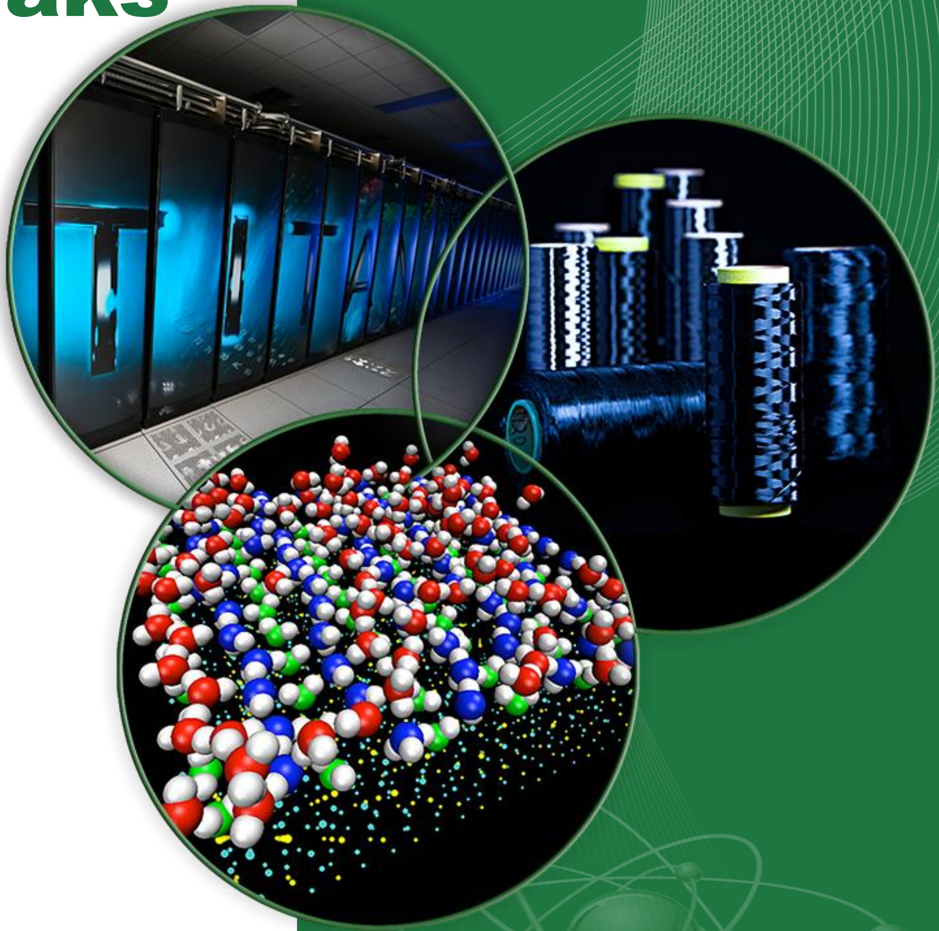
3D Edge Transport Modeling on Tokamaks and Stellarators



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Savannah, Georgia
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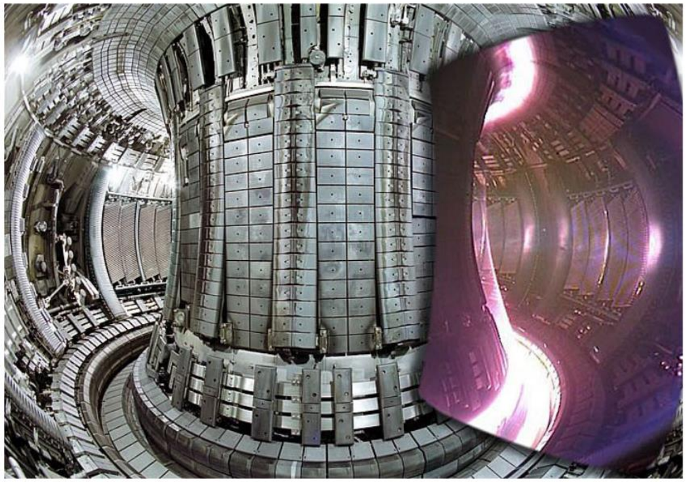
Alcator C-Mod NSTX DIII-D NATIONAL FUSION FACILITY SAN DIEGO IPP

OAK RIDGE National Laboratory

3D edge transport modeling is required for data interpretation and prediction for tokamaks

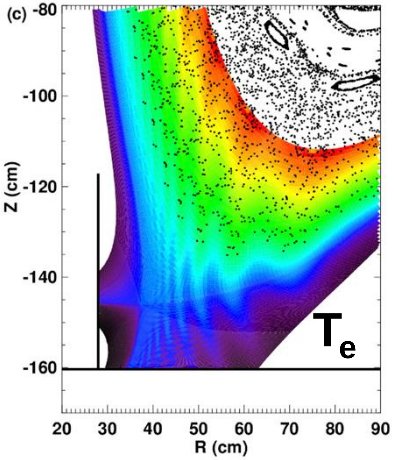
- Impact of nonaxisymmetric effects is widely recognized in tokamaks
  - 3D plasma facing components → localized heating, erosion
  - Applied and intrinsic 3D fields → stochasticity, strike point splitting, 3D flows
  - Toroidally and poloidally localized heat and particle sources
  - **3D models are required**
- Goals of fluid plasma modeling
  - Analyze current experiments, reduced model → physical interpretation
  - Develop validated models for predictive simulations → advance by comparing to experiment
  - Component of integrated simulation capability

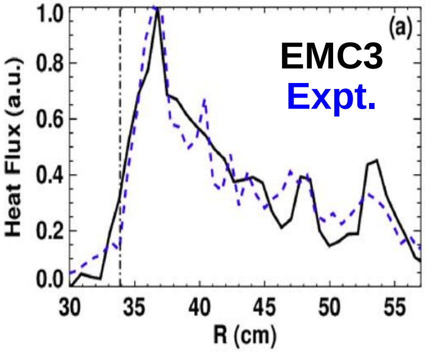
JET



https://sciencenode.org/feature/small-sun-earth.php

NSTX





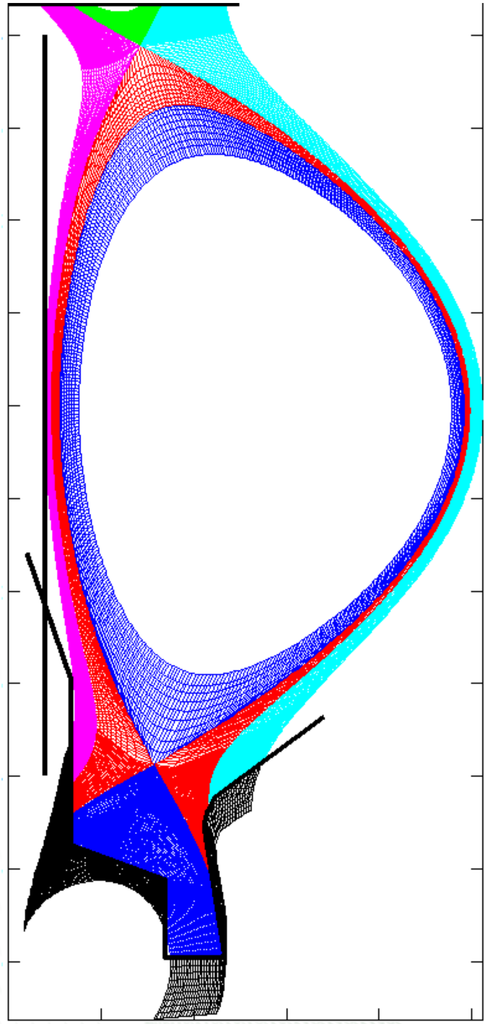
Outline

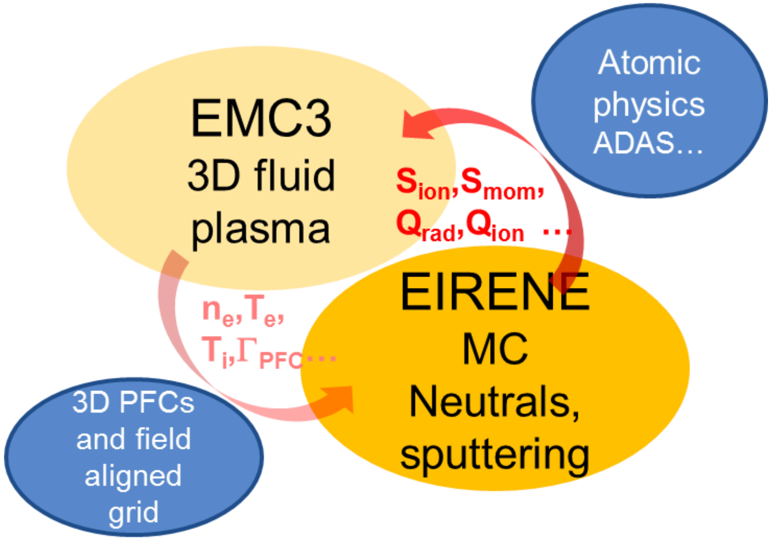
- The EMC3-EIRENE code
- 3D modeling of tokamaks
  - C-Mod: localized divertor impurity gas injection
  - NSTX: effect of 3D fields on detachment
  - DIII-D: testing plasma response models
- Connection to stellarators
  - Transport in different field models, prediction of component heat and particle fluxes, divertor geometry optimization
- Summary
  - C-Mod: Seeding asymmetry dependent on neutral ionization location
  - NSTX: Heat flux peaks can remain attached w/ 3D fields
  - DIII-D: B field models must be consistent in pedestal & edge

