Simulation of 3D effects on partially detached divertor conditions in NSTX and Alcator C-Mod

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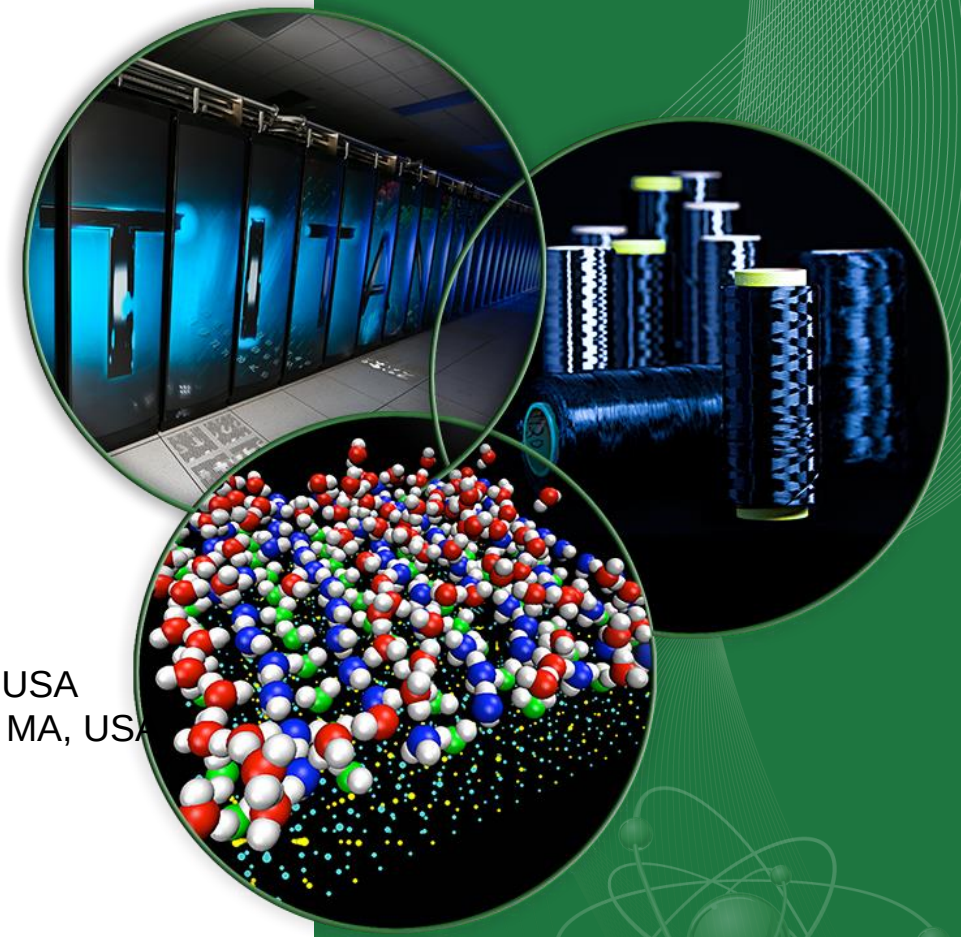


Alcator C-Mod @ MIT PSFC NSTX PPPL

OAK RIDGE National Laboratory

ITER will run with partially detached divertor conditions

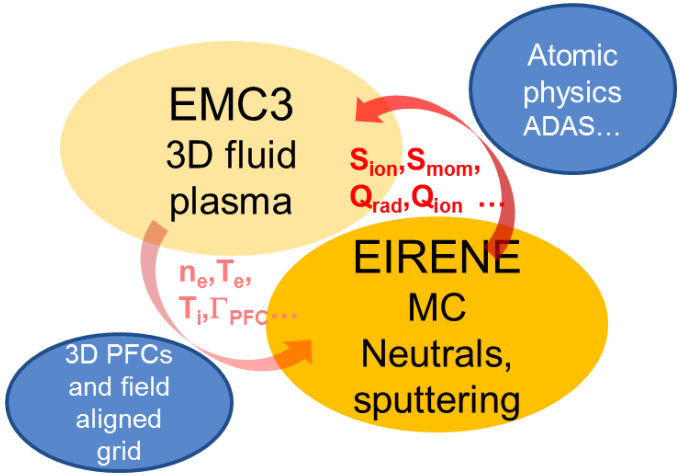
- Partial detachment required to reduce heat flux to targets to meet technical limits, T_e must be low to reduce sputtering
- 3D effects may affect divertor conditions
  - 3D fields (applied or intrinsic) can cause striated flux patterns, cause local reattachment of divertor plasma
  - Extrinsic gas injection will be used to control detachment; localized injectors may result in non-axisymmetric radiated power and fluxes
- Experiments have been performed to investigate these effects, validated 3D modeling tools are required to make reliable predictions for ITER

Outline

- The EMC3-EIRENE code
- C-Mod experiments to investigate effect of localized divertor gas injection
  - Level of toroidal asymmetry depends on downstream conditions, impurity ionization in the private flux region
- NSTX experiments on divertor reattachment due to 3D field application
  - With 3D fields heat flux peaks at large radius remain in sheath limited regime due to short connection length
- Conclusions

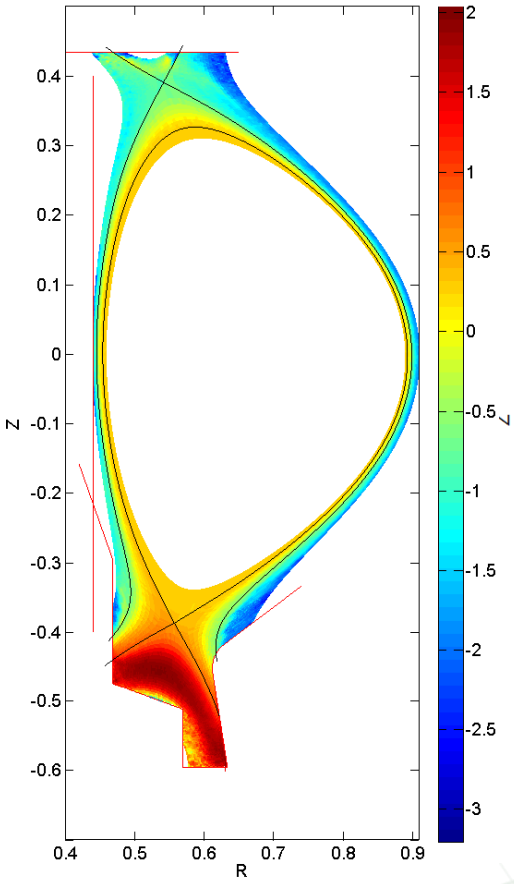
The EMC3-EIRENE code is used to model 3D effects in tokamaks

- Steady-state 3D fluid plasma model (EMC3) coupled to kinetic neutral transport and PSI (EIRENE)

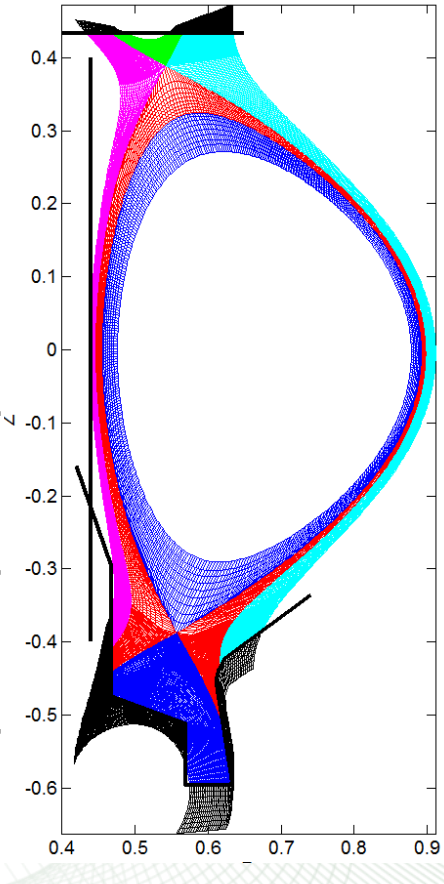


- Fully 3D geometry for plasma, PFCs
- Classical parallel transport ($\eta_{||}$, κ_e, κ_i) with prescribed anomalous cross-field diffusivities $D_\perp$, $\chi_{i\perp}$, $\chi_{e\perp}$ $\eta_\perp$
- Trace fluid impurity model ($T_a=T_i, n_a Z_a << n_i$) with feedback to main plasma through electron energy loss
- Outputs: 3D neutral and fluid plasma quantities, surface loads on to PFCs
- Inputs: 3D grid aligned to magnetic field, core density and input power, cross field diffusivities, impurity sources
- Limitations: No cross-field drifts, kinetic corrections or volume recombination in current version

log10(n_e) [10^{14} cm^{-3}]



