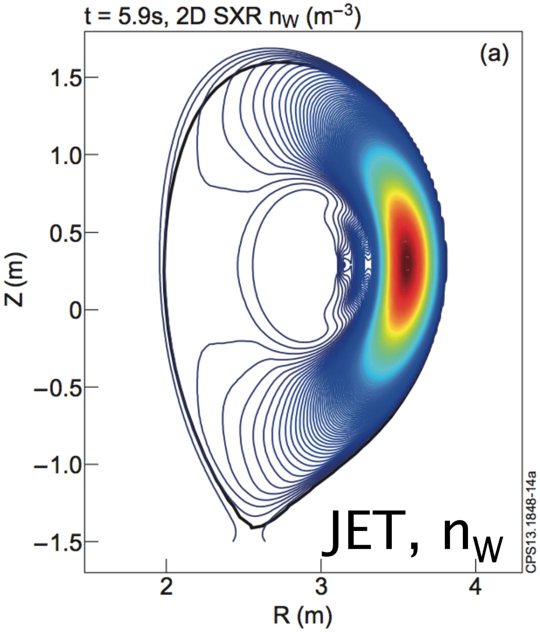
A new synthetic capability has been built to compute the two-dimensional mapping of impurity density asymmetries in NSTX-U. This technique relies on flux-surface quantities like electron and ion temperature ($T_{e,i}$) and rotation frequency ($\omega\phi$), but finds the 2D electron, deuterium and carbon density profiles self-consistently assuming the presence of a poloidal variation due to centrifugal forces. The solution for the electrostatic potential for the measured carbon density (n_C) and central toroidal rotation using NSTX data will be shown and compared with the values derived using Wesson's formalism which assumed that the main intrinsic impurity was in the trace limit. The presence of O, Ne, Ar, Fe, Mo and W are considered at the trace limit ($n_Z<Z>^2/n_e<1$) with very small changes to quasineutrality and Z_{eff}. The few assumptions made considered a zero electron mass, a deuterium plasma, a trace impurity with charge "Z" given by coronal equilibrium ($<Z>=<Z>(T_e)$) and equilibrated ion temperatures (e.g. $T_D=T_C=T_Z$). This synthetic capability will help in the understanding of asymmetries before tearing modes onsets as well as aid the design of new diagnostics (e.g. ME-SXR, XICS, Bolometers, XUV-spectrometers, etc) for NSTX-U.

Background

- With the selection of W for the divertor in ITER, understanding the sources, transport, confinement of high-Z impurities is crucial to ITER success.

- It is imperative to address key issues associated with impurity sources, core transport and high-Z impurity accumulation.

- Controlling Z-transport to avoid accumulation is necessary to achieve and maintain high fusion performance in the presence of high-Z PFCs.

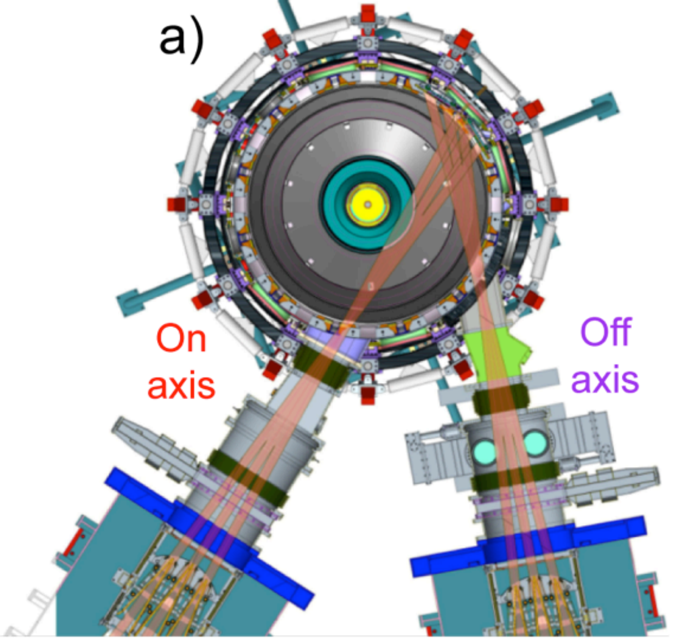


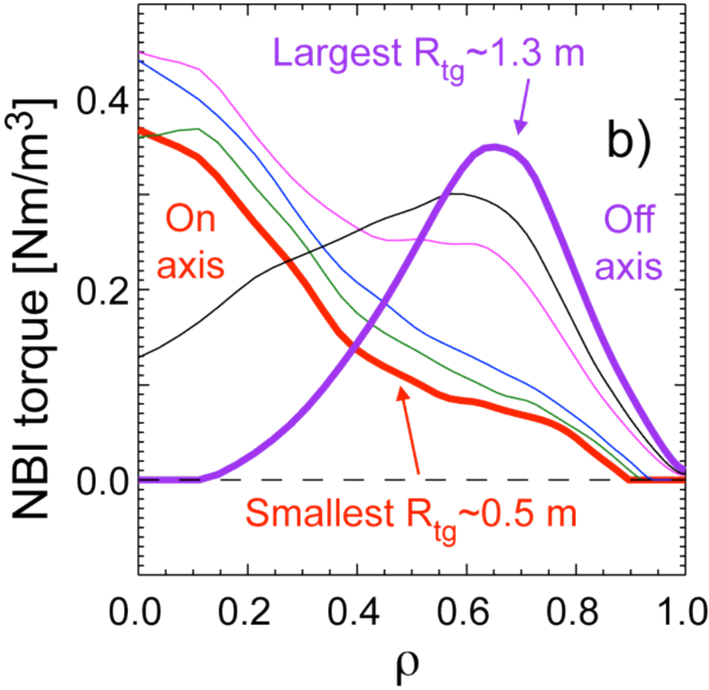
- Understanding poloidal asymmetries and its role for the “outward convection” of impurities is highly desirable.

- The impact of the plasma composition on the linear and non-linear stability of gradient driven modes on particle and heat transport has to be assessed, with particular emphasis on the role of the heavy impurities.

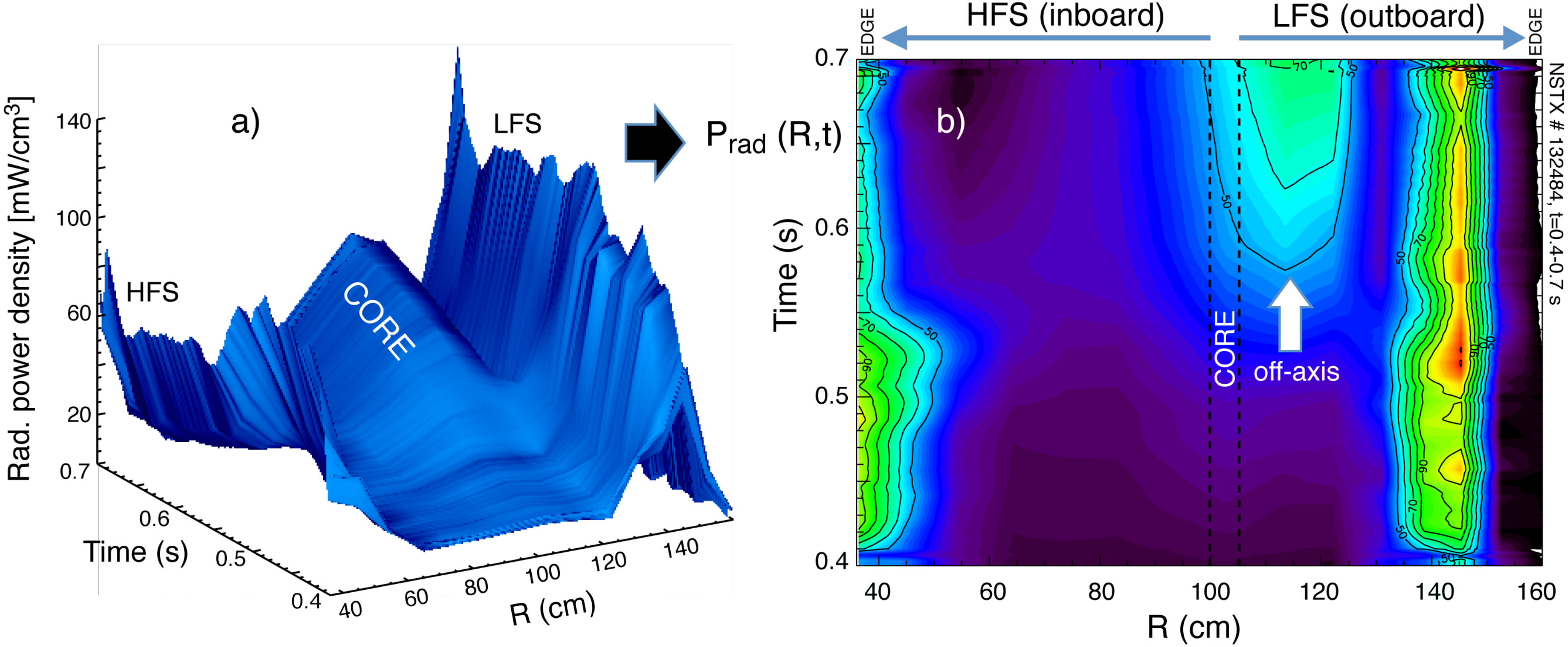
Motivation

- Off-axis NBI have been implemented with the main goal of broadening J & p profiles and study effects on confinement and stability
- Torque will be imparted <u>also</u> at mid-radius possibly increasing the MACH-corrections due to centrifugal forces
- Understanding poloidal asymmetries and its role for the “outward convection” of impurities is highly desirable.
- An electrostatic potential $(\Delta\varphi)$ is setup mainly between electron, deuterium ions and low-Z impurities (e.g. C, B).
- The impact of a reduction in the underline turbulence due to the $E_{\Delta\varphi}$xB shearing rates should be explored
- Impact operation with high-Z PFCs.





