NSTX

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Modification of edge plasma characteristics and divertor profiles with applied 3-D fields in NSTX

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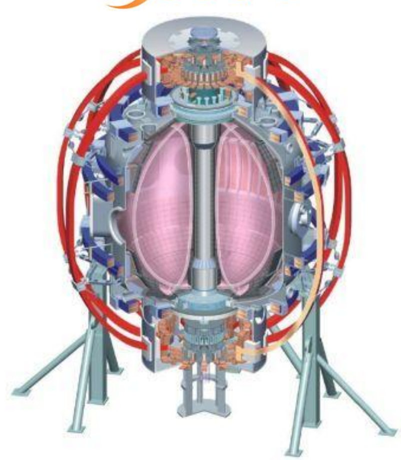
[1]ORNL, [2]PPPL , [3]LLNL, [4]UCLA , [5]JHU

ISHW/APPTC Meeting
Canberra, Australia
January 29-Feb 3, 2012

PPPL



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Motivation

- Small external magnetic perturbations used for ELM control
  - ELM suppression (DIII-D, KSTAR) and mitigation (JET, AUG)
  - ELM triggering (NSTX, MAST)

- 3-D magnetic perturbations can change pedestal and divertor plasmas and cause toroidally asymmetric heat and particle deposition

- The formation of 3-D magnetic field structures, and the transport of heat and particles through those structures are poorly understood

Understanding the 3-D field effects on pedestal and divertor plasmas is crucial for future machines, where such 3-D fields are probably unavoidable and likely to be imposed intentionally

Outline

- Background and diagnostics
- Divertor profile modification by 3-D fields
- Effects of 3-D fields on pedestal plasma characteristics
- 3-D fields and divertor detachment
- EMC3-Eirene 3-D transport modeling
- Summary and conclusion

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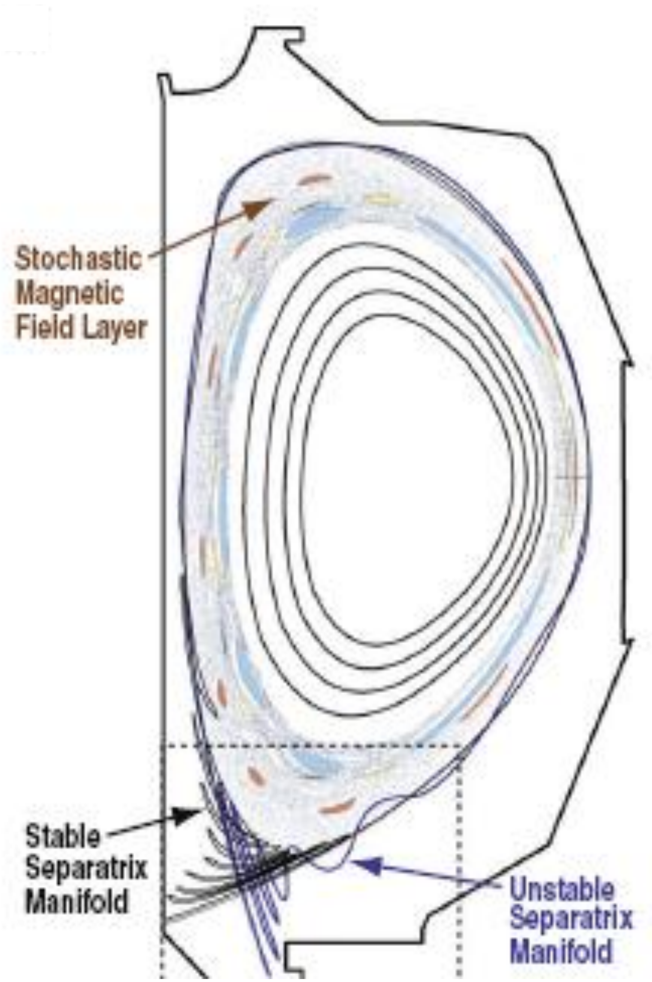
How do non-axisymmetric magnetic perturbations affect boundary plasma?



- Interaction of non-axisymmetric magnetic perturbation with 2-D equilibrium field → 3-D topology of perturbed field lines in the edge[1]
- Stochastic plasma boundary and enhanced radial transport due to high diffusivity of magnetic field lines
- Poloidal magnetic flux is organized by complex topological structures known as homoclinic tangles
  → Strike point splitting
  → Modification of divertor flux profiles

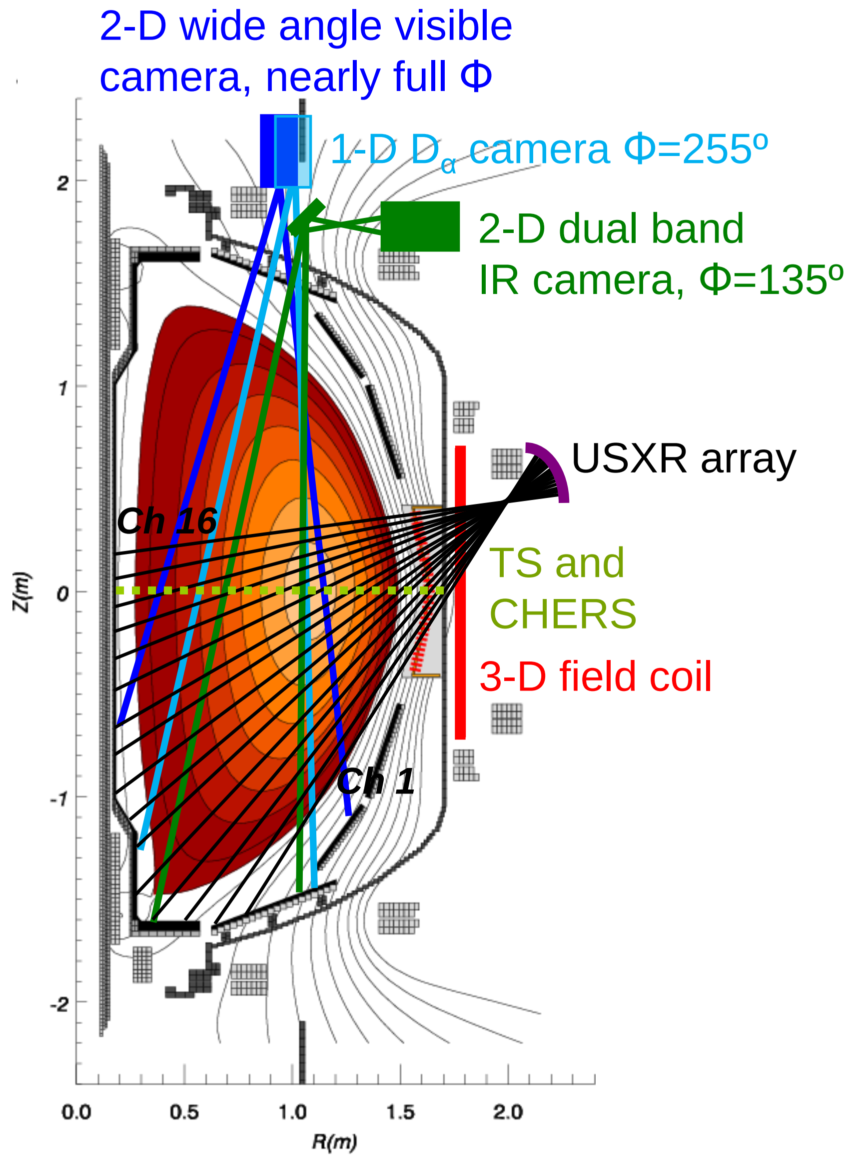
T.E. Evans, J. Nucl. Mater. 390-391 (2009), 789

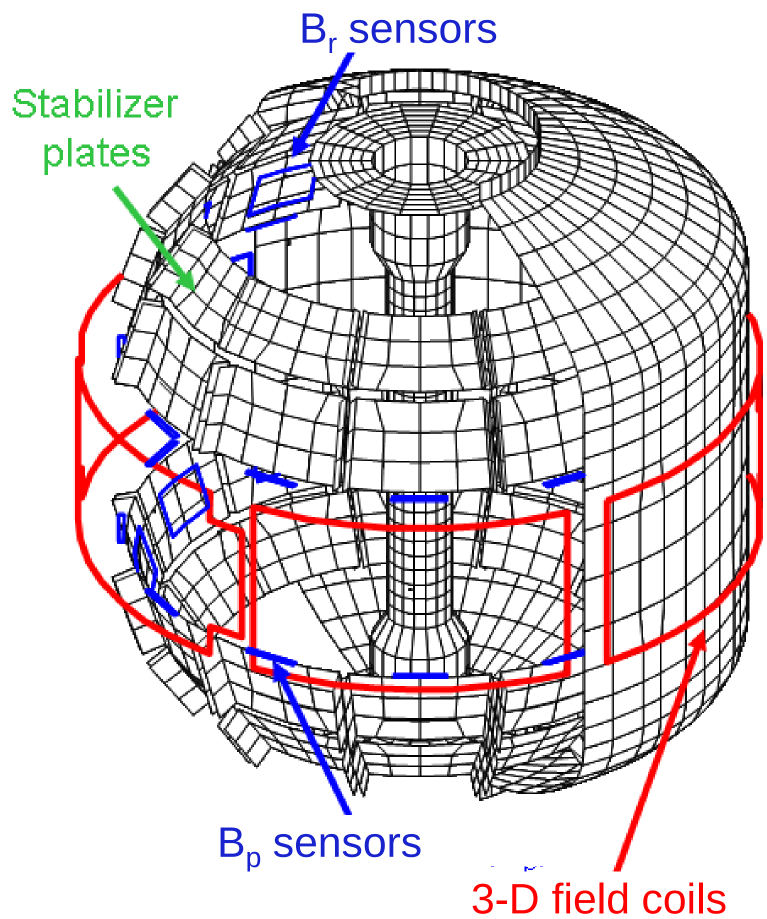
[1]T.E. Evans, Contrib. Plasma Phys. 44 (2004), 235

Examples of 3-D field effects on the edge and divertor transport in NSTX

- Strike point splitting → asymmetric divertor deposition
- Inconsistent effect on the pedestal profile
  → reduction *or* increase in pedestal pressure gradient
  Divertor condition appears to play a role
- Robust effect on edge stability → ELM triggering
- Triggering of enhanced confinement regime
- Reattachment of detached divertor plasma with low gas puffing → effect on both divertor and pedestal profiles

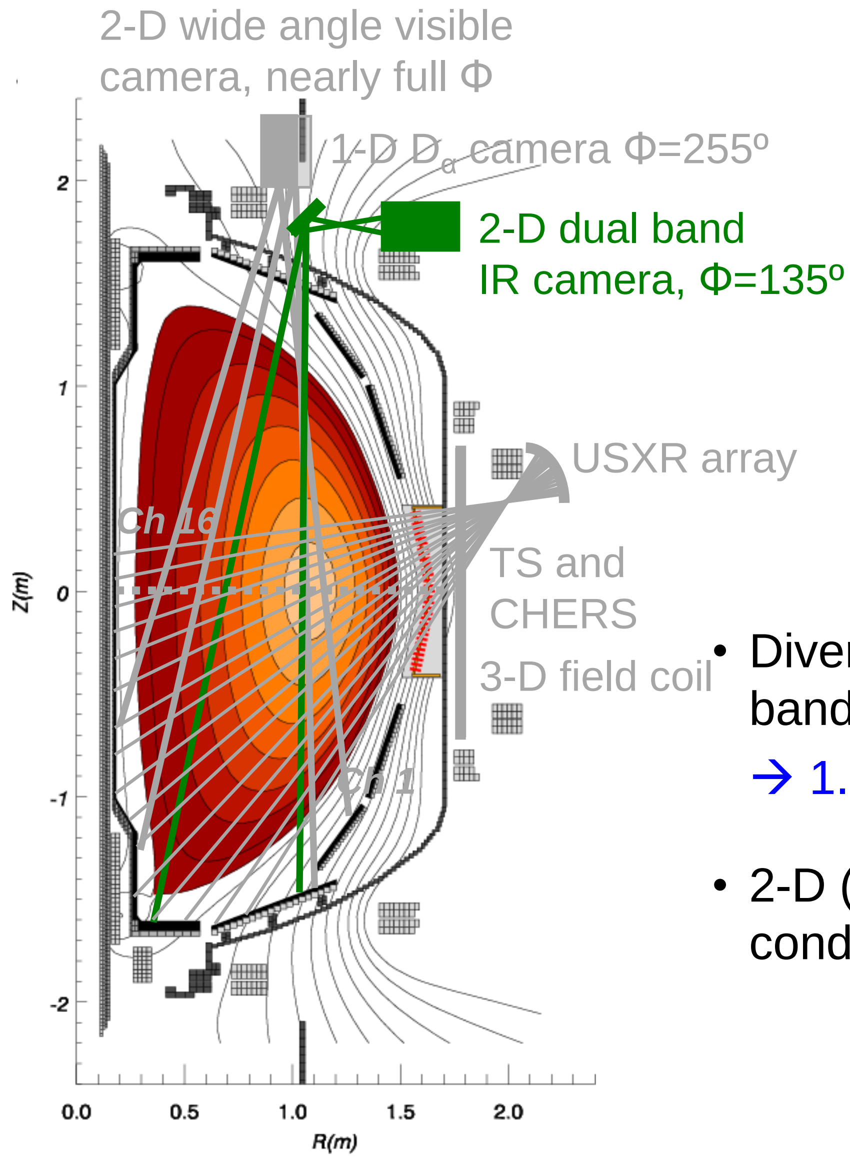
Diagnostics and 3-D field coil arrangement

