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

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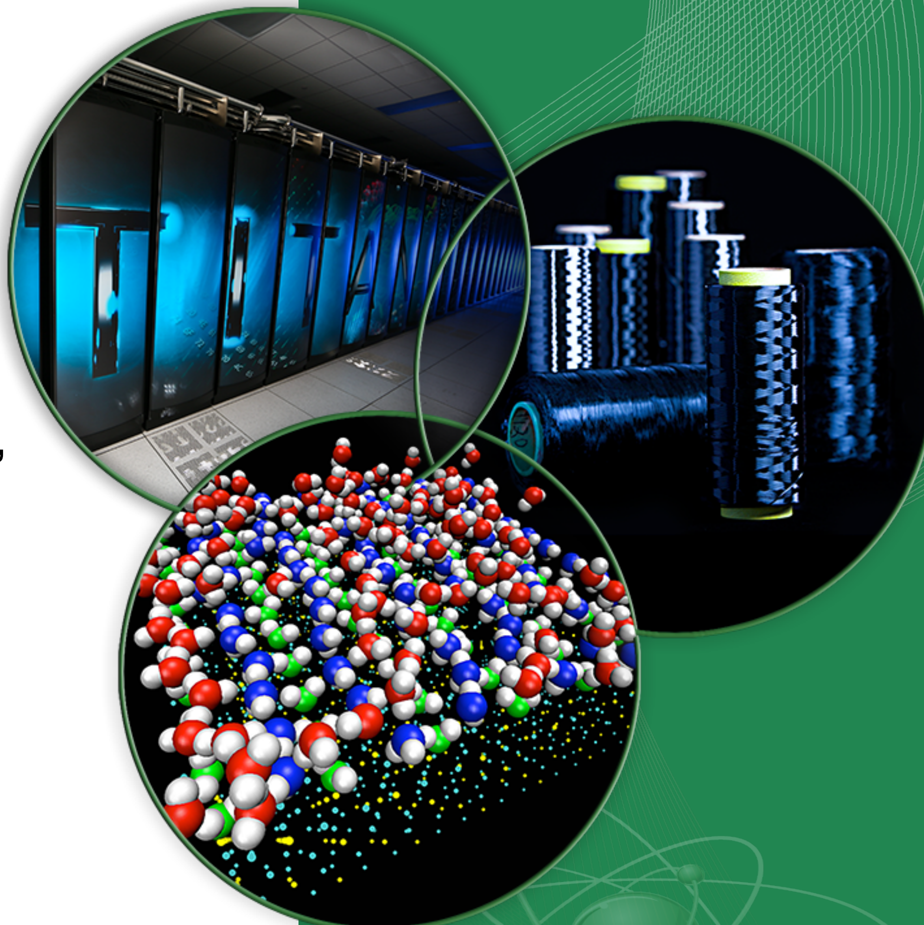


Partially detached divertor conditions may be modified by 3D effects

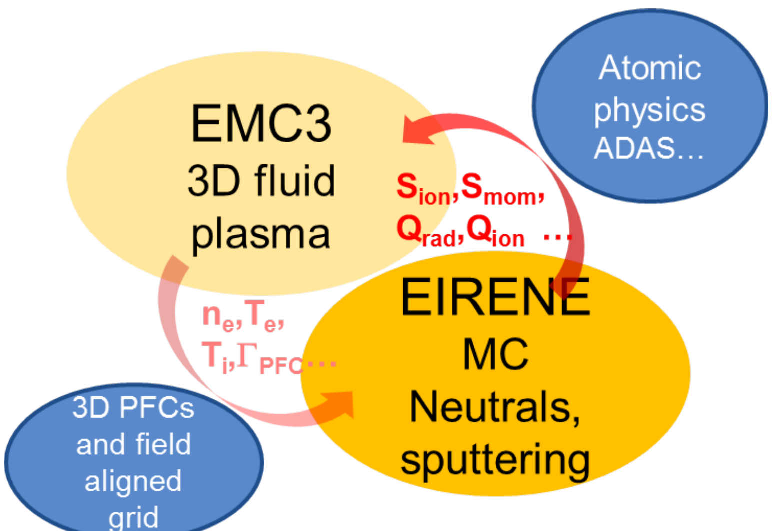
- Partial detachment is required in ITER to reduce $q_{||}$, T_e
- 3D effects may disturb divertor plasma state
  - Extrinsic gas injection will be used to control detachment; localized injectors may result in non-axisymmetric radiated power and fluxes
  - 3D fields (applied or intrinsic) can cause striated flux patterns, local reattachment of divertor plasma
- Experiments have been performed to investigate these effects, validated 3D modeling tools are required to make reliable predictions for ITER

Outline

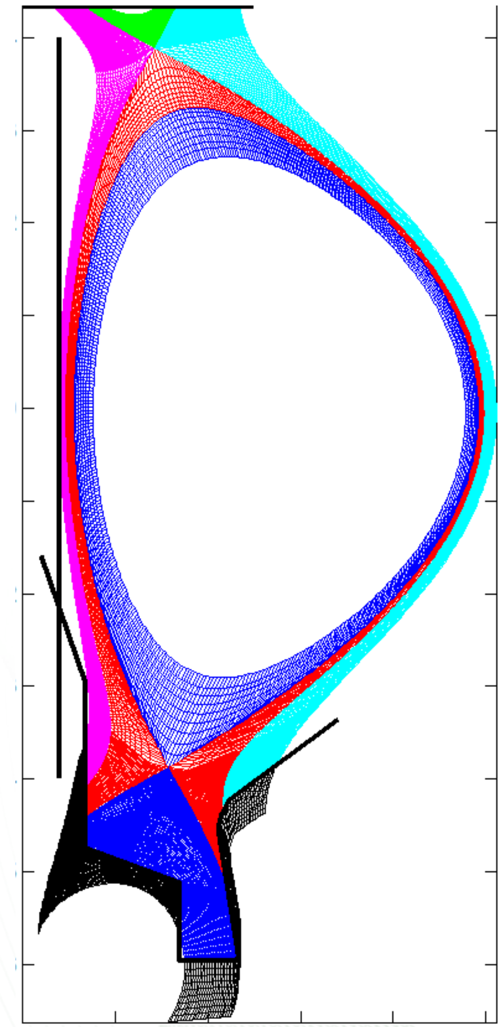
- The EMC3-EIRENE code
- C-Mod experiments were performed to investigate the effect of localized divertor gas injection
  – Level of toroidal asymmetry depends on downstream conditions, impurity ionization in the private flux region
- NSTX experiments show divertor reattachment due to 3D field application
  – With 3D fields, striated heat flux patterns are peaked at large radius due to short connection length to hot plasma
- 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, grid aligned to magnetic field
- 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
- **Limitations: No cross-field drifts, kinetic corrections or volume recombination in current version**