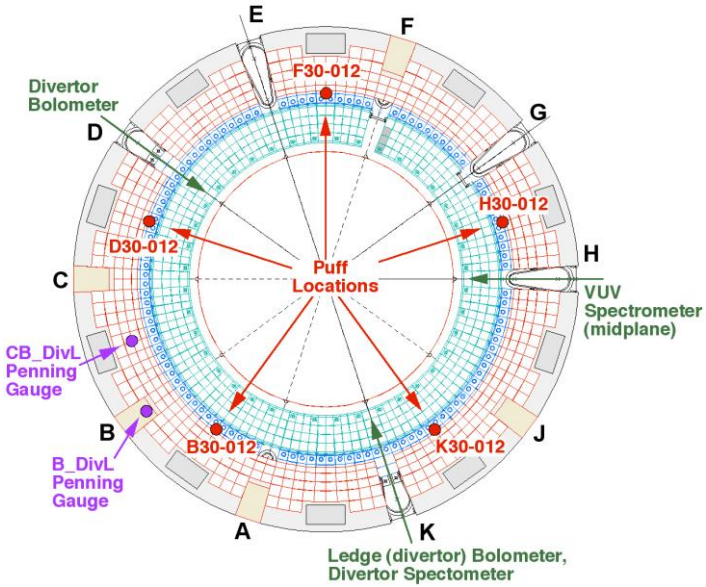
Double null grid for C-Mod

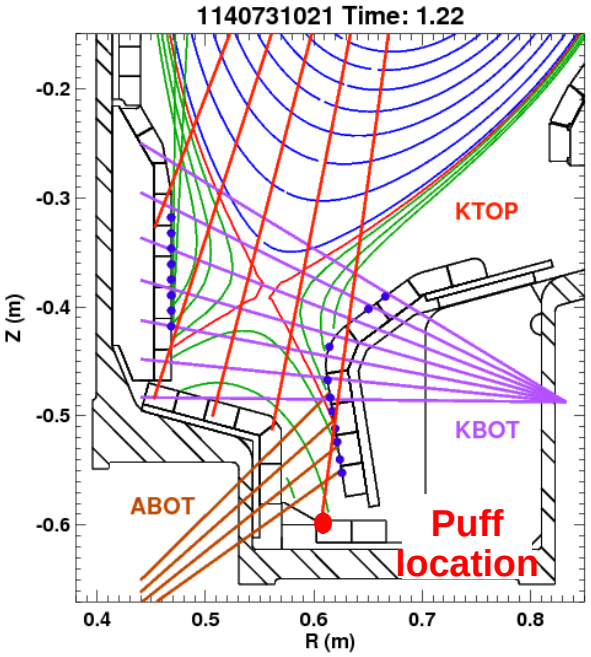


[1] Feng, J. Nucl. Mater. 266-269 (1999) 812

C-Mod gas injection system allows for investigation of non-axisymmetric effects

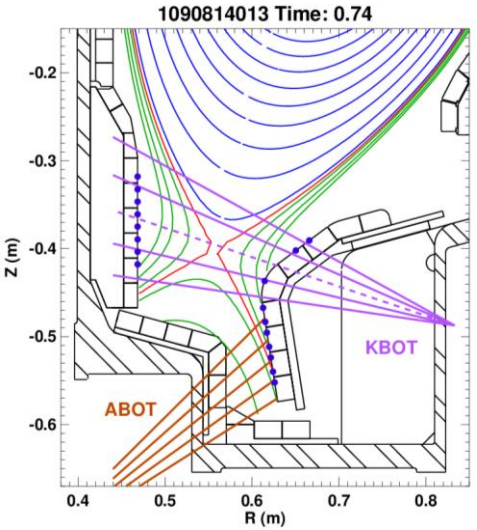
- 5 gas injection locations located in divertor slot with layout similar to ITER
- Toroidally fixed diagnostics are compared as active gas valve changed each shot
- Many divertor diagnostics enable validation of main plasma and impurity transport modules of code
- Experiments were performed in Ohmic L-mode and high-power EDA H-mode

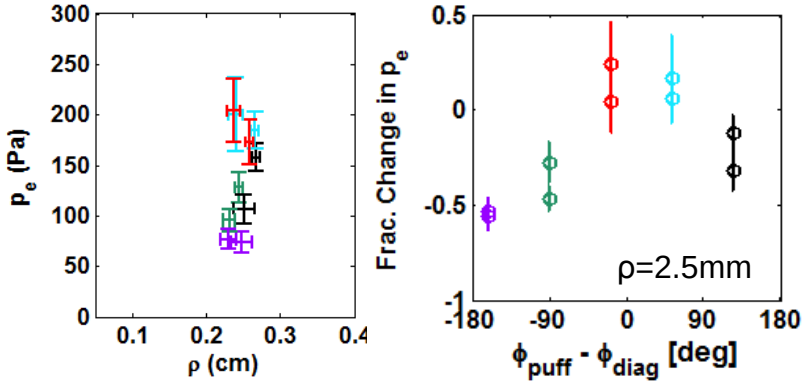


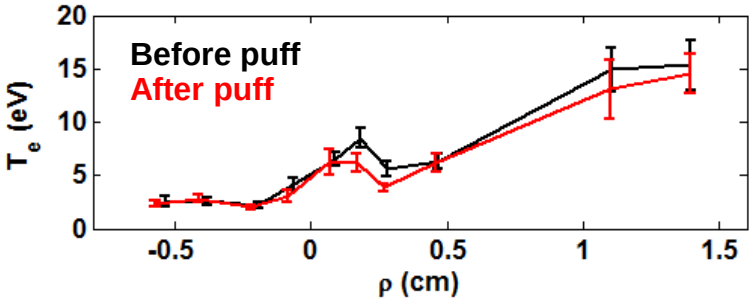


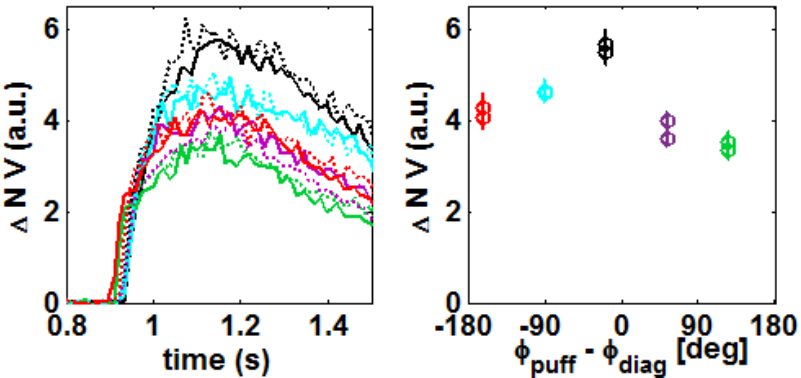
L-mode experiments show clear toroidal asymmetries

- Puff only weakly perturbs divertor plasma, which is already in high-recycling regime
  - Clear toroidal asymmetry in pressure perturbation near separatrix
- Repeatable toroidal variation in nitrogen line emission and radiated power on many divertor views





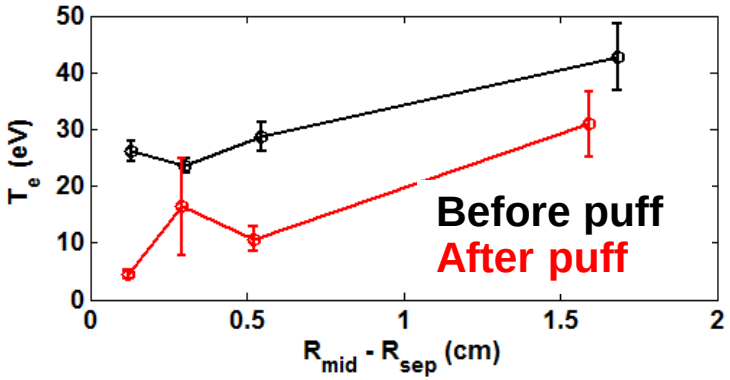


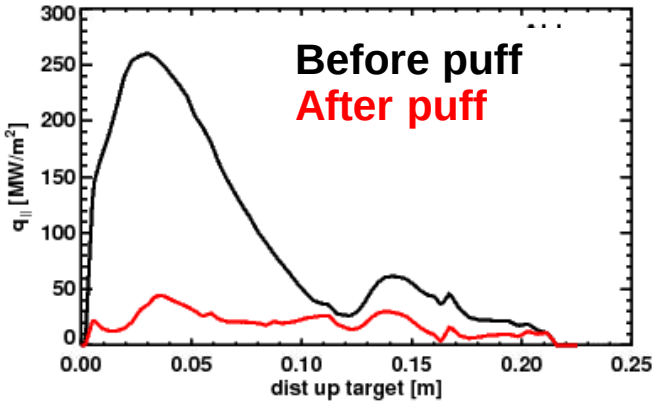


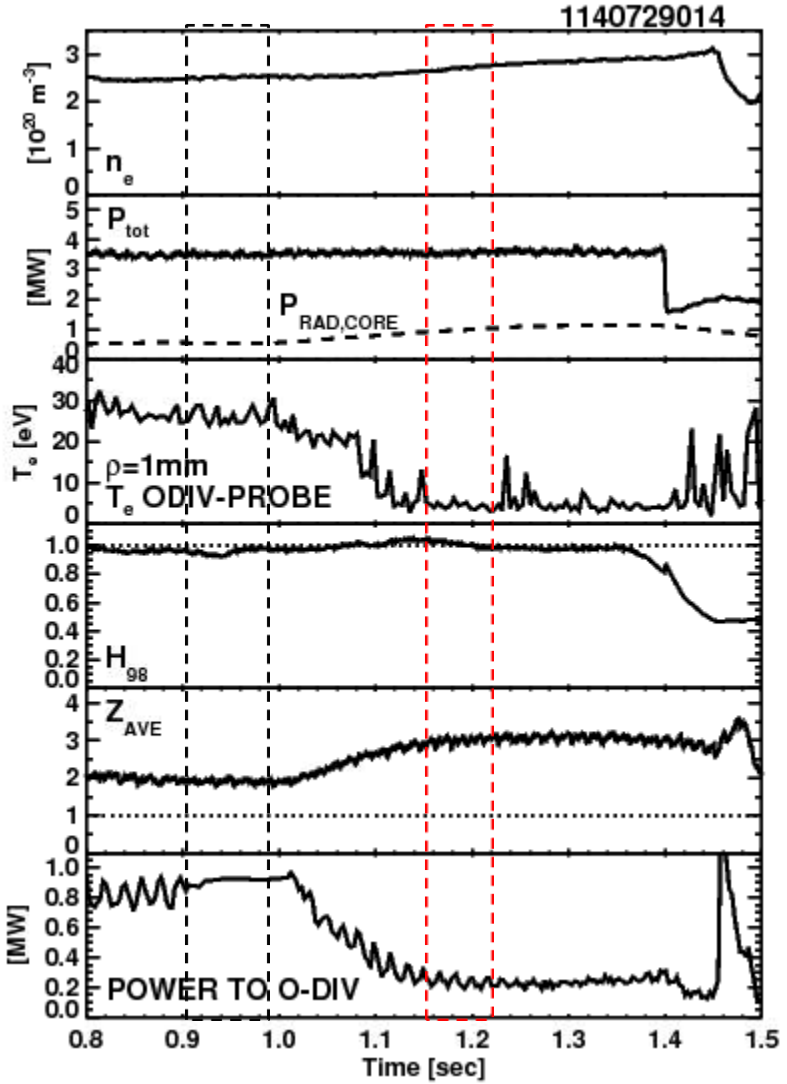
See M.L. Reinke, et al., PSFC Research Report PSFC/RR-14-3