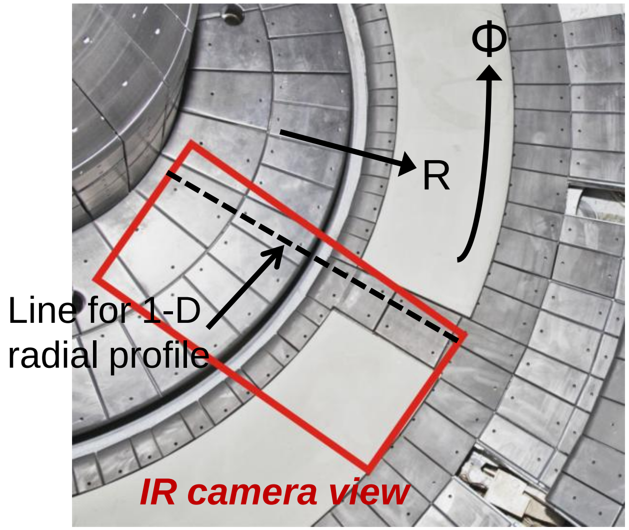




3-D fields (n=1, 2, 3) applied by mid-plane EFC coils

2-D dual band IR camera for heat flux measurement

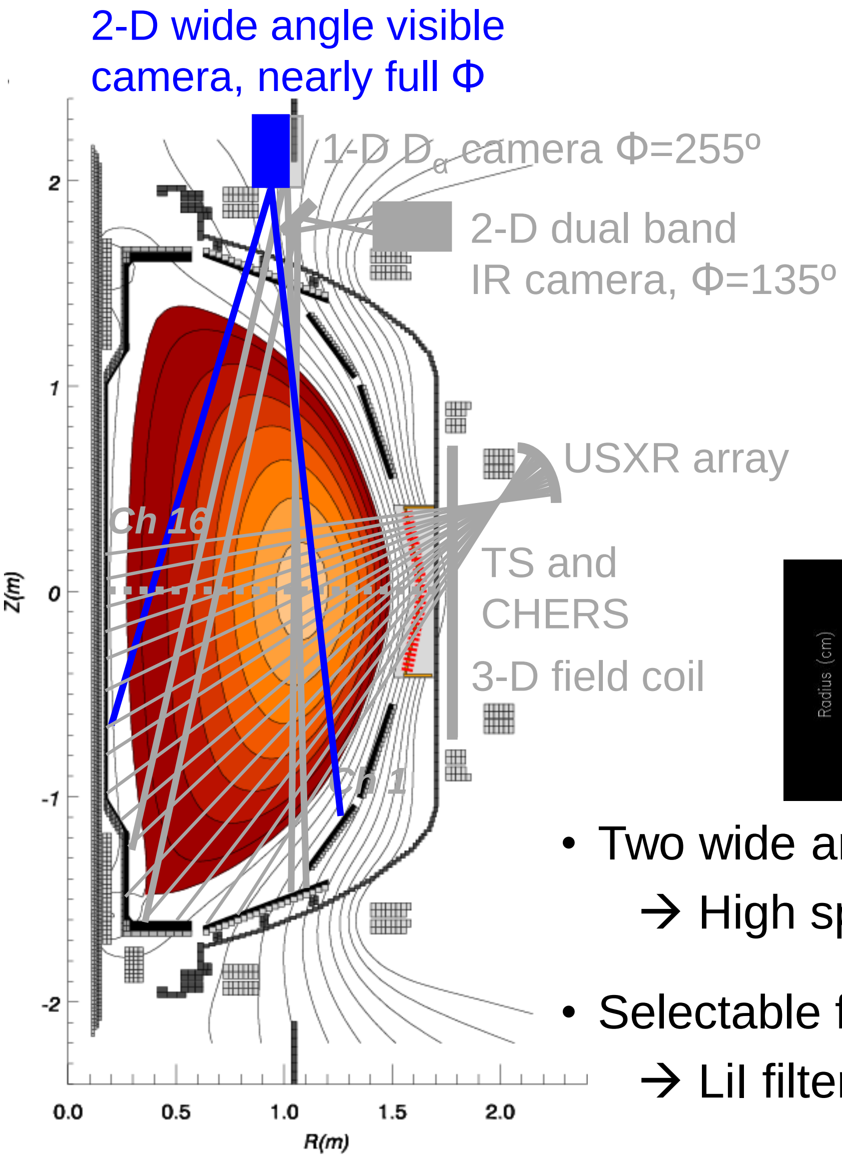


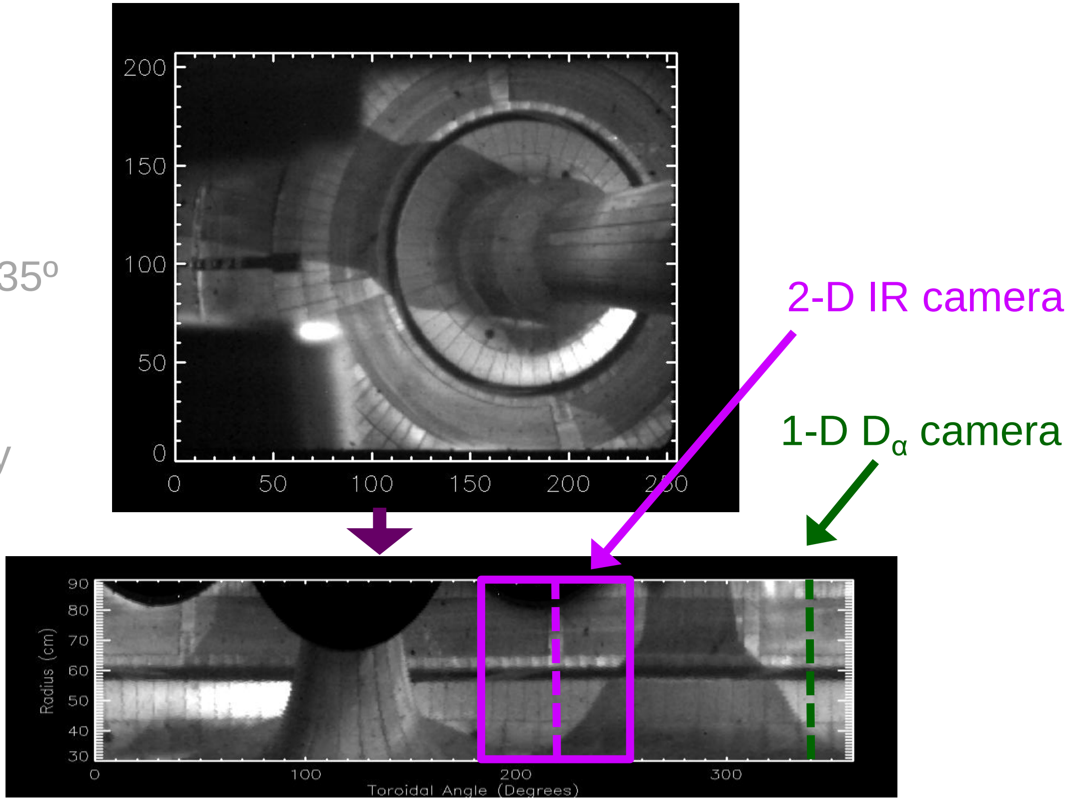


- Divertor surface temperature is monitored by dual band (4-6μm and 7-10 μm) IR camera[1,2]
  → 1.6kHz frame speed, 15-40º toroidal coverage
- 2-D (THEODOR)[3] and 3-D (TACO)[4] heat conduction solvers for heat flux calculation

[1]A.G. McLean, to be published in RSI (2012)
[2]J-W. Ahn, RSI 81 (2010), 023501
[3]Collaboration with IPP Garching, A. Hermann
[4]K. Gan, to be submitted to RSI (2012)

Wide angle visible camera provides access to nearly full toroidal angle





- Two wide angle visible cameras for lower divertor plates[1]
  - → High speed (10-20kHz), Inversion to full (r, Φ) plane
- Selectable filters of >10 wavelength windows
  - → LiI filter (λ=670.9nm) best to resolve fine structures

[1]F. Scotti, to be submitted to RSI (2012)

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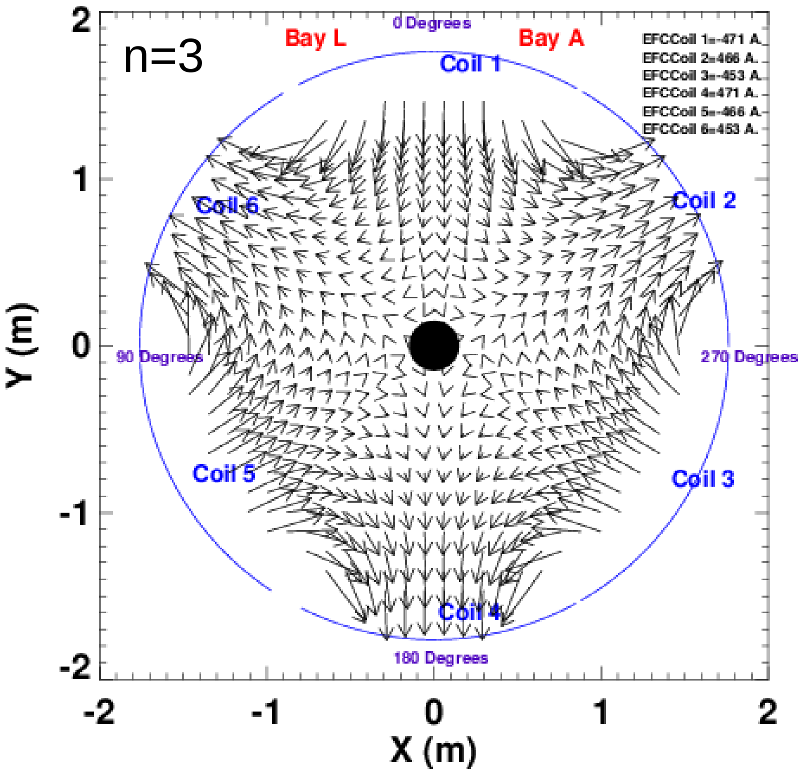
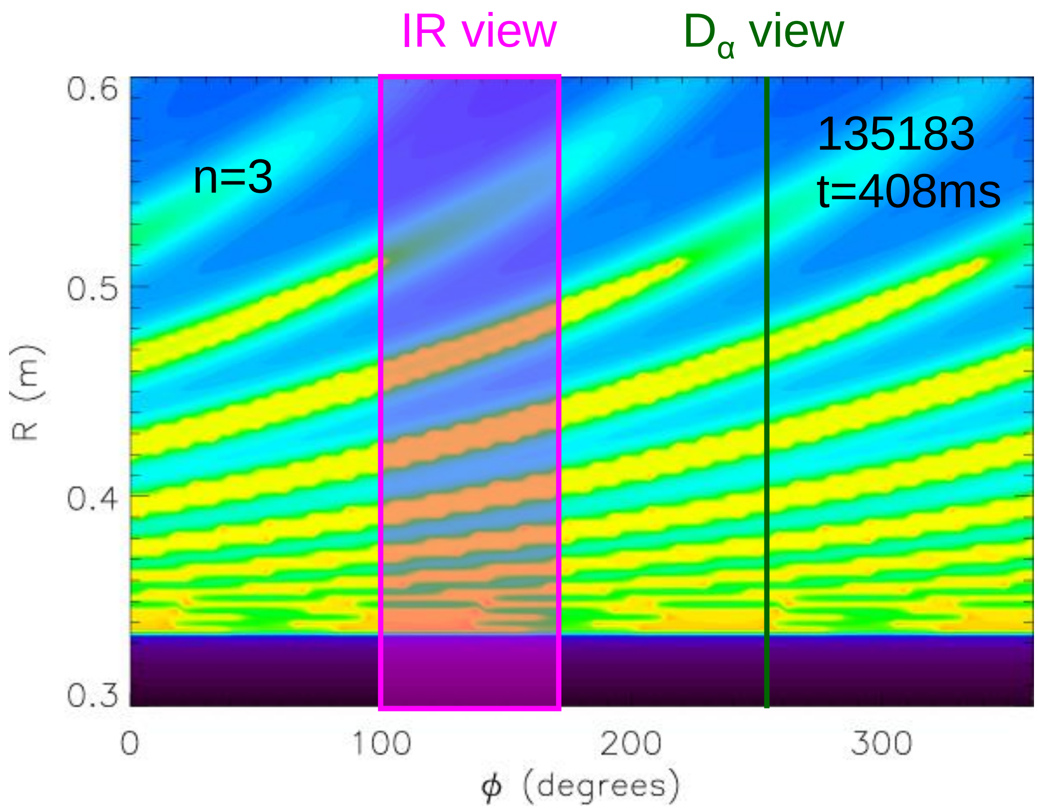
Strike point splitting is predicted by 3-D fields application

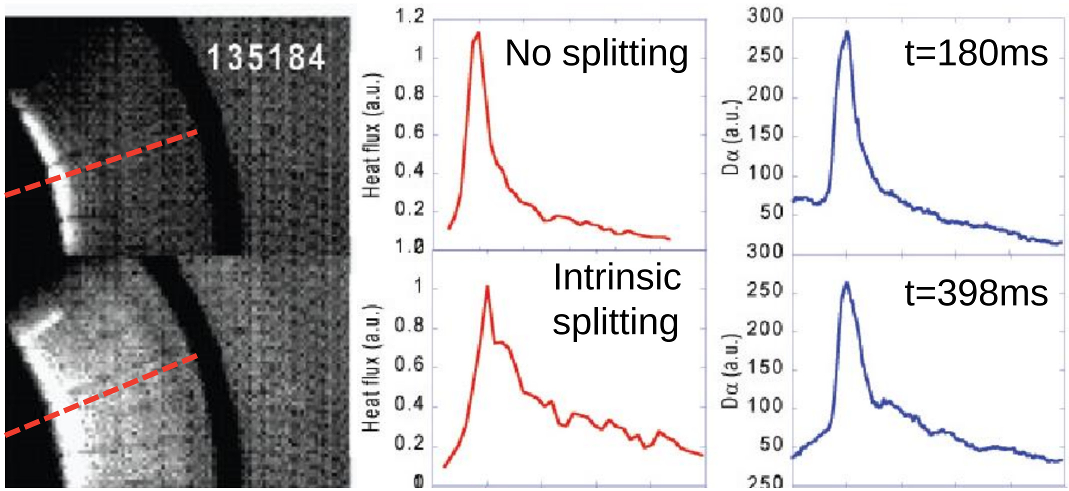




- Connection length of field lines to divertor target, computed by vacuum field line tracing
- Field line tracing uses superposition of vacuum n=3 fields and 2-D equilibrium fields

