Centrifugal and Fast-Ion Effects on Poloidal Impurity Density Asymmetries in Tokamaks

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OAK RIDGE INSTITUTE FOR SCIENCE AND EDUCATION
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Alcator C-Mod

“He's mad that trusts in the tameness of a wolf(ram)”

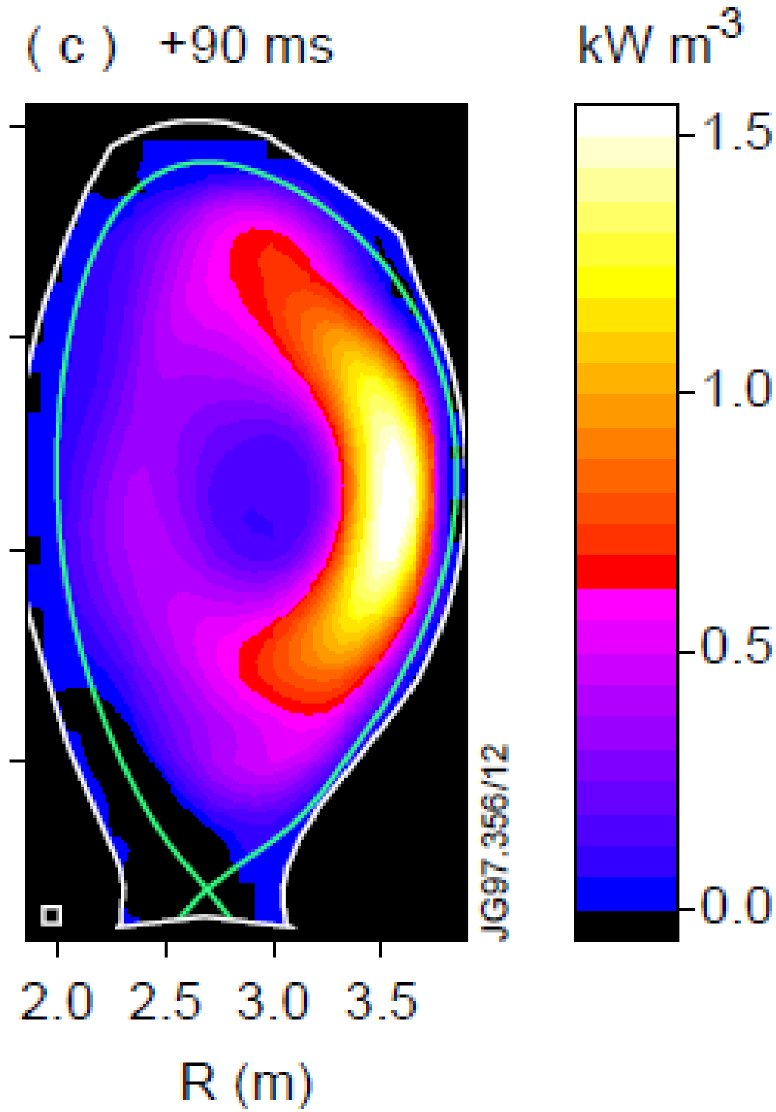
The JET ITER-like Wall Project is a Important Step Towards a Reactor

- bold programmatic decision making
- well planned and executed engineering and physics tasks

Operational Changes with High-Z PFCs

- tokamak response to startup/fueling
- high-Z response to ICRF heating
- looming worry of permanent damage

characterizing high-Z impurities requires different techniques and involves physics that drive poloidal imp. density variation



Overview

- Neoclassical Parallel Impurity Transport Physics*
  - qualitative & quantitative explanation of asymmetry drives
  - examples of strong in/out high-Z impurity asymmetries
- Alcator C-Mod Diagnostic and Analysis Techniques
  - 2-D Tomography using horizontally viewing arrays
  - measurements of low-order poloidal variation of n_z
  - comparisons to predictions of low-order poloidal variation
- Possible Impacts on Flux-Surface Averaged Radial Transport
- Suggested Diagnostic Upgrades/Modifications for JET

<u>Upfront Apology</u> – will show you your own data…patronizing?

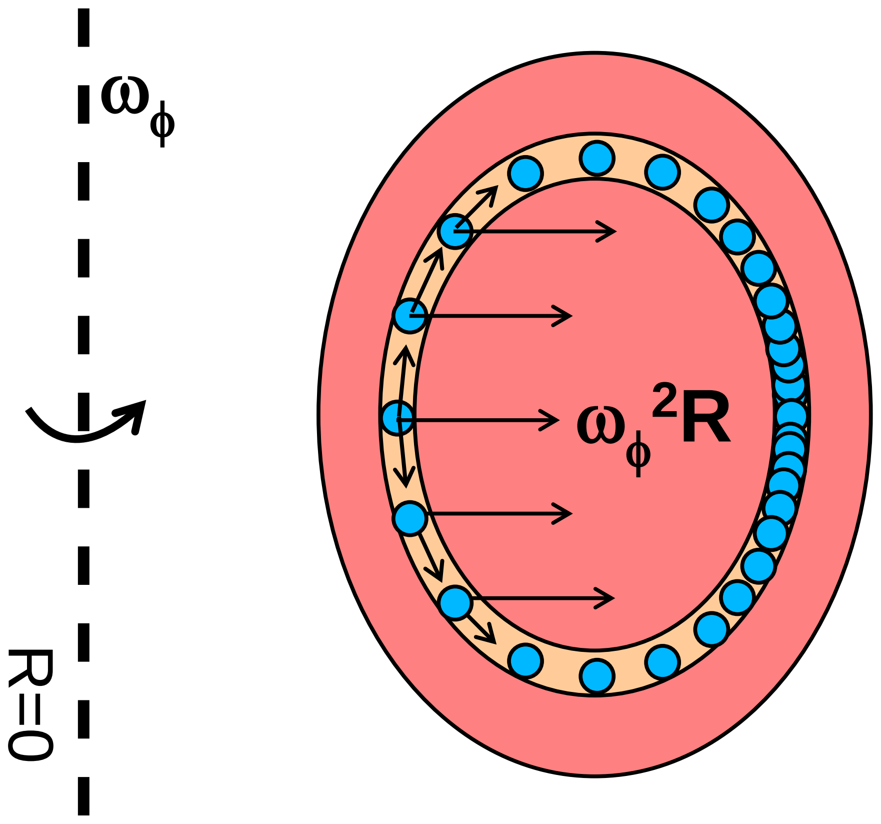
*see M.L. Reinke Ph.D thesis for a review of exp. & theory of density asymmetries in tokamaks

The Centrifugal Force – LFS Accumulation

- for a tor. rotating plasma, centrifugal force pushes ions to the low-field side (LFS) of a flux-surface
- in $v_i/v_{th,I} = M_i \sim 1$ plasmas, impacts main ions (MAST, NSTX)
- effect scales as $m_z\omega^2R^2/T_z$ but since $T_z \sim T_i$, scales with $\mathbf{M_i^2(m_z/m_i)}$
- heavy impurities can vary on a flux surface, $\tilde{n}_z(\theta)/\langle n_z\rangle \sim 0.3$, even in when the main ions are nominally flux surface symmetric, $\tilde{n}_i(\theta)/\langle n_i\rangle << 1$

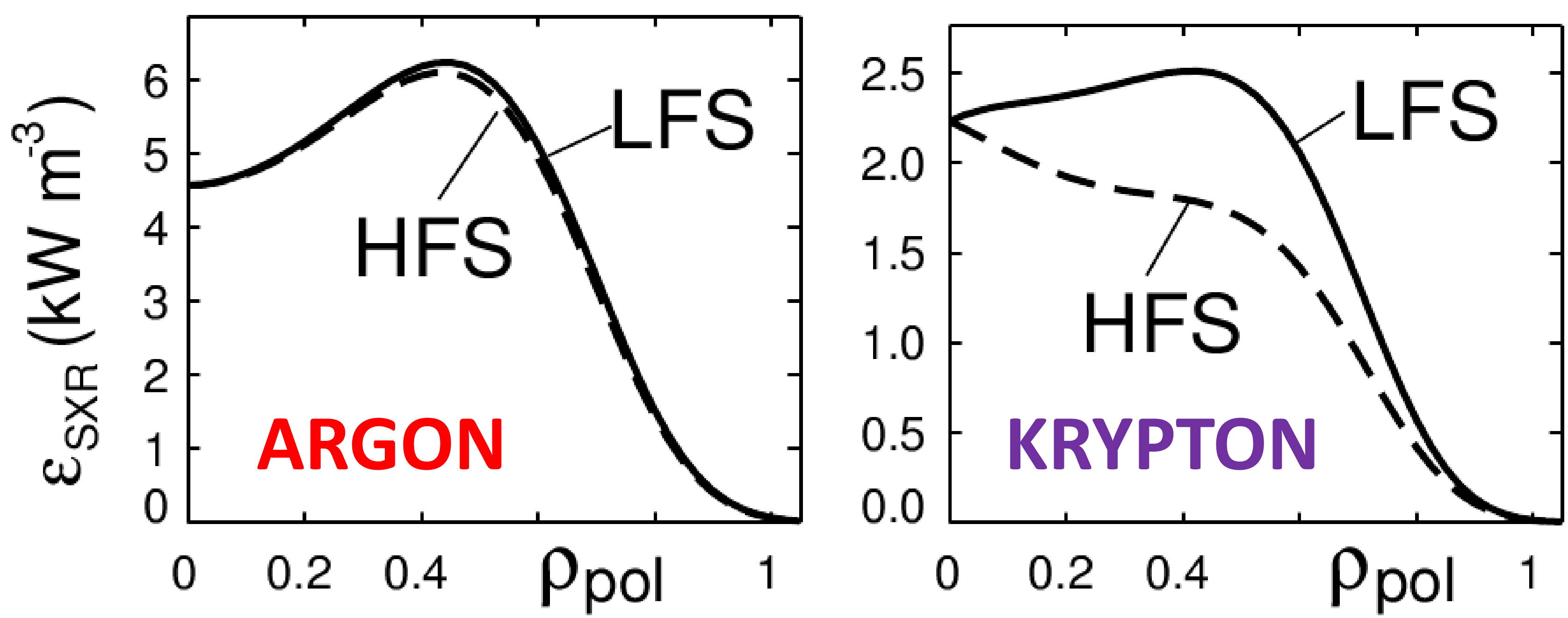
OUTBOARD ACCUMULATION

centrifugal force from toroidal rotation moves impurities to LFS



LFS Accumulation in AUG Soft X-rays

- Importance of inertia in parallel transport known since the 70's [Hazeltine and Ware 1976] and discussed w/r/t impurities repeatedly [Burrell 1981, Wong 1987, Wesson 1997, Helander 1998]
- Effect first observed on ASDEX [Smeulders 1986], viewing brem. and Fe emission in a NBI-heated ELM-free H-mode plasmas (M_i ~ 0.5)
- Seen on ASDEX-U in mid/high-Z impurity seeded plasmas (below) with strong neutral beam heating [Dux – 1999]



LFS Accumulation in JET Soft X-rays

- JET has observed and studied LFS accumulation of impurities [Gianella 1992, Alper 1996, Ingesson 98, 2000, Chen 2000]
- used 6-camera, 210 ch. SXR tomography diagnostic
- $V_z/v_{th,z}$ ~ 4 in hot-ion H-mode led to strong in/out asym. of Ni emission from LBO
- completed the first comparison to theory

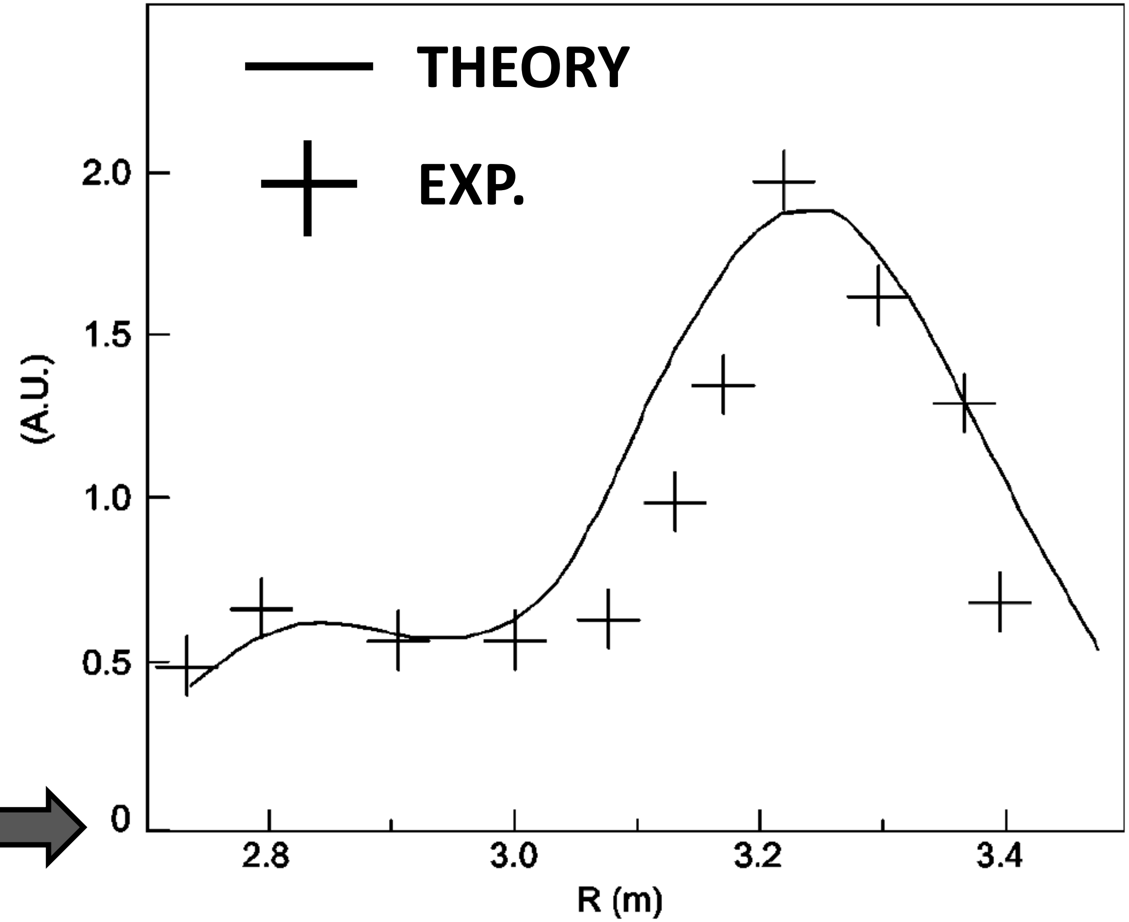


FIG. 4. Ni density derived from the soft x-ray emissivity at t=6.72 s (cross) and calculated Ni density at the same time (line).

H. Chen, *et al*. Phys. Plasmas **7** 4567 (2000)

But did this include all the necessary physics?

