Nonlinear MHD Modeling of Divertor Striations in DIII-D RMP ELM Suppressed Discharges

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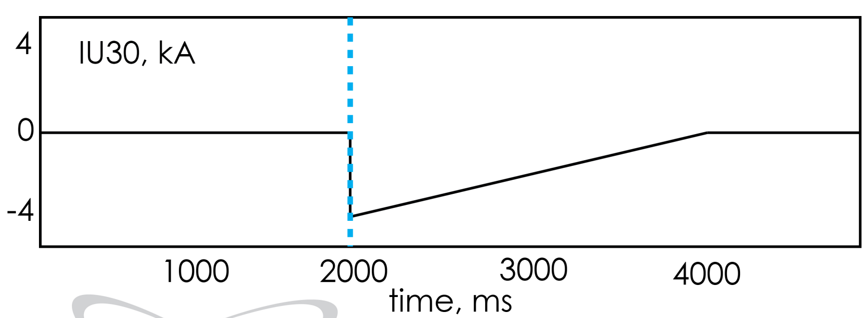
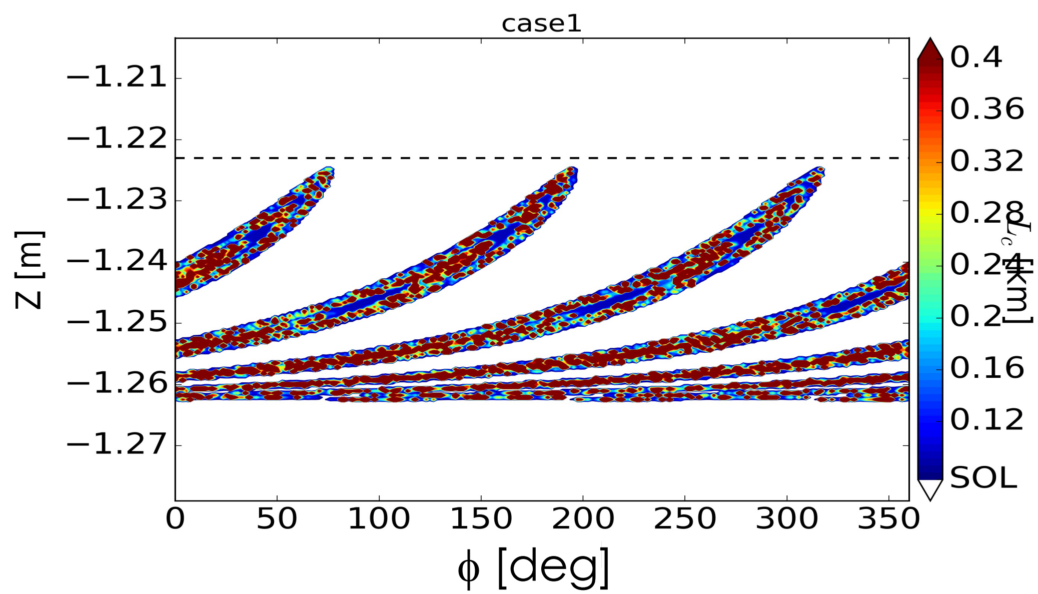
Ramps in Subsets of DIII-D I-coils are Used to Study Impact on Heat and Particle Fluxes to Divertor

- **Resonant Magnetic Perturbation (RMP) ELM control in ITER may result in toroidally asymmetric divertor heat and particle flux distributions**
- **Reduction of heat and particle flux asymmetries possible via:**
  - **rigid toroidal rotation of RMP fields**
    - may be limited due to mechanical and thermal stress on the coils and divertor components
  - **current modulation in a subset of the ITER ELM coils (toroidal perturbation spectra)**
- **DIII-D I-coil Quartet Configuration Provides Independent Control of 3 Quartets with 4 Coils Each**

I-coil, n=3 even parity, ϕ=60°, 4kA

Angle (deg)	30	90	150	210	270	330
Current (IU)	- 4 kA	+ 4 kA	- 4 kA	+ 4 kA	- 4 kA	+ 4 kA
Current (IL)	- 4 kA	+ 4 kA	- 4 kA	+ 4 kA	- 4 kA	+ 4 kA





