Numerical Study of the Impact of Resonant Magnetic Perturbations on Recycling Sources In Advanced Divertor Configurations of NSTX-Upgrade

I. Waters[1], K. Flesch[1], H. Frerichs[1], O. Schmitz[1], J-W Ahn[2], G. Canal[3], T.E. Evans[3], S. Kaye[2], R. Maingi[2], V. Soukhanovskii[4]

[1]University of Wisconsin-Madison,[2] Princeton Plasma Physics Laboratory, [3] General Atomics, [4] Lawrence Livermore National Laboratory

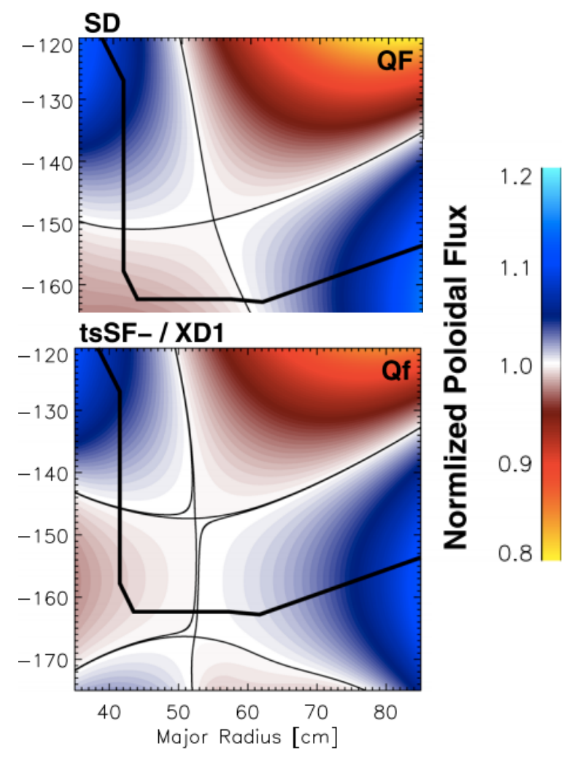
Contact:
iwaters@wisc.edu
kbflesch@wisc.edu
3dpsi.engr.wisc.edu

Introduction

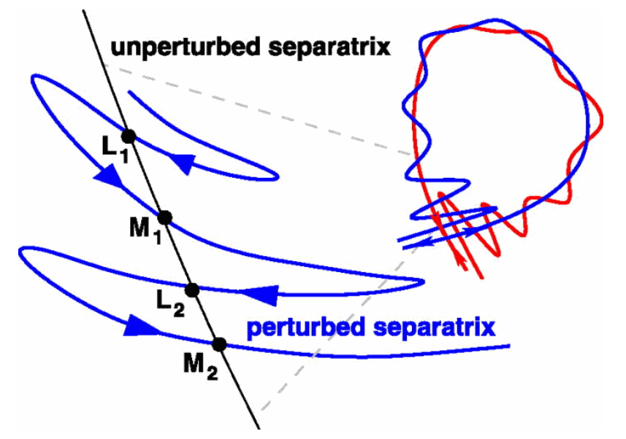
- Transient instabilities in the plasma edge are a major problem in future tokamaks
- Steady State heat loads also threaten divertor integrity and lifetime
- How do solutions work together and how does that impact **fueling and exhaust**?

Advanced Divertors

- Advanced Divertors use more complex magnetic configurations than Standard Divertors to lower steady state heat loads
  - Either by using second order nulls, or additional X-Points
- Designed to expand particle and heat flux or facilitate access to detached scenarios
- This work compares a Snowflake minus/X-Divertor case (bottom) to a Standard Divertor (top)



RMPs



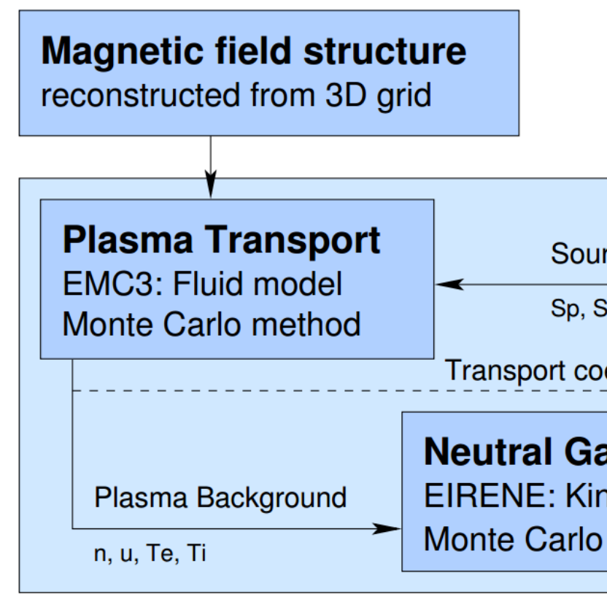
- RMPs break up rational q=m/n flux surfaces in the plasma, creating stochastic layers
- They also perturb the stable (red) and unstable (blue) manifolds that define the separatrix
  - These lobes can intersect with the walls and divertor targets, creating locally enhanced particle and power fluxes
- RMPs have also experimentally been linked to density 'pump-out' of plasmas

