NSTX-U

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Rotation-induced electrostatic-potential and its effects on E_r, n_Z & P_{rad} asymmetries in NSTX

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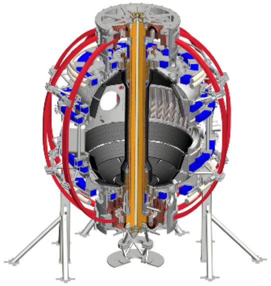
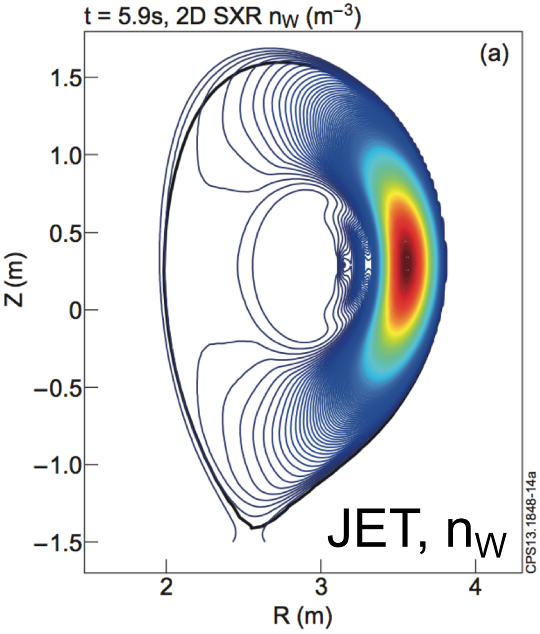


Background

- 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.

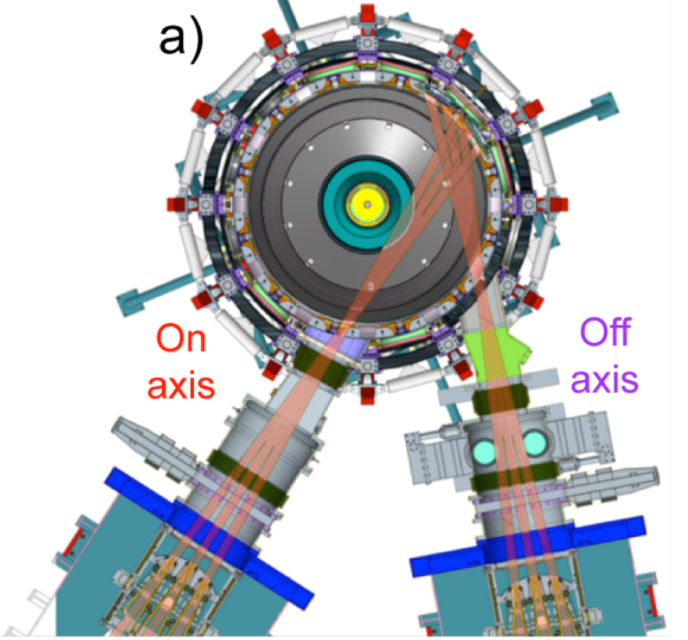


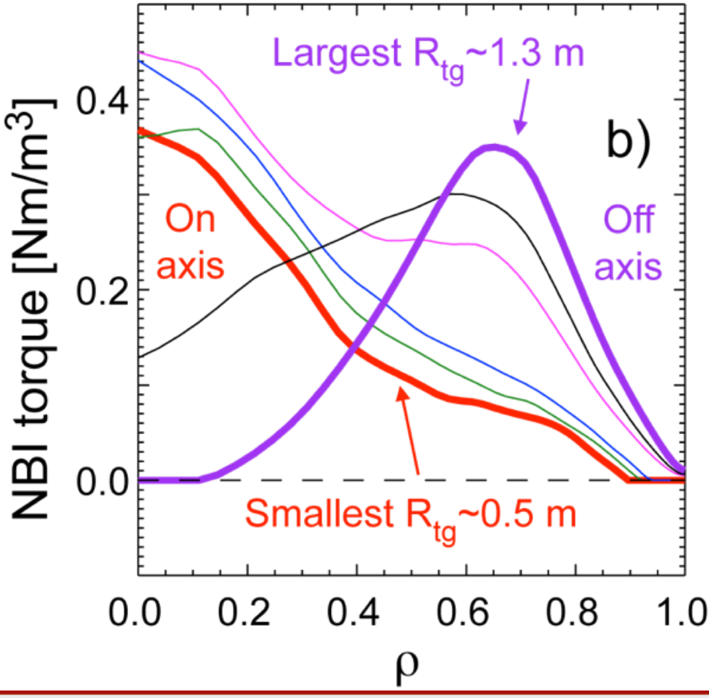
- Understanding poloidal asymmetries and its role and its role reducing the impurity peaking of impurities is highly desirable.

- 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.