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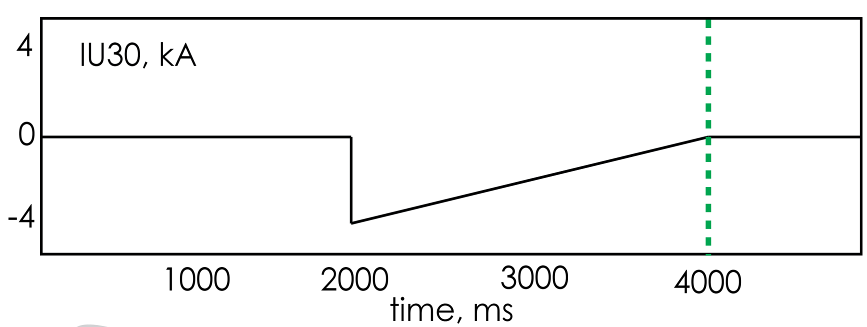
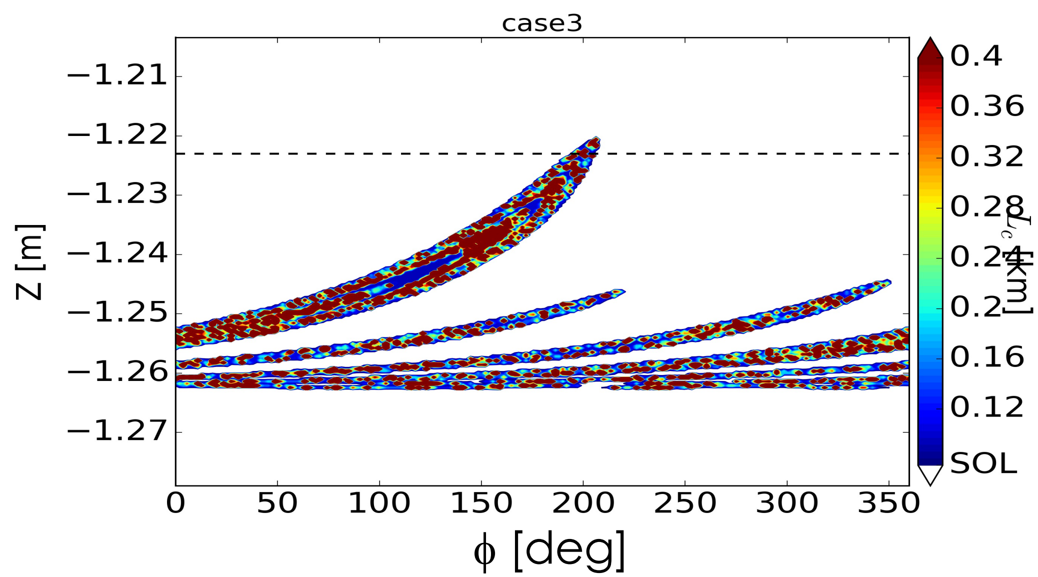
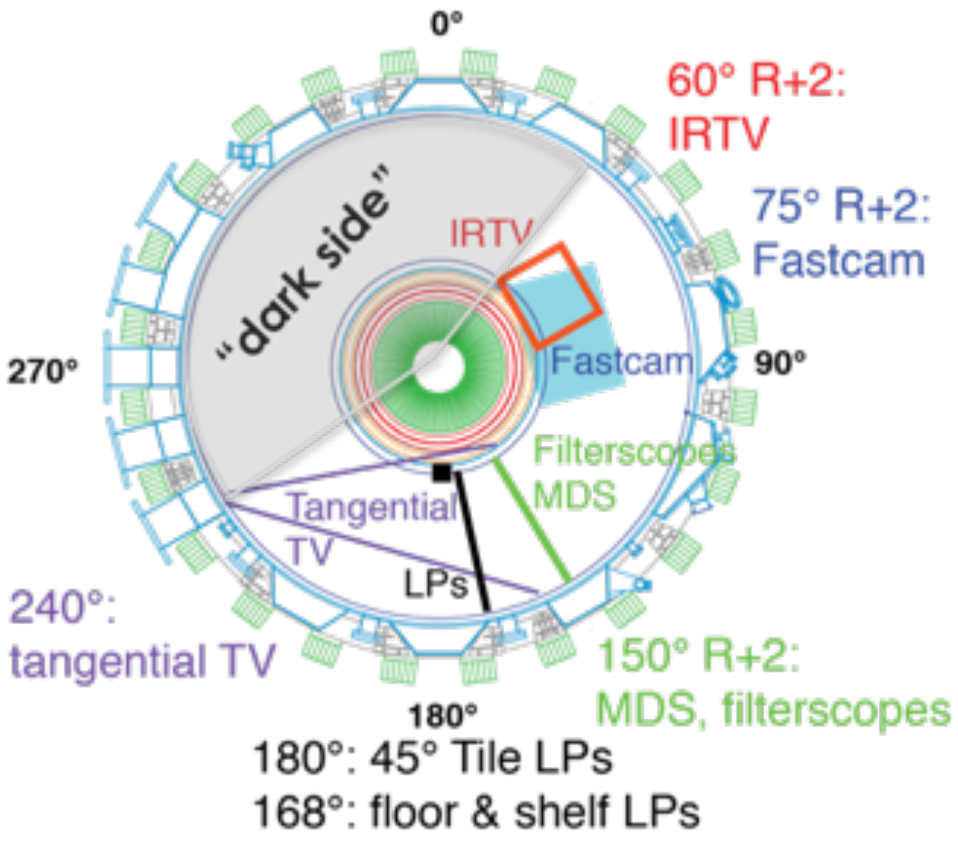
Current (IU)	0 kA	+ 4 kA	- 4 kA	0 kA	- 4 kA	+ 4 kA
Current (IL)	- 4 kA	0 kA	- 4 kA	+ 4 kA	0 kA	+ 4 kA

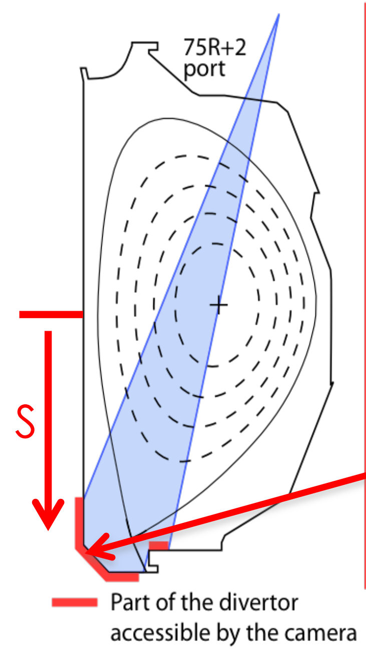




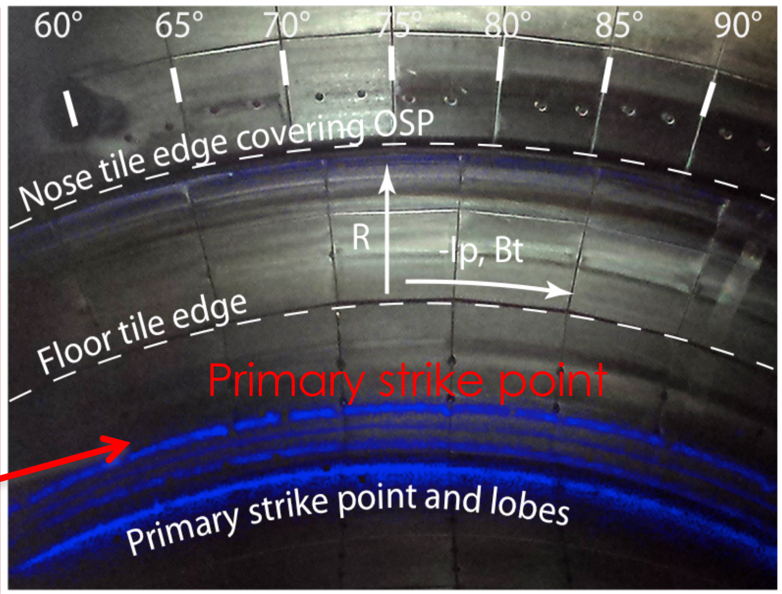
Particle and Heat Fluxes are Measured at Different Toroidal Locations in DIII-D



- Clear view of ISP
- OSP shaded by shelf (in pumping position)