Particle Balance

- The rate of change in a reservoir's inventory (N) is given by the difference between the sources and sinks: $$\frac{dN}{dt} = \phi_{In} - \phi_{Out}$$
- Define a characteristic dwell time τ in a reservoir by the ansatz: $\phi_{Out} = \frac{N}{\tau}$
  - $-\frac{N}{\tau}$ then gives an exhaust flux out of the reservoir
- Use this to characterize the fueling and exhaust balance of a tokamak
  - Tokamak is a special case because we have external fueling, **and recycling flux** (ϕ_{REC}) which can be much greater than external sources: $$\boxed{\frac{dN}{dt} = -\frac{N}{\tau} + \phi_{REC} + \phi_{Ext\,Fuel} = \phi_{In} - \phi_{Out}}$$
  - Even if $\phi_{Ext\,Fuel} = 0$, there are still ϕ_{REC} and $-\frac{N}{\tau}$ terms in a tokamak!
- Analysis can be expanded to include multiple reservoirs

EMC3-EIRENE

- Coupled 3D plasma fluid and kinetic neutral transport code
- Suite of post processing routines in EMC3-EIRENE (e.g. Zone Resolved Particle Balance)
- Flexible grid generator (FLARE) allows modeling of both Snowflake and X-Divertor in 3D