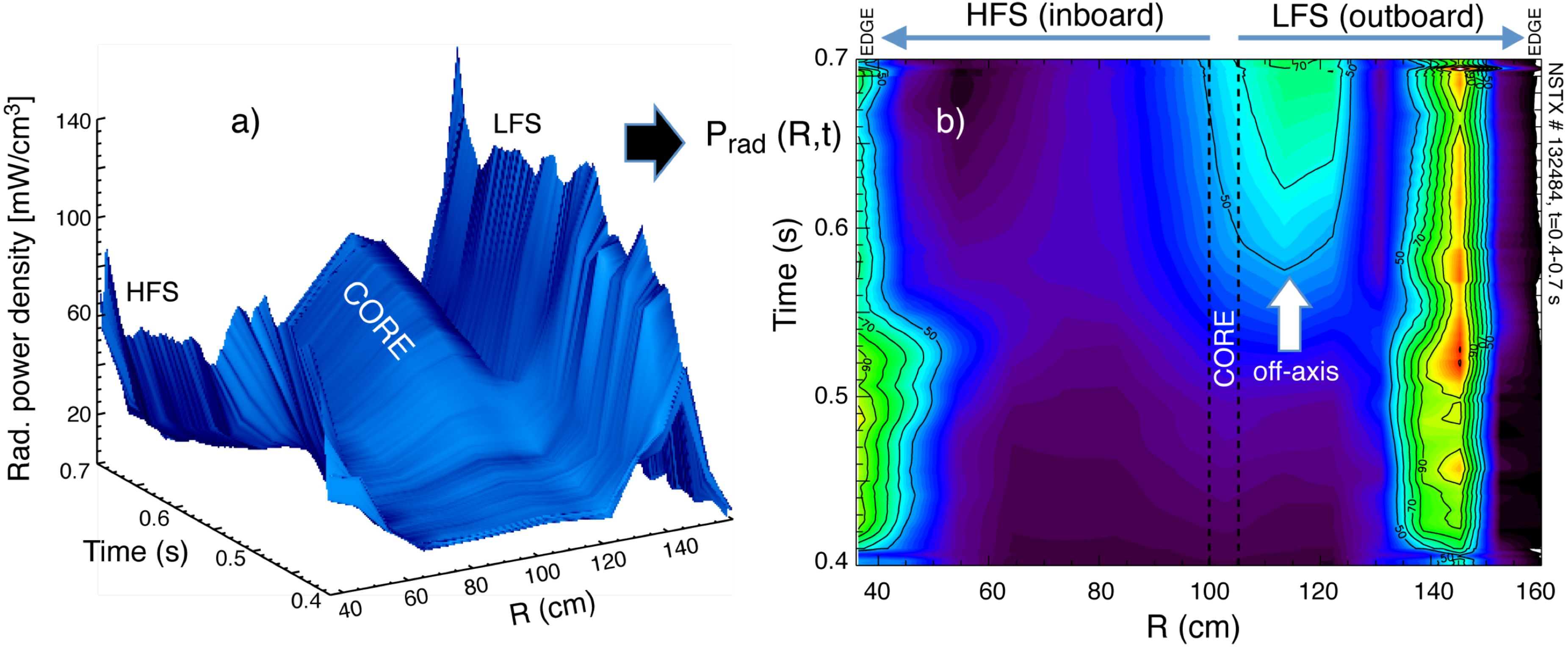
Motivation

- 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 off-axis accumulation has been measured in NSTX



- Experimental P_{rad} profile is asymmetric: off-axis peaking !
- Measured $P_{rad}(r)$ and asymmetry can not be explained only as a function the D+C content
- <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)

Mathematical 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 can be written as (see E. Belli, PPCF'09):

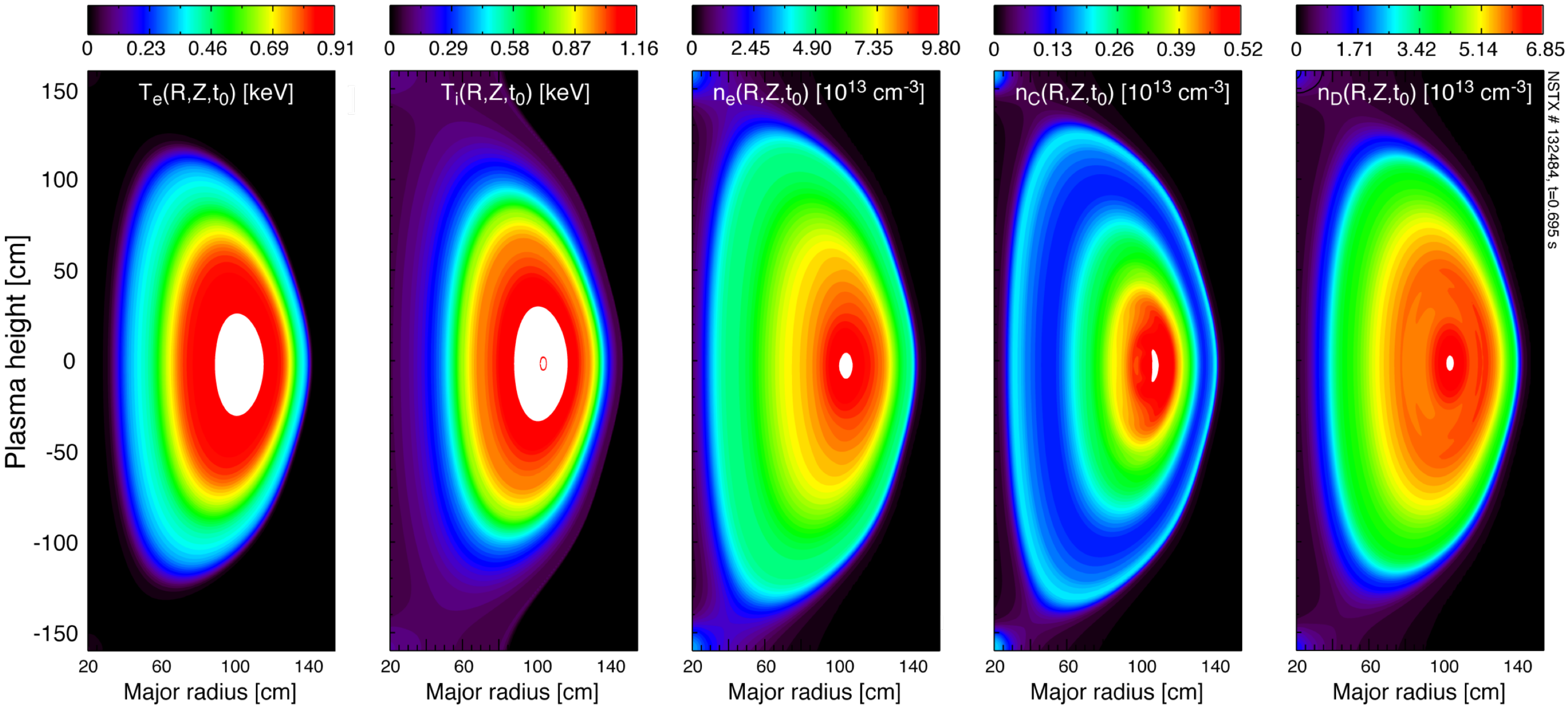
$$n_j(\theta) = n_j(\theta = 0)\exp\left(\frac{\omega_0^2[R^2(\theta) - R^2(\theta = 0)]}{2V_{th,j}^2} - \frac{eZ_j\Delta\varphi(\theta)}{T_j}\right)$$