Camera image* from shot 166450 @2.8s

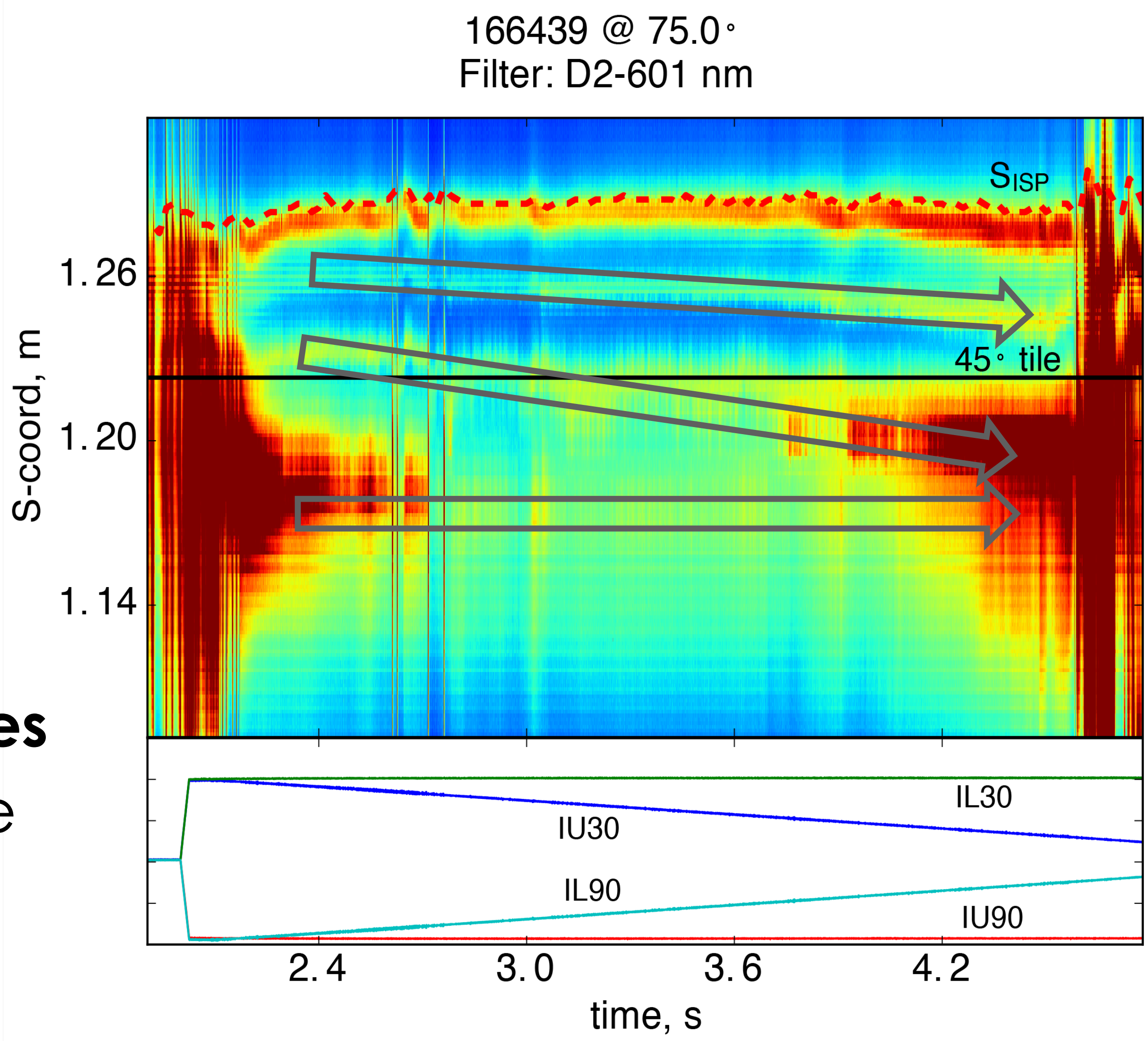


*Filtered image of the SP (blue) overlaid with an overview image (gray)

- Fastcam at 75° covers 40°-50° toroidally, good view of ISP
- IRTV in line mode at 60° (q_{perp})
- Langmuir probes at 180° (J_{sat}, f(V), $q_{||}$)
- Tangential TV camera at 240° (CII emission)

HFS Recycling Emissions at ϕ = 75° Shows Separatrix Evolution during IU30 Ramp

- **During I-coil quartet ramp, inner 2 lobes move radially**
  - Primary strike point stationary (due to PCS control)
- **Visible imaging (Fastcam) provides spatially localized emission near the target plates**
  - allows strikepoint structure to be resolved



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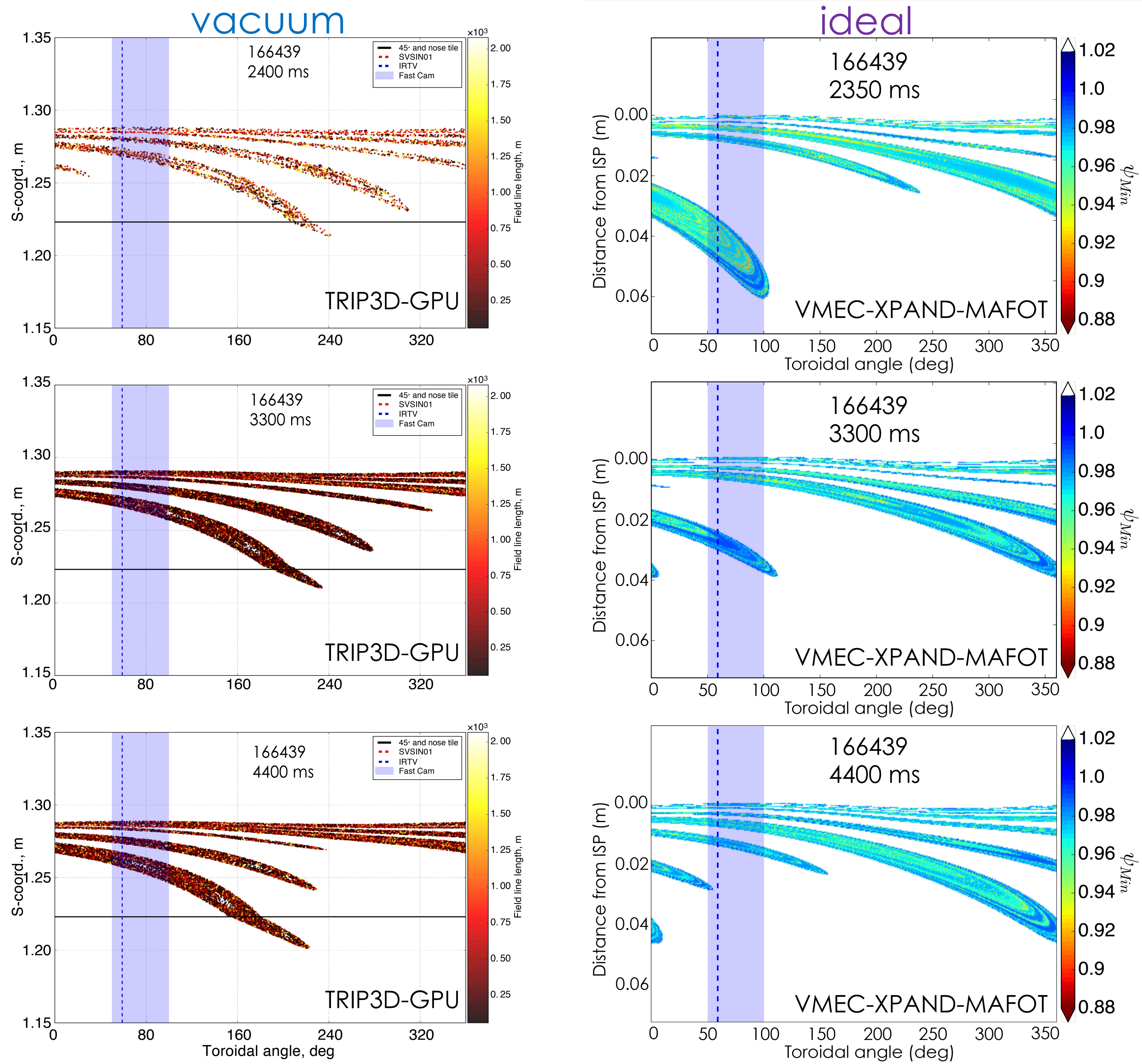
Vacuum and Ideal Plasma Response Models Predict Footprint Structure Qualitatively