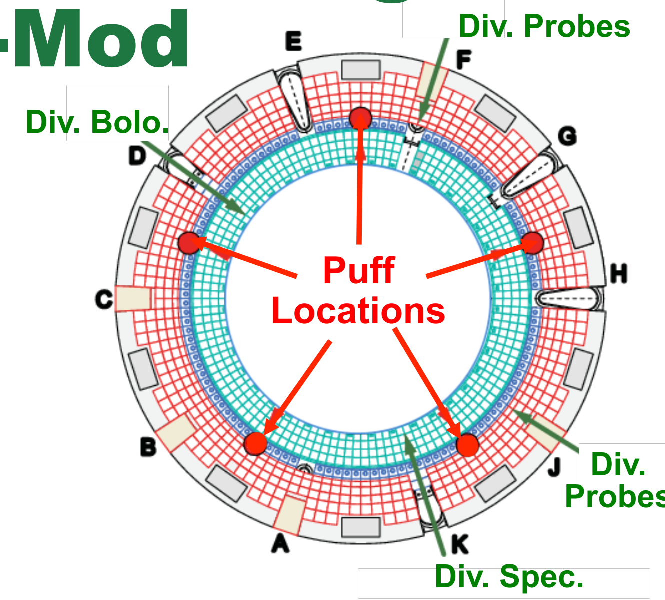
Double null grid for C-Mod

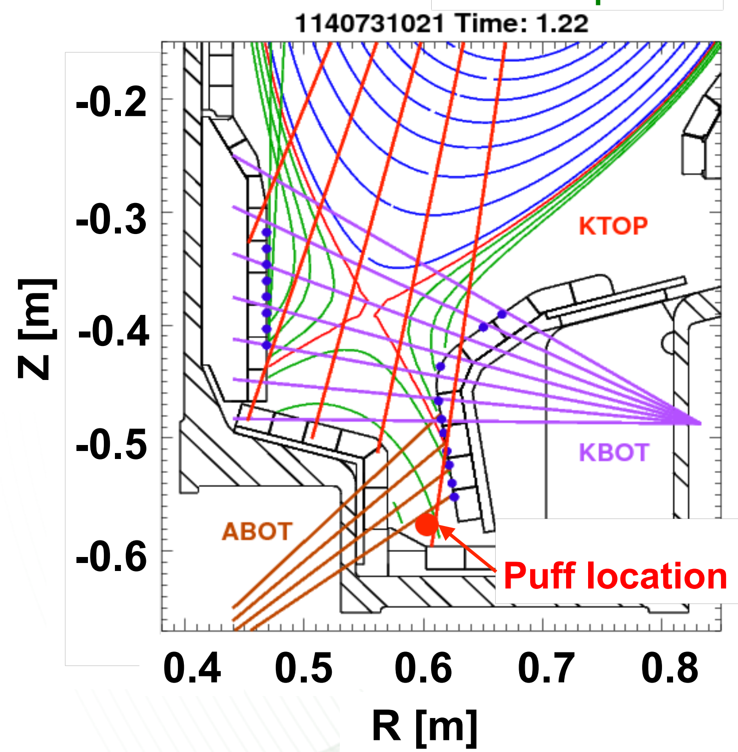


Y. Feng, J. Nucl. Mater. 266-269 (1999) 812

3D effects due to localized divertor gas injection are explored on C-Mod

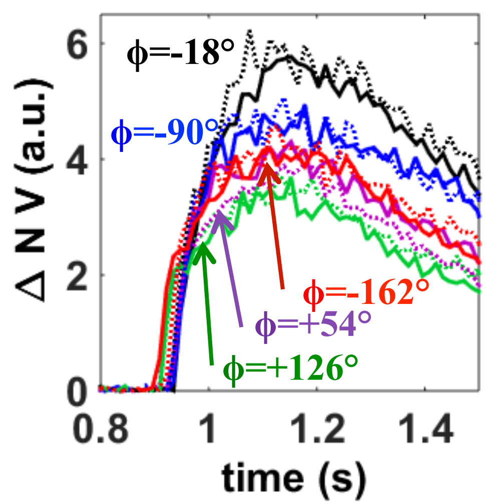
- 5 gas injection locations located in divertor slot with layout similar to ITER
- Data from toroidally fixed diagnostics are compared as active gas valve changed each shot
- Many divertor diagnostics enable validation of main plasma and impurity transport modules of code
- 2014 run campaign allowed initial L-mode scan to be supplemented with ITER relevant high-power H-mode data

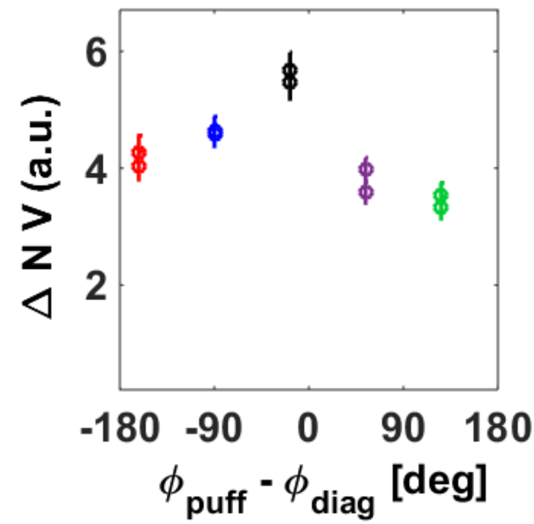


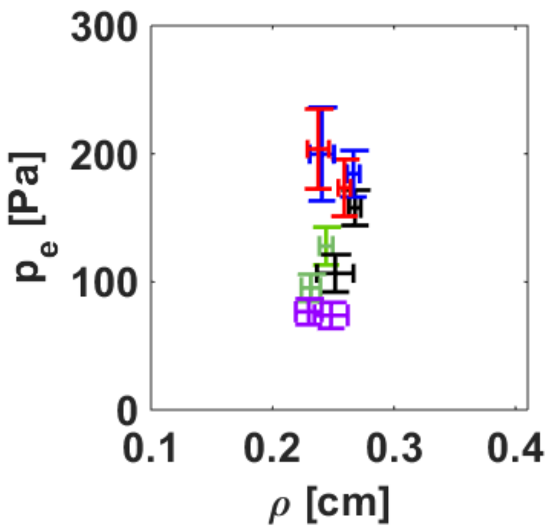


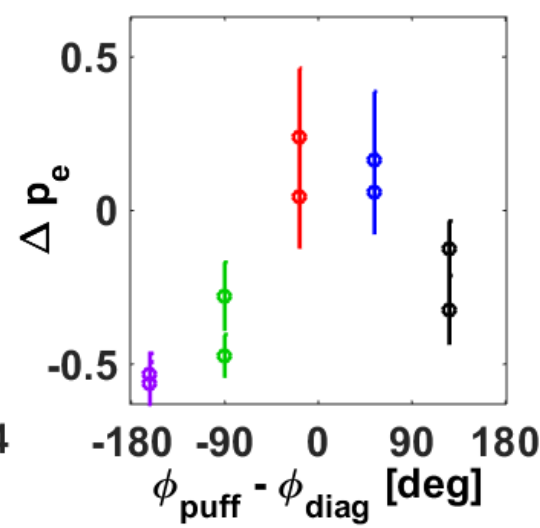
L-mode experiments show clear toroidal asymmetries in N V emission and p_e

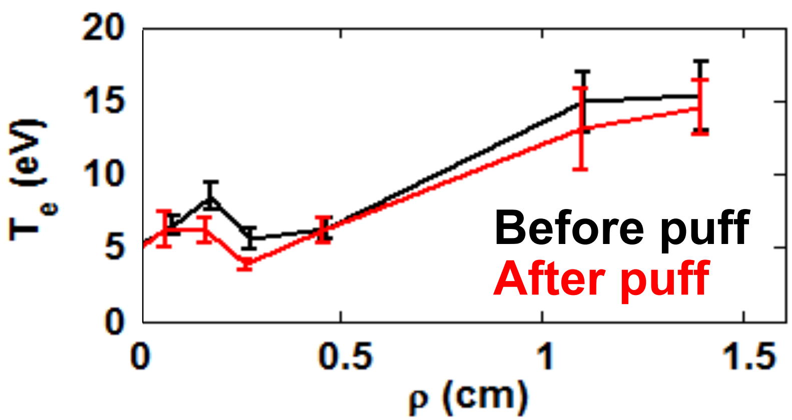
- Repeatable toroidal variation observed on many divertor diagnostics
- Clear toroidal asymmetry in pressure perturbation measured near separatrix
- Single injection location results in strong asymmetries
  - Puff only weakly perturbs divertor plasma, which is already in high-recycling regime











