M3D-C^1 Simulations of the Plasma Response to Magnetic Perturbations in the NSTX-U Snowflake Divertor

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in collaboration with

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GENERAL ATOMICS

The development of new divertor configurations is crucial on the road to a fusion reactor

- **Steady-state power handling in DEMO and future fusion reactors will only be possible with plasmas operated with high core radiation fraction**
  - About 90% of the heating power has to be radiated [M. Kotschenreuther, *Phys. Plasmas* (2007)]
  - ELMs will not be tolerated at all [H. Zohm, *Nucl. Fusion* (2013)]

- **Alternative solutions have to be researched to mitigate the risk that highly radiating regimes may not be extrapolated towards DEMO**
  - The snowflake (SF) is one of several alternative divertor configurations [D.D. Ryutov, *Phys. Plasmas* (2007)]

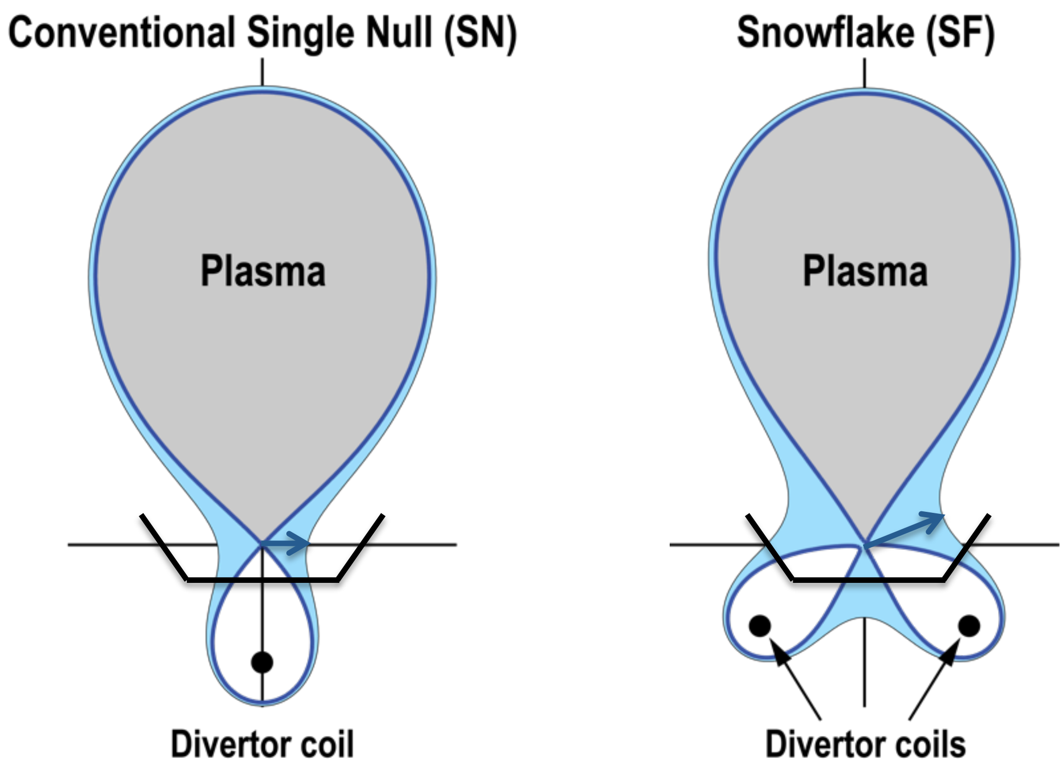
- **Solution for ELMs come in the form of applied 3D magnetic perturbations** [A. Loarte, *Nucl. Fusion* (2014)]
  - The effect of 3D magnetic perturbations in the SF configuration has to be investigated

Improved physics understanding & modeling of 3D fields in the SF divertor are needed in order to extrapolate towards larger devices

Snowflake configuration proposed as a possible solution to reduce target power loads

- **Snowflake ≡ second order null point** [D.D. Ryutov, *Phys. Plasmas* (2007)]

$\mathbf{B}_p = 0$ versus $\mathbf{B}_p = 0$ and $\nabla \mathbf{B}_p = 0$

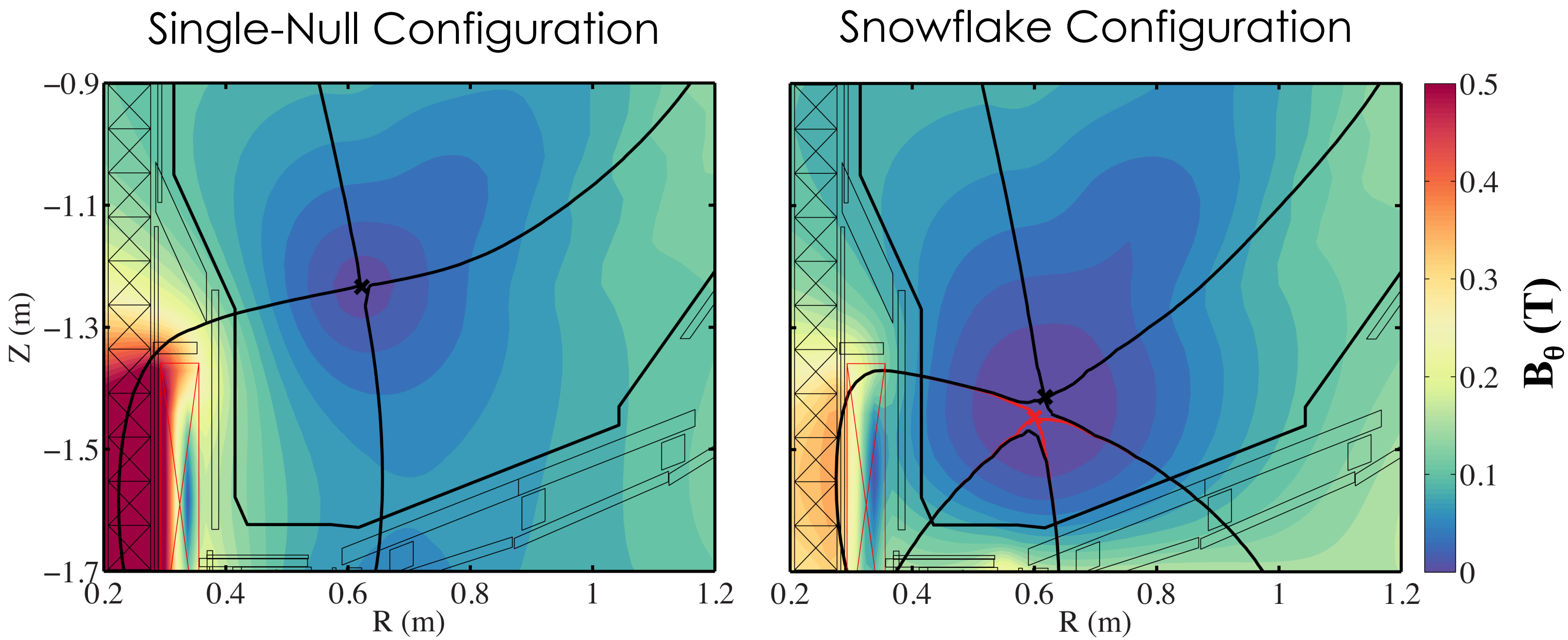


$$\left|\mathbf{B}_{\mathrm{P}}^{\mathrm{SN}}\right| \propto \rho_{\mathrm{npt}} \qquad \left|\mathbf{B}_{\mathrm{P}}^{\mathrm{SF}}\right| \propto \rho_{\mathrm{npt}}^{\;2}$$

- **Two additional divertor legs**
- **Lower poloidal field near the null point**
  - Larger flux expansion
  - Larger divertor volume
  - Longer connection length

The snowflake configuration is more sensitive to magnetic perturbations than a single-null configuration

- **The effect of magnetic perturbations in the plasma is expected to be magnified in the SF configuration due to its lower B_θ near the null-point**

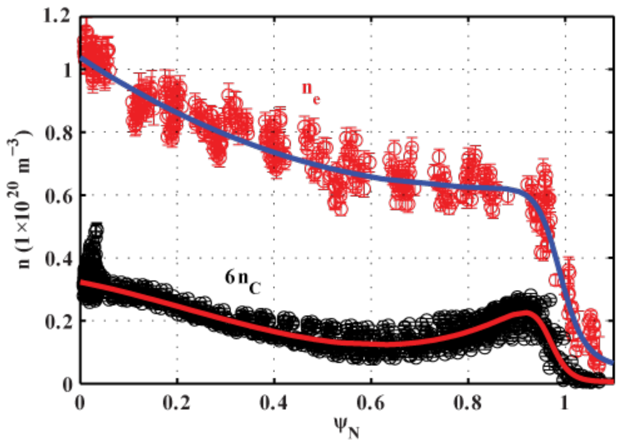


The SF configuration provides an excellent environment to study the plasma response to magnetic perturbations

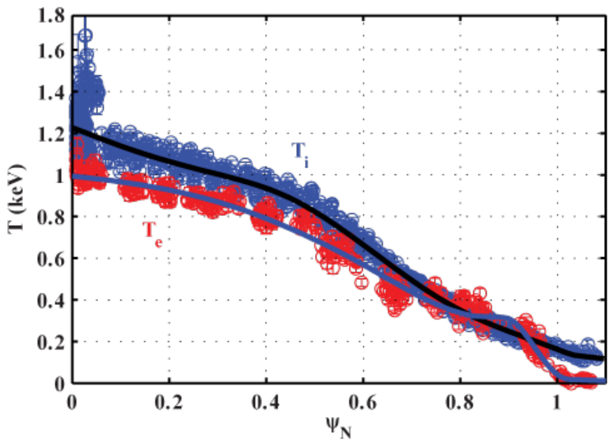
NSTX discharge provides the equilibrium profiles for the ISOLVER calculations of the NSTX-U SF divertor

- **Reference Discharge (#132543 @ 700 ms)**
  - $I_P = 1.0$ MA
  - $B_T = -0.44$ T
  - $P_{NBI} = 6.0$ MW
  - $\kappa = 2.1$
  - $\delta_{top} = 0.37$
  - $\delta_{bot} = 0.71$

