Transition to a helical core equilibrium in a toroidal plasma

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Transport Task Force
San Diego, CA (9 April 2011)

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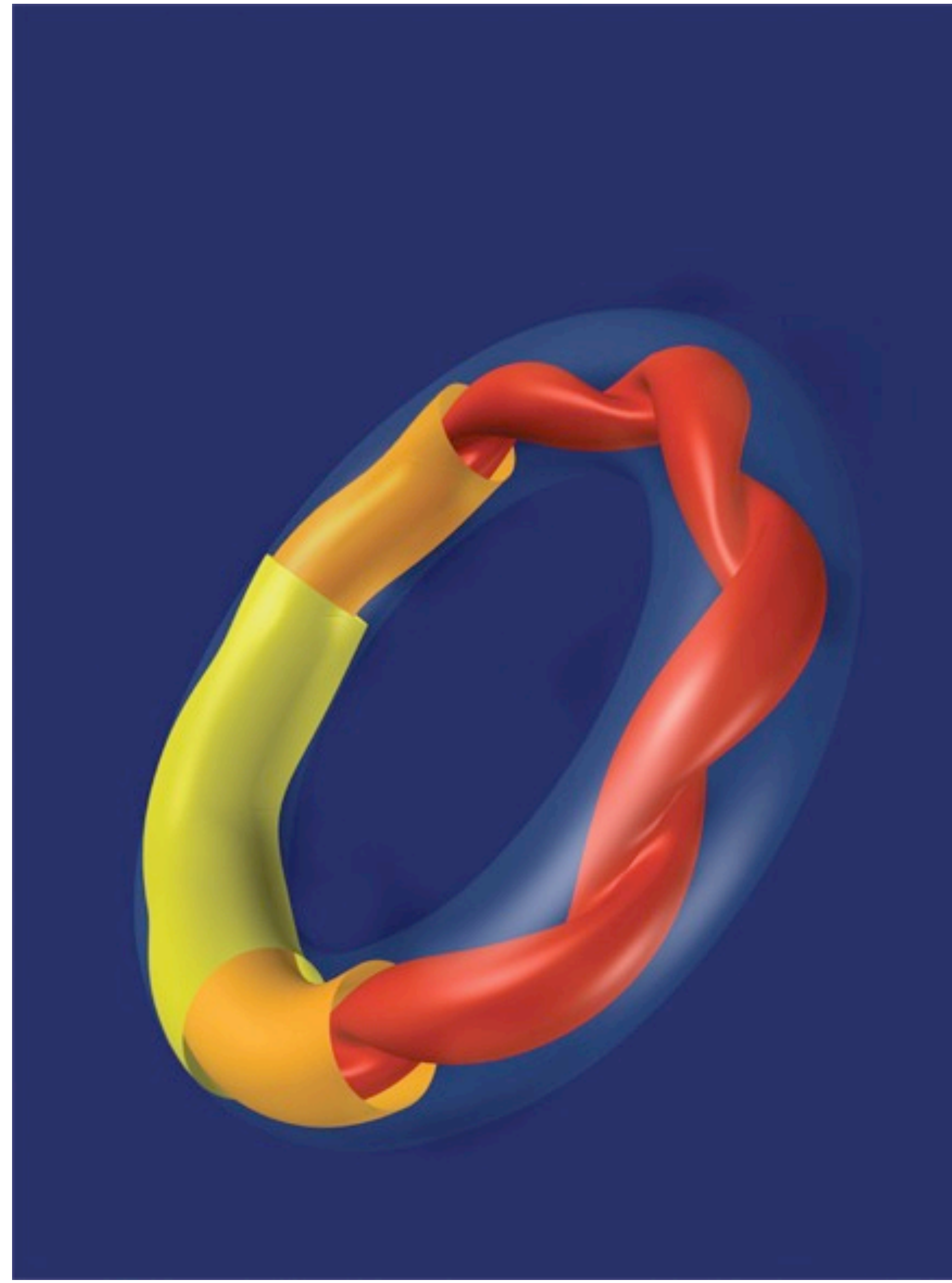
Do core measurements of the plasma provide direct evidence for helical equilibrium?

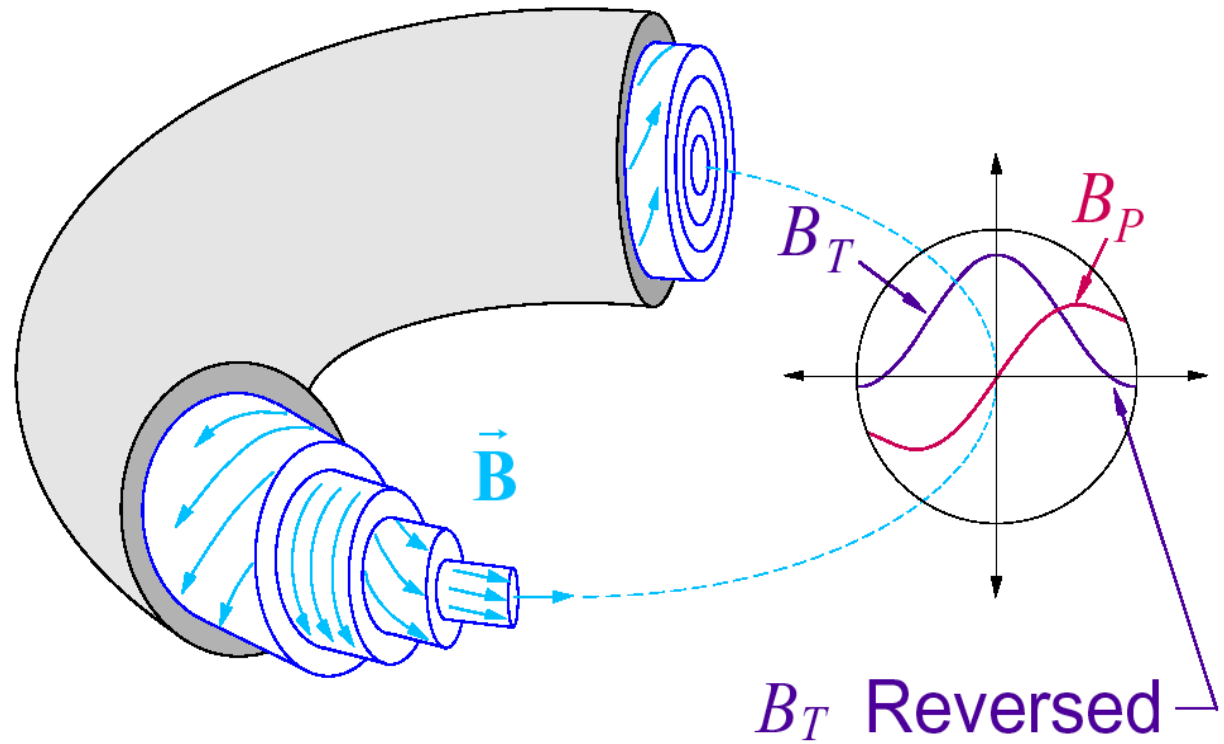
Do plasmas with helical equilibria have improved confinement?

Helical core

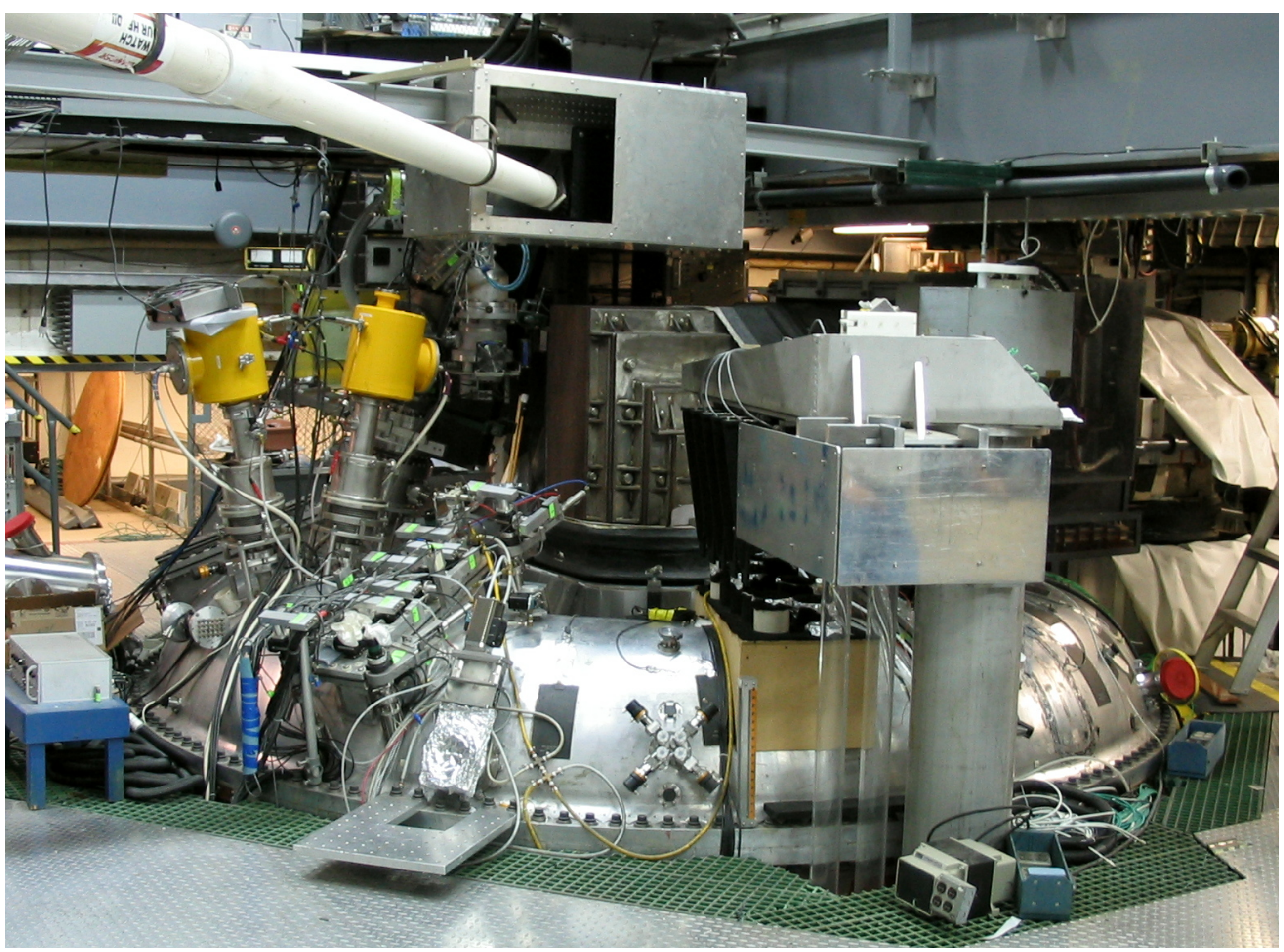


Measurements made at Madison Symmetric Torus

reversed field pinch (RFP): self organized system with dynamo action sustaining B_ϕ