Magnetic field structure
reconstructed from 3D grid

Plasma Transport
EMC3: Fluid model
Monte Carlo method

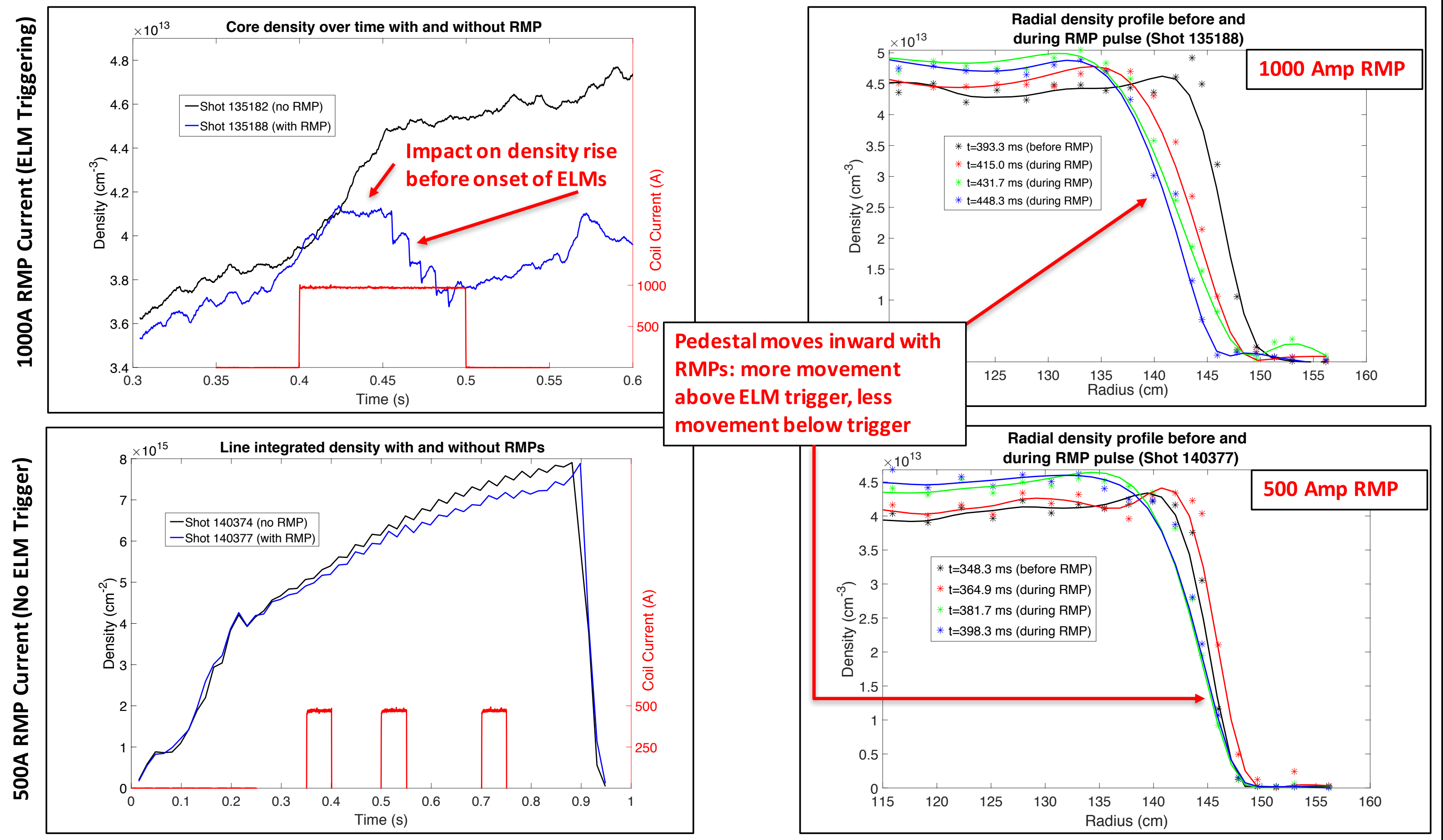
Sources/Sinks
Sp, Sm, See, Sei

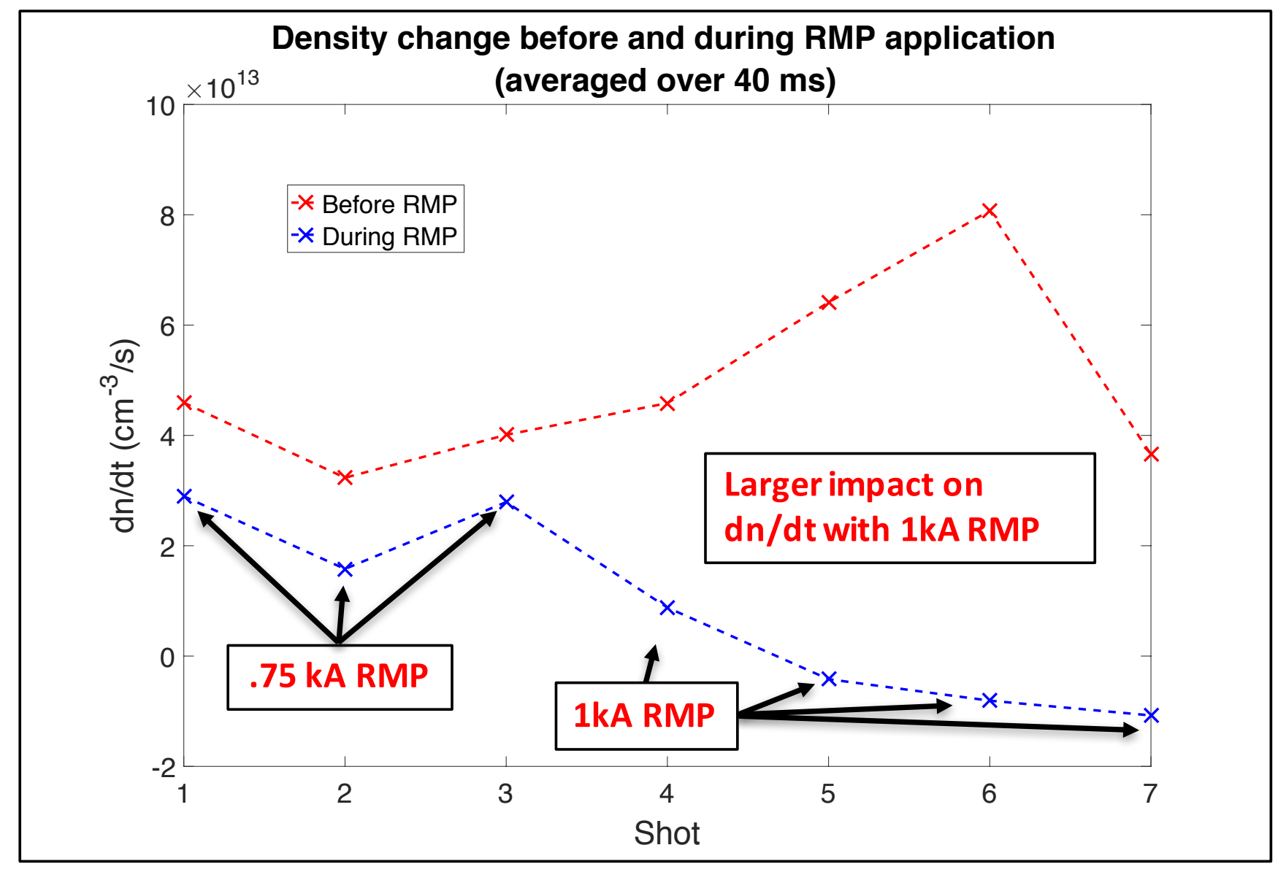
Transport coefficients

Plasma Background
n, u, Te, Ti

Neutral Gas Transport
EIRENE: Kinetic Model
Monte Carlo method

Observed Changes to dn/dt

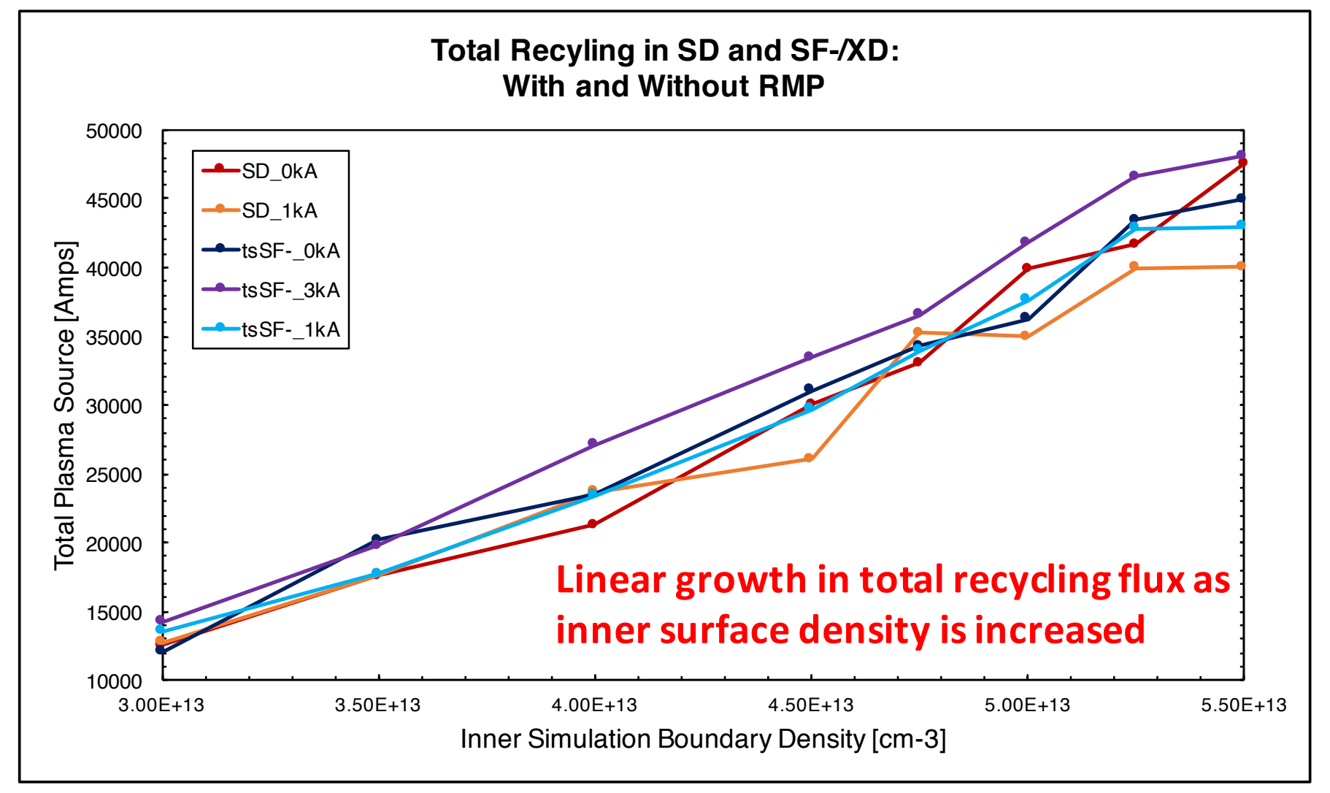


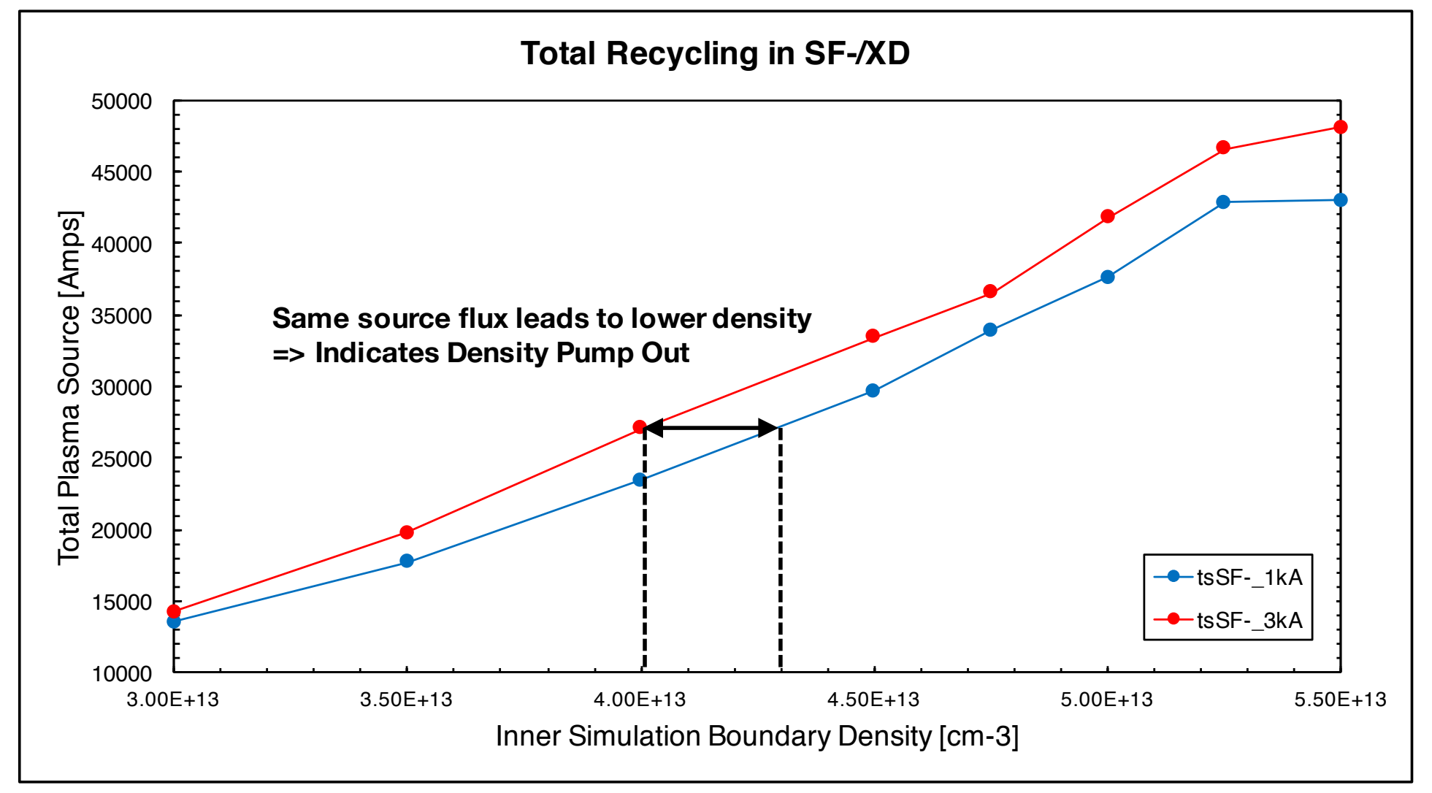


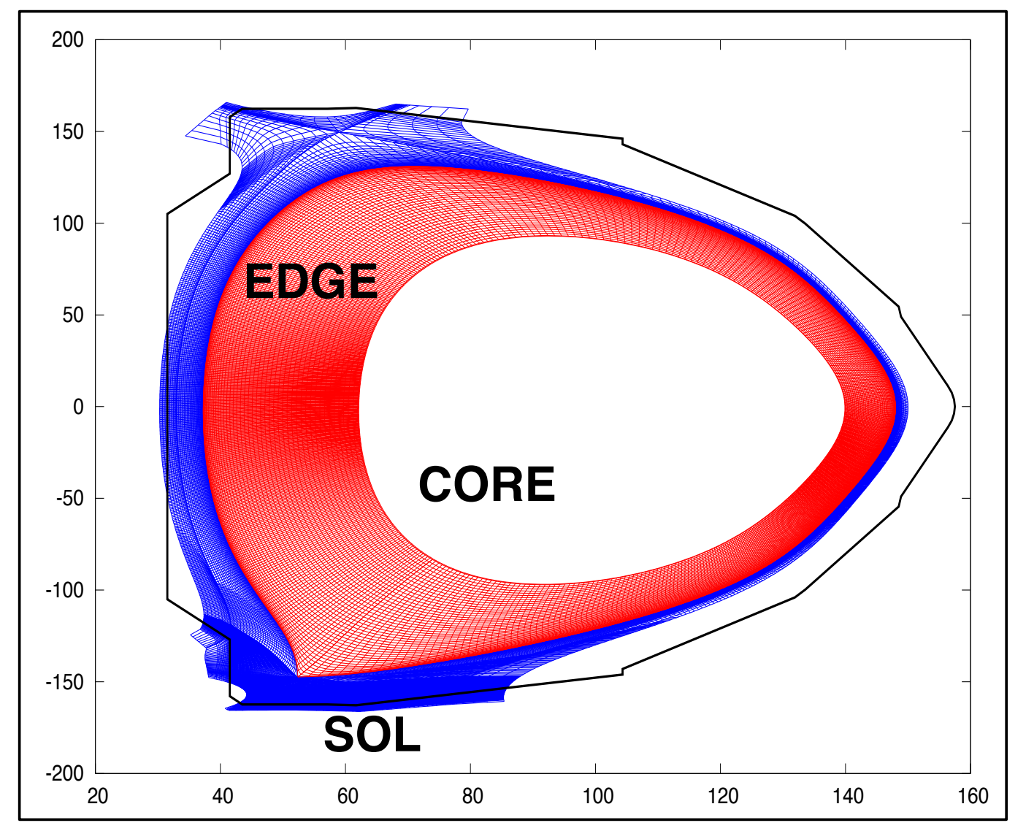
- RMP impacts dn/dt in pre-ELM phase in 1000 Amp RMP current case (top)
  - Pump out effect close to ELM triggering threshold
  - May be important for ELM triggering