Fast-Particle Driven Poloidal Elec. Fields

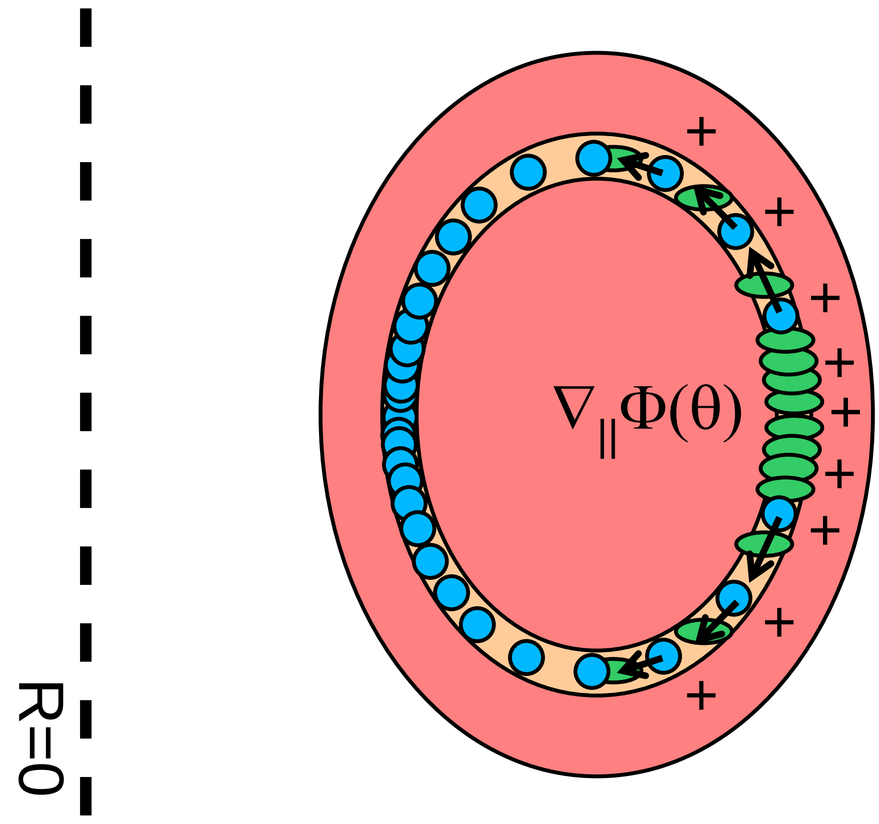
- the high charge of imp. leads to sensitivity to poloidal variation of electrostatic potential

$$n_z/\langle n_z \rangle = \exp[-Ze\Phi(\theta)/T_z]$$

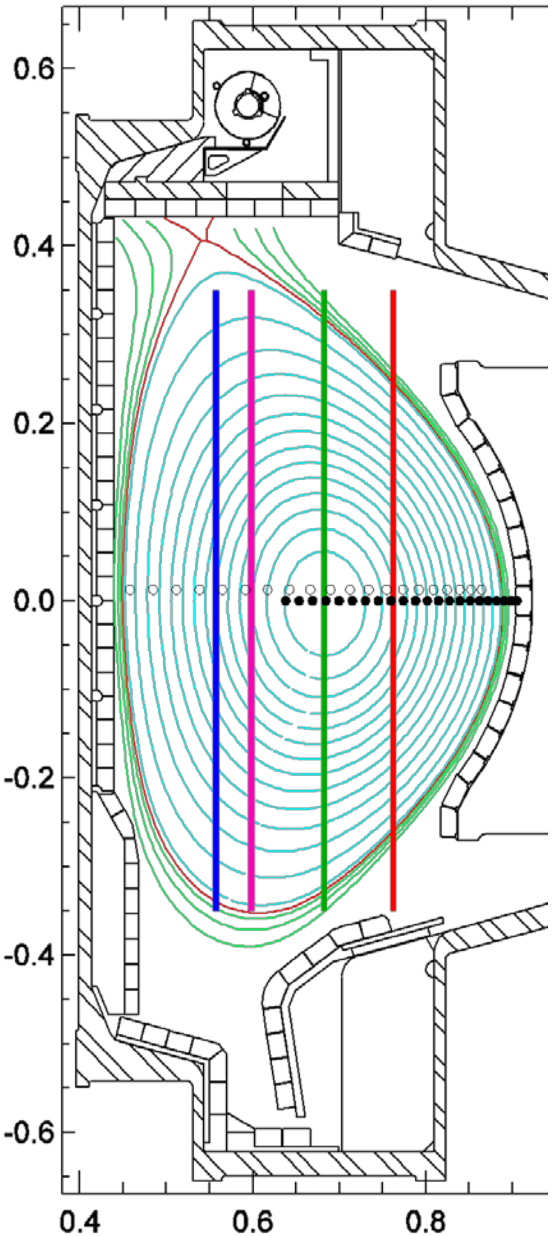
- first exp. observation in ICRF-heated Ni LBO shots on JET [Ingesson – 2000]
- should also be an effect from neutral beam ions and ECRH electrons

INBOARD ACCUMULATION

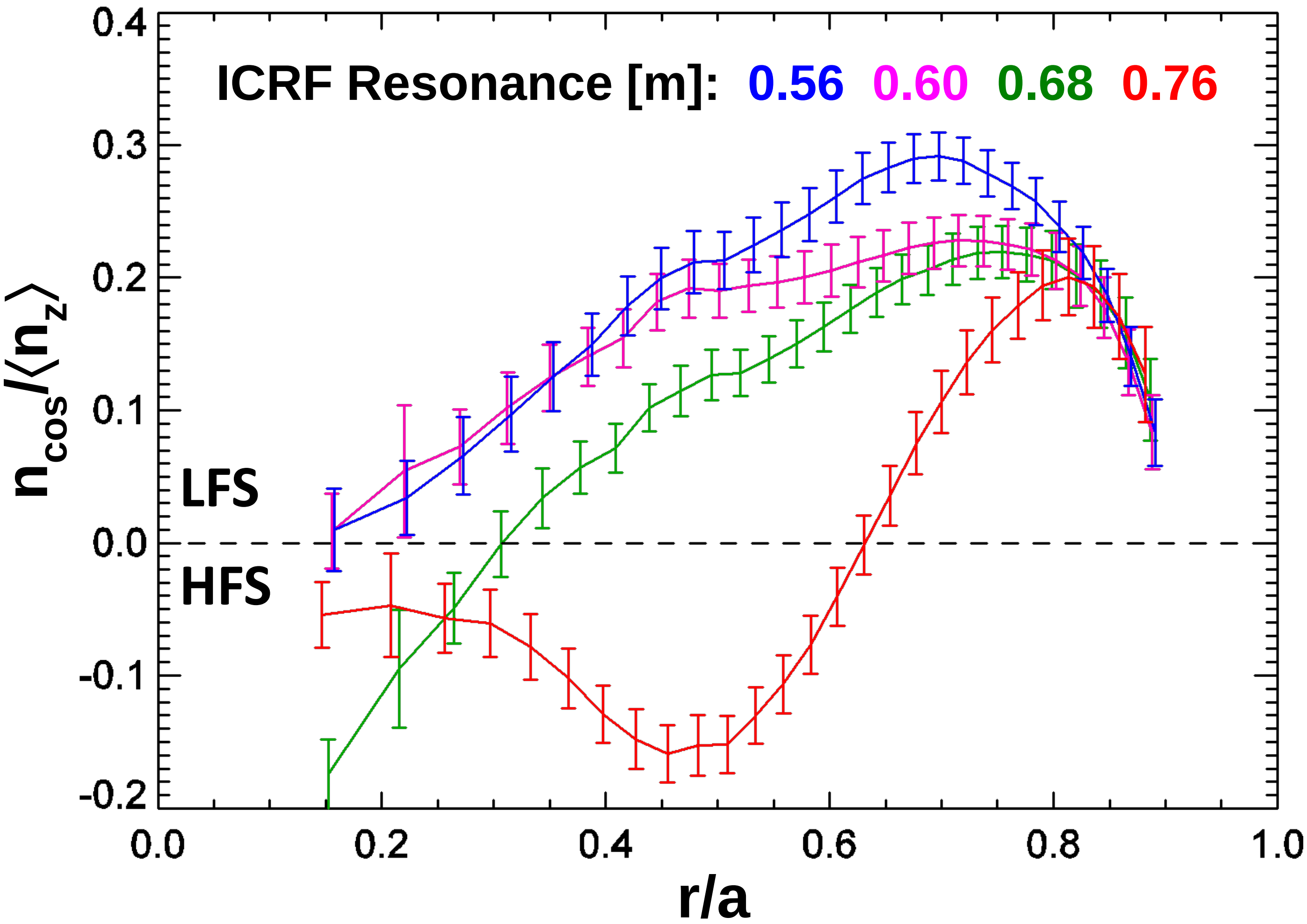
electric field from rf-heated minority ions moves impurities to HFS



HFS Accumulation in C-Mod Radiation



- scanning D(H) resonance layer modifies minority trapping leading to in/out Mo asymmetry balance of inertia + electrostatic



HFS Accumulation in JET Soft X-rays

- evidence of neutral beam fast-ion effect exists
  - AUG: wrong m_z scaling
  - JET: Z_{eff}, ICRF ignored
- early JET asymmetry experiments showed difference between co/counter beam heating
  - reduced LFS accumulation for co-injected
  - observation of HFS accumulation in weakly rotating co-injected

R. Gianella 19th EPS Conf. Proceedings (1992)

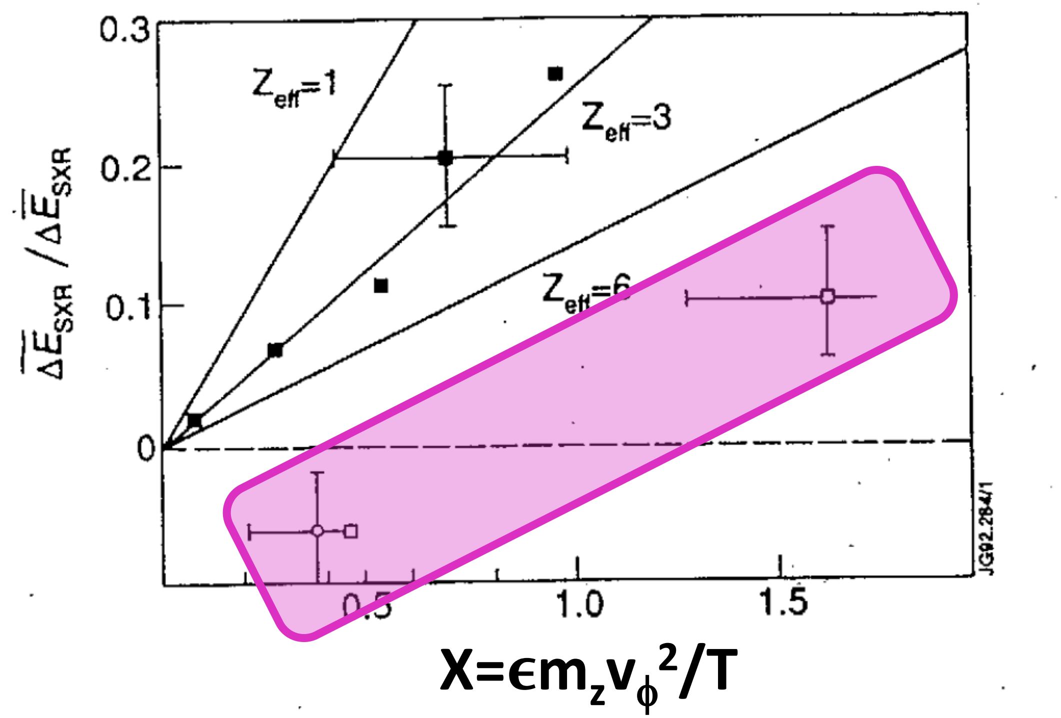


Fig. 4 Relative in/out modulation of the soft X-ray emissivity perturbation after metal injection in beam heated plasmas. ■ Ni, ctr.-inj.; ▯ Ni, co-inj.; ⓒ Fe, co-inj. The straight lines represent the prediction of eq.(1) for different values of Zeff in D plasma.

State of ||-Impurity Transport Validation

$$\underbrace{\frac{m_z n_z \omega^2}{2}\nabla_{||}R^2}_{\text{inertia (centrifugal)}} + \underbrace{Z n_z e \nabla_{||}\Phi}_{\text{electrostatic}} + \underbrace{T_z \nabla_{||} n_z}_{\text{pressure}} = \underbrace{R_{z,||}}_{\text{friction}}$$

inertia: widely observed, understood for strong flows, possible issues $(\mathbf{v}\cdot\nabla)\mathbf{v}$ for $v_\theta/v_\phi \sim 1$

electrostatic: non-thermal particle densities lead to $\Phi(\theta)$ with $Ze\Phi(\theta)/T_e \sim 1$, demonstrated for ICRH, need to validate for ECH and NBI

pressure: assumed to be all in n_z with $T_z(\theta)$

friction: disagreements seen, critical for setting $v_{\theta,z}$ and interpreting $v_{\theta,i}$ from CXRS/XICS

other: sources/sinks, C-X at large minor radii

Analytical Theory for ICRH + Inertia

$$\frac{m_z n_z \omega^2}{2}\nabla_{\|}R^2 + Z n_z e \nabla_{\|}\Phi + T_z \nabla_{\|} n_z = \cancel{R_{z,\|}}$$

THERMALIZED IONS

$$n_a = \langle n_a \rangle \exp\left[-\frac{Z_a e\tilde{\Phi}}{T_a} + \frac{m_a\omega^2}{2T_a}\left(R^2 - \langle R^2\rangle\right)\right]$$

ELECTRONS

$$n_e = \langle n_e \rangle \exp\left(e\tilde{\Phi}/T_e\right)$$

use quasi-neutrality to find the Φ(θ)

$$\boxed{Z_m n_m + \sum_{j\neq m} Z_j n_j - n_e = 0}$$

for details see: Reinke PPCF **54** 045004 (2012)

Model the fast-ion using a bi-Maxwellian dist. w/ η=(T$_\perp$/T$_\|$ -1)

$$\frac{n_m}{\langle n_m\rangle} = \left\langle \frac{1}{B^\eta}\right\rangle^{-1}\frac{1}{B^\eta}\exp\left(-\frac{Z_m\tilde{\Phi}}{T_{m,\|}}\right)$$

Kazakov PPCF **54** 105010 (2012) has shown a more detailed computation

$$\frac{e\tilde{\Phi}}{T_e} = \left(\langle n_e\rangle + \sum_{j\neq m} Z_j^2\langle n_j\rangle\frac{T_e}{T_j}\right)^{-1}\left[Z_m\langle n_m\rangle\left(\left\langle\frac{1}{B^\eta}\right\rangle^{-1}\frac{1}{B^\eta} - 1\right) + \sum_{j\neq m} Z_j\langle n_j\rangle\frac{m_j\omega^2}{2T_j}\left(R^2 - \langle R^2\rangle\right)\right]$$

$\Phi(\theta)$ From Neutral Beams Needs Investigation

- poloidal electric fields from neutral beam ions have not been thoroughly investigated
- complicated by geometry, beam energy/penatration
  - perp. Injection puts fast-ions on trapped orbits – look like ICRH?
  - no “resonance layer” which localizes the effect
- can this be parameterized as a temperature anisotropy?
  - toroidal NBI leads to $\mathbf{T_{\perp}/T_{||} < 1}$
  - additional LFS accumulation on top of centrifugal force
- can be computed using Monte-Carlo beam modeling codes
- is there a way to get this empirically using FIDA diagnostics?

none of this can be done at C-Mod, requires others to be interested in asym. physics & devote exp. time

Ion-Impurity Friction Links $n_z(\theta)$ and $v_z(\theta)$

$$(1+\alpha_z n)\frac{\partial n}{\partial \vartheta} = g\left[n + \gamma\left(n - \frac{K_z}{\langle n_z\rangle u_i}\right)b^2\right] + \frac{\partial M^2}{\partial \vartheta} n$$

friction + inertia in banana regime: T. Fülöp, *et al.* Phys. Plasmas. **6** 3066 (1999)

- 1D equation for $n=n_z(\theta)/\langle n_z\rangle$ using B.C. $n(0)=n(2\pi)$ defines K_z
- poloidal rotation, $\mathbf{v}_\theta(R,Z)=[K_z(\psi)/n_z(\psi,\theta)]\mathbf{B}$, sensitive to n_z

Comparing with NCLASS assumes n_z doesn't vary on a flux surface

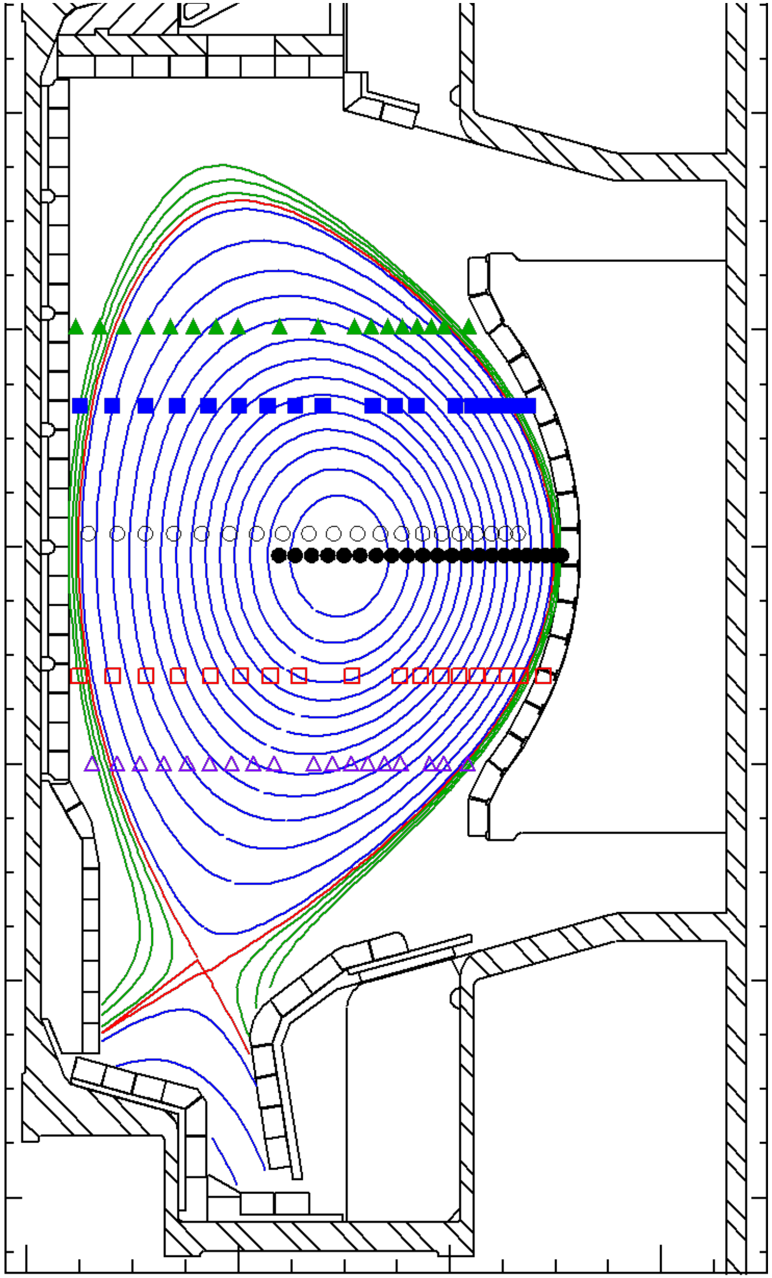
NEO has inertia, need to validate friction and include $\Phi(\theta)$ effects

no evidence of a sig. drive for core high-Z asymmetries

friction thought to be driving HFS acc. of low-Z impurities in the pedestal – important for rad. layer in seeding studies?
[C-MOD: Pedersen – 2002, Marr - 2010, Churchill – 2012 AUG: Putterich – 2012]