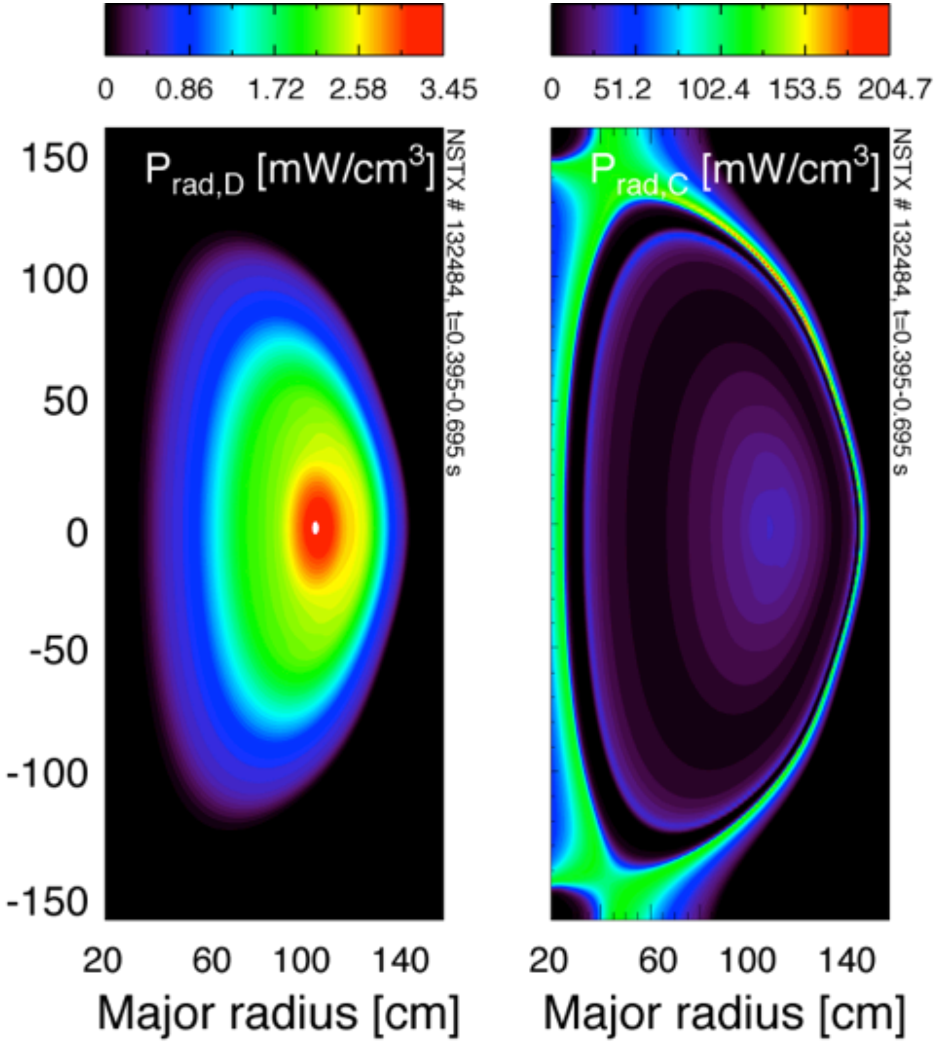
Asymmetry in the P_{rad} density with possible off-axis accumulation has been measured in NSTX



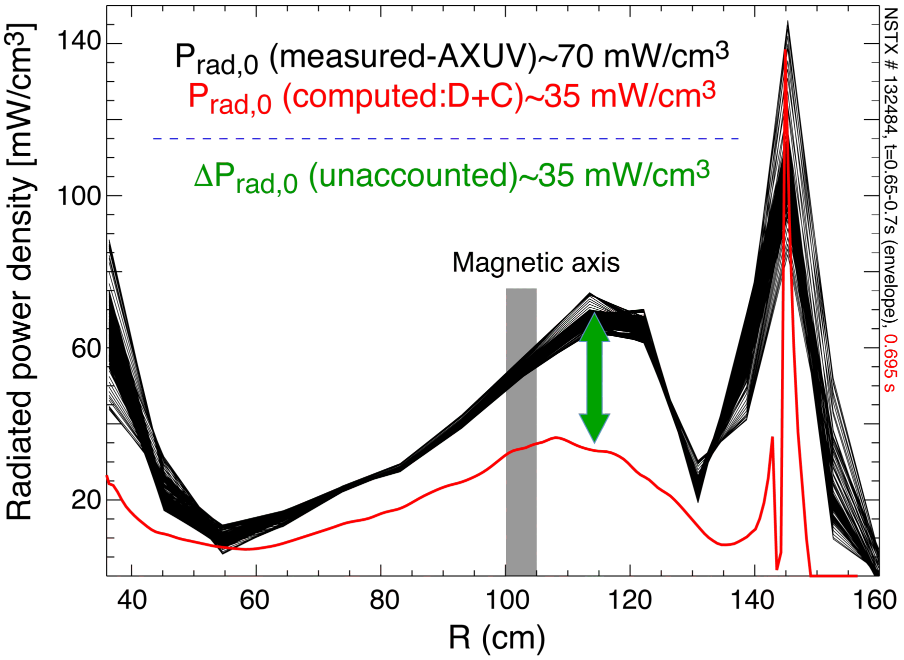
- Experimental P_{rad} profile is asymmetric: off-axis peaking !
- P_{rad} at the LFS is higher than @ core possibly due to C and Z’s accumulation
- <u>For t~0.7 s</u>: $P_{rad,0}$~70 mW/cm^3
  $P_{rad,edge}$~60-140 mW/cm^3 (most probably is much higher)

Measured power density and asymmetry can not be explained only as a function the D+C content

Computed P_{rad} profiles for H and C



- ○ $P_{rad,C,0}$ ~10x$P_{rad,H,0}$
- ○ $P_{rad,C,0}$ is slightly asymmetric
- ○ ½ of the measured P_{rad} in the core is unaccounted for (shortfall of computed $P_{rad,D}+P_{rad,C}$)
- ○ Peaking factor is also stronger

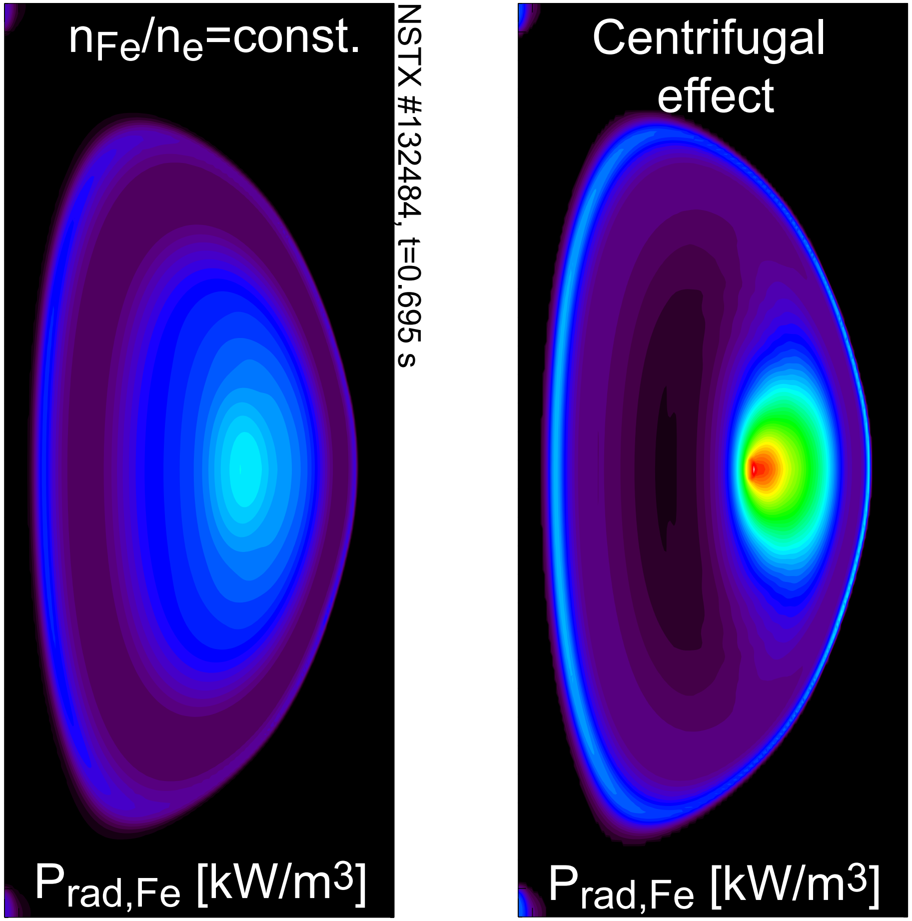


Challenge and goals

- Compute 2D mapping of flux-surface quantities like $T_{e,C}$ and $\omega\phi$
- Find $n_{e,D,C}(R,t)$ self-consistently assuming presence of a poloidal variation due to centrifugal forces.
- Estimate electrostatic potentials ($\Delta\varphi$) and compare with derived using Wesson's formalism.
- Compute 2D mapping of n_Z asymmetries and P_{rad} in NSTX-U.
- <u>Contribute understanding of</u>:

a) Medium- & high-Z asymmetries
b) Reduction of Z-peaking
c) Reduction of turbulence ($E_{\Delta\varphi}$xB)
d) Radiation effects before TM-onsets
e) Aid the design of new NSTX-U diagnostics (e.g. ME-SXR, XICS, Bolometers, XUV-spectrometers, etc)

L. F. Delgado-Aparicio, et. al., RSI, **85**, 11D859, (2014).
L. F. Delgado-Aparicio, et. al., in-prep., NF, (2017).



Formalism

- The transport equations retaining strong rotation ($V_\phi \sim V_{th}$) were first derived by Hinton and Wong [PoF'85] via extension of Hazeltine's original NCLASS treatment [Plasma Phys.'73].
- The density at a given flux surface ψ can be written as (see E. Belli, PPCF'09):

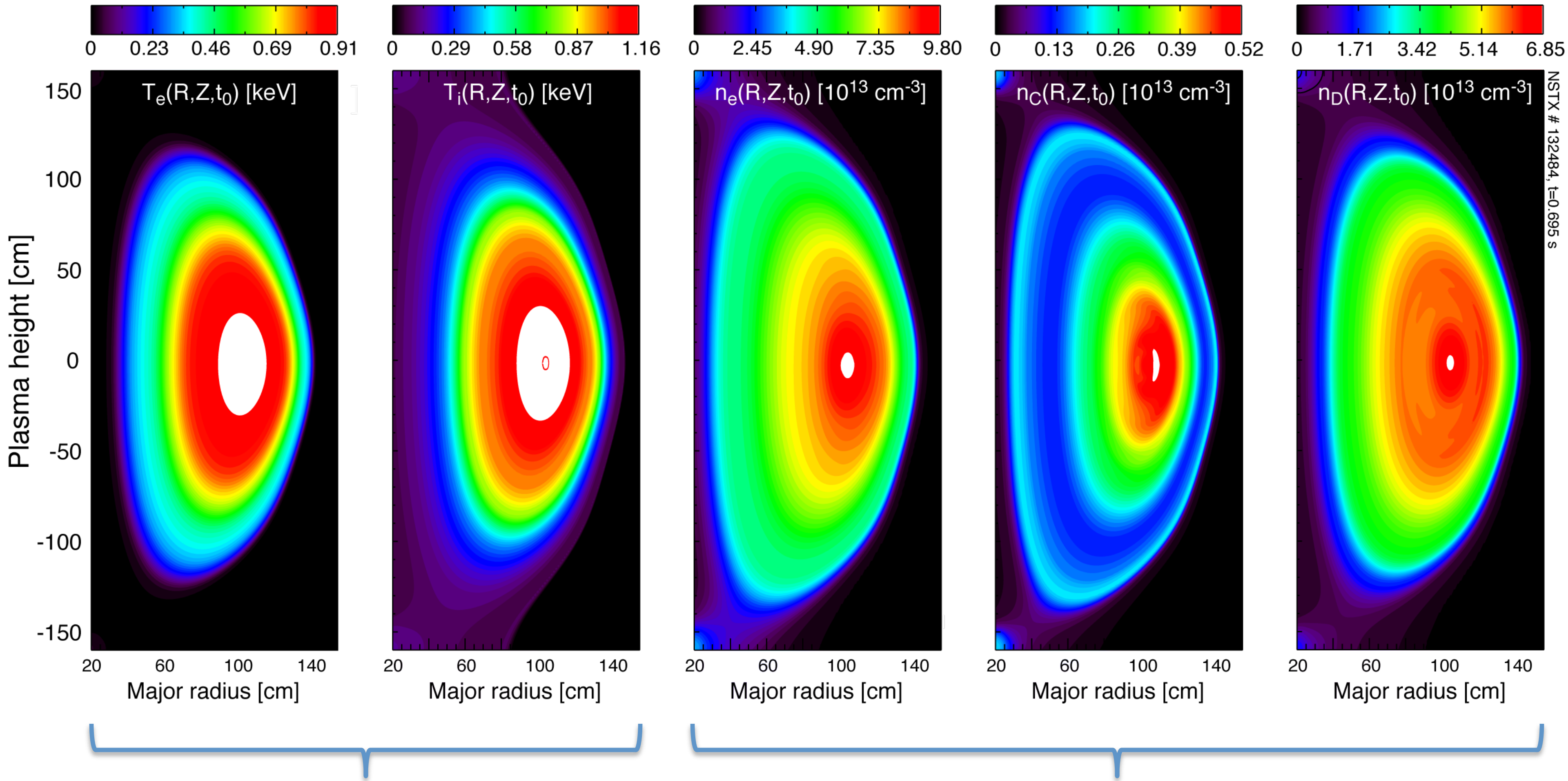
$$n_j(\theta) = n_j(\theta=0)\exp\left(\frac{\omega_0^2[R^2(\theta)-R^2(\theta=0)]}{2V_{th,j}^2} - \frac{eZ_j\Delta\varphi(\theta)}{T_j}\right)$$