Divertor profile is modified by intrinsic and applied n=3 magnetic perturbations

Raw IR image **Heat flux profile** **D_α profile**

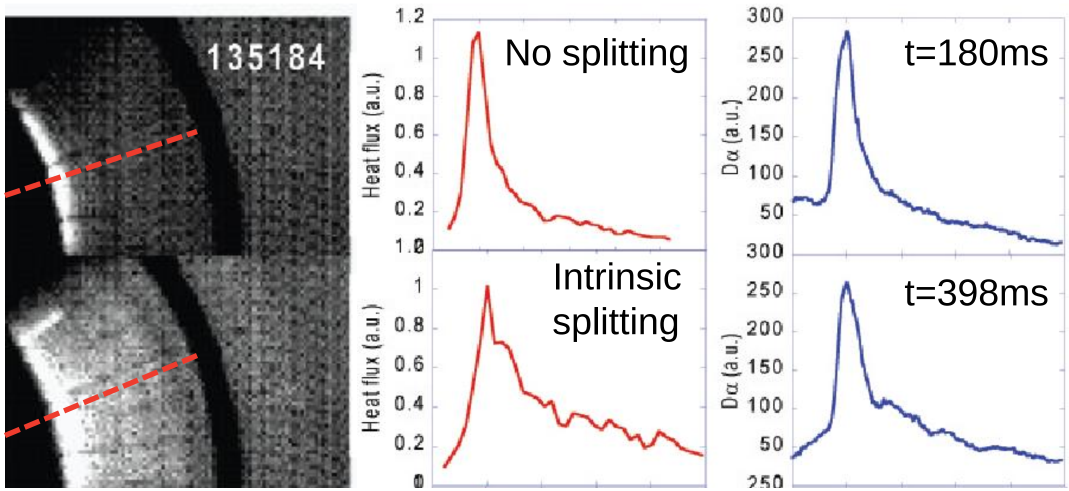


At earlier time slice

2ms before 3-D field application

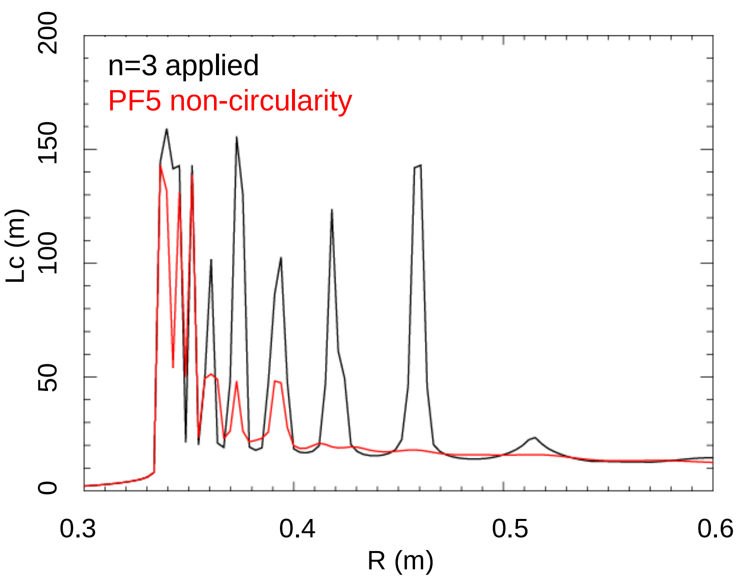
Divertor profile is modified by intrinsic and applied n=3 magnetic perturbations

Raw IR image **Heat flux profile** **D_α profile**



At earlier time slice

2ms before 3-D field application

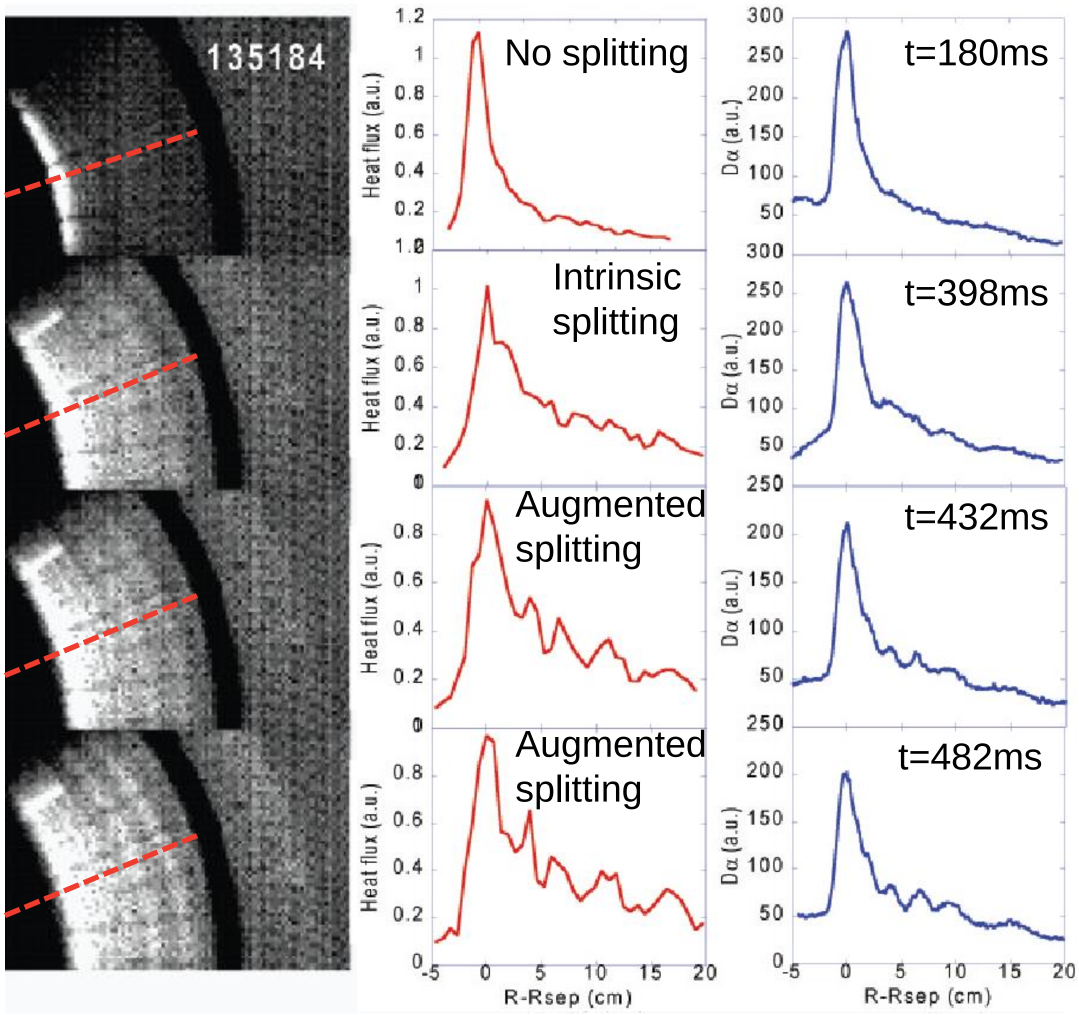


- Vacuum field line tracing modeling for intrinsic error fields from the non-circularity of PF5, n=3 component is known to be dominant component
- Radial location of local peaks agree between PF5 and n=3 application cases