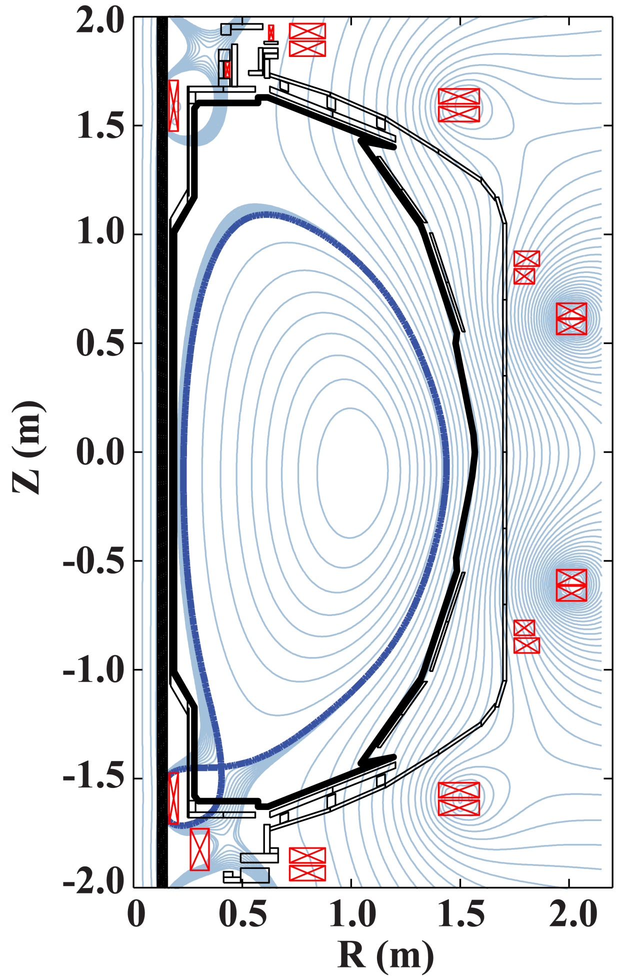
Plasma density



Plasma Temperature

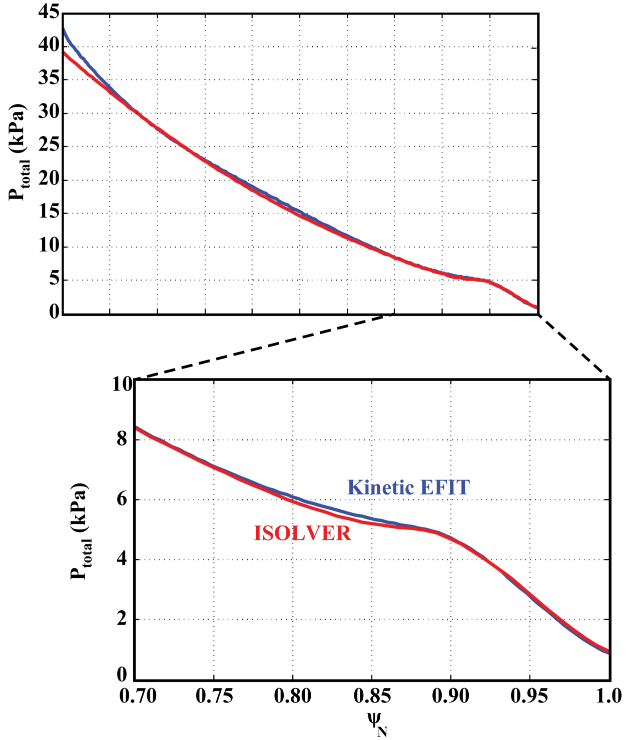


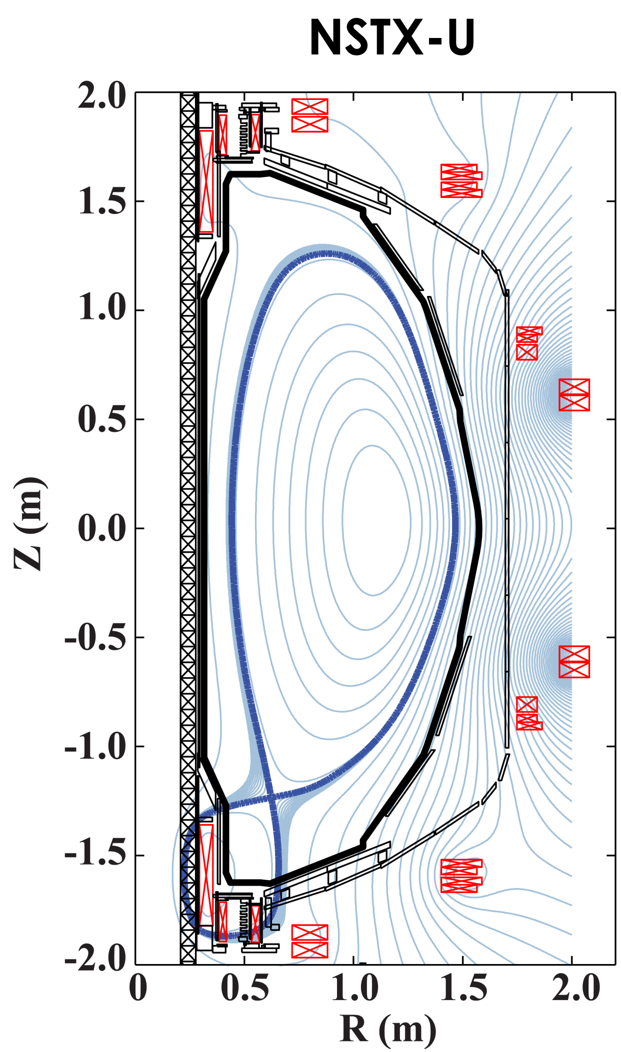
NSTX



ISOLVER calculations of the NSTX-U SF divertor assume approximately the same total plasma pressure profile

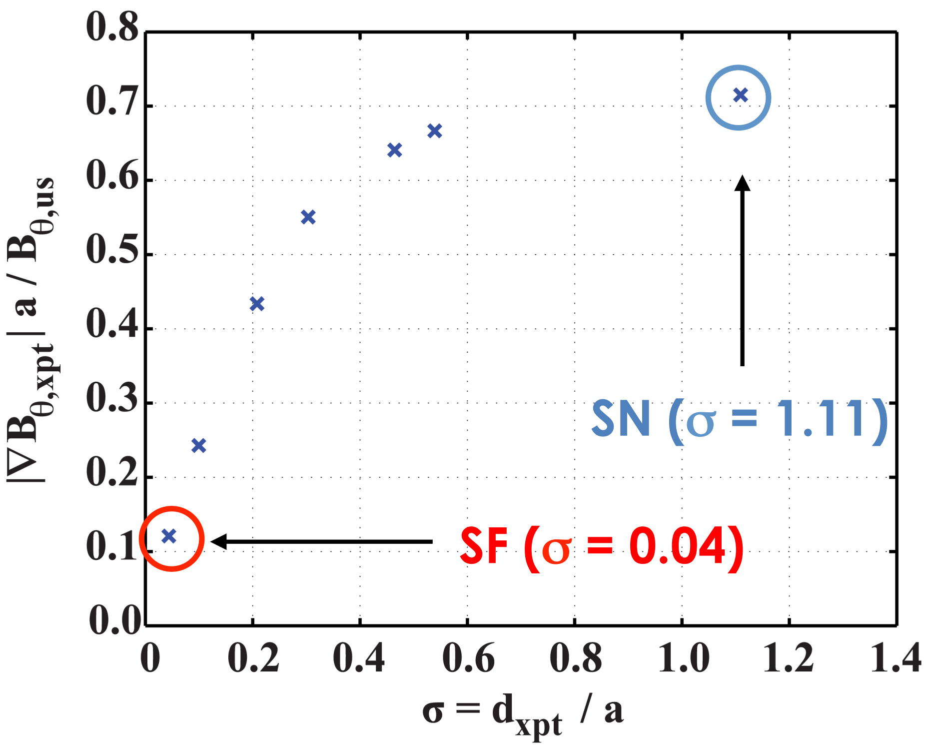
- **SF configurations generated by ISOLVER have approximatly the same P', FF' and total plasma pressure of the reference NSTX discharge**
  - Total pressure profile does not depend on divertor configuration [V.A. Soukhanovskii, *Phys. Plasmas* (2012)]

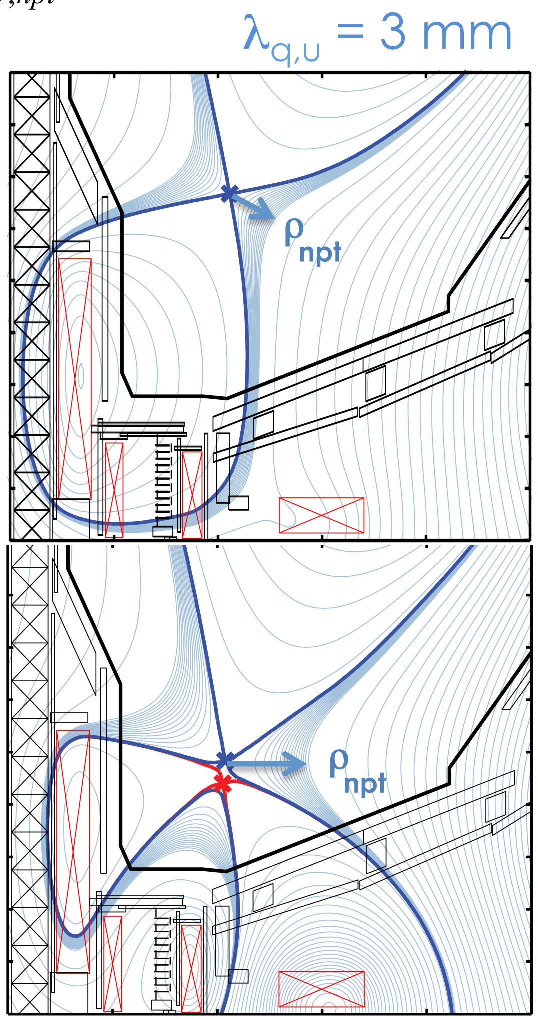




Configuration is varied from a SN reference to a SF

- **An exact SF configuration (σ = 0) features $\vec{\nabla} B_{\theta,npt} = 0$**
  - → $\vec{\nabla} B_{\theta,npt}$ is a measure of the "proximity" of a divertor configuration from an exact SF





Estimate the Plasma Response to Externally Applied Non-Axisymmetric Magnetic Fields Using Modelling

- **The M3D-C[1] code is a two-fluid, resistive MHD code[1]**
- **The M3D-C[1] computational domain includes the confined plasma, the separatrix and the open field-line region**
- **Unstructured mesh allows increased spatial resolution near rational surfaces and x-point**
- **Two-fluid effects governed by ion inertial length, d_i**
  - Electron and ion fluids decouple at finite d_i

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0$$

$$n\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi$$

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\Gamma p \nabla \cdot \mathbf{u} - \frac{d_i}{n}\mathbf{J} \cdot \left(\Gamma p_e \frac{\nabla n}{n} - \nabla p_e\right) - (\Gamma - 1)\nabla \cdot \mathbf{q}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} + \frac{d_i}{n}(\mathbf{J} \times \mathbf{B} - \nabla p_e)$$

$$\Pi = -\mu\left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right]$$

$$\mathbf{q} = -\kappa \nabla\left(\frac{p}{n}\right) - \kappa_{\parallel} \mathbf{bb} \cdot \nabla\left(\frac{p_e}{n}\right)$$

$$\mathbf{J} = \nabla \times \mathbf{B}$$

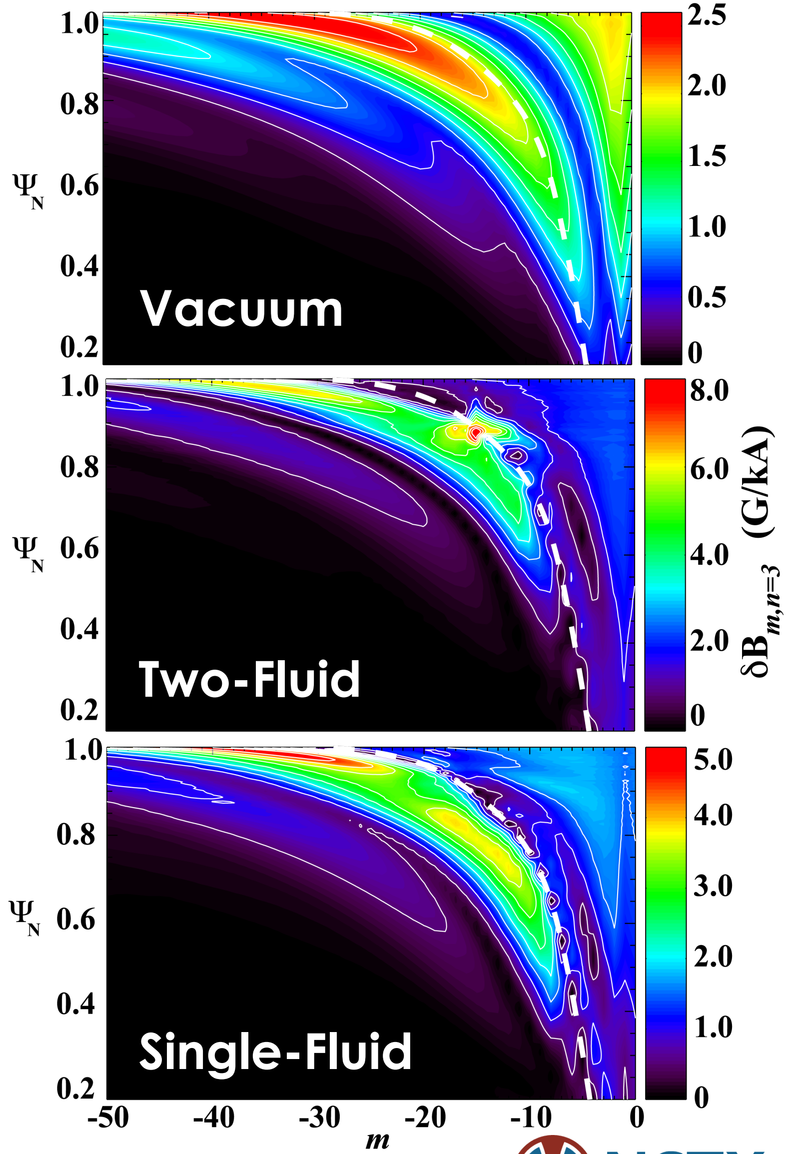
[1] N. Ferraro, *Phys. Plasmas* (2010)

Two-fluid effects significantly enhance resonant field components in the plasma edge of the SN configuration

- **Vacuum field reveals broad Fourier spectrum of poloidal harmonics in the plasma edge**
  - Spectrum depends on the configuration of perturbation coil currents (n = 1, 2, etc.)