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

Alcator C-Mod
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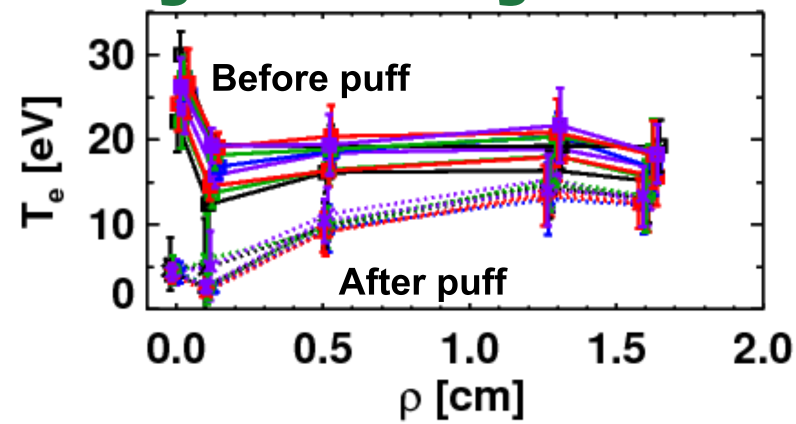
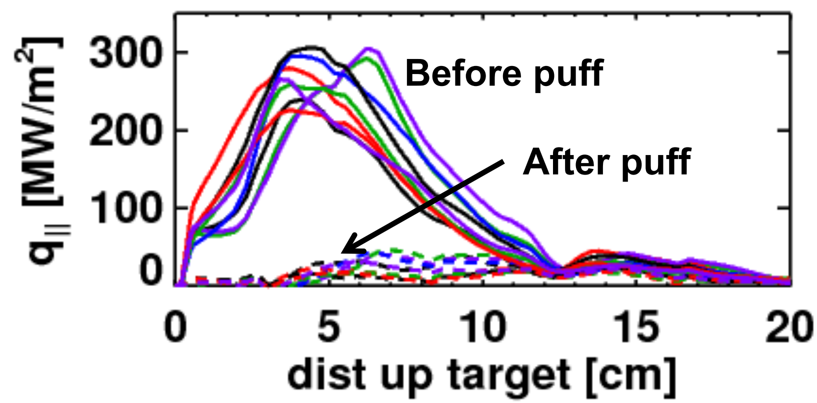
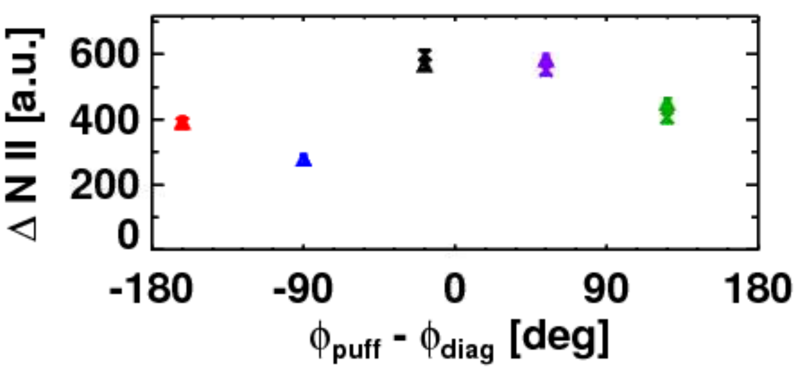
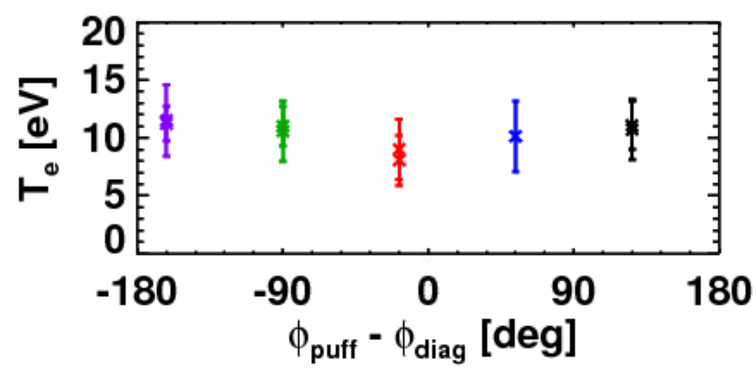
H-mode experiments show strong heat flux reduction with small asymmetry

- Divertor $q_{||}$ and T_e show small asymmetry, on order of shot-to-shot variation
- Asymmetry stronger in Nitrogen data
  - Particularly in the PFR, near OSP
  - Asymmetry from higher charge states is weaker: strong variation in N II, weaker in N III, not apparent in N IV
- Single puff can be used to detach divertor with small asymmetry







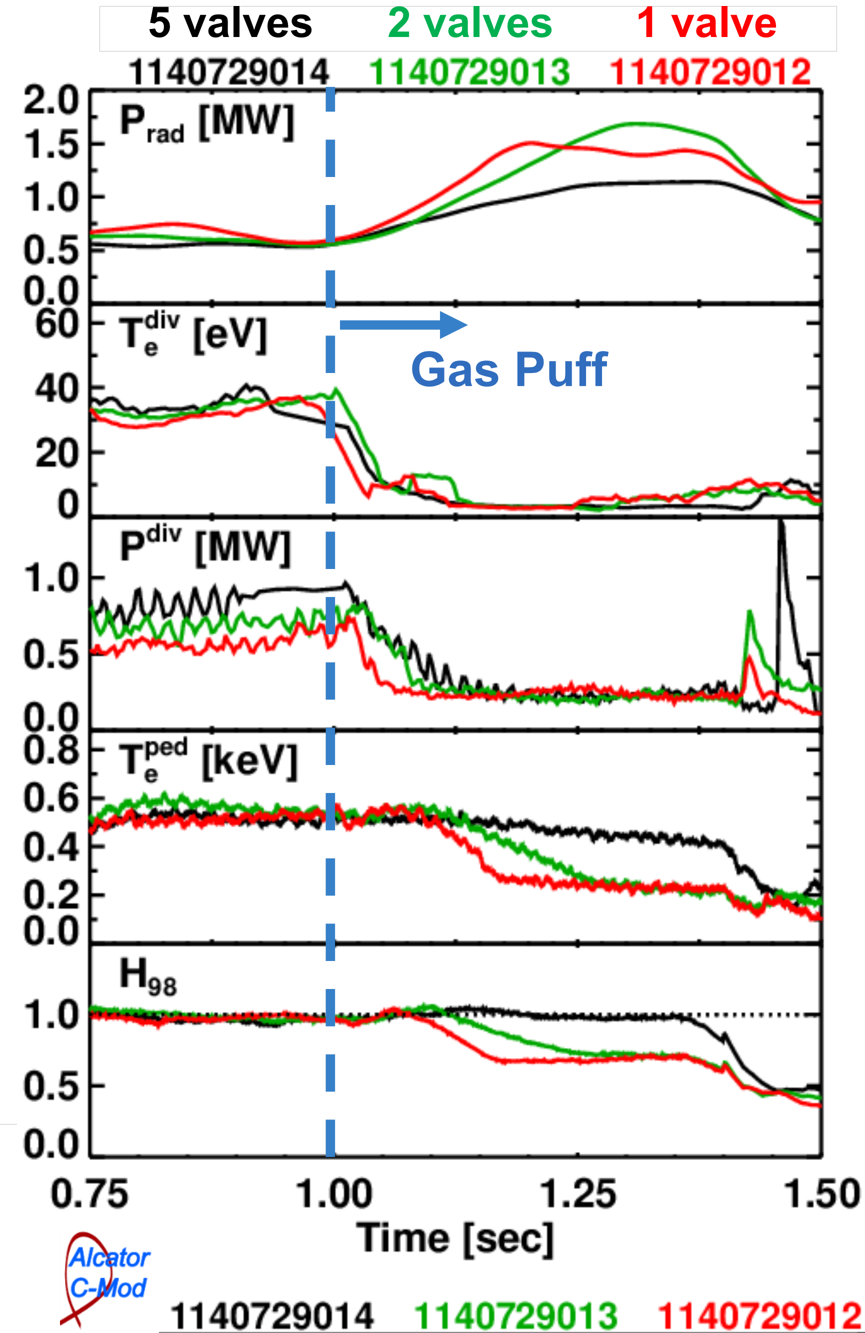


Alcator C-Mod

Detachment stability does not scale linearly with gas input

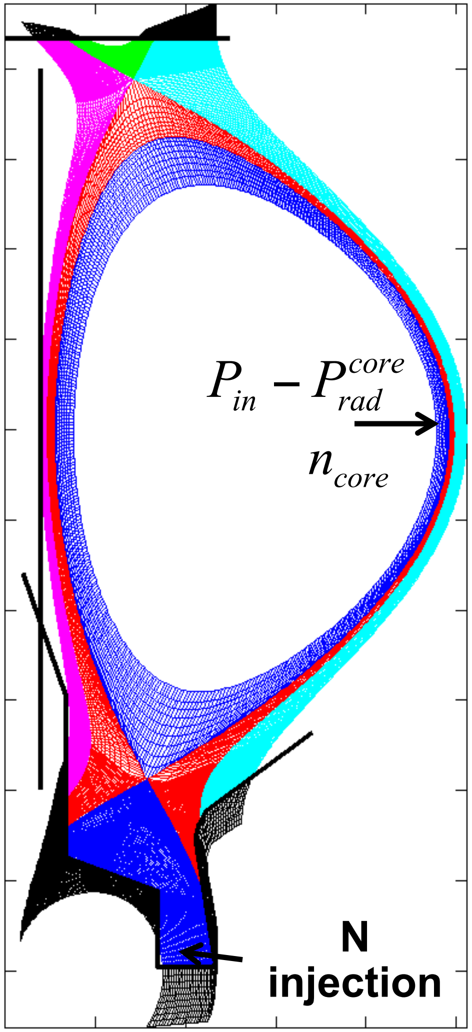
- Strong detachment with small asymmetry can be achieved with 1 or 5 gas valves
  - Stable partial detachment with 1 valve achieved with 70% of 5 valve gas flow rate