- $n_j(\theta=0)$ is the impurity density profile at the equatorial-midplane
- As a result of quasi-neutrality, $\Delta\varphi(\theta)$ is a poloidal electrostatic potential generated to balance the density asymmetries ($\Delta\varphi(\theta)=\varphi(\theta)-\varphi(\theta=0)$).

- **STEPS**:

i. Assume T_j and ω_0 are flux surface functions (ψ).
ii. Find n_D profiles using the experimental values of n_e and n_C (@ midplane first)
iii. Solve the quasi-neutrality condition for $\Delta\varphi(\theta)$ sequentially at each value of θ
iv. Assume arbitrary n_Z profiles at trace-limit ($\alpha_Z=\delta Z_{eff}=\langle Z\rangle^2 n_Z/n_e \ll 1$): $n_j(\theta=0)$
v. Map particle density profiles asumming also $\langle Z\rangle=\langle Z\rangle(T_e)$
vi. Map radiated power density using: $P_{rad}=n_e n_Z L_Z(T_e)$

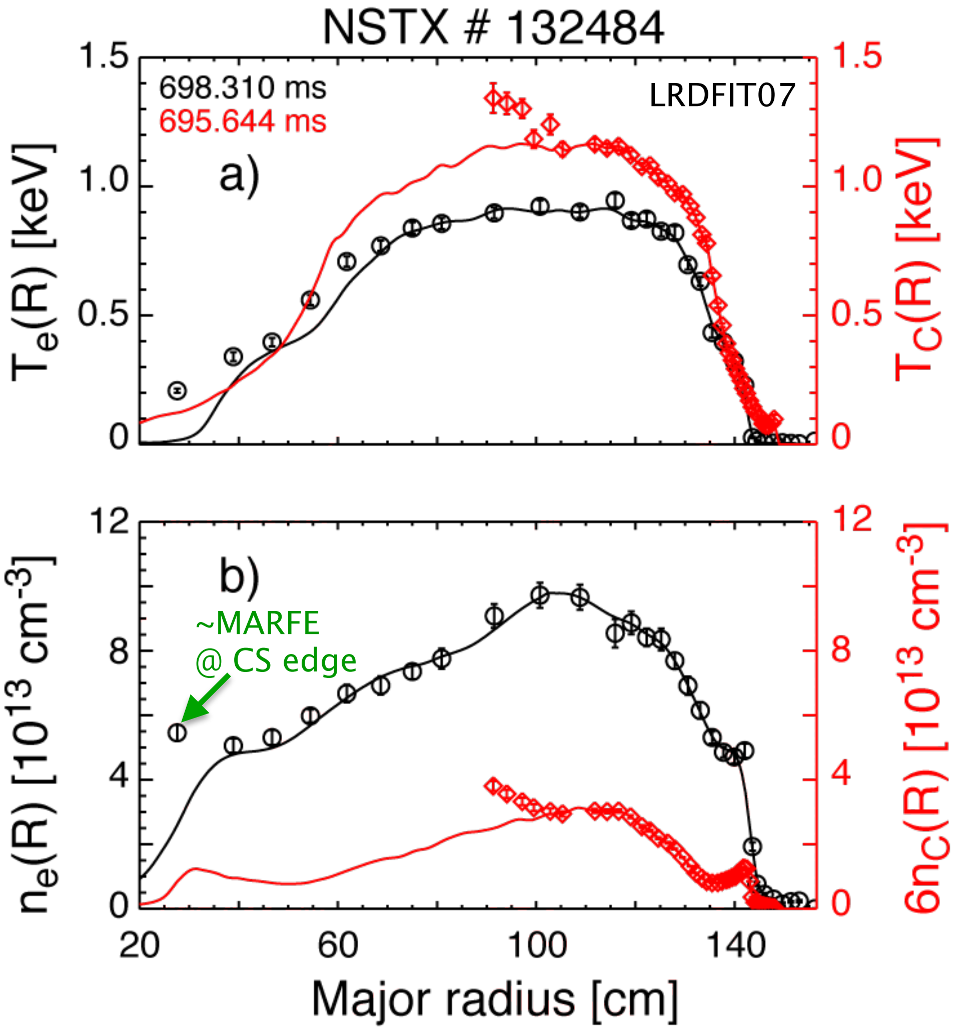
Mapping of mid-plane data in 2D (R,Z) is needed to account for centrifugal asymmetries in n_Z



$$T_{e,i} \equiv T_{e,i}(\psi)$$

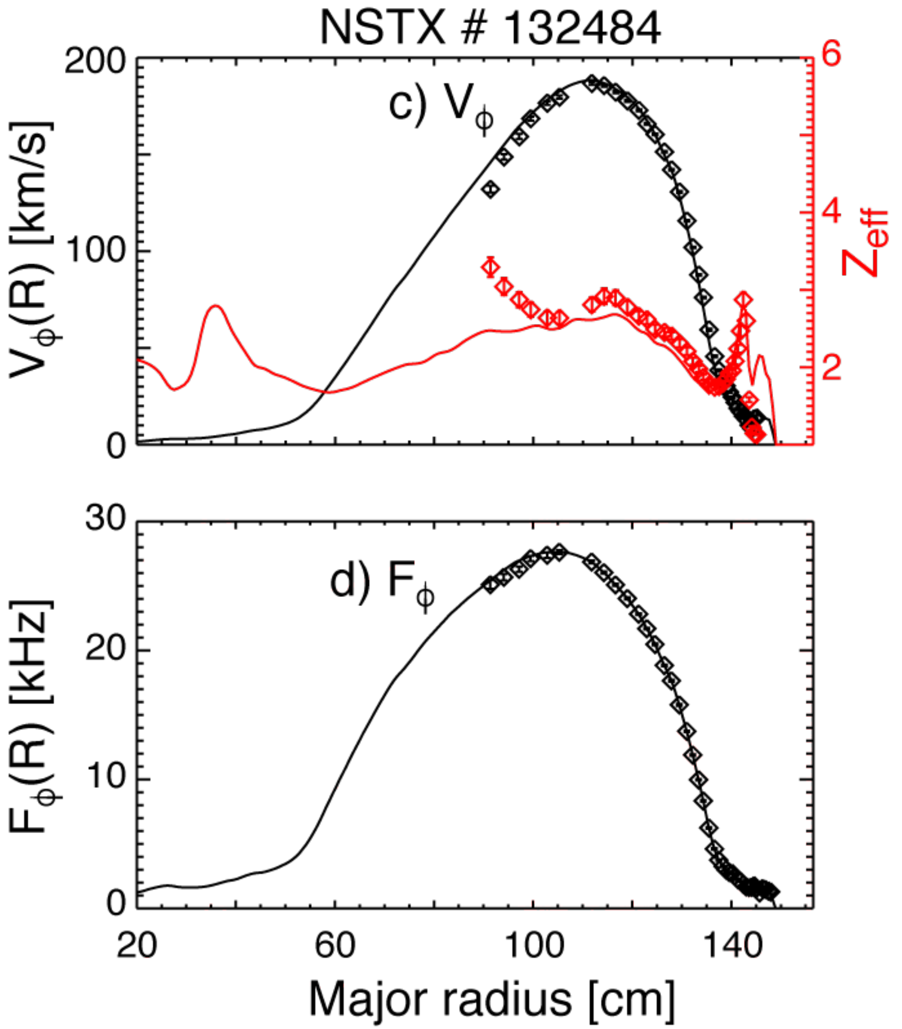
$$n_j = n_{j,0}\exp\left(\frac{\frac{1}{2}m_j\omega^2(R^2-R_0^2)-eZ_j\Delta\varphi}{k_BT_j}\right)$$