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

- 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





EMC3
3D fluid
plasma

Atomic
physics
ADAS…

S_{ion}, S_{mom},
Q_{rad}, Q_{ion} …

n_e, T_e,
T_i, Γ_{PFC}…

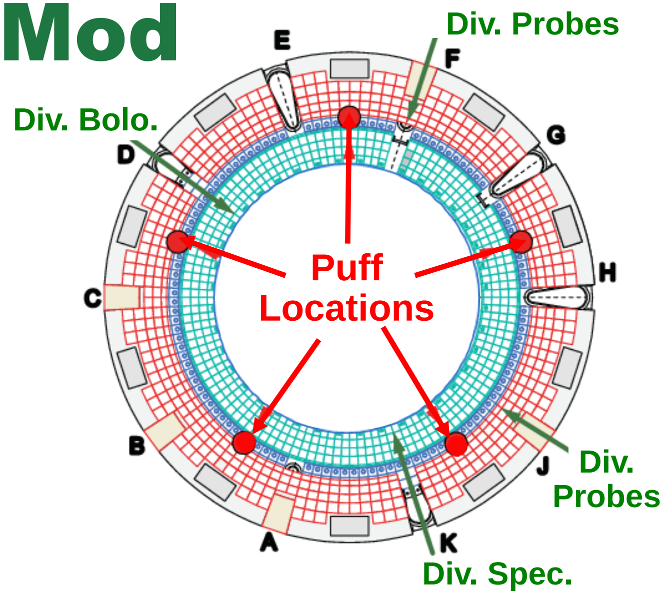
EIRENE
MC
Neutrals,
sputtering

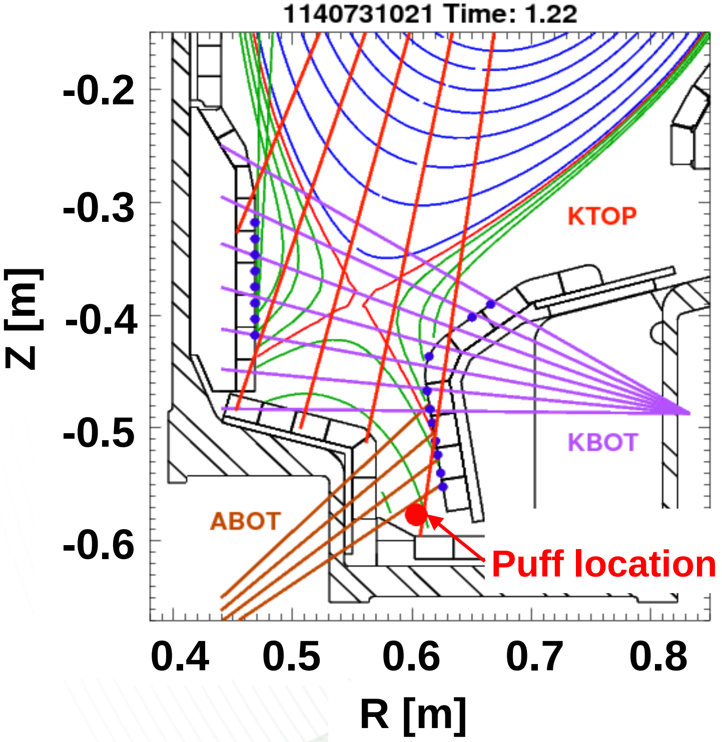
3D PFCs
and field
aligned
grid

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

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

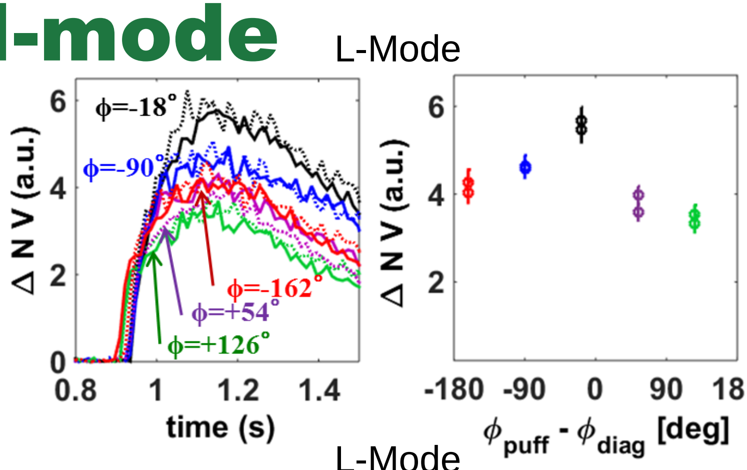
- 5 gas injection locations in divertor slot with layout similar to ITER
- Data from toroidally fixed diagnostics are compared as active gas valve changed each shot
- Many divertor diagnostics enable validation of main plasma and impurity transport modules of code
- Scans performed in both L- and H-mode

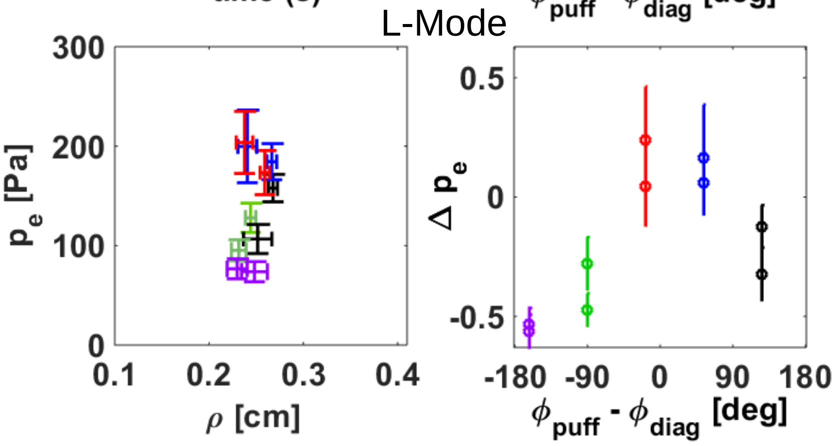


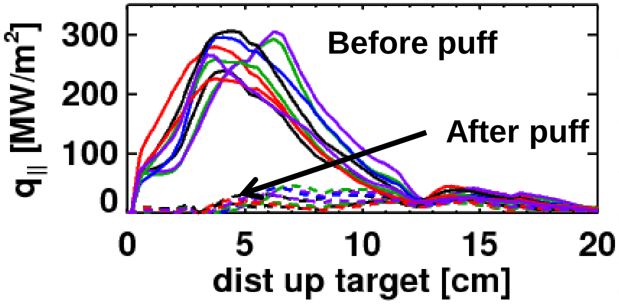


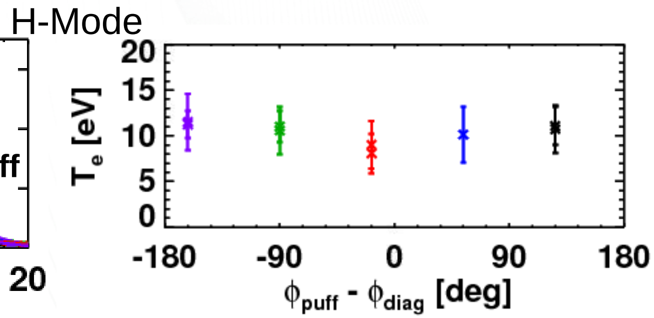
Strong toroidal asymmetries in L-mode are greatly reduced in H-mode

- **L-mode:**
  - Clear, repeatable toroidal variation observed on many divertor diagnostics
  - Toroidal asymmetry in pressure measured near separatrix
  - Single injection location results in strong asymmetries
- **H-mode:**
  - Divertor $q_{||}$ and T_e show small asymmetry, on order of shot-to-shot variation
  - No clear, repeatable asymmetries in highly radiating N charge states
  - Single puff can be used to detach divertor with small asymmetry