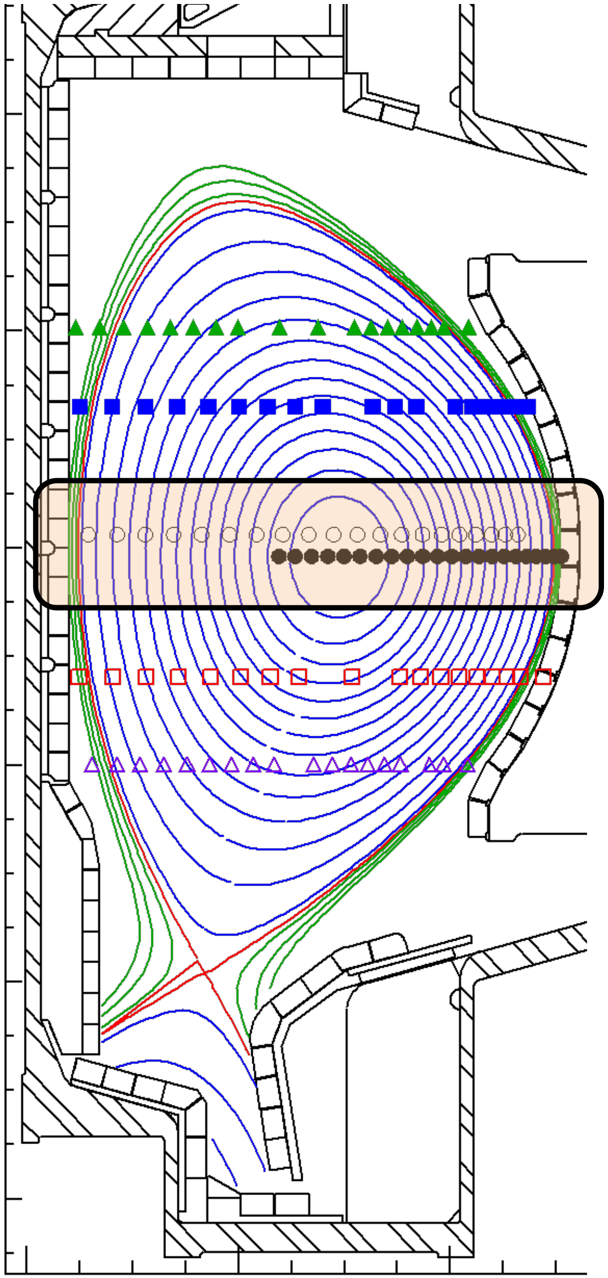
Alcator C-Mod Approach to the Measurement and Study of Poloidal Variation in High-Z Impurities

2D Radiation Measurements in C-Mod



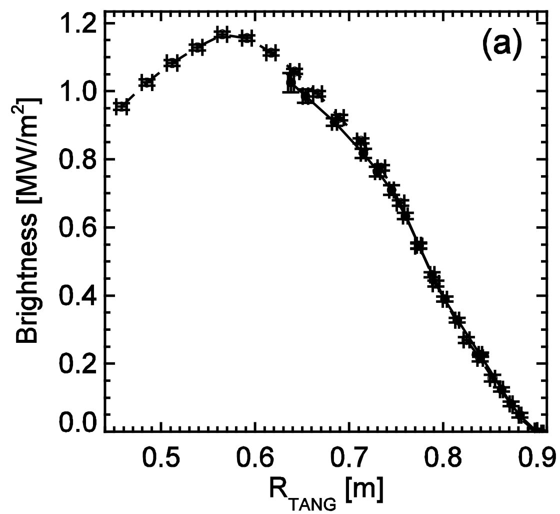
- investigated the 2-D radiation in C-Mod plasmas with significant molybdenum contamination
- use multiple, horizontally viewing pinhole cameras at different heights
  - measure $B(R,Z_o)$, invert each to get $\varepsilon(R,Z_o)$ [in/out asymmetry]
  - combine all cameras to find low-order poloidal variation [in/out & up/down]
- standard poloidal tomography difficult
  - divertor radiation
  - inner-wall MARFE
  - poor HFS/vertical diagnostics access

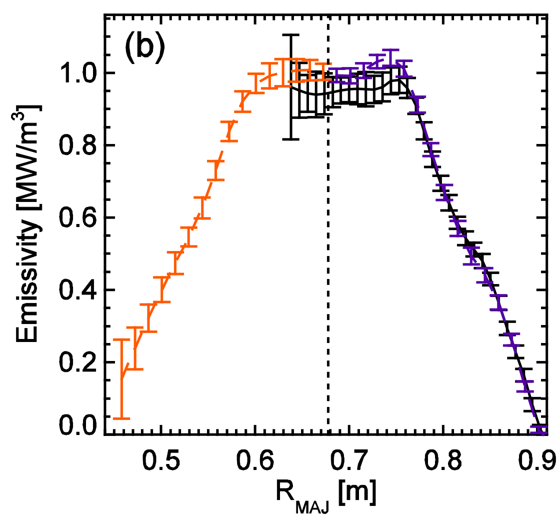
Symmetric Emission in Ohmic Plasmas



EXAMPLE DATA FROM MIDPLANE ARRAYS

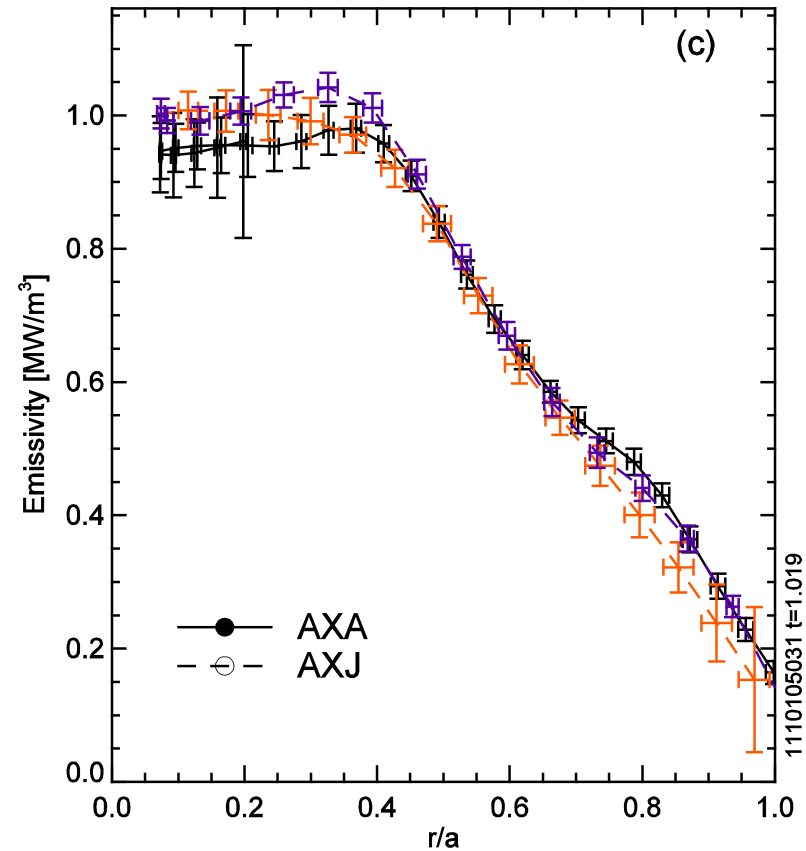
BRIGHTNESS PROIFILE





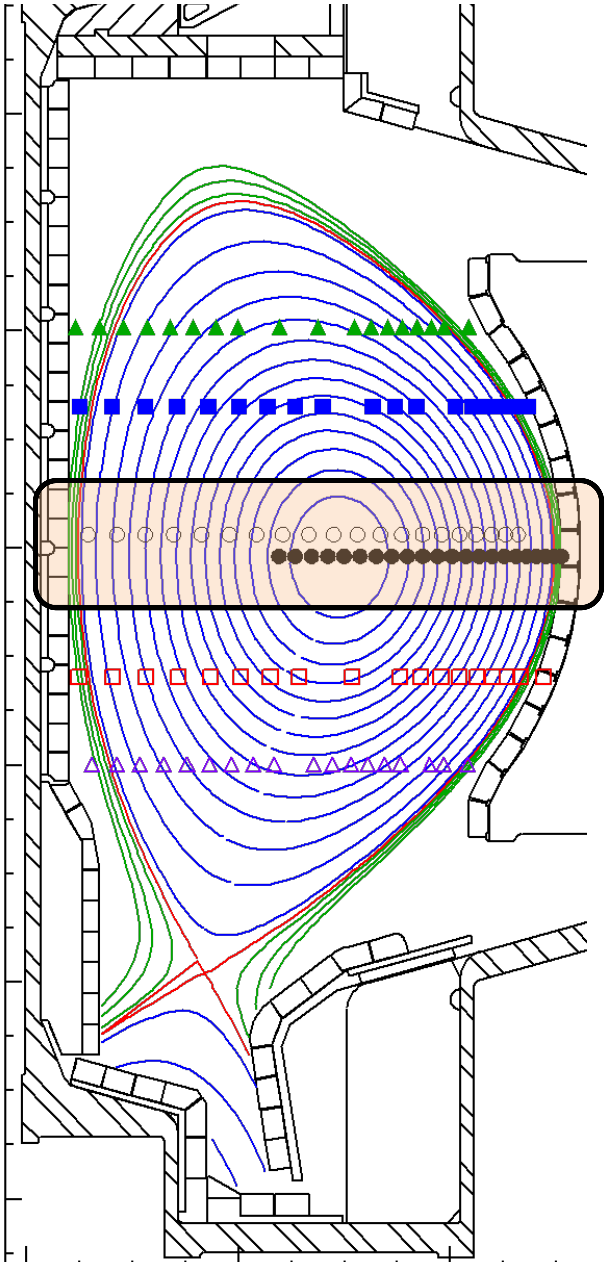
EMISSIVITY PROIFILE

EMISSIVITY MAPPED TO MINOR RADIUS



HFS **LFS**

LFS Accumulation in EDA H-mode



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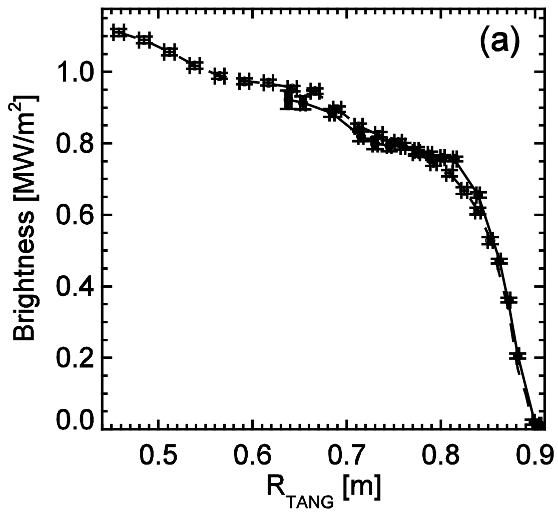

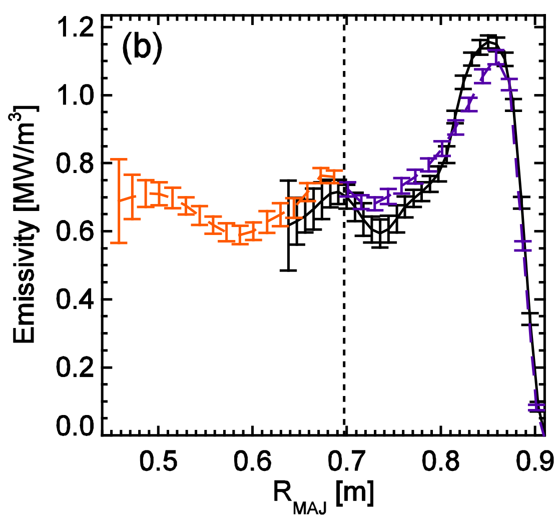

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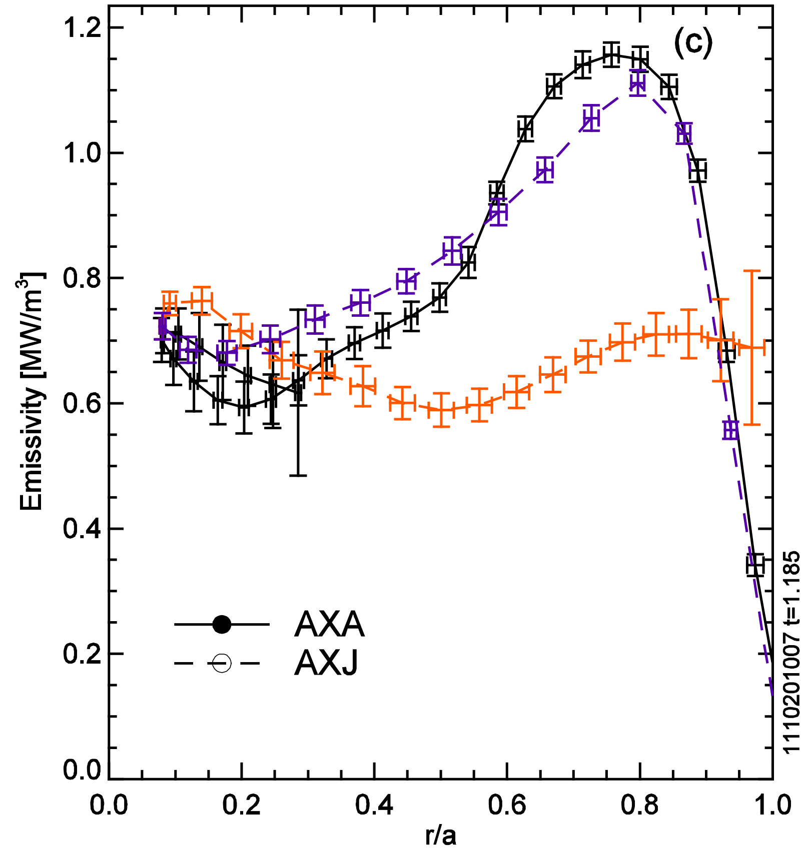
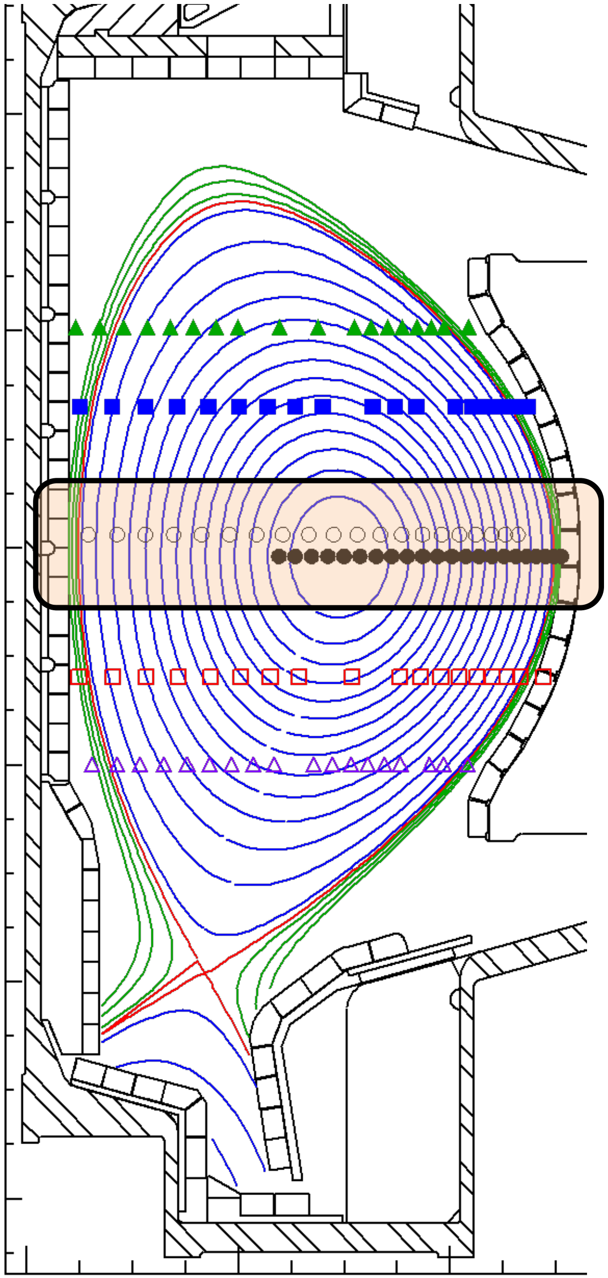