- Inconclusive impact in non-ELMing 500 Amp RMP current case
- RMP modifies pedestal in both cases–lowering of edge density gradient
- $\frac{dN_e}{dt} = -\frac{N_e}{\tau_p} + \Phi_{rec} + \Phi_{fuel}$
  - Observed changes in $\frac{dn_e}{dt}$ may indicate change in τ_p

Acknowledgments: This work is funded by the Department of Energy under grants DE-SC0012315, and DE-FC02-04ER54698.

Density 'Pump Out' Without Enhanced Edge Exhaust







- Single Reservoir/Global analysis=> **shows density 'pump out' in NSTX-U** for snowflake/X-Divertor
- Multi-Reservoir Model (right) treats plasma edge (EDGE) region and scrape off layer (SOL) separately
  - Can provide insight into transport and fueling phenomena in the EDGE and in the SOL specifically
  - Define an exhaust coefficient (ε) and a fueling coefficient (f) for the recycling source with respect to the **goal** of fueling the CORE & EDGE regions
  - f fuels the CORE and EDGE while ε is exhausted into the SOL
  - Boundary determined by **unperturbed separatrix**
- τ_{EDGE} calculation (below) shows **increase** with increasing RMP strength for fixed reference inner boundary density in the snowflake/X-Divertor across the modeled densities

$$\cancel{\frac{dN_{EDGE}}{dt}} = -\frac{N_{EDGE}}{\tau_{EDGE}} + \phi_{EDGE} + \phi_{CORE}$$

$$\cancel{\frac{dN_{SOL}}{dt}} = -\frac{N_{SOL}}{\tau_{SOL}} + \phi_{SOL} + \frac{N_{EDGE}}{\tau_{EDGE}}$$