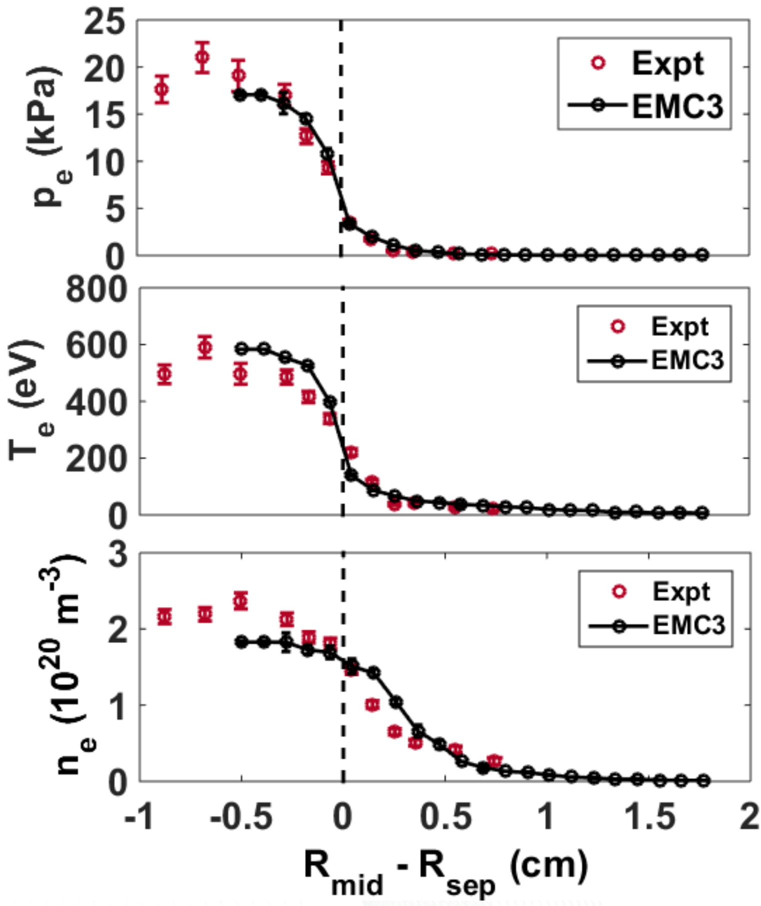
- Same total gas input from reduced number of valves results in degraded confinement
  - T_e, $q_{||e}$ drop to similar level but pedestal T_e and H_{98} drop



Setup of EMC3-EIRENE simulations

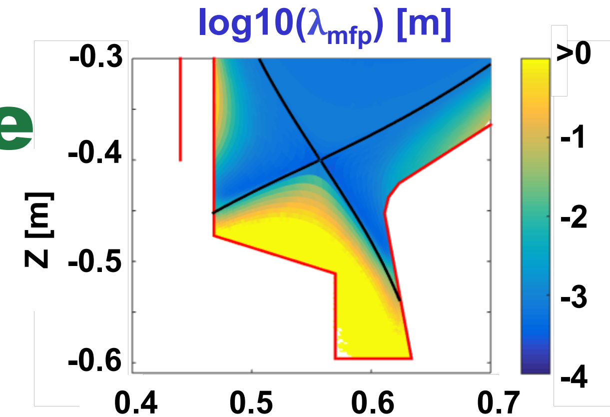
- Inputs:
  - Field aligned grid: axisymmetric **B**, ~8M cells spanning entire torus
  - Core density and power from experimental conditions
  - Cross-field diffusivities scaled to approximately match upstream conditions
  - Nitrogen injected in divertor slot with recycling coefficient (self sputtering) of R=0.5
- Total simulation time, ~2-3 weeks

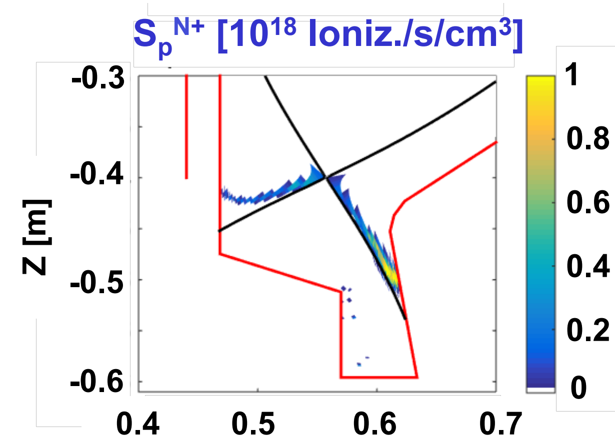


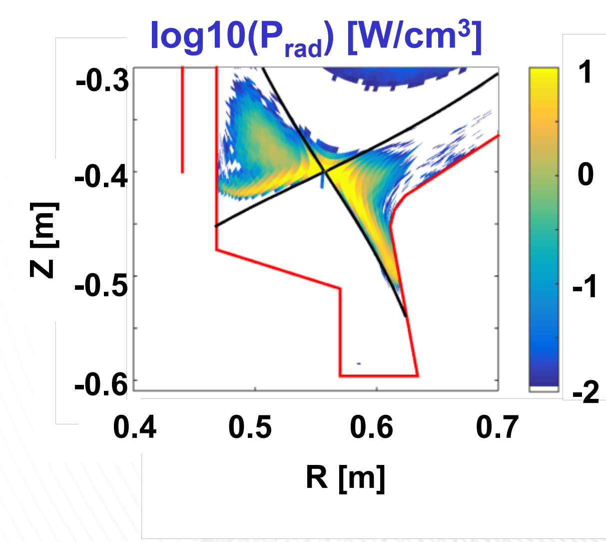


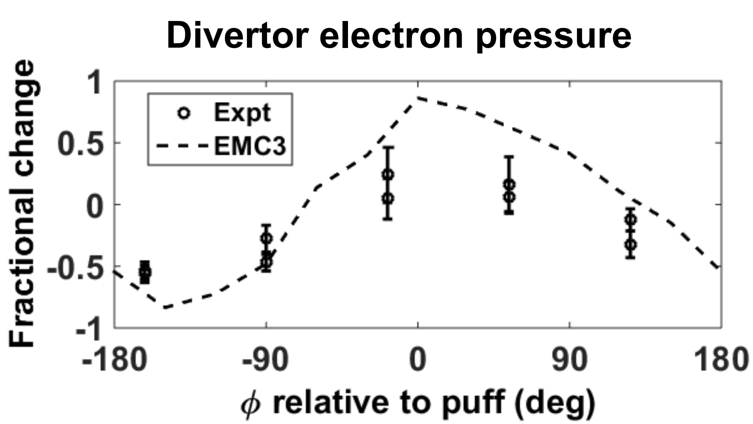
Low T_e, n_e in PFR leads to strong asymmetries in L-mode

- 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
- Pressure asymmetry near outer strike point shows qualitative agreement between code and experiment









J.D. Lore, et al., J. Nucl. Mater. (in press)