TRIP3D-GPU: vacuum model, no plasma response included

VMEC: nonlinear ideal MHD equilibrium code

XPAND: "virtual casing" solver for plasma fields external to plasma domain

MAFOT: field line integration using VMEC-XPAND fields



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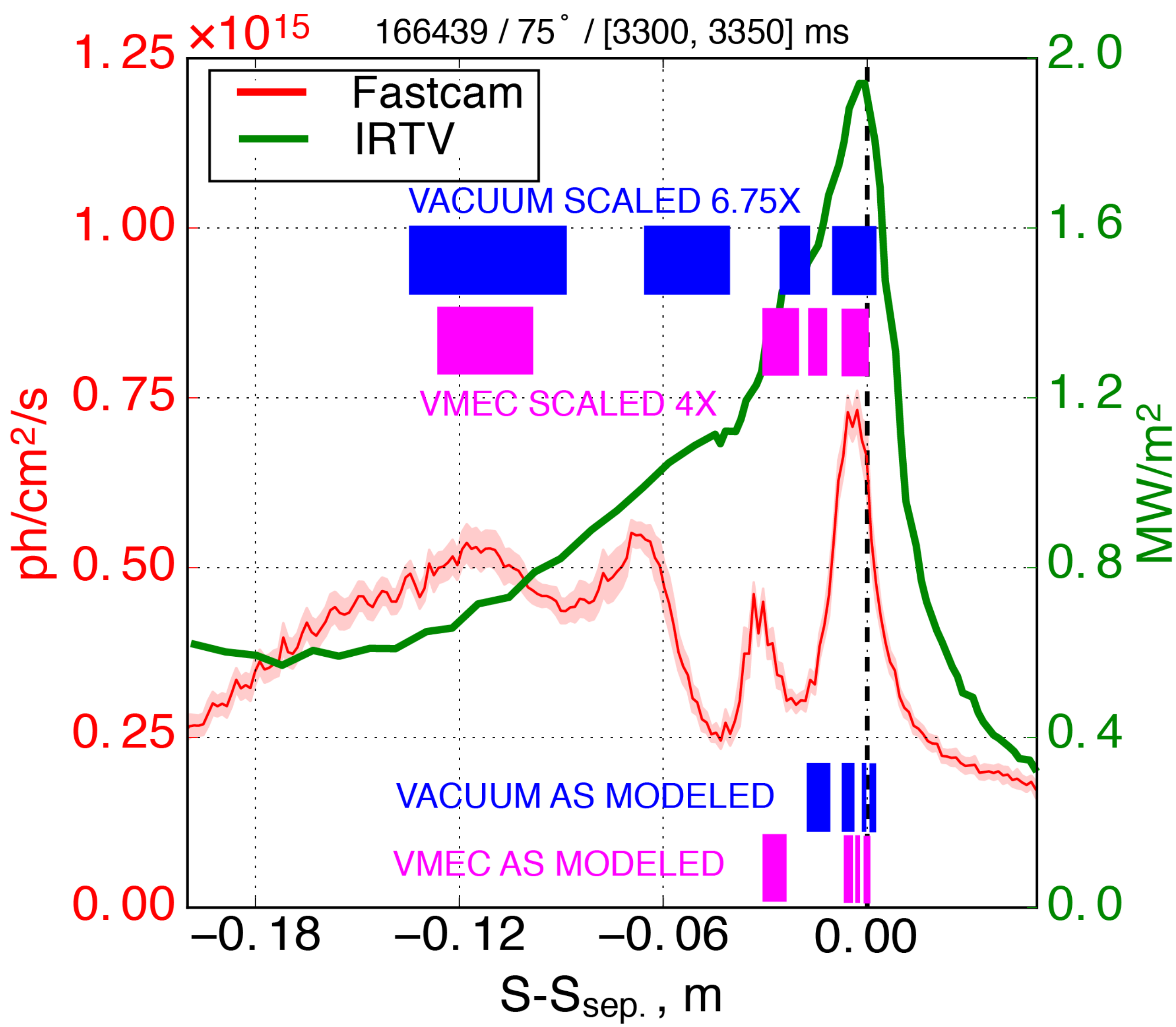
Vacuum and Ideal Plasma Response Models do not Reproduces the Measured Splitting Quantitatively

- Degree of splitting (lobe separation) is underestimated by both vacuum (TRIP3D) and nonlinear ideal MHD (VMEC) modeling by 3x-5x. Consistent with previous results.