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

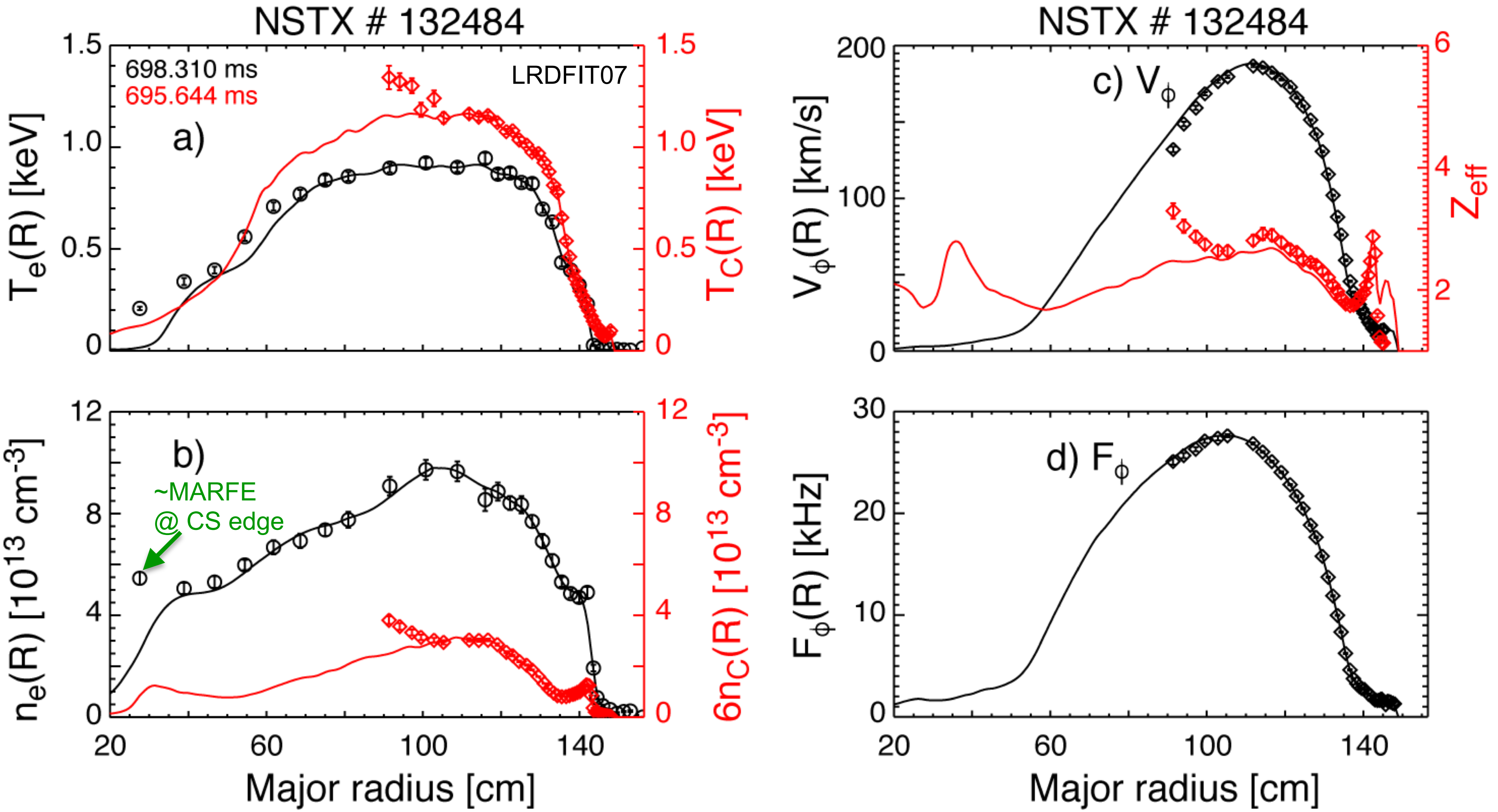
Mapping of mid-plane data in 2D is needed to account for centrifugal asymmetries in n_Z