H-mode experiments with 5 puff locations show in strong drop in T_e, $q_{||e}$

- Nitrogen injected from 5 valves, reaches plasma at ~1s
- Puff is used to reduce heat flux to outer divertor by 4-5x, T_e reduced by 2-5x

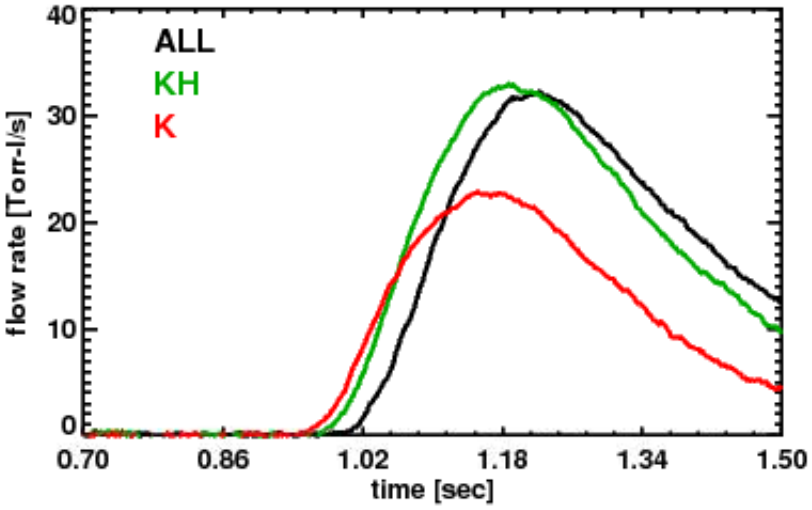


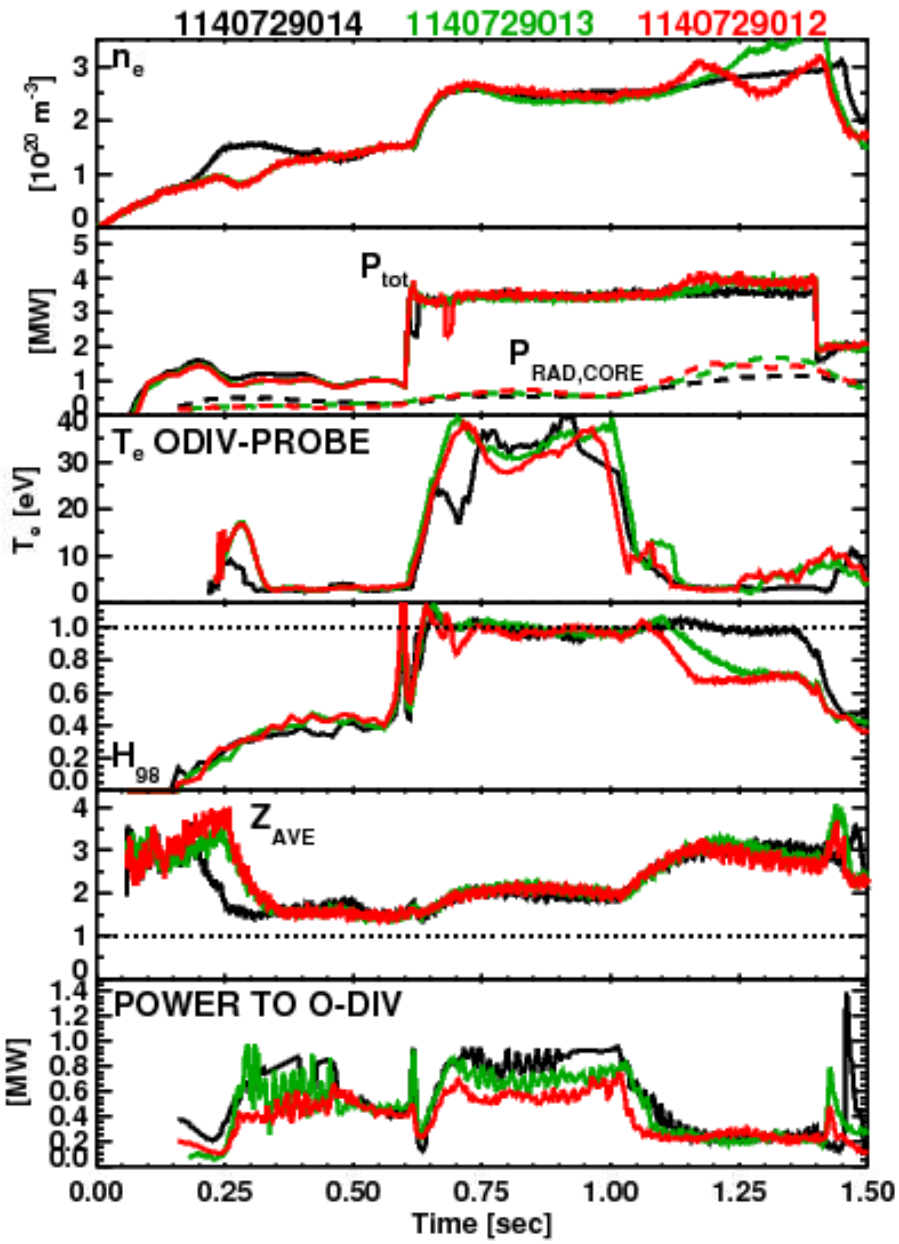




Gas injection from 1-2 valves results in confinement reduction

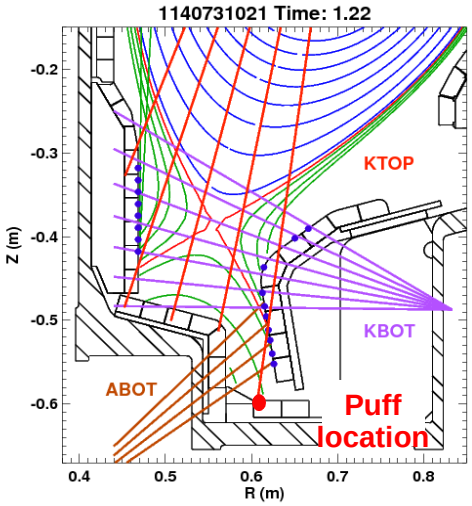
- T_e, q_{lle} drop to similar level, but strong asymmetric puff results in pedestal degradation

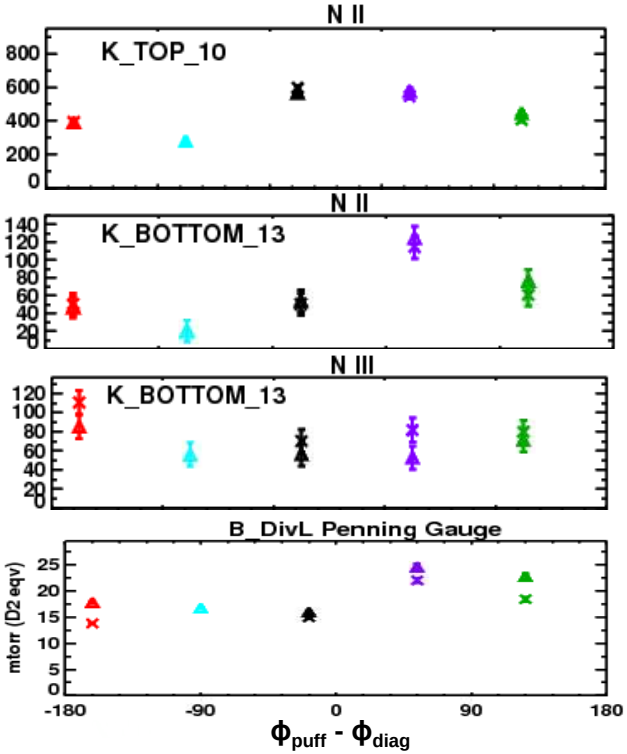


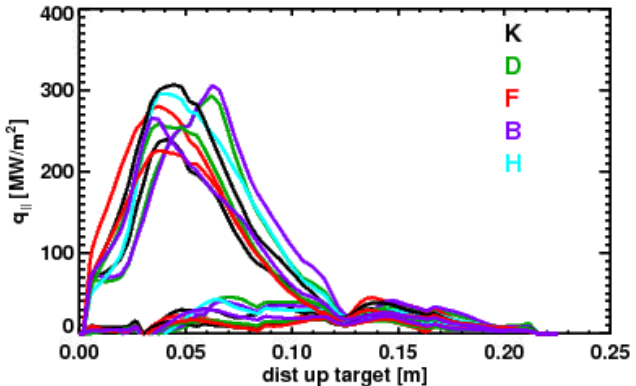


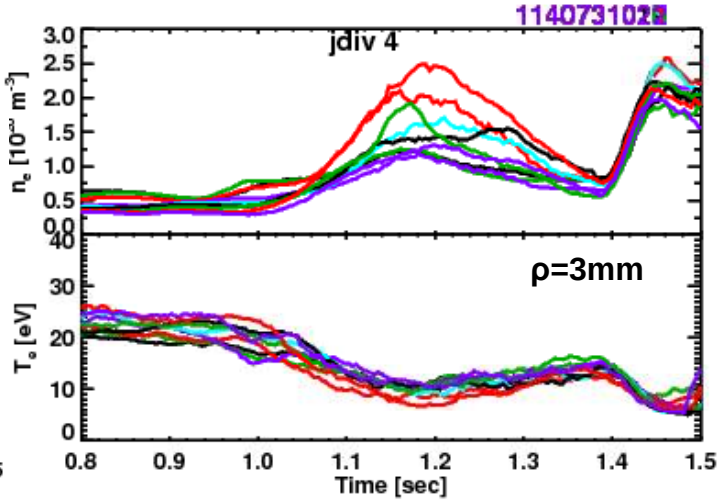
Single puff at lower level results in detachment with small asymmetry