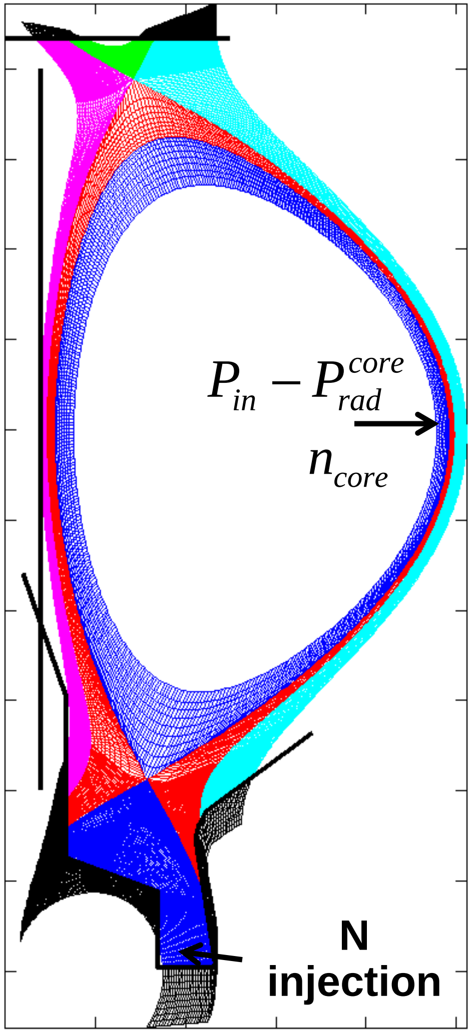


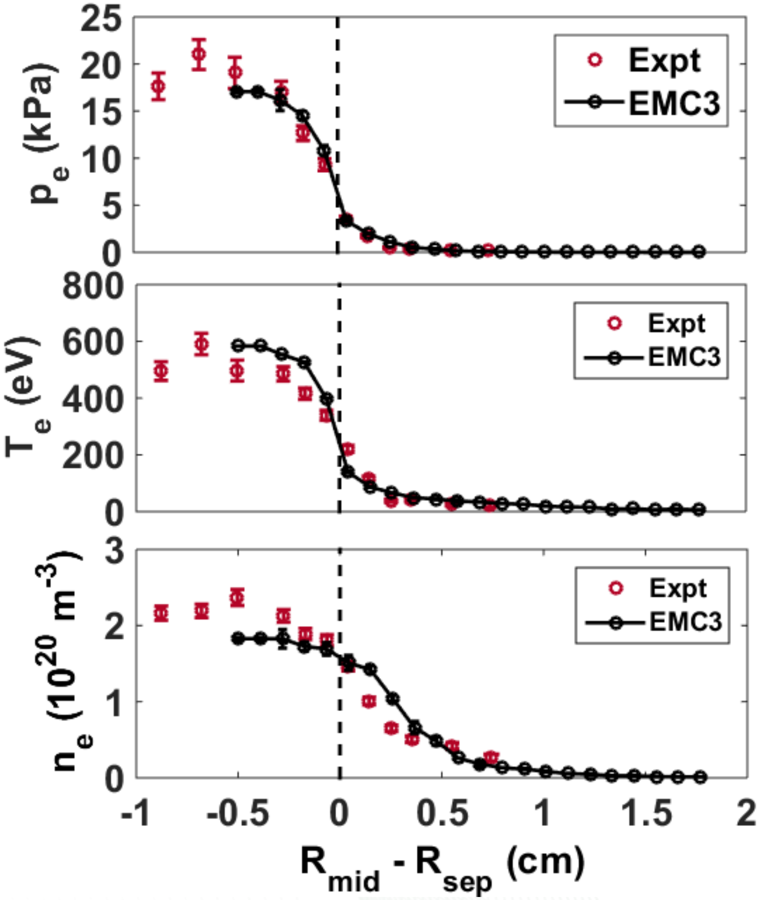


M.L. Reinke, et al., PSFC Research Report PSFC/RR-14-3
J.D. Lore et al, Phys. Plasmas 22, 056106 (2015)

Setup of EMC3-EIRENE simulations

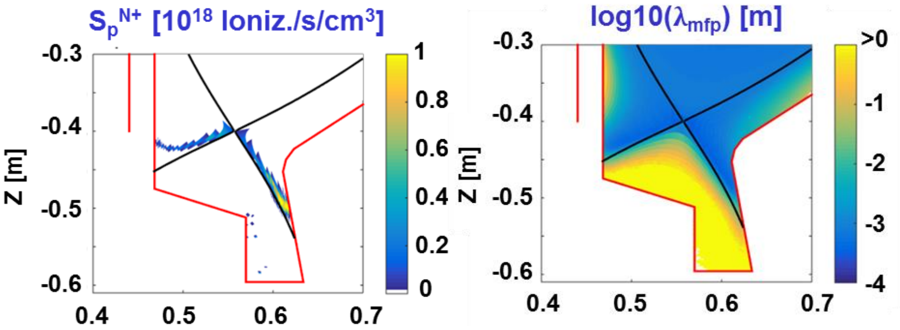
- Inputs:
  - Field aligned grid: axisymmetric **B**, ~8M cells spanning entire torus
  - Core density and power from experimental conditions
  - Cross-field diffusivities scaled to approximately match upstream conditions
  - Nitrogen injected in divertor slot with recycling coefficient (self sputtering) of R=0.5
- Total simulation time, ~2-3 weeks on ~100 cores



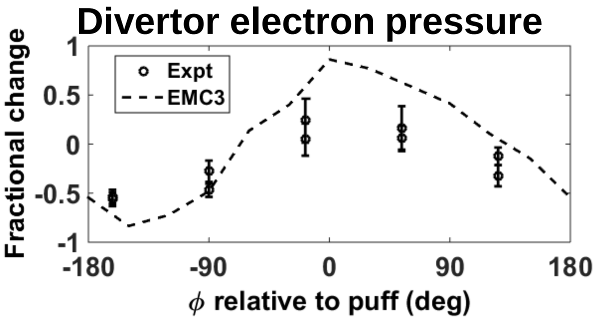


J.D. Lore et al, Phys. Plasmas 22, 056106 (2015)

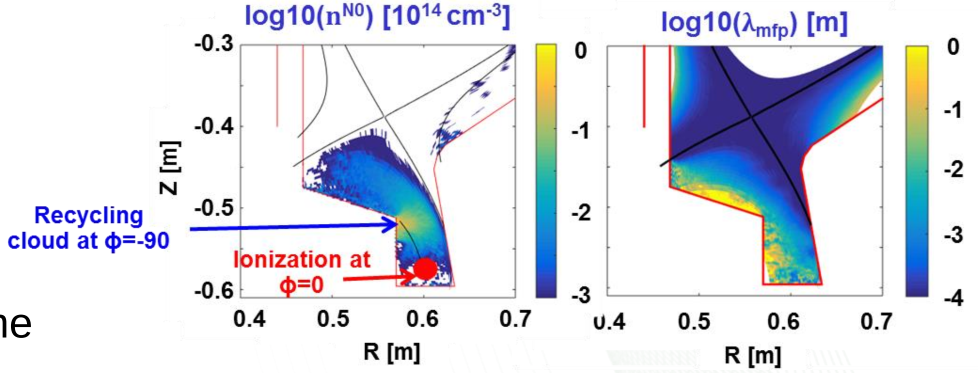
Simulations qualitatively reproduce results, difference due to impurity ionization location



- **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



- **H-mode:**
  - PFR plasma is opaque to neutrals → nearly all ionization is in the PFR
  - Slow cross-field transport required for nitrogen to reach core and SOL
  - Nitrogen recycling in PFR further symmetrizes source
  - Asymmetry is reduced, details of PFR T_e, n_e distribution will depend on drifts, volume recombination



J.D. Lore, et al., J. Nucl. Mater. 463, 515 (2015)

J.D. Lore et al, Phys. Plasmas 22, 056106 (2015)

Nitrogen asymmetries qualitatively explained by impurity forces in SOL

- Parallel impurity forces qualitatively explain impurity trends for views through and above x-point
- Cross-field drifts likely to be important in PFR