J-W. Ahn, PoP 18 (2011), 056108

Divertor profile is modified by intrinsic and applied n=3 magnetic perturbations

Raw IR image | **Heat flux profile** | **D_α profile**



At earlier time slice

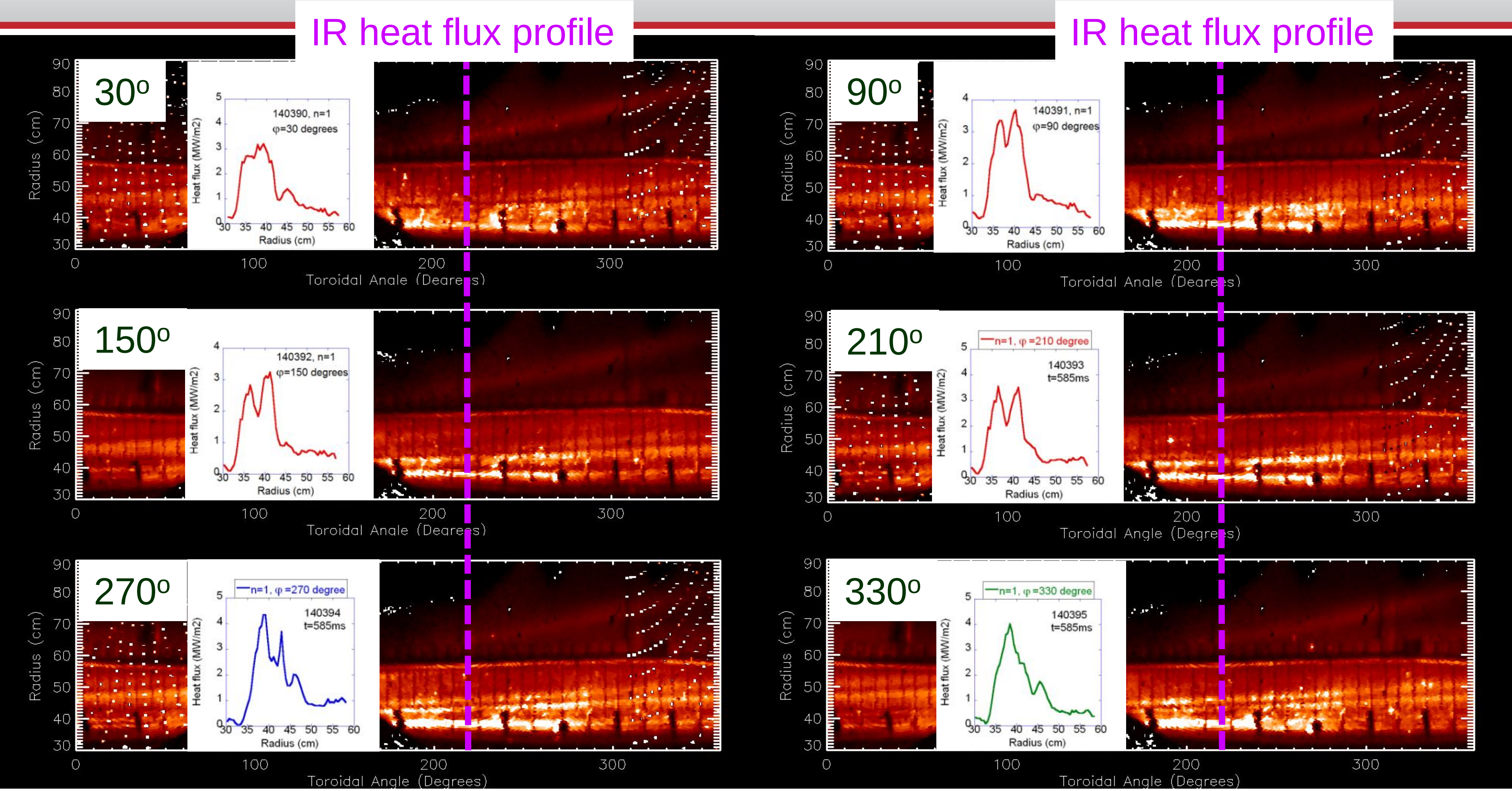
2ms before 3-D field application

32ms after 3-D field application

82ms after 3-D field application

J-W. Ahn, NF 50 (2010), 045010

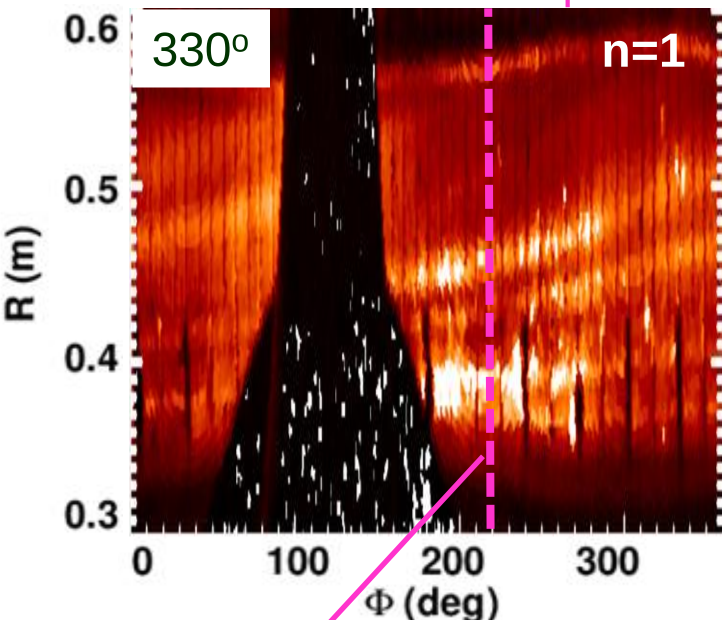
Toroidal rotation of applied n=1 fields

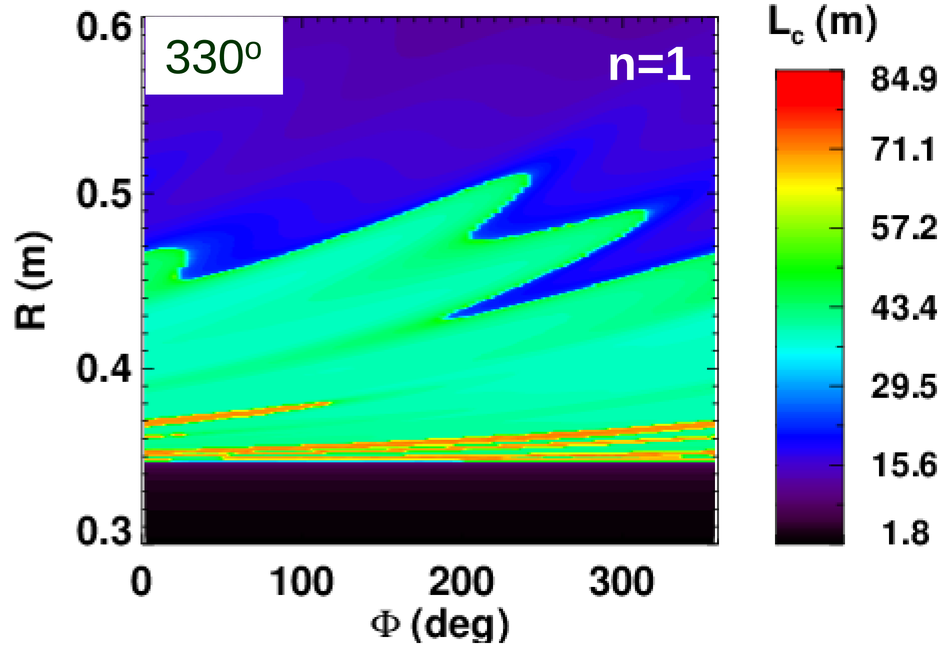


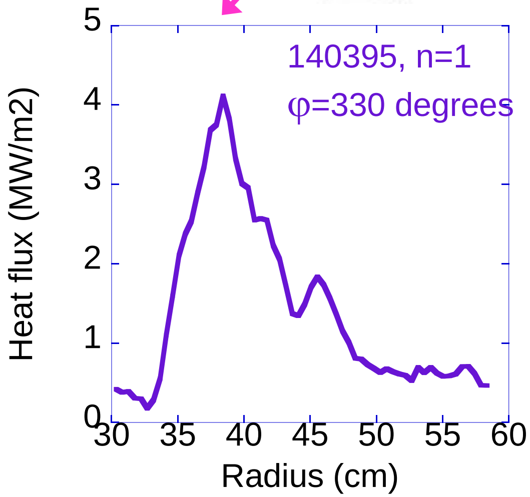
- The phase angle of the applied n=1 perturbation was rotated in a static manner
- The measured IR heat flux profile agrees well with the visible camera image

Vacuum field line tracing reproduces the observed strike point splitting pattern

IR heat flux profile

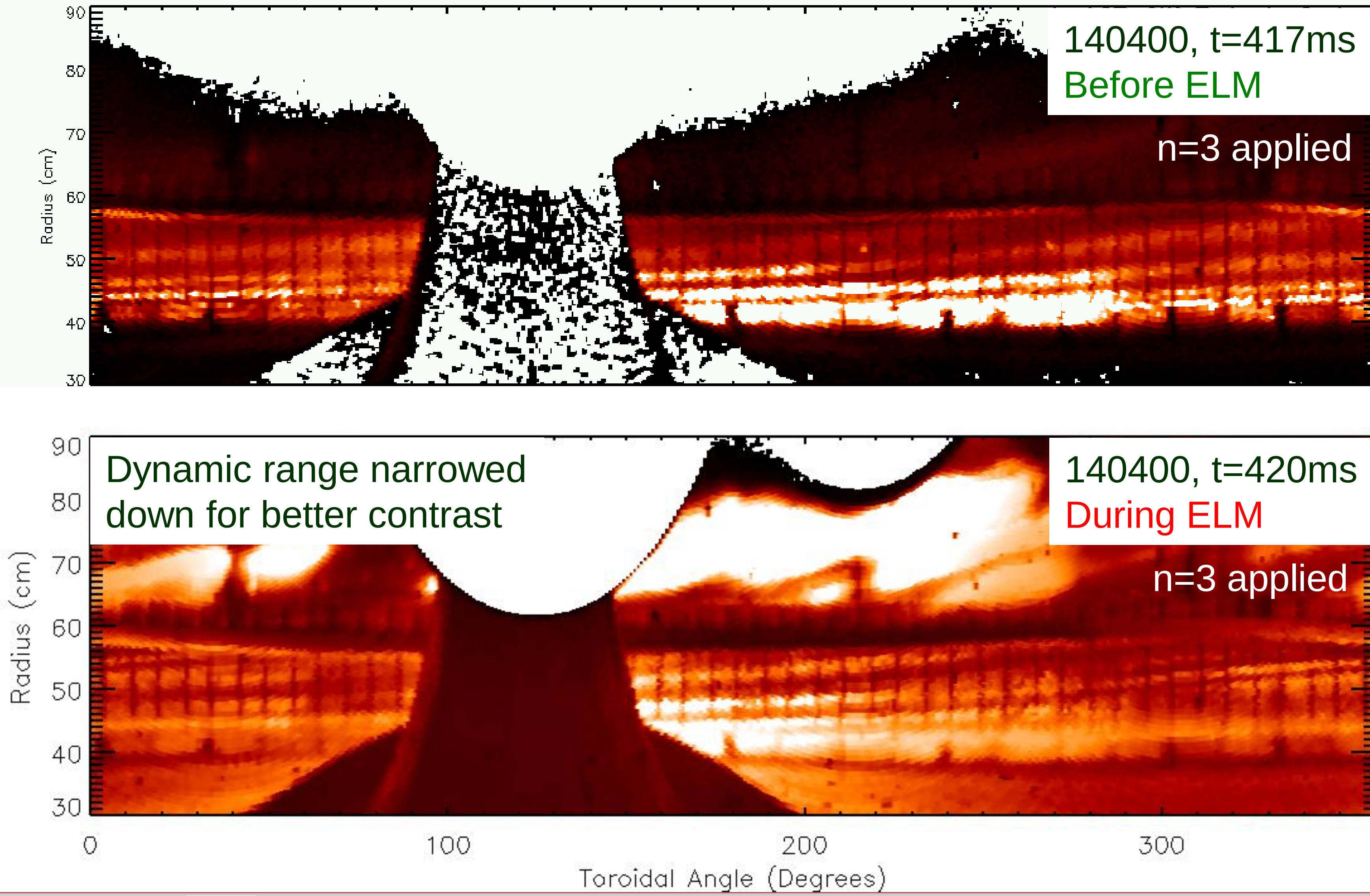




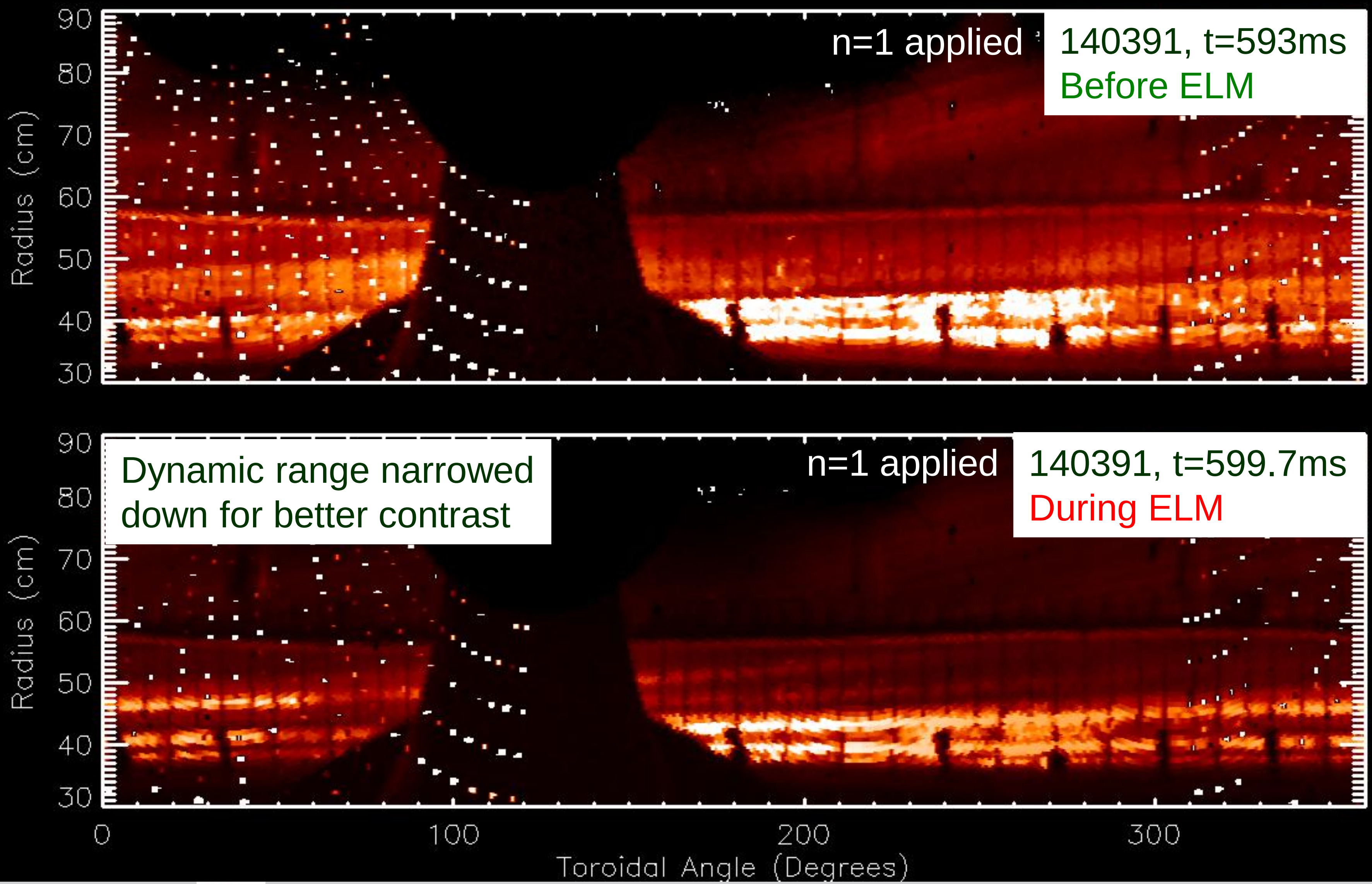


- The peak heat flux is shifted outward from the nominal strike point location by ~3cm
- This is contrary to the prediction of simple vacuum field line tracing, which always puts some long L_c field lines near the strike point, therefore high heat and particle flux is expected

The full Φ 2-D image reconfirms the phase locking of triggered ELMs to the imposed n=3 perturbation



The full Φ 2-D image also shows the phase locking of triggered ELMs by n=1 perturbation



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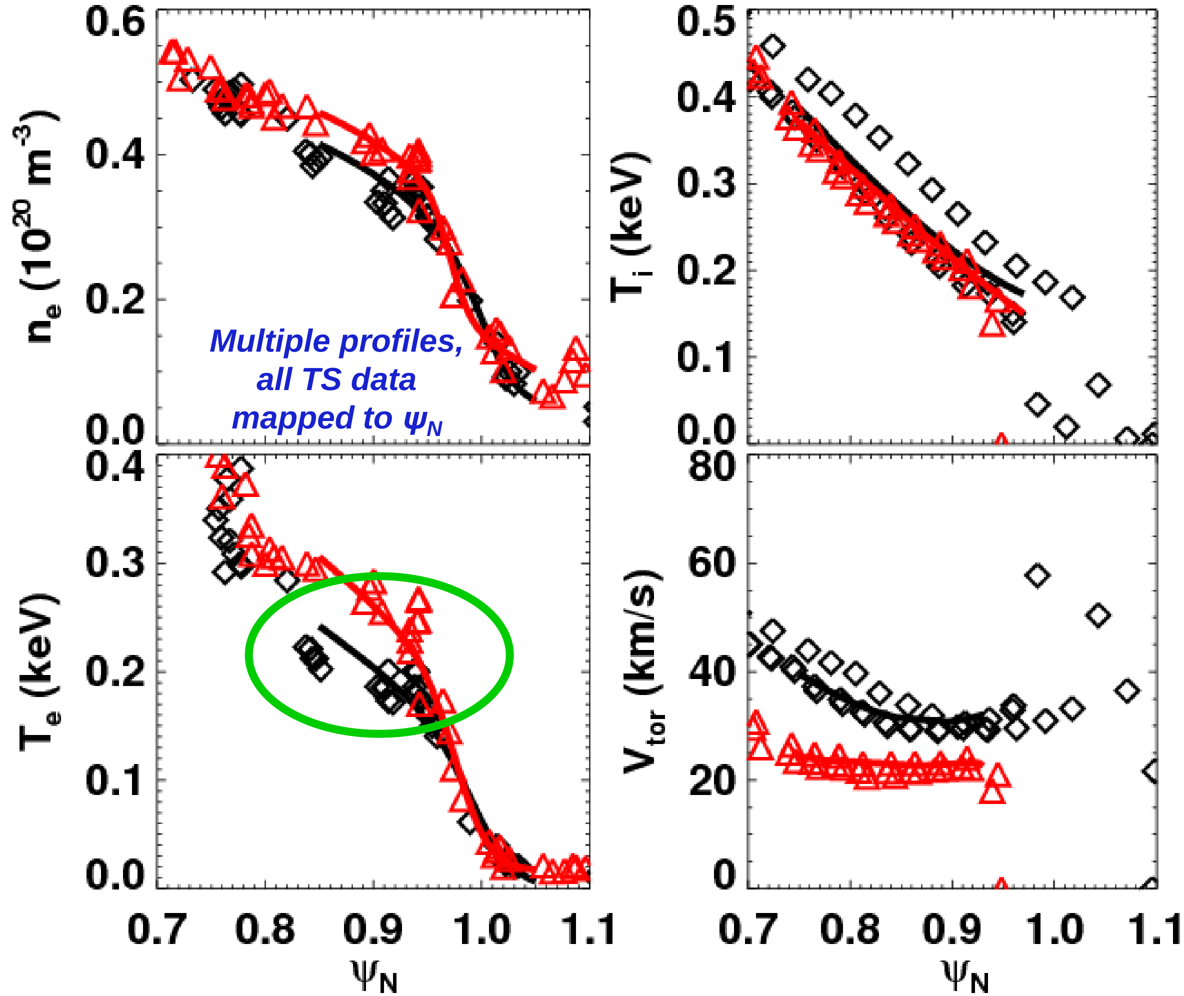
Without lithium, T_e^{ped} increase leads to p_e^{ped} increase and can explain ELM triggering