- Asymmetry in divertor heat flux, T_e small
  - Some probes show stronger asymmetry in n_e
- Asymmetry stronger in Nitrogen data
  - Neutral pressure, line emission
- Strong variation in N II, weaker in N III, not apparent in N IV
  - NV, divertor bolometry still to be analyzed



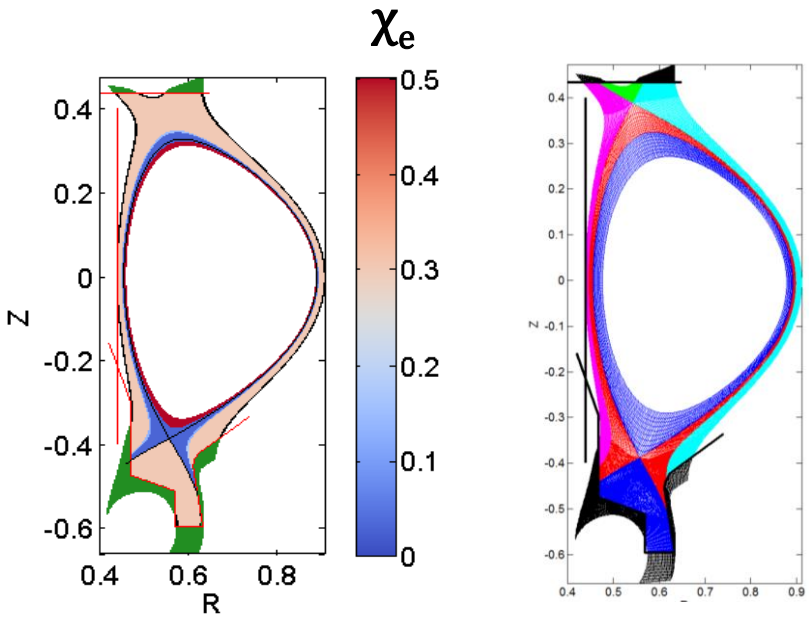


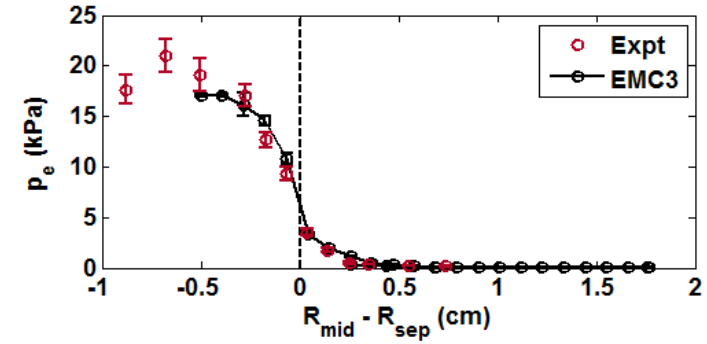


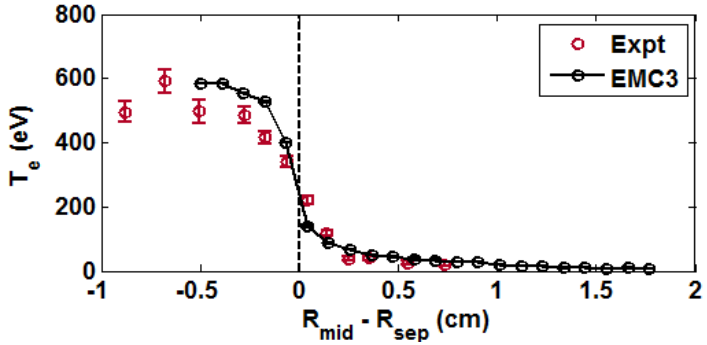


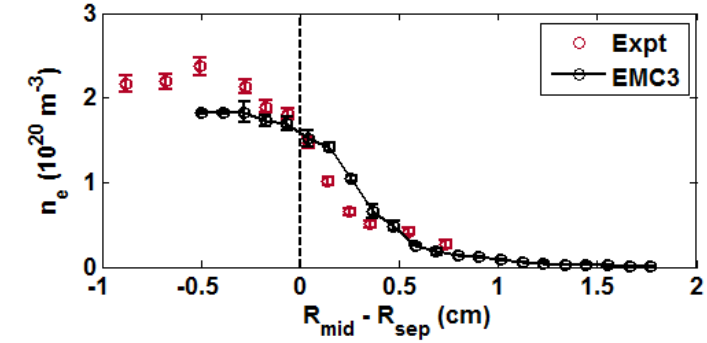
Modeling C-Mod with EMC3-EIRENE

- Disconnected double null grid
  - ~8M cells spanning entire torus
  - Nitrogen injected in divertor slot, R=0.5
- Density and input power on core boundary from experimental conditions
- Upstream conditions approximately matched by setting cross-field coefficients. In H-mode electron thermal diffusivity is not spatially constant



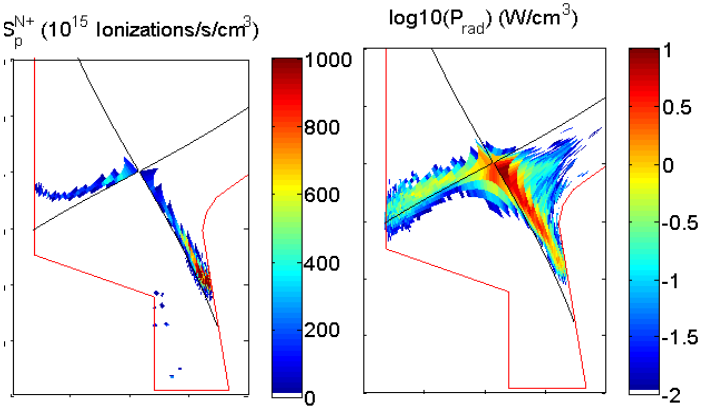




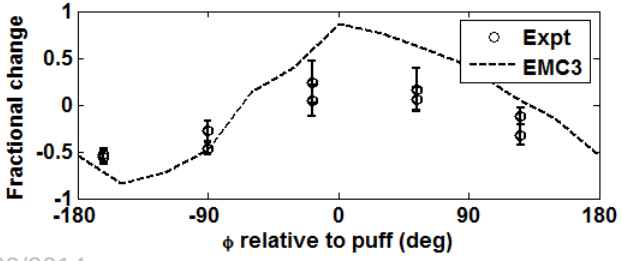


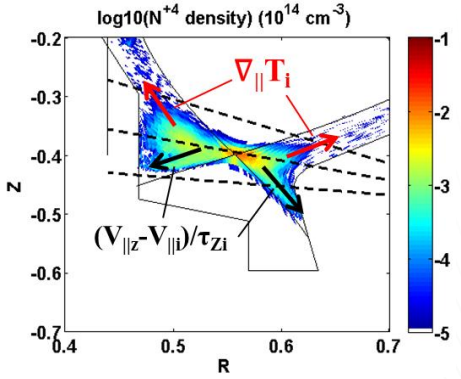
Low T_e and n_e in PFR leads to strong asymmetries in L-mode

- Plasma in divertor slot (T_e ~ 1eV) is nearly transparent to neutral nitrogen, ionization occurs above separatrix leg
- Electron energy sinks occur in flux tubes that carry power to the outer strike point
  - Qualitative agreement between code and experiment in electron pressure asymmetry near strike point
- Ion flow friction causes nitrogen to be lost to target before one toroidal transit, resulting in asymmetric impurity density
  - Trends in impurity line emission similar for views through and above x-point, deviations found in PFR
  - Could be due to lack of cross-field drifts or kinetic corrections to better match downstream conditions