Madison Symmetric Torus - MST



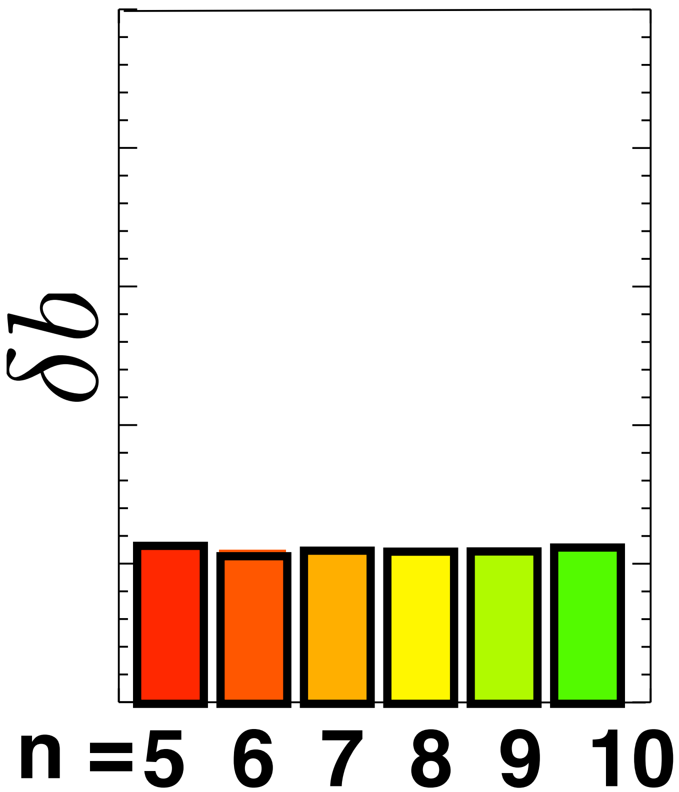
B_ϕ peaked on axis and reverses at edge

R_0 = 1.5 m
a = 0.51 m
I_p ~ 400-600 kA
n_e ~ 10^{19} m^{-3}

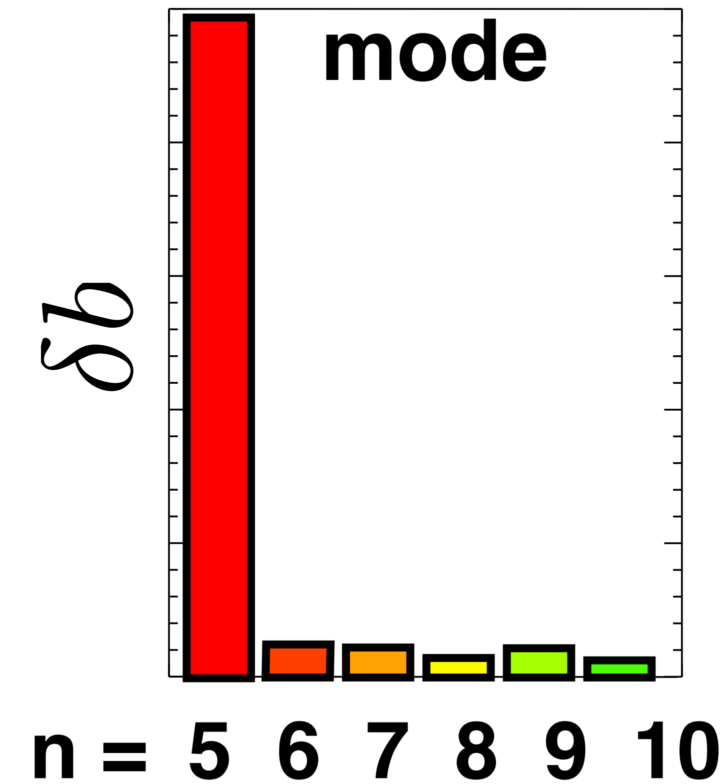
T_e ~T_i ~
0.4 keV - 1 keV

Reversed field pinch has a bifurcated equilibrium

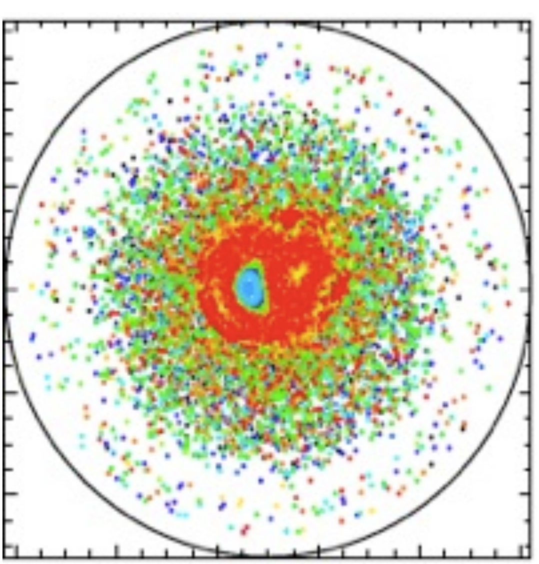
many modes



single dominant mode



spontaneous bifurcation between states



OUTLINE:

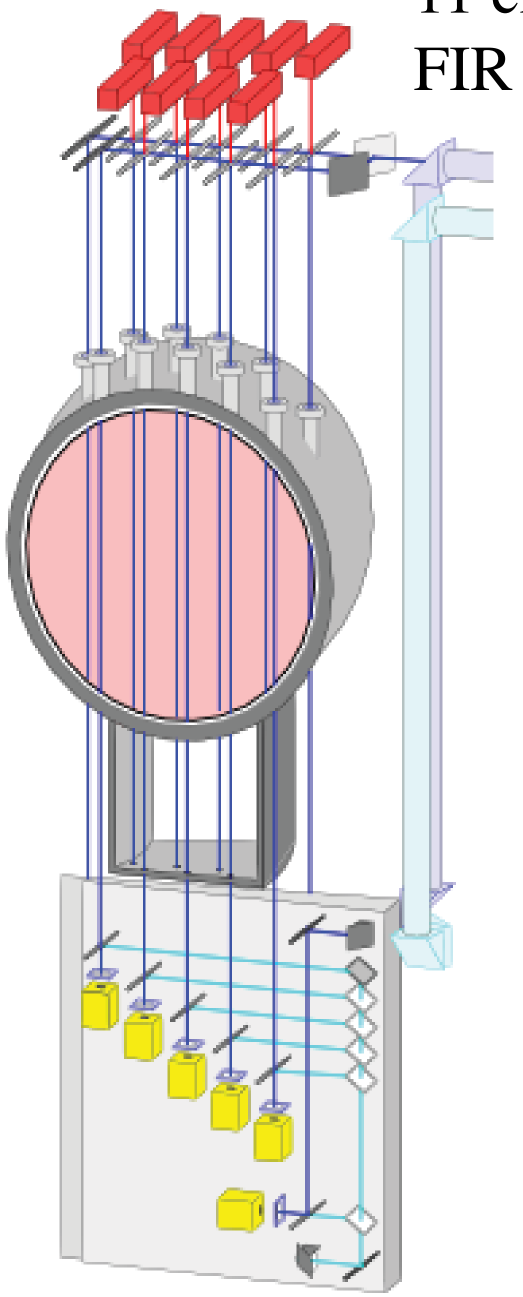
1) Evidence for helical equilibria

Non-axisymmetric internal structure identified in B_θ, and n_e

2) Improved plasma performance

Laser based polarimeter - interferometer diagnostic

11 chord FIR laser



$$\Phi \propto \int n_e \cdot dl \longrightarrow n_e \quad \delta n_e$$

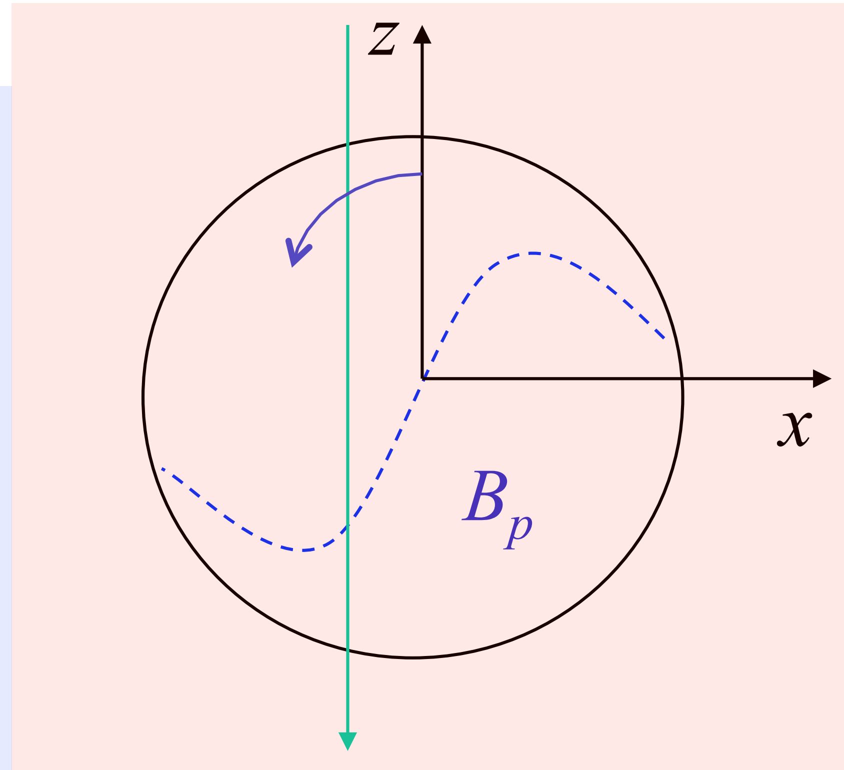
$$\Psi \propto \int n_e B \cdot dl \longrightarrow B_\theta \quad \delta b_r \quad \delta J_\phi$$

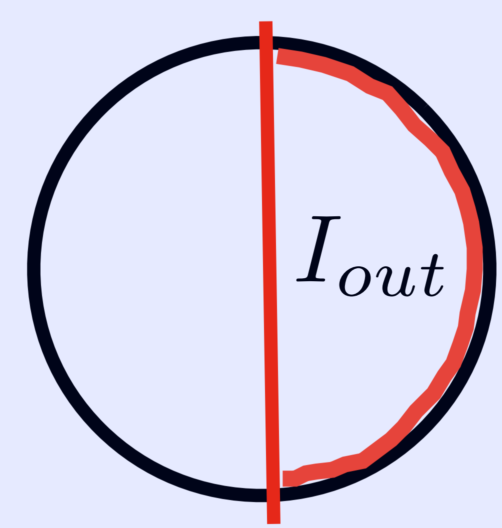
symmetry breaking term is measured directly

Measure $\bar{B}$ on individual chords or combine with $B_\theta(a)$ to measure current in outboard section

$$\frac{\int n_e B \cdot dl}{\int n_e \cdot dl} = \bar{B}$$

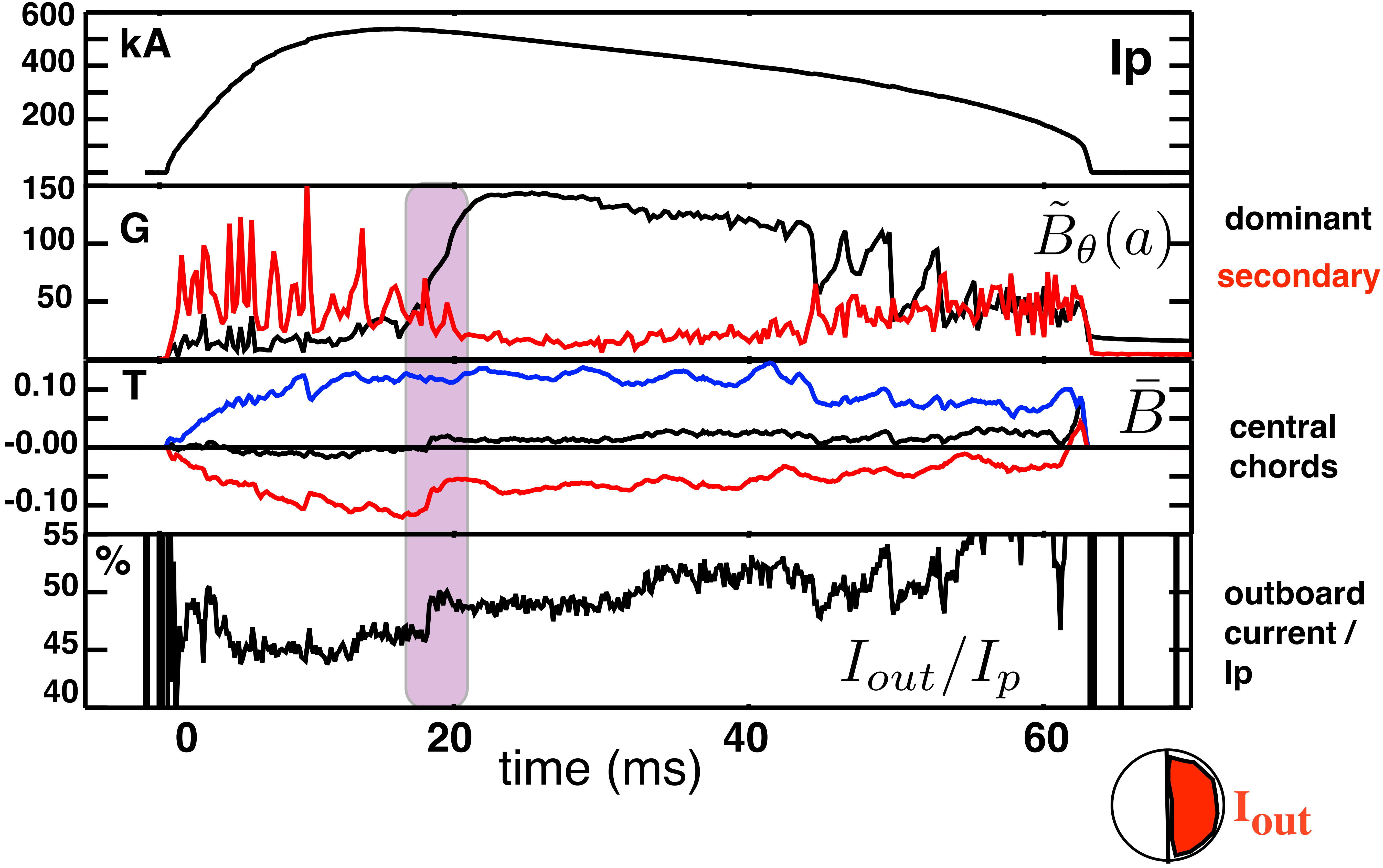
$$\int (B_z + B_\theta) \cdot dl = \mu_0 I_{out}$$