Black profiles: no n=3 applied

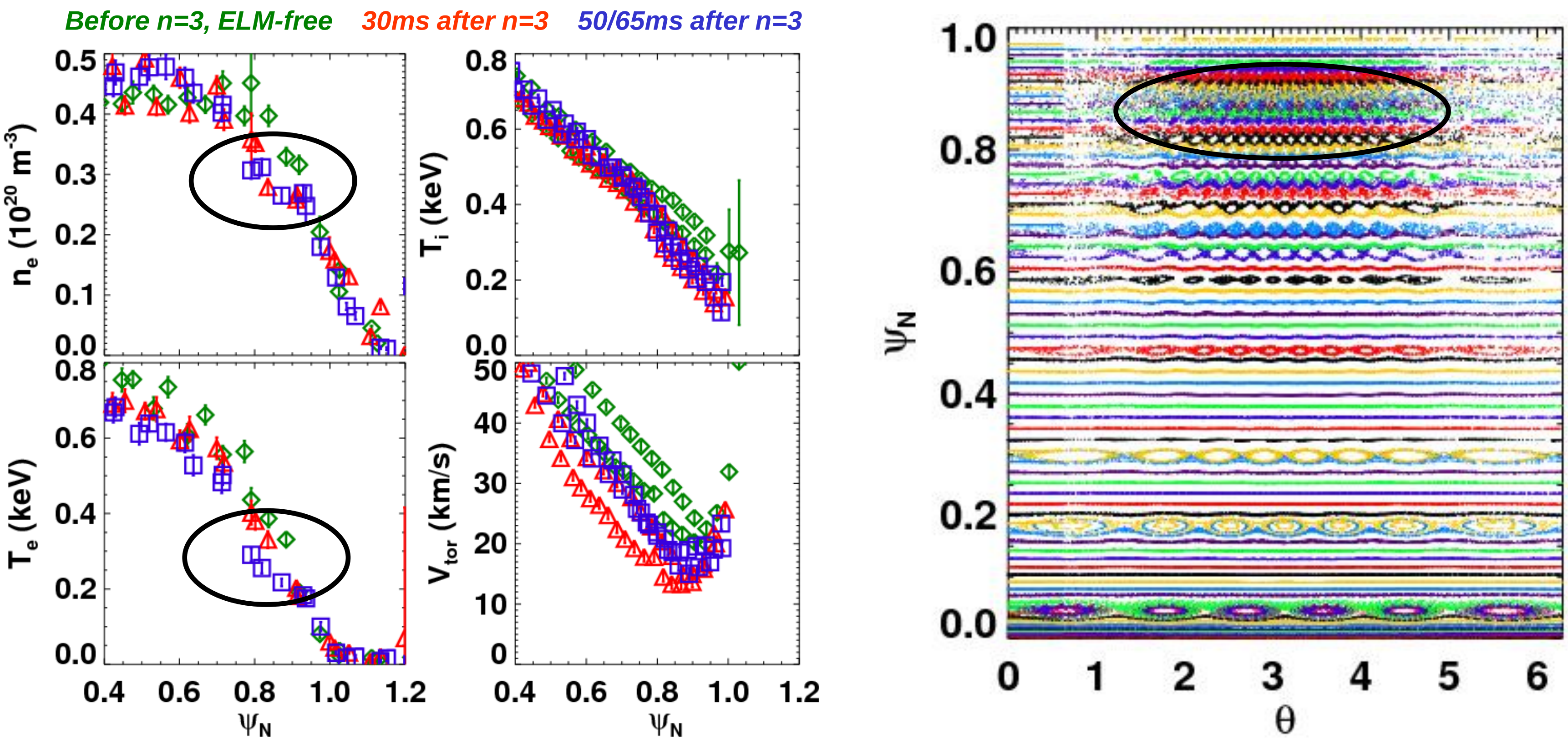
Red profiles: 20 ms after n=3 applied (before ELMs)



- No density pumpout is observed
- T_e and p_e gradient increases after n=3 field is applied
  - Tanh fitting gives ~30% increase in peak pressure gradient
  - PEST shows edge unstable after n=3 application
  - May be related to divertor conditions

J.M. Canik, PRL 104 (2010) 045001

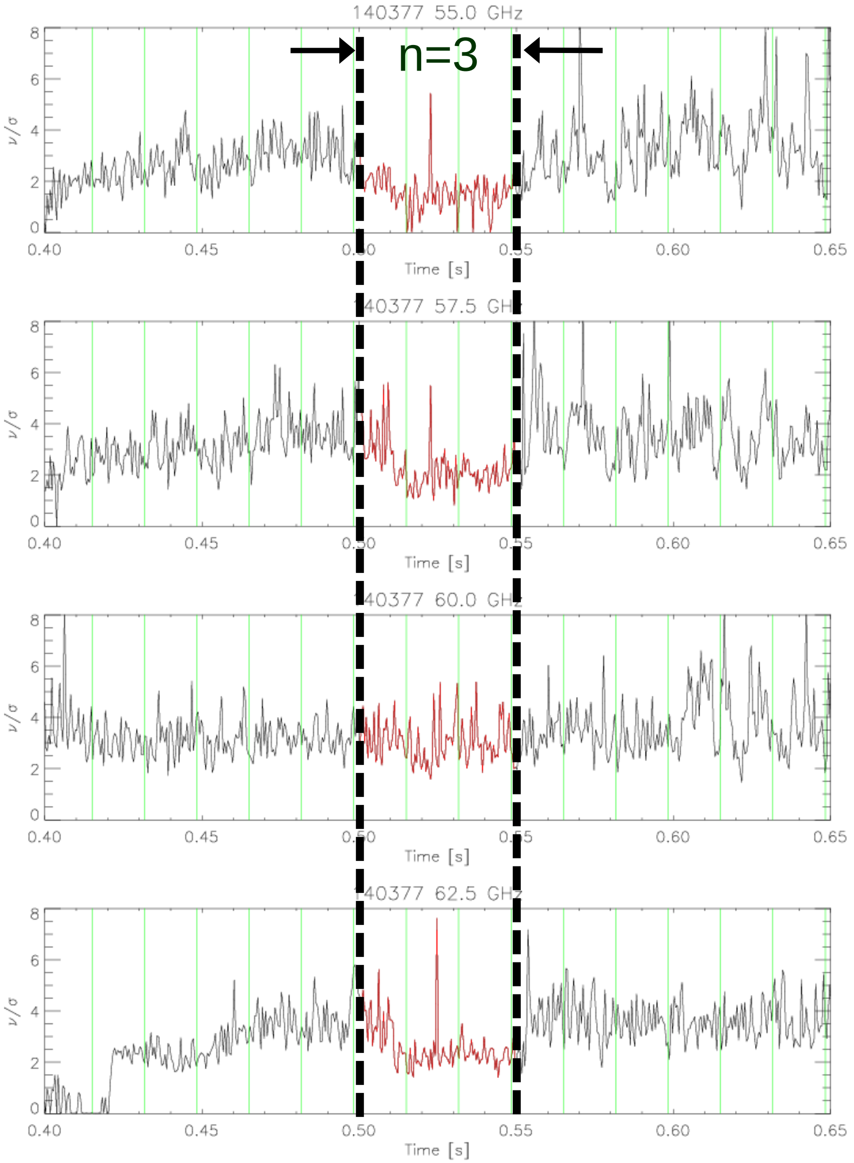
With lithium coatings, flat spots observed in pedestal profiles with 3-D fields

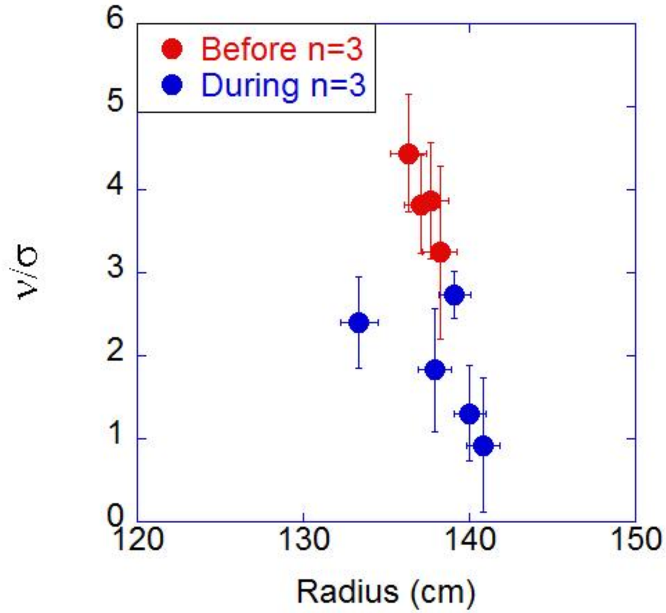


- Edge T_i and V_t drops after n=3 field is applied. T_e and n_e show flattening for ψ_N ~0.8-0.9, similar gradient outside 0.9
- SIESTA modeling shows edge island overlap
  - Position is roughly consistent with flattening observed in experiment, but more work is needed to see if this may be the cause of the flattening

J.M. Canik, submitted to NF (2011)

Turbulence at the density pedestal top increases with n=3 perturbation, with lithium coatings





- Reflectometer measurement for lithium enhanced, ELM-free H-mode with n=3
- ν/σ signal shows clear decrease during the 3-D field application
  → increase of high-k turbulence, assuming Gaussian distribution
- Consistent with the flattening of density by applied n=3

S. Kubota, UCLA

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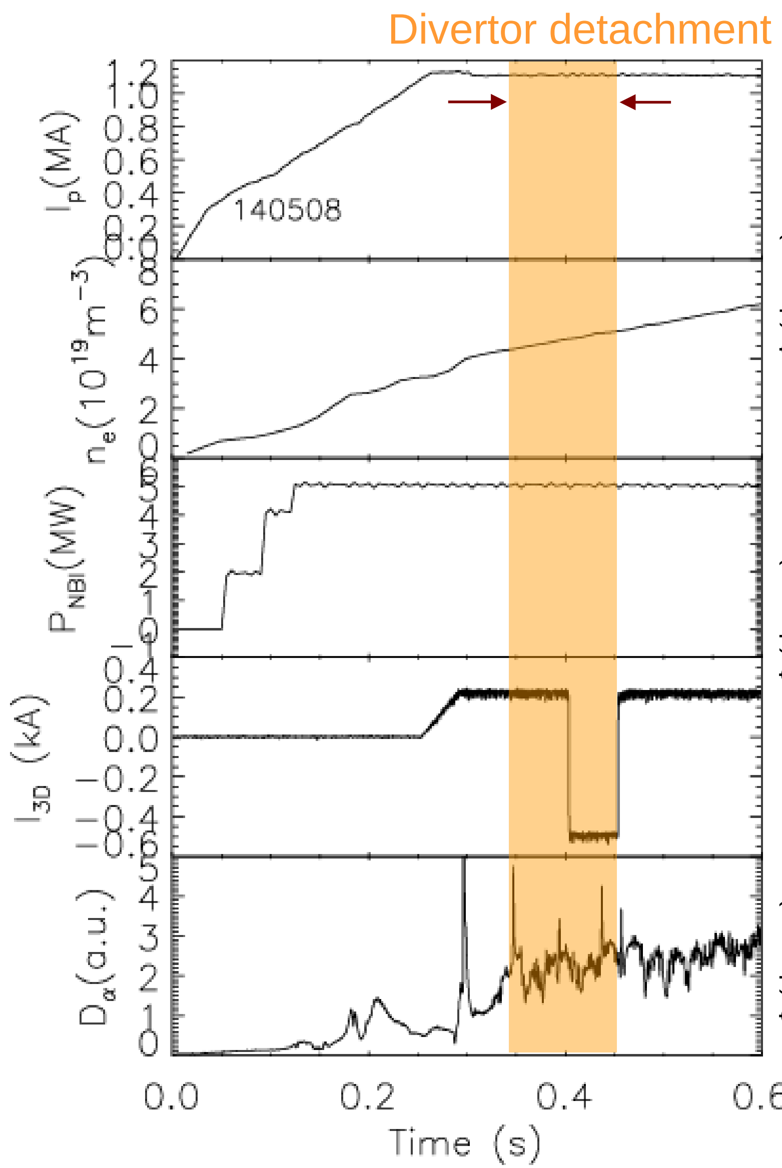
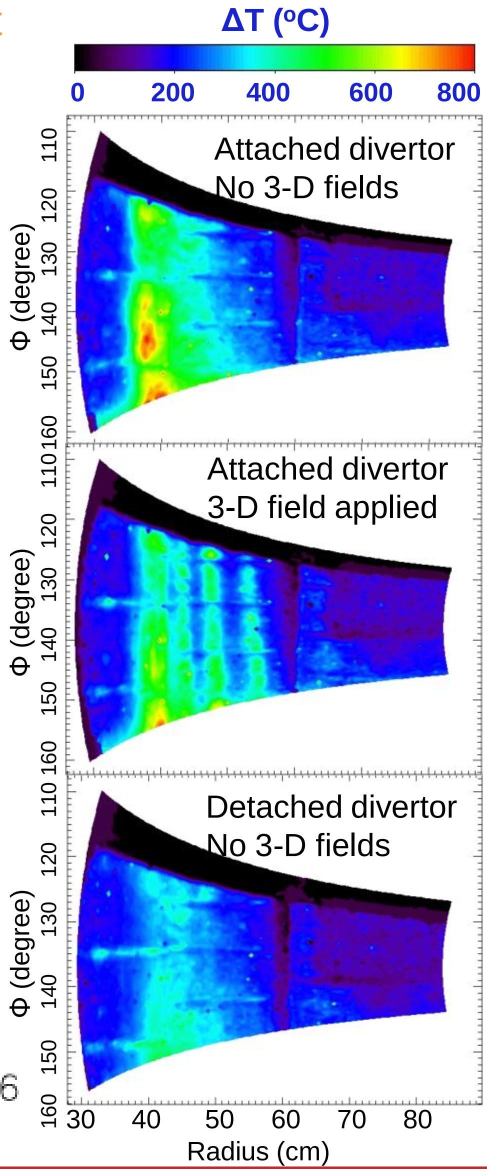
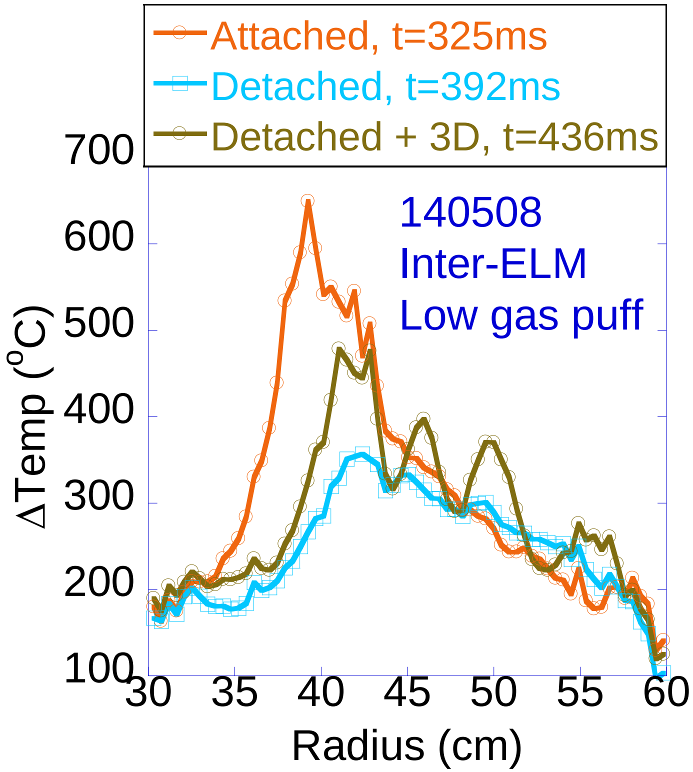
Experimental approach to the effect of 3-D fields on divertor detachment