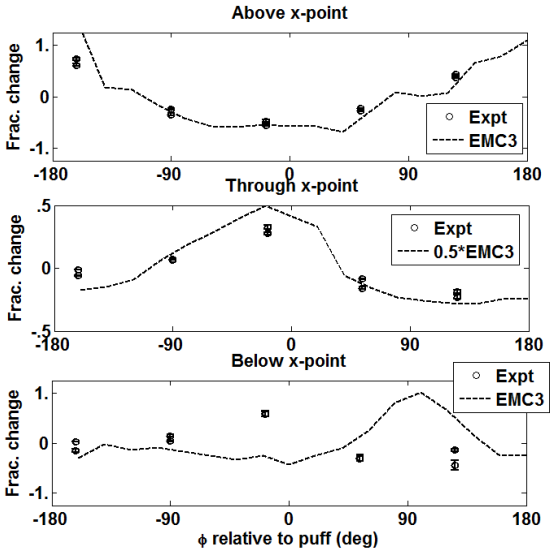


Divertor electron pressure





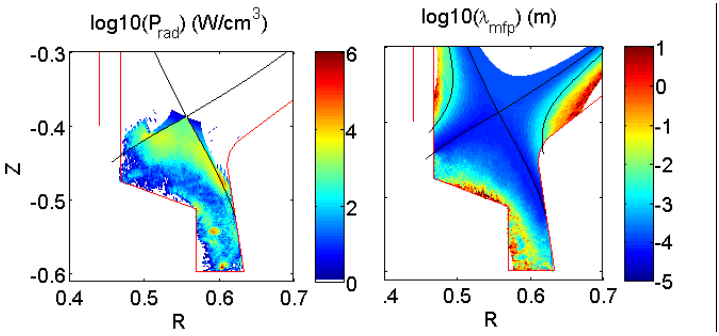
N^{+4} density / N V emission

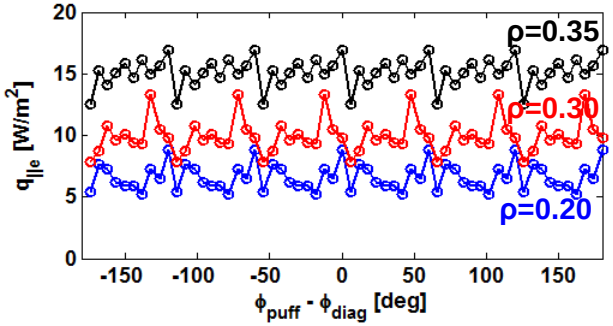


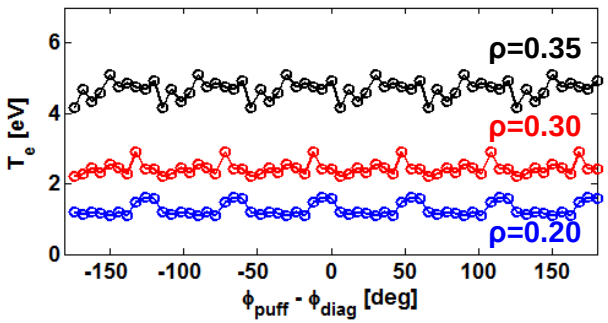
J.D. Lore, et al., JNM (accepted 2014)

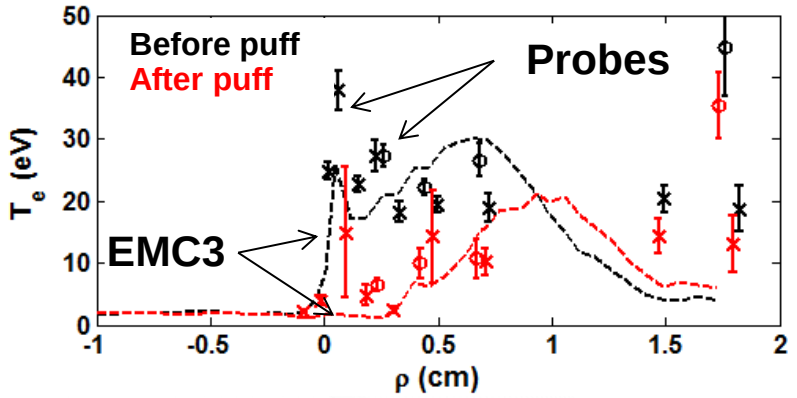
Simulation of 5 puffs shows detachment with small toroidal asymmetry

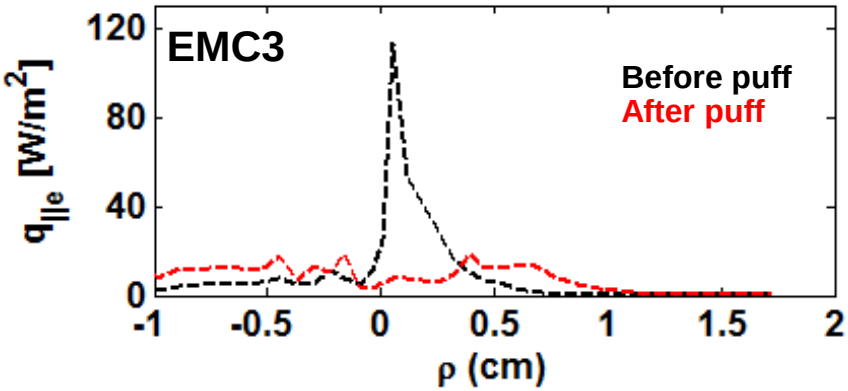
- Hotter, denser slot plasma results in nitrogen ionization in PFR (λ^{iz} ~ cm)
- Divertor T_e, $q_{||e}$ is strongly reduced, with only small toroidal asymmetry
- Some variation in PFC nitrogen radiation predicted, asymmetry small in SOL and near x-point





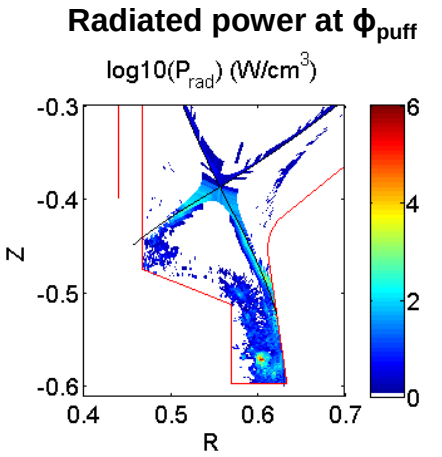


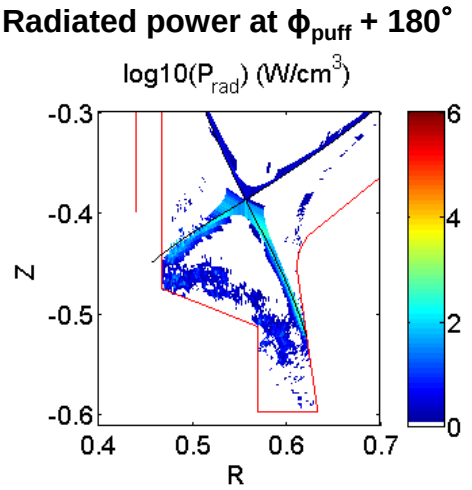


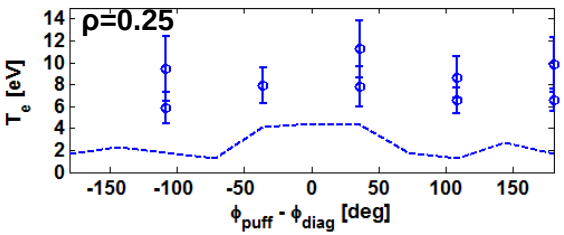


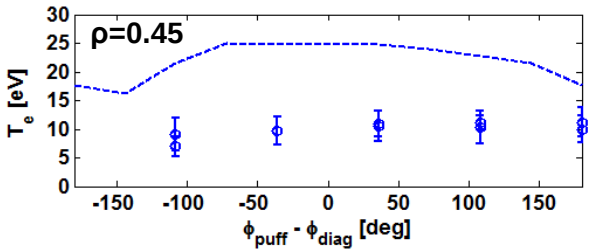
Single puff modeling shows small asymmetry, detachment weaker than experiment

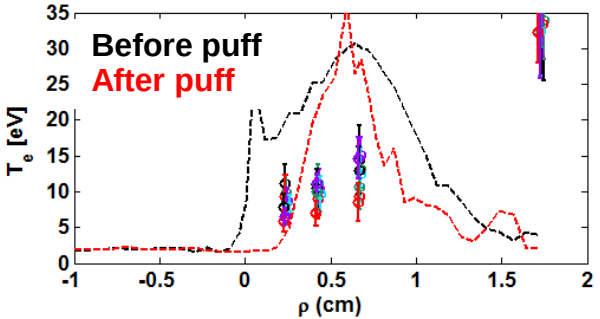
- Single puff results in weak detachment. Greatly increasing nitrogen input causes numerical instability.
  - Level of detachment does not scale linearly with N input
- Asymmetry predicted in downstream T_e, n_e, on the order of experimental uncertainty
  - Quantitatively agreement may require kinetic corrections, volume recombination
- Nitrogen emission is asymmetric in PFR
  - Stronger asymmetry than in experiment
  - Addition of small percentage N from strike points improves agreement
  - Matching of main plasma conditions important, cross field drifts may be required