- **Two-fluid effects amplify resonant components in the plasma edge**
  - Indicative of stable tearing modes near marginal stability in the unperturbed case

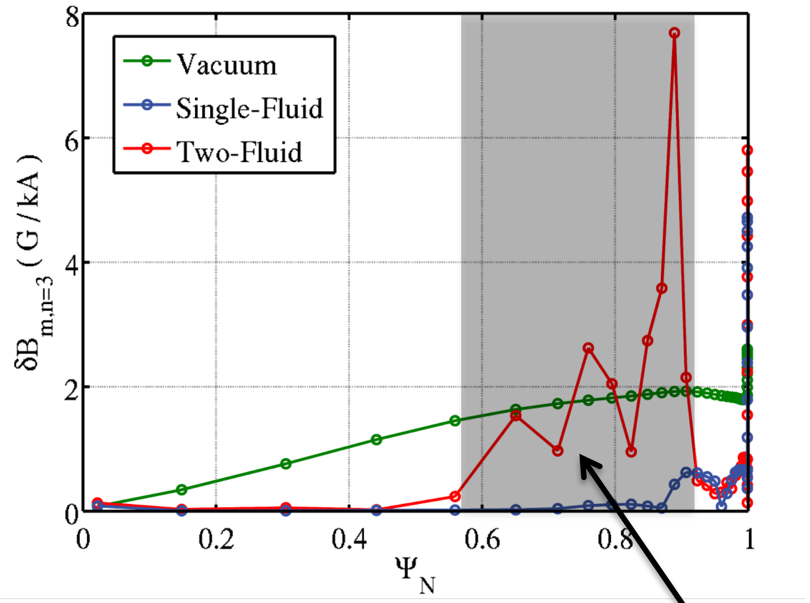
- **Single-fluid calculations show strong screening of perturbation fields**



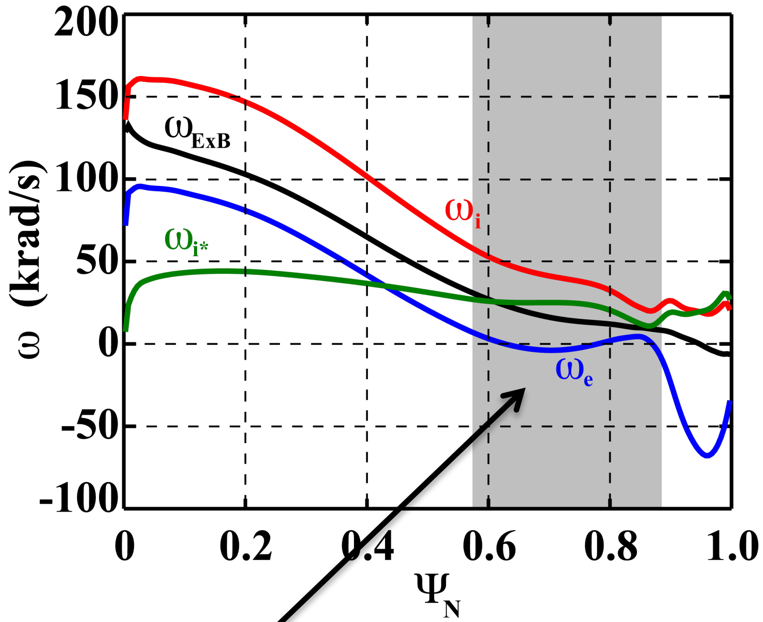
Enhancement of resonant field components is caused by low electron fluid rotation in the plasma edge

- **Region of enhancement of resonant components coincides with region of low electron fluid rotation** [N. Ferraro, *Phys. Plasmas* (2012)]

Resonant Magnetic Perturbation



Plasma Rotation Profiles



Low electron fluid rotation

Enhancement of resonant field components is caused by low electron fluid rotation in the plasma edge

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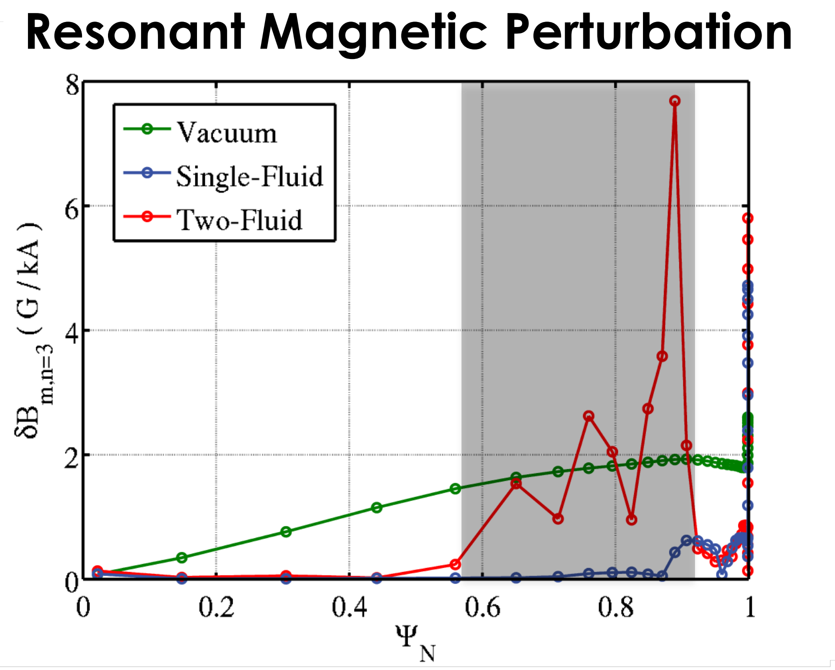
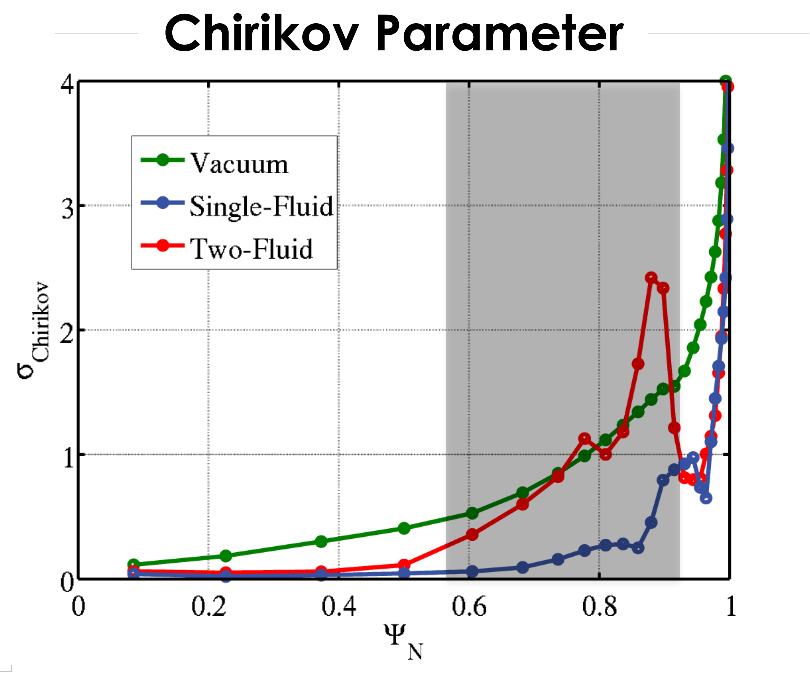


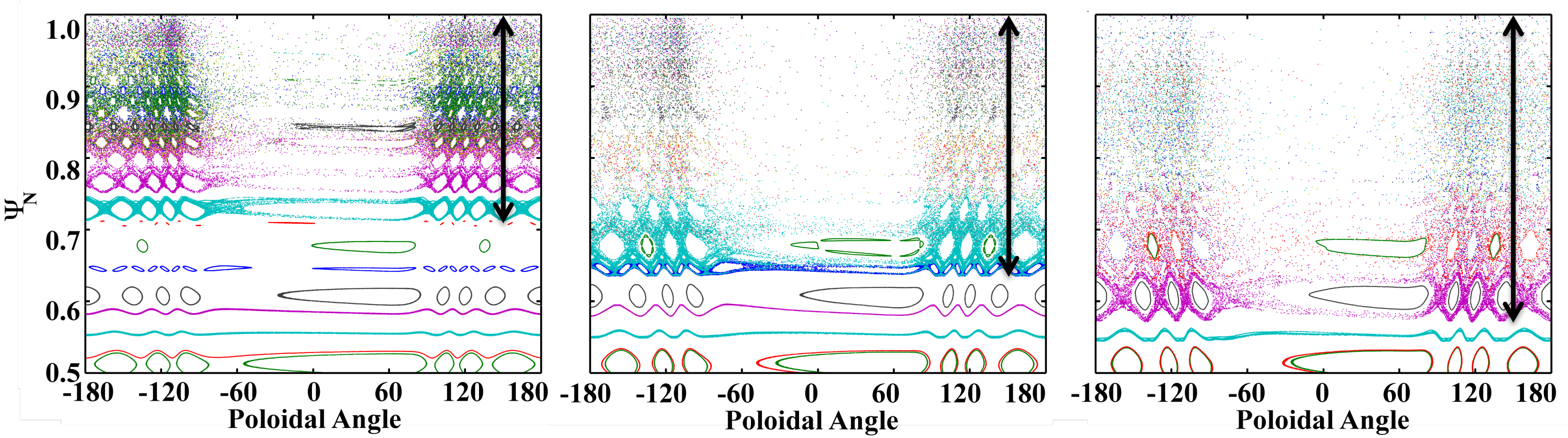


- **Enhanced resonant fields indicate the formation of magnetic islands**
  - Two-fluid calculations predict stochastic layer in the plasma edge as large as in the vacuum field approach

M3D-C[1] calculations predict strong stochastization of plasma edge with increasing perturbation coil current

- **Vacuum, two-fluid and single-fluid calculations predict the formation of magnetic islands in the plasma edge**
  - For sufficiently large coil currents, islands overlap leading to stochastic layer in the edge

Vacuum (I_C = 0.5 kA) Vacuum (I_C = 1.0 kA) Vacuum (I_C = 1.5 kA)



  - Flux surfaces in the plasma edge are all broken in the vacuum calculations

M3D-C^1 calculations predict strong stochastization of plasma edge with increasing perturbation coil current

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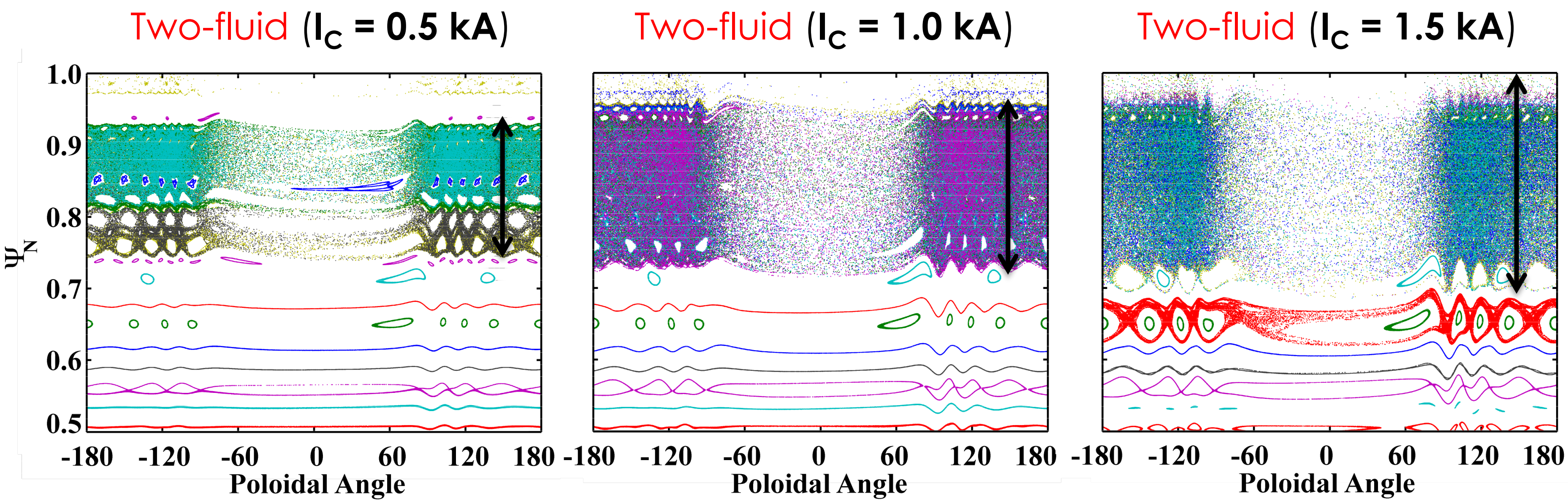

  - Stochastic edge does not increase significantly with perturbation coil current in the two-fluid approach

M3D-C[1] calculations predict strong stochastization of plasma edge with increasing perturbation coil current

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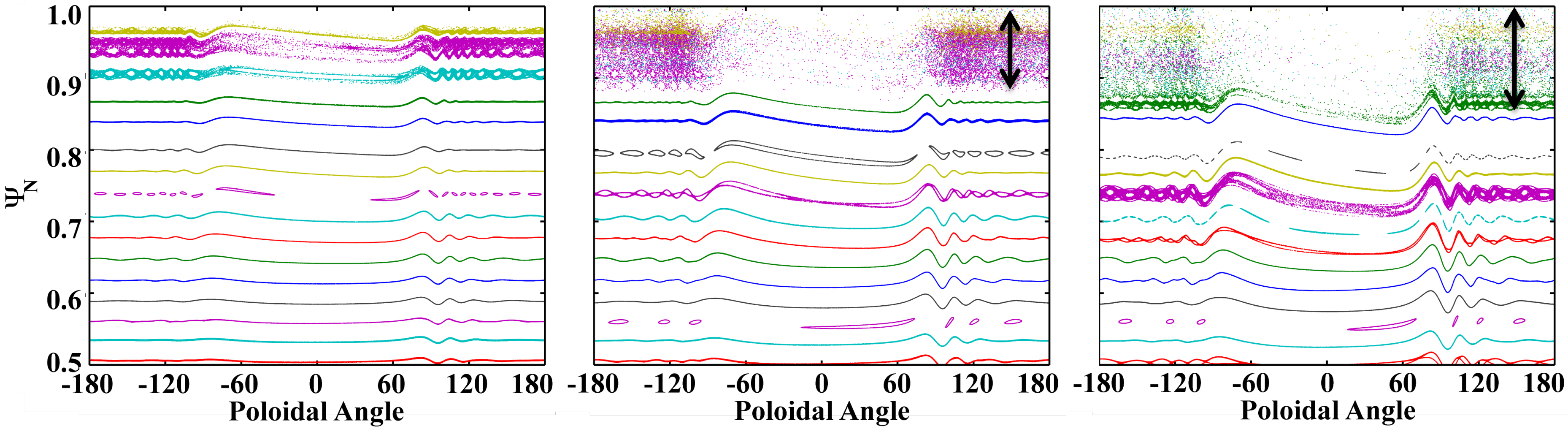
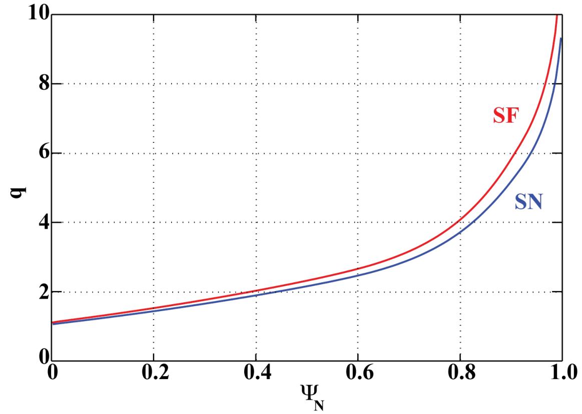
Single-fluid (I_C = 0.5 kA) Single-fluid (I_C = 1.0 kA) Single-fluid (I_C = 1.5 kA)