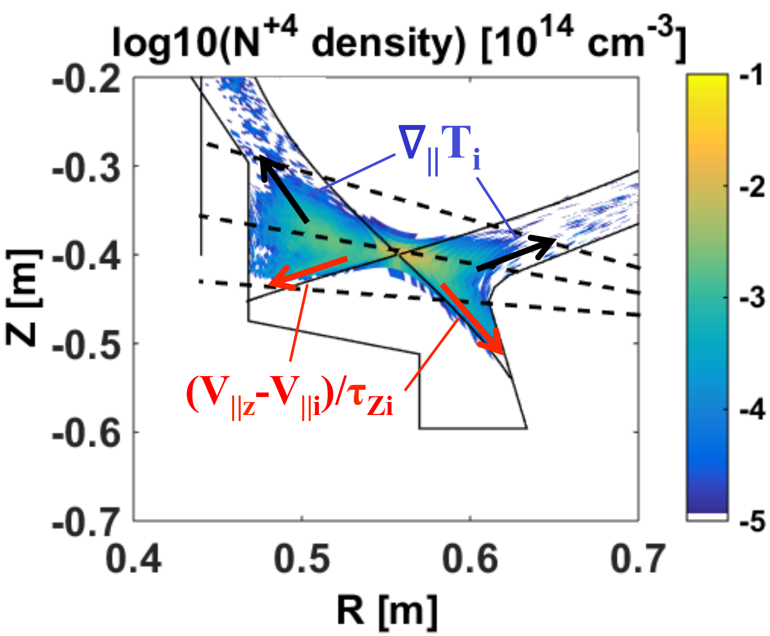
Alcator C-Mod

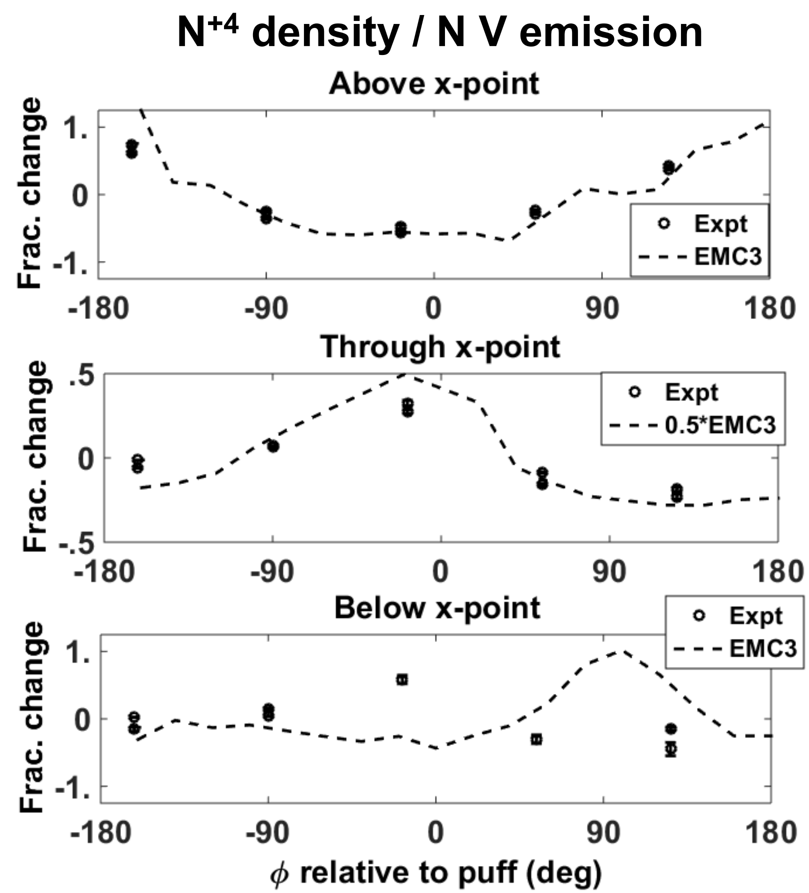
Nitrogen asymmetries qualitatively explained by impurity forces in SOL

- Parallel impurity forces qualitatively explain impurity trends for views through and above x-point
- Experimental trends not matched in PFR → need drifts?

$$F_z = -\frac{1}{n_z}\nabla_\parallel p_z + \boxed{m_z \frac{(V_i - V_z)}{\tau_{Zi}}} + eZ_zE_\parallel + \alpha_{Ze}\nabla_\parallel T_e + \boxed{\beta_{Zi}\nabla_\parallel T_i}$$

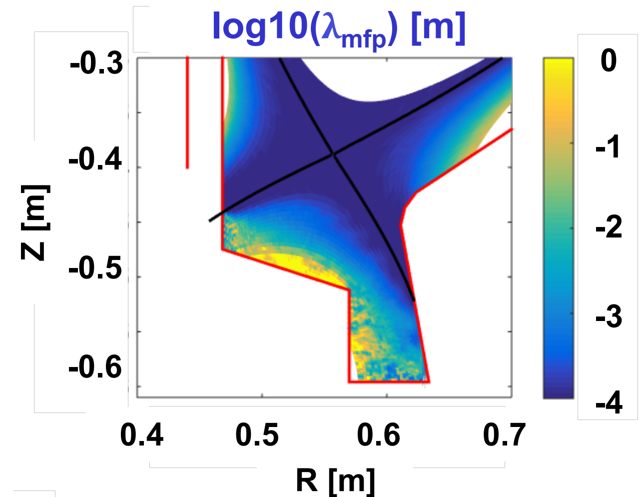
Impurity pressure gradient	Main ion friction	Electro-static	Electron Temp. Gradient	Ion Temp. Gradient

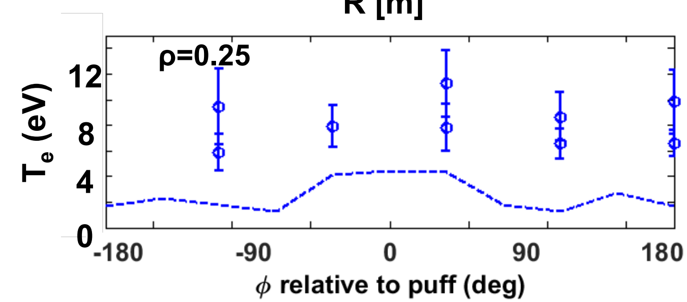


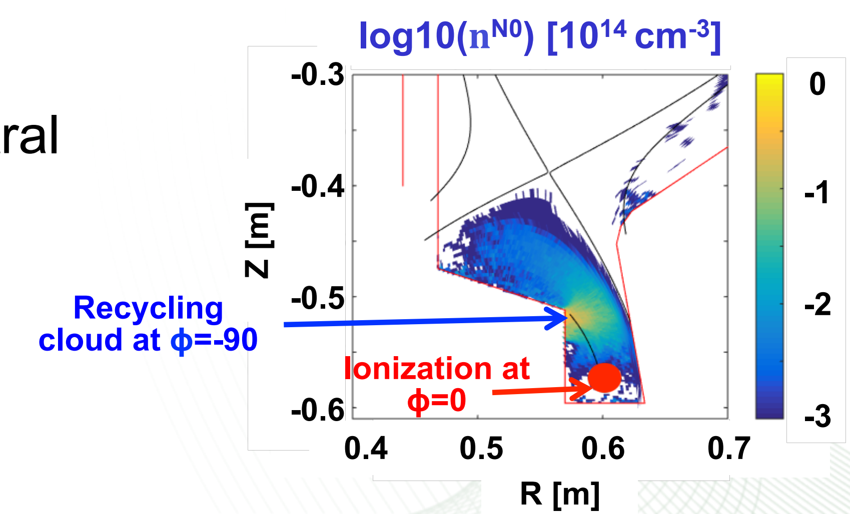


Opaque H-mode PFR results in weak asymmetries in SOL plasma

- PFR plasma is much more opaque to neutrals than in L-mode
  - Nearly all ionization is in the PFR
- Slow cross-field transport required for nitrogen to reach core and SOL
  - Results in mostly toroidally symmetric radiated power above separatrix
- Asymmetry predicted in downstream T_e, n_e, on the order of experimental uncertainty
- Parallel transport results in additional neutral nitrogen sources where flux tubes map to divertor on HFS



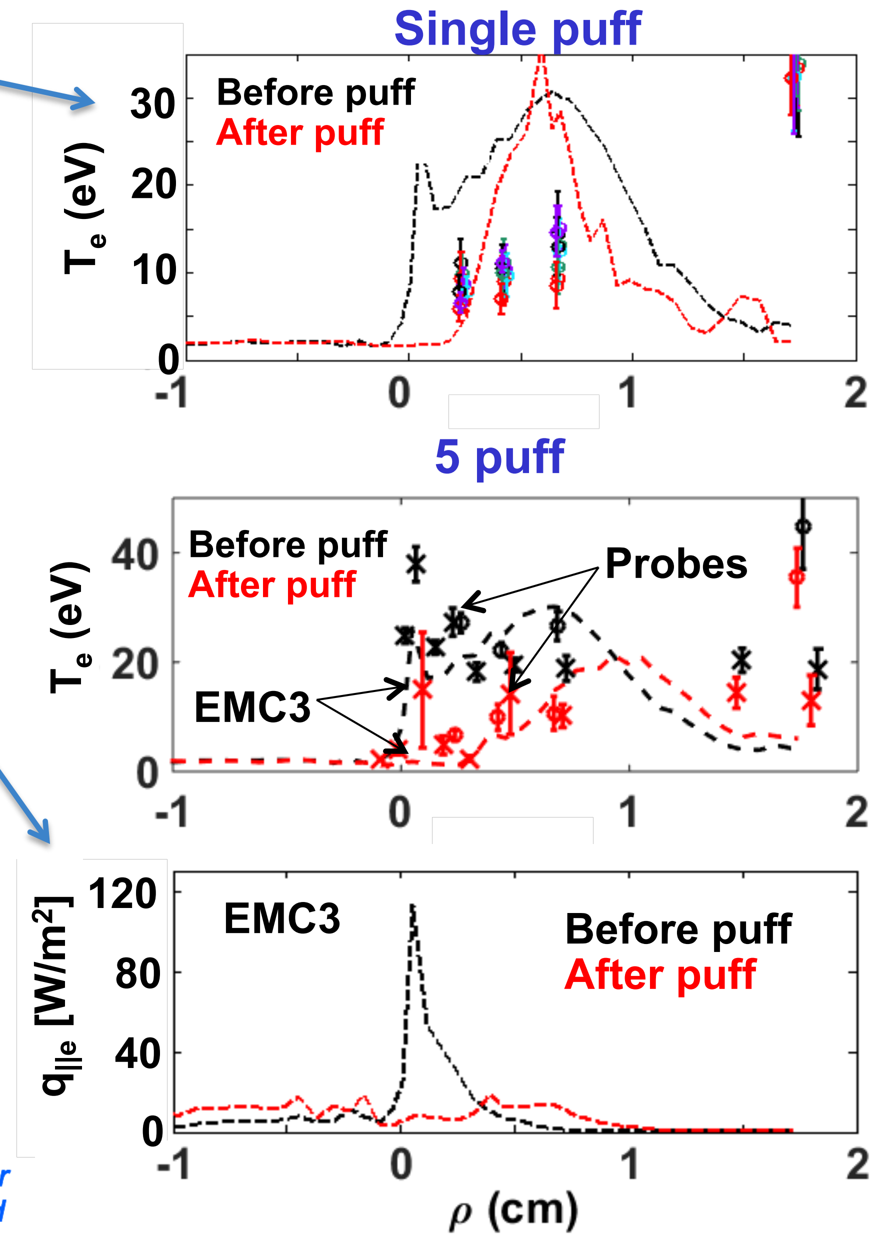




Alcator C-Mod

Simulation does not reproduce strong heat flux reduction with single puff

- Single puff results in weak detachment. Greatly increasing nitrogen input causes numerical instability.
  - Level of detachment does not scale linearly with N input
- With additional gas puff locations, strong detachment can be achieved
- Nitrogen emission is asymmetric in PFR
  - In general toroidal trends in PFR do not well match experimental trends
  - Matching of main plasma conditions important, → quantitative agreement may require kinetic corrections, volume recombination