Mapping of mid-plane data agrees well with experimental MPTS and CHERS data



~MARFE @ CS edge

MPTS: n_e, T_e



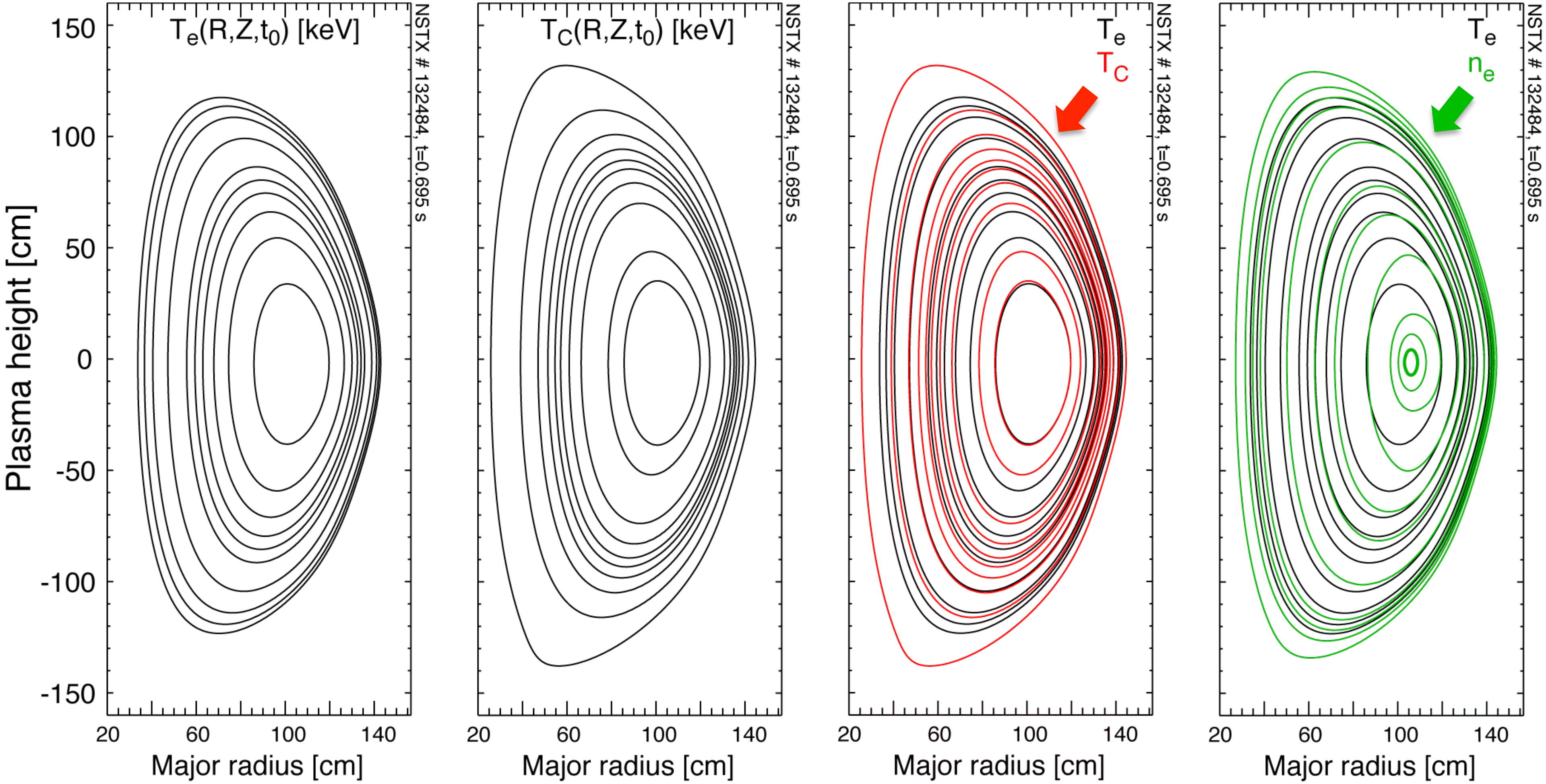
CHERS: n_C, T_C, V_ϕ

$T_{e,C}$ are mapped on $\Psi(R,Z)$ while n_e (MPTS) shows small asymmetry due to centrifugal effects

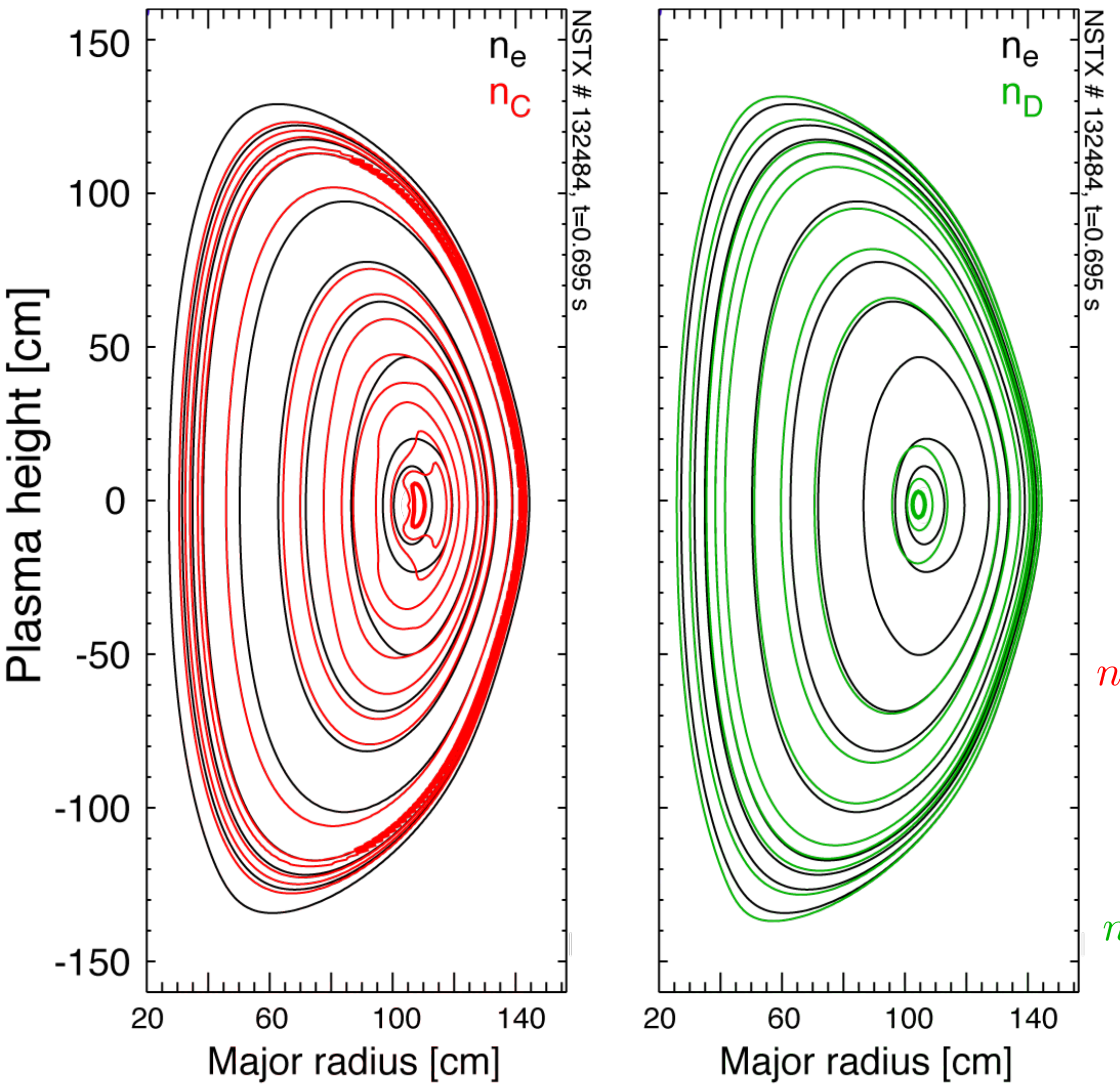
$T_{e,C}$ are mapped on $\Psi(R,Z)$

SUPERIMPOSED

Core n_e departs from $\Psi(R,Z)$



Measured n_C (CHERS) and inferred n_D ($\approx n_e - 6n_C$) show core effects from centrifugal effects



New capability at NSTX-U finds n_e, n_D and n_C profiles self-consistently assuming the presence of a poloidal variation due to centrifugal forces.

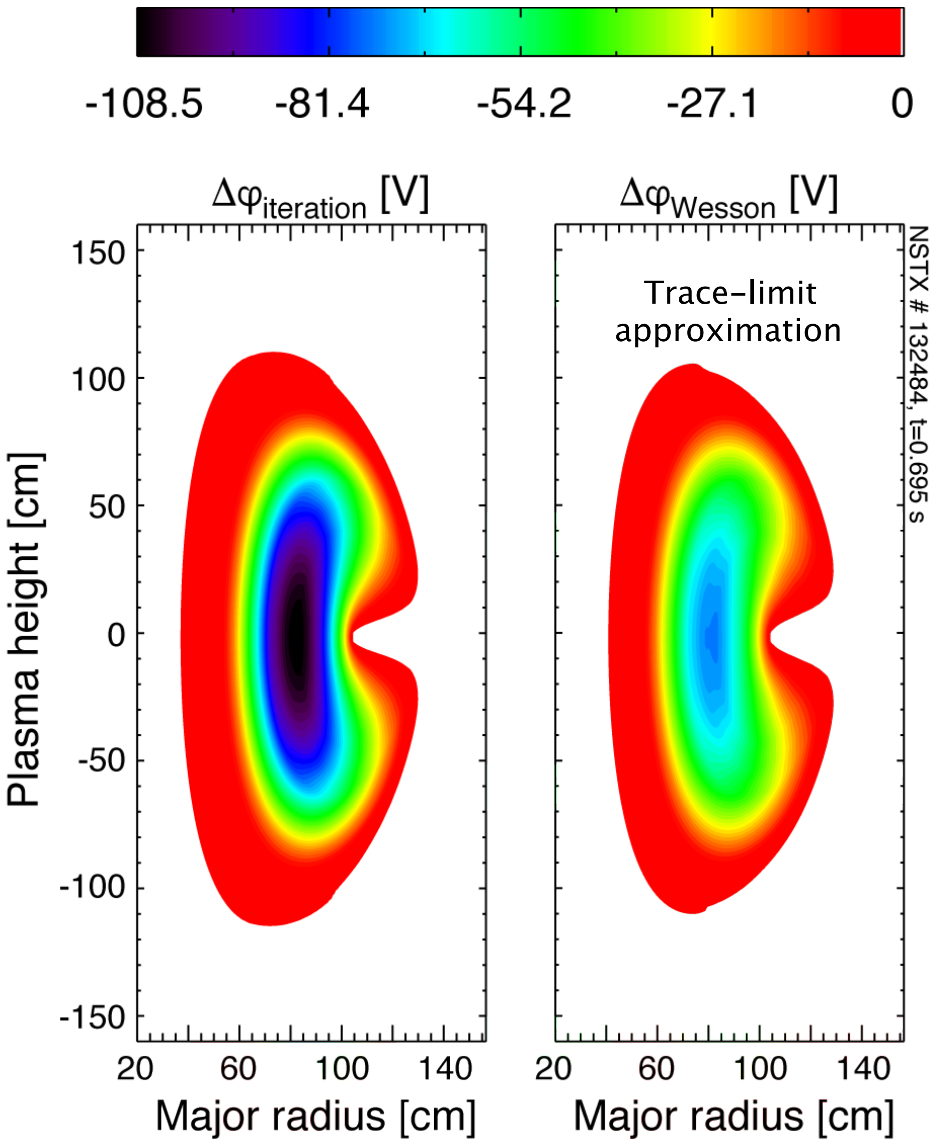
$$n_e \approx n_{e,0} \exp\left(\frac{e\Delta\varphi}{k_B T_e}\right)$$

(considering a zero electron mass)

$$n_C = n_{C,0} \exp\left(\frac{\frac{1}{2} m_C \omega^2 (R^2 - R_0^2) - 6e\Delta\varphi}{k_B T_C}\right)$$

$$n_D = n_{D,0} \exp\left(\frac{\frac{1}{2} m_D \omega^2 (R^2 - R_0^2) - e\Delta\varphi}{k_B T_D}\right)$$

Electrostatic potential (Δφ) from data is stronger than obtained using a trace-limit approximation