- Visible imaging (Fastcam) shows multiple striations in particle flux

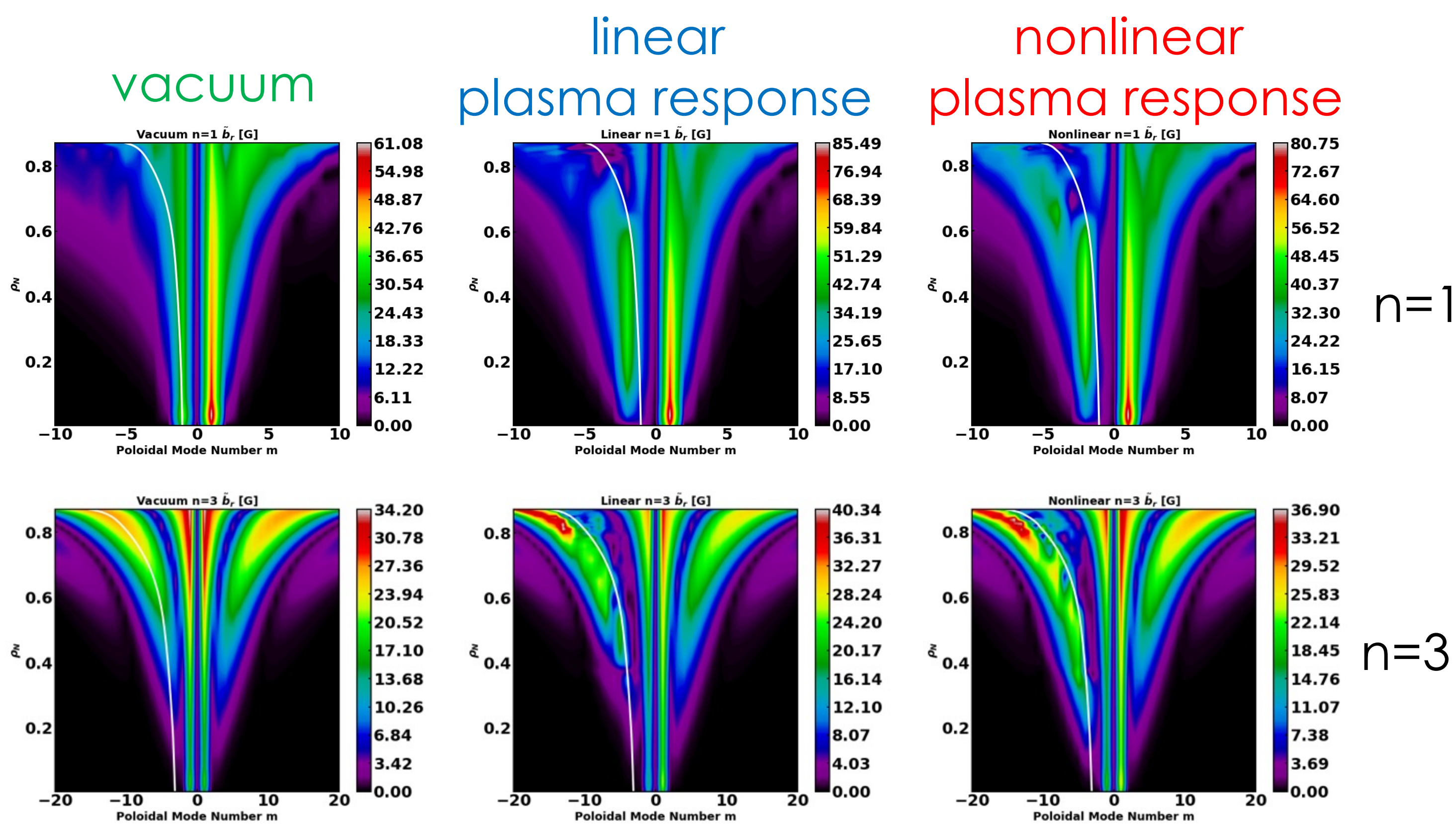
- IR camera shows one broad peak in heat flux



Investigation of nonlinear plasma response to externally applied perturbation fields performed with MHD code NIMROD

- Nonlinear MHD code NIMROD
  - viscoresistive MHD model with anisotropic transport, Spitzer resistivity (based on T_e)
  - DIII-D #166439 at 3300ms equilibrium q_0=1.04, q_{95}=3.56 and β_N=1.58
  - equilibrium ExB and poloidal flow profiles included to model screening
  - diamagnetic flows were neglected consistently with MHD
  - anisotropic thermal conduction $\chi_{||} = 10^6 \chi_{\perp}$ and anisotropic viscosity $\nu_{||} = 10^6 \nu_{\perp}$
  - computational domain approximated DIII-D limiter and excluded I-coils
  - conducting wall boundary conditions, normal magnetic field at the boundary fixed
  - separate simulations performed with a thin resistive wall yielded qualitatively similar results

- n=1 response - combination of screening, bending/kinking (m/n = - 4/1) and tearing (m/n = -2/1)
  - n=1 component of perturbation field is mainly due to intrinsic error fields in DIII-D and error field correction with C-coils
- n=3 strongly screened for m ≤ -4 in the linear plasma response simulations,
  - minimal effect on the nonresonant m ≥ -3 spectrum
  - bending/kinking response for m ≤ -7
  - tearing at higher m resonant surfaces
  - n=3 perturbation field from DIII-D I-coils



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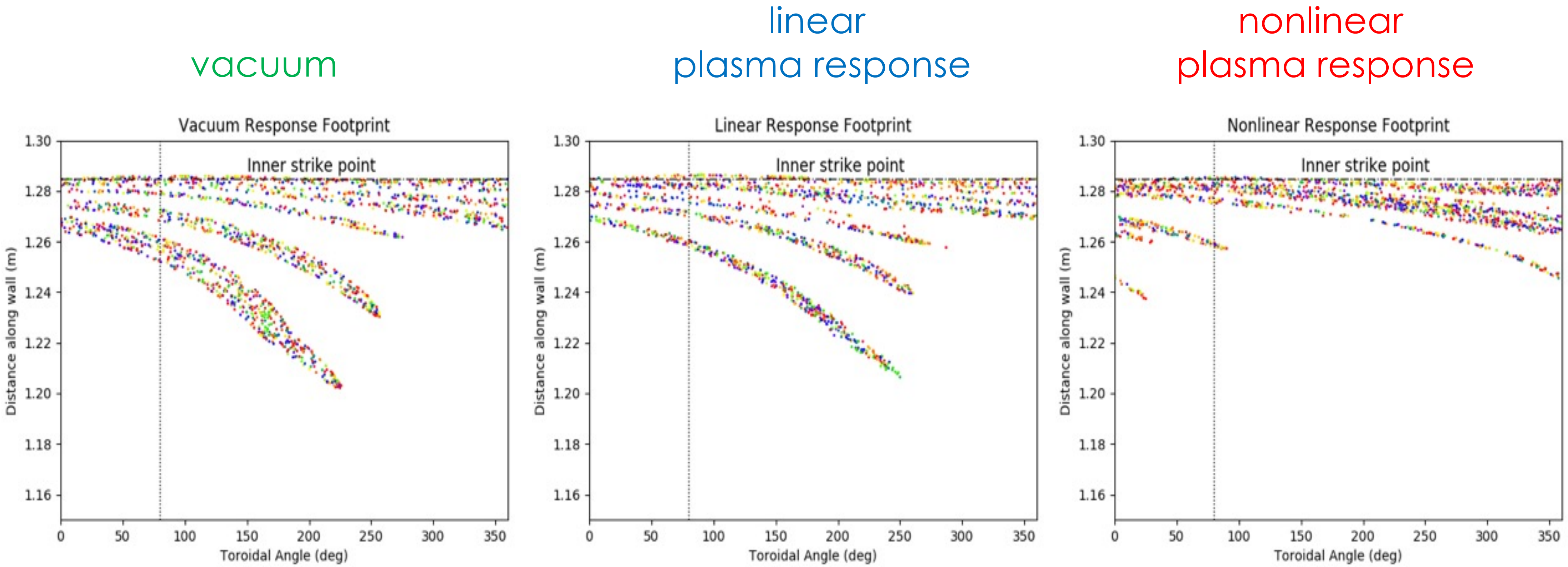
Footprint decay was observed throughout the nonlinear NIMROD simulations, no increase in radial separation