  - Single-fluid calculations predict a thinner stochastic edge than vacuum and two-fluid calculations

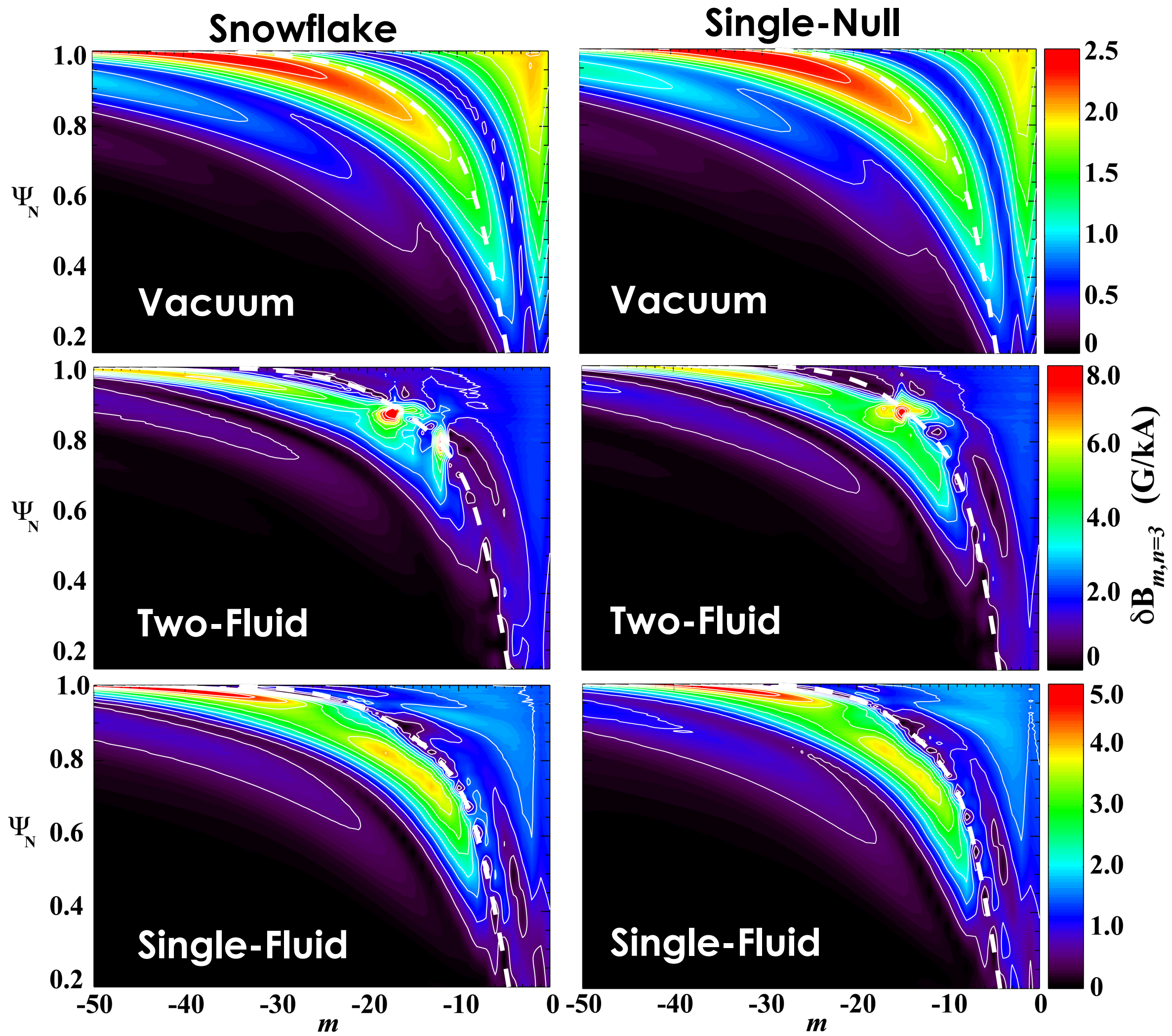
Two-fluid effects significantly enhance resonant field components in the plasma edge of the SF configuration

- **Plasma response in a SF is not significantly different than in a SN**
  - Differences come from slightly different q-profiles



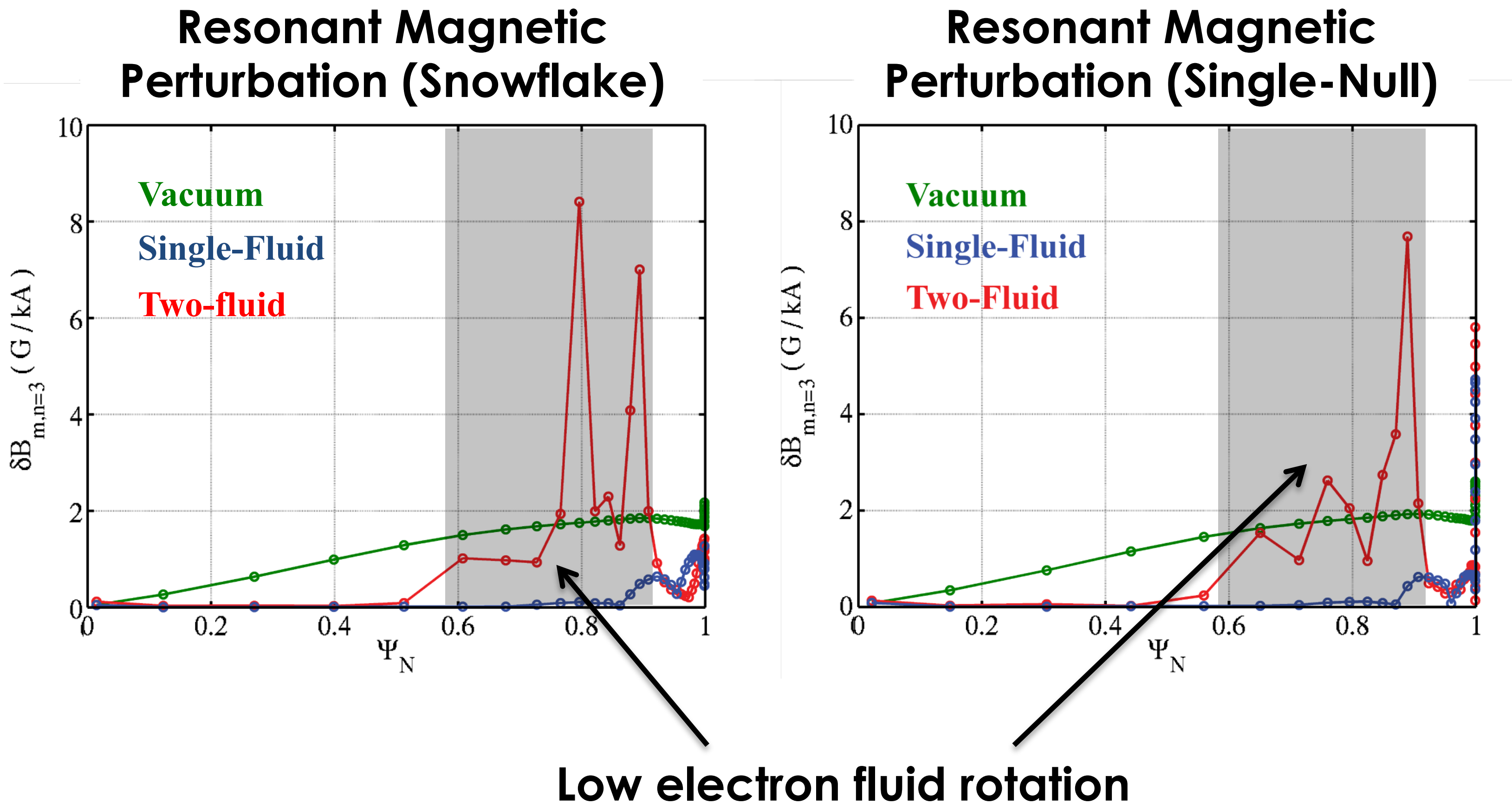
  - Differences in q-profile come from change in poloidal current

$$J_\theta = \frac{dF}{d\psi} B_\theta$$



Enhancement of resonant field components is caused by low electron fluid rotation in the plasma edge

- **Region of enhancement of resonant components coincides with region of low electron fluid rotation** [N. Ferraro, *Phys. Plasmas* (2012)]



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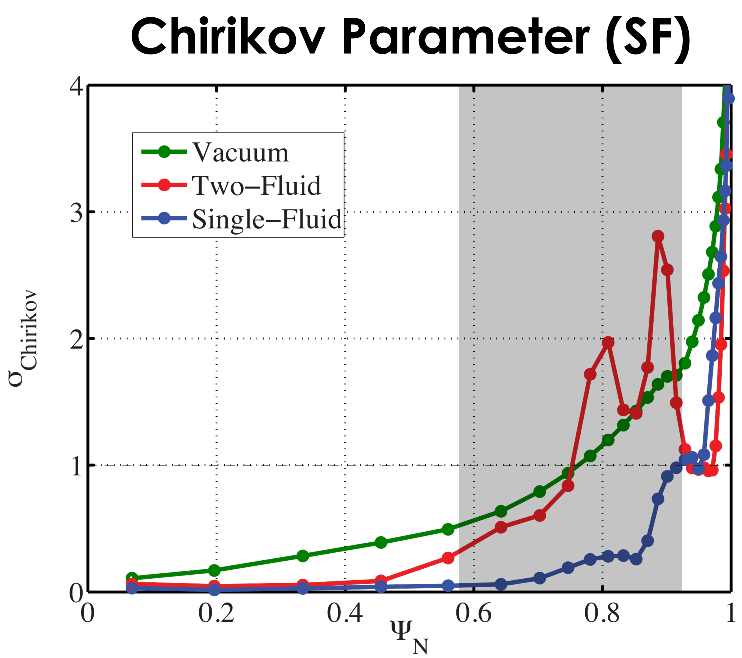