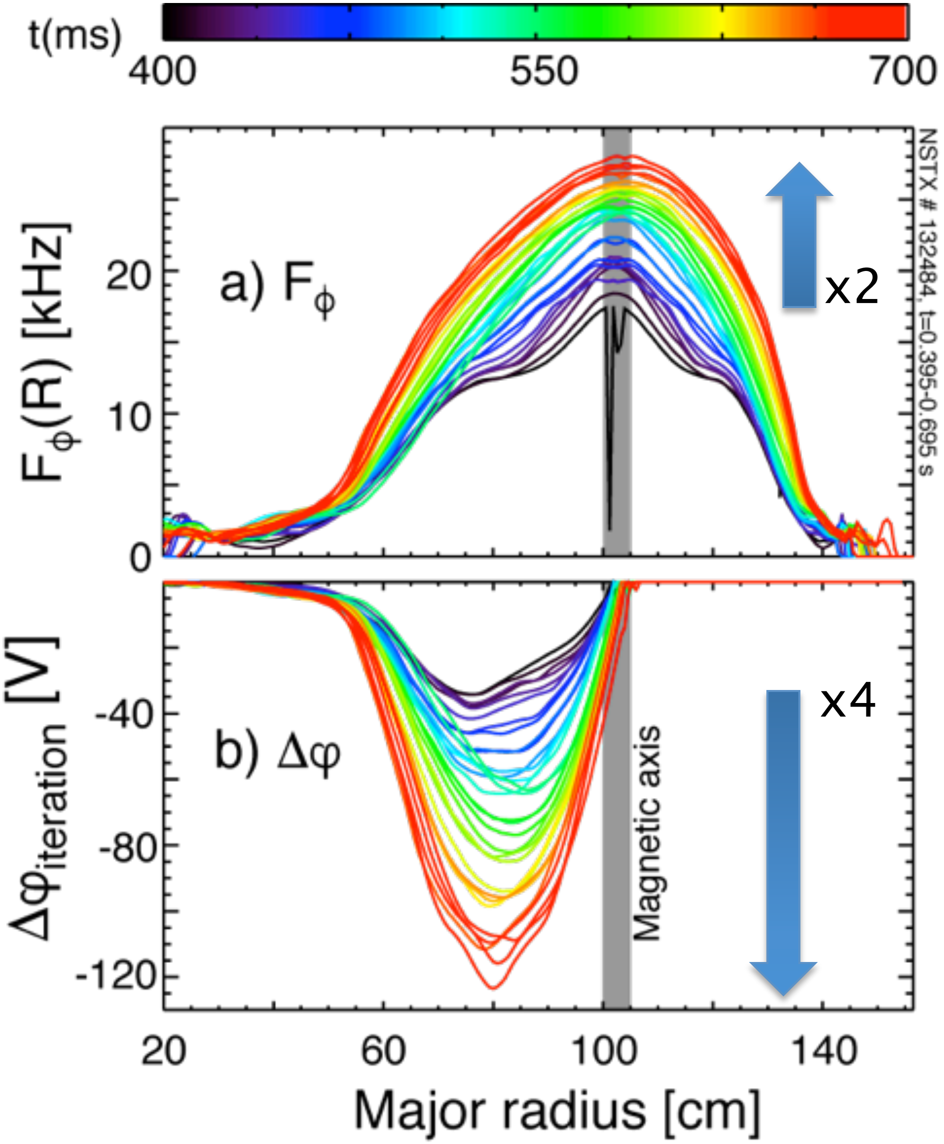


- The electrostatic potential obtained assuming that the main intrinsic impurity (Carbon) is at the trace limit ($\alpha_C=36n_C/n_e \ll 1$) reduces to:

$$\Delta\varphi|_{\alpha_Z \ll 1} = \frac{T_e}{T_e+T_i}\frac{m_i\omega^2}{2e}\left(R^2-R_0^2\right)$$

- In this limit the strongest Δφ is of the order of −60 V.
- Main intrinsic impurity is NOT at the trace-limit. Experimental value: $\alpha_{C,0}=36n_{C,0}/n_{e,0}\approx 1.57$.
- The Δφ-inferred from the experimental data is nearly twice as strong (for Fϕ~28 kHz).

Time-dependent solution for $\Delta\varphi$ shows in/out asymmetry evolution with strong ω^2 scaling

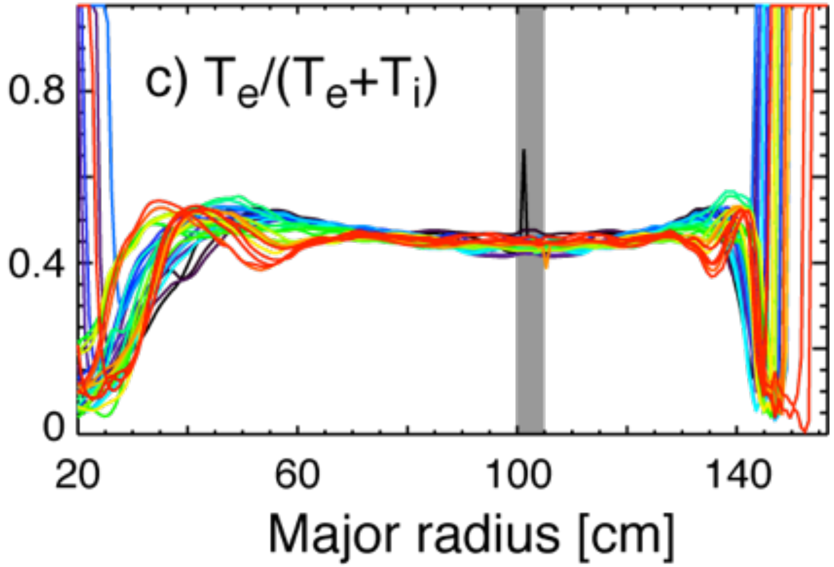


- The scaling of electrostatic potential with rotation frequency is not linear:

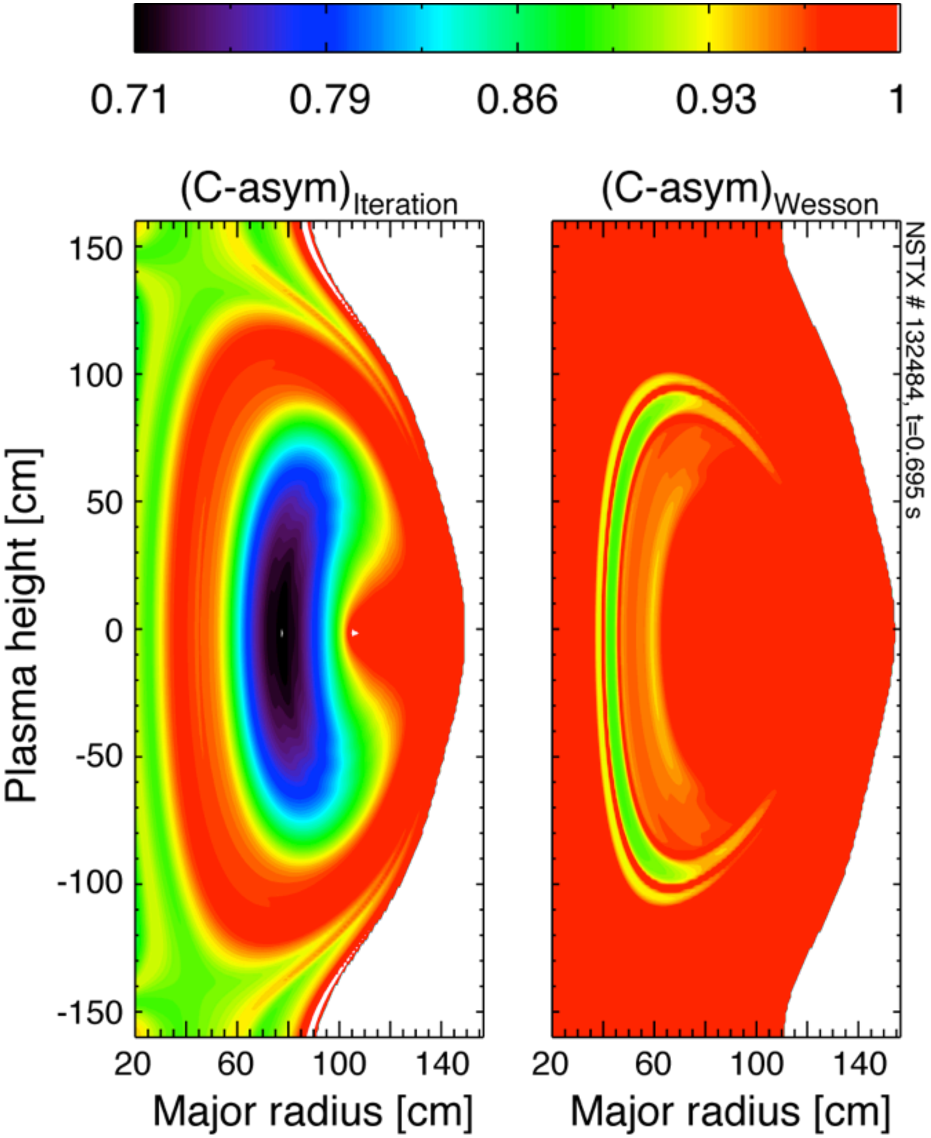
$$\Delta\varphi\big|_{\alpha_Z \ll 1} \propto \omega^2$$

- Experimental data (R=80 cm):

i. t=0.4 s, $F\phi$~12 kHz, $\Delta\varphi$~−32 V
ii. t=0.7 s, $F\phi$~22 kHz, $\Delta\varphi$~−120 V



Carbon asymmetry is twice as strong as in the trace limit ($\alpha_C=36n_C/n_e\ll 1$) approximation



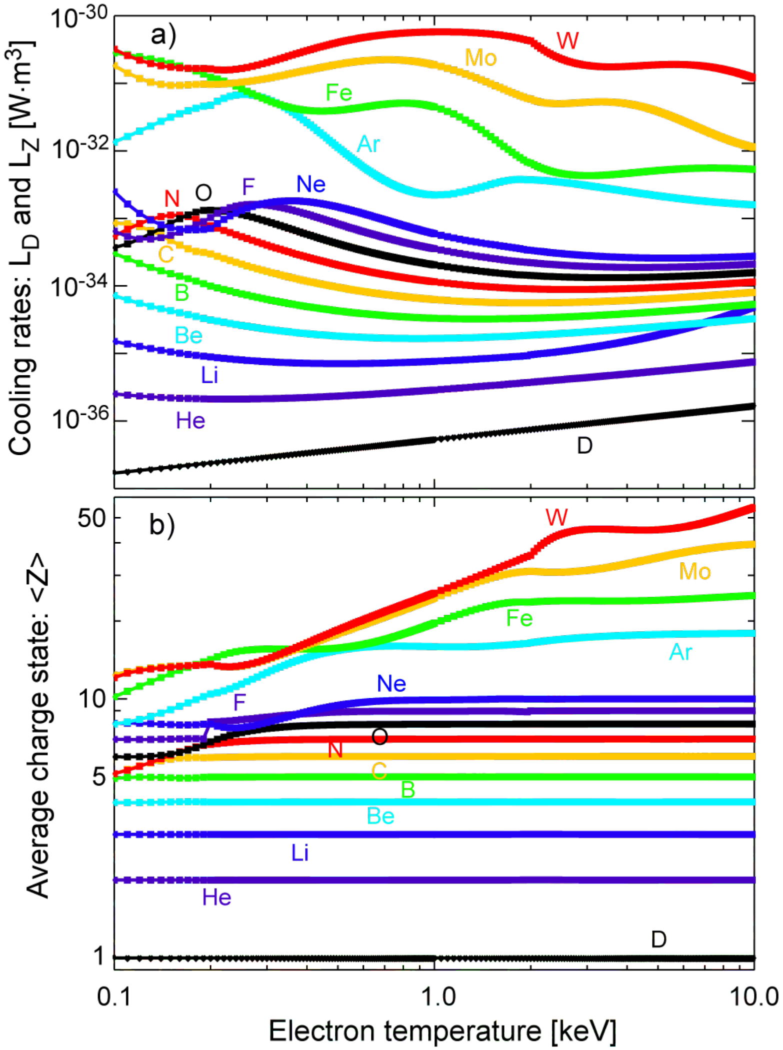
- In the trace limit approximation ($\alpha_C=36n_C/n_e\ll 1$) and with $T_i+T_e\approx 2T_e$, the C-asymmetry reduces to:

$$\frac{n_C}{n_{C,0}} \approx \exp\left[\frac{1}{2}\frac{m_C\omega^2(R^2-R_0^2)}{2T_C}\right]$$