Alcator C-Mod

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  - Level of toroidal asymmetry depends on downstream conditions, impurity ionization in the private flux region
- NSTX experiments show divertor reattachment due to 3D field application
  - With 3D fields, striated heat flux patterns remain peaked at large radius due to short connection length to hot plasma
- Conclusions

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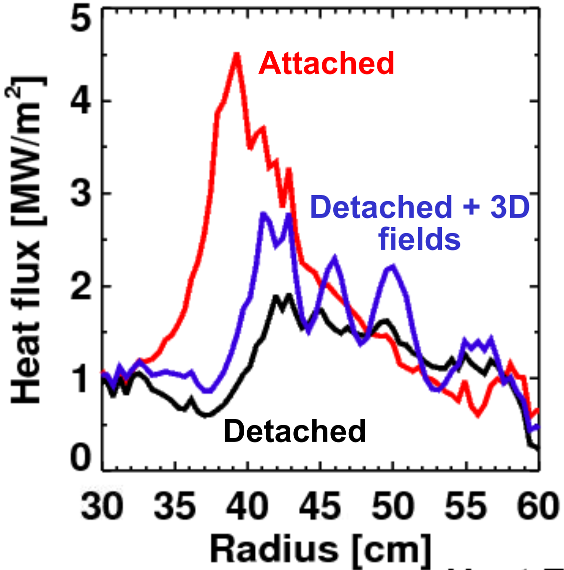
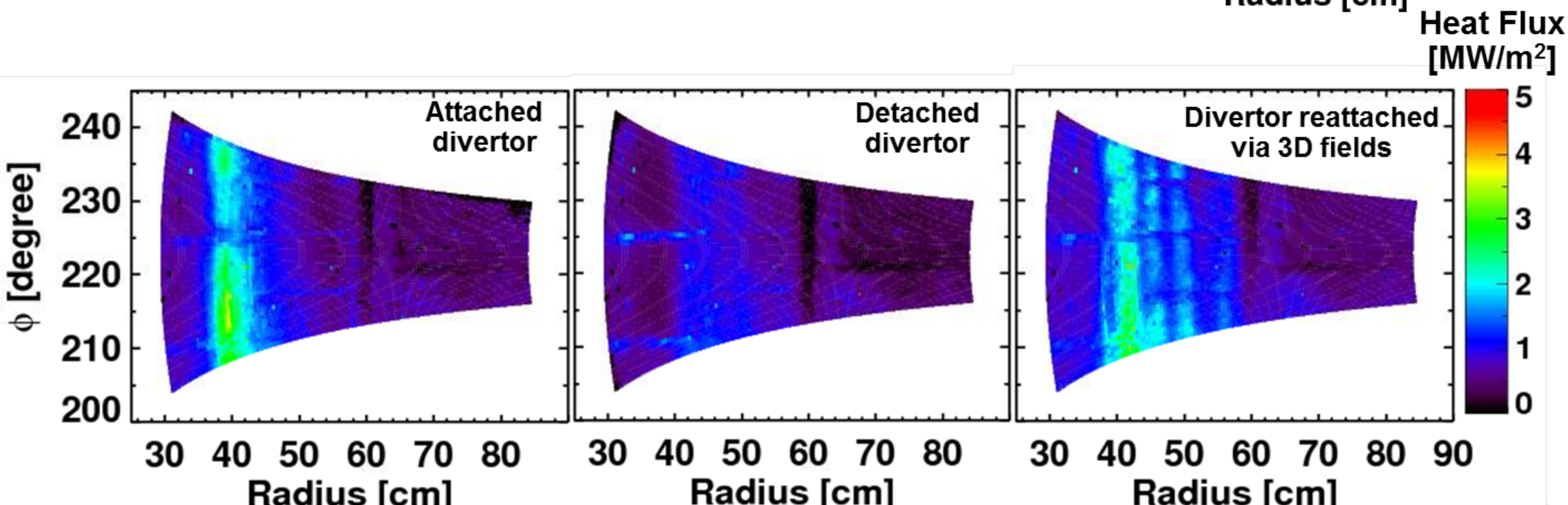
NSTX experiments have shown 3D fields can cause divertor to re-attach

- Gas puff is used to detach divertor
  - High-n Balmer emission increases, indicative of volume recombination
- 50ms later n=3 3D fields are applied, resulting in striated heat flux pattern



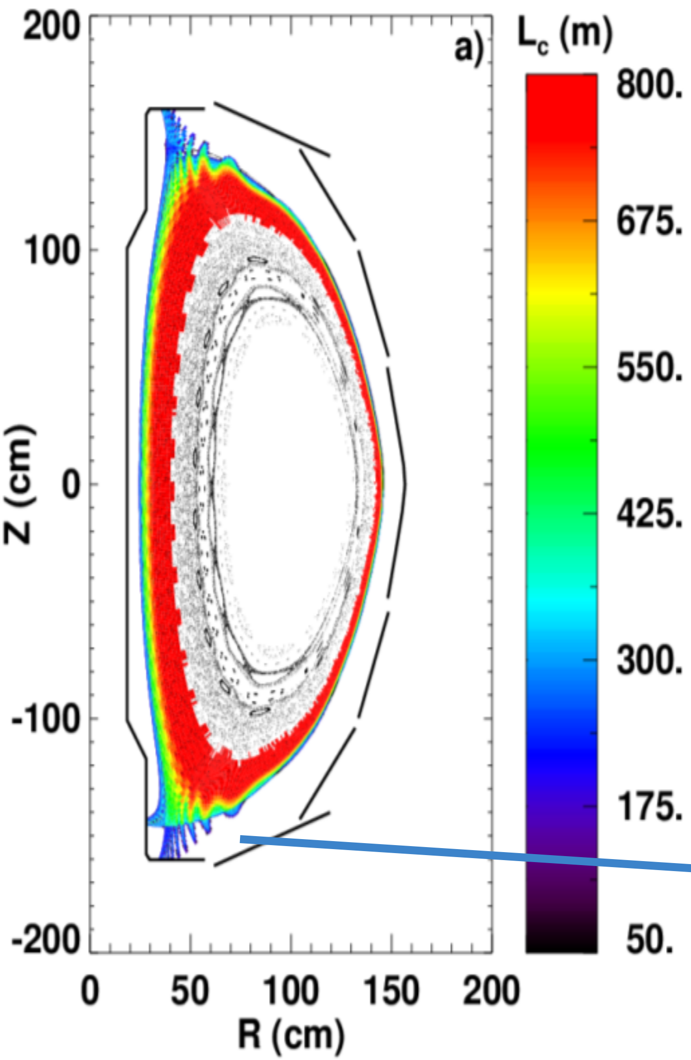


J.-W. Ahn, et al., PPCF 56 (2014) 015005

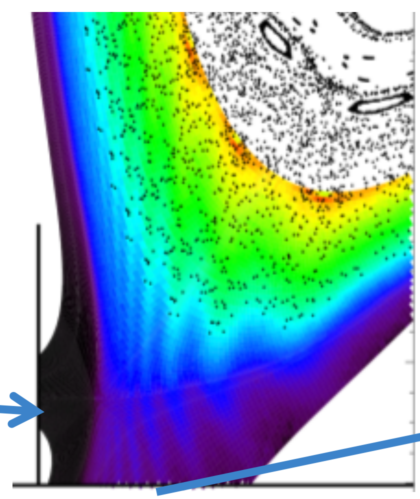
NSTX simulations are performed using vacuum approximation

- Vacuum approximation results in strong strike point splitting, with clear heat flux striations on horizontal target at low density
- Other field models will be tested in future simulations: e.g., IPEC, SIESTA → Screening important?