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

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

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



MPTS: n_e, T_e

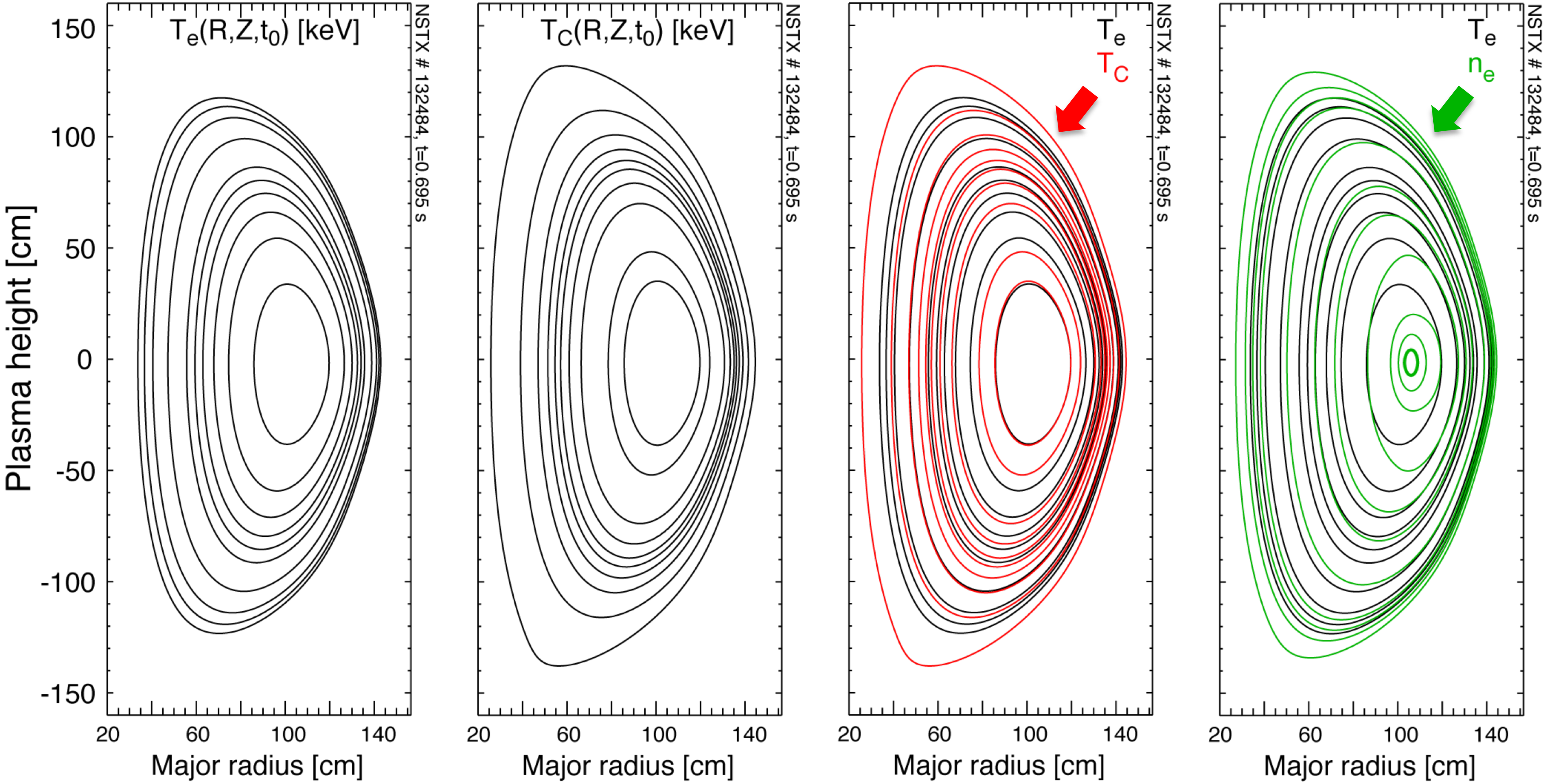
CHERS: n_C, T_C, V_ϕ

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

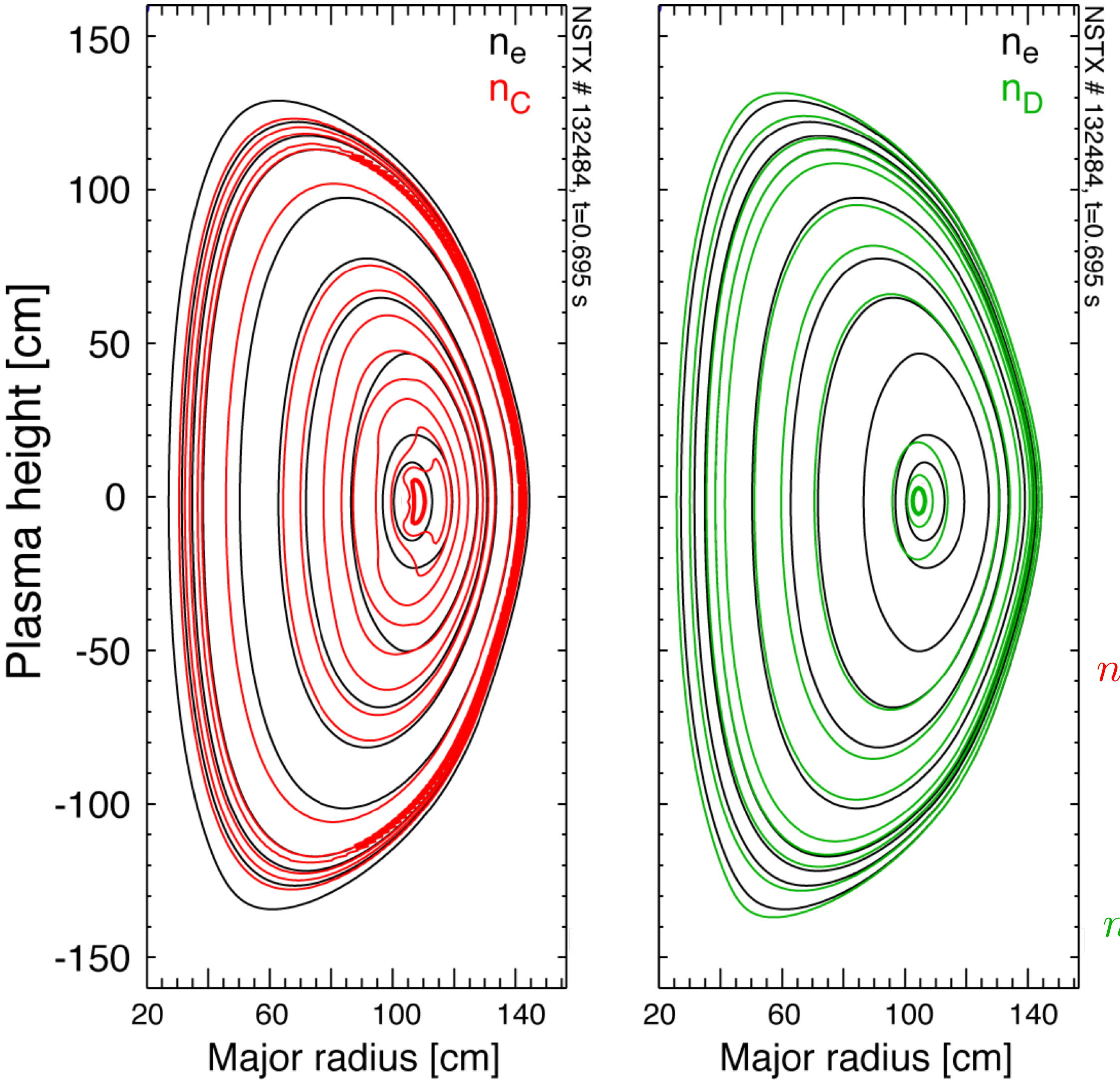
$T_{e,C}$ are mapped on $\Psi(R,Z)$

SUPERIMPOSED

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



Measured n_C 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.