HFS LFS

HFS Accumulation in ICRH L-mode



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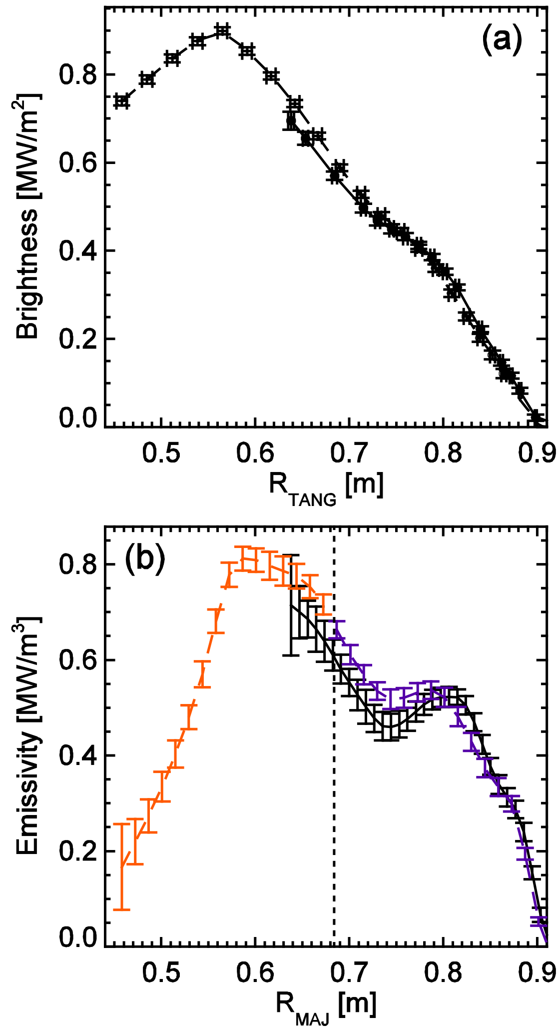

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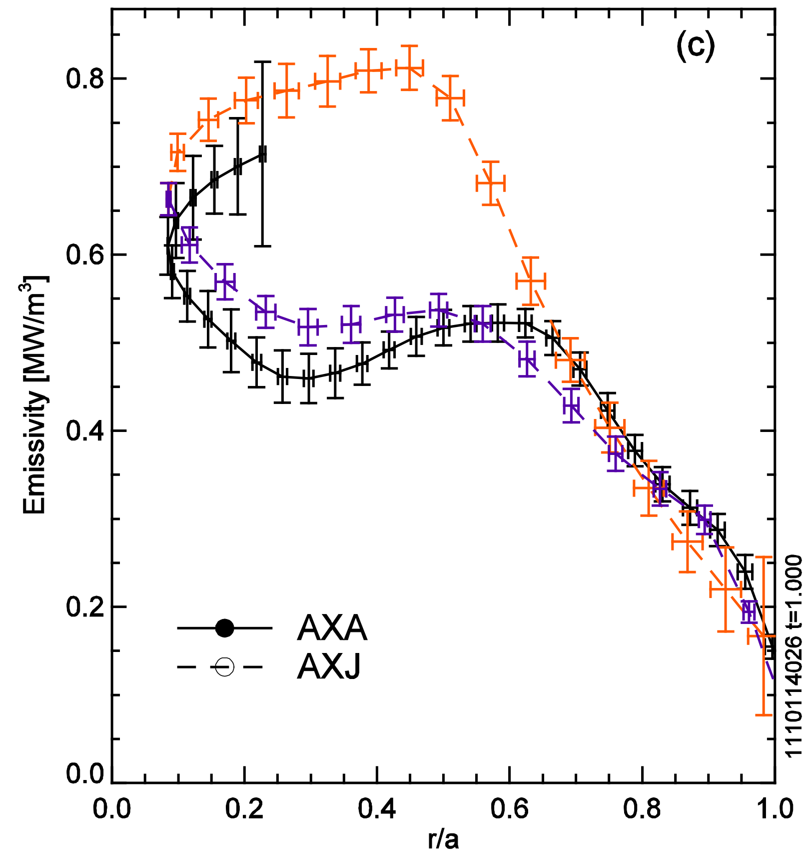
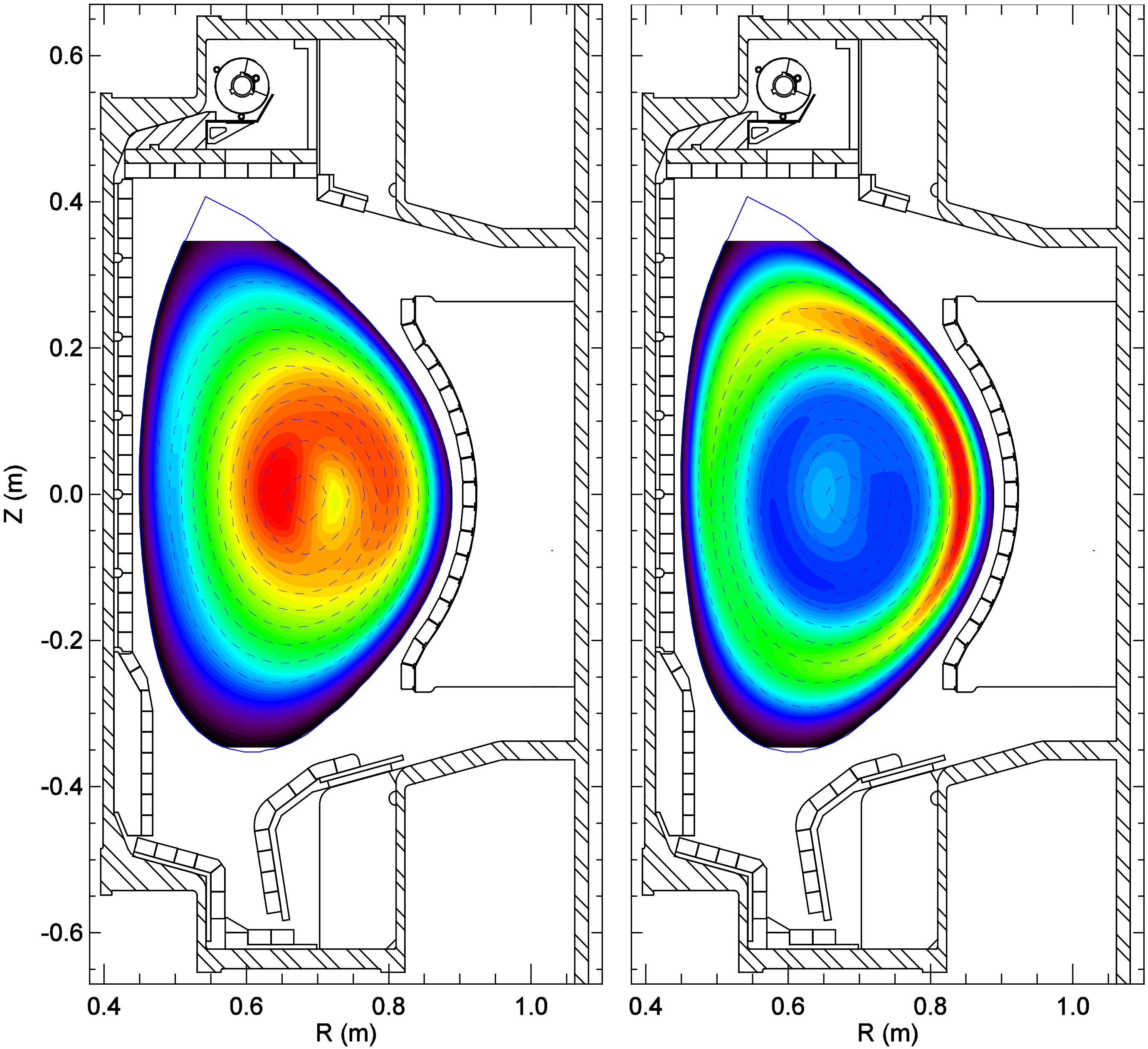


HFS LFS

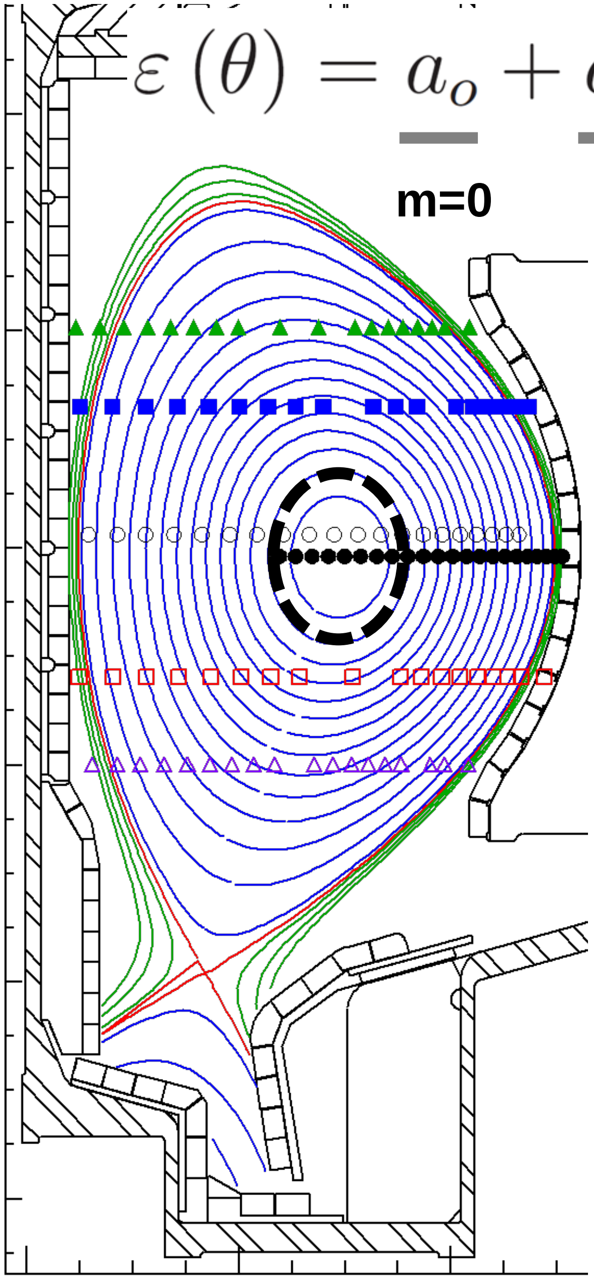
Computing the In/Out and Up/Down Asym.

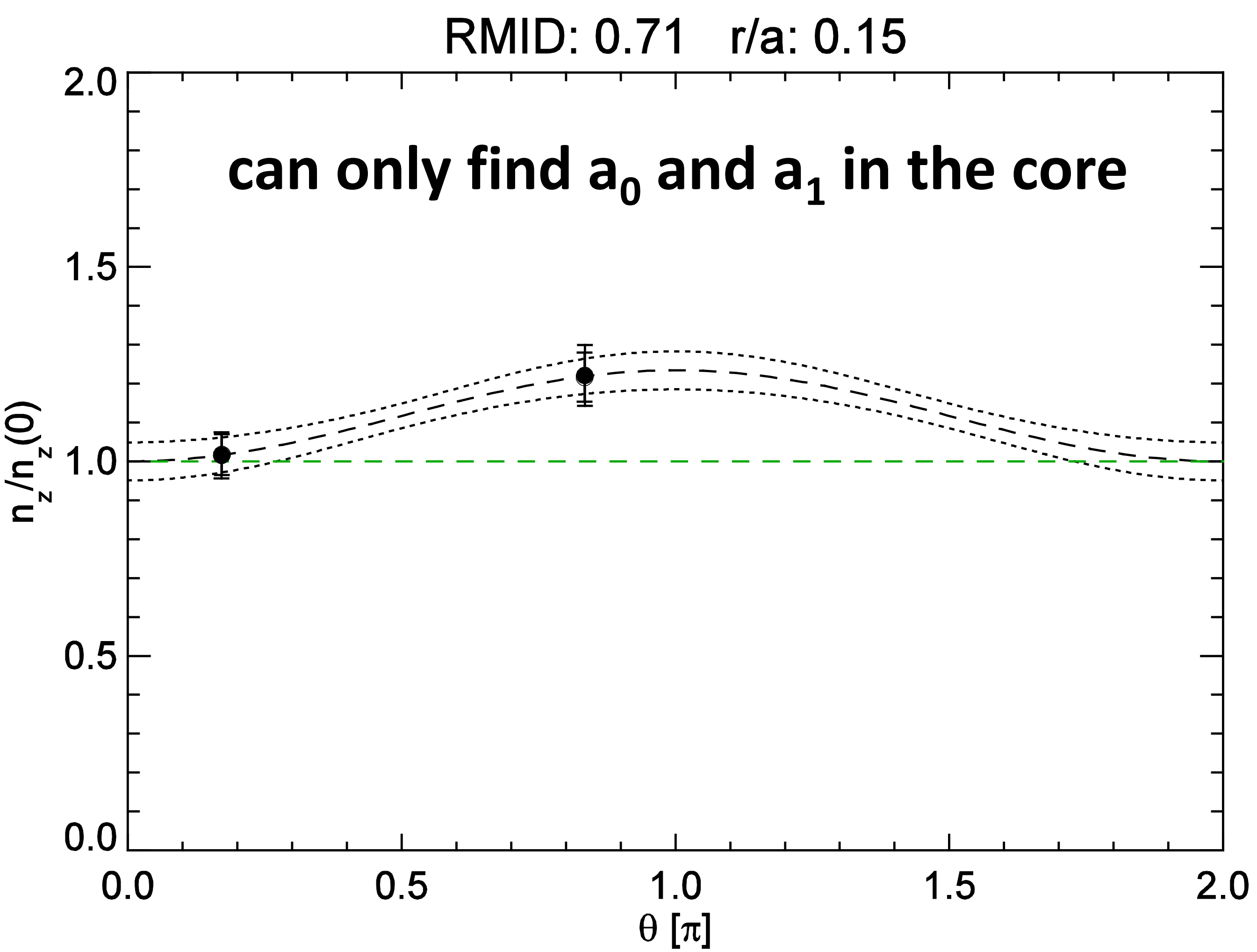


- demonstrate that the $n_{z,cos}$ and $n_{z,sin}$ terms can be found independent of $\langle n_z(r) \rangle$
- peaked and hollow profiles (left) have the same asym.
  - $n_{z,sin}(r)/\langle n_z(r) \rangle$
  - $n_{z,cos}(r)/\langle n_z(r) \rangle$
- compute synth. brightness profiles, Abel invert and fine the m=1 terms

Fit Poloidal Variation to m=0,1,2 Terms

$$\varepsilon(\theta) = \underbrace{a_o}_{m=0} + \underbrace{a_1 \cos\theta + a_2 \sin\theta}_{m=1} + \underbrace{a_3 \cos 2\theta + a_4 \sin 2\theta}_{m=2\ \text{(optional)}}$$