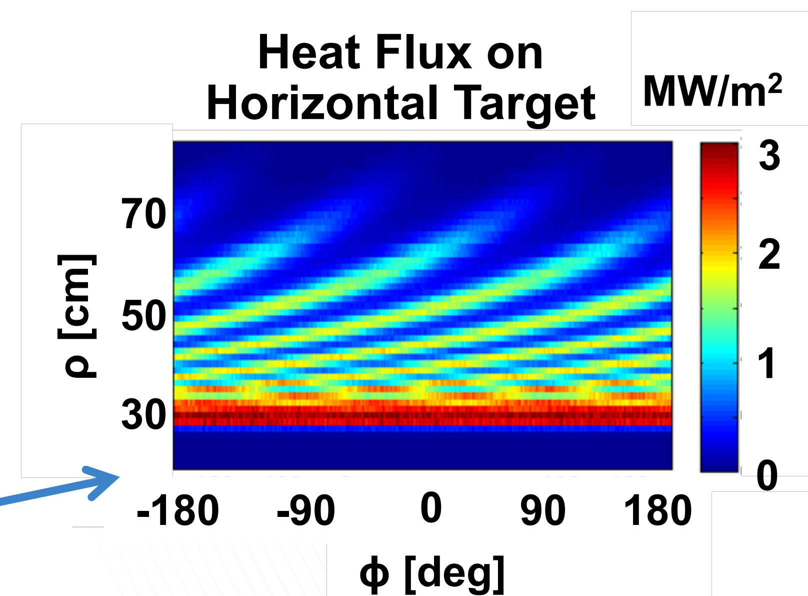
Connection Length



Electron Temperature

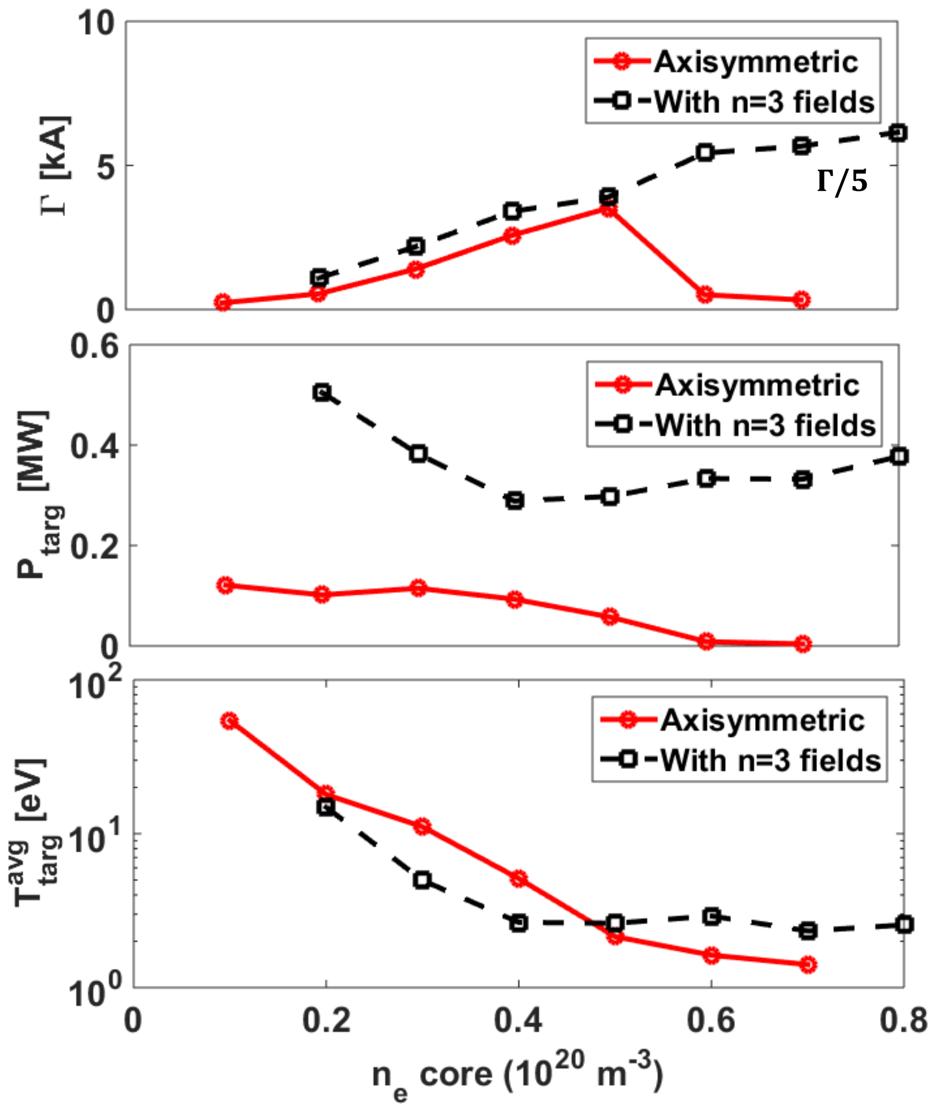


Heat Flux on Horizontal Target



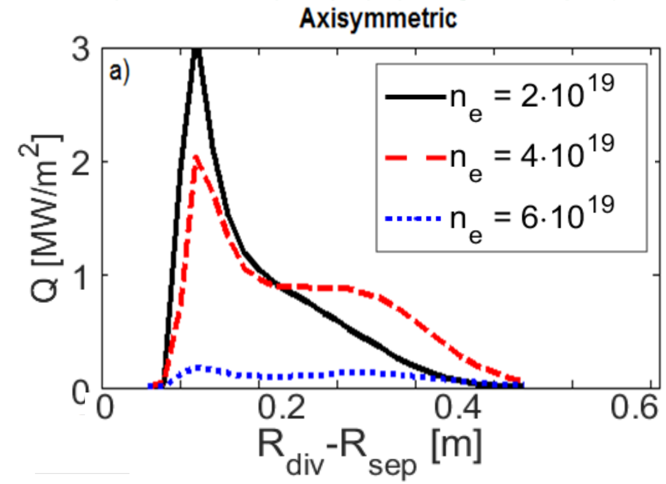
Modeling shows axisymmetric plasma detaches at lower density than 3D case

- Particle flux rollover not observed when 3D fields are applied over tested density range
- Power carried by the plasma to the divertor and electron temperature at the target level off instead of continuing to decrease



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



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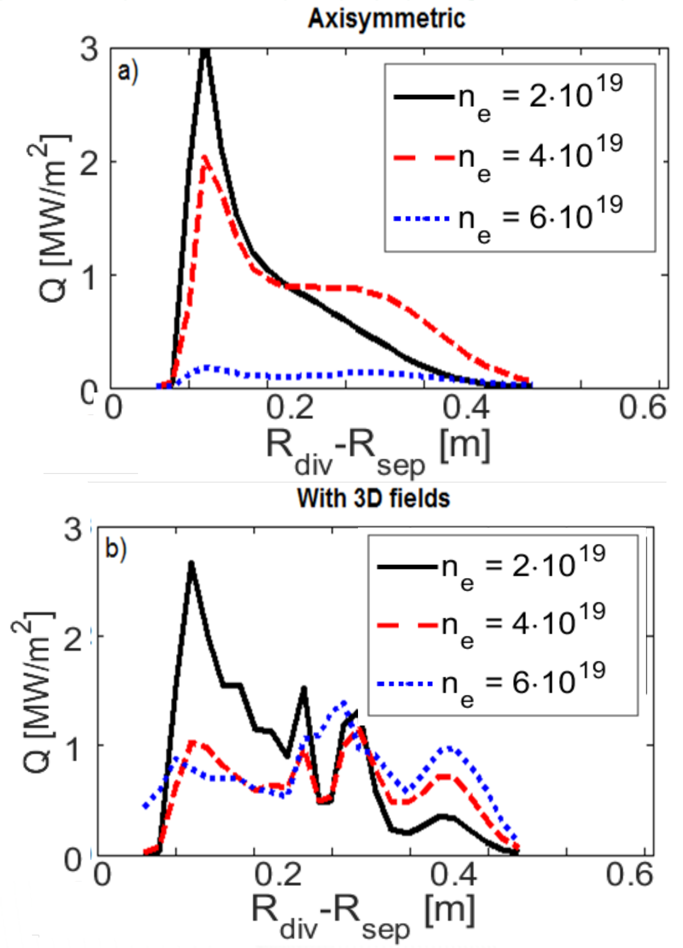
- Axisymmetric case shows clear reduction in heat flux with increasing density
  - Heat flux increases at larger radius due to greater effect of cross-field diffusion
- With 3D fields the maximum heat flux shifts to the outer peaks
  - Outer lobes connected to hot plasma with short connection length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