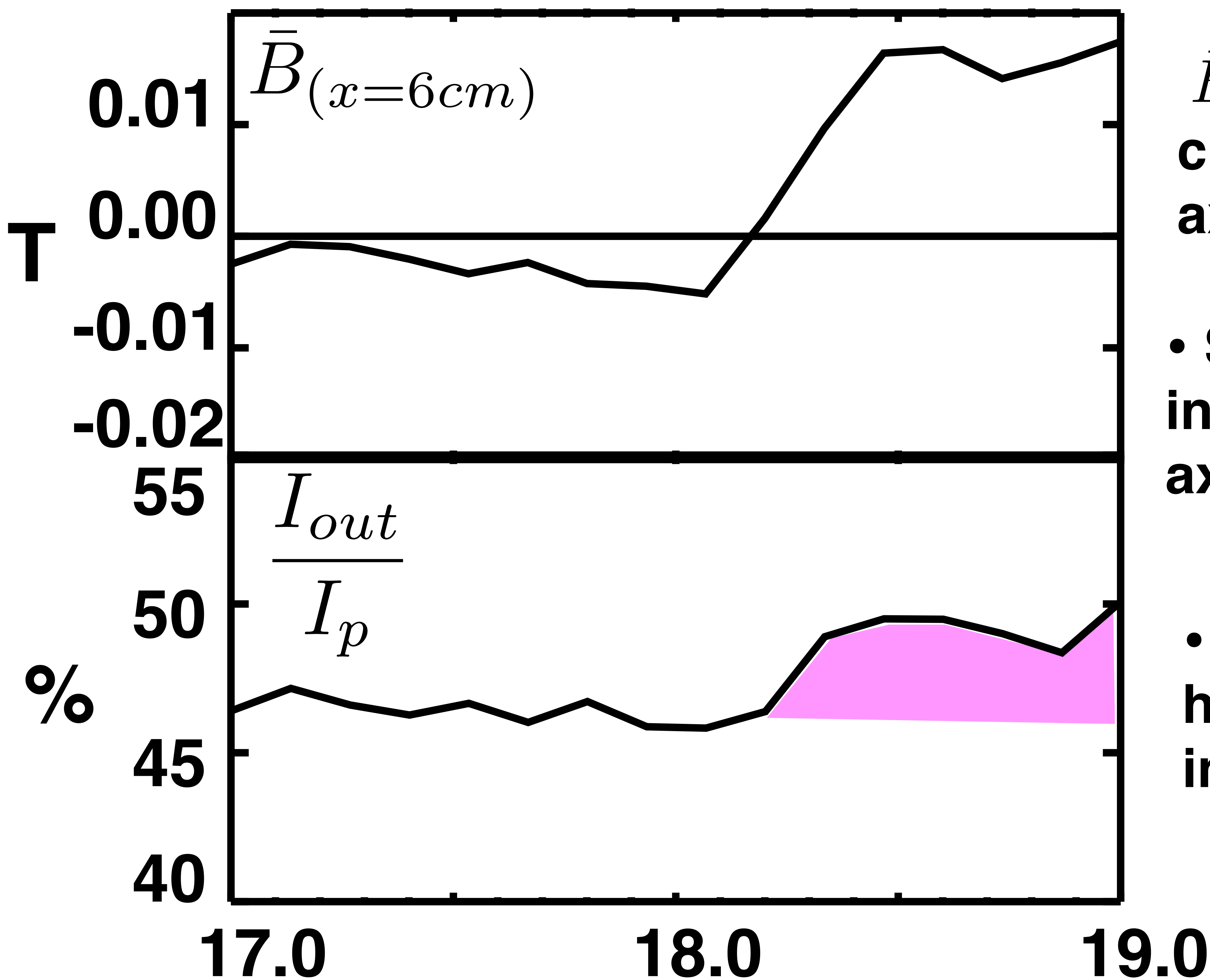


64 B_θ, B_ϕ coil pairs mounted at the plasma surface to resolve magnetic modes

Equilibrium transitions to helical state



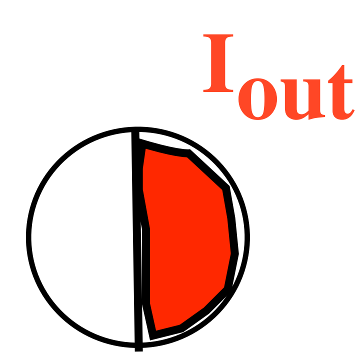
Core flux spontaneously reorganizes



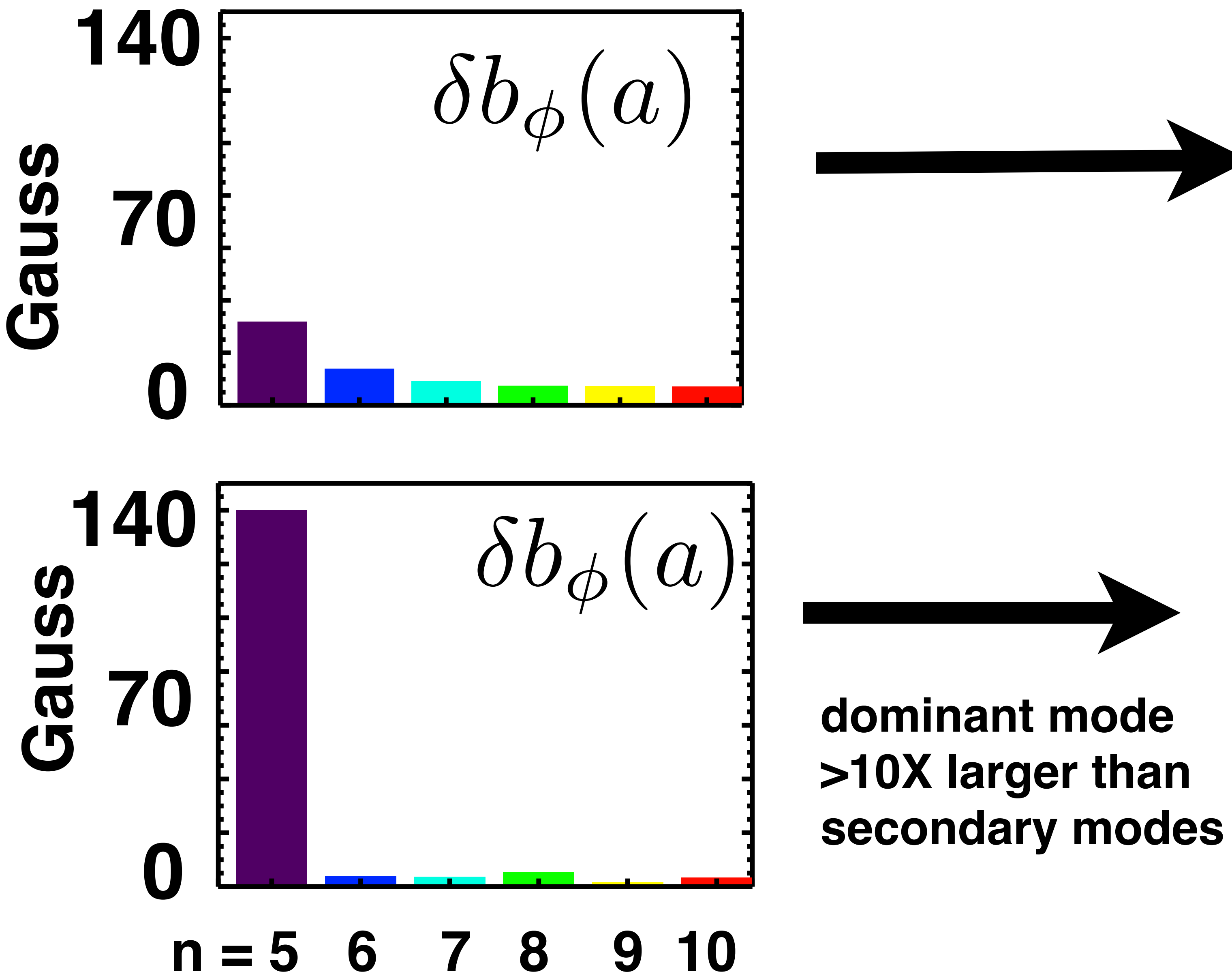
$\bar{B}(x = 6cm)$ **is closest to magnetic axis**

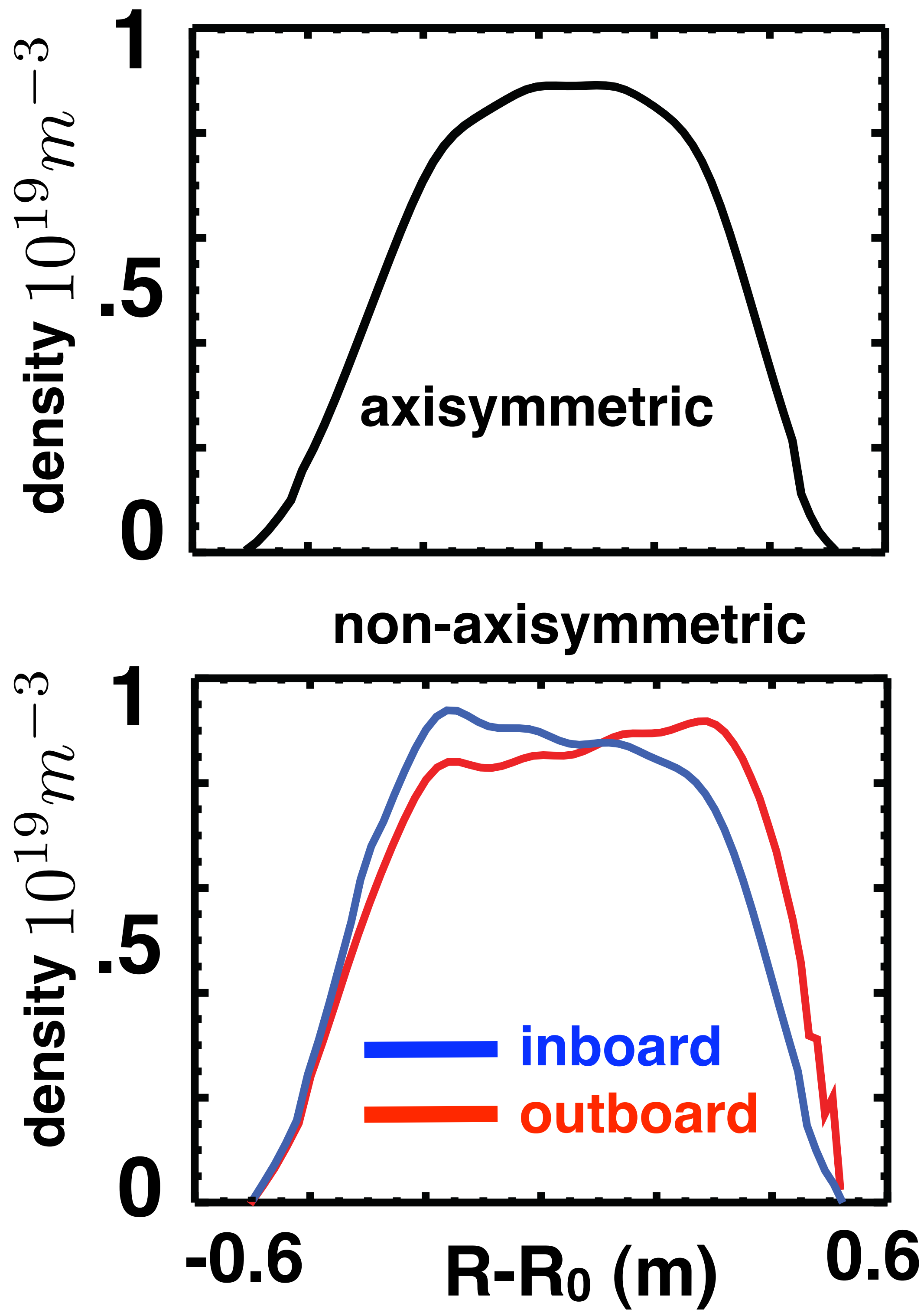
- **Sign change indicates magnetic axis movement**