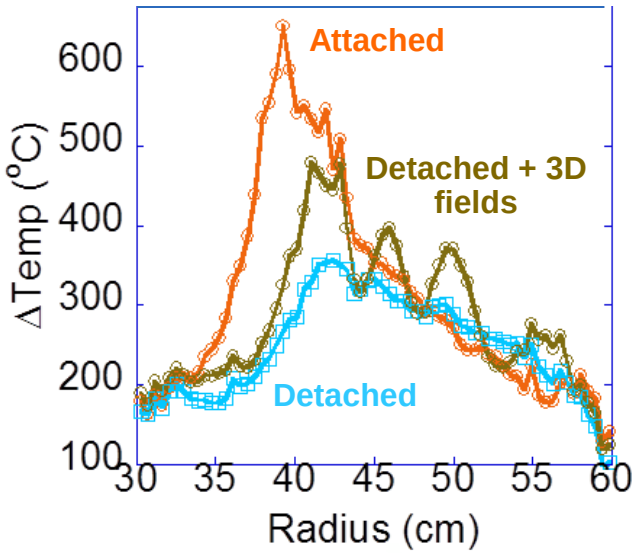


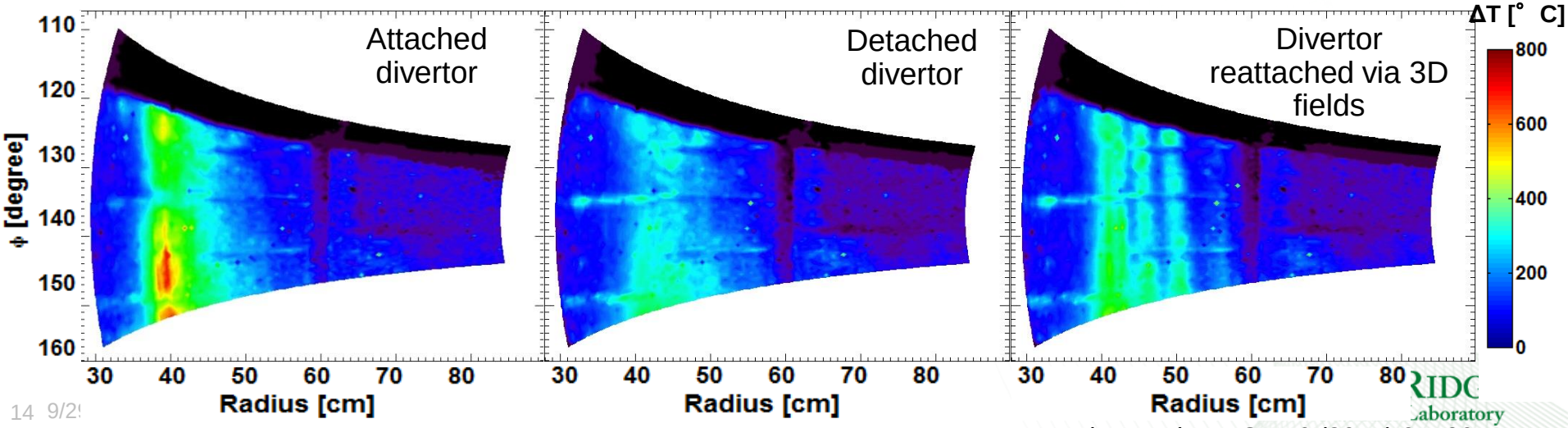




NSTX experiments have shown 3D fields can cause divertor to re-attach

- Gas puff is used to detach divertor
- 50ms later n=3 3D fields are applied, resulting in striated heat flux pattern
- Reattachment of main peak can be prevented with increased gas input

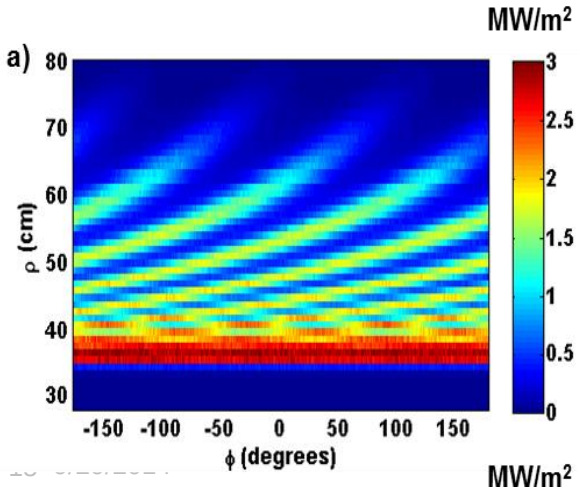


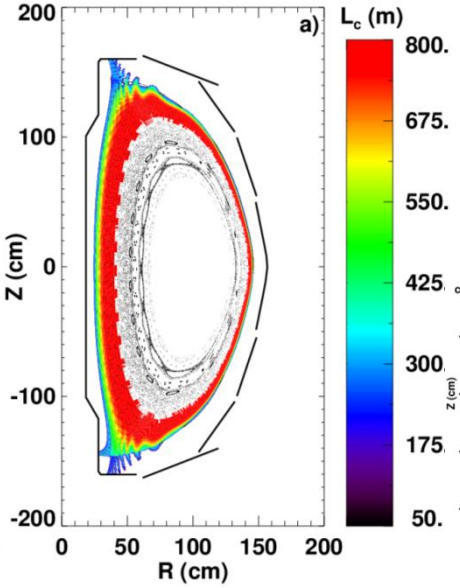


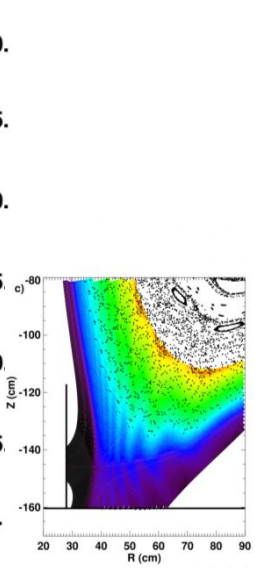
J.-W. Ahn, et al., PPCF 56 (2014) 015005

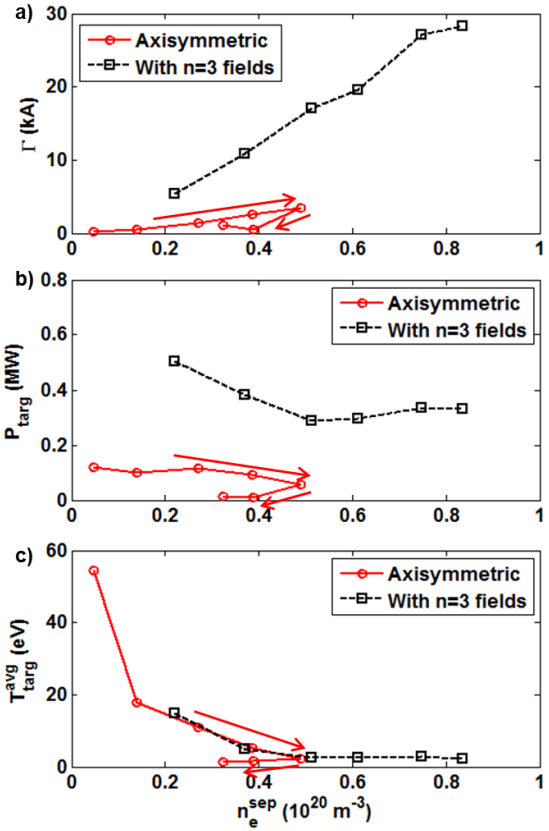
Modeling shows axisymmetric plasma detaches at lower density than 3D case

- Modeled with EMC3-Eirene using vacuum approximation
  - Other field models will be tested in future simulations: IPEC, SIESTA, ad-hoc screening
  - Results in strong strike point splitting, with clear heat flux striations on horizontal target at low density
- Density scan shows axisymmetric case detaches at lower density than when 3D fields applied









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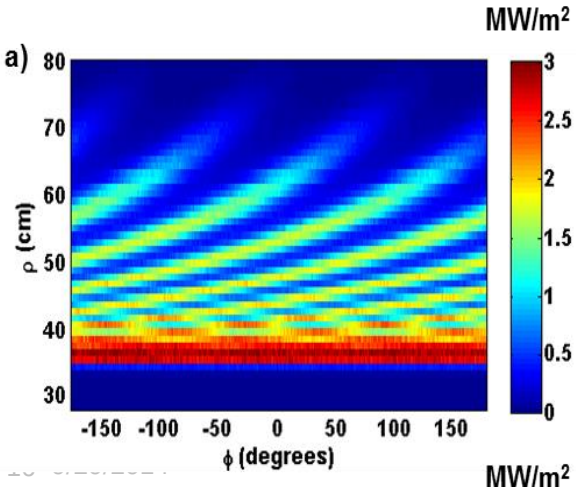
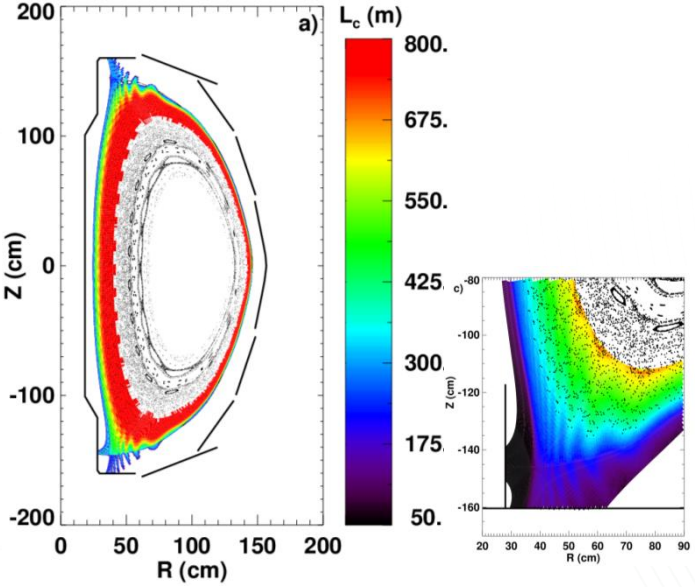
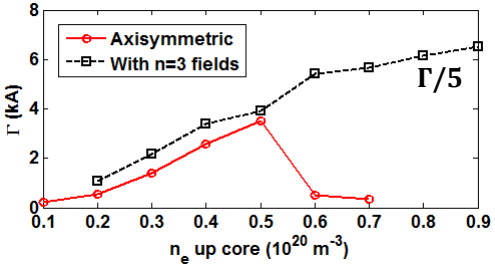
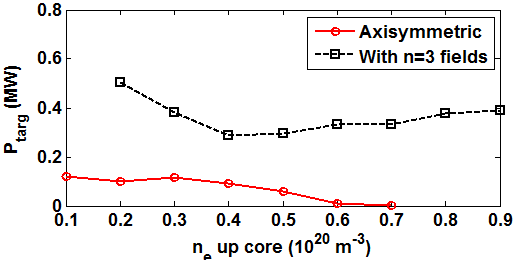
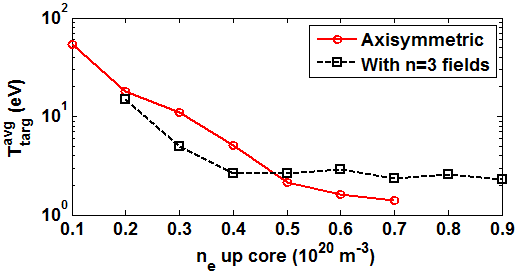