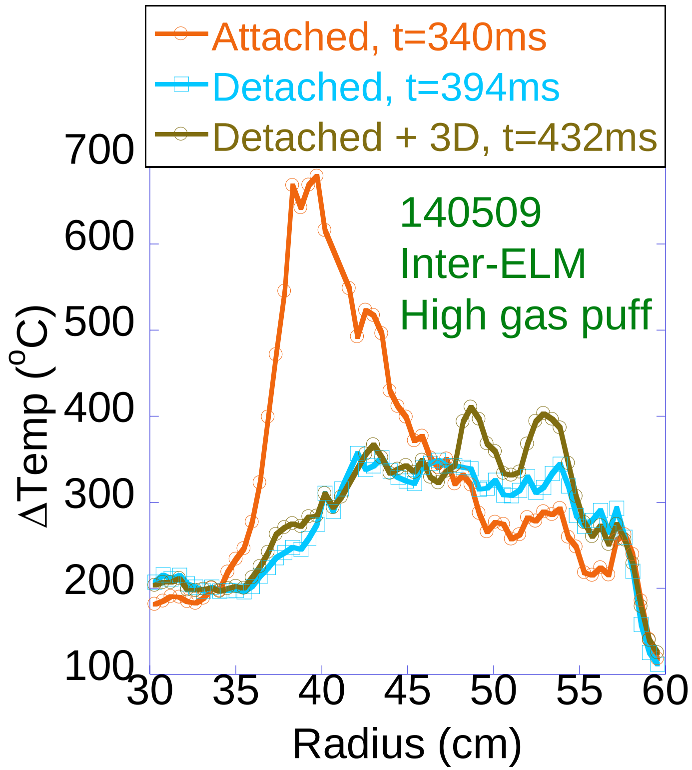




- Natural ELMy H-mode
- Step 1: Divertor gas puffing to produce partially detached divertor plasmas
- Step2: Apply 3-D fields (n=3) on top of the n=3 EFC field (~200A) below ELM triggering threshold to see the effect on the divertor and pedestal plasmas

Applied 3-D fields can reattach weakly detached plasma but no effect on strong detachment



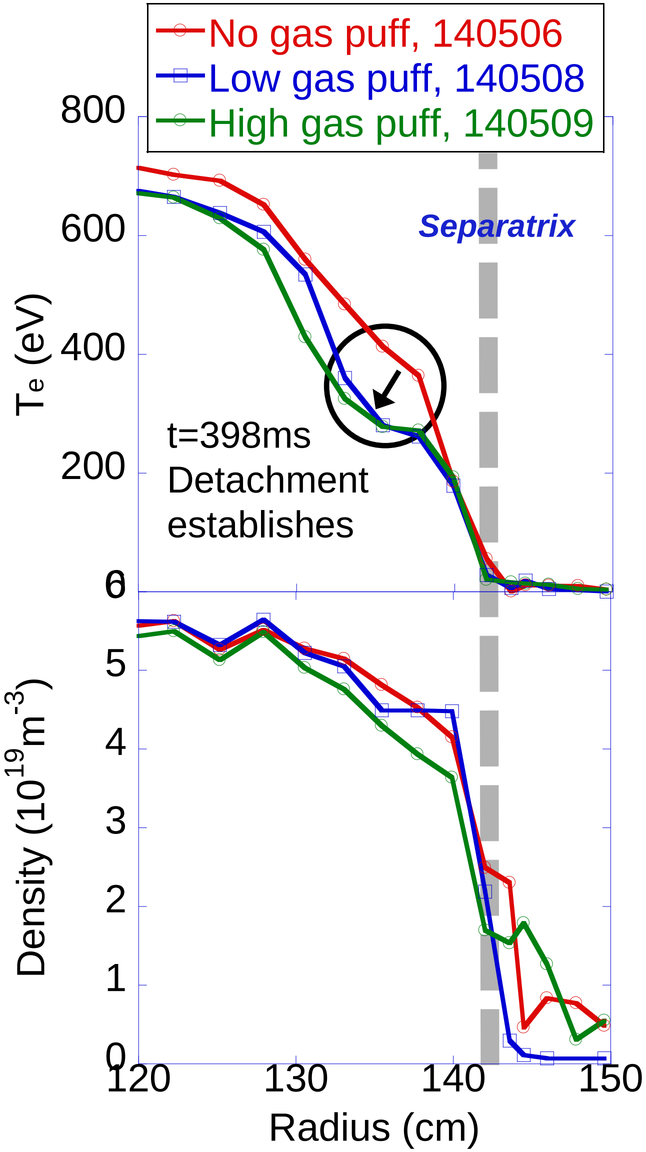


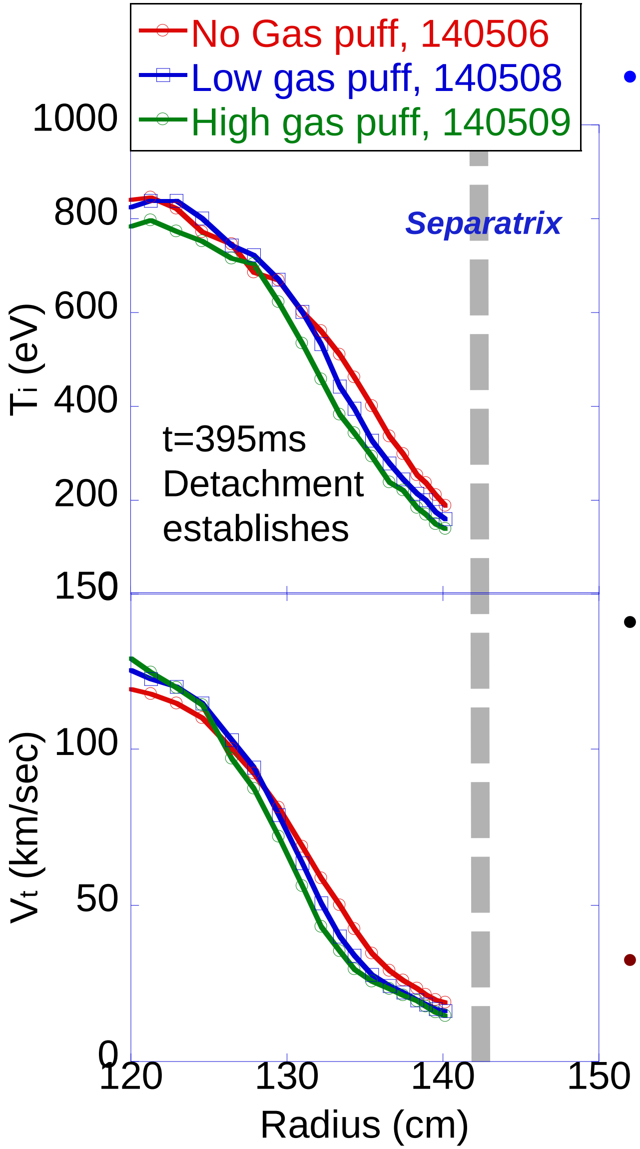
- Applied 3-D fields make the detached divertor plasma re-attach in low gas puff rate, leading to a peaked surface temperature profile again. The peak temperature in the re-attached plasma is lower than the original peak value

- If the divertor gas puffing is high enough, plasma stays in the partially detached regime even with 3-D field applied

J-W. Ahn, PoP 18 (2011), 056108

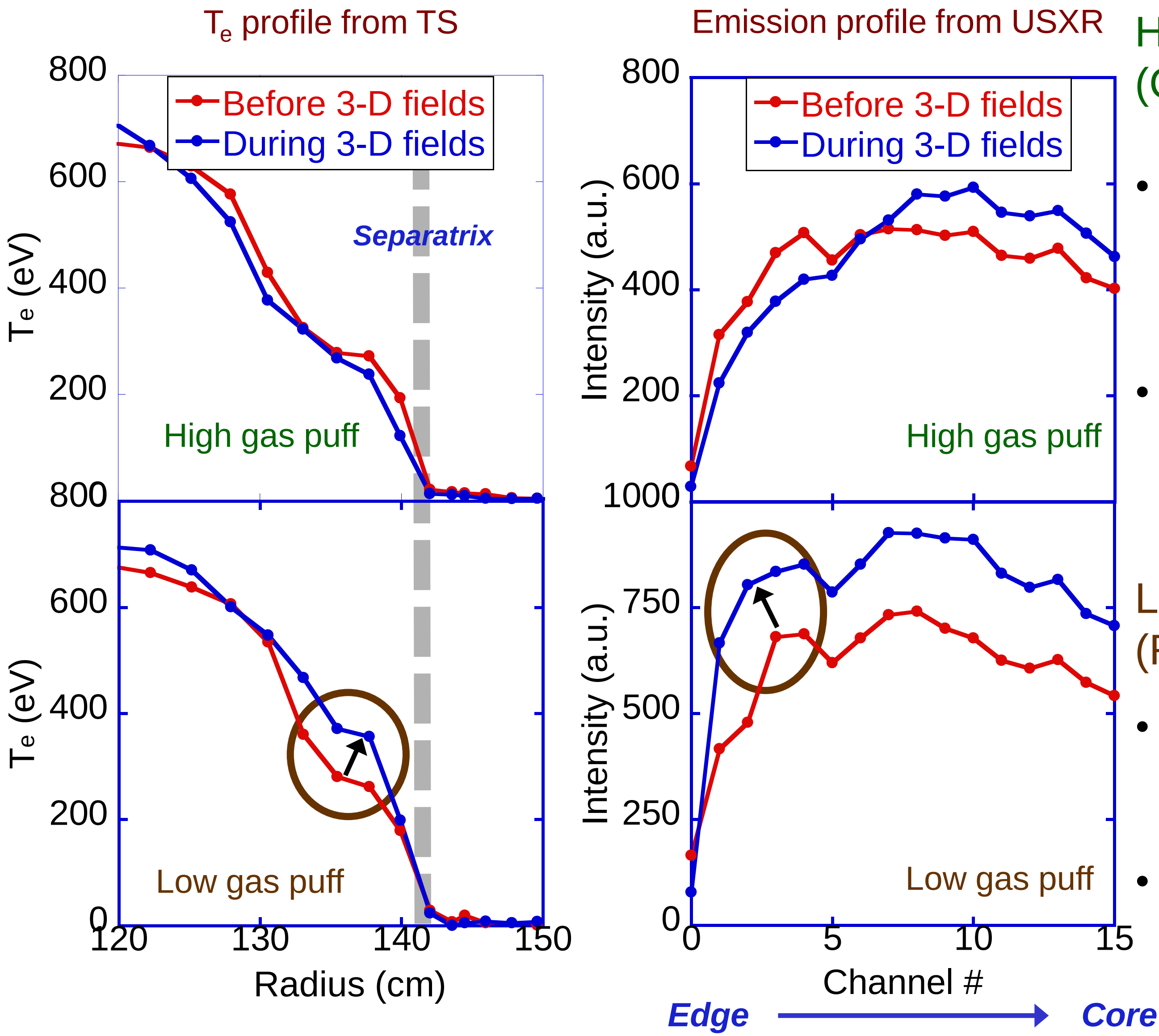
Pedestal T_e drop is prominently observed when divertor detachment is established





- T_e profile reduction near the pedestal top is most prominent. Pedestal density only slightly decreases
  - → Correlated with divertor heat flux profile reduction
- Overall pedestal T_i and V_t profiles also decrease as the detachment is established but the change is relatively small
- This is commonly observed in detached plasmas in NSTX

Divertor re-attachment by applied 3-D fields is related with rise of pedestal T_e profile