- **Current in outer half of vessel increases**



Helical core alters density profile



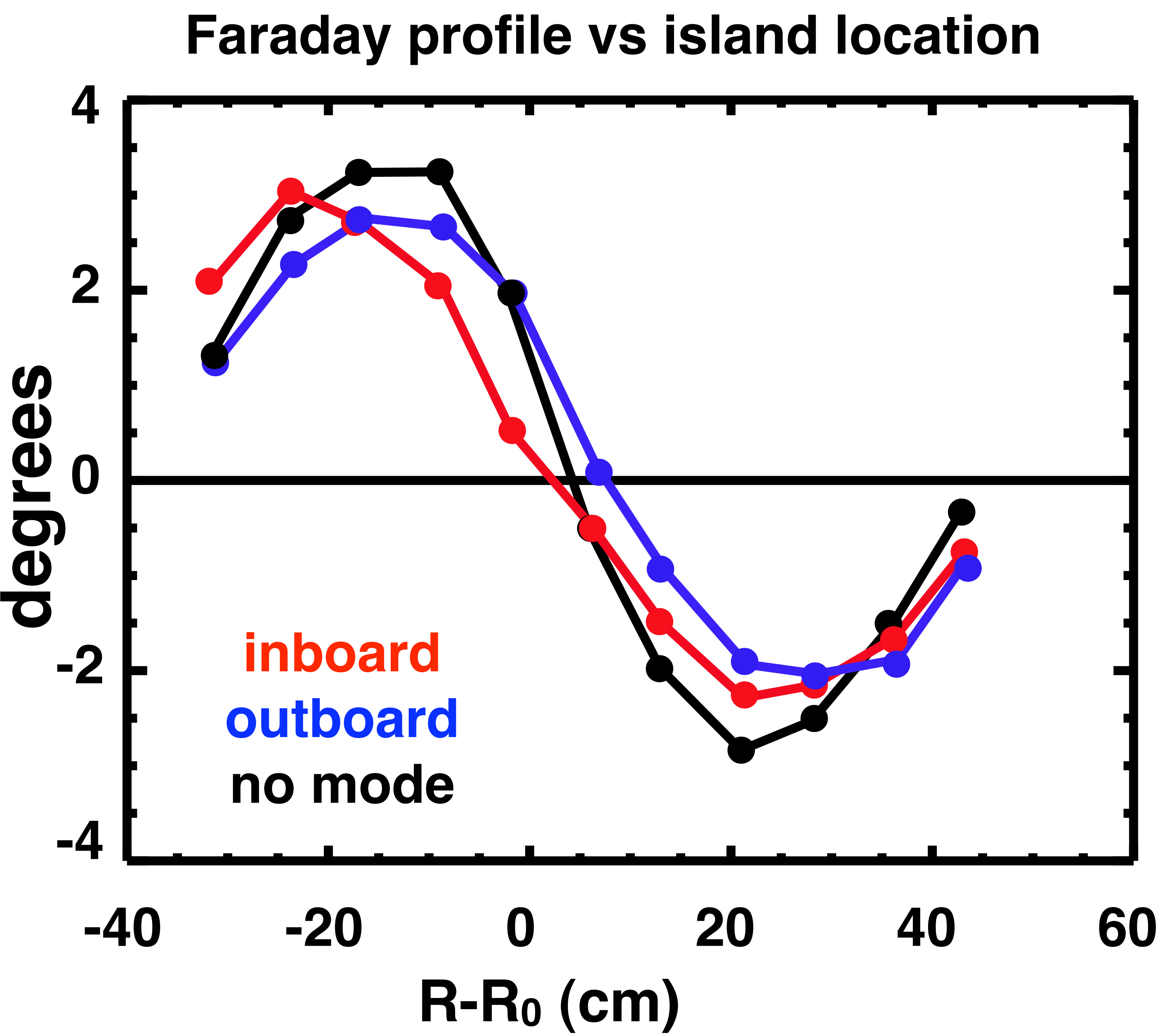


Abel inversion with mode in different positions

Fit produces flux surface gradients and motivates better model

Direct measure of internal helical magnetic structure

Mode location alters profile of Faraday rotation



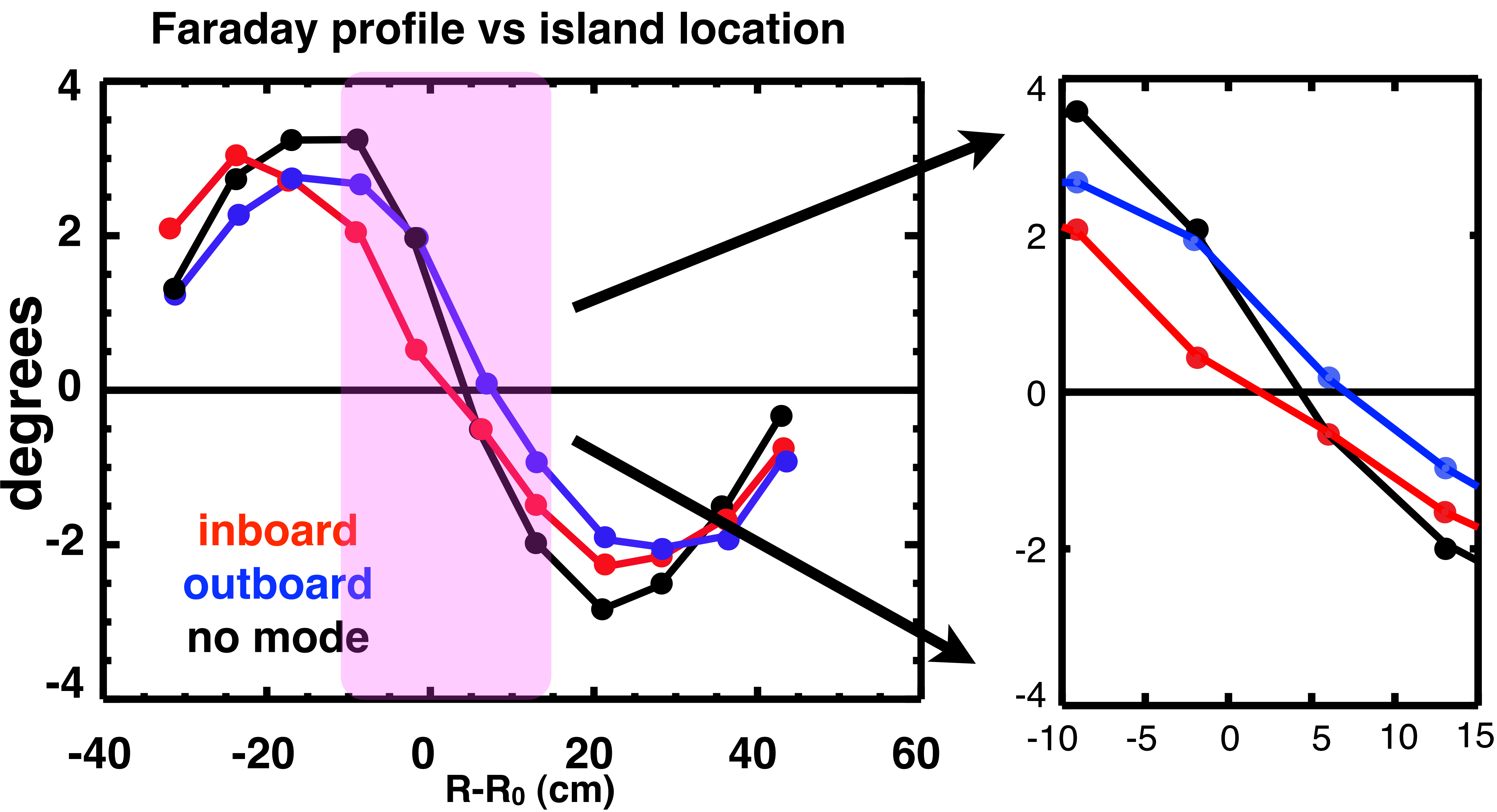
Faraday profile is measured for three conditions

1) **Large mode inboard**
2) **Large mode outboard**
3) **no mode (control case)**

1) Measurement of axis shift highlights

- **sensitivity of diagnostic**
- **ability to resolve helical effect in plasma core**

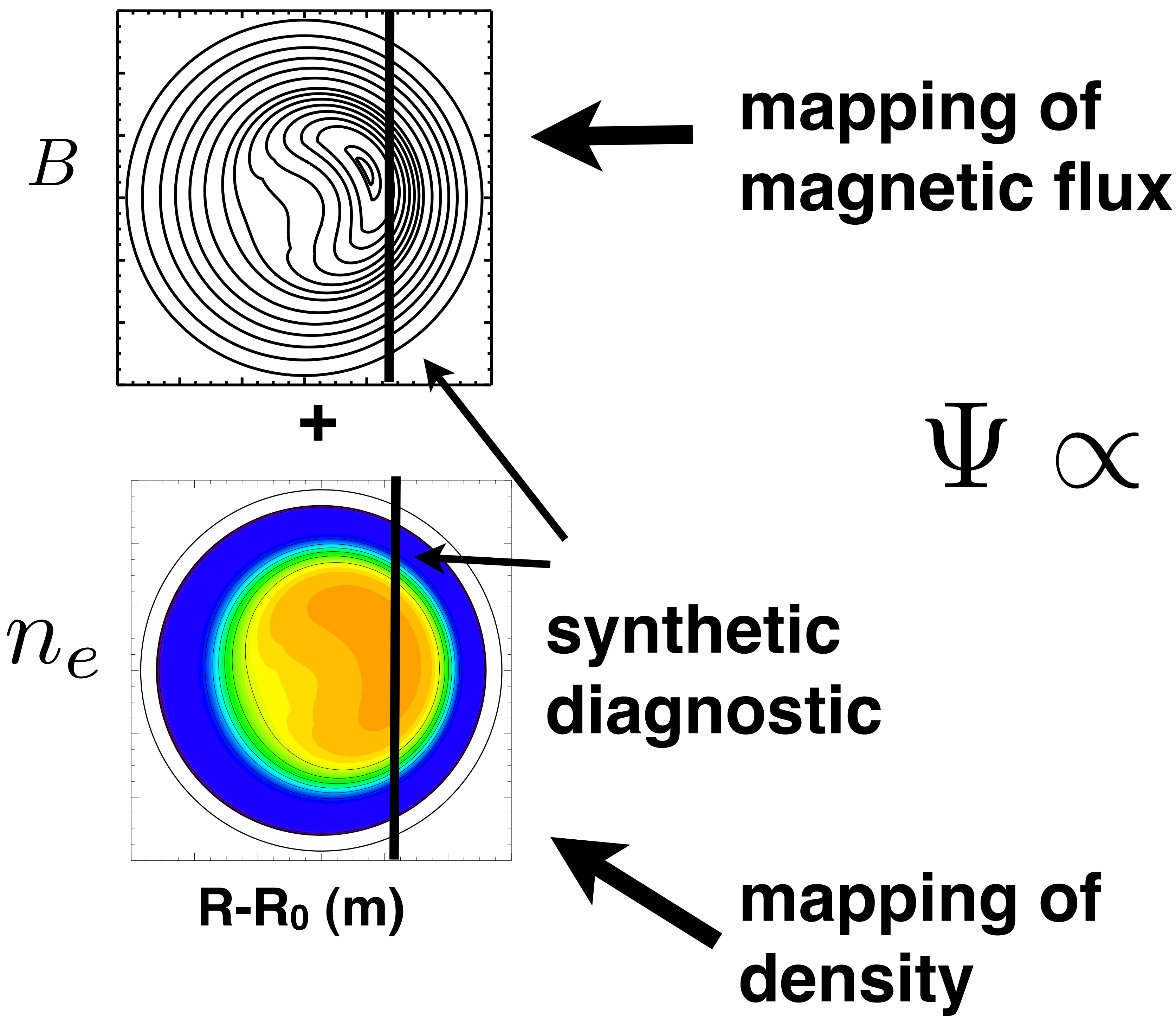
Mode location alters profile of Faraday rotation