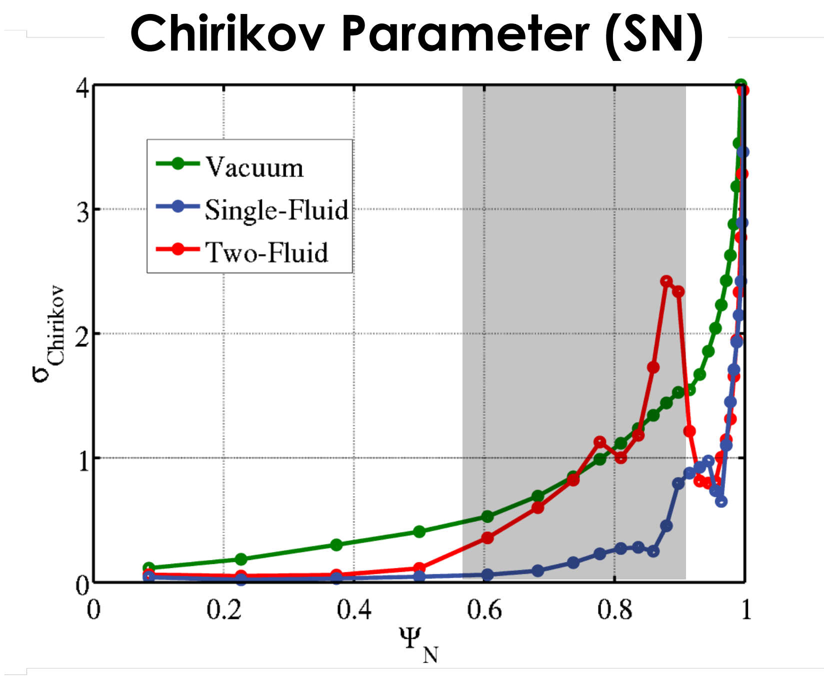

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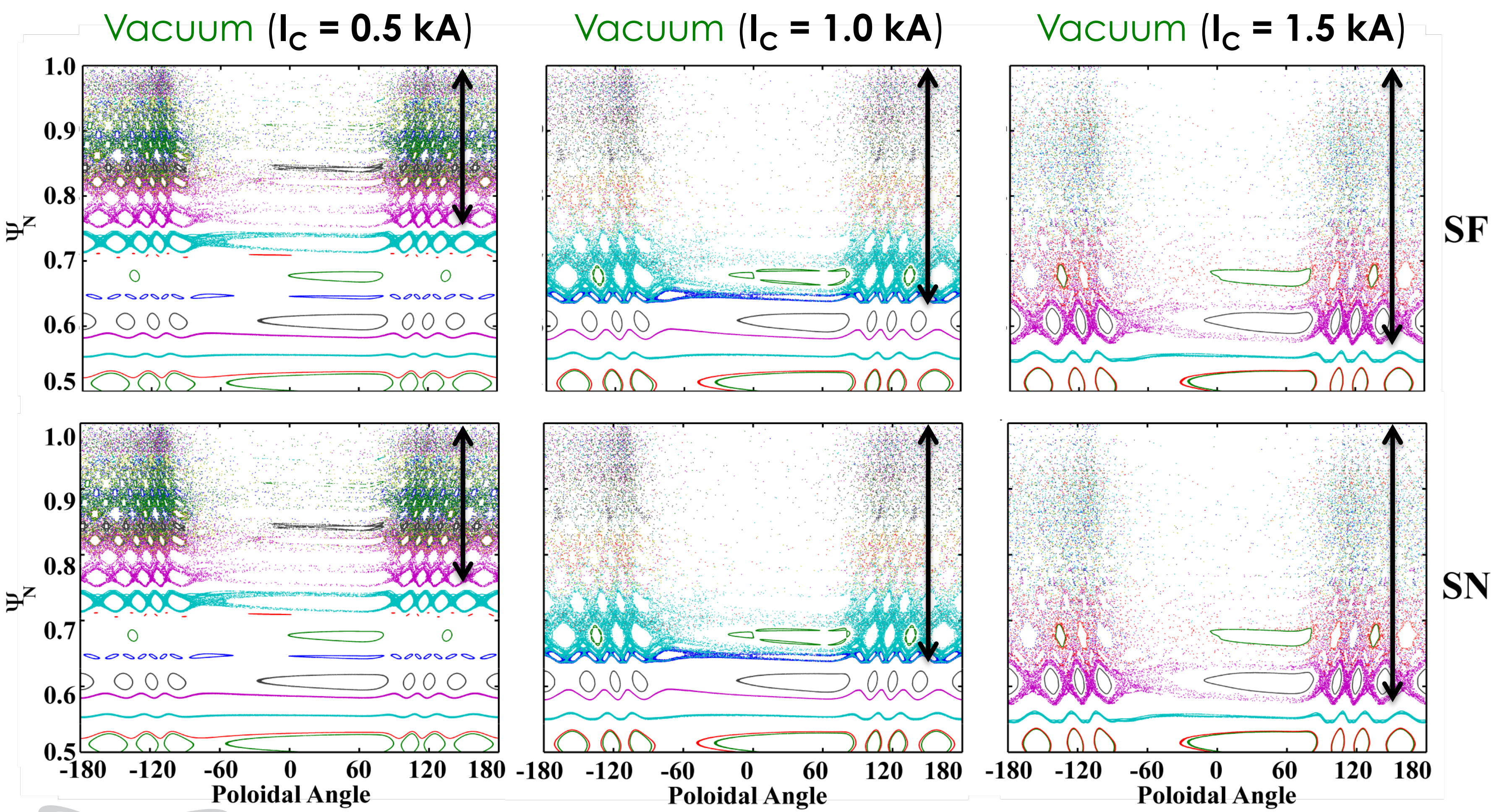
Calculations show no difference between edge stochastization in SN and SF configurations

- **As in a SN, vacuum, two-fluid and single-fluid calculations predict an increasing of the edge stochasticity with I_C in a SF configuration**



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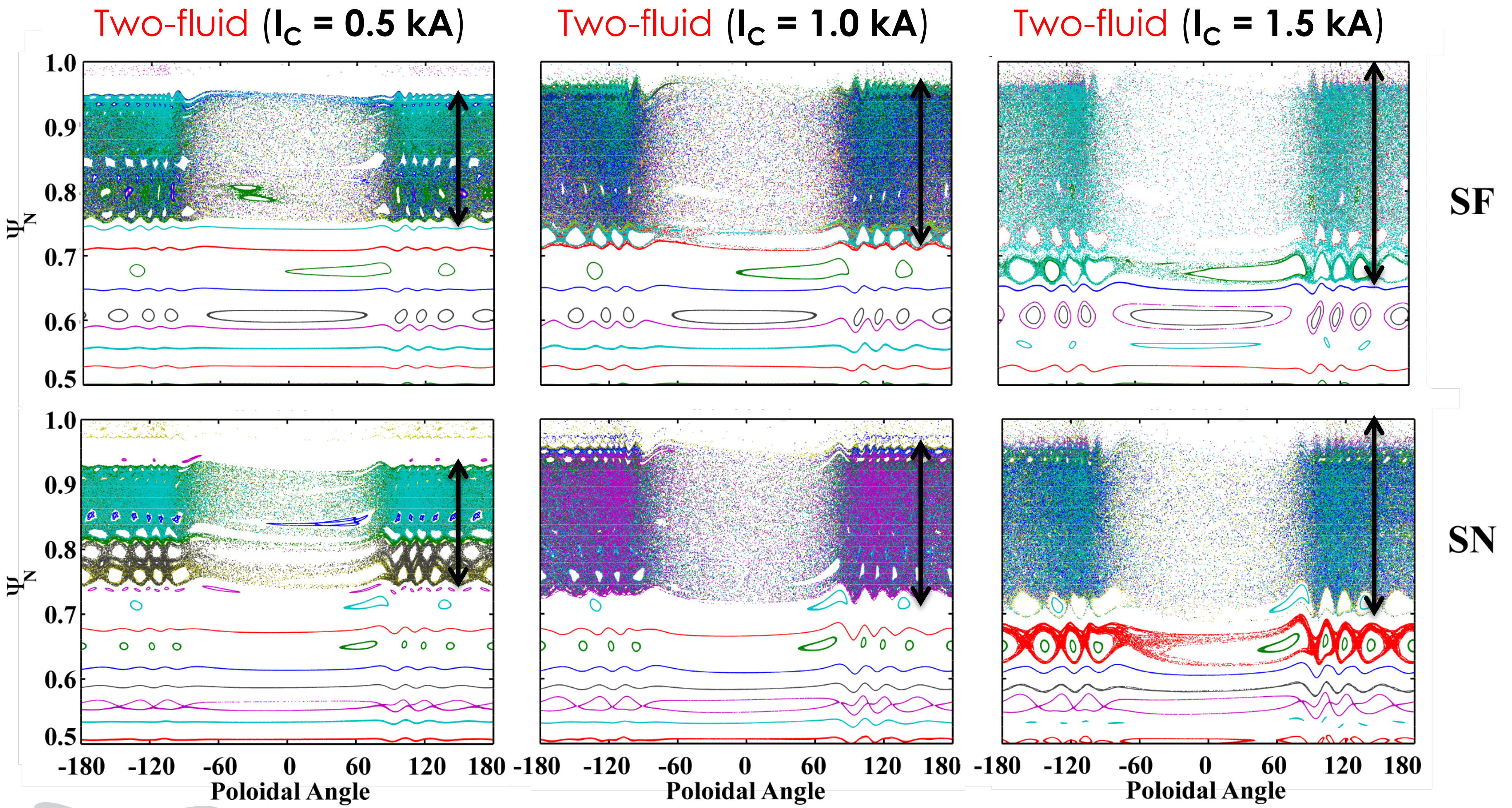

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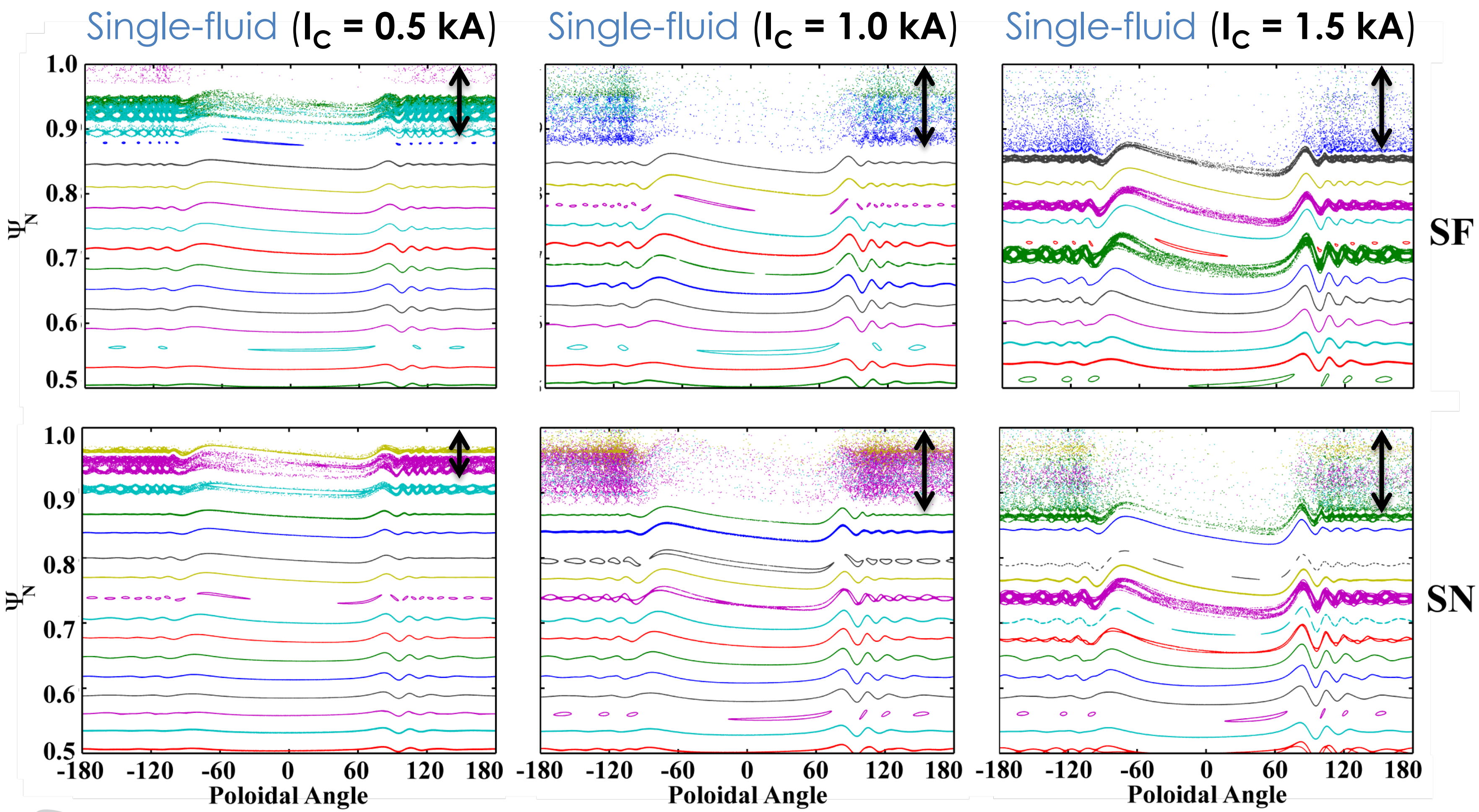
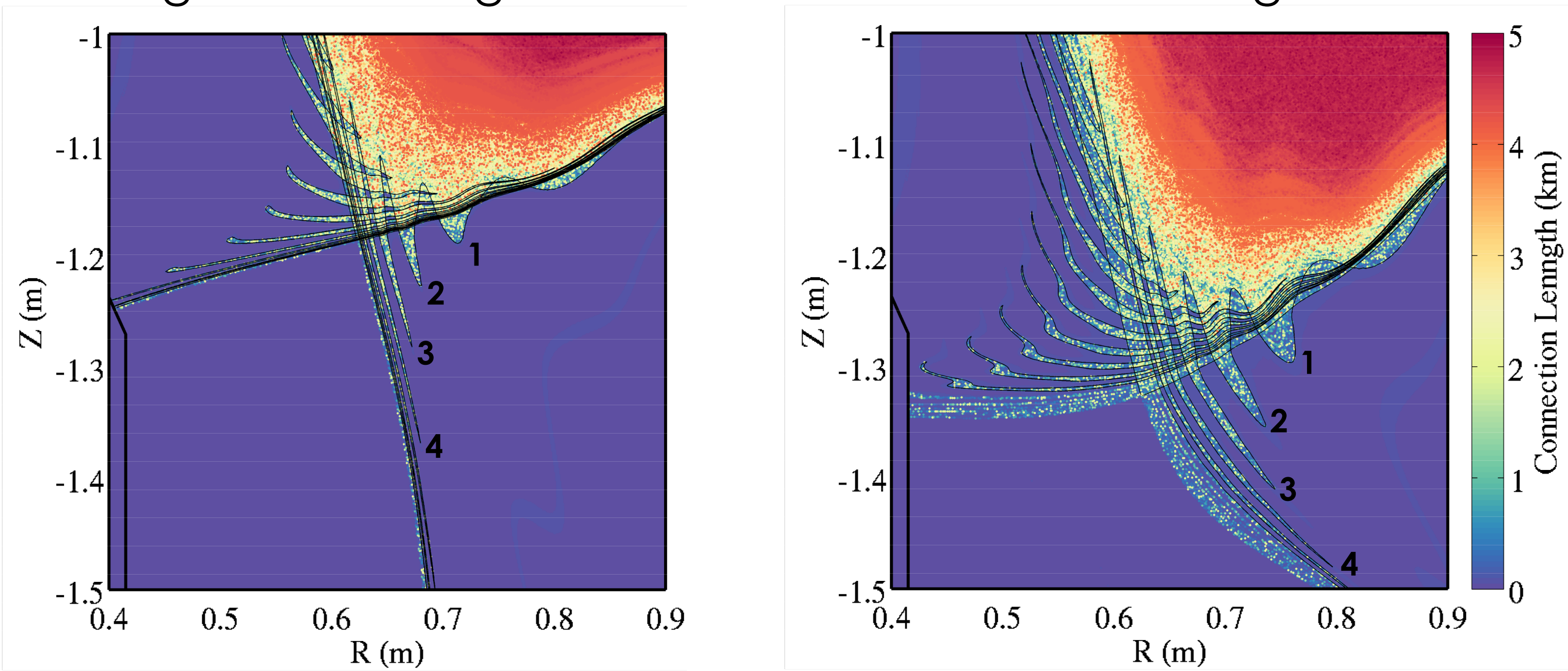