- In this limit the C-asymmetry must be of the order of 10-15%.
- However, the main intrinsic impurity is NOT at the trace-limit.
- Experimental values of $\alpha_C>1$ (e.g. $\alpha_{C,0}=36n_{C,0}/n_{e,0}\approx 1.57$).
- The C-asymmetry is nearly three times stronger

Estimates of average charge state <Z> and P_{rad} density can be done using coronal equilibrium

D. E. Post, *et al.*, Atomic Data and Nuclear Data Tables, **20**, 397–439, (1977).



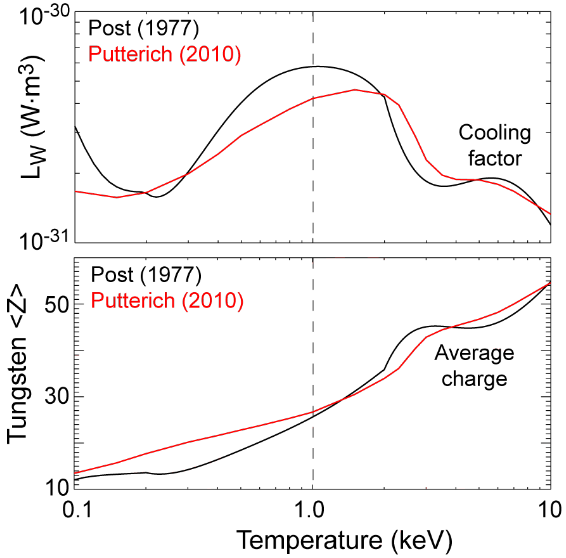
Parameterizing equations of interest for two-impurity plasma

$$1 = \frac{n_D}{n_e} + \langle Z_1 \rangle \frac{n_{Z1}}{n_e} + \langle Z_2 \rangle \frac{n_{Z2}}{n_e}$$

$$Z_{eff} = \frac{n_D}{n_e} + \langle Z_1 \rangle^2 \frac{n_{Z1}}{n_e} + \langle Z_2 \rangle^2 \frac{n_{Z2}}{n_e}$$

$$\hat{P}^V_{rad} \equiv \frac{P^V_{rad}}{n_e^2 L_D} = \frac{n_D}{n_e} + \frac{n_{Z1}}{n_e}\frac{L_{Z1}}{L_D} + \frac{n_{Z2}}{n_e}\frac{L_{Z2}}{L_D}$$

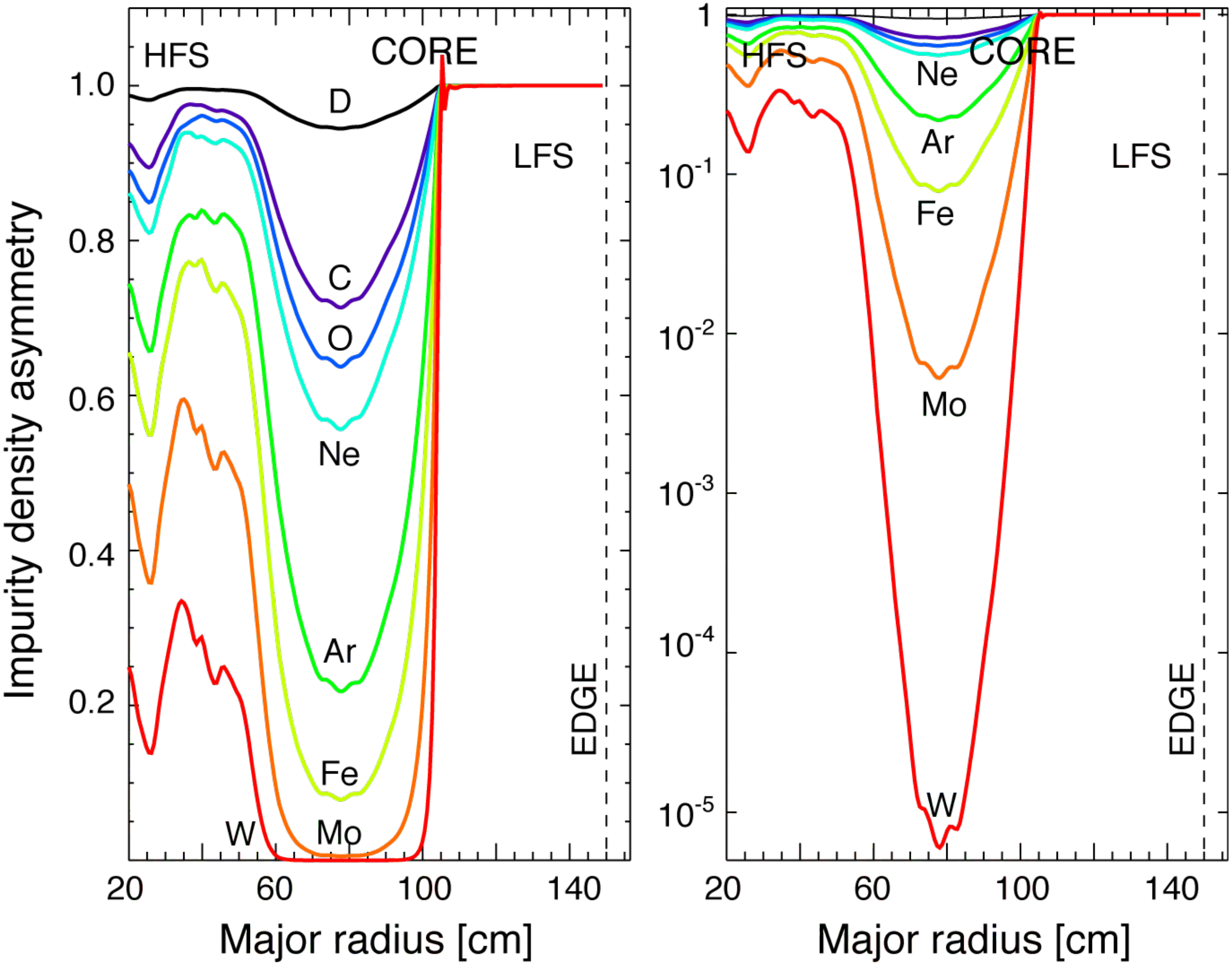
Modern references for high-Z impurities include details of the electronic structure & excitation cross sections



L. Delgado-Aparicio, et al., to be submitted to PoP,(2017)

Density asymmetry & its mass-dependences can be estimated using $\langle Z \rangle \approx \langle Z(T_e) \rangle$ and $T_Z \approx T_C$

$$n_j = n_{j,0} \exp\left(\frac{\frac{1}{2} m_j \omega^2 (R^2 - R_0^2) - e Z_j(T_e) \Delta\varphi}{k_B T_j}\right)$$



<u>HFS vs LFS</u>:

C: 70%

O: 65%

Ne: 55 %

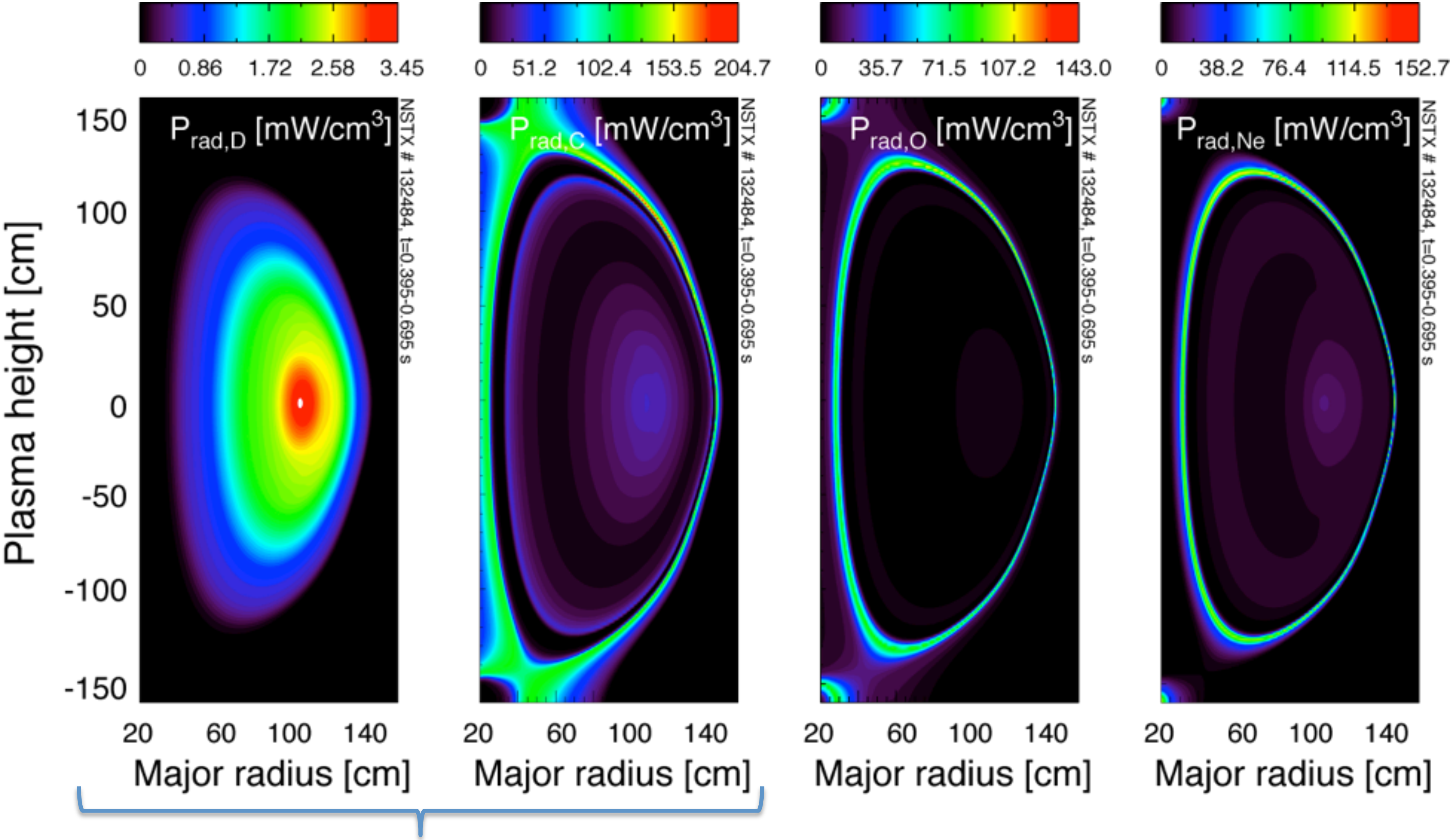
Ar: 20%

Fe: 10%

Mo: 1%

W: <0.01%

Core radiated power from low-Z ions (e.g. D, C, O, Ne) is small but show asymmetric radiation