zero - crossing moves -> magnetic axis shifting

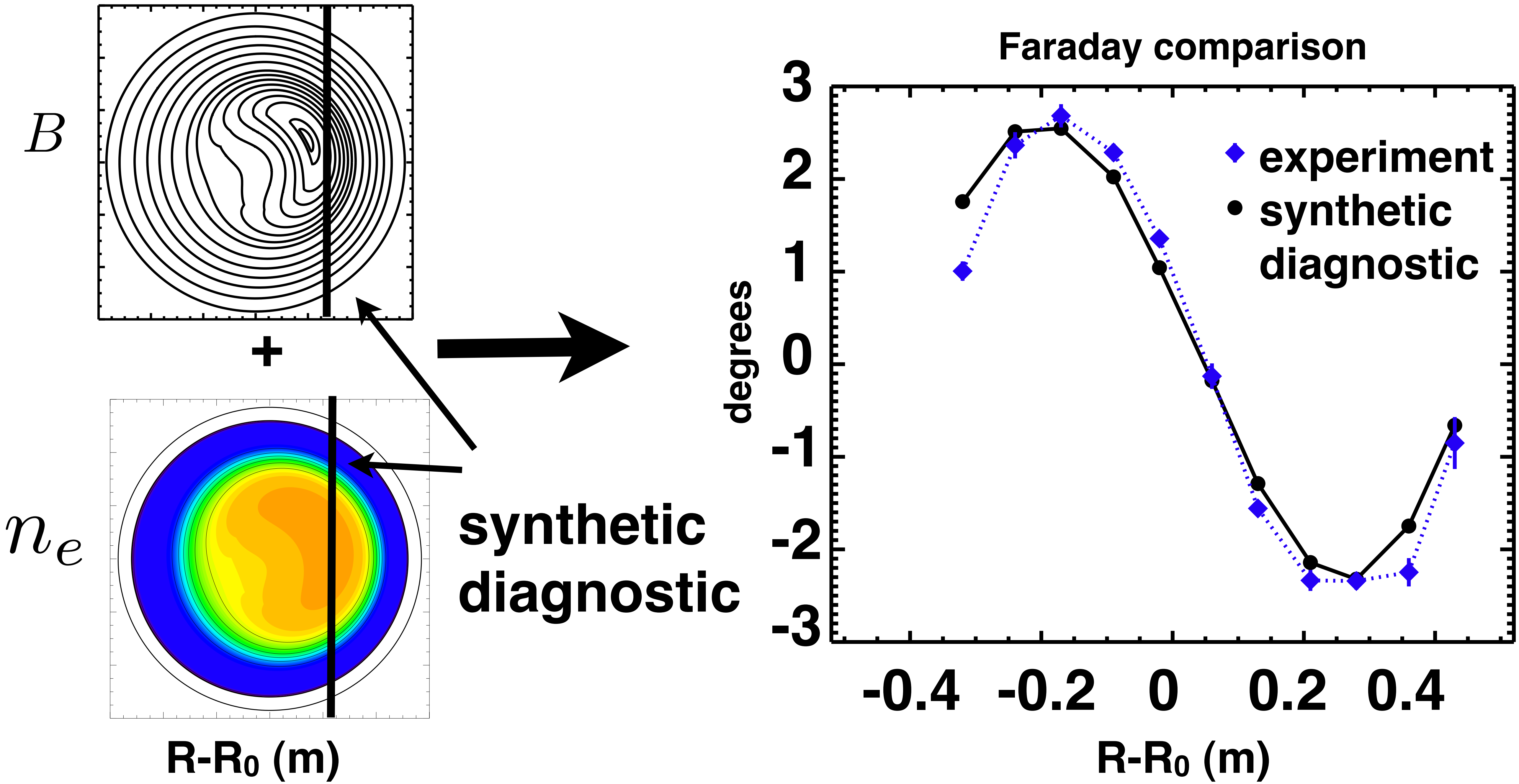
steeper slope without helical core -> higher current density in core

Helical reconstruction probed with synthetic diagnostics



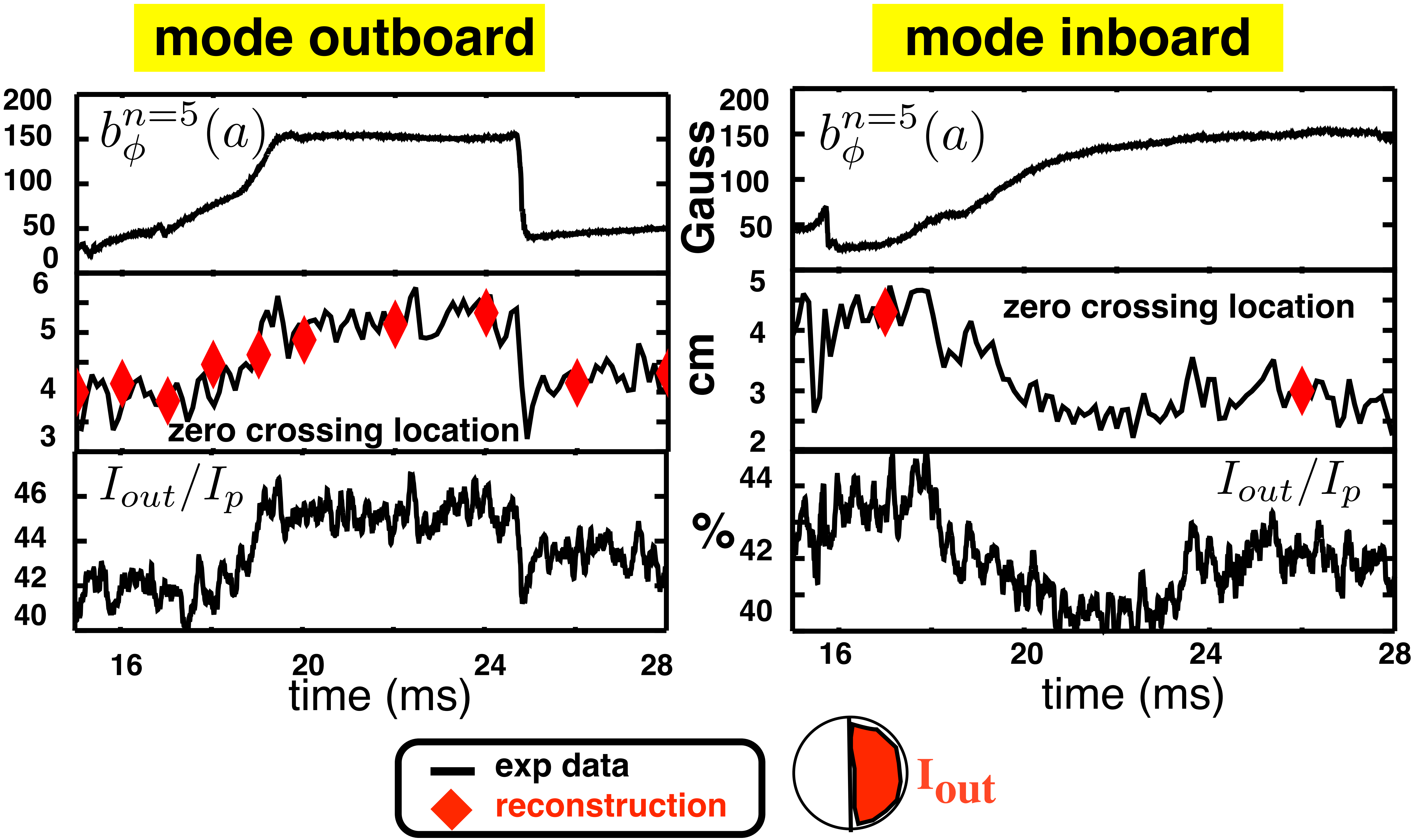
$$\Psi \propto \int n_e B \cdot dl$$

Faraday rotation confirms helical reconstruction profile



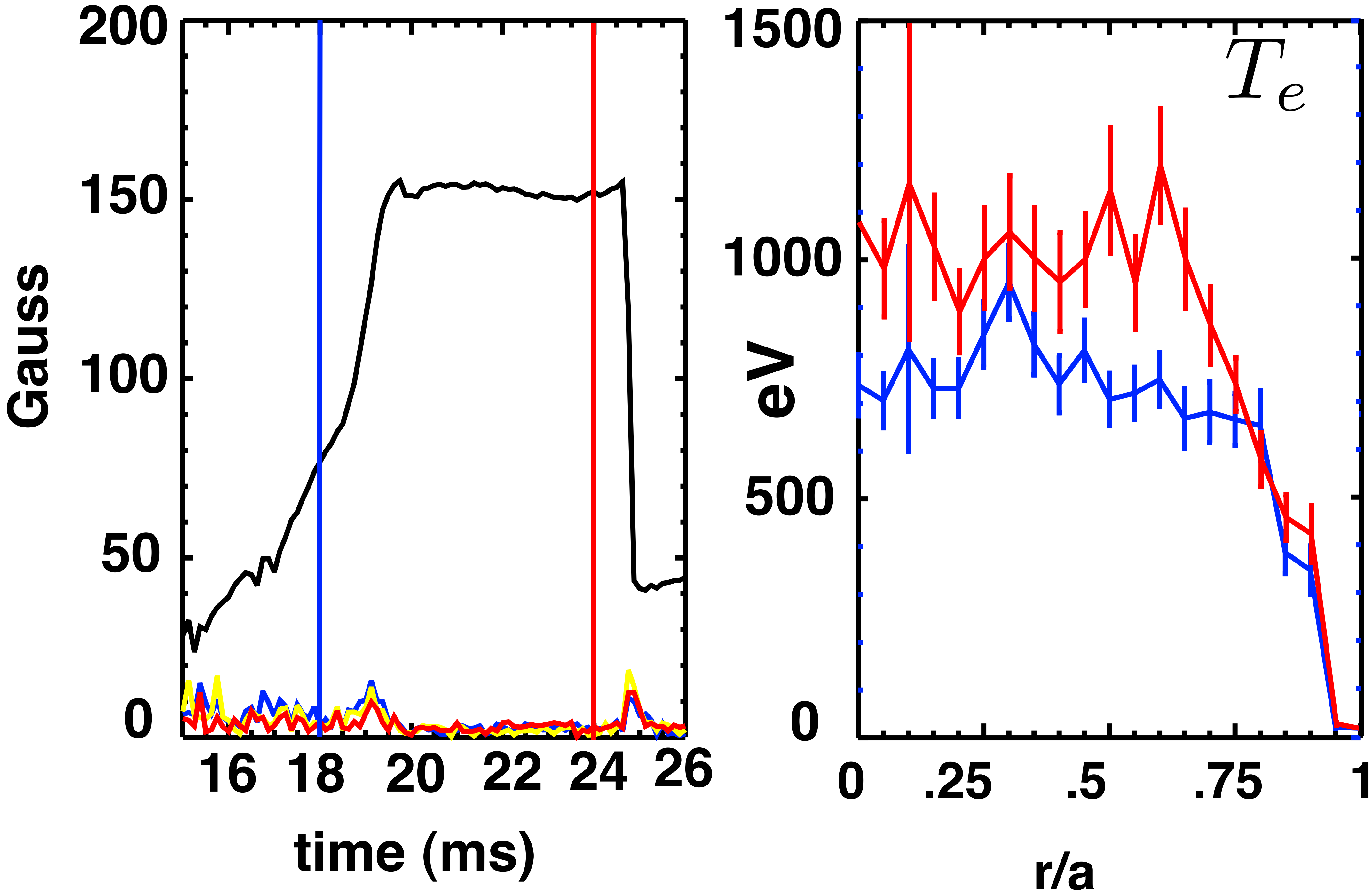
Faraday rotation is not a constraint in reconstruction