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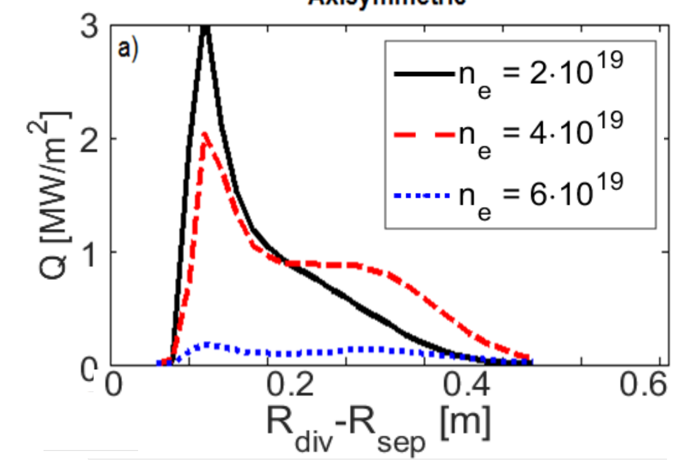
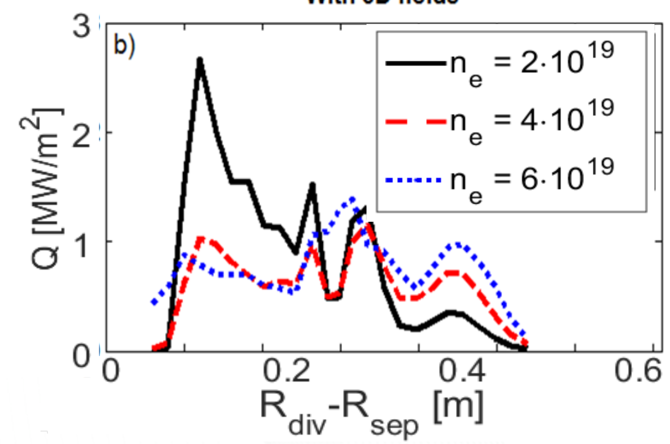
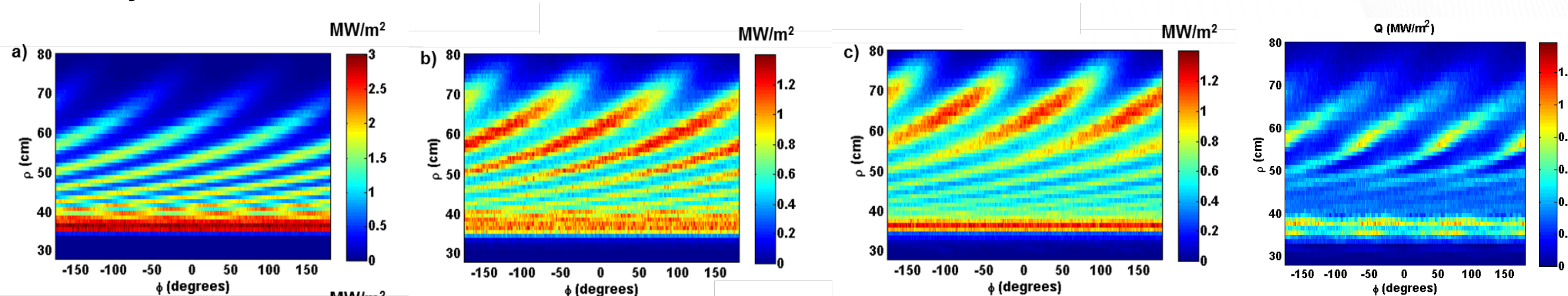
Axisymmetric



With 3D fields

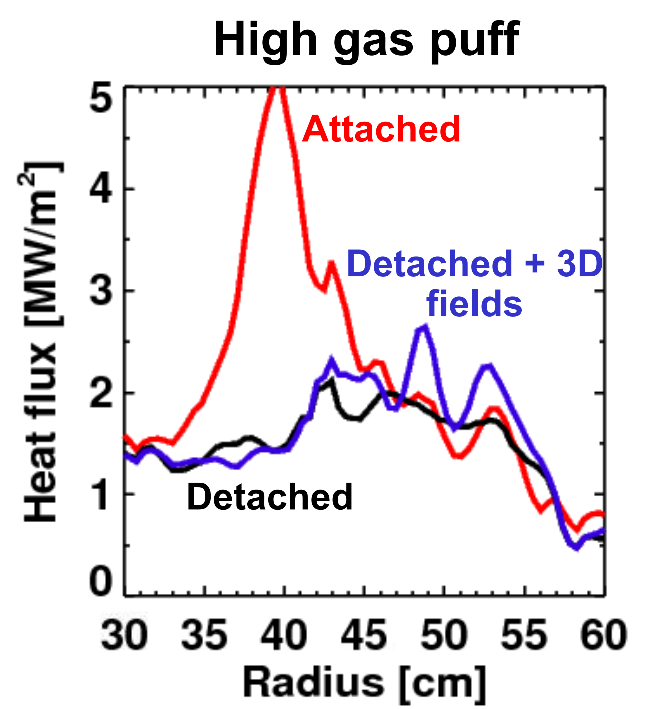


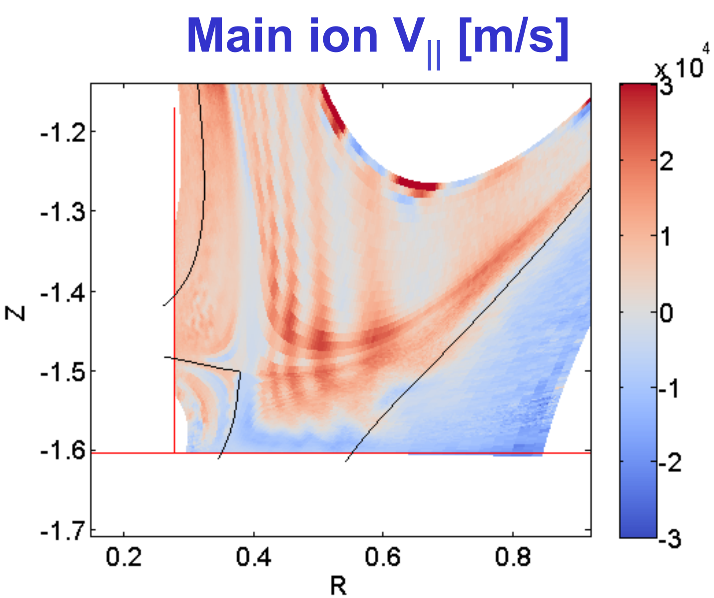
Increasing density

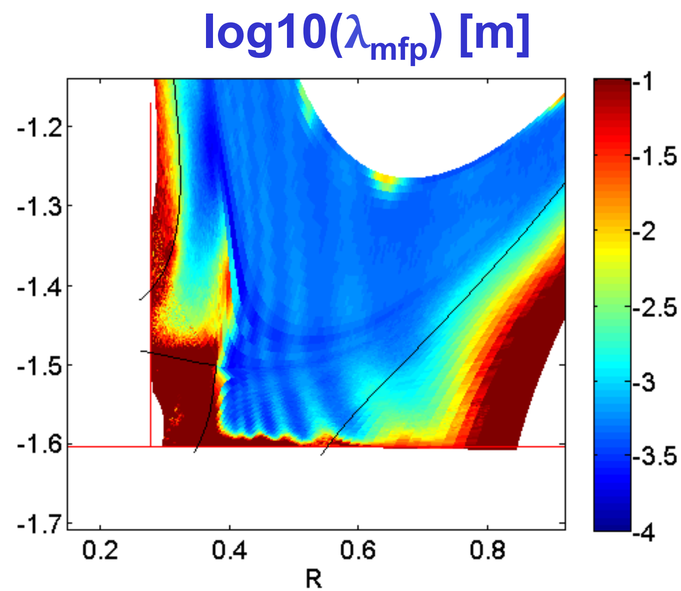


Heat flux in outer lobes remains even with increased gas input

- Additional gas can be used to keep more of the divertor detached with 3D fields
  - Outer heat flux peaks remain
  - Too much gas results in pedestal degradation
- Flow patterns with 3D fields are complex
  - Divertor impurity injection as on C-Mod would be affected by counter-streaming flows, ionization mfp patterns







NSTX

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Summary

- C-Mod: Toroidal asymmetry due to localized divertor impurity injection strong in L-mode, weak in H-mode
  - Modeling shows that ionization in PFR results in smaller asymmetry in radiated power, divertor conditions
- NSTX: 3D field application can cause divertor plasma to re-attach with striated flux
  - Modeling reproduces trends, caused by hot plasma with short connection length to divertor at large radius.
- 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 and volume recombination to code