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

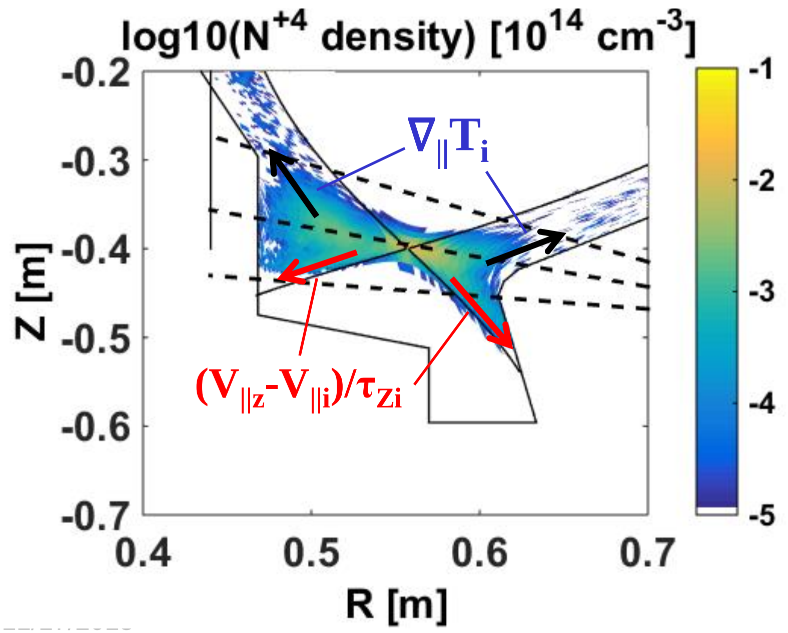
Impurity pressure gradient

Main ion friction

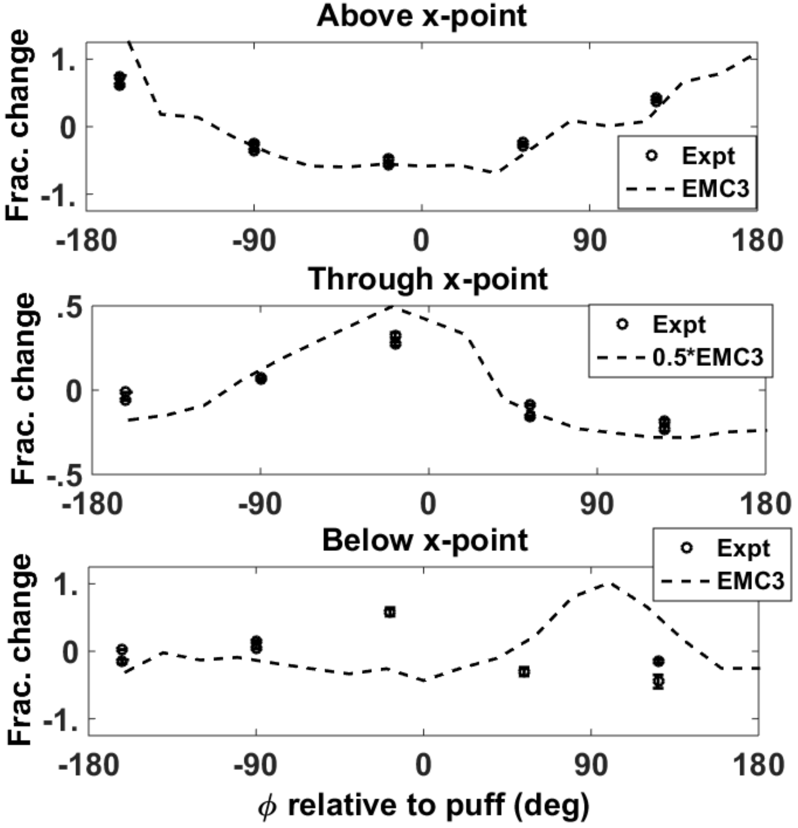
Electro-static

Electron Temp. Gradient

Ion Temp. Gradient

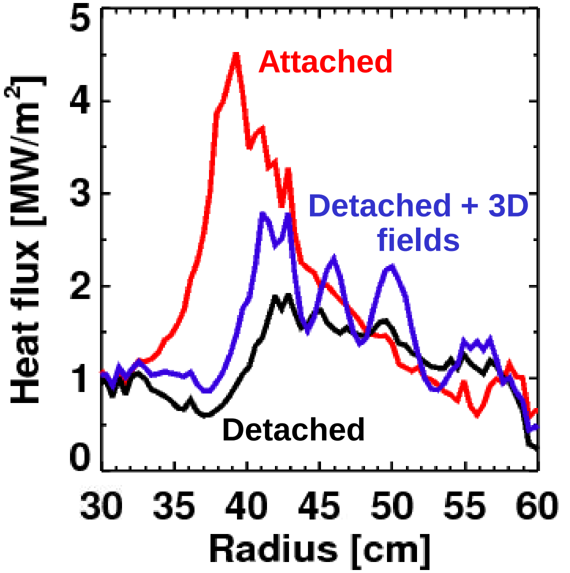


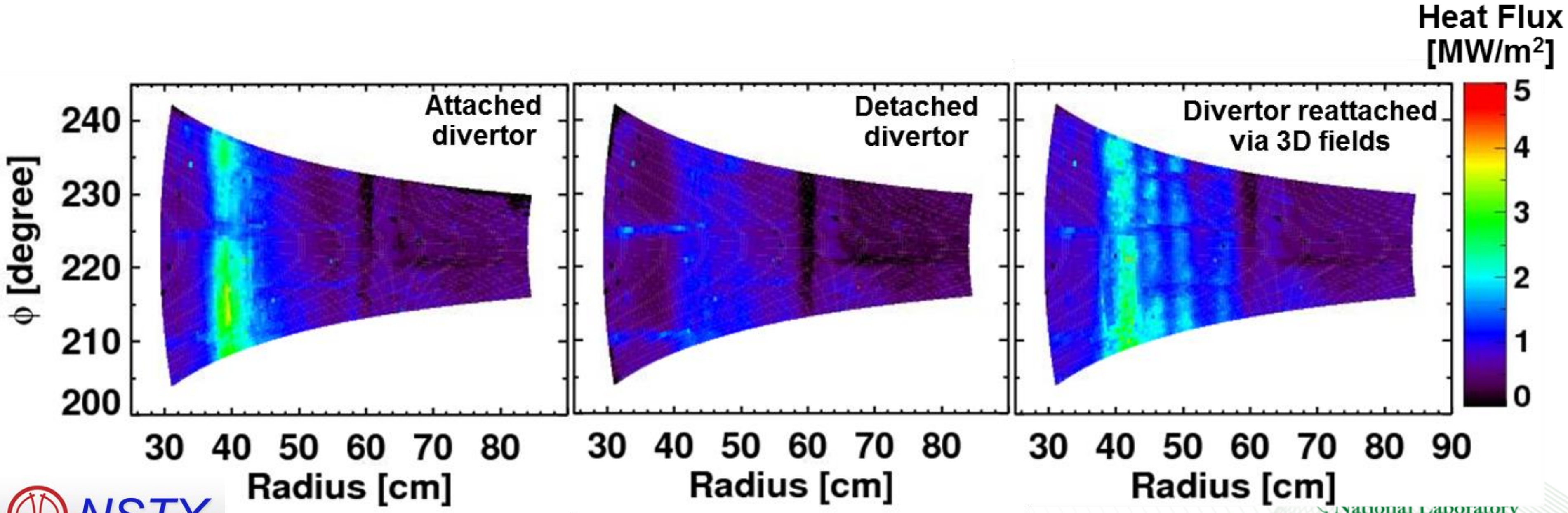
N^{+4} density / N V emission



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

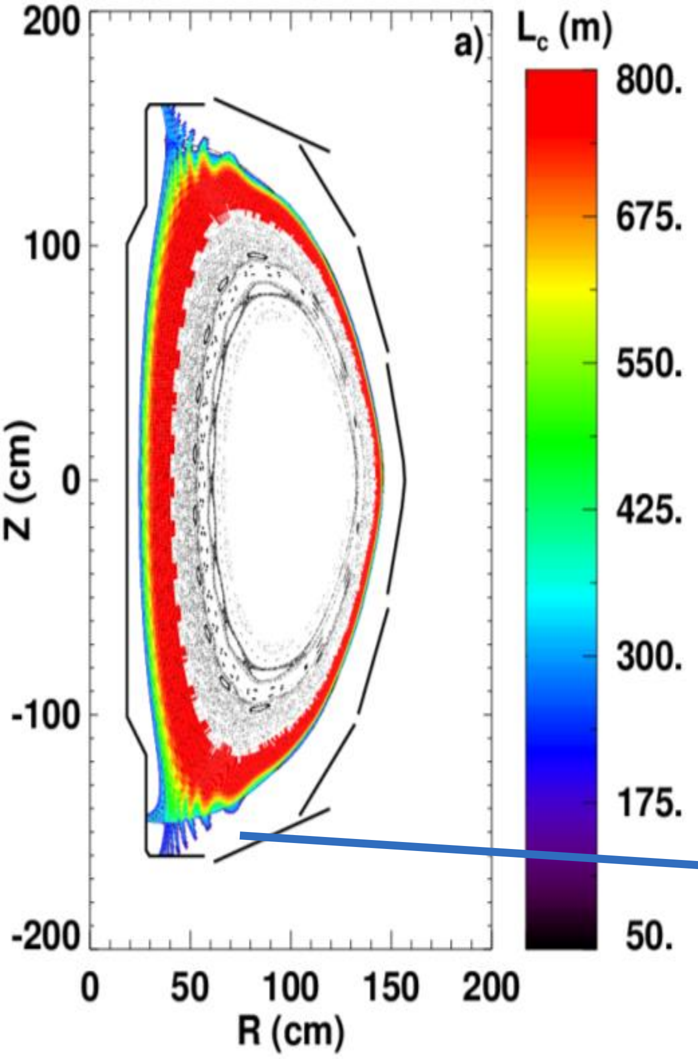

J.-W. Ahn, et al., PPCF 56 (2014) 015005



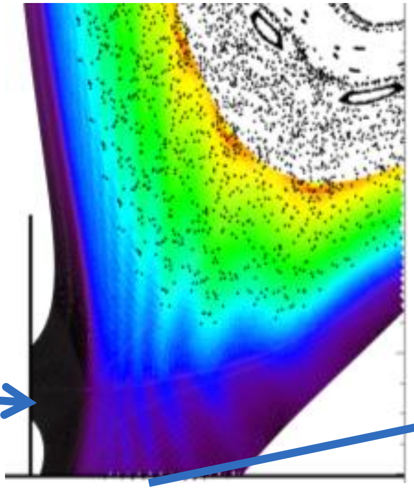
NSTX simulations are performed using vacuum approximation

- Vacuum approximation results in strong strike point splitting, with clear heat flux striations on horizontal target at low density
- Other field models (IPEC, SIESTA, M3D-C1) may change results→ Screening important?