Magnetic axis shifts and current accumulates at helix location, inboard or outboard



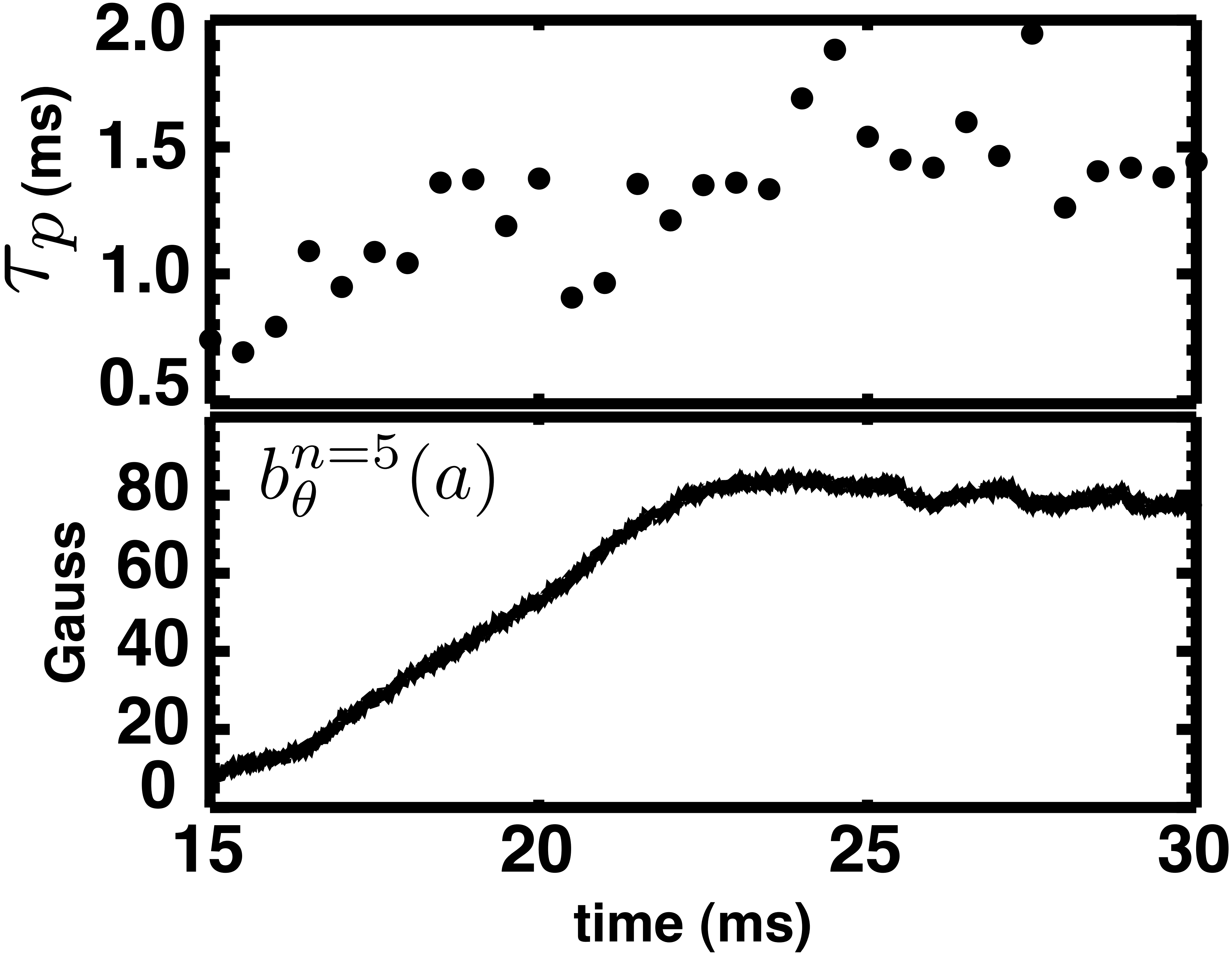
Improved confinement characteristics with a helical core

Central temperature increases with helical equilibrium



T_e ~50% hotter in helical equilibrium

τ_p improves ~50% with core helical structure



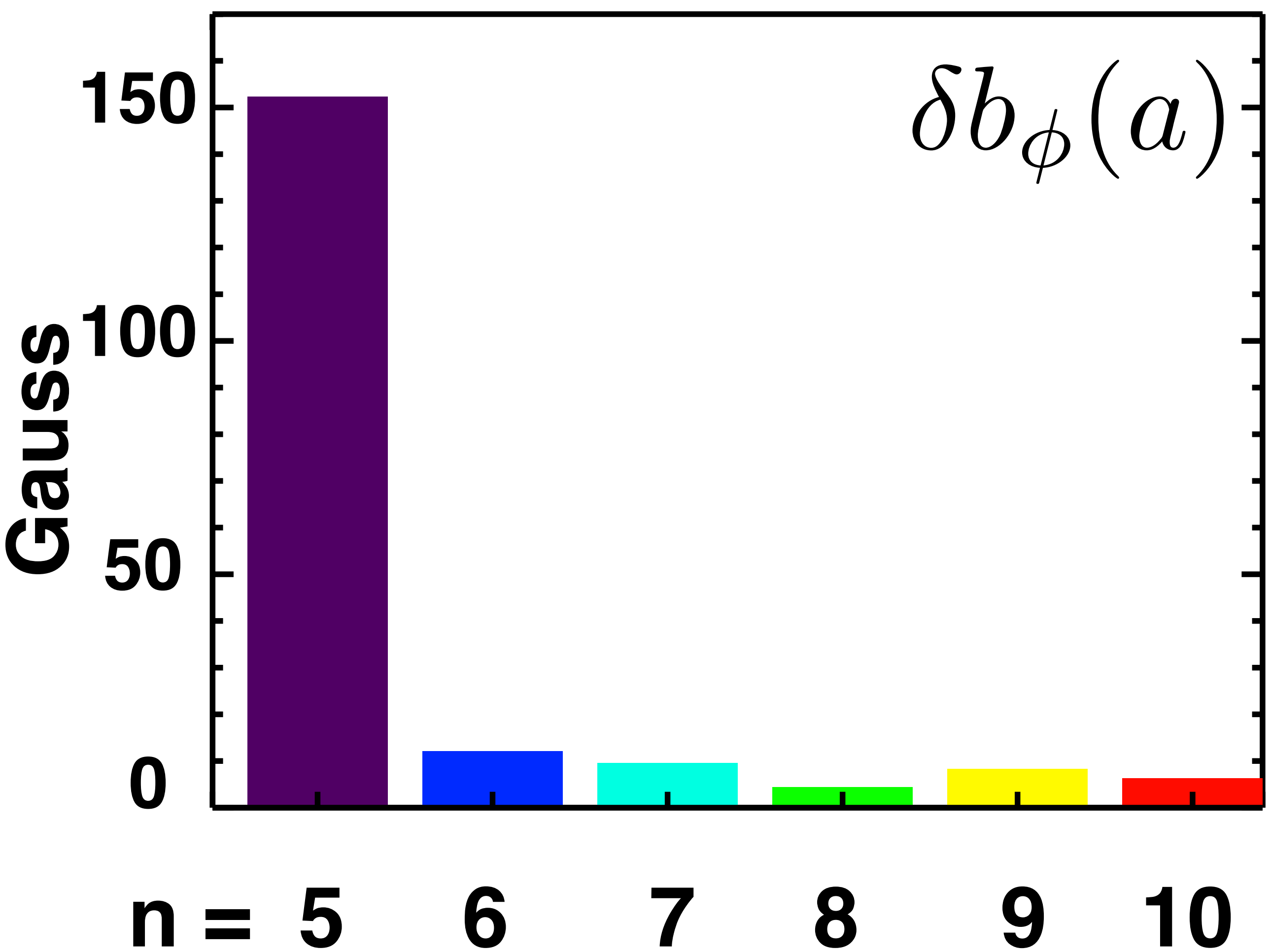
$$\tau_p = \frac{N_e}{S - \frac{dN_e}{dt}}$$

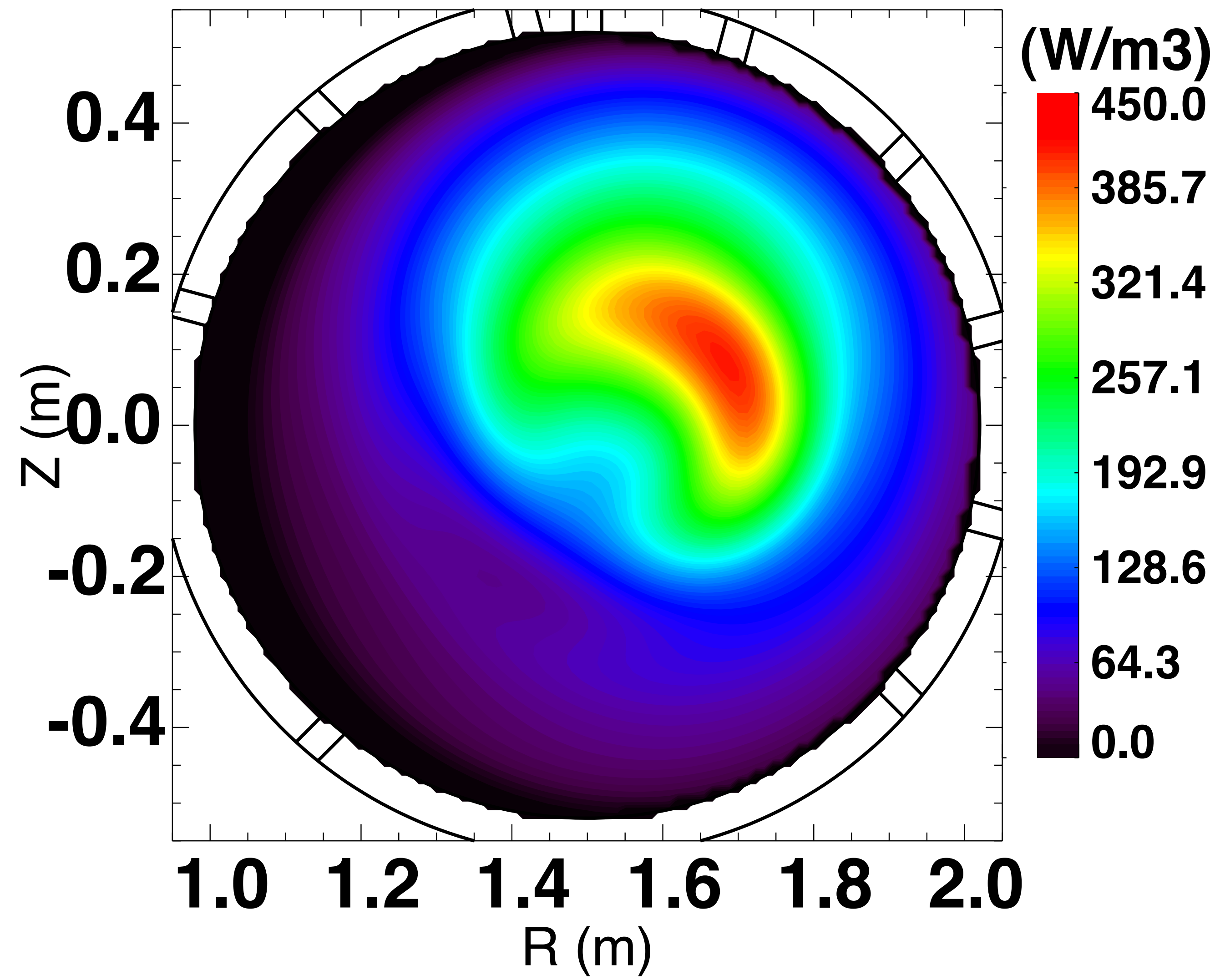
Conclusion

- **Identify helical state**
  - Faraday rotation and density measurements provide direct measurements of helical core
  - Spontaneous helical self - organization observed in current and magnetic flux in core