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

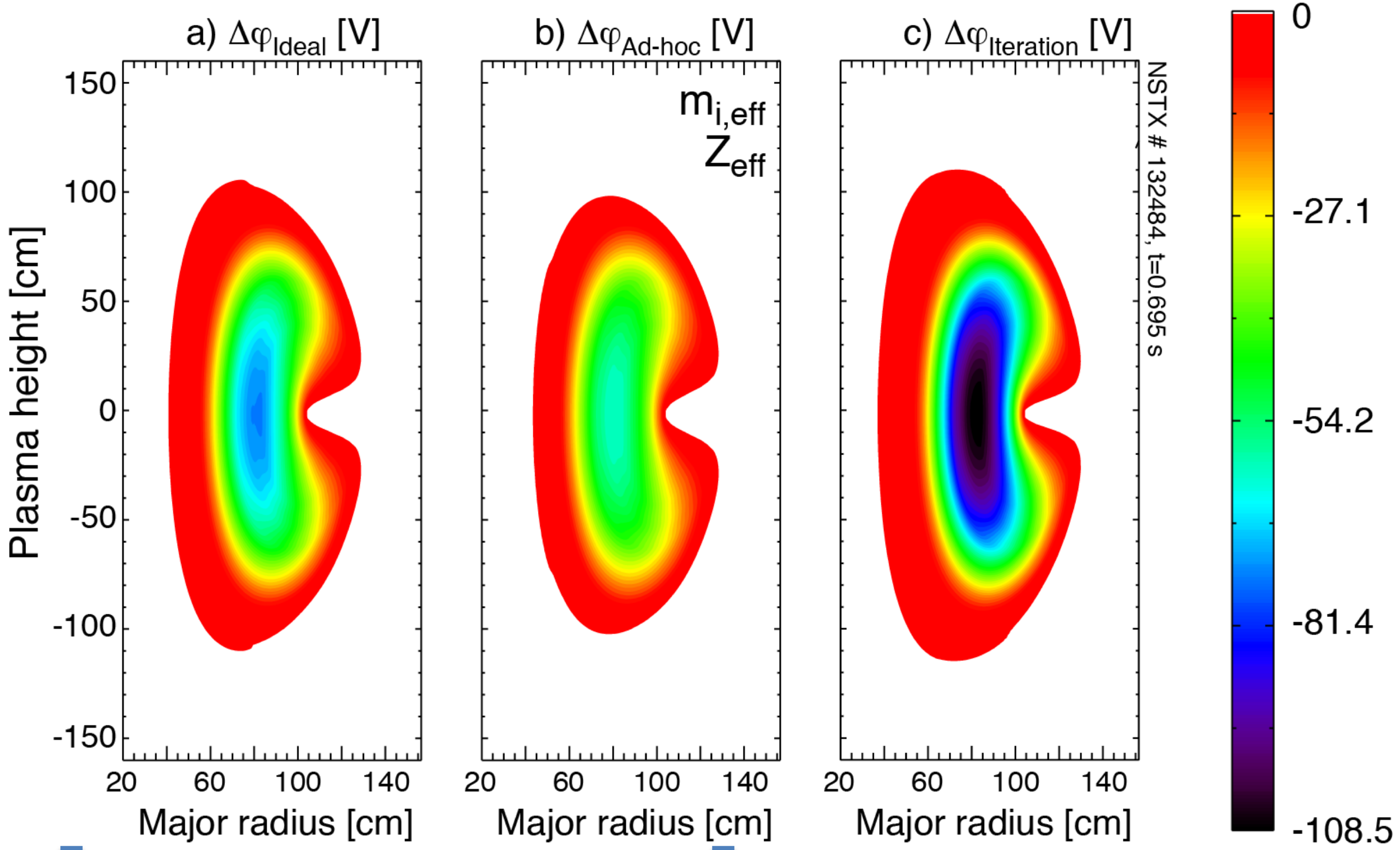
(considering a zero electron mass)

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

⬇

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

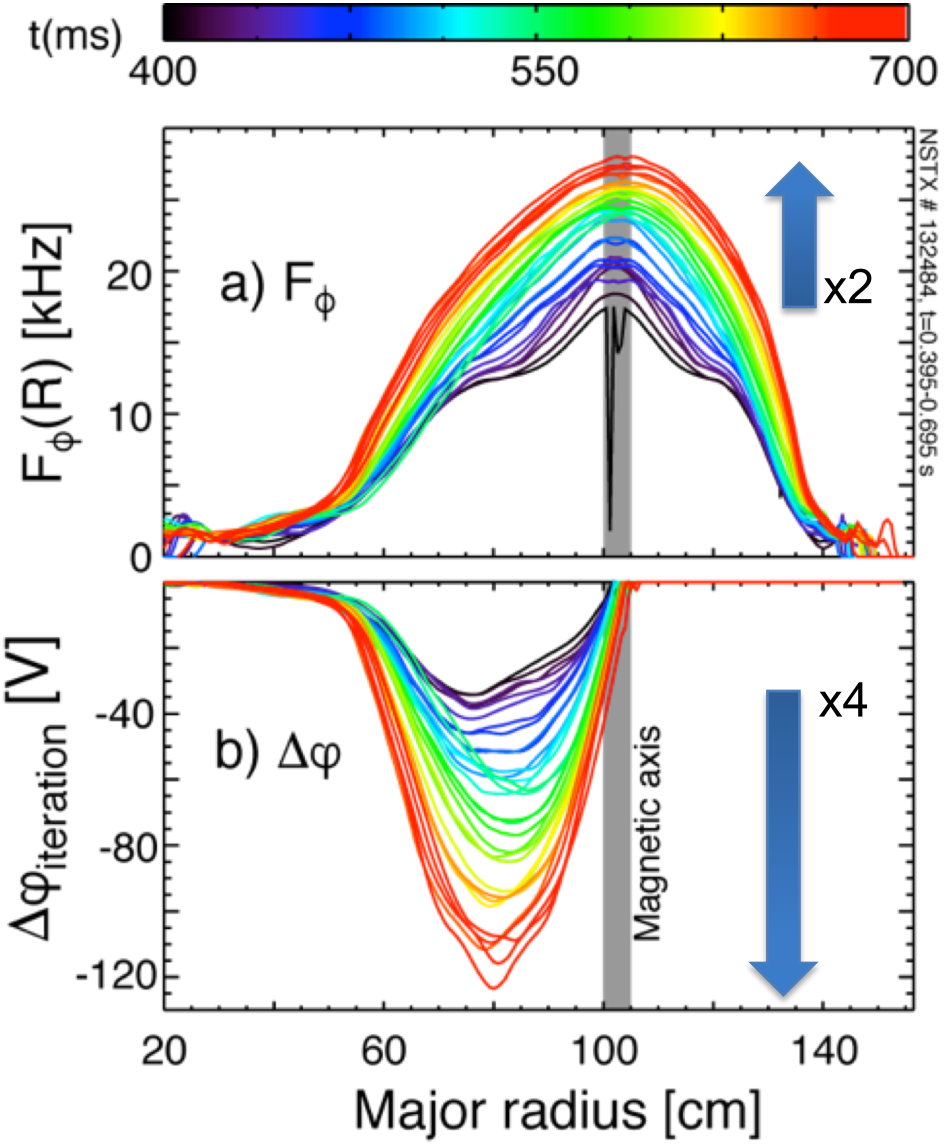
Δφ from data is stronger than obtained using trace-limit & *ad-hoc* approximations