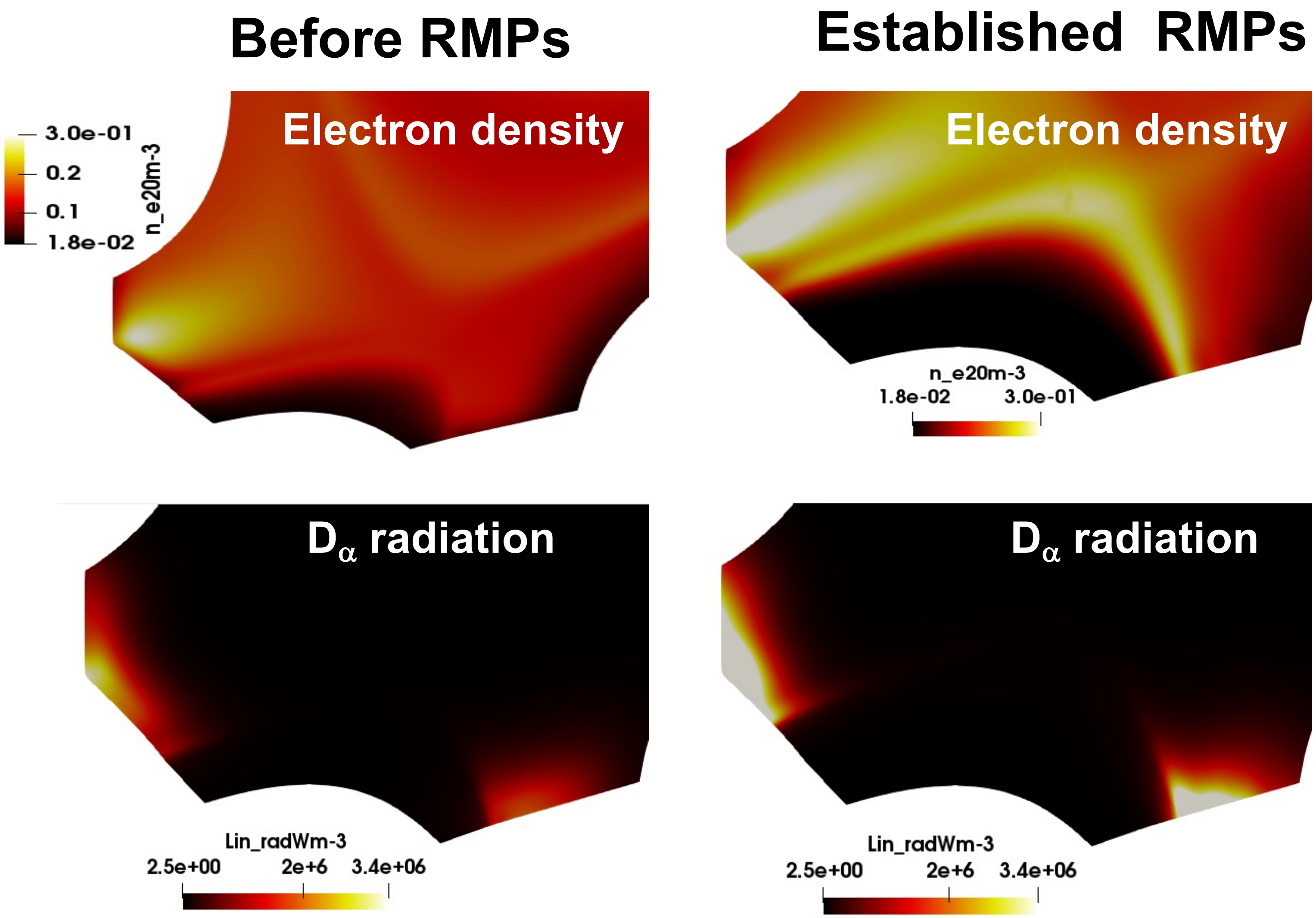
- **Field line tracing and footprint modeling using the linear NIMROD model**
  - **verified earlier predictions – both single fluid and two-fluid linear plasma response models reduce size of non-axisymmetric lobes, predict radial lobe separation to be even smaller than that in vacuum response models**
- **Nonlinear NIMROD simulation was performed for 150 ms reaching a steady solution**
  - **footprint structure qualitatively similar to vacuum and linear plasma response simulations**
  - **did not show any increase in the radial separation of the divertor lobes**
  - **footprint decay was observed throughout the nonlinear NIMROD simulations**
- **Results of linear and nonlinear NIMROD simulations indicate other physics (i.e., neutrals, SOL structures) may be responsible for far-most lobes in DIII-D experiments.**



Nonlinear MHD code JOREK was used to understand the effects of neutrals on plasma edge topology

- JOREK simulations were performed for the DIII-D discharge 166439 at 3300ms
  - same set of initial equilibrium, profiles, and external perturbation fields as in previous simulations
  - toroidal modes n=1, 2, and 3 of external perturbation field were included in the simulation,
    - n=1 and n=3 are most dominant
  - particles at target were reflected as neutrals, recycling coefficient of 0.9
  - diffusion for neutrals ($D_{neutrals} = 10^{-4}$), ionization, and radiation of D were included

- Substantial increase in neutrals and electron densities on divertor targets
  - after the RMPs were established
  - increase is largest in the corner of the High-Field Side (HFS) divertor.
- Accompanied by an increase in D_α radiation and ionization near targets
  - especially in the corner of the HFS divertor
  - when RMPs are fully established