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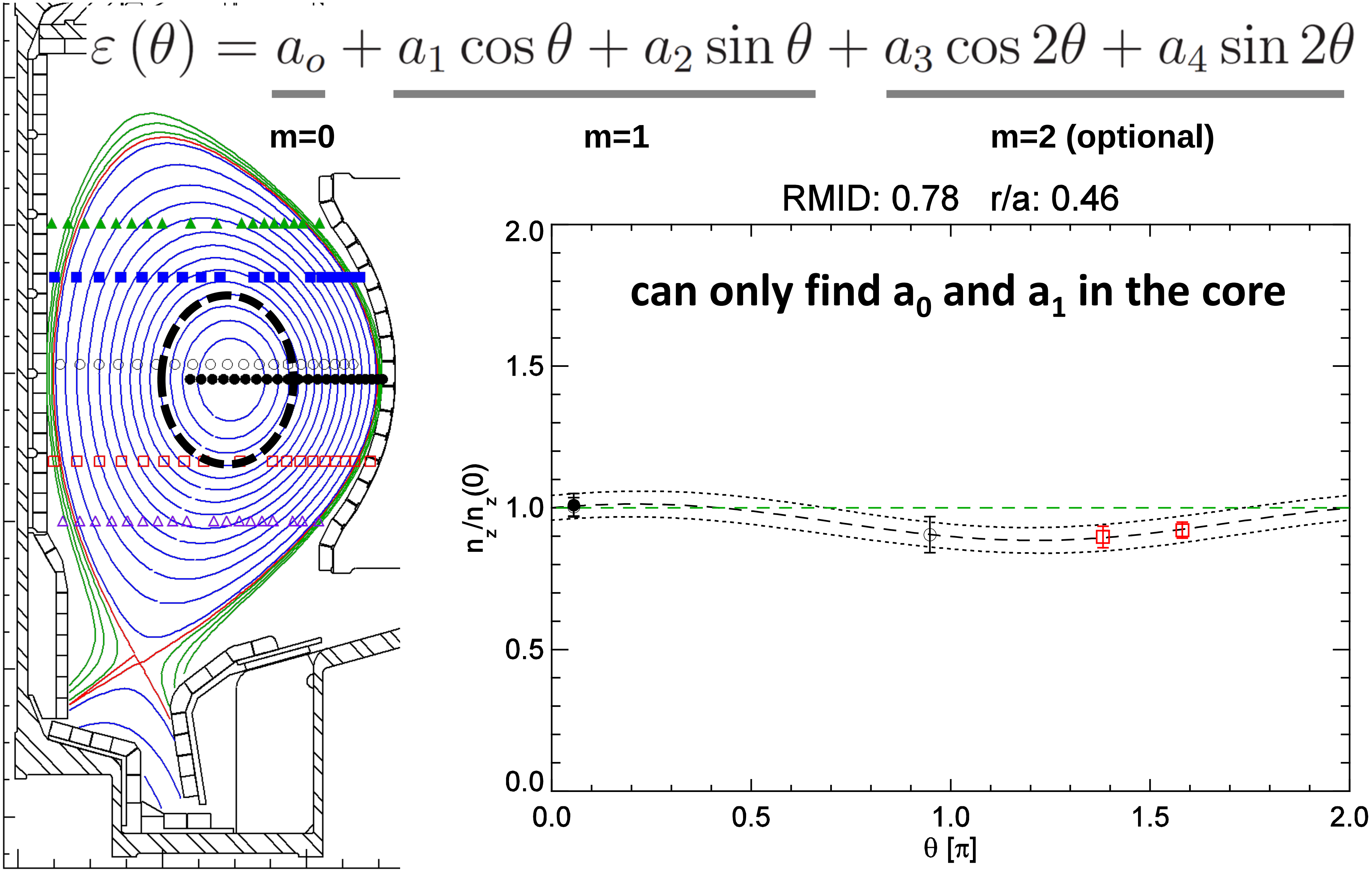

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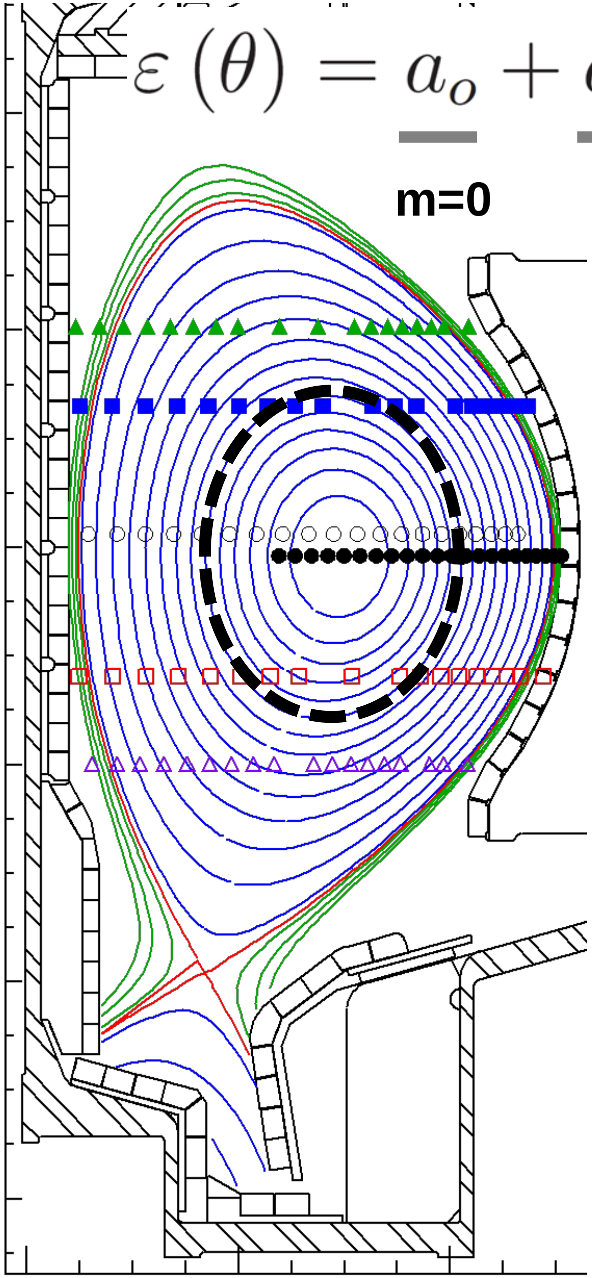

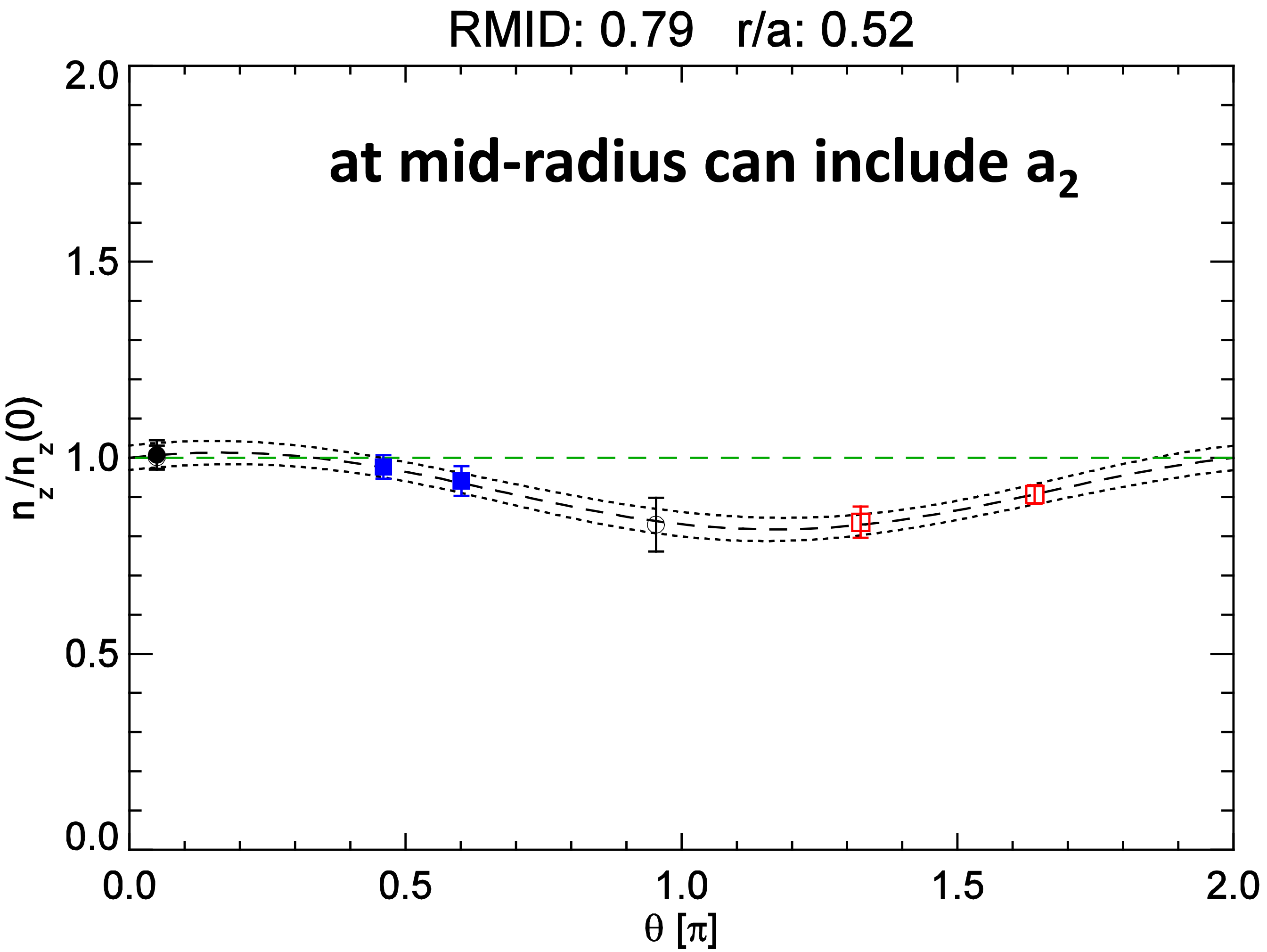

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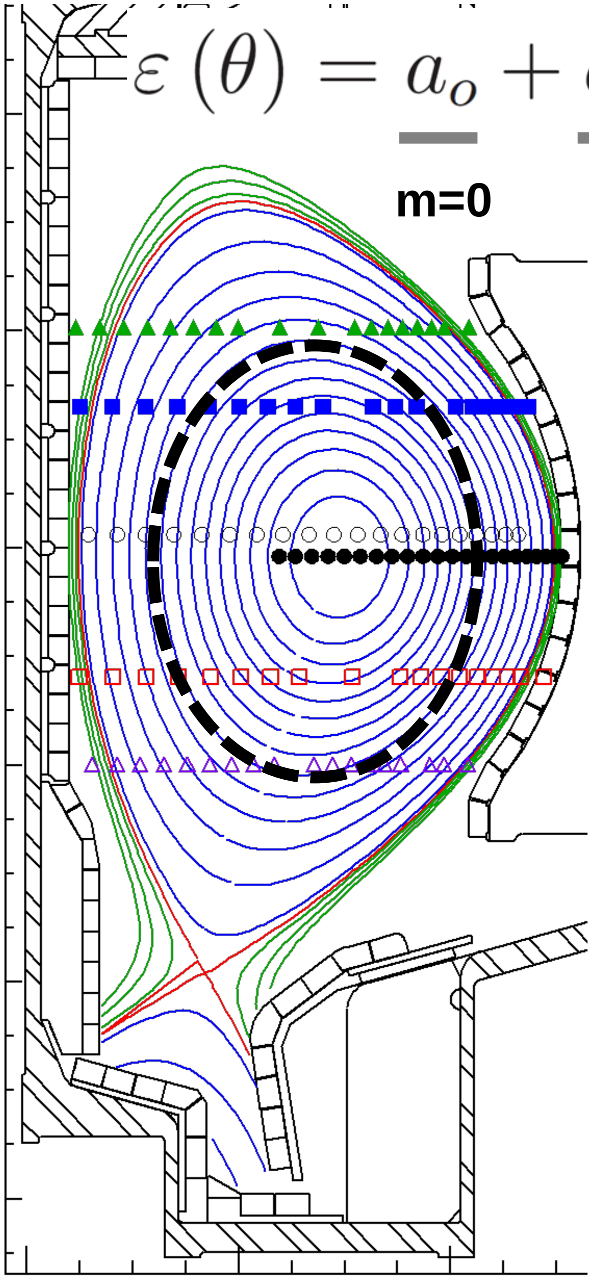
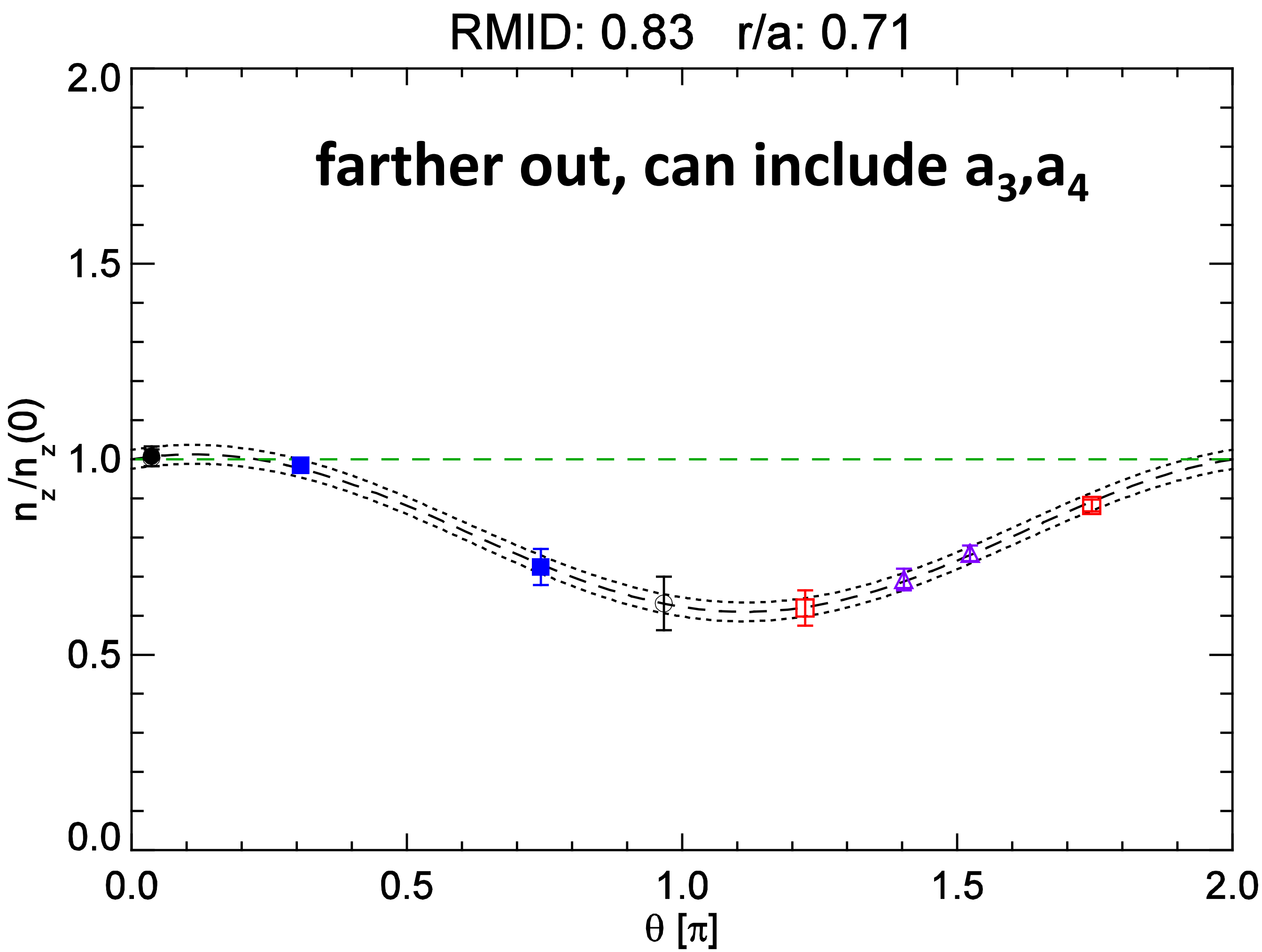
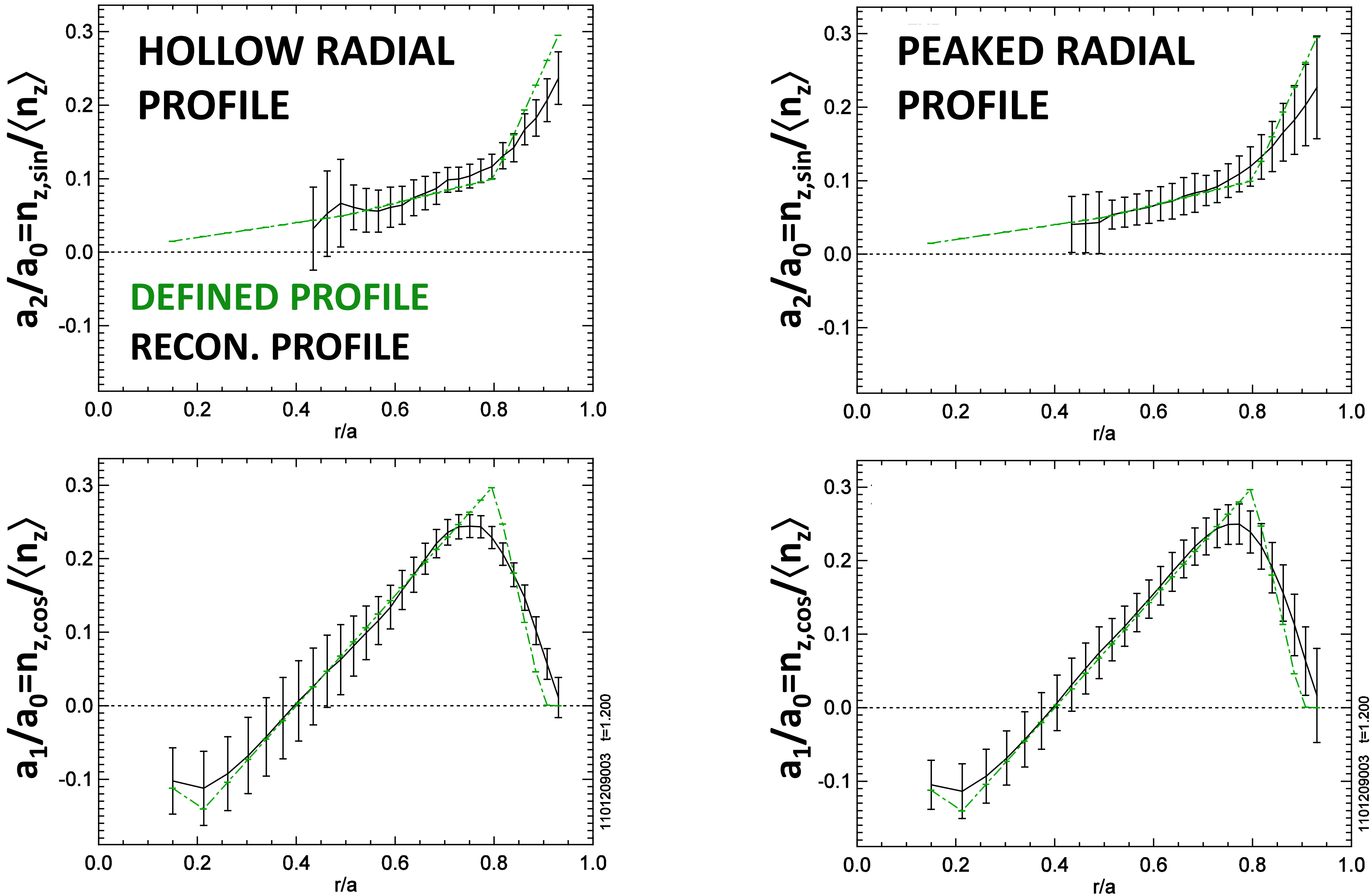