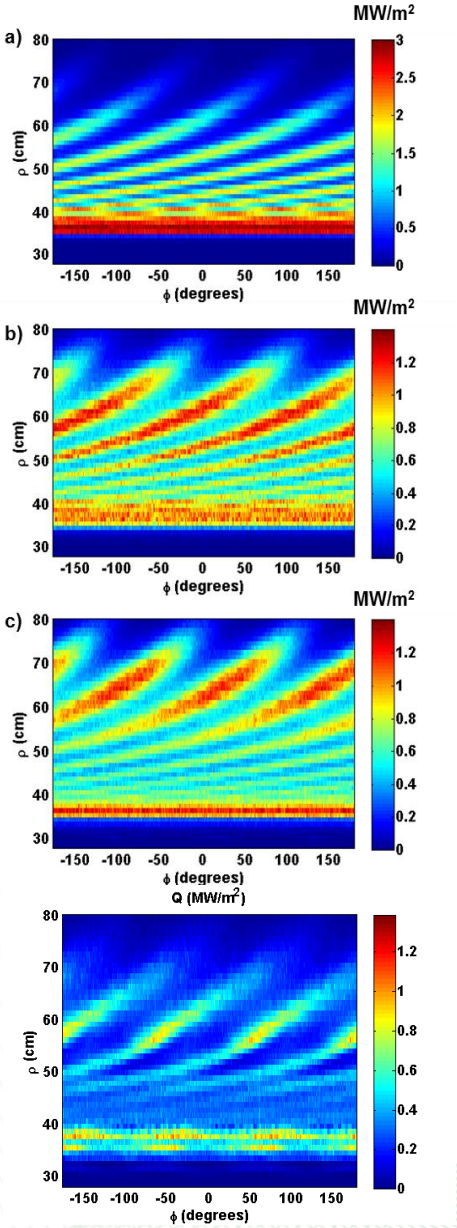


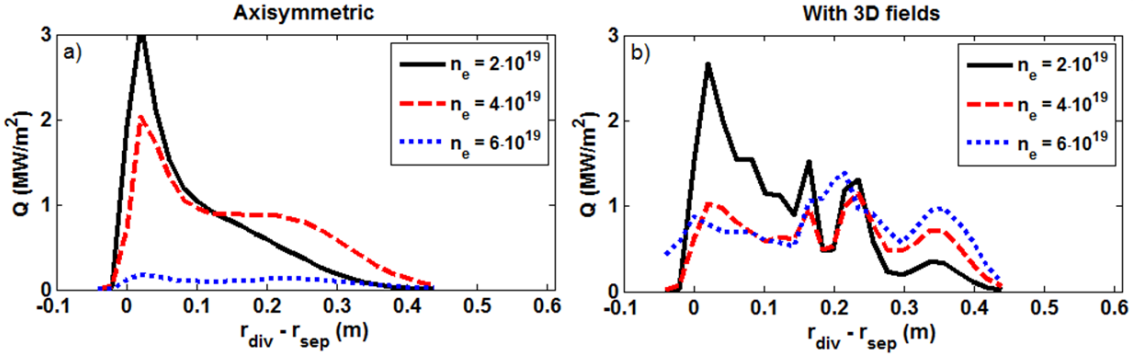




With 3D fields primary strike point detaches, but outer lobes remain attached

- Axisymmetric case shows clear reduction in heat flux with increasing density
  - Heat flux increases at larger radius due to greater effect of cross-field diffusion
- With 3D fields the maximum heat flux shifts to the outer peaks
  - Outer lobes connected to hot plasma with short connection length
  - Still in sheath limited regime at intermediate density, more heat at larger radius from cross-field diffusion
  - Eventually toroidally and poloidally localized hot spots form





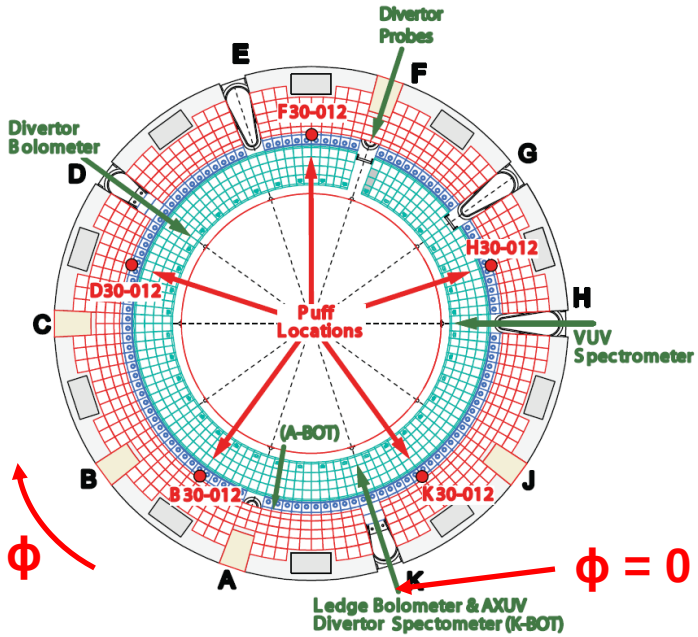
Summary

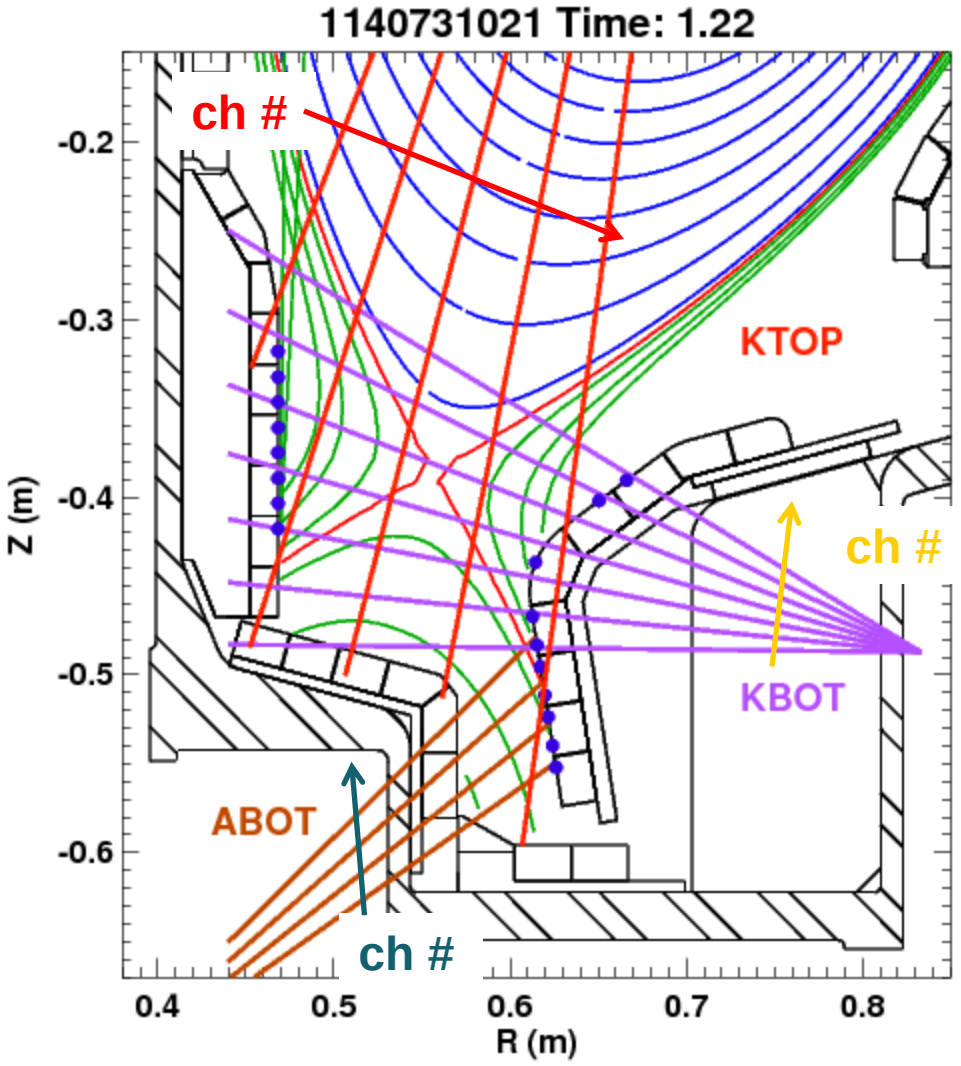
- C-Mod L-mode results show that localized divertor impurity injection can result in significant toroidal asymmetry
  - Asymmetry greatly reduced in H-mode; modeling shows that ionization in PFR results in smaller asymmetry in radiated power, divertor conditions
- NSTX experiments show 3D field application can cause divertor plasma to re-attach with striated flux
  - Modeling with vacuum approximation reproduces these trends, caused by hot plasma with short connection length to divertor at large radius.
  - Code will be used to test other field penetration models
- 3D modeling provides useful tool for understanding experimental results, quantitative comparison requires further development
  - Active research areas to improve quantitative comparison: addition of flux limiters to and volume recombination to current code version
  - Significant discrepancies in impurity emission in PFR, cross field drifts and better matching of main plasma conditions likely required