$$\phi_{REC} = \phi_{SOL} + \phi_{EDGE} + \phi_{CORE}$$

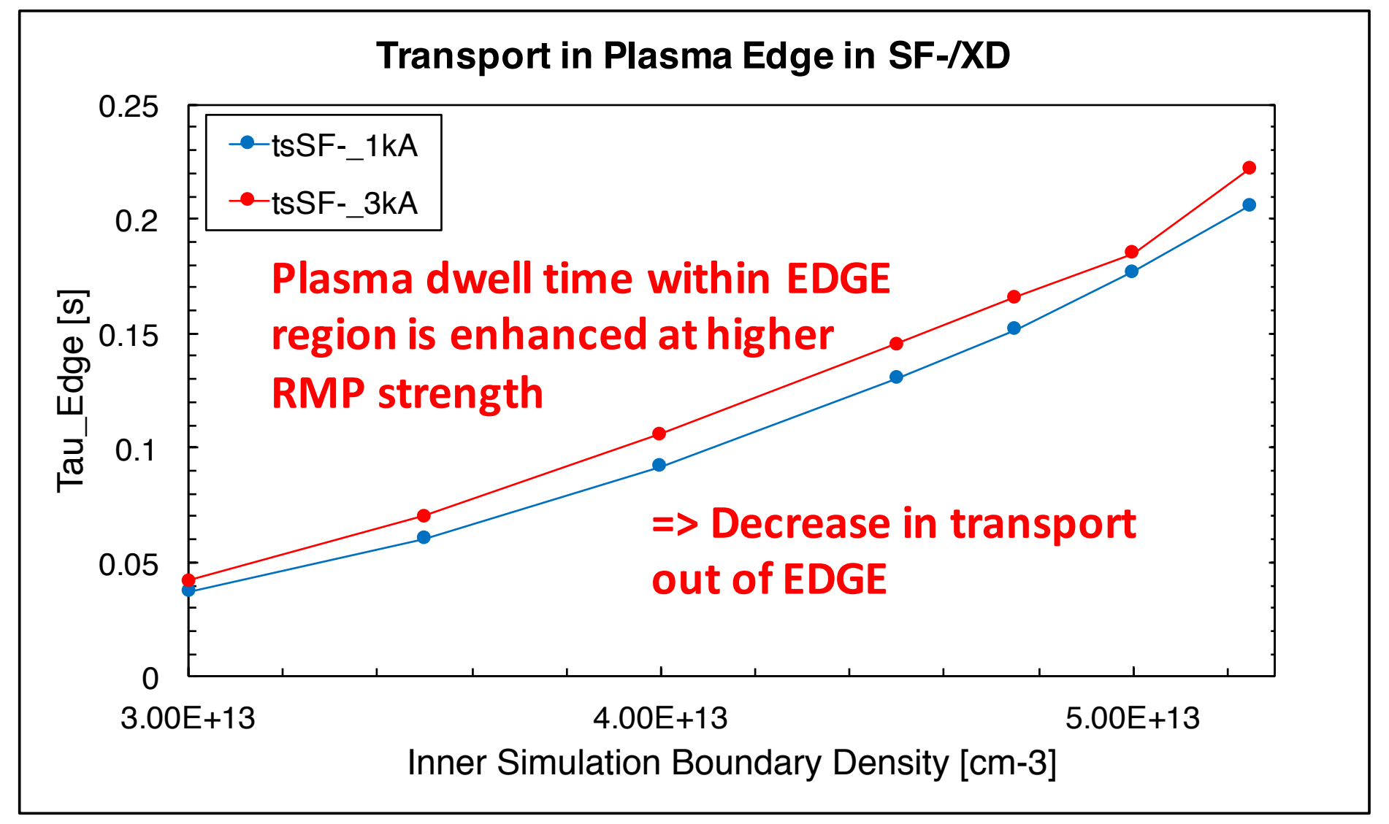
$$\phi_{SOL} = \varepsilon\phi_{REC}$$

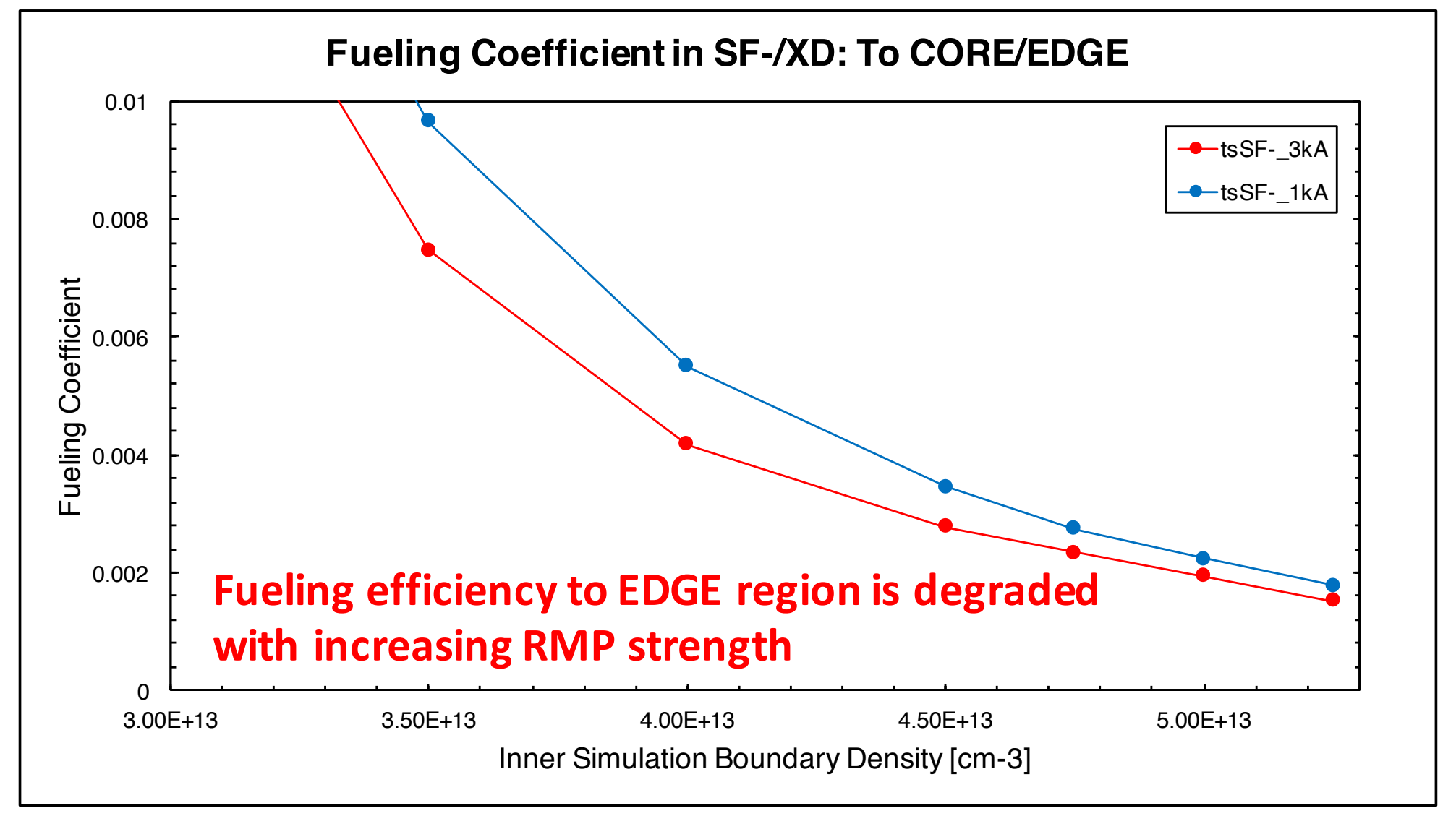
$$\phi_{EDGE} + \phi_{CORE} = f\phi_{REC}$$