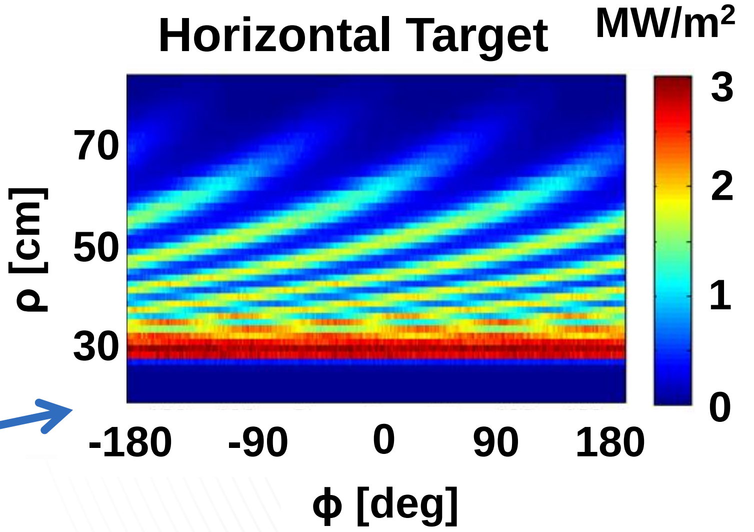
Connection Length



Electron Temperature

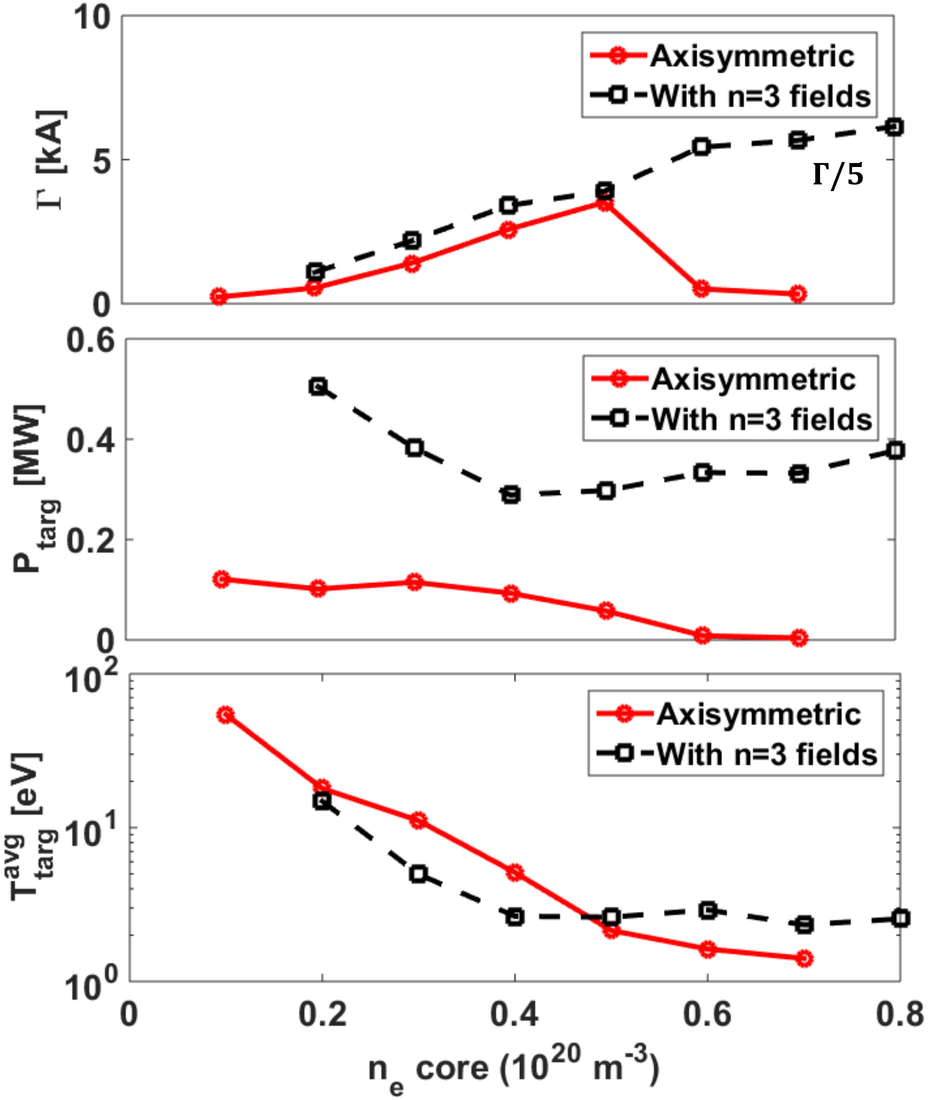


Heat Flux on Horizontal Target



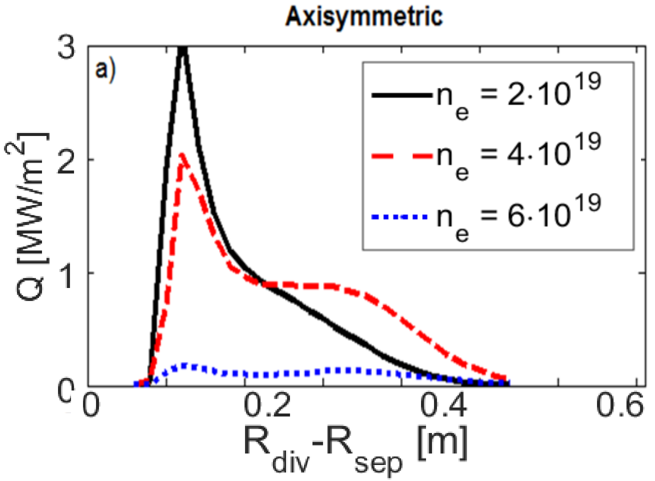
Modeling shows axisymmetric plasma detaches at lower density than 3D case

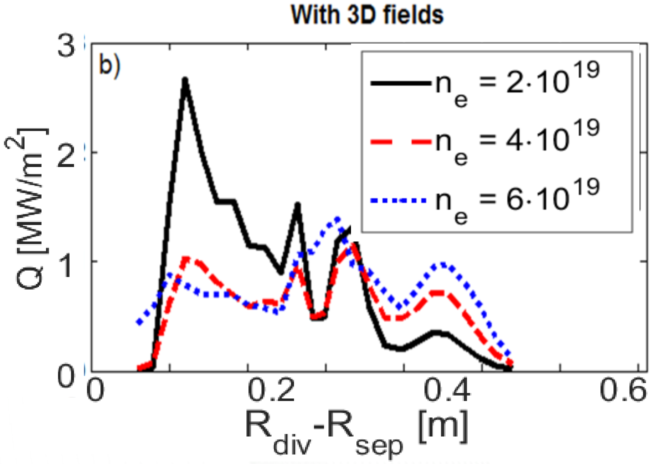
- Particle flux rollover not observed when 3D fields are applied over tested density range
- Divertor power and T_e level off instead of continuing to decrease
- Capturing detachment transition quantitatively challenging even in 2D codes, additional physics are important (volume recombination, kinetic corrections, …)



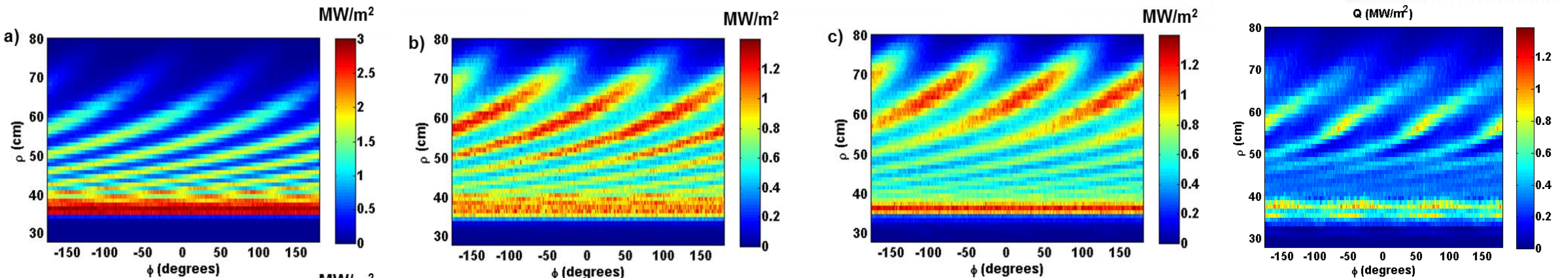
With 3D fields primary strike point detaches, but outer lobes remain attached

- 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 → remain in sheath limited regime