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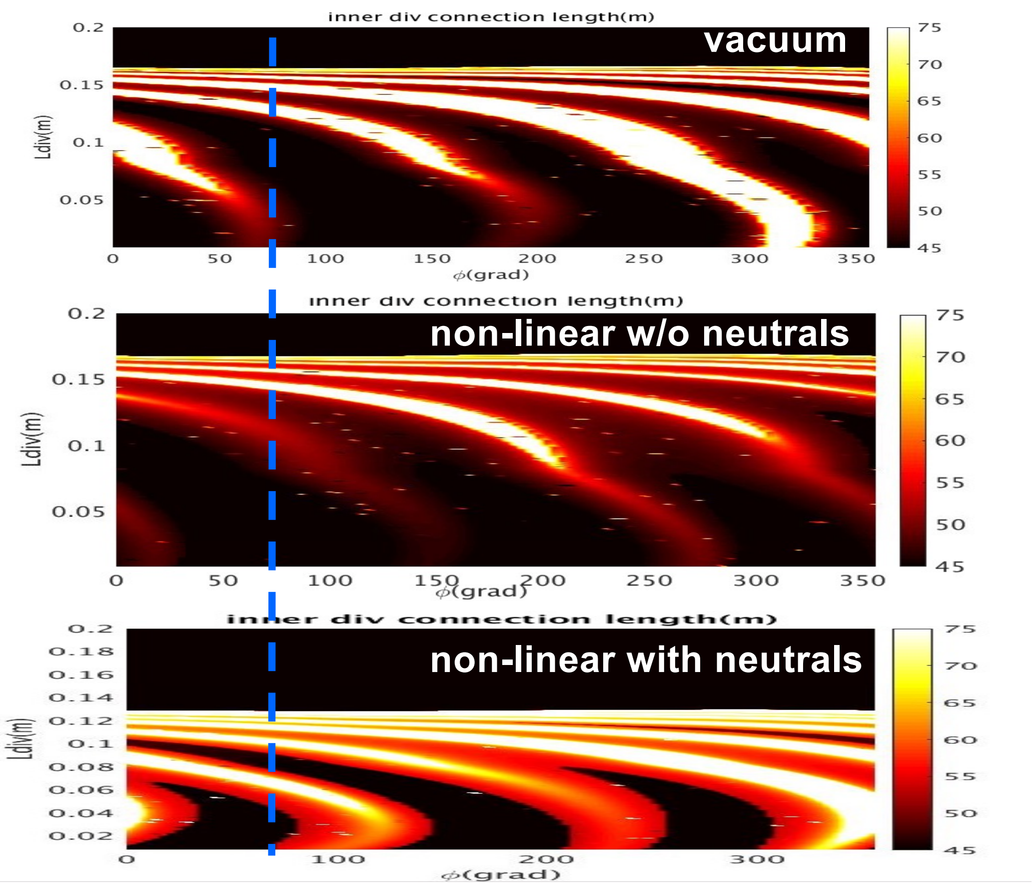
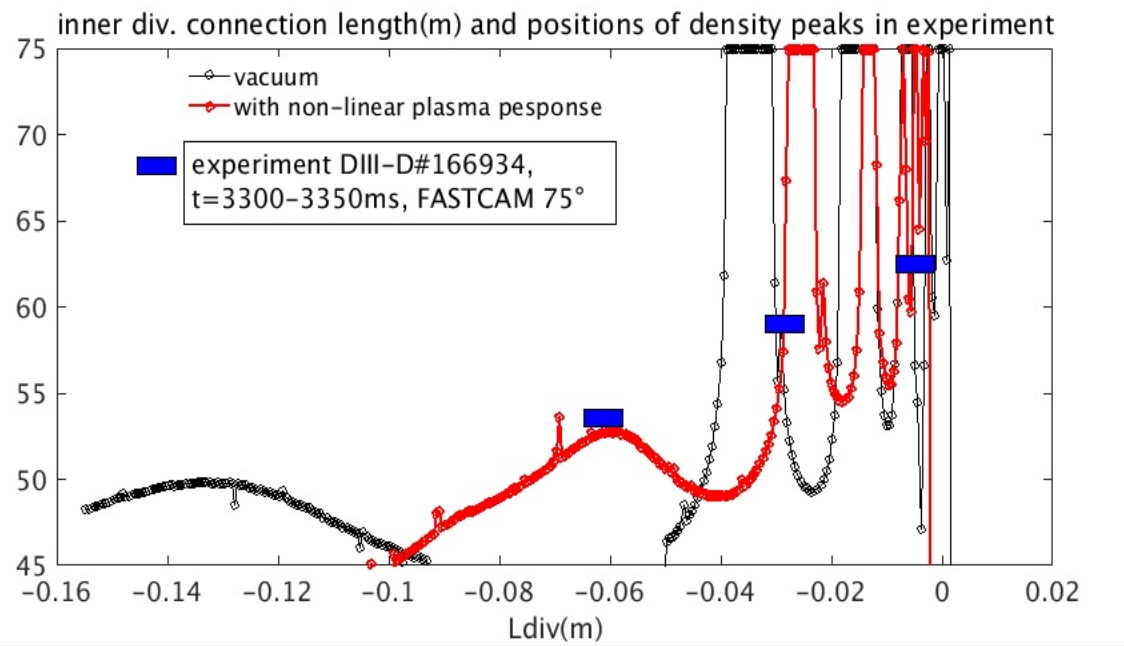
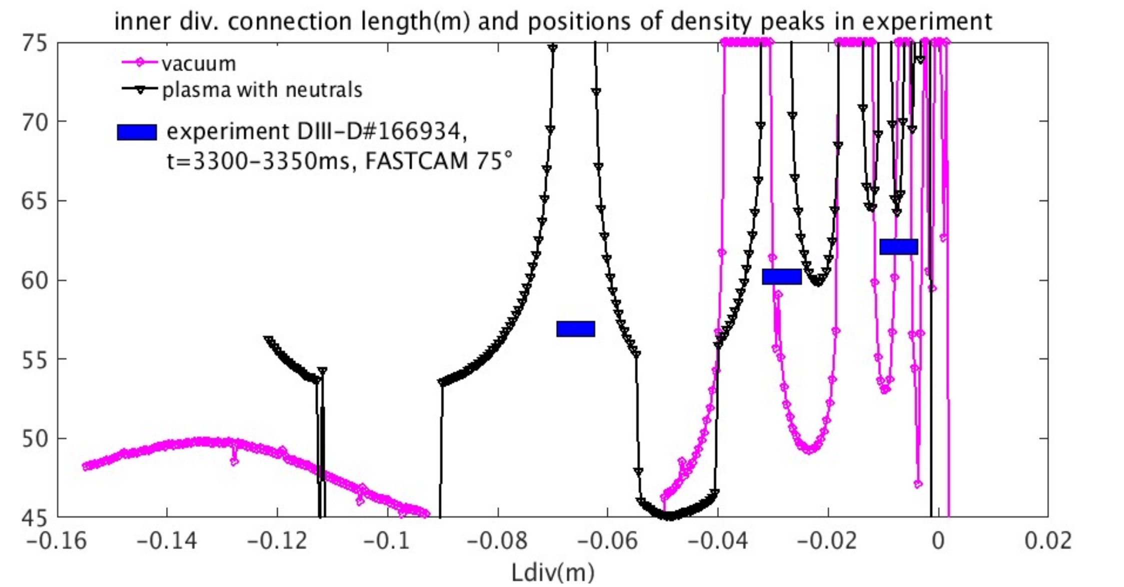
Neutrals physics addition in nonlinear JOREK simulations led to increase in non-axisymmetric lobes size and separation