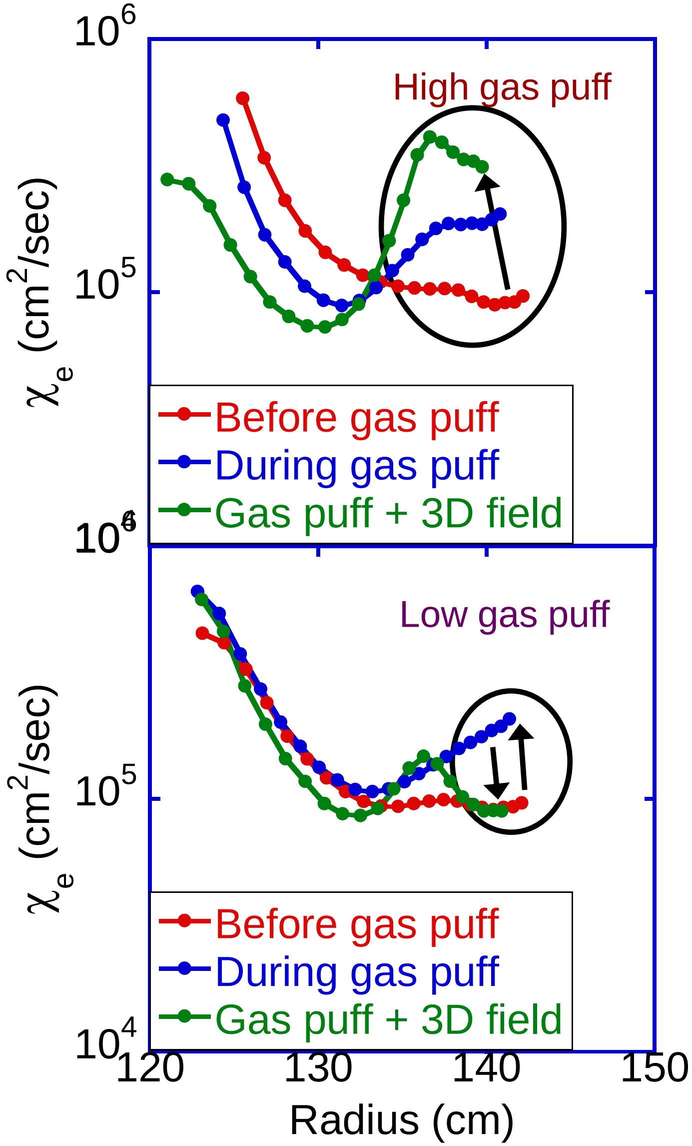
High gas puff
(Continued detachment)

- Pedestal T_e profile remains decreased, ie unaffected, after 3-D field application
- USXR edge data (toward channel 0) also continuously decrease

Low gas puff
(Re-attachment by 3-D field)

- Pedestal T_e rises back up by the applied 3-D fields
- Edge USXR data also shows increase

TRANSP modeling indicates change in the pedestal electron heat diffusivity



High gas puff (continued detachment)

- Pedestal χ_e continuously increases during the whole detachment and the later 3-D field application phases

Low gas puff (re-attachment)

- Pedestal χ_e increases during the detachment phase and then decreases again with the onset of re-attachment

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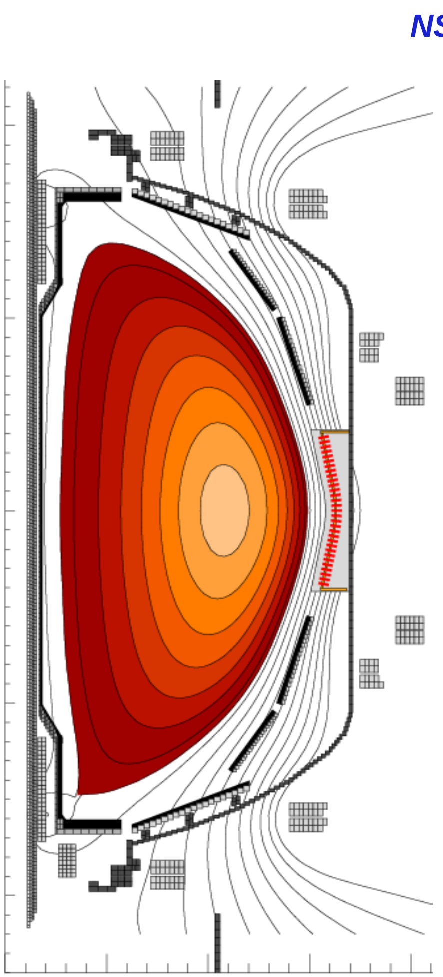
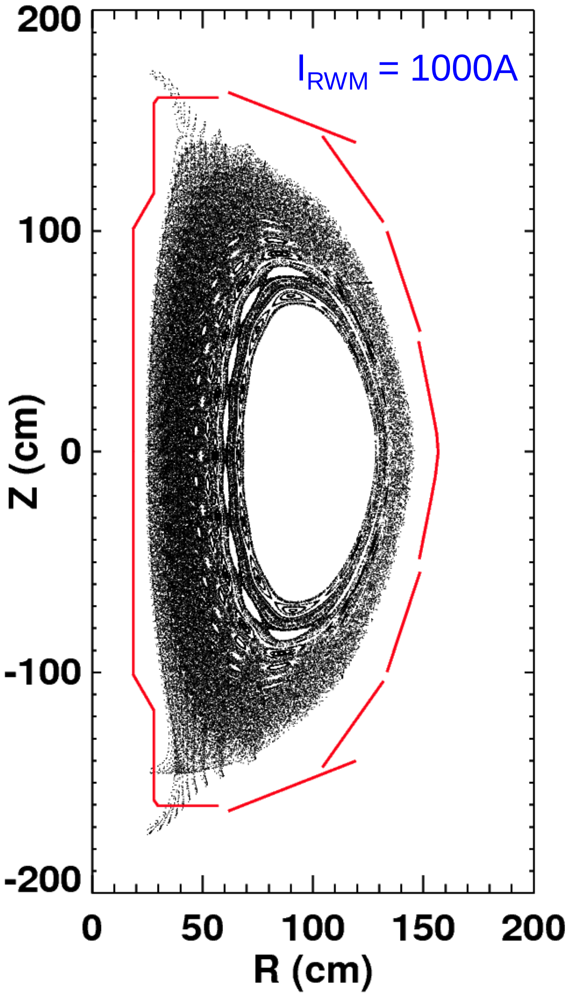
Fully 3-D geometry is used for modeling

3-D PFC Geometry



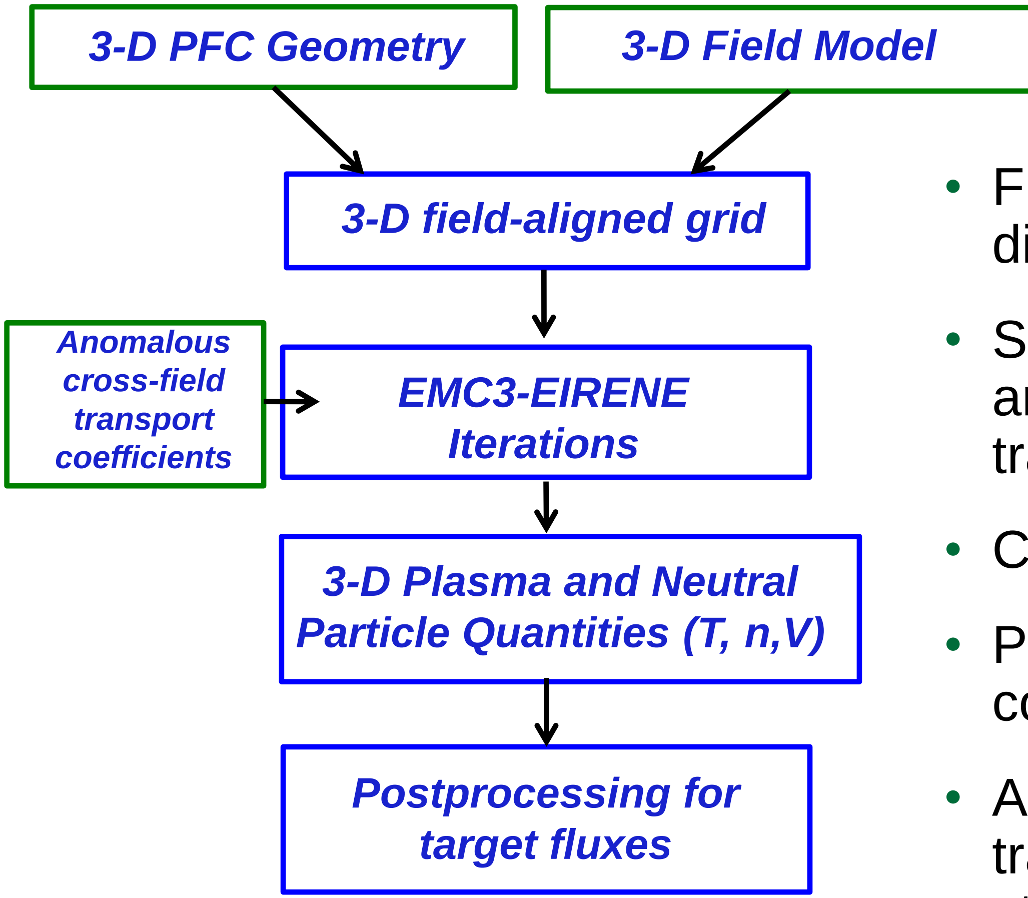
3-D Field Model



- 3-D magnetic field model required
- "Vacuum Paradigm"
  - 2-D equilibrium (EFIT) + 3-D vacuum perturbation field
  - Currently implemented for EMC3-Eirene in NSTX
- Plasma response model
  - IPEC, SIESTA, current sheets on resonant surfaces
  - In progress

J.D. Lore, NF 2012 (accepted)

Flow chart of EMC3-Eirene[1] modeling



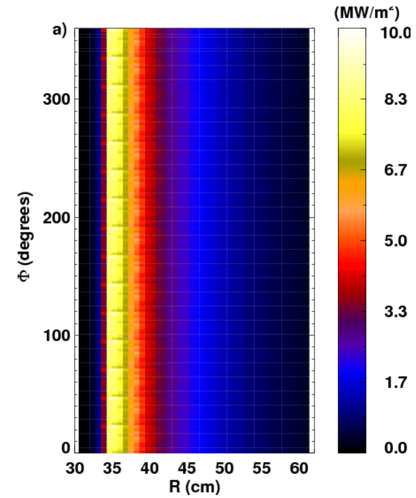
- Power load distribution
- Particle deposition
- Neutral flux distribution
- Energy spectrum of neutral particles

- Fully 3D geometry for plasma, divertor, PFCs
- Self-consistent coupling of fluid ions and electrons, kinetic neutral transport and PSI
- Classical parallel transport ($\eta_{||}$, κ_e, κ_i)
- Prescribed anomalous cross-field coefficients
- Allows for calculation of fluid transport in stochastic and non-stochastic fields.

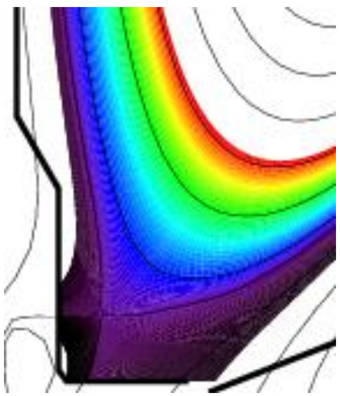
[1]Y. Feng, PPCF 44, 611 (2002)

Strike point splitting qualitatively reproduced

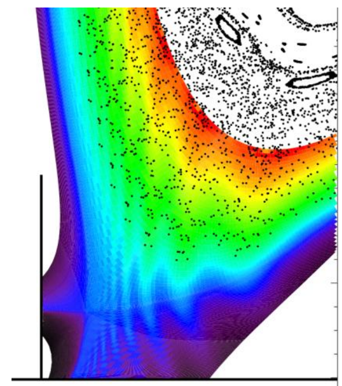
- Results shown for lower horizontal target, at $\phi = 0^\circ$