Lower poloidal field in the null-point region of the SF configuration leads to the formation of longer lobes

- **The SF configuration magnifies the effect of magnetic perturbations**
  - More striations in the divertor may lead to lower peak heat fluxes

Single-Null Configuration   Snowflake Configuration



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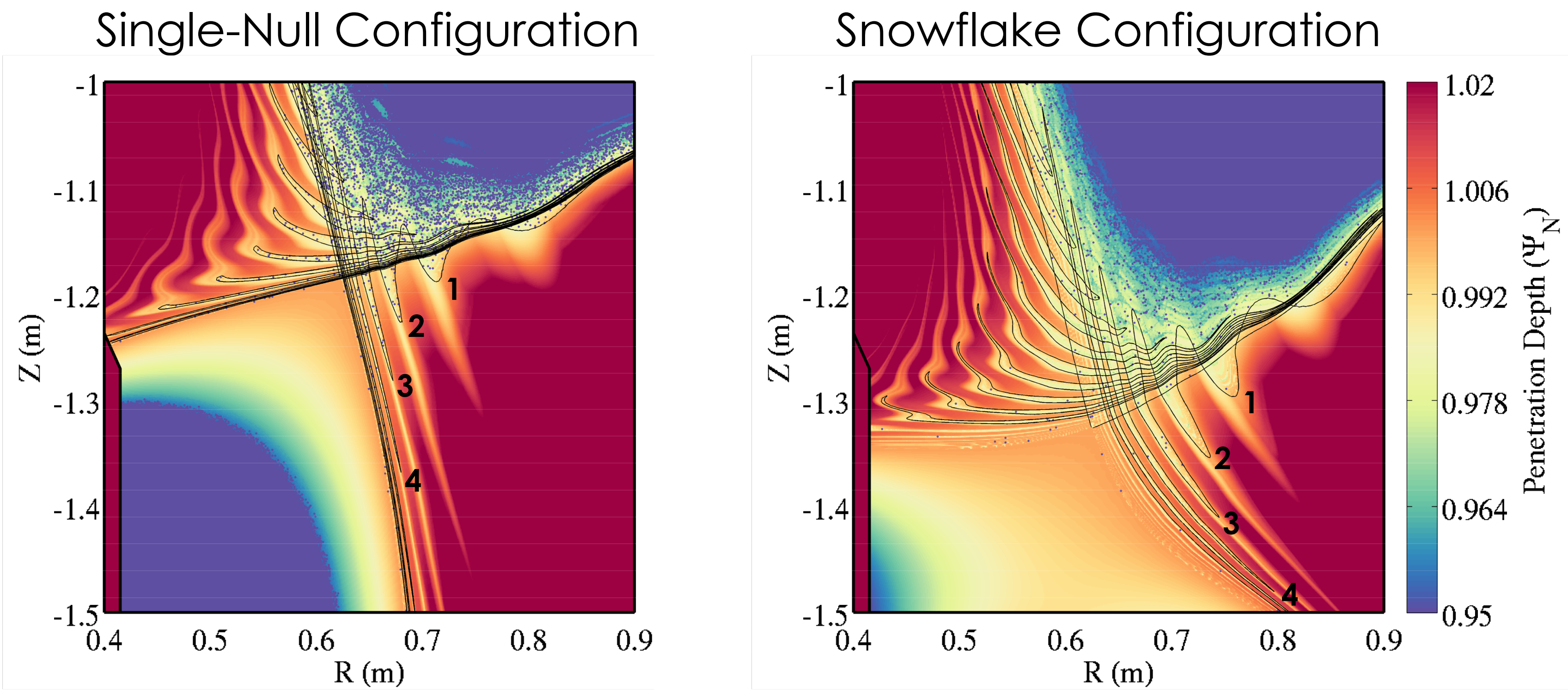

Magnetic field lines in the null-point region of the SF divertor remain close to the edge

Impurities can be used as a tool to manipulate the contribution of two-fluid effects to the plasma response

- **Two-fluid effects governed by ion inertial length, d_i**
  - Ions may decouple from electrons within d_i

- **Ion inertial length depends on effective ion charge, Z_{eff}**

$$d_i \equiv \frac{c}{\omega_{pi}} = \frac{c}{Z_{eff}} \sqrt{\frac{M_i}{4\pi n_0 e^2}}$$

➢ **Two-fluid effects are more significant in plasmas with low values of Z_{eff}**

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0$$

$$n\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi$$

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\Gamma p \nabla \cdot \mathbf{u} - \frac{d_i}{n}\mathbf{J} \cdot \left(\Gamma p_e \frac{\nabla n}{n} - \nabla p_e\right) - (\Gamma - 1)\nabla \cdot \mathbf{q}$$

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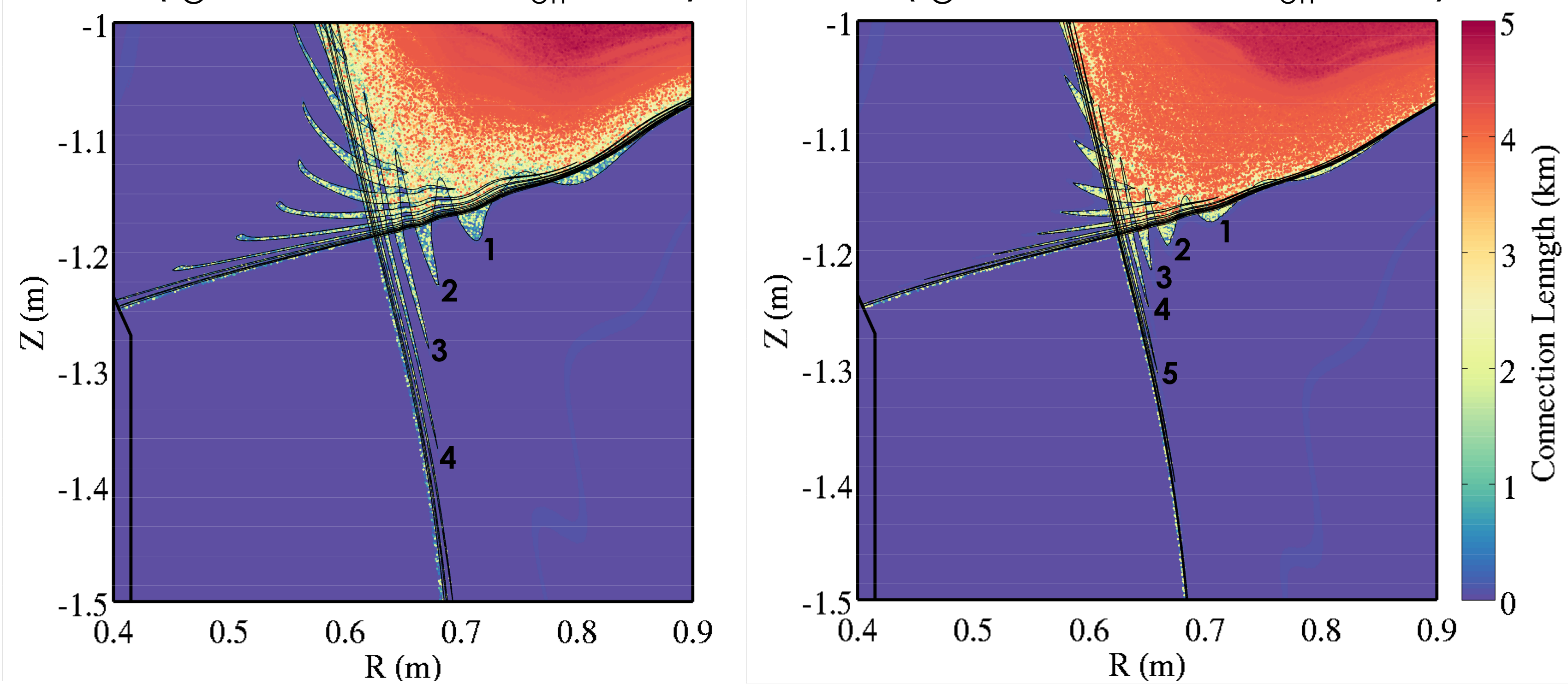
$$\mathbf{J} = \nabla \times \mathbf{B}$$

M3D-C[1] calculations predict shorter lobes in plasmas with higher values of ion effective charge

- **Impurities tend to reduce two-fluid effects in both SN and SF configurations**
  - Plasma respond as a single-fluid in plasmas with high Z_{eff}

SN (I_C = 1.0 kA and Z_{eff} = 1.0) SN (I_C = 1.0 kA and Z_{eff} = 2.5)



Magnetic field lines in lobes of higher Z_{eff} plasmas have longer L_C

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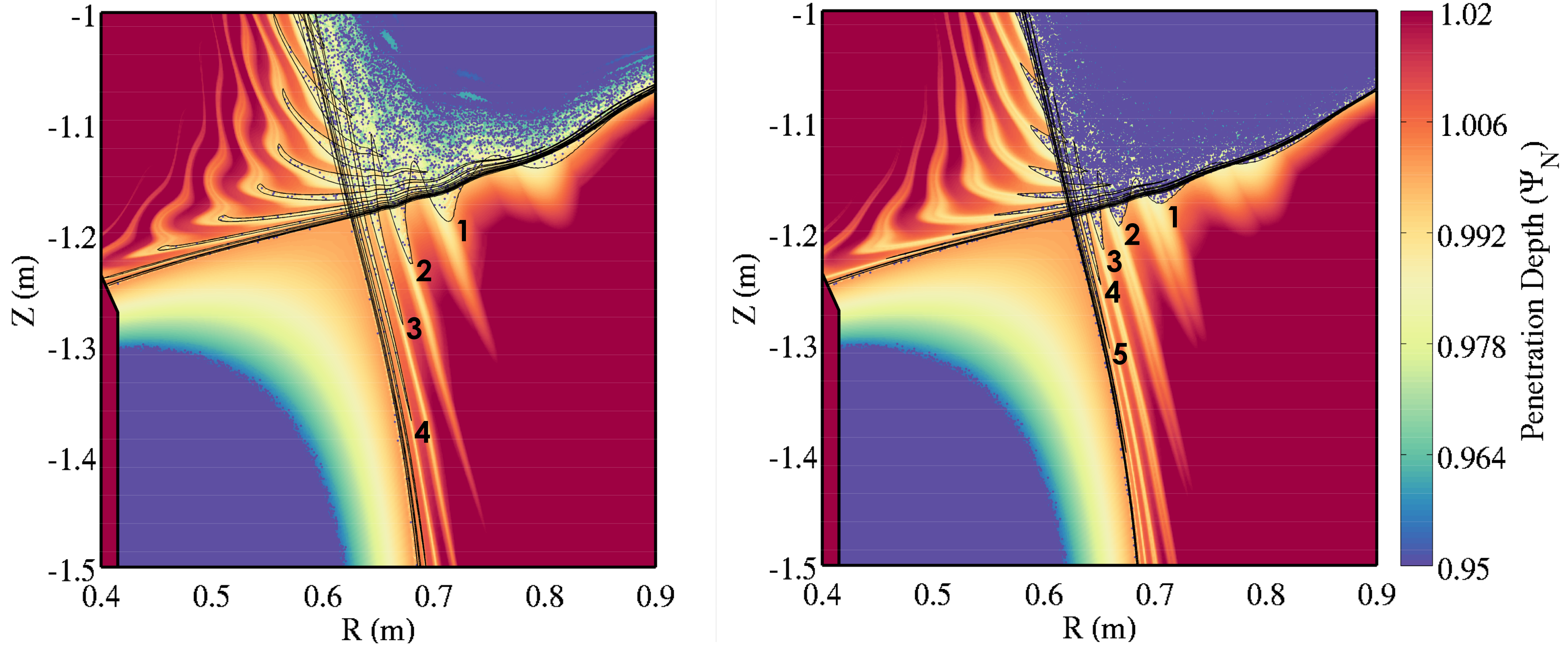
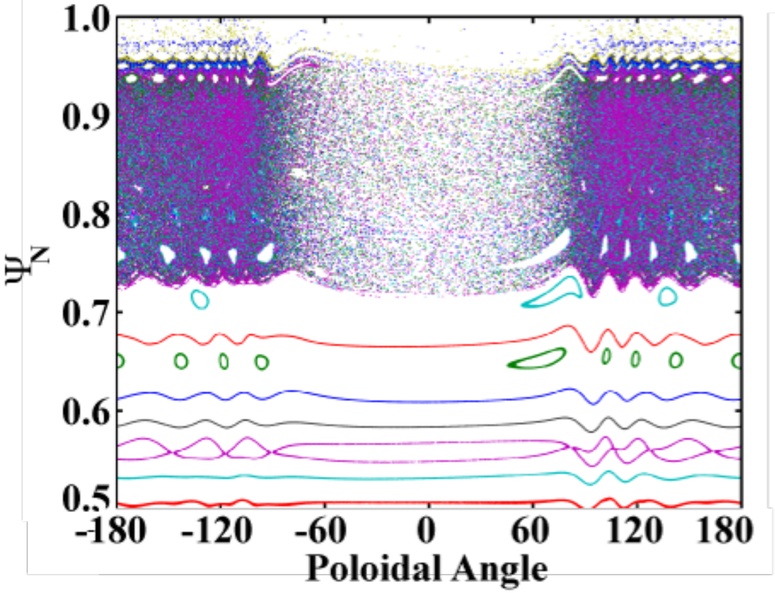