$$\Rightarrow$$

$$\boldsymbol{\tau_{SOL}} = \frac{N_{SOL}}{\epsilon\phi_{REC} + f\phi_{REC}}$$

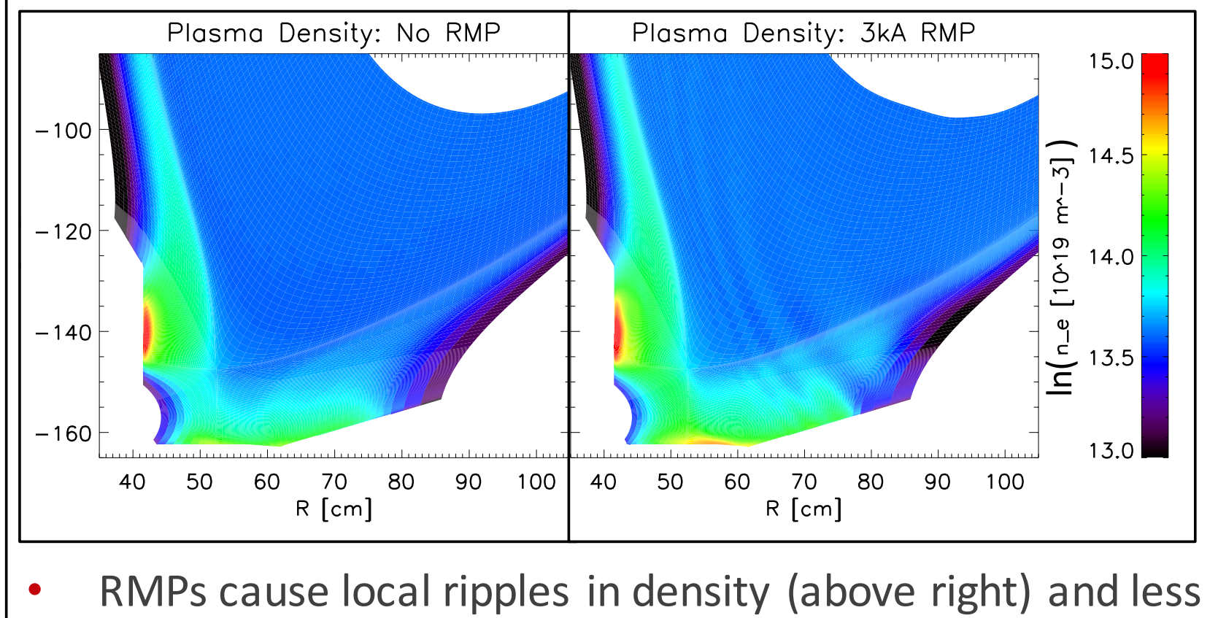
$$\boldsymbol{\tau_{EDGE}} = \frac{N_{EDGE}}{f\phi_{REC}}$$