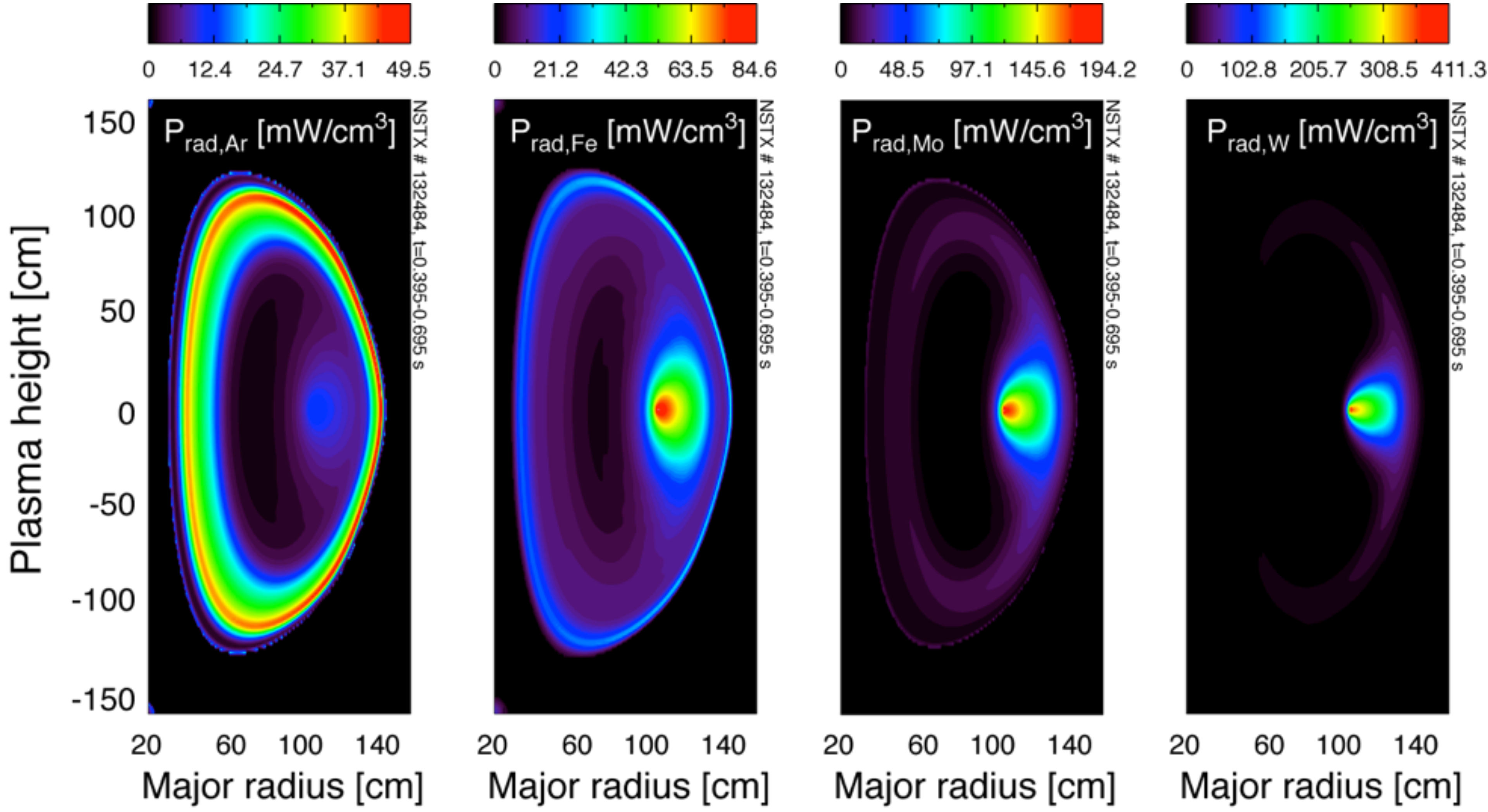


$$P^{D}_{rad}|_{Tot} + P^{C}_{rad}|_{Tot} \sim 0.655 \text{ MW}$$

$$P^{O}_{rad}|_{Tot} \sim 0.2 \text{ MW}$$

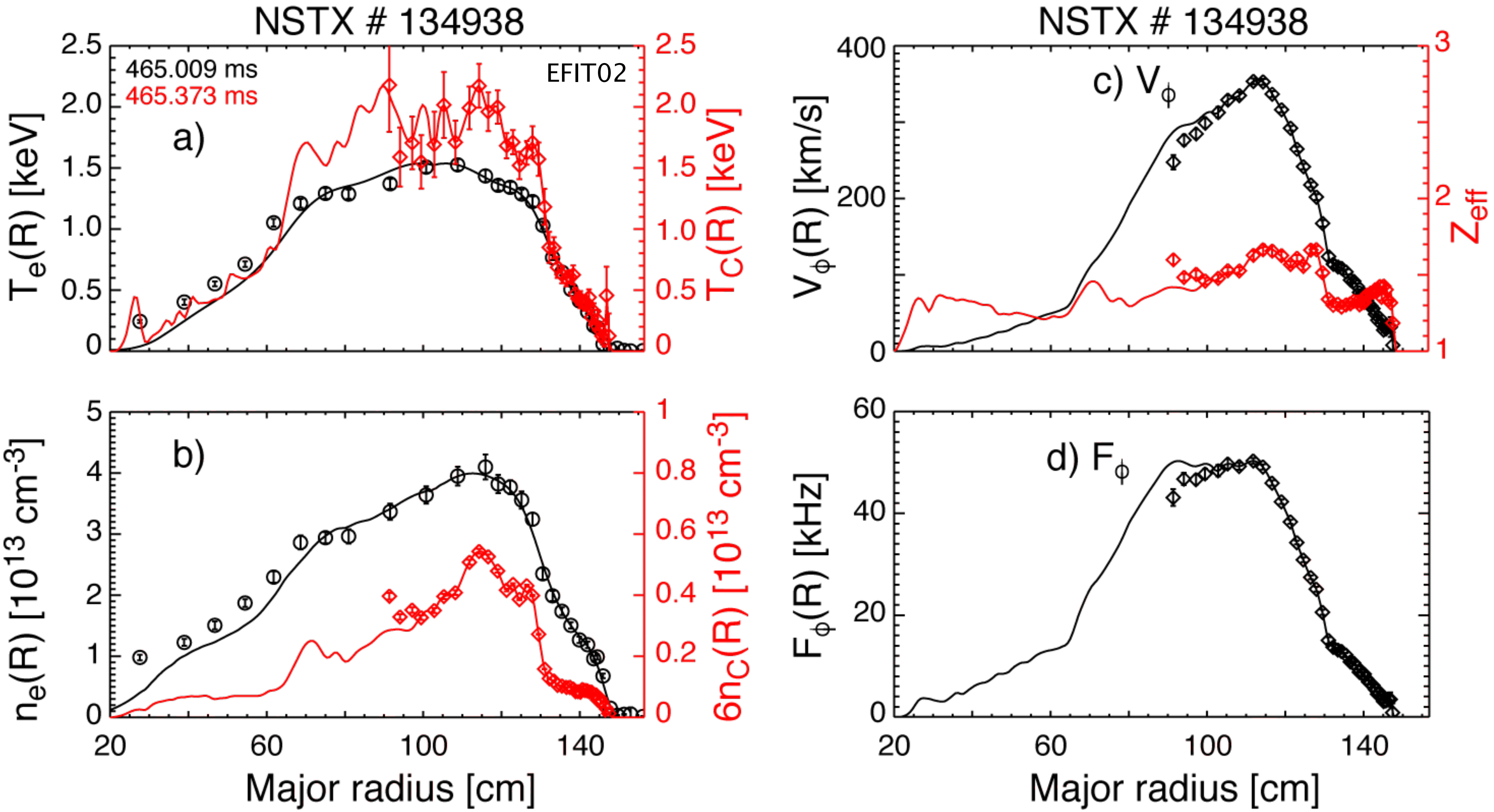
$$P^{Ne}_{rad}|_{Tot} \sim 0.2 \text{ MW}$$

Core n_Z and radiation from medium- to high-Z's will be strongly affected by centrifugal forces



$P_{rad}^{Ar}|_{Tot} \sim 0.2$ MW $P_{rad}^{Fe}|_{Tot} \sim 0.2$ MW $P_{rad}^{Mo}|_{Tot} \sim 0.2$ MW $P_{rad}^{W}|_{Tot} \sim 0.2$ MW

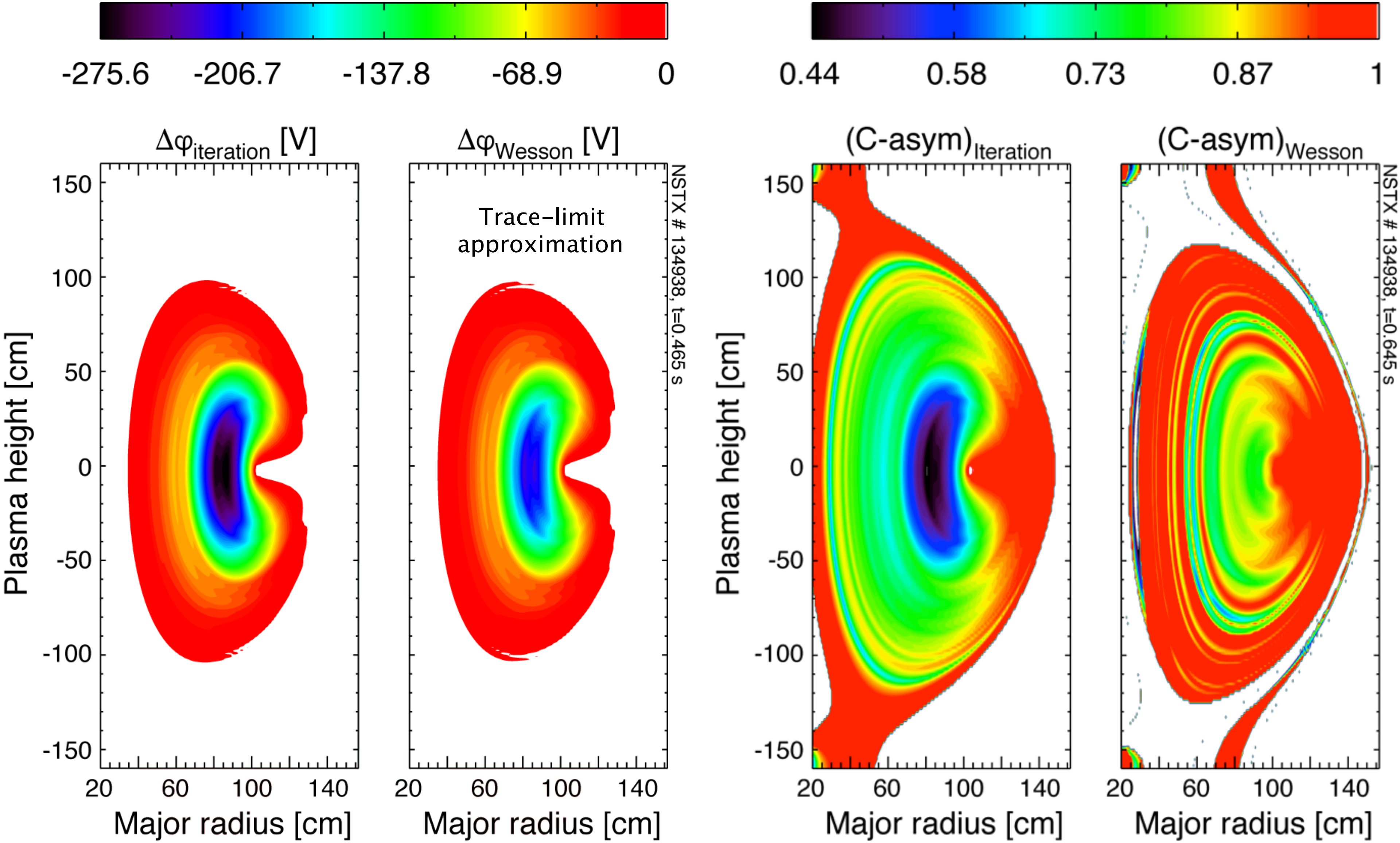
Applying new capability for fastest rotating plasma in NSTX ($V_{\phi,0}$~360 km/s, $F_{\phi,0}$~50 kHz)