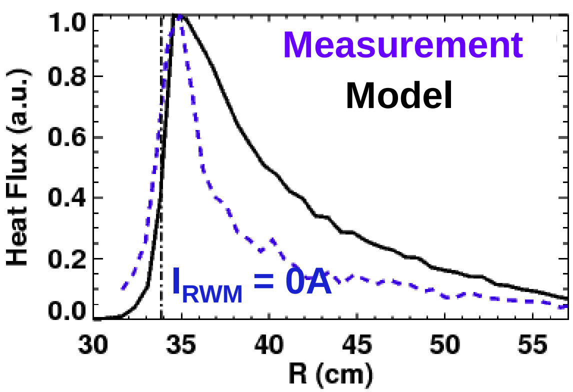


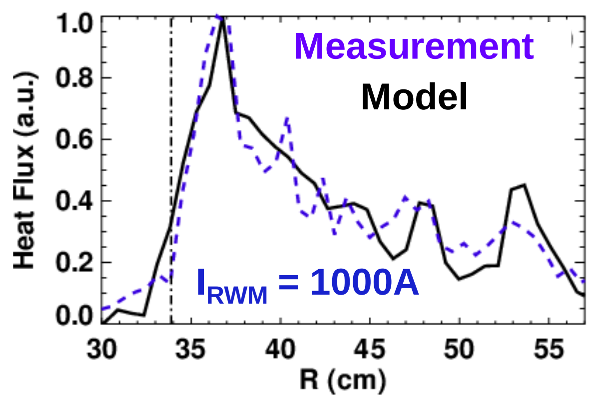
$I_{3\text{-}D}$ = 0A

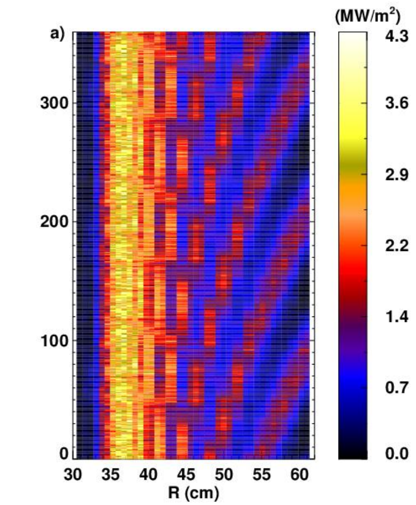


$I_{3\text{-}D}$ = 1kA









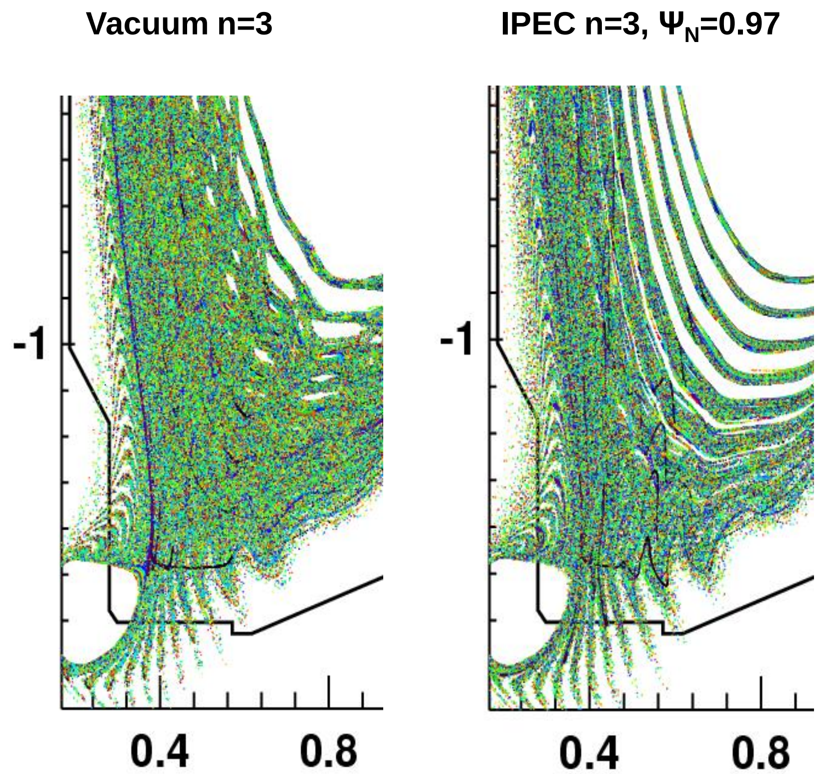
J.D. Lore, NF 2012 (accepted)

NSTX modeling goals using EMC3-Eirene

- Further investigations are in progress now that grid generation and postprocessing tools have been developed
  - Vary cross-field transport coefficients to match midplane profiles
  - Modeling of divertor plasma reattachment with 3-D fields
  - Addition of synthetic diagnostics for D_α comparison
  - Implementation of more sophisticated B-field models

    (e.g., VMEC+EXTENDER, IPEC)

J.D. Lore, NF 2012 (accepted)



Vacuum field line tracing has indicated insensitivity of locations of split strike points to ideal plasma response

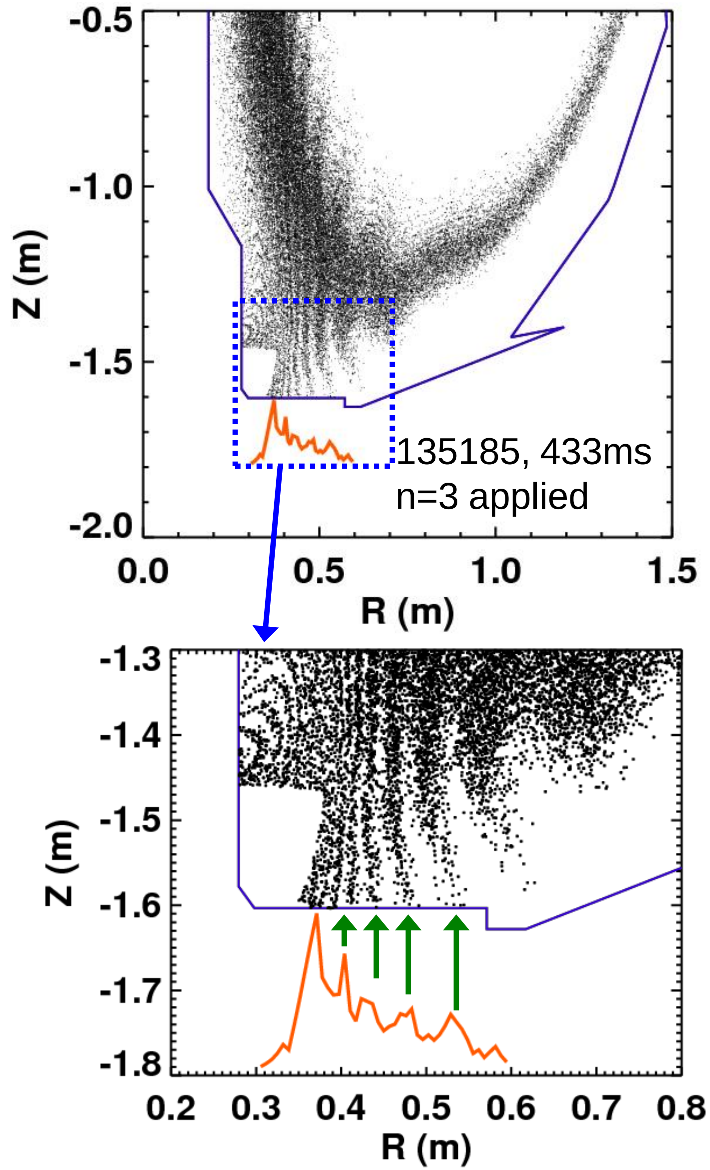
J-W. Ahn, J. Nucl. Mater. 415 (2011), S918

Summary and conclusion

- Applied 3-D fields have strong and clear impact on divertor profiles
  - Non-axisymmetric divertor profiles often occur for various reasons (error fields, MHD modes, etc) → affects peak heat flux location, power accounting, etc
  - Vacuum field line tracing well reproduces the strike point splitting pattern
  - Triggered ELMs are phase locked to the imposed 3-D fields for n=1 and n=3
- Effect on pedestal transport is relatively weak and inconsistent
  - Without Li coating, T_e^{ped} increases but with Li coating, flat spots in n_e, T_e profile
  - Effect on edge stabilty more robust: PEST shows edge unstable with n=3, consistent with the triggering of ELMs
- Applied 3-D fields can reattach detached divertor plasma
  - Sufficient gas puffing can prevent the reattachment
  - Reattachment is associated with pedestal T_e rise by applied 3-D fields and is consistent with χ_e profile change from TRANSP modeling
- EMC3-Eirene simulation qualitatively reproduces the observed strike point splitting and aims to address various experimental observations

Backup slides

Distribution of splitting locations from measurement and vacuum field line tracing in good agreement

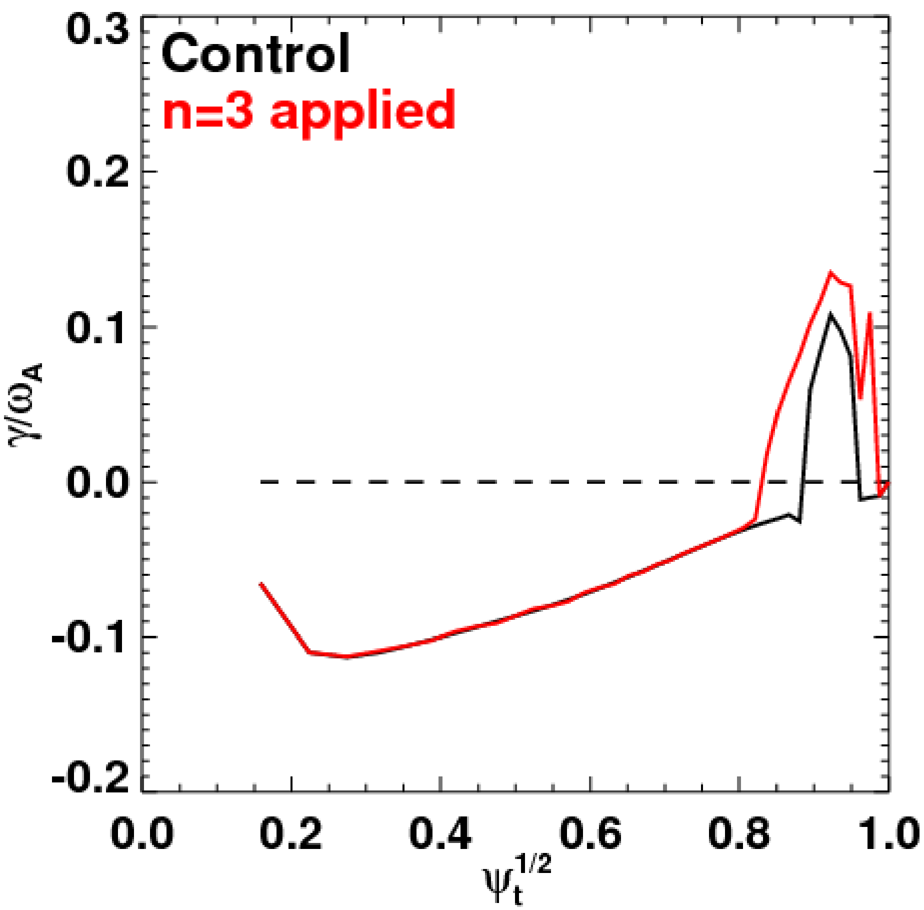


- Measured heat flux profile (orange) overlaid with vacuum field line tracing plot

- Dense regions in the puncture plot correspond to long connection length lobes from the pedestal region, therefore expected to have higher heat and particle fluxes

J-W. Ahn, PoP 18 (2011), 056108

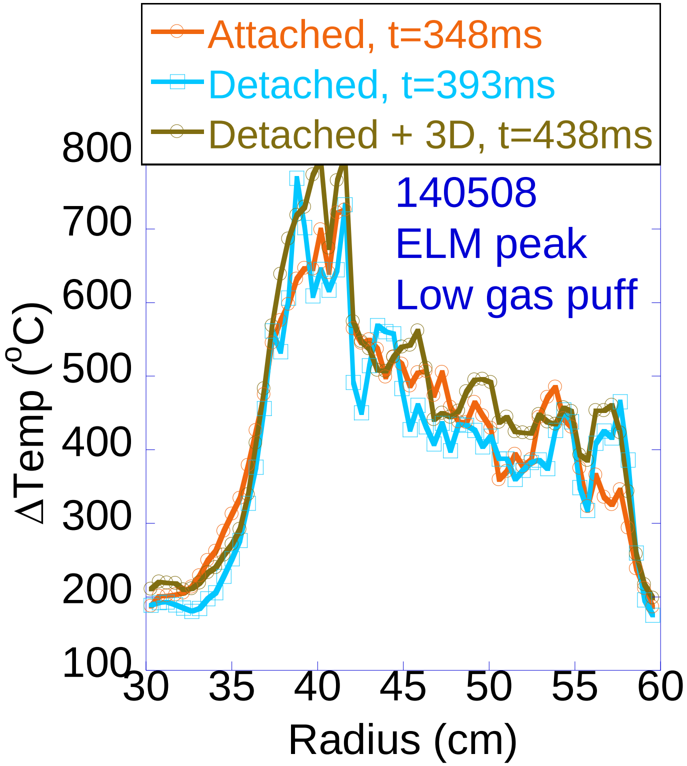
Ballooning stability is degraded by n=3 fields

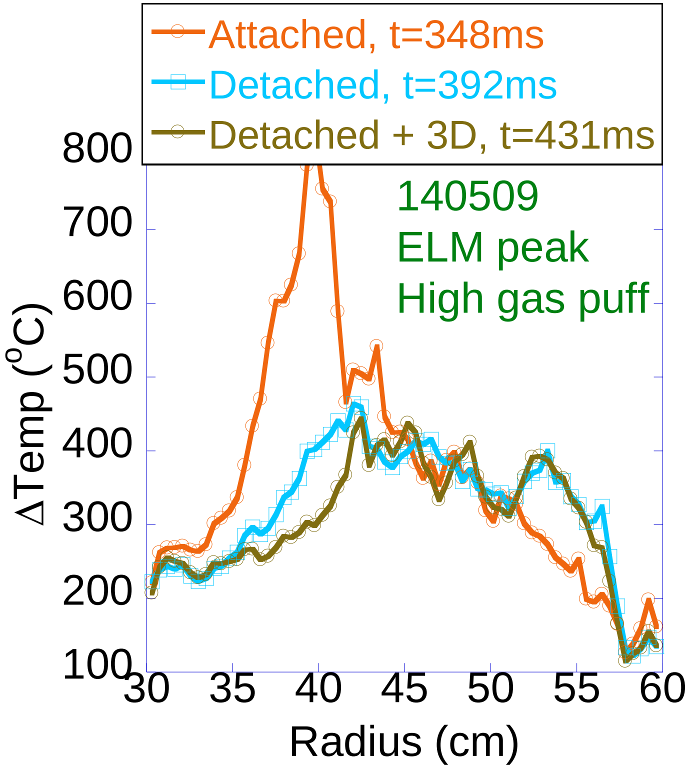


- Infinite-n ballooning stability calculated with COBRA code
- Control case (no n=3 field applied) shows region of instability near edge
- n=3 field increases instability
  - Region with positive growth rate becomes wider
  - Growth rates in unstable region higher
  - Consistent with robust ELM triggering with n=3
- Suggests at least a trend towards instability with 3-D fields applied

J.M. Canik, APS 2011

At ELM peak times: High gas puff keeps the ELMy plasma in detached regime





- ELMs burn through the detachment in low gas puff, making the peak temperature similar to the value in the attached phase. 3-D field application keeps the ELM size from dropping

- High gas puff rate significantly reduces the ELM size and the plasma remains in the partial detachment regime even at the ELM peak times. 3-D field application does not return the plasma to the attached phase