Increasing density

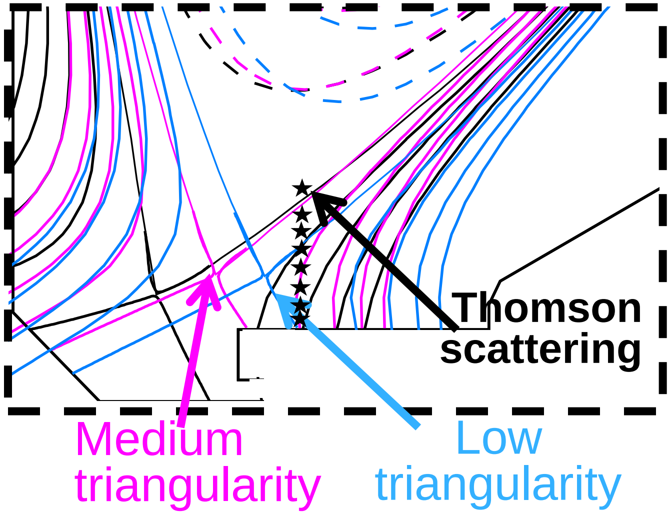


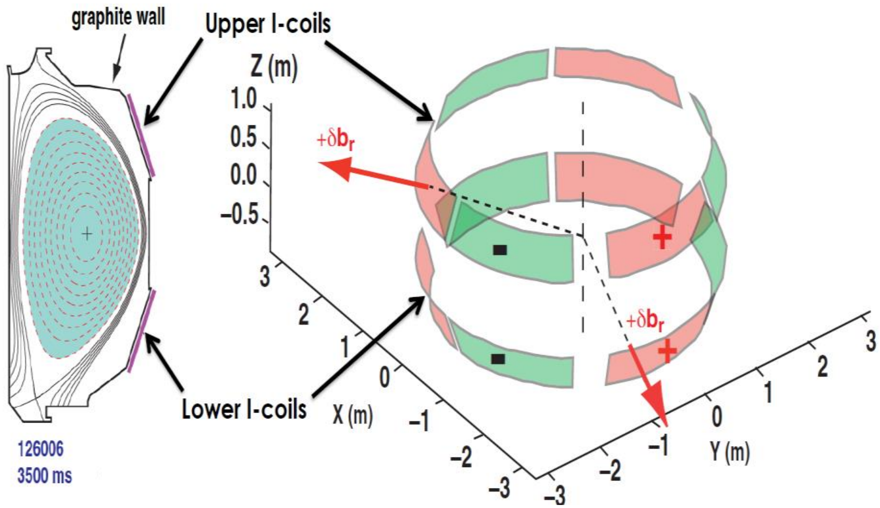
Motivation for modeling of DIII-D 3D detachment experiments

- ITER is planning to run under partially detached conditions with 3D fields applied for ELM control
- 3D field structure can result in undesired effects
  - Strike point splitting: heat flux at large radius, localized flux
  - 3D fields may change density at which detachment occurs, outer heat flux peaks may remain attached (NSTX)
- DIII-D detachment + RMP experiments showed 3D effects on several divertor diagnostics
  - Heat flux splitting (IR), ‘Structure’ in mapped 2D TS images, 3D patterns in UV radiation
  - At high density no/small divertor heat flux striations
- Vacuum and M3D-C1 fields are different → Use 3D transport code to determine if either method gives consistent solution (pedestal + divertor + bfield)

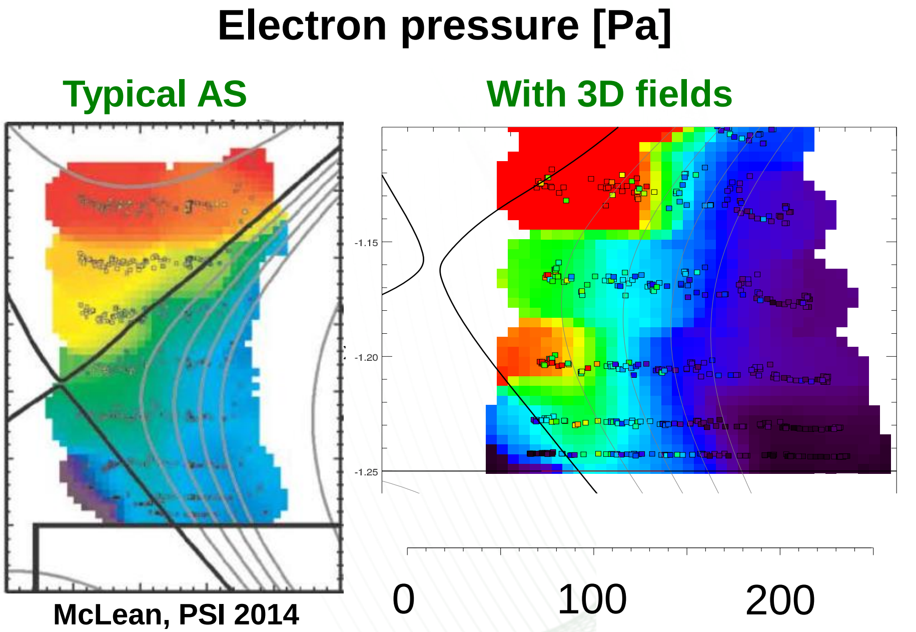
DIII-D RMP experiments show 3D effects on several divertor diagnostics

- 3D fields applied using I-coils with odd parity
- Mapped divertor TS shows structures that do not follow typical axisymmetric mapping





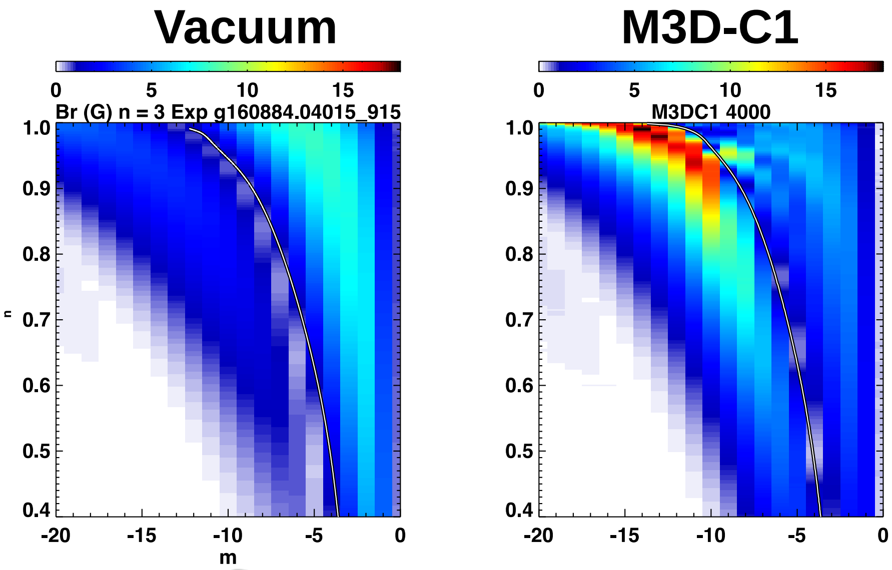
Briesemeister, ITPA DivSOL '15

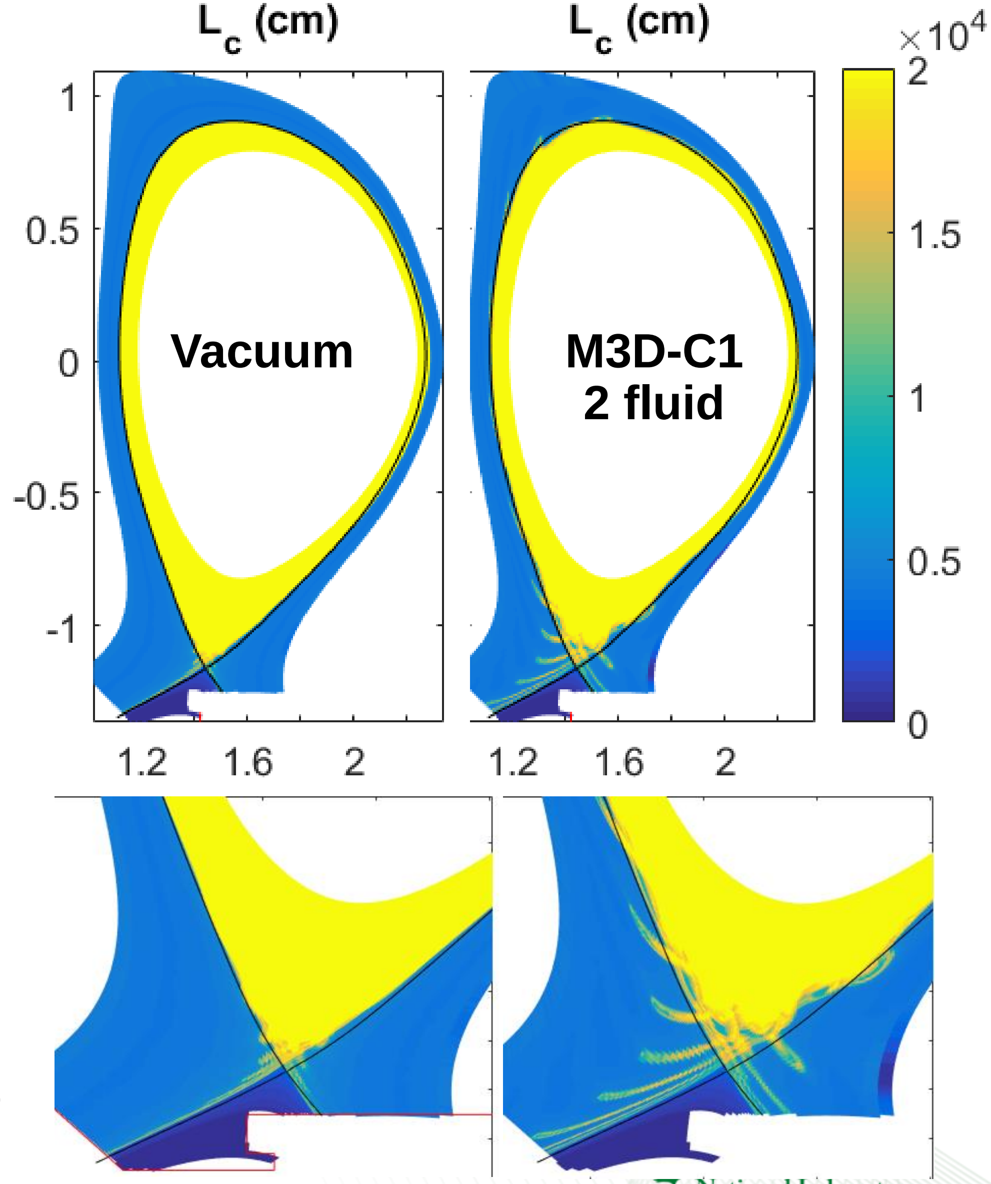


McLean, PSI 2014

Vacuum approximation and M3D-C1 fields show large differences (3000ms)