$$\Delta\varphi|_{\alpha_C<<1} = \frac{T_e}{T_e + T_i}\frac{m_i\omega_\phi^2}{2e}\left(R^2 - R_0^{*2}\right)$$

$$\Delta\varphi|_{eff} = \frac{T_e}{Z_{eff}\cdot T_e + T_i}\frac{m_{eff}\omega_\phi^2}{2e}\left(R^2 - R_0^{*2}\right)$$

Time-dependent solution for Δφ shows in/out asymmetry evolution with strong ω^2 scaling



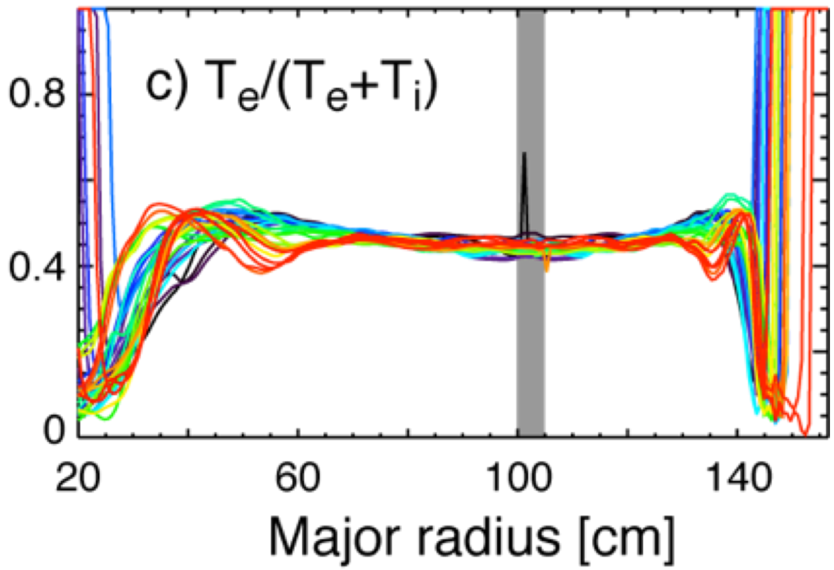
- The scaling of electrostatic potential with rotation frequency is <u>not</u> linear:

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

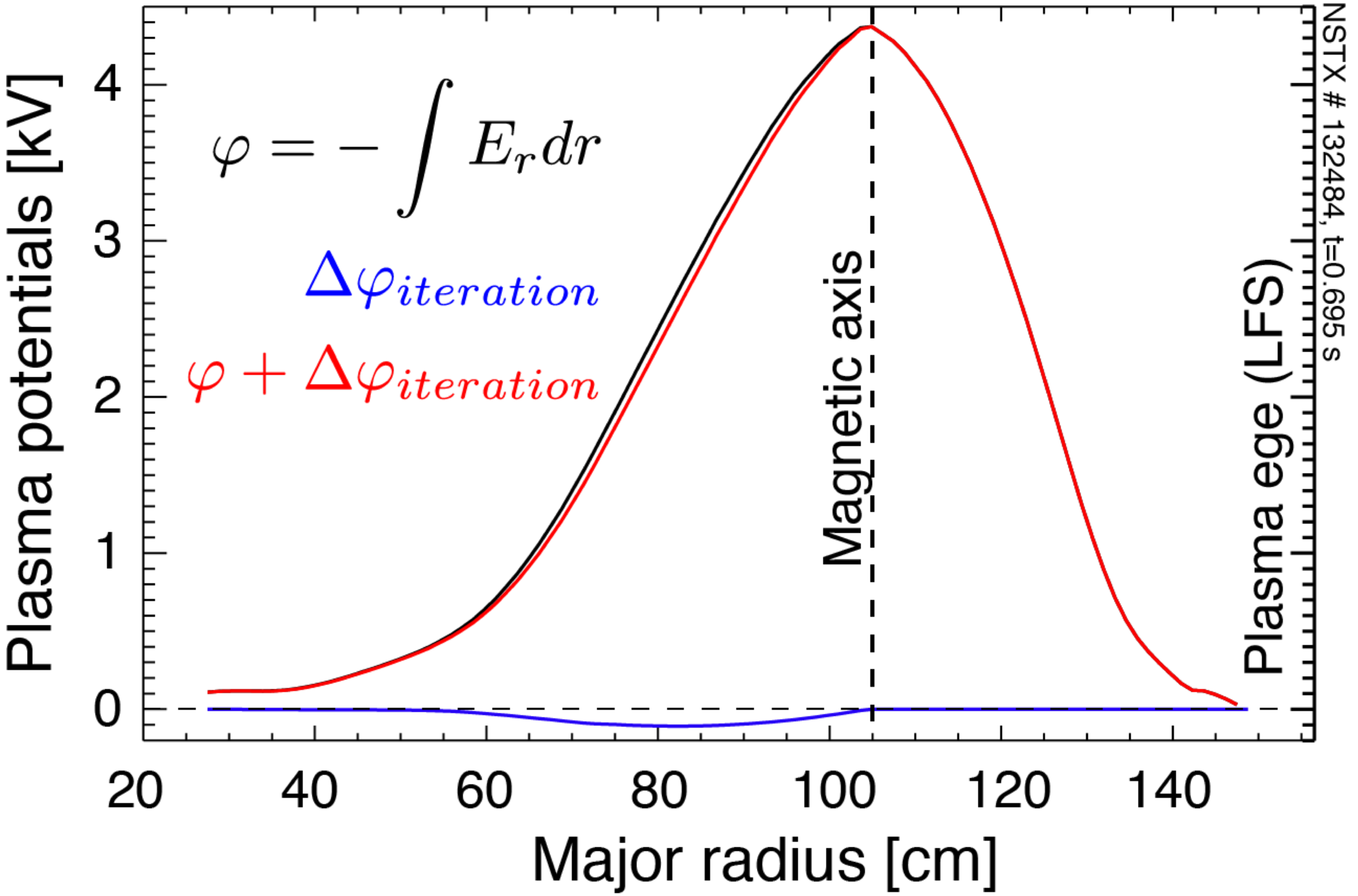
- <u>Experimental data (R=80 cm)</u>:

i. t=0.4 s, Fϕ~12 kHz, Δφ~-32 V

ii. t=0.7 s, Fϕ~22 kHz, Δφ~-120 V



Change in the plasma potential (φ)and radial electric field (E_r) is ***very small*** (~ 5%)



Change in radial electric field ($\Delta E_r/E_r$~5%) is consistent with analytic scaling $\propto\omega_\phi(r)/\Omega_{i,0}$

- The rotation-induced electrostatic potential and related change of the local electric field can be easily calculated as:

$$\Delta\varphi(r,\theta=\pi) \equiv \frac{\mathcal{C}T_e}{T_e+T_i}\frac{m_i\omega_\phi^2}{2e}\left(R^2 - R_0^{*2}\right) \approx -2\mathcal{C}R_0 r\frac{T_e}{T_e+T_i}\frac{m_i}{e}\omega_\phi^2$$

$$\Rightarrow \Delta E_r(r,\theta=\pi) \equiv -\nabla_r(\Delta\varphi(r,\theta=\pi)) = 2\mathcal{C}R_0\frac{T_e}{T_e+T_i}\frac{m_i}{e}\omega_\phi^2\left(1+2r/L_{\omega_\phi}\right)$$

- The E_r in NSTX is mainly determined by the $V\phi B\theta$ term:

$$E_r \approx V_\phi B_\theta \sim \frac{R_0 r^2}{q(r)R^2}\omega_\phi B_{\phi,0}$$

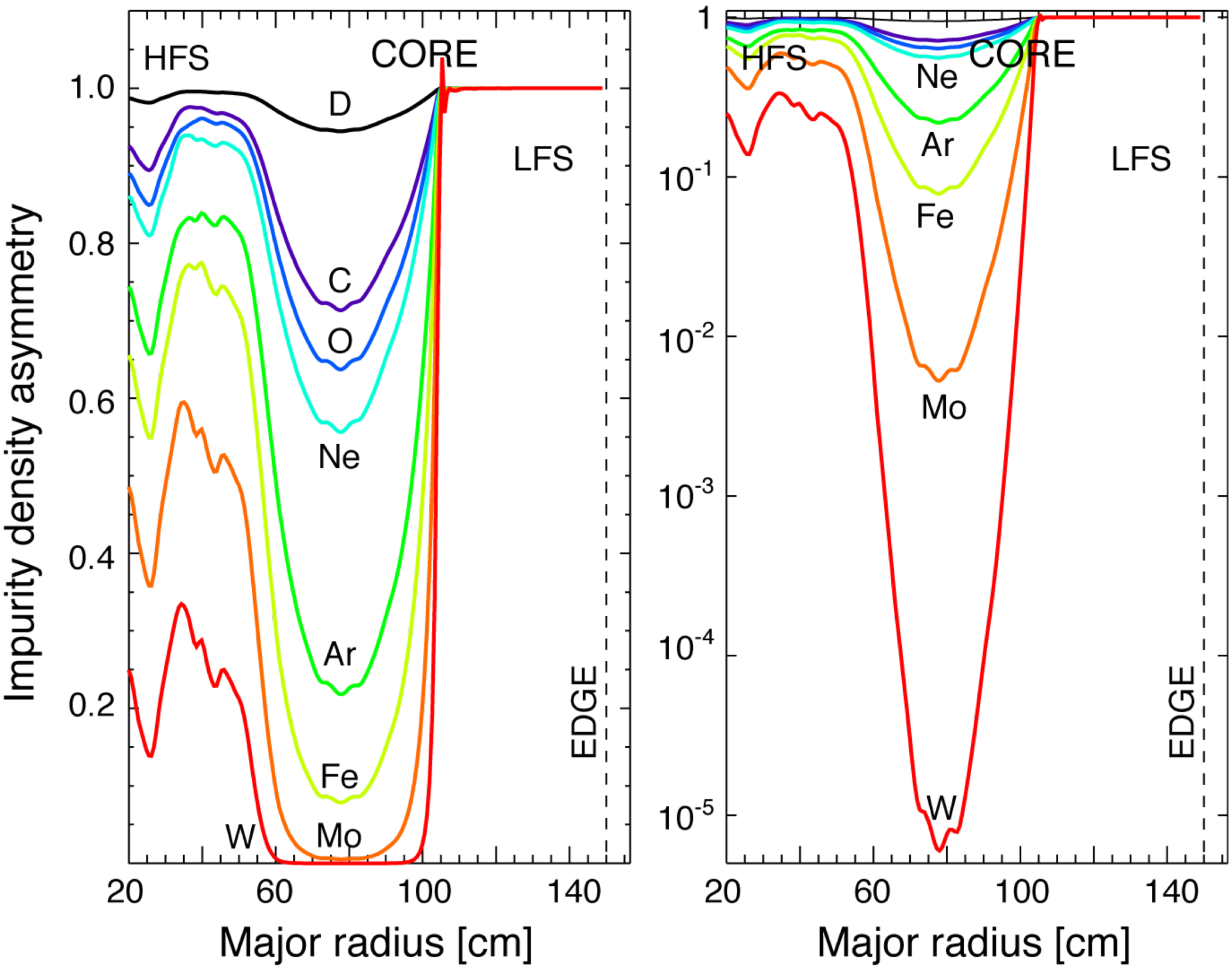
- Using the equations shown above and $T_e/(T_e+T_i)$~0.45:

$$\Rightarrow \frac{\Delta E_r}{E_r}(r,\omega_\phi,\theta=\pi) \sim 0.9\mathcal{C}q(r)\left(\frac{R}{r}\right)^2\frac{w_\phi(r)}{\Omega_{i,0}}\left(1+2r/L_{\omega_\phi}\right)$$