- **Improved plasma performance in helical state**
  - Hotter electron temperatures in plasmas observed
  - Increased global particle confinement time

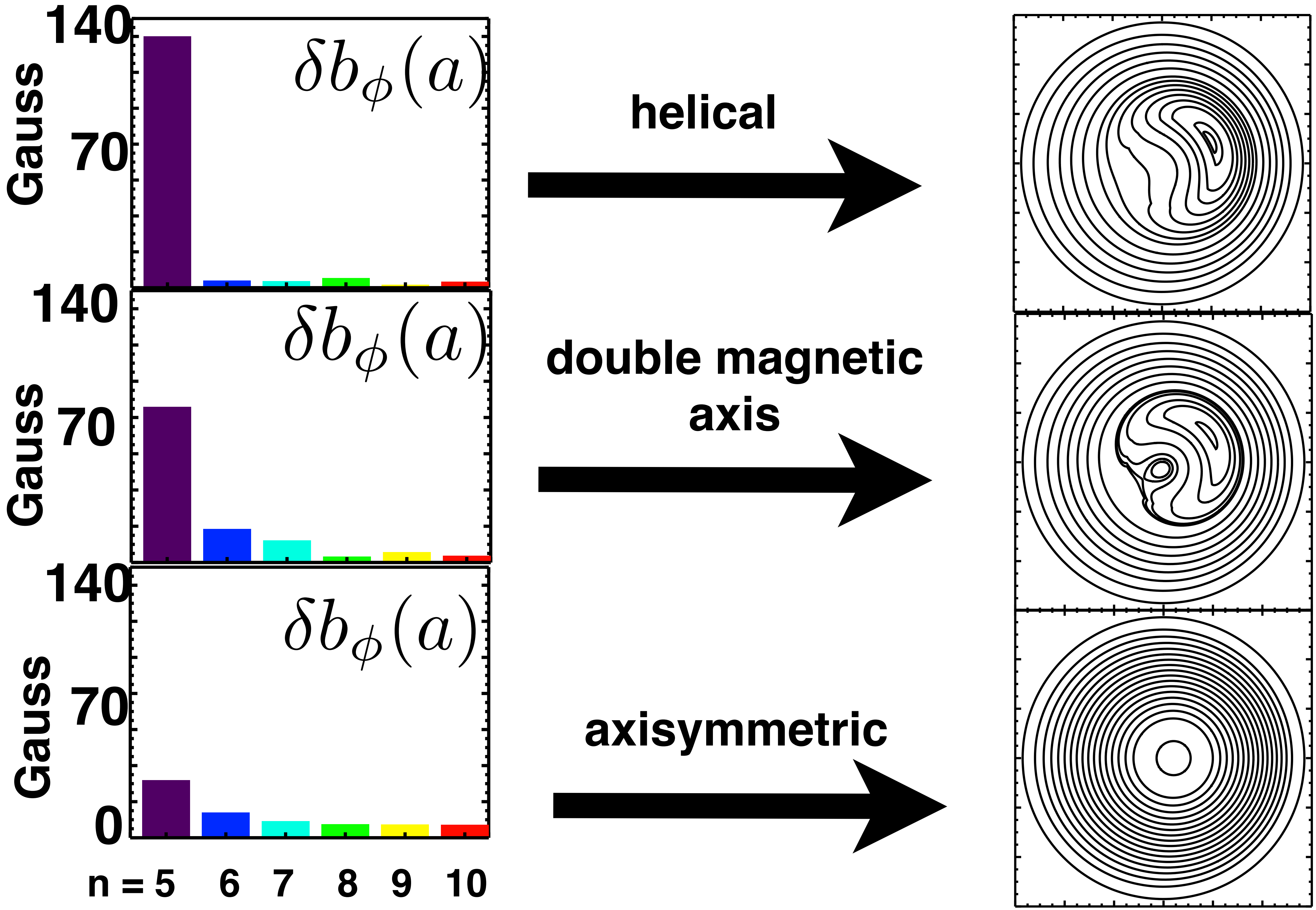
Non-axisymmetric profile seen with SXR tomography



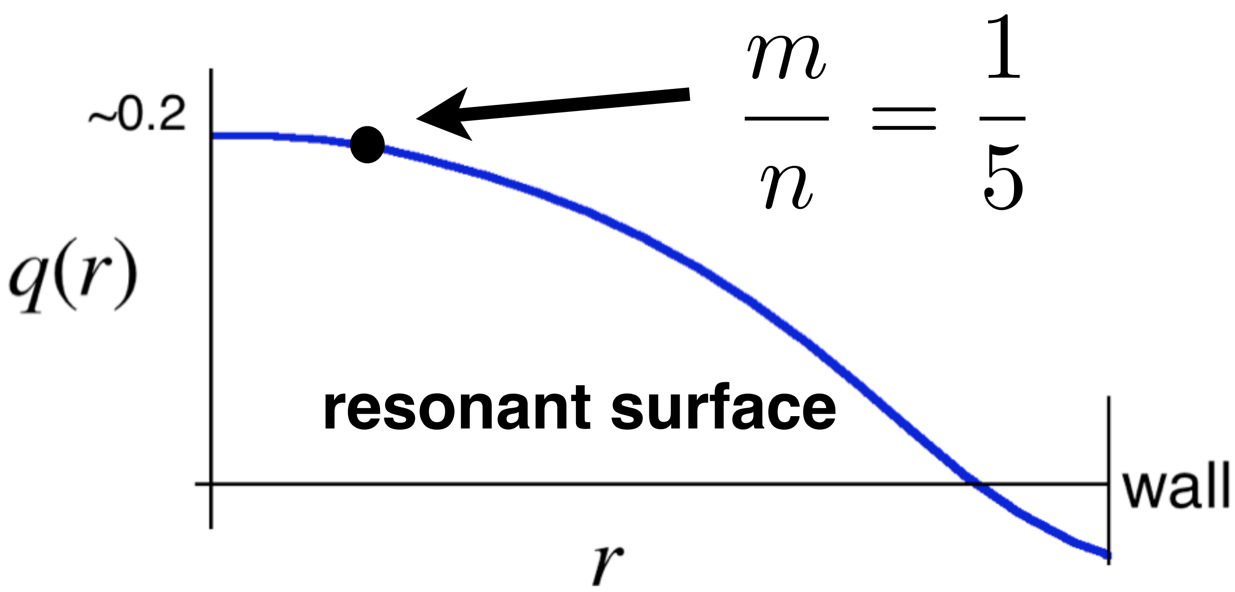


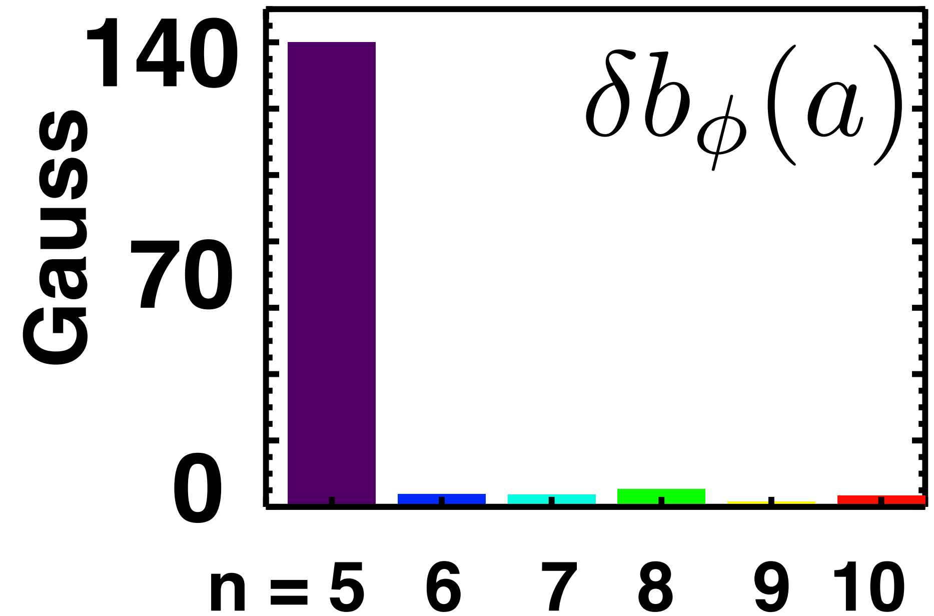
Diagnostic at a single poloidal cross section
View constructed from 2 arrays

As mode amplitude increases, equilibrium becomes helical



Helical magnetic reconstruction





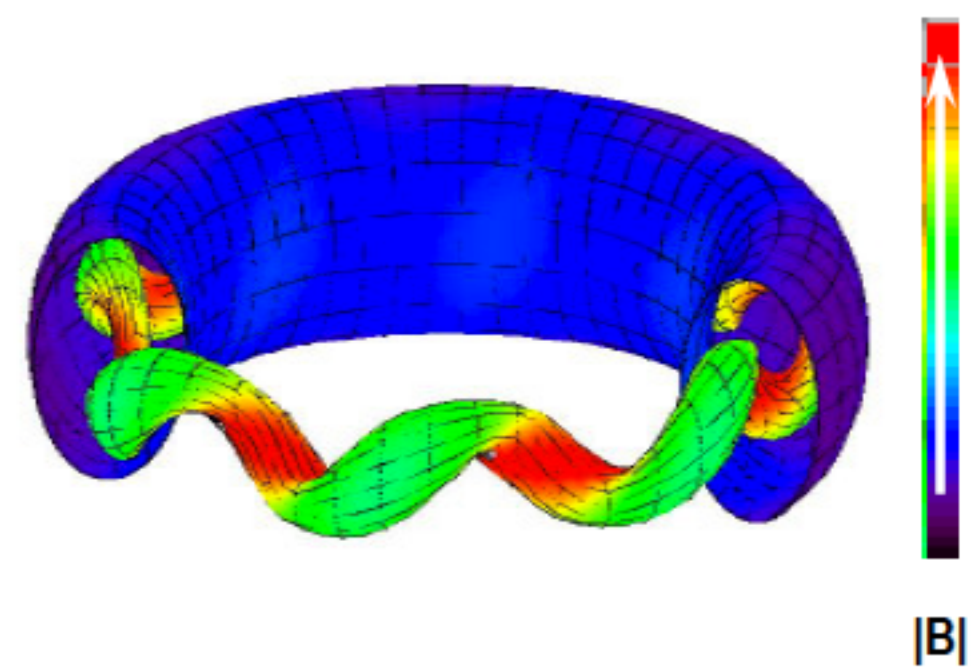
Axisymmetric equilibrium computed with a cylindrical model constrained by poloidal and toroidal fields

+

Non-axisymmetric contribution computed by solving Newcomb's equation in toroidal geometry for the eigenfunction of the dominant mode