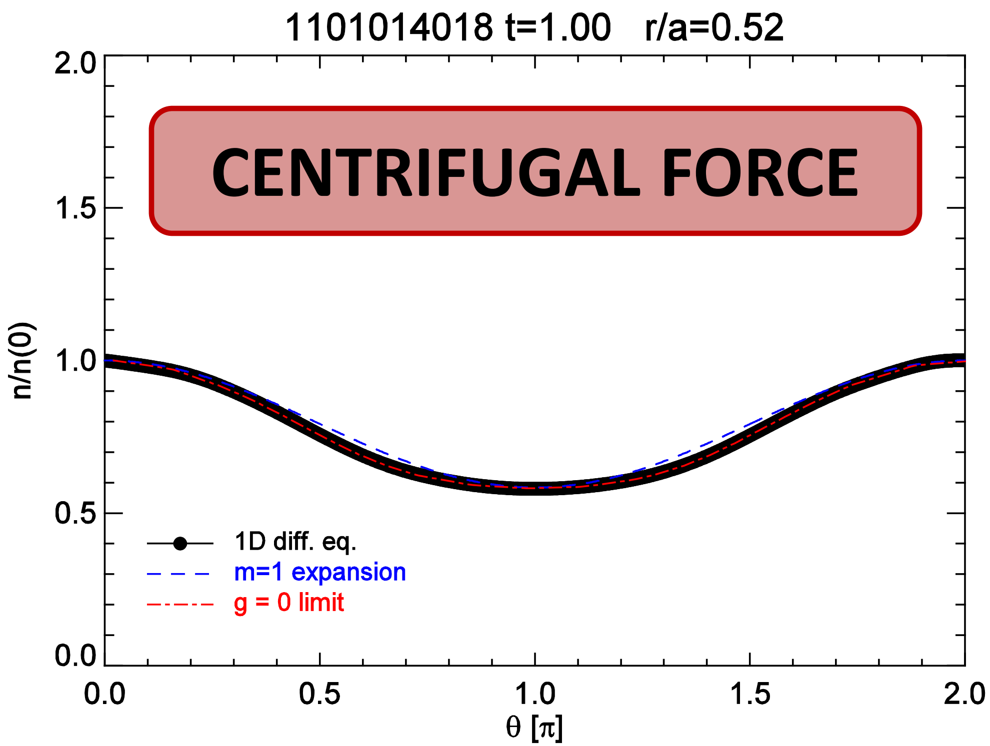


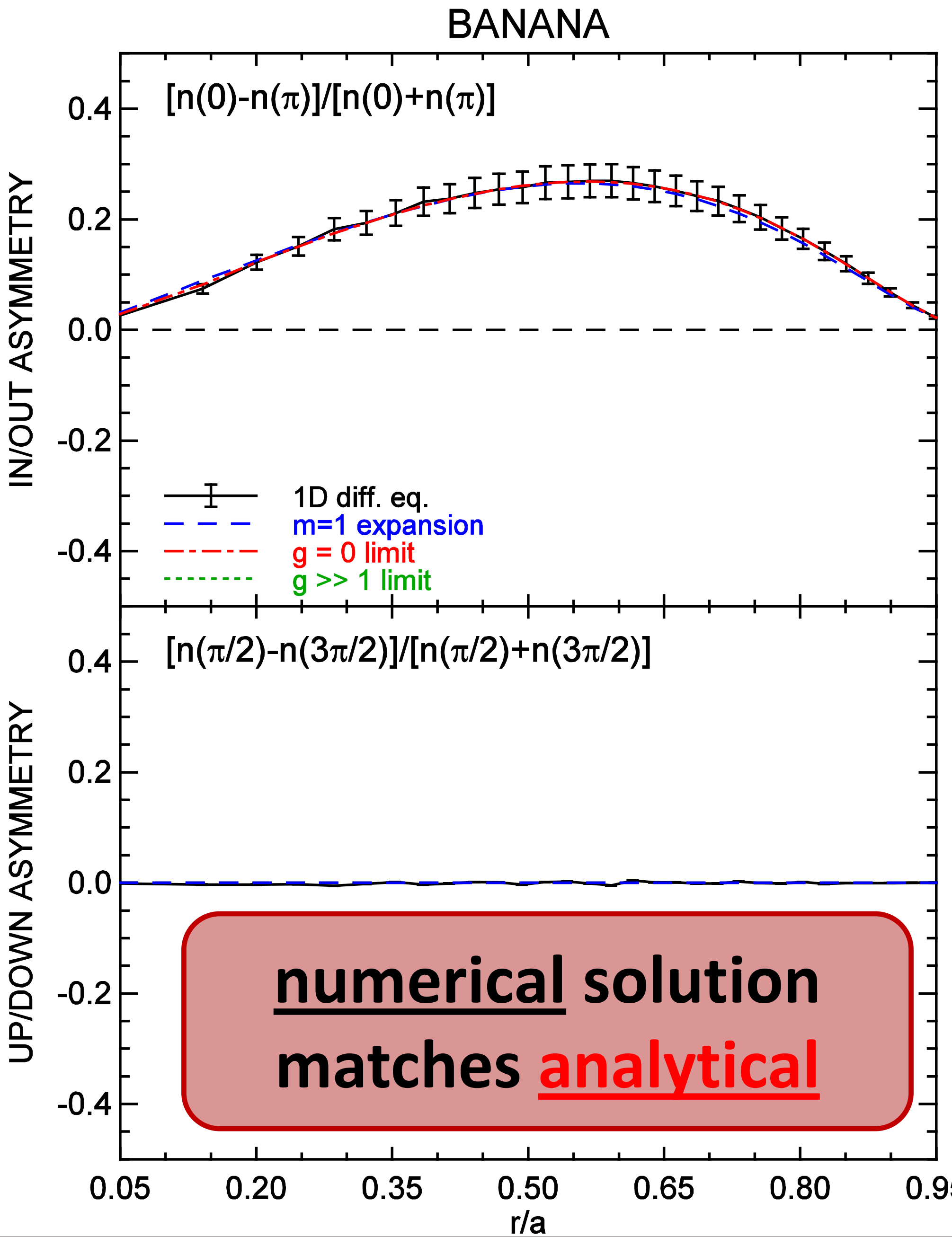
Asym. Profiles Indep. of Radial Profile



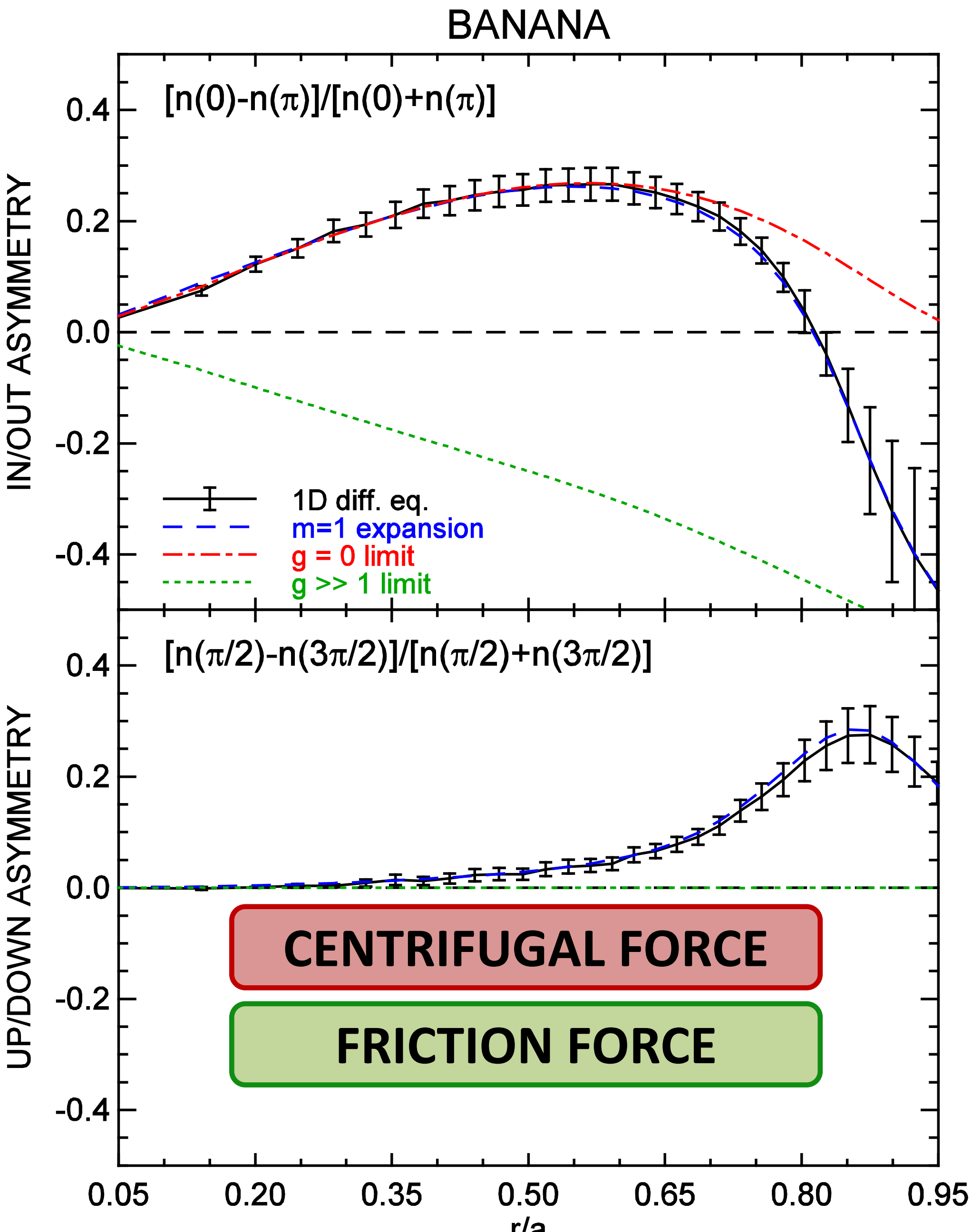
Comparing Measurements to Theory

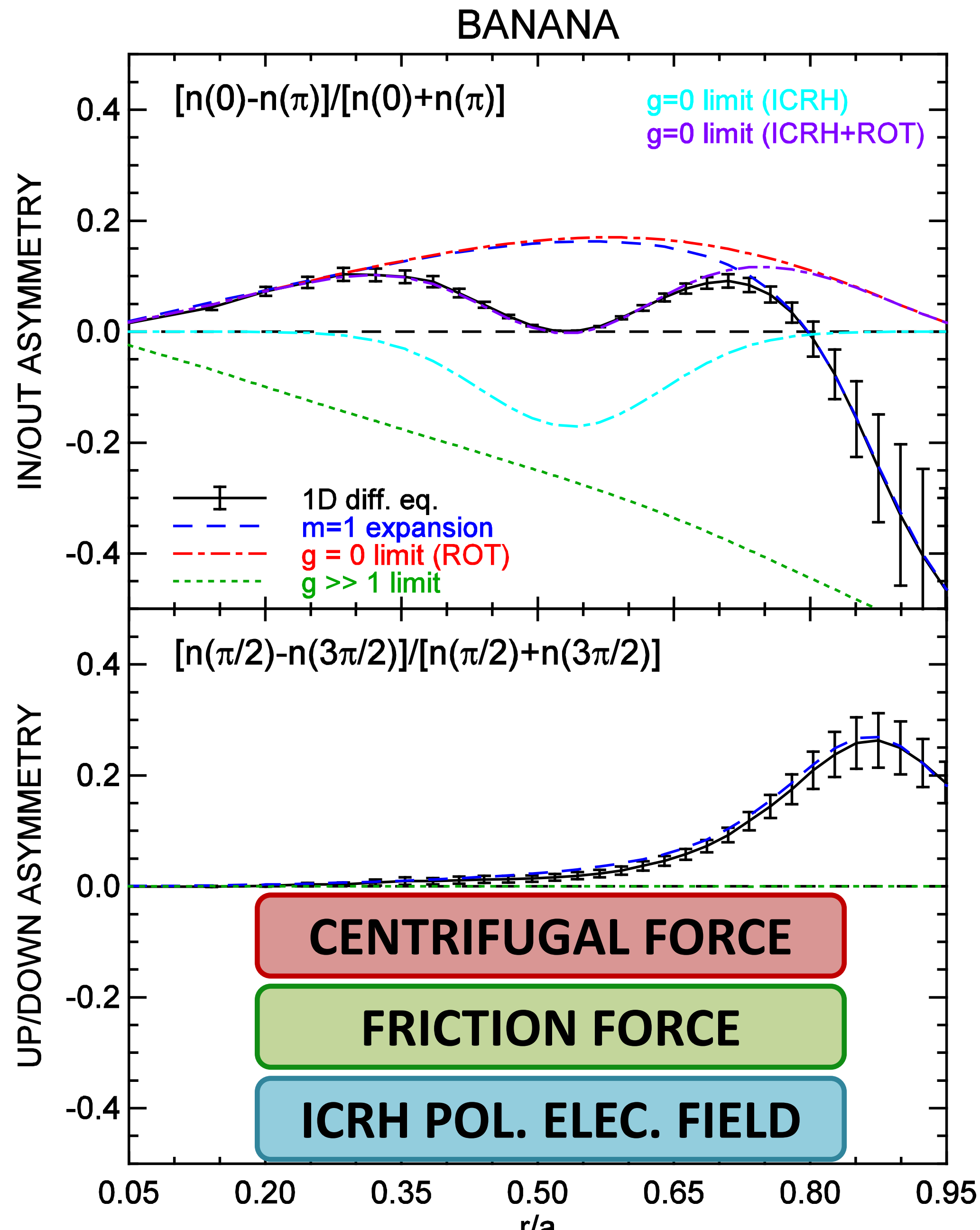
- need to compute expected $n_z(\theta)$ profile to compare to or supplement measurements
- solve the 1D diff. eq. for $n_z(\theta)/n_z(0)$