- The ratio of the expressions for the asymmetric Er to the background radial field for $\omega\phi$=21.5 kHz and $\Omega_{i,0}$=21.5 MHz is of the order of 5% !!!

n_Z asymmetry & its mass-dependences can be estimated using $<Z>\approx<Z(T_e)>$ & $T_Z\approx T_C$

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



HFS vs LFS:

C: 70%

O: 65%

Ne: 55 %

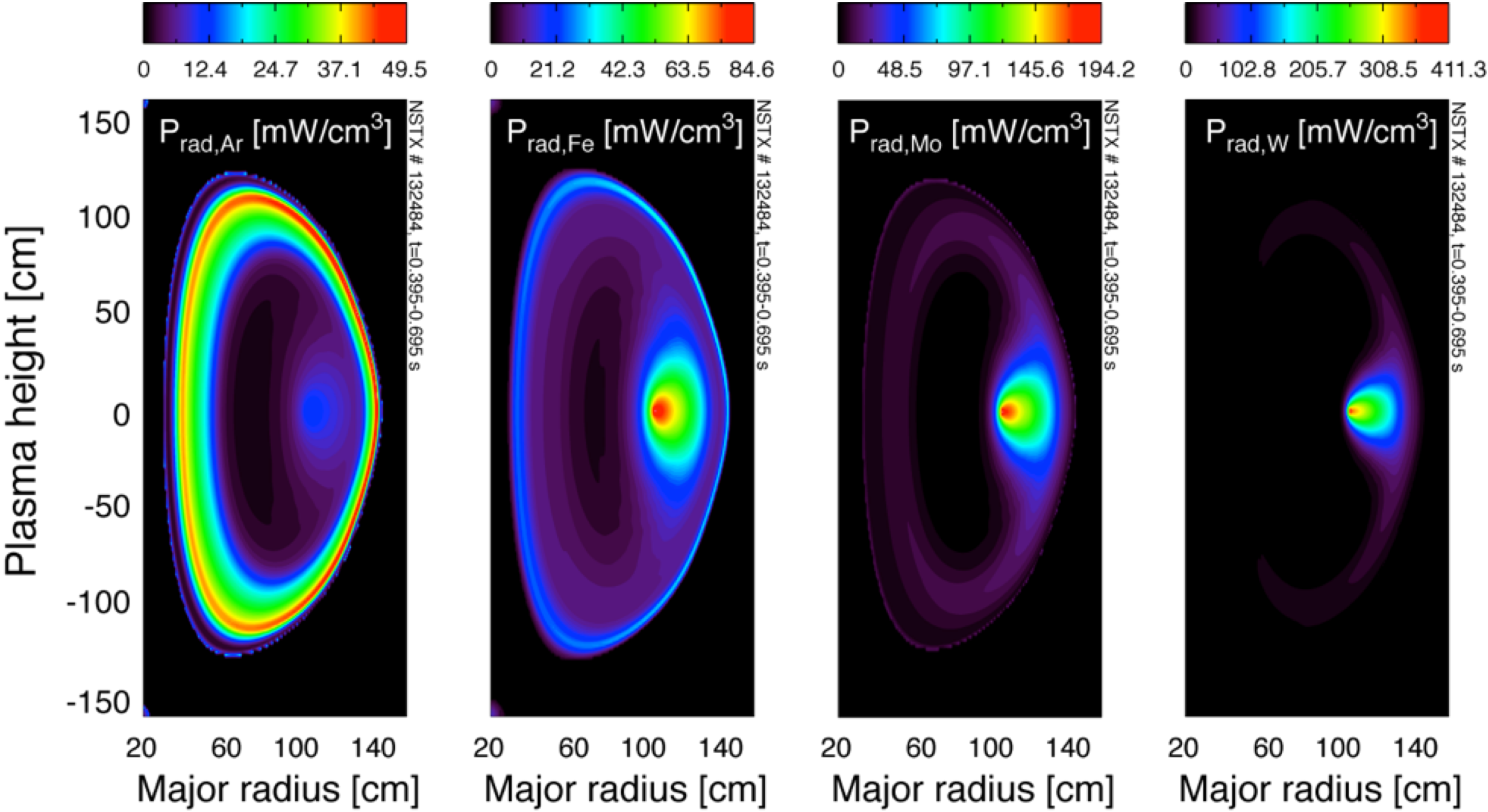
Ar: 20%

Fe: 10%

Mo: 1%

W: <0.01%

Core n_Z and P_{rad} from medium- to high-Z's will be strongly affected by centrifugal forces



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

Summary

○ The computation of rotation-induced electrostatic potentials is being used to study the associated two-dimensional distribution of impurity density asymmetries in NSTX.

○ This calculation relies on flux-surface quantities like Te, Ti and $\omega\phi$. The iterative process finds the 2D density profiles and the electrostatic potentials ($\Delta\varphi$) self-consistently assuming poloidal variation due to centrifugal forces.

○ The depth of the potential well can reach -110 to -280 V for core NSTX rotation between 180 – 360 km/s but remains very small if one compares with the core plasma potential or the energy of fast ions.

○ The net-change of the plasma potential and radial electric field is of the order of just 5-6% and in accordance with a simple theoretical calculation.

○ This computation is being used to increase our understanding of asymmetries and the reduction of Z-peaking, to examine the effect of $\Delta\varphi$ possibly changing the heat and particle transport, radiation asymmetries before tearing mode onsets, as well as to aid the design of new diagnostics for NSTX-U.