Magnetic field lines in lobes of higher Z_{eff} plasmas goes deeper into the plasma

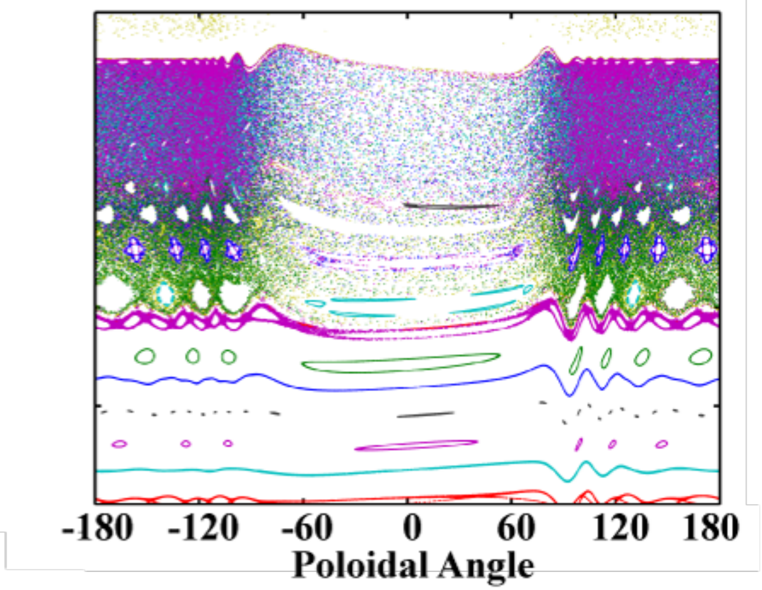
Plasma edge stochasticity increases in plasmas with higher values of Z_{eff}

- **Impurities tend to increase edge stochasticity in both SN and SF configurations**

SN (I_C = 1.0 kA and Z_{eff} = 1.0)



SN (I_C = 1.0 kA and Z_{eff} = 2.5)



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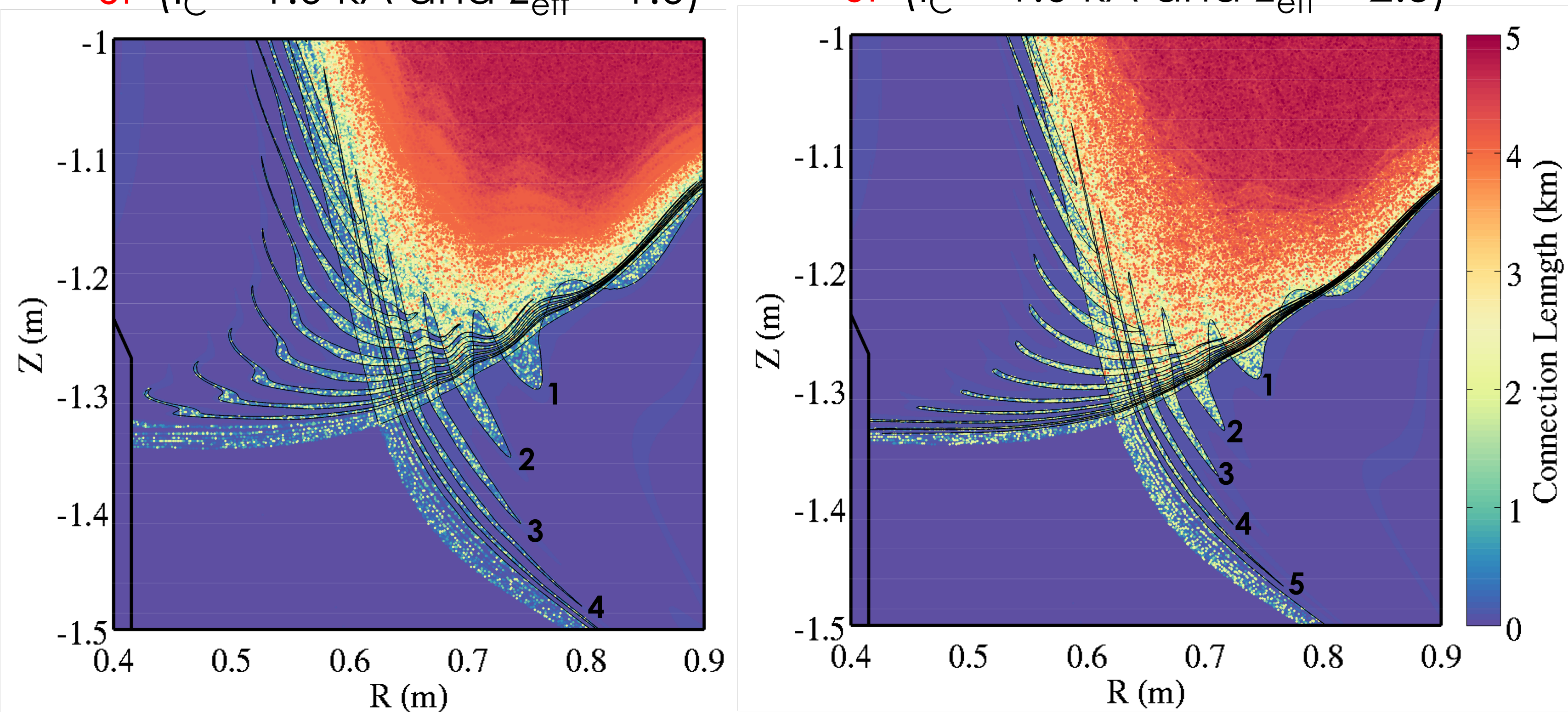

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M3D-C1 calculations predict shorter lobes in plasmas with higher values of ion effective charge

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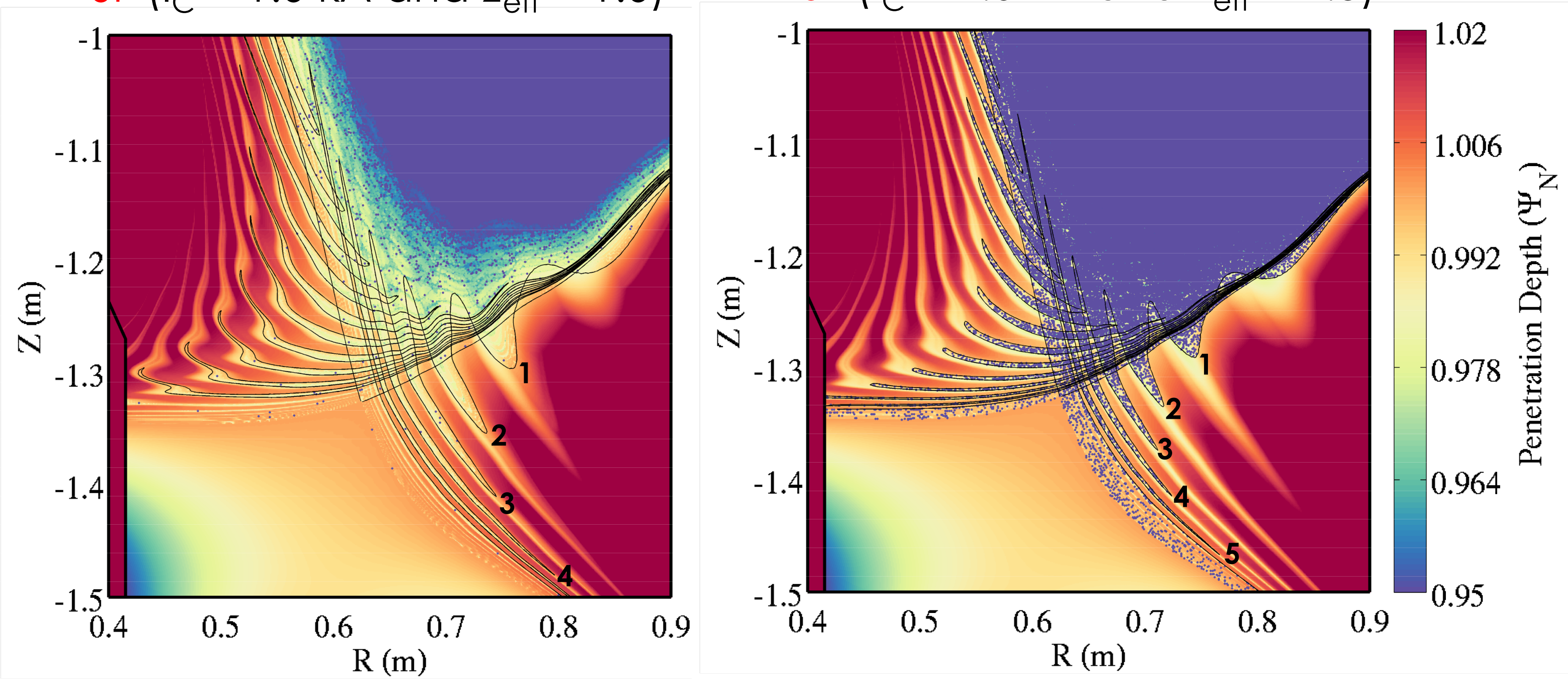

Magnetic field lines in lobes of higher Z_{eff} plasmas goes deeper into the plasma

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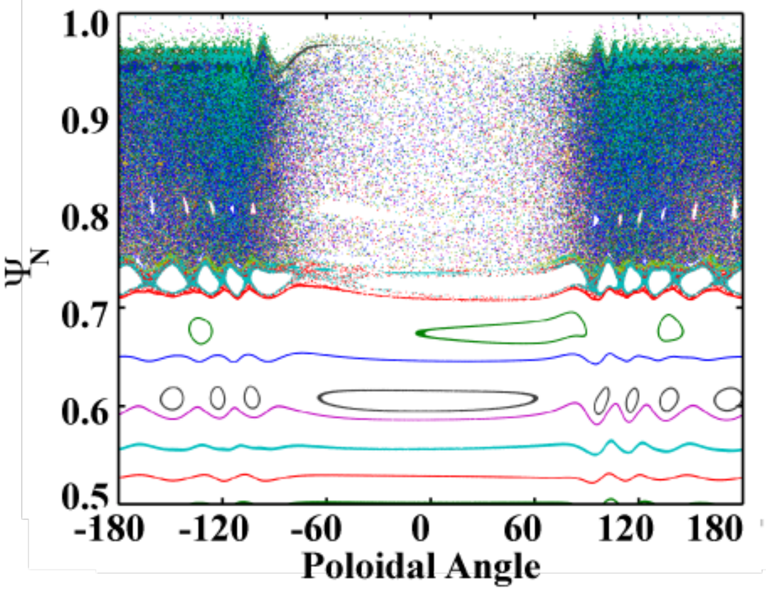
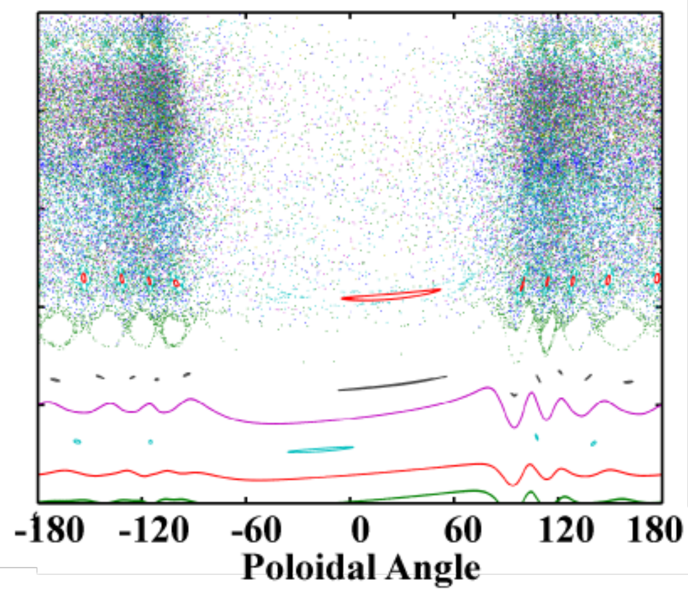
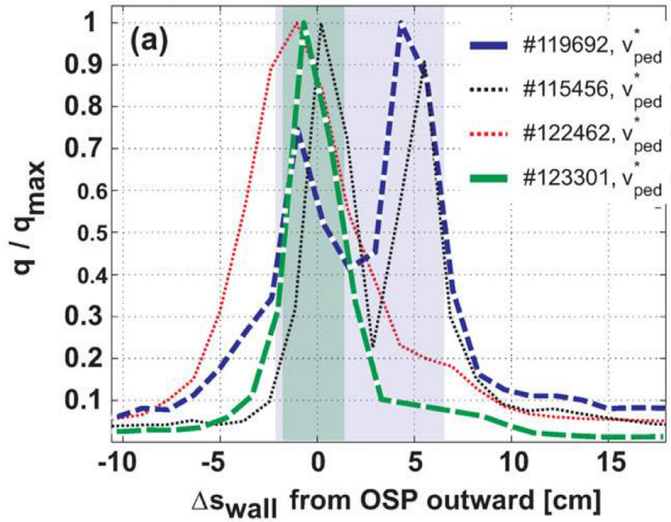