- Lobes are much larger in M3D-C1 cases (linear, 2 fluid)
- M3D-C1 two fluid calculations show strong kink response at edge → large extended lobes

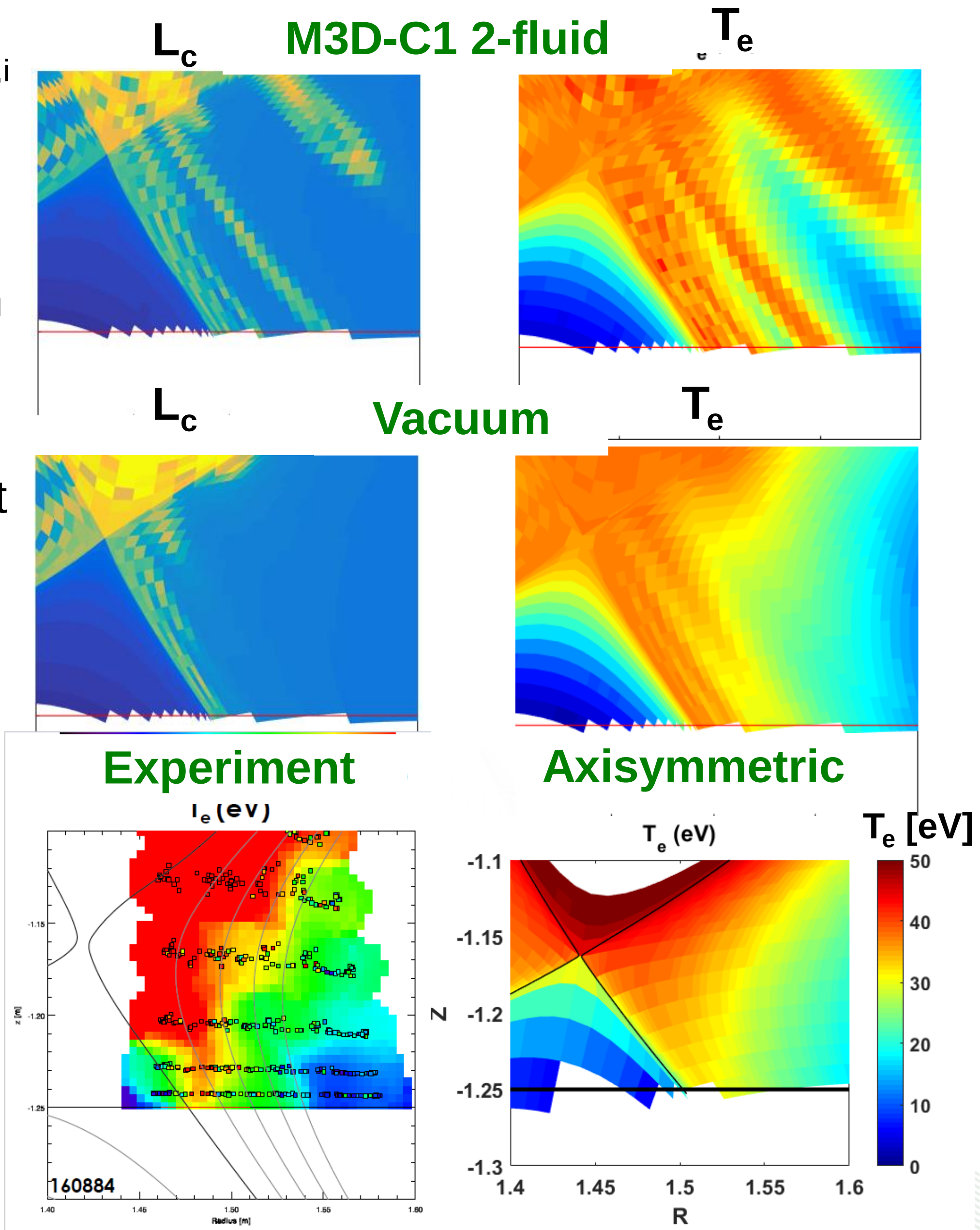


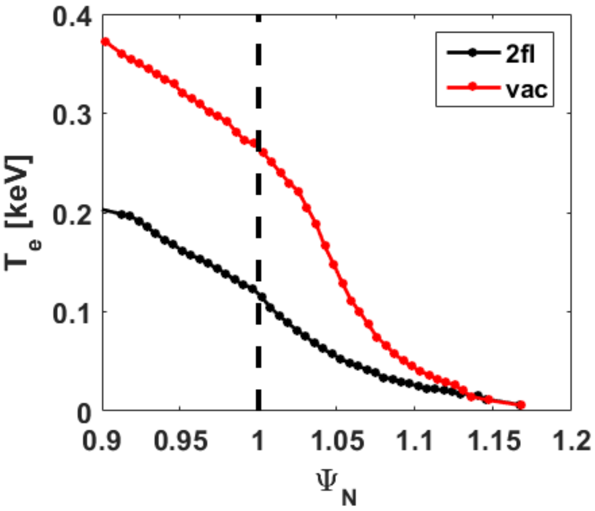


M3D-C1 runs courtesy of N. Ferraro

Both field combinations show lobe structure in T_e for sheath limited conditions

- Simulations for constant n_e, constant $\chi_{e,i}$ – upstream profiles not matched
  - Definition of T_e lobes depends on χ, transport regime
- M3D-C1 case has larger T_e perturbation
  - Need to implement 2DTS synthetic diagnostic
- Vacuum fields support larger T_e gradient
  - Field model must be consistent with pedestal and divertor measurements



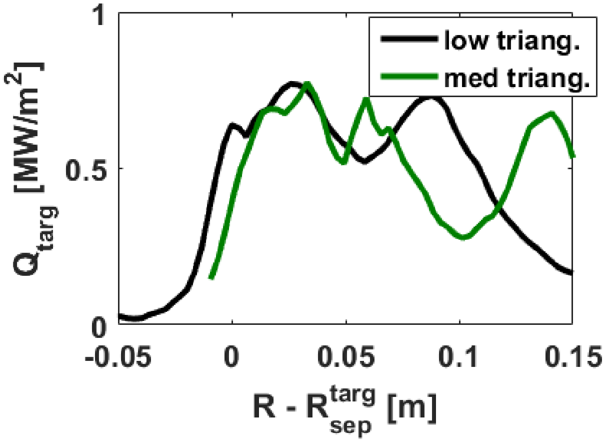


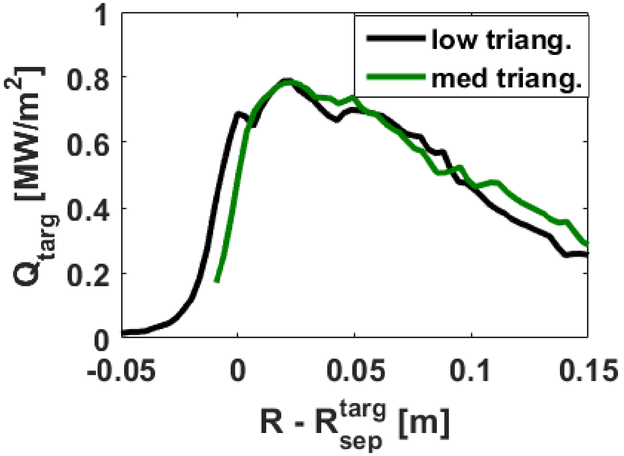
Vacuum field does not show strong strike point splitting

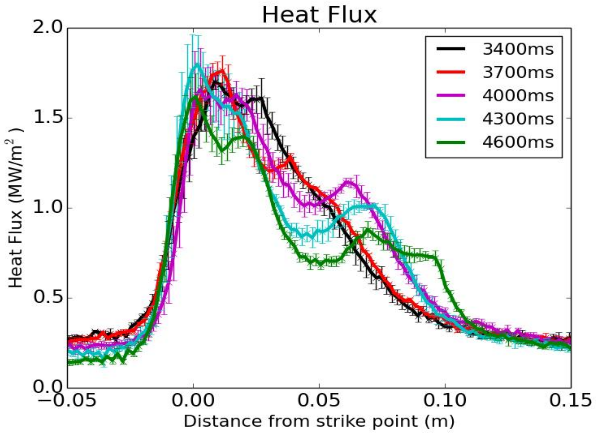
- Vacuum fields have striations in close proximity to unperturbed strike point
  - Individual peaks blurred due to finite cross-field diffusion
- Shift of second peak inward in M3D-C1 case consistent with IR data
- Results depend on diffusivity