Num. Code Critical for Multiple Forces





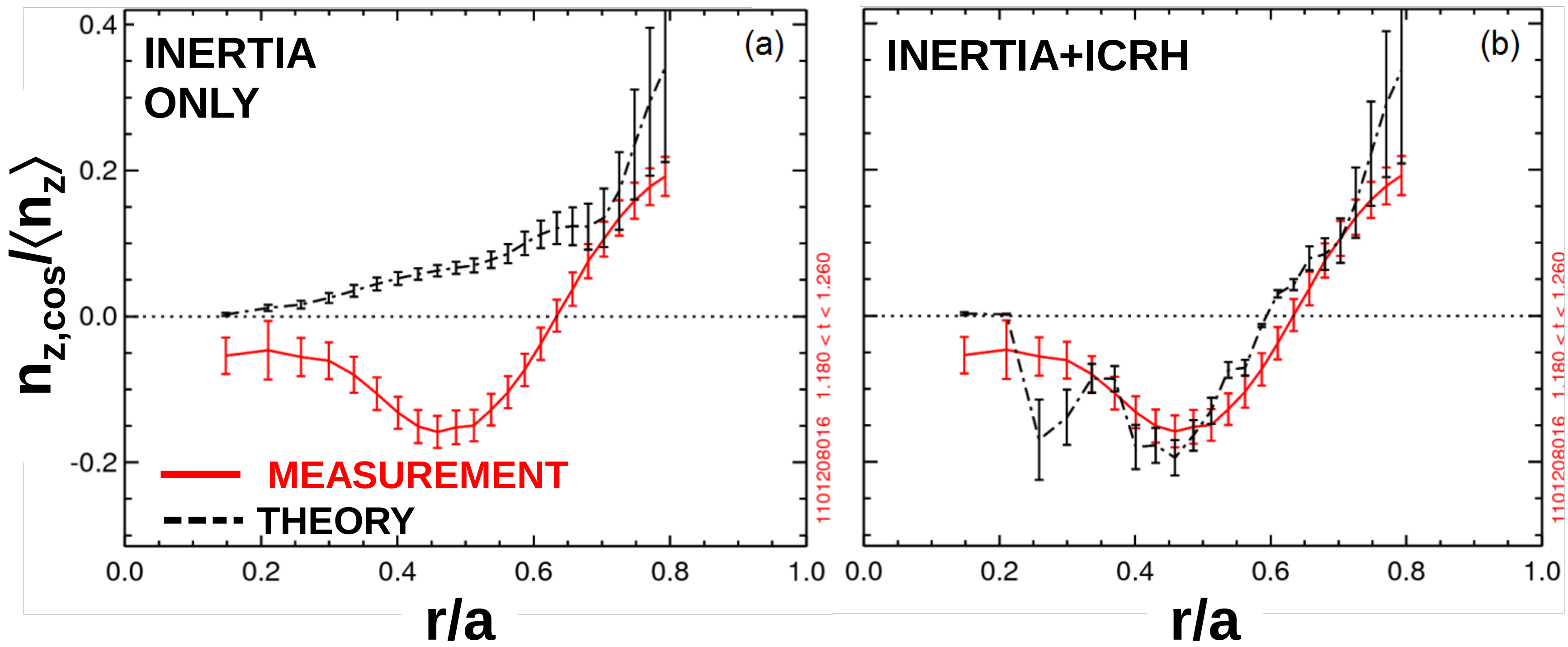
Validation of HFS Accumulation due to ICRH

$$\frac{n_z}{\langle n_z \rangle} = 1 + \frac{m_z \omega^2}{2T_i}\left(1 - \frac{Z m_i}{m_z}\frac{Z_{eff} T_e}{T_i + Z_{eff} T_e}\right)\left(R^2 - \langle R^2 \rangle\right) - Z f_m \frac{T_e}{T_i + Z_{eff} T_e}\left(\left\langle \frac{1}{B^\eta} \right\rangle^{-1} \frac{1}{B^\eta} - 1\right)$$

$$\frac{n_{z,cos}}{\langle n_z \rangle} = 2\frac{r}{R_o}\left[\boxed{\frac{m_z \omega^2 R_o^2}{2T_i}\left(1 - \frac{Z m_i}{m_z}\frac{Z_{eff} T_e}{Z_{eff} T_e + T_i}\right)} \boxed{- Z f_m \frac{T_e}{Z_{eff} T_e + T_i}\left(\frac{T_\perp}{T_\parallel} - 1\right)}\right]$$

LFS accumulation due to centrifugal force

HFS accumulation due to minority anisotropy



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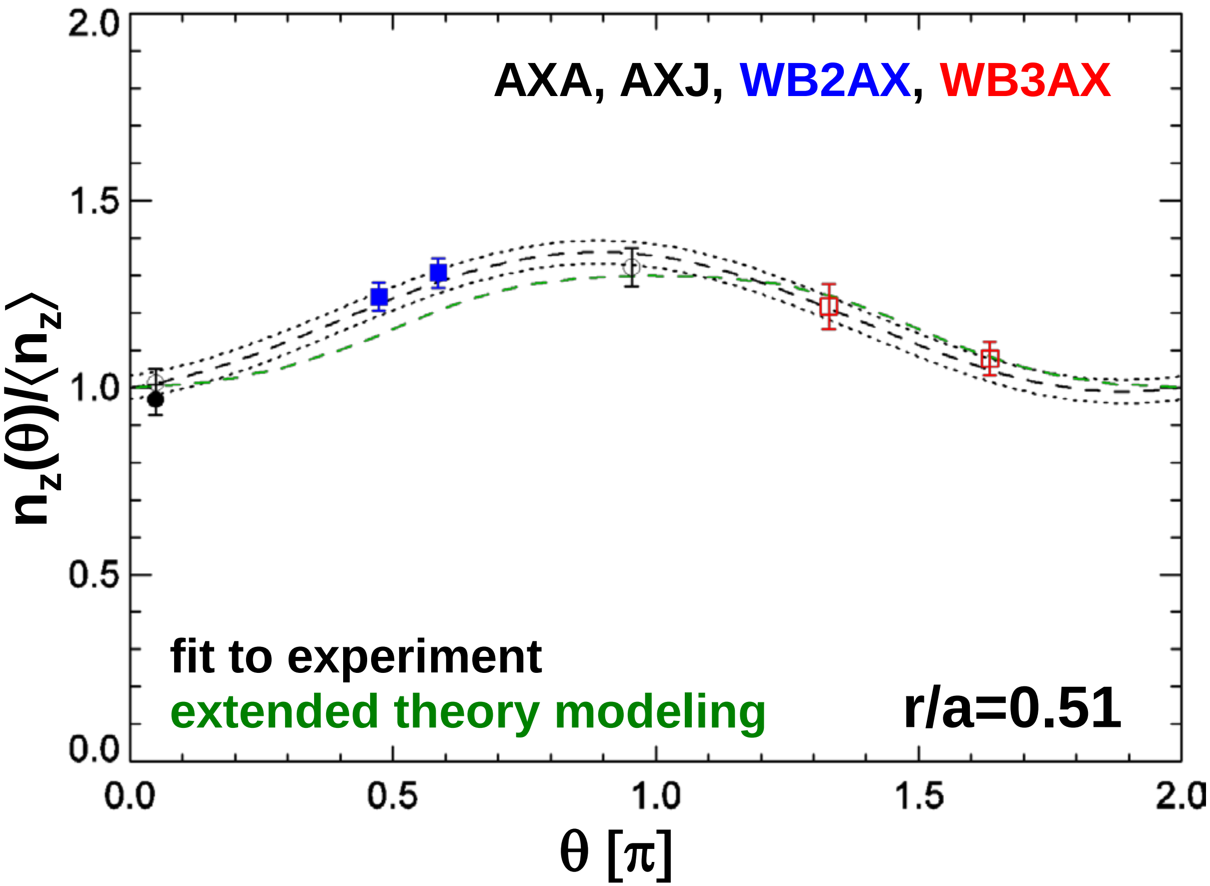
no peaking in $n_z(\theta)$ profile around the resonance layer



Implications for “Radial” Impurity Transport Studies: Is 1D Enough?

Impact on “Radial” Impurity Transport

$$n_z(\theta) \rightleftharpoons \langle n_z \rangle \;\; ??$$

in most cases parallel and radial transport can be separated

- neoclassically $\tau_\perp >> \tau_{||}$ easily satisfied
- turbulent radial transport can lead to cases $\tau_\perp > \tau_{||}$ or $\tau_\perp \sim \tau_{||}$
  - note that $\tau_{||} \neq L_{||}/v_{th,z}$, high-Z leads to diffusive or $\tau_{||} = L_\theta/v_{\theta,z}$

at a minimum, STRAHL/SANCO simulations should use $\langle n_z \rangle$

- if asymmetries present, diagnostic views must be tailored to either average-out in/out asymmetries or measure them directly

what role, if any, does $n_z(\theta)$ have on turbulent $\langle \Gamma_z \cdot \nabla\psi \rangle$?

- rapidly evolving theoretical work 2009+
- first dedicated experiment run at C-Mod on Sept. 13th, 2012

Centrifugal Effects in QL Radial Imp. Flux

Warwick and IPP-Garching groups have worked on including centrifugal force effects on radial transport using a fluid model and Vlasov flux-tube code GKW

- using a fluid model, the quasi-linear impurity flux is identified to have 4 components and enhanced by centrifugal force (CF)

$$R\Gamma_s = n_s D_s\left[R/L_{n_s} + \left(C_T + {C_T}^{CF}\right) R/L_{T_s} + \left(C_u + {C_u}^{CF}\right)u'_s + C_p + {C_p}^{CF}\right]$$

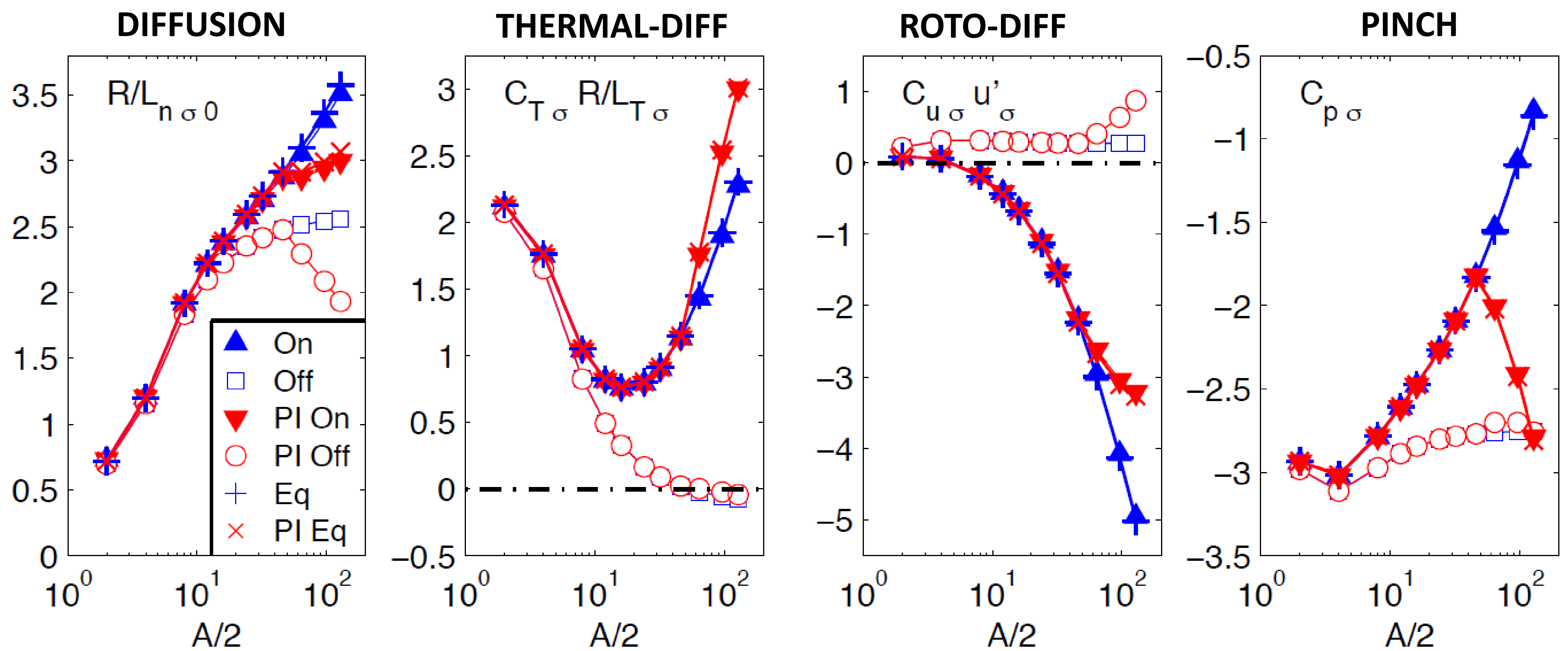
DIFFUSION **THERMAL-DIFF** **ROTO-DIFF** **PINCH**

- high $M_i(m_z/m_i)$ "imp. Mach #" modifies the turbulent transport
  - additional particle drifts
  - free energy in the rotation
  - increased particle trapping at LFS (vs. ballooning turbulence)
- For more information see:

A. Peeters, PoP **16** 012503 (2009)
Y. Camenen, PoP **16** 0125003 (2009)
F.J. Casson, PoP **17** 102305 (2010)
C. Angioni, IAEA 2012

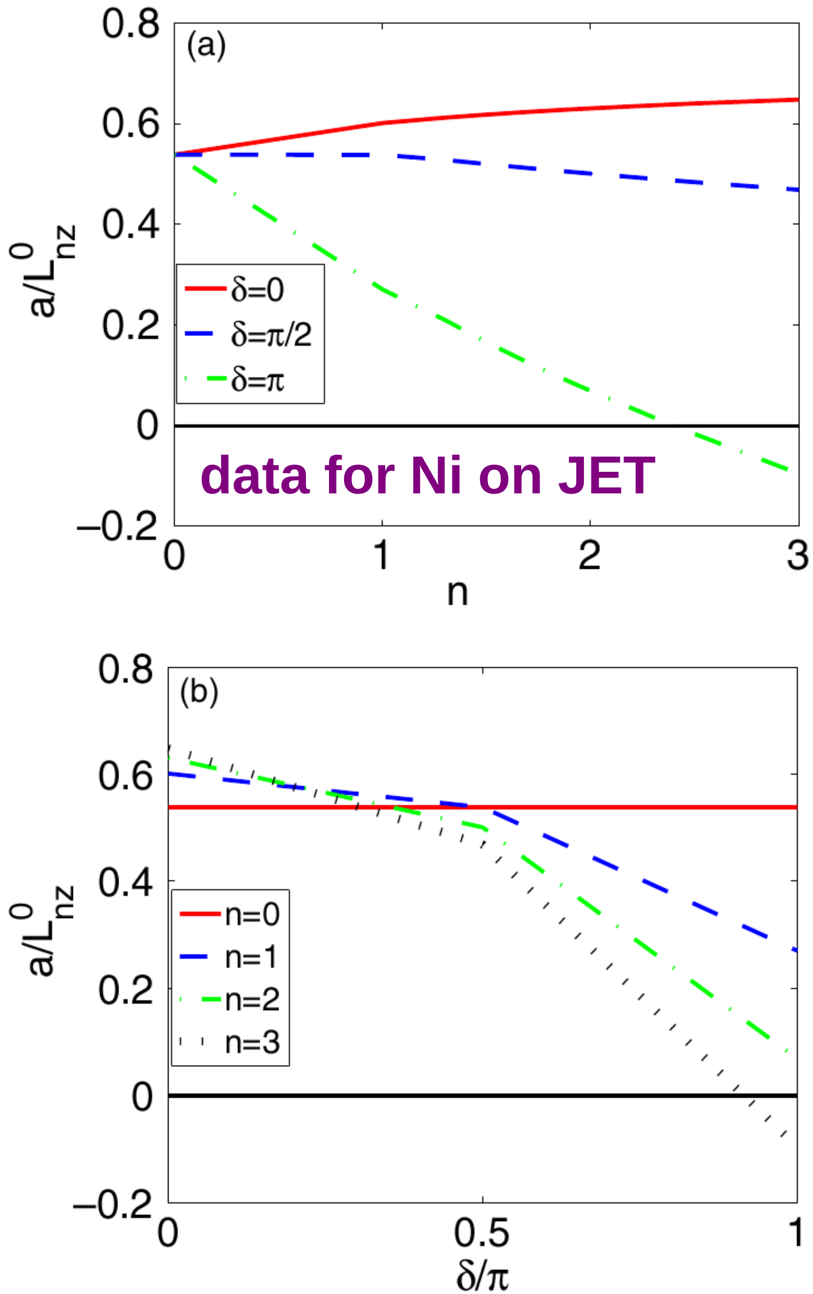
Centrifugal Effects Important in QL Flux

- "ON" includes CF effects with impact terms at high mass Z=A/2
- for weak (M_i < 0.3) main-ion flows, analytical (EQ) matches GWK
- degree of ionization matters as well (for PI Z=46 for A > 92)



used with permission from C. Angioni IAEA - 2012

Effect Using Generic Poloidal Variation



Chalmers group is studying the effect of a generic $n_z(\theta)$, not limited to centrifugal

work is just beginning[a] to look at effect on radial transport driven by ITG turb.

decompose measured $n(\theta)/n(0)$ in form:

$$\frac{n_z}{n_{z0}} = \sum_n \left[f_n \cos\left(\frac{\theta-\delta}{2}\right)\right]^{2n}$$

different (θ, n) have different zero-flux gradient scale lengths, find weighted ave.