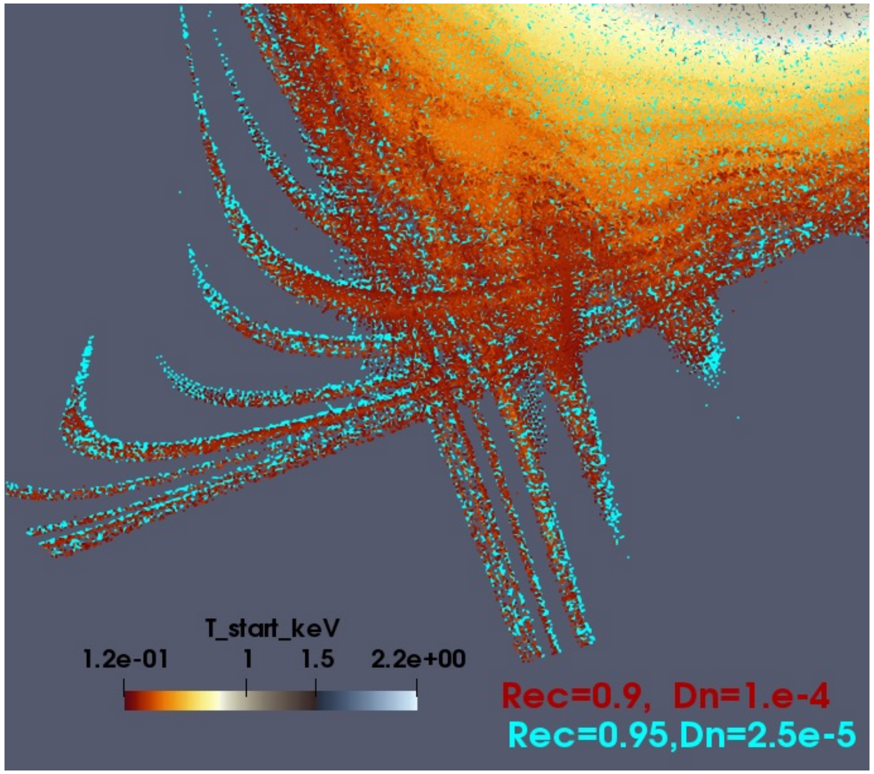


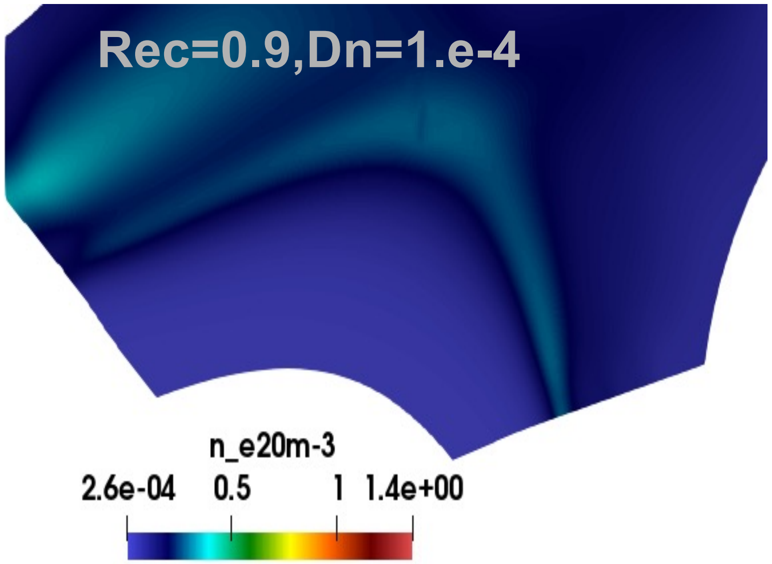


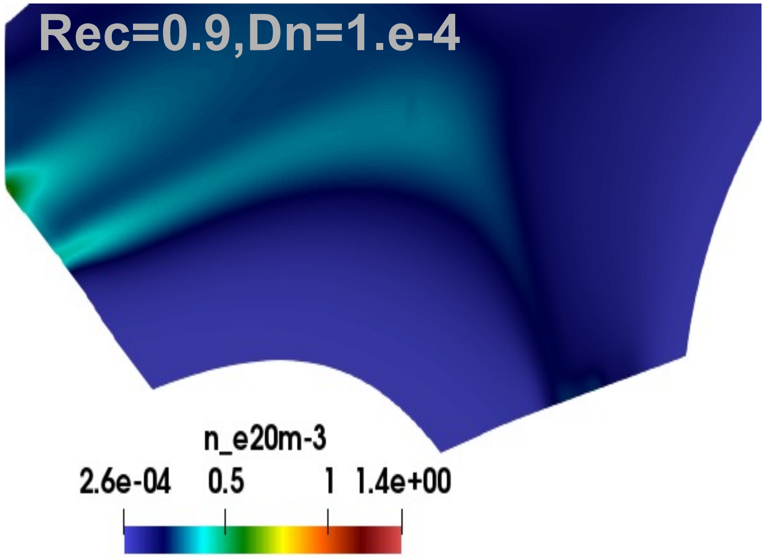


- Magnetic footprints in the nonlinear JOREK simulation without neutrals are smaller than in the vacuum case
    - smaller radial separation of the lobes
    - consistent with other linear and nonlinear plasma response simulations
- Addition of the neutrals in the simulation leads to an increase in the size of the footprints.

Higher recycling in JOREK leads to less screening of the external perturbation







- Scan for recycling coefficient was also performed for a range from 0.9 to 0.99.
- Larger values of recycling coefficient lead to higher densities and lower temperatures in divertor region.
- Strong recycling and D_α radiation observed in the HFS divertor corner.
- Higher recycling resulted in less screening of the external perturbation
    - due to higher edge density and hence higher resistivity

Conclusions

- **Small current modulations in a subset of DIII-D I-coils used to control position of the divertor particle fluxes.**
  - Vacuum and ideal plasma response models mostly reproduce the overall structure of the footprints in the particle flux, neither model reproduces the observed splitting quantitatively.
- **NIMROD nonlinear plasma response simulations performed for DIII-D 166439 at 3300ms.**
  - Simulations show that the nonlinear plasma response reduces the size of the divertor footprints and their radial separation below the vacuum and linear plasma response predictions.
- **Addition of the neutrals physics in the nonlinear plasma response JOREK simulations leads to the increase in the non-axisymmetric lobes size and their separation.**
  - Matches the location of the first three of experimentally measured particle flux lobes.