M3D-C1 2-fluid

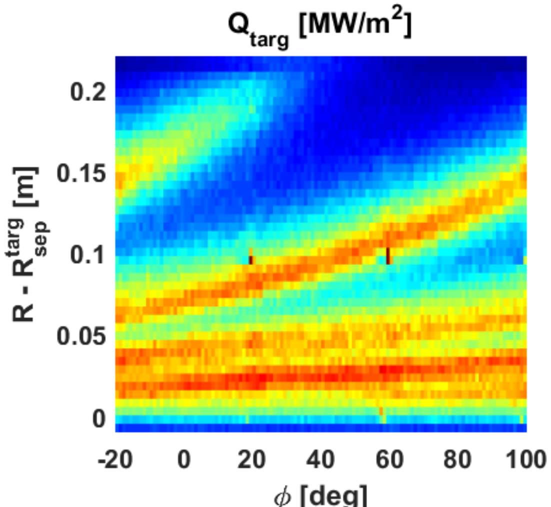
Vacuum

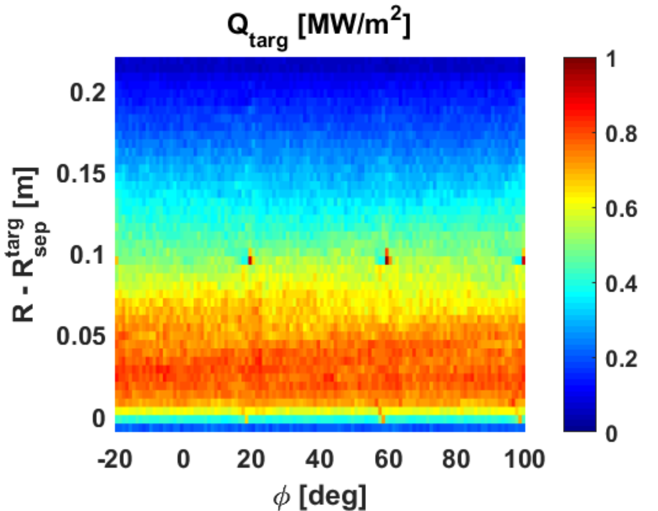






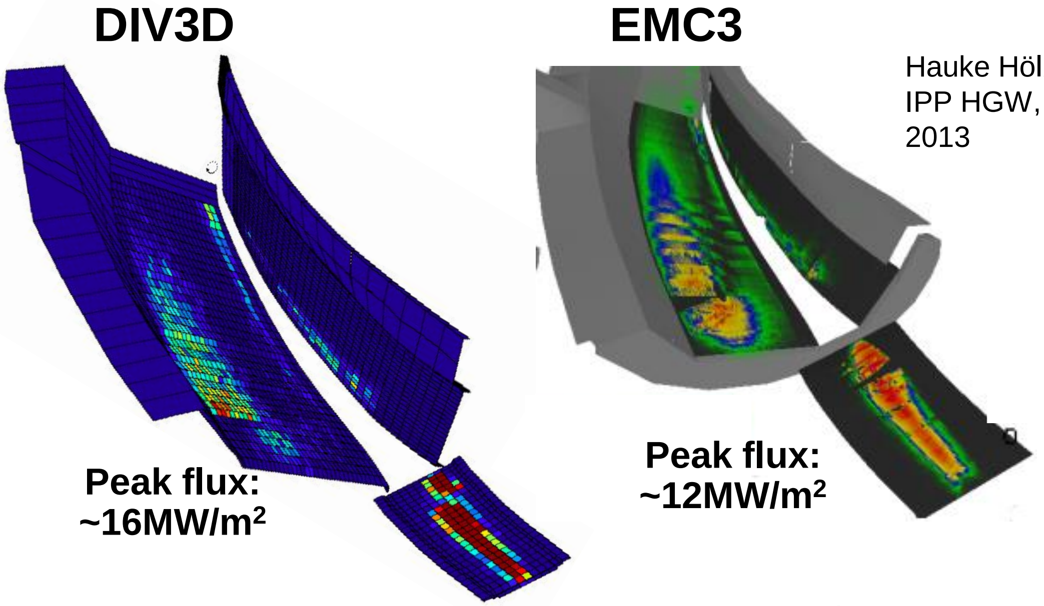
Briesemeister, ITPA DivSOL ‘15





W7-X experiments will be used to validate transport models

- Components were designed by mapping flux based on field line following
  - Conservative: no neutral energy sinks, radiation, parallel gradients
- Divertor measurements will be used to determine cross-field diffusivities
- Results depend on magnetic field model
  - Need consistency with core and divertor measurements

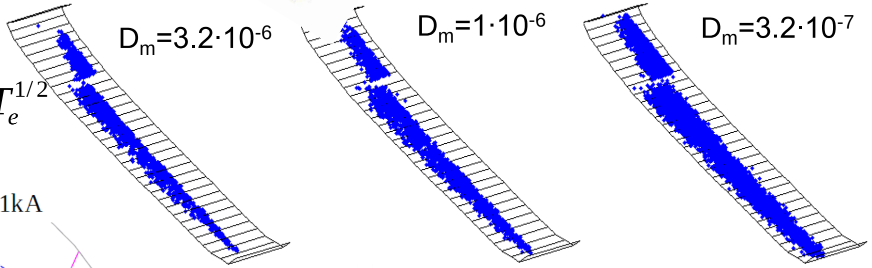


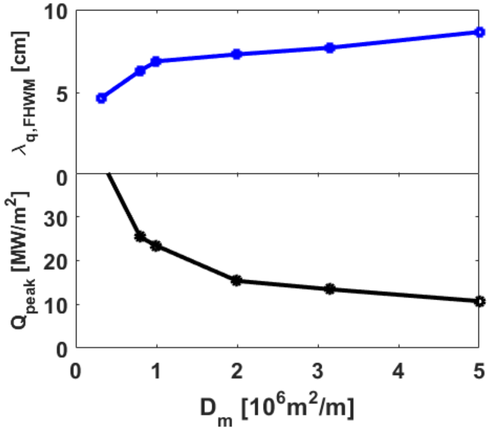
Peak flux: ~16MW/m²

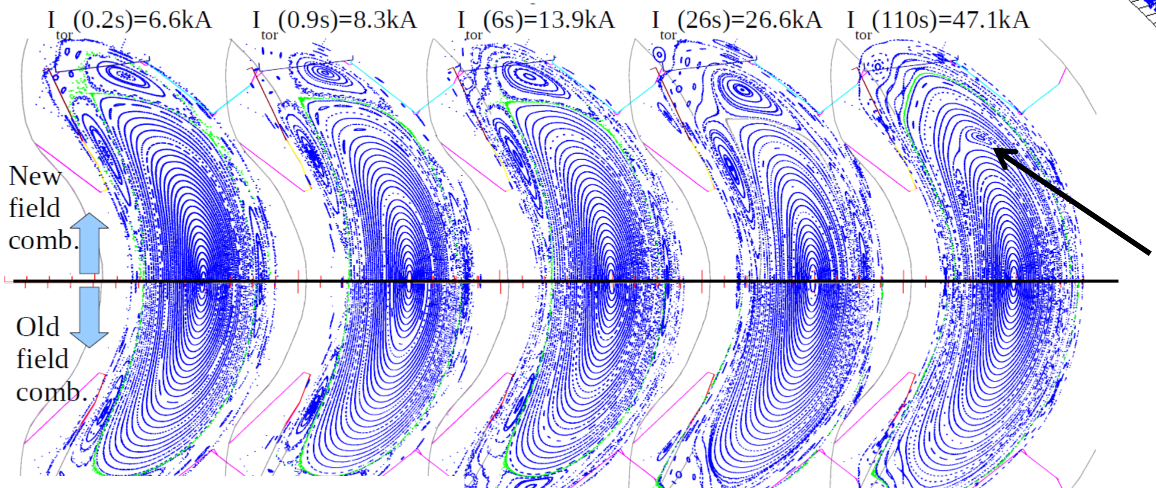
Peak flux: ~12MW/m²

Hauke Hölbe, IPP HGW, 2013

$$D_m \sim \chi_e / T_e^{1/2}$$







Core Islands

J. Geiger, ISHW 2013

Summary

- 3D modeling is used to qualitatively describe a variety of measured effects in tokamaks
  - C-Mod: Seeding asymmetry dependent on neutral ionization location
  - NSTX: Heat flux peaks can remain attached w/ 3D fields
  - DIII-D: B field models must be consistent in pedestal & edge
- Advancements to model will aid in quantitative comparisons
  - Cross-field drifts to match PFR measurements, flux limiters for pedestal transport, volume recombination for detachment
- Validated model will give confidence in extrapolation to future devices
  - Also as part of an integrated simulation, component of divertor optimization for stellarators