Extra Slides

Spectroscopic views

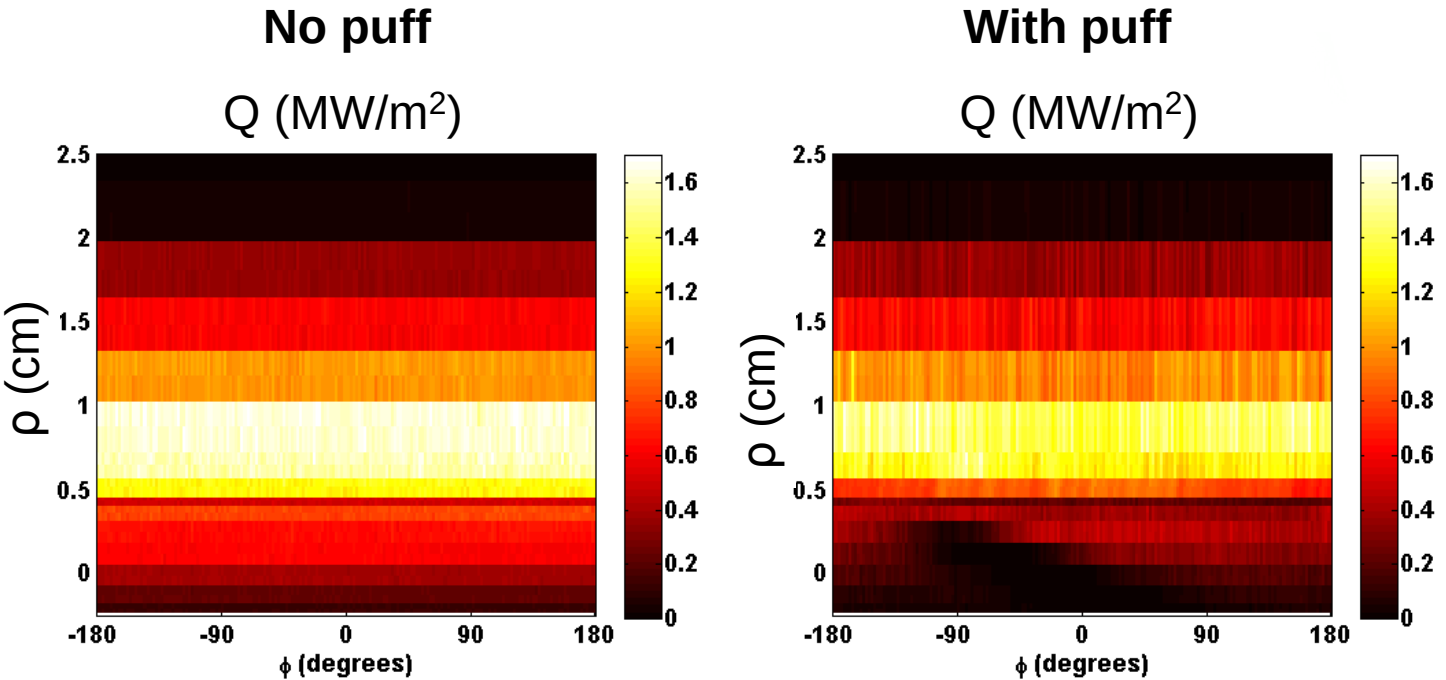
- Three views:
  - KBOT, chs: [3:2:15]
  - ABOT, chs: [9:2:15]
  - KTOP, chs: [2:2:10]



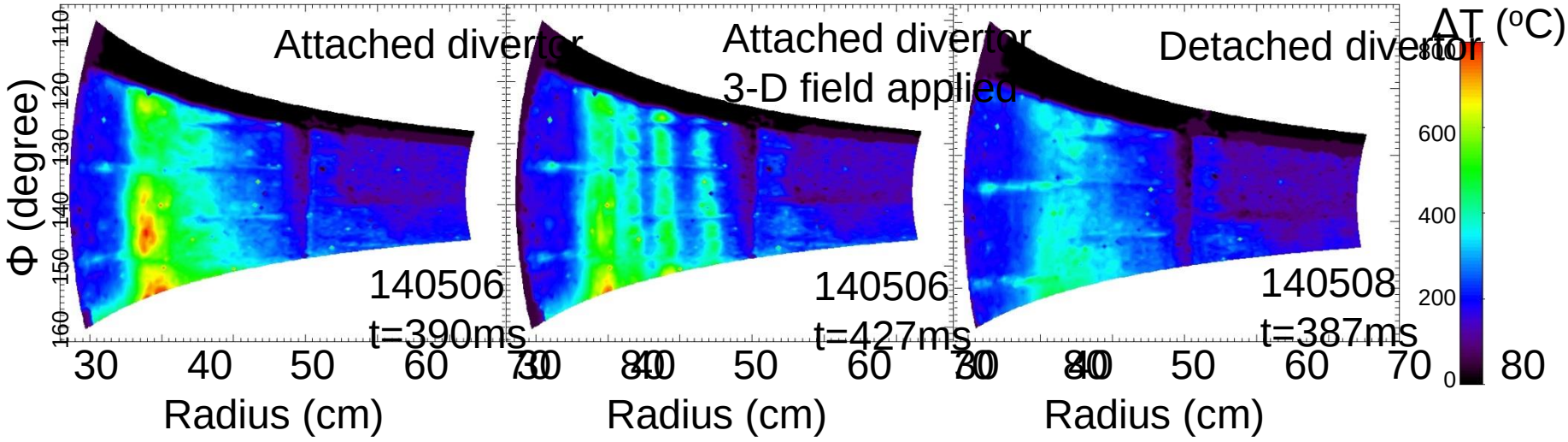


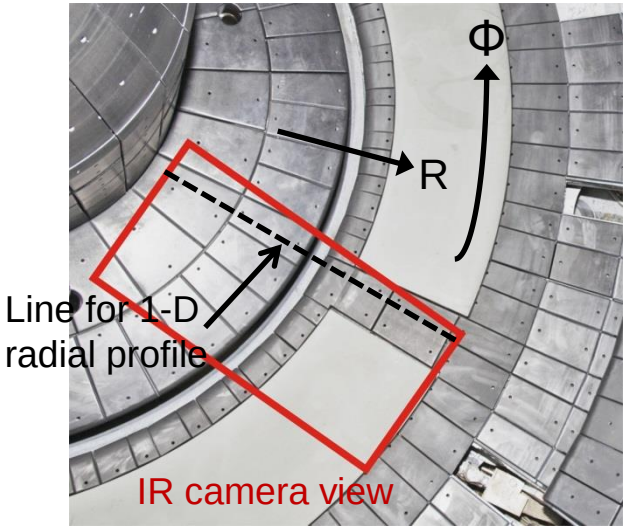
Toroidally asymmetry in target heat flux predicted near outer strike point

- Impurity radiation results in net reduction in power carried by plasma to targets
  - P_{targ}^{plasma} reduced from 930kW to 730kW (P_{in}=1.25MW)
- Toroidal asymmetry in P_{rad} results in toroidal asymmetry in heat flux near outer strike point
  - Toroidal extent will depend on machine size, divertor geometry



2-D dual band IR image shows various divertor plasma conditions

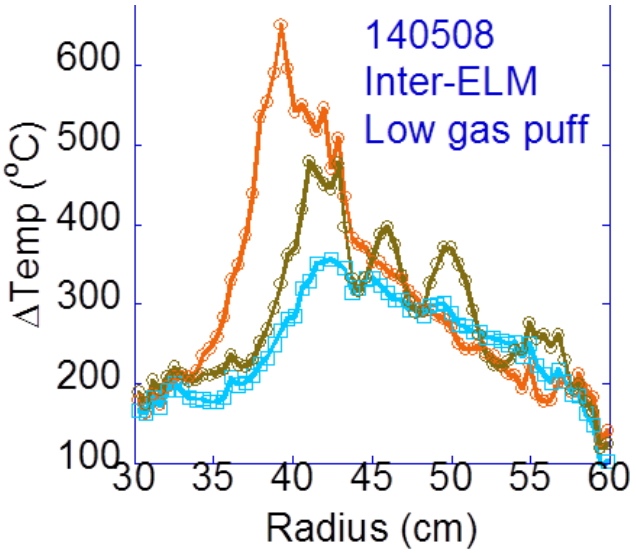


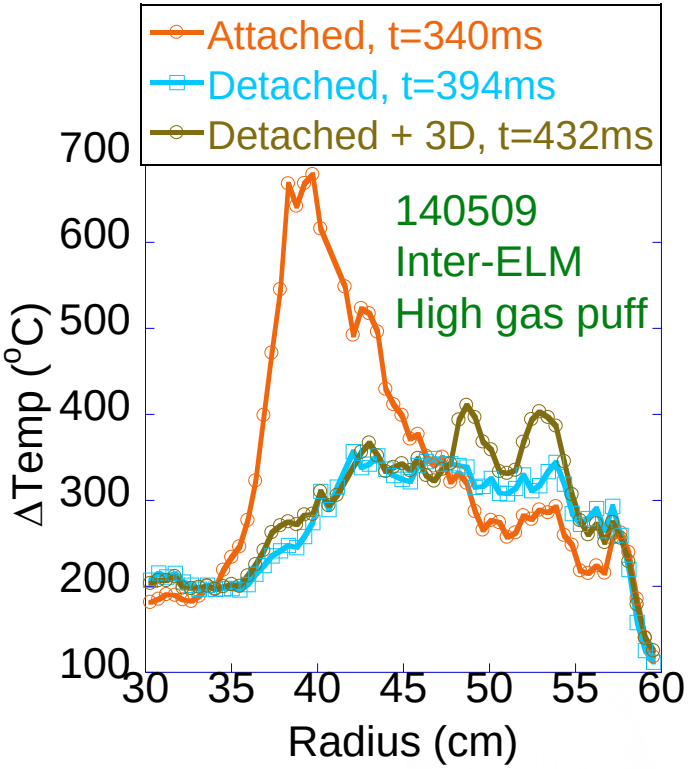


- Divertor surface temperature is monitored by dual band (4-6μm and 7-10 μm) IR camera[1,2]
  → 1.6kHz frame speed, 15-40° toroidal coverage
- Applied 3-D fields generates homoclinic tangles and causes strike point splitting
- Surface temperature shows significant reduction only near the strike point in case of divertor detachment → 'Partial detachment'

[1]A.G. McLean, to be published in RSI (2011)
[2]J-W. Ahn, RSI 81 (2010), 023501

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

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