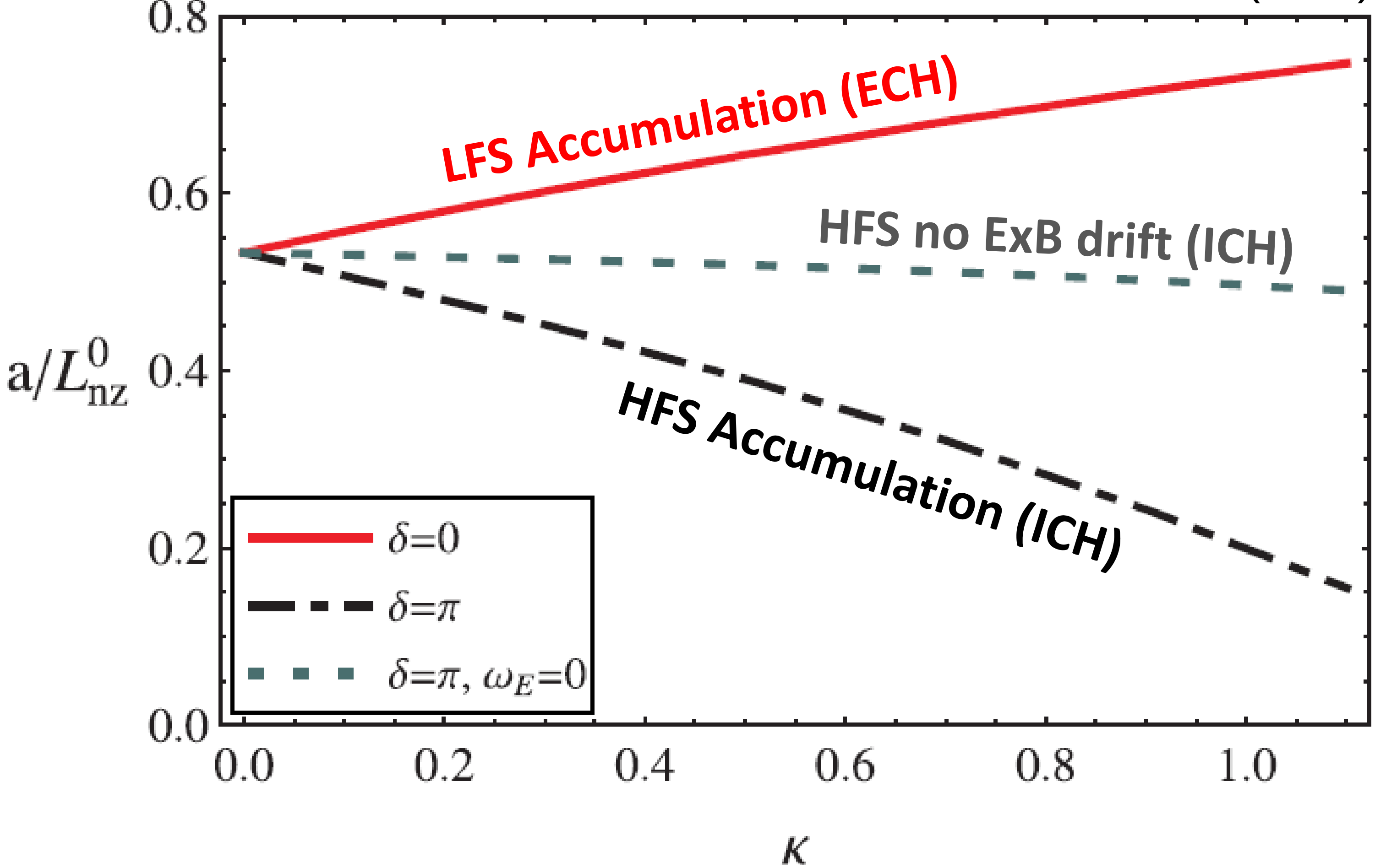
$$\frac{a}{L_z} \simeq \frac{\sum_n f_n \frac{a}{L_{z,n}}}{\sum_n f_n}$$

[a]S. Moradi, *et al.* PPCF **53** 115008 (2011)

E×B Drift From Pol. Elec. Field Important

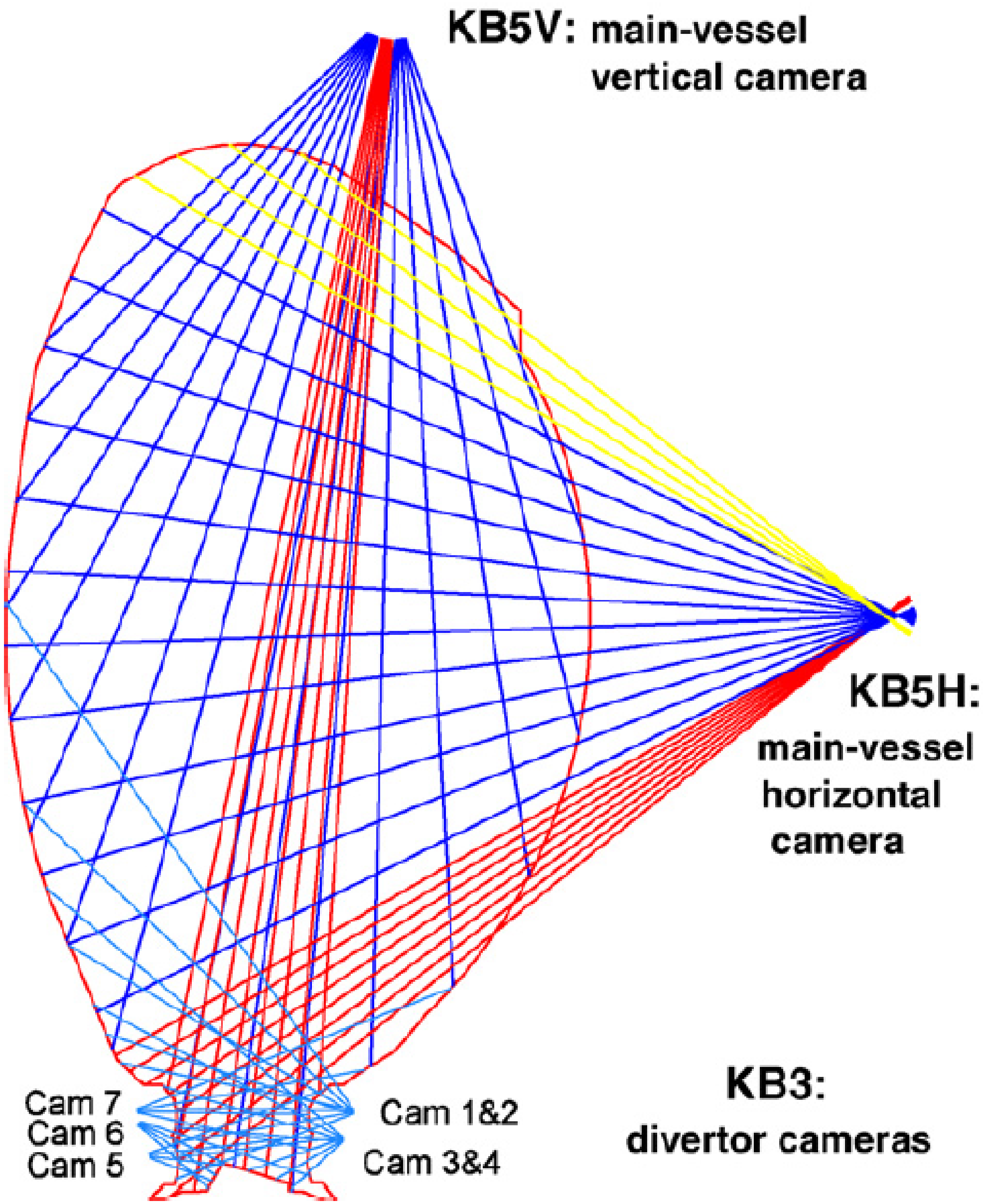
Recent work by Mollen[a] has shown impact of including the drift from $E_\theta \times B_\phi$ which also has an explicit mag. shear dependence

A. Mollen, *et al*. PoP **19** 052307 (2012)



Current JET Bolometer Diagnostic

Huber FED **82** 1327 (2007)

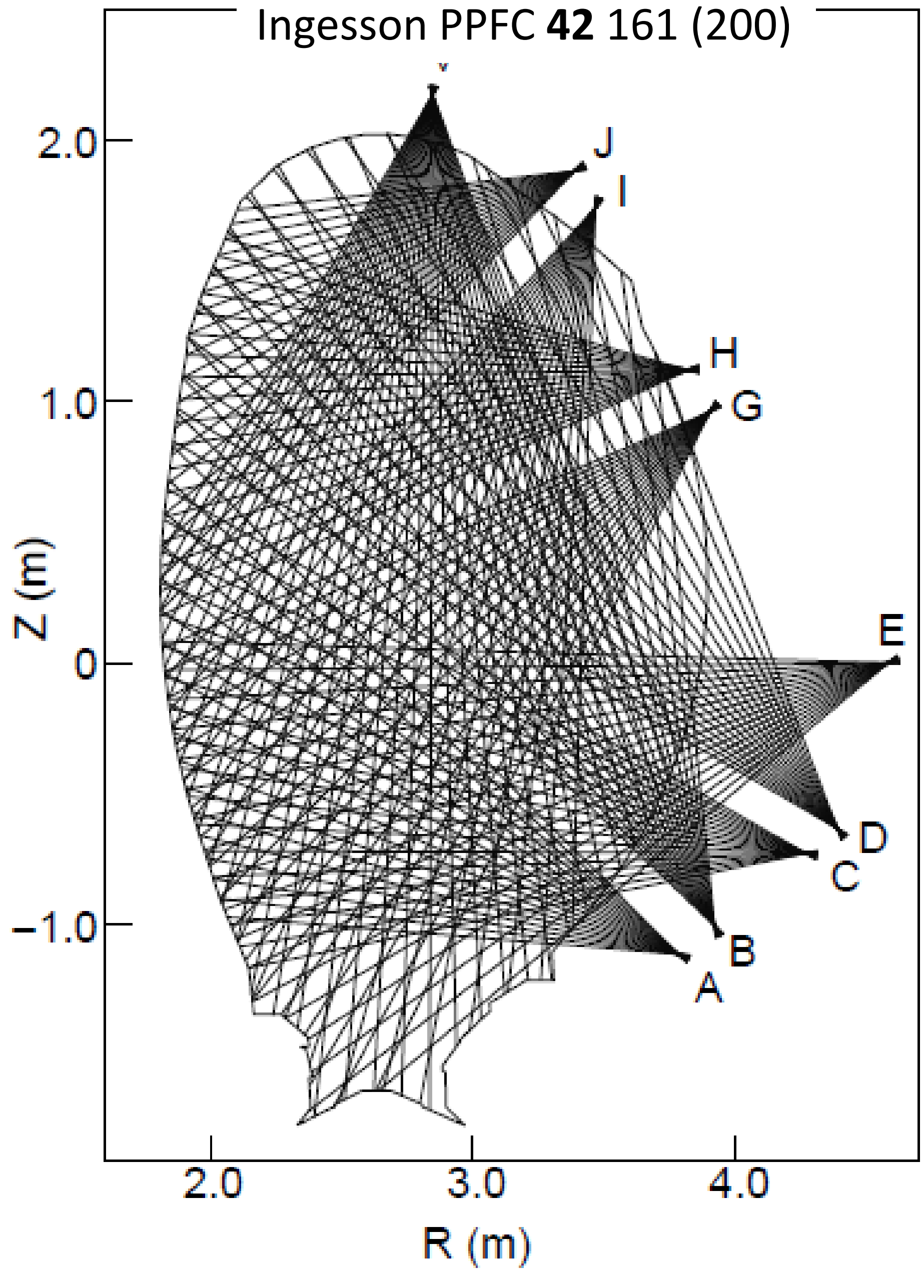


- KB5H should do OK for total radiated power
- asymmetric part will be hard to get with KB5V
  - core views see divertor region and $B_{CORE} \sim B_{DIV}$
  - all views terminate at different poloidal points

is a horizontal midplane viewing array possible?

- toroidally symmetry robust on non-MHD timescales
- easy to invert, feedback control of asymmetry?

Full Operation of SXR Tomography



- previous JET asymmetry research was done with a comprehensive diagnostic set
- nearly 200 channels with a wide range of poloidal viewing angles
- **extensive** verification efforts completed by C. Ingesson

What fraction is functional?

Are filters optimized to view W emission?

Consider Installation of XICS

X-ray imaging crystal spectroscopy (XICS) well suited to asym. studies

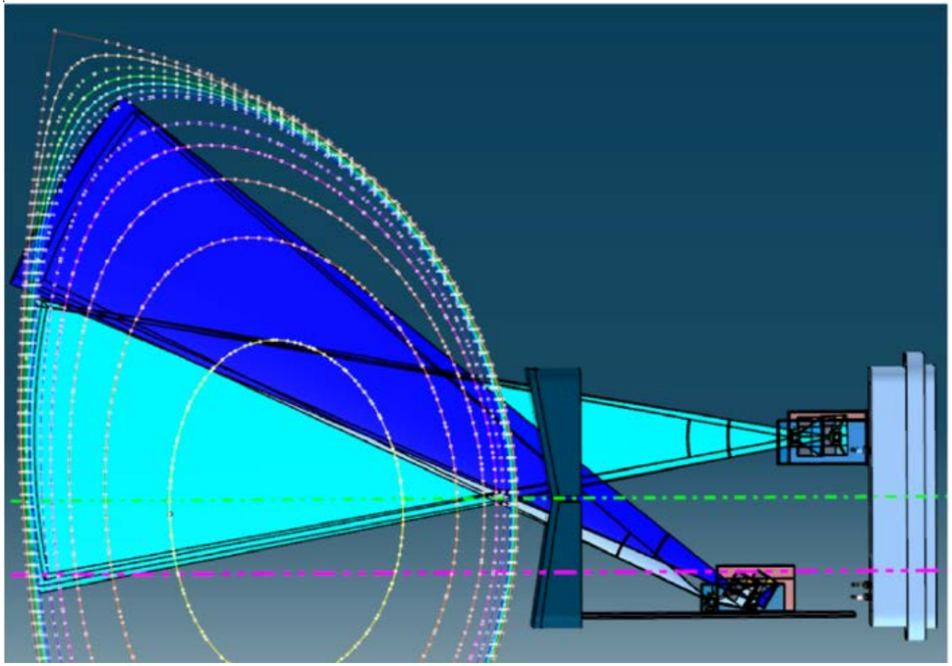
- measure high-Z impurities radiation profiles
- measure radial profiles of flows and temperatures

JET can answer important ITER-relavent XICS questions

- can we measure profiles using tungsten emission w/o it killing the plasmas?
- can we use a limited poloidal view if we expect asymmetries?

XICS requires detectors close to the plasmas - will it survive D/T

[1]P. Beiersdorfer, *et al.* J. Phys. B. **43** 144008 (2010)
[2]P. Beiersdorfer, *et al*. LLNL-SR-464953 (2011)



Summary

- Poloidal variation of high-Z impurities is a dramatic and important effect in rotating, auxiliary-heated tokamak plasmas
  - the centrifugal force leads to strong LFS accumulation
  - poloidal electric fields can be driven non-thermal particles
- Alcator C-Mod has a mature program for asymmetry studies
  - measurements using horizontally viewing arrays
  - agree with theory based on combined ICRH and inertial effects
- Impact of Asymmetries on Flux-Surface Averaged Radial Transport is an Area of Expanding Research
  - theory identifies importance but experiments are just beginning
- JET is well suited to contribute to effort on both topics but should critically evaluate diagnostic set for easy upgrades

Extra Slides

Can Account for Plasma Shaping Effects