Result is 3D helical equilibrium

=



Density reconstruction with helical equilibrium

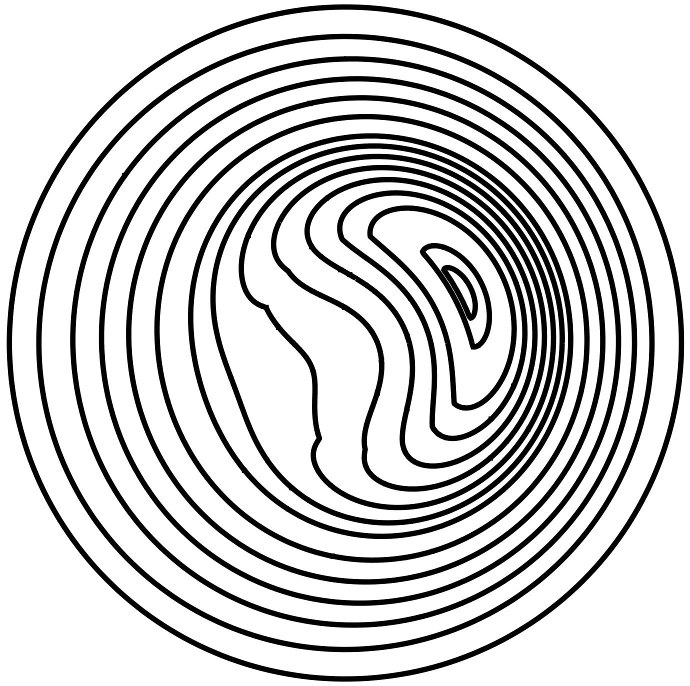
1. Magnetic flux reconstruction is basis set for density

2. Density constant on flux surface and assigned a value

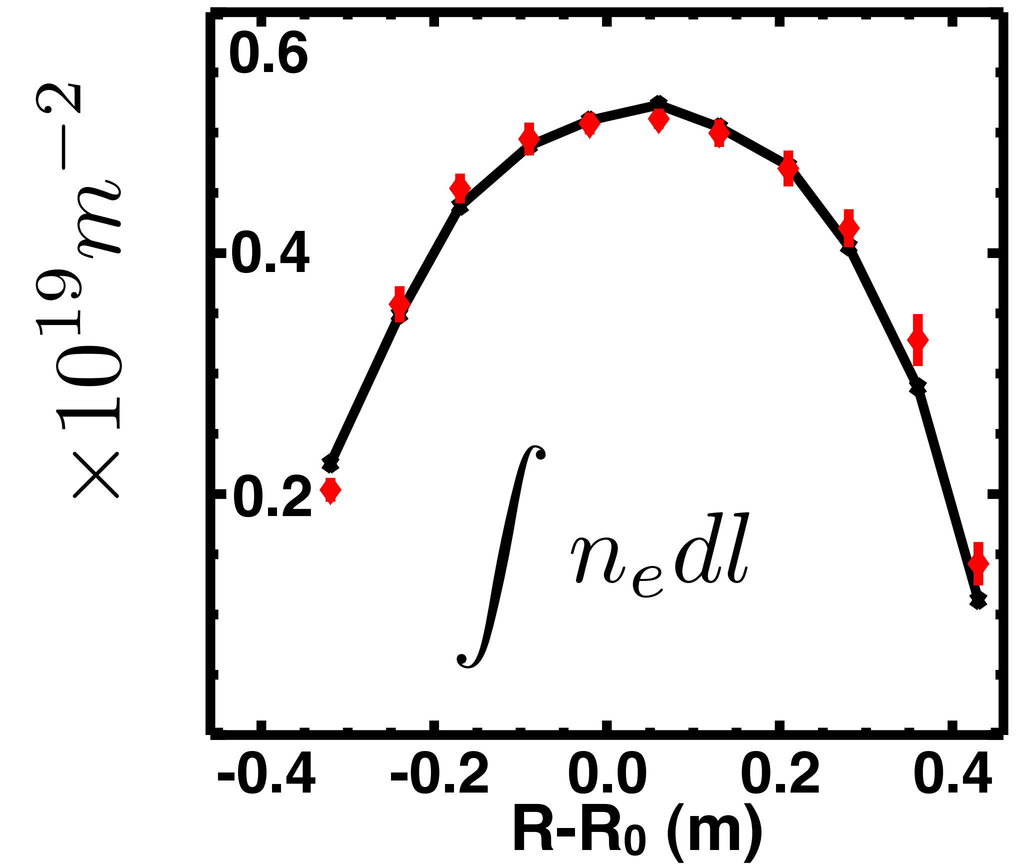
3. Difference between model and measurement minimized

4. Helical basis (χ^2= 155) fits measurement better than axisymmetric model (χ^2= 273)

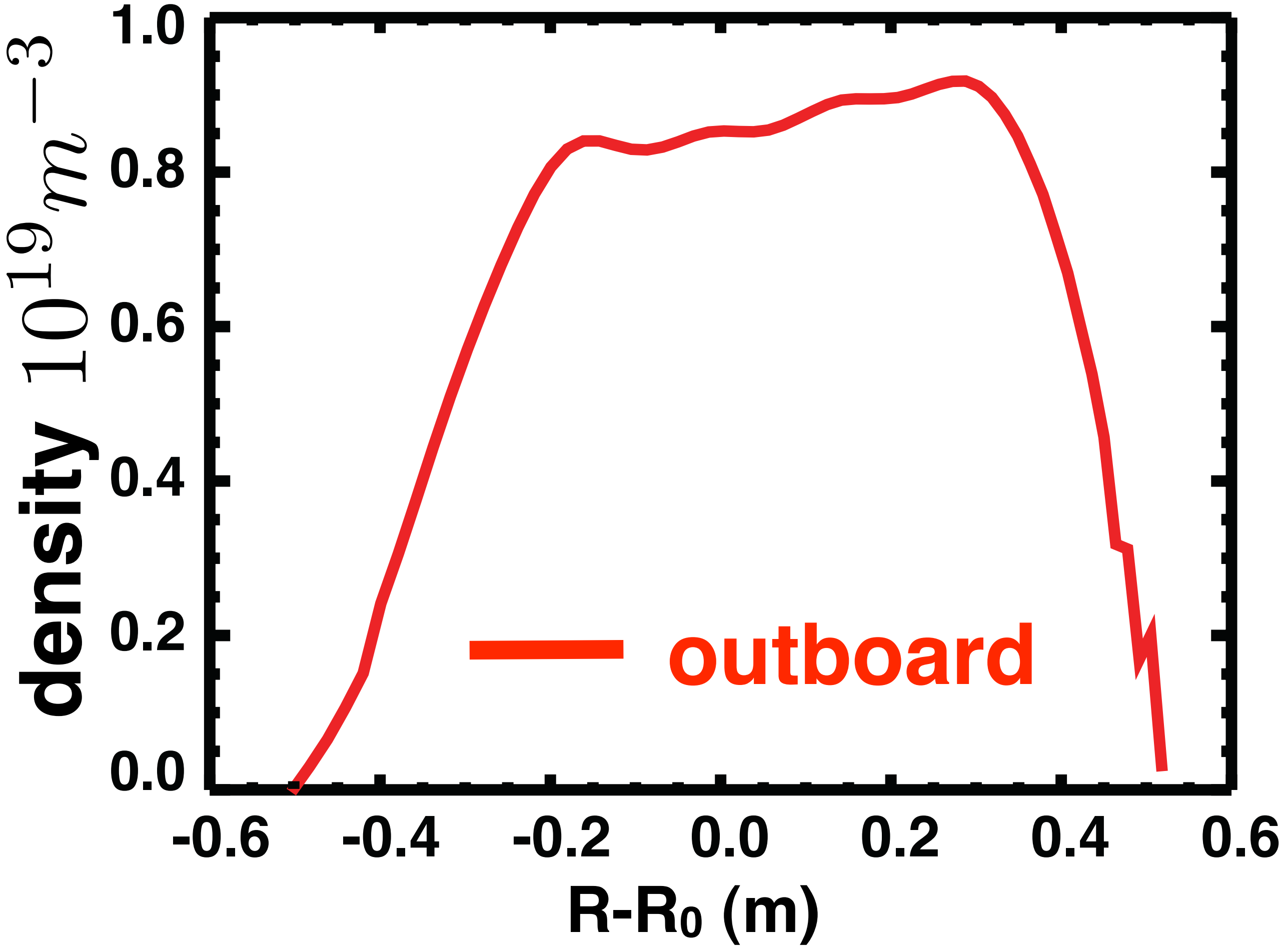
5. Final reconstruction is a 2D cut of helical fit

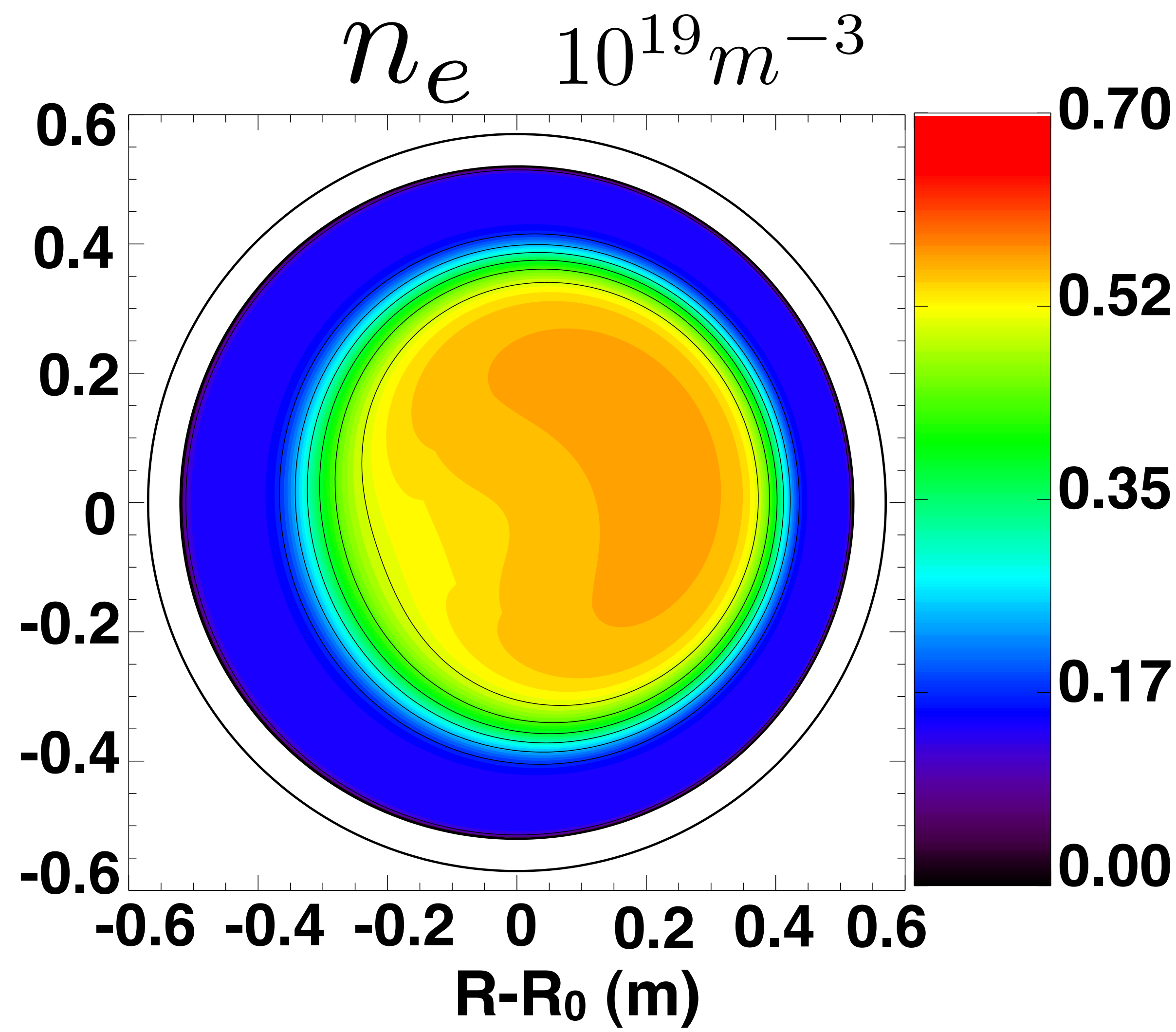


inverted (helical) and experimental data



3D density inversion reveals helical core





- **axisymmetric**
- **density gradient on flux surface**
- **up / down symmetry**

- **helical equilibrium**
- **constant density on flux surface**
- **better fit to data**