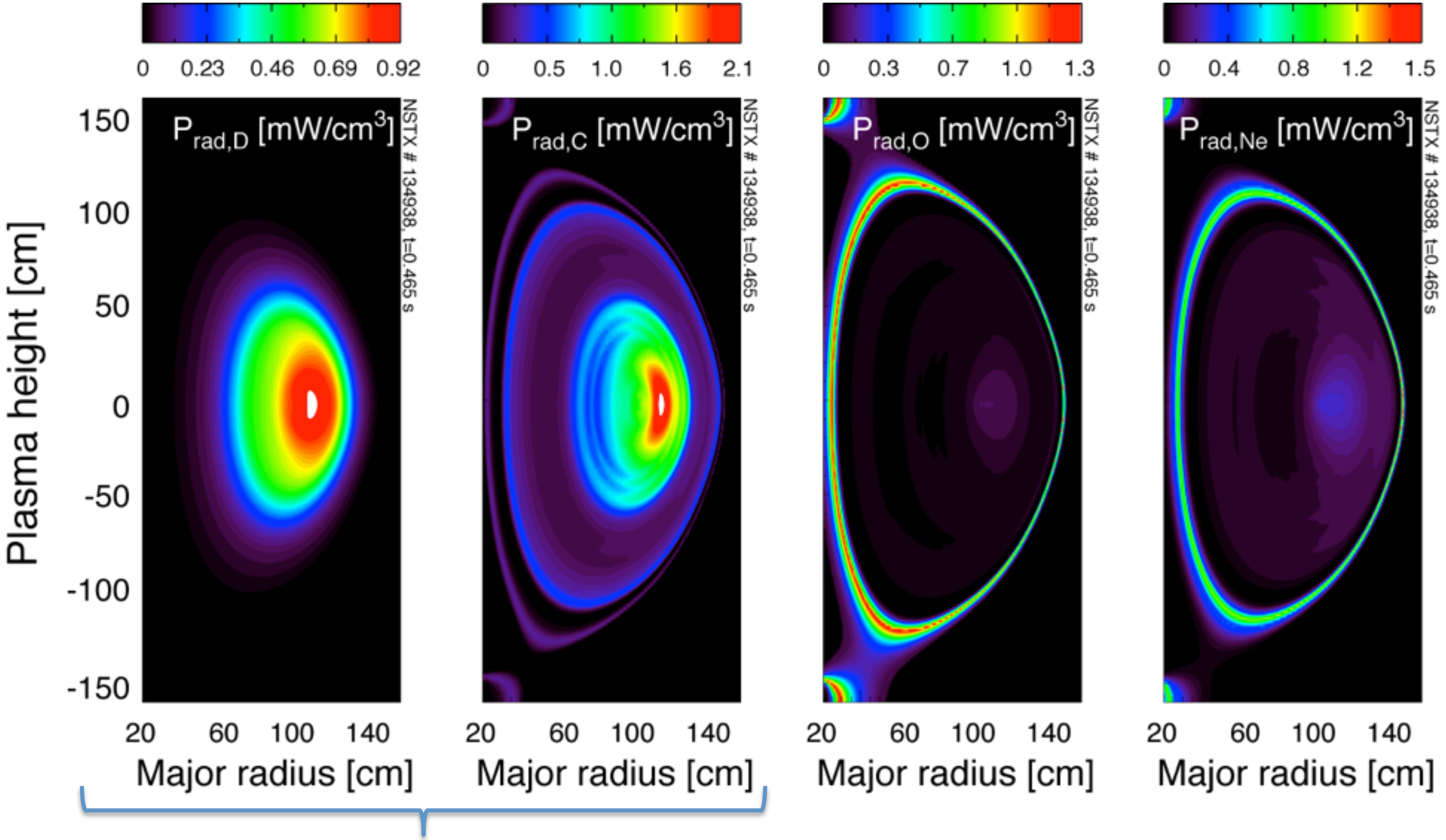
MPTS: n_e, T_e

CHERS: n_C, T_C, V_ϕ

At 360 km/s the electrostatic potential increases to -275 V while C-asymmetry nearly doubles



The degree of impurity and radiated power density asymmetry is now evident also for low-Zs

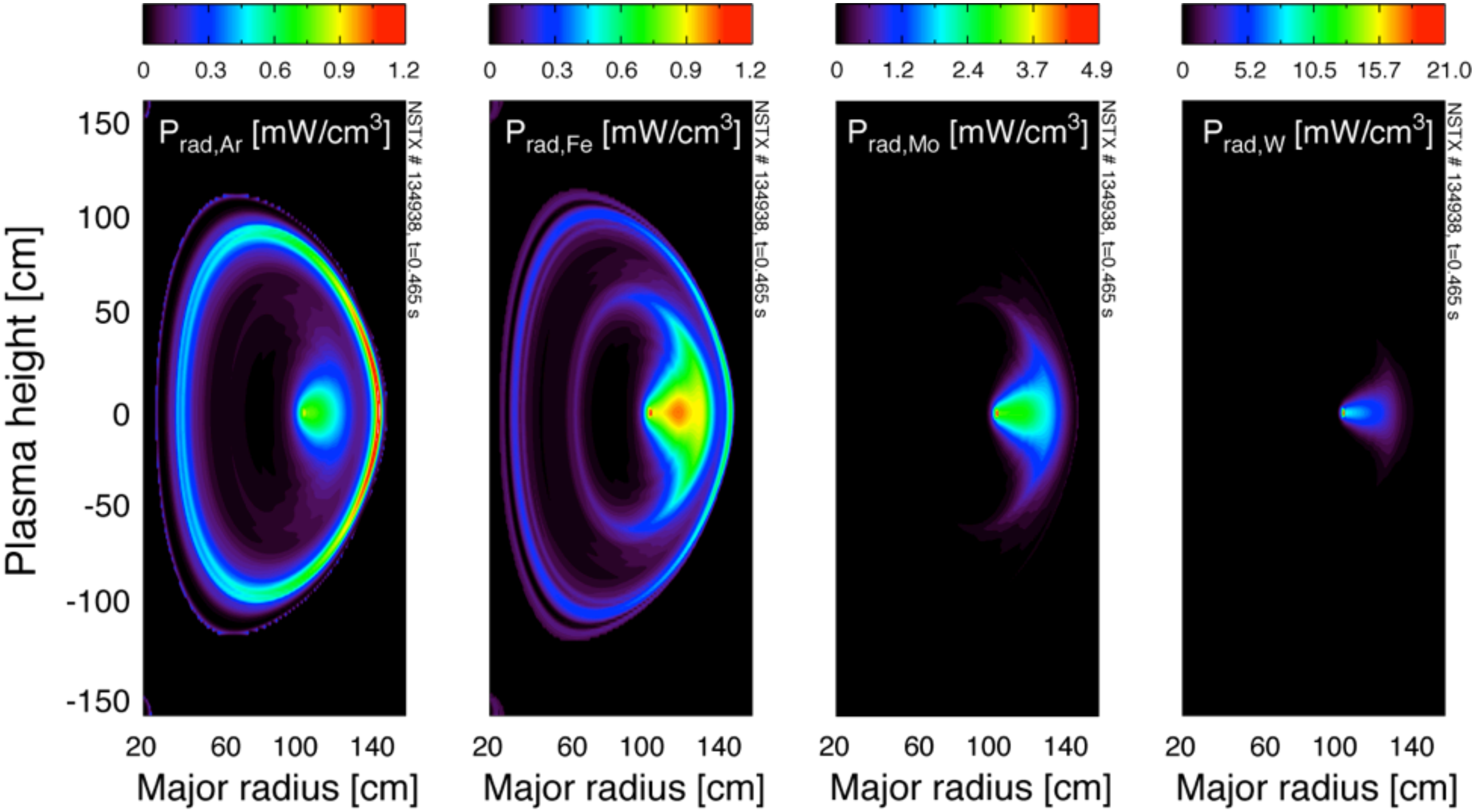


$P^{D}_{rad}|_{Tot} + P^{C}_{rad}|_{Tot} \sim 8.835\ \mathrm{kW}$

$P^{O}_{rad}|_{Tot} \sim 2.5\ \mathrm{kW}$

$P^{Ne}_{rad}|_{Tot} \sim 2.5\ \mathrm{kW}$

…asymmetry increases reducing the Fe, Mo and W radiated power to only the low-field-side (LFS)



$P_{rad}^{Ar}|_{Tot} \sim 2.5 \text{ kW}$ $P_{rad}^{Fe}|_{Tot} \sim 2.5 \text{ kW}$ $P_{rad}^{Mo}|_{Tot} \sim 2.5 \text{ kW}$ $P_{rad}^{W}|_{Tot} \sim 2.5 \text{ kW}$

Summary

- A new capability has been built to compute the two-dimensional mapping of impurity density asymmetries in NSTX-U.
  - a. Compute 2D mapping of flux-surface quantities like $T_{e,C}$ and $\omega\phi$
  - b. Find $n_{e,D,C}(R,Z,t)$ self-consistently assuming poloidal variation due to centrifugal forces.
  - c. Estimate electrostatic potentials $(\Delta\varphi)$.
  - d. The presence of O, Ne, Ar, Fe, Mo and W are considered at the trace limit $(n_Z<Z>^2/n_e<1)$ with very small changes to quasineutrality and Z_{eff}.

- The solutions for $\Delta\varphi$ and the C-asymmetry have been compared with the values derived using a theoretical approximation.

- Computed mapping of particle and radiated power density asymmetries in NSTX for $v_{\phi,0}$~100-400 km/s. Apply this new capability for NSTX-U!

- This new tool will contribute understanding of:
  - a) Medium- & high-Z asymmetries and reduction of Z-peaking
  - b) Possible reduction of turbulence due to $E_{\Delta\varphi}$xB effetcs
  - c) Radiation effects before TM-onsets
  - d) Aid the design of new NSTX-U diagnostics (e.g. ME-SXR, XICS, Bolometers, XUV-spectrometers, etc)