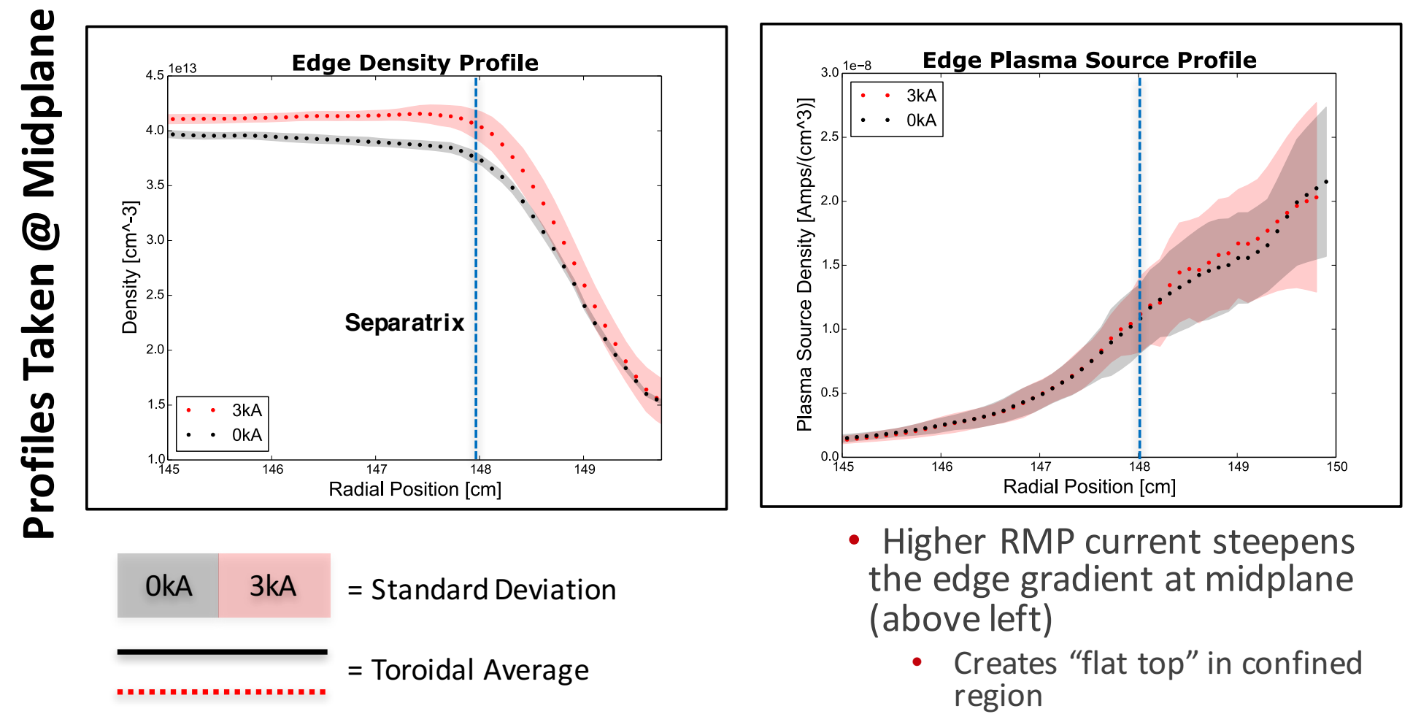




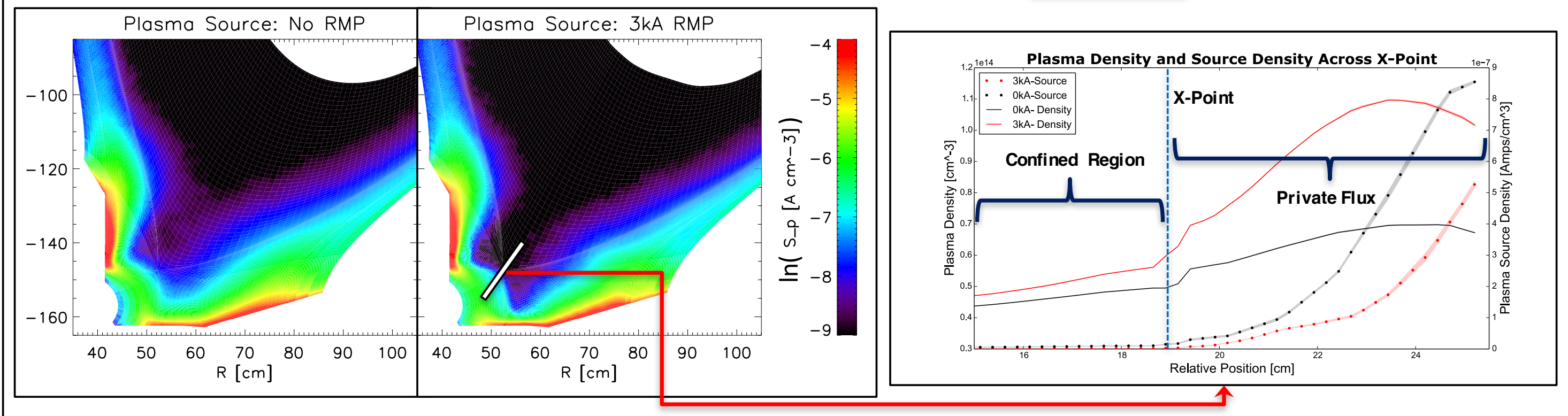
- Global RMP density 'pump out' is **driven by change in fueling behavior**, *NOT* increased plasma transport out of EDGE region
  - For these *self-fueled* plasmas with fixed inner densities
  - Choice of EDGE/SOL boundary may impact derived exhaust behavior

Plasma Sources and Edge Gradients





- RMPs cause local ripples in density (above right) and less plasma source density within the separatrix (below right)



- Higher RMP current steepens the edge gradient at midplane (above left)
  - Creates "flat top" in confined region
- RMPs don't impact midplane edge source average
  - Dominant SOL source term is near strike points
- RMPs lead to much higher plasma density in PFR
  - Drives increased density near x-point in confined region
  - May be result of self-fueled nature of the simulation
  - RMP => Lower fueling coefficient f =>Higher Total Recycling Source ϕ_{REC} => Higher PFR density

Next Steps

- Experimentally constrain the equilibria
  - Introduce core fueling rates from Neutral Beam Injection (NUBEAM)
  - Simulate lithium wall pumping (by adjusting recycling coefficients), and investigate cryo pump upgrade (use external pumping in model)
- Experimentally validate the modeled results using existing NSTX data analysis
- Investigate role of plasma response on pump-out
- Investigate impact of boundary choice between EDGE and SOL

Conclusions

- Self fueled simulations in EMC3-EIRENE **indicates global RMP induced density 'pump out' in NSTX-U for Snowflake/X-Divertor**
  - Effect not seen with marginal RMP strength
- Global RMP density 'pump out' **driven by change in fueling behavior** and neutral transport, *NOT* increased plasma transport out of edge region ($\boldsymbol{\tau_{EDGE}}$ increases!) for self-fueled plasmas with fixed inner surface density
- **RMPs impact the edge profile** and change source distribution
  - Can be used to compare with experiments
  - May explain $\boldsymbol{\tau_{EDGE}}$ increase

58th Meeting of the APS Division of Plasma Physics, San Jose, November 2016