SF (I_C = 1.0 kA and Z_{eff} = 2.5)

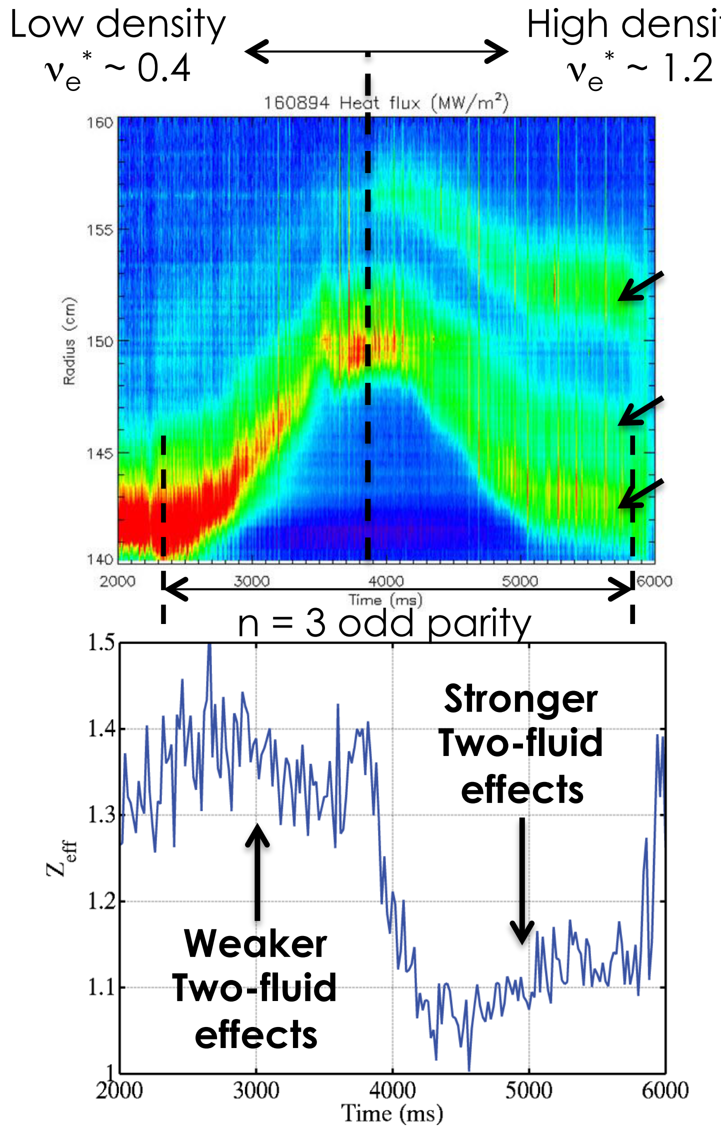


The impact of impurities on the importance of two-fluid effects may be related to transport effects in high ν_e^* plasmas

- **Heat flux splitting is visible only for ν_e^* > 0.5**
  - Particle flux splitting occurs at lower values of ν_e^*

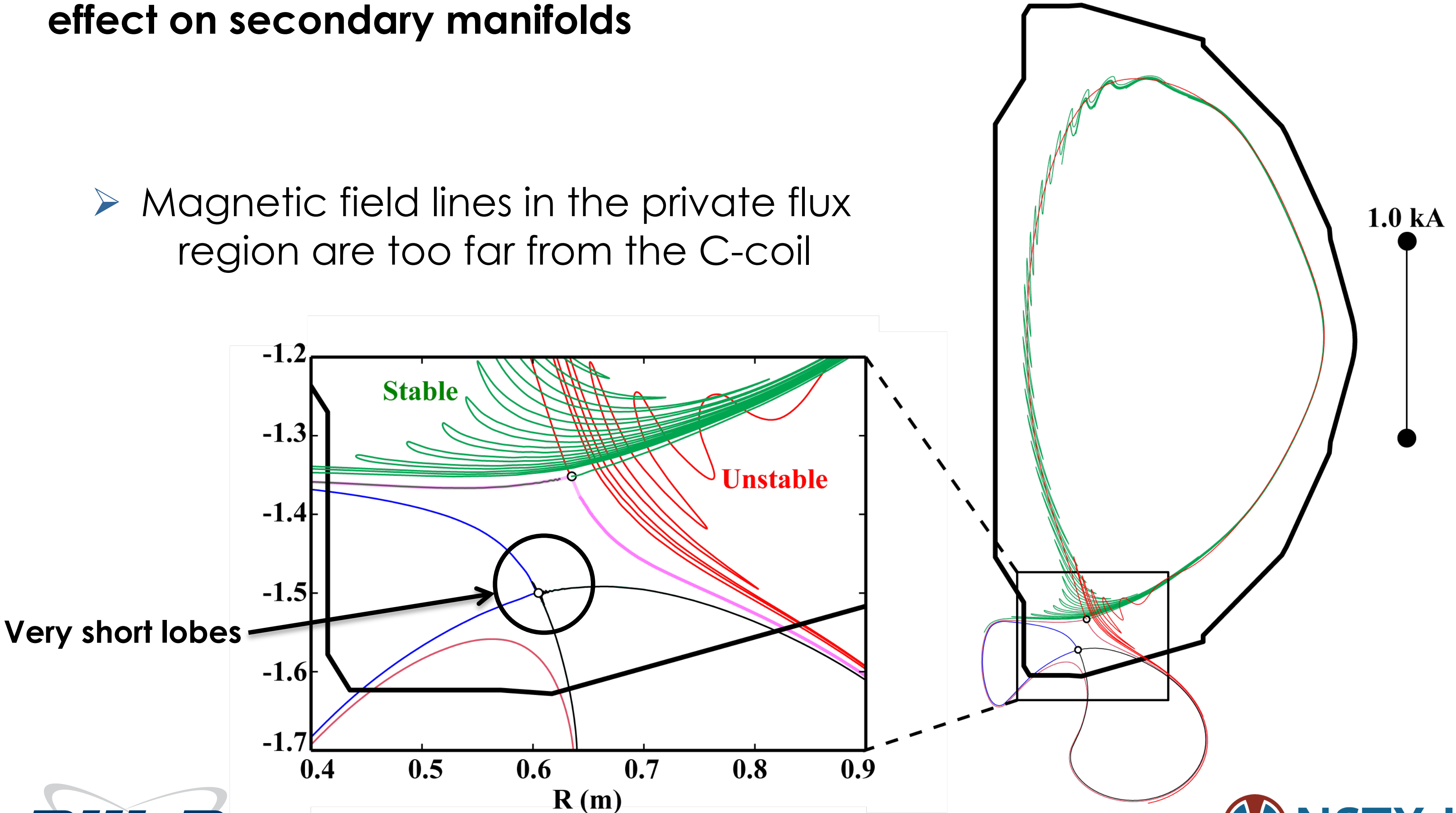


[M.W. Jakubowski, *Nucl. Fusion* (2009)]



Effect of 3D magnetic perturbations on secondary manifolds is negligible

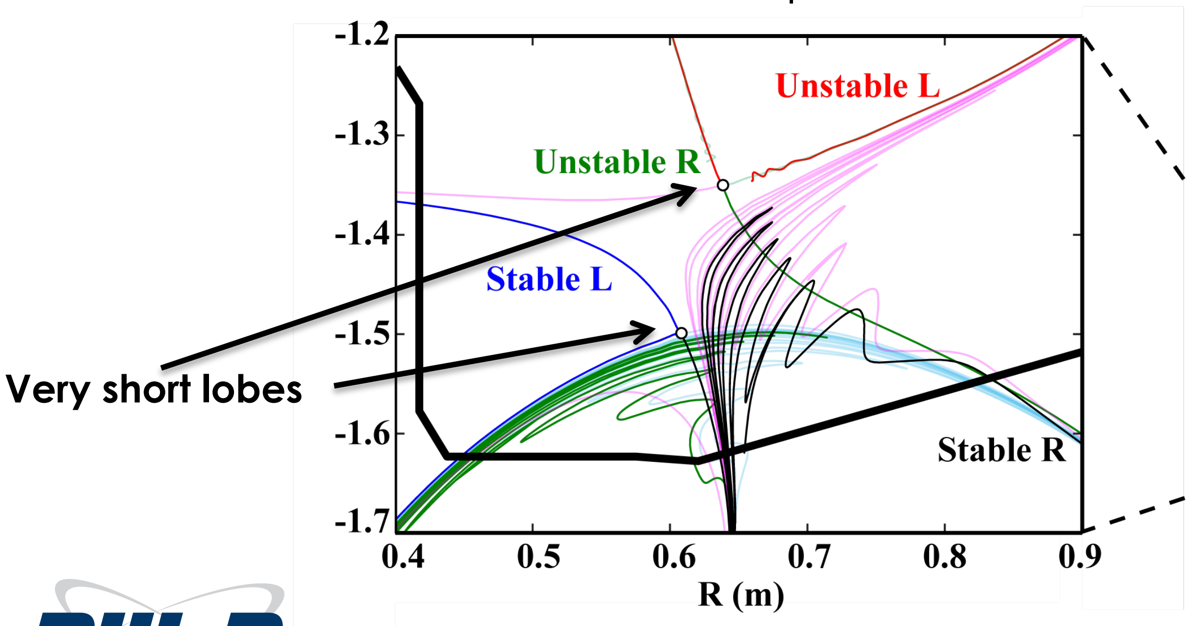
- **Vacuum approach calculations show that C-coil currents have no significant effect on secondary manifolds**
  - ➢ Magnetic field lines in the private flux region are too far from the C-coil

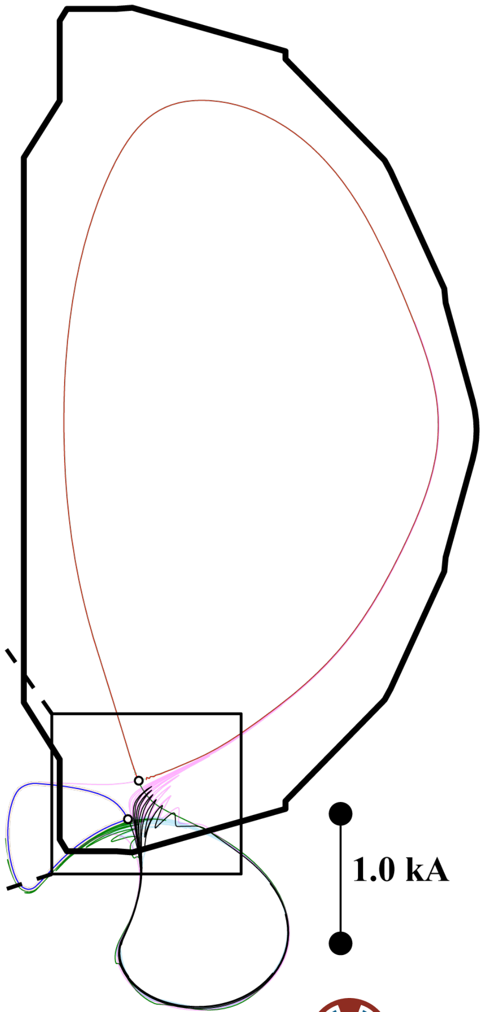


Secondary manifolds become apparent when perturbation coil is placed close to secondary x-point

- **Vacuum approach calculations show that only field lines passing close to the perturbation coil are affected**
  - Manifolds are affected by radial (non-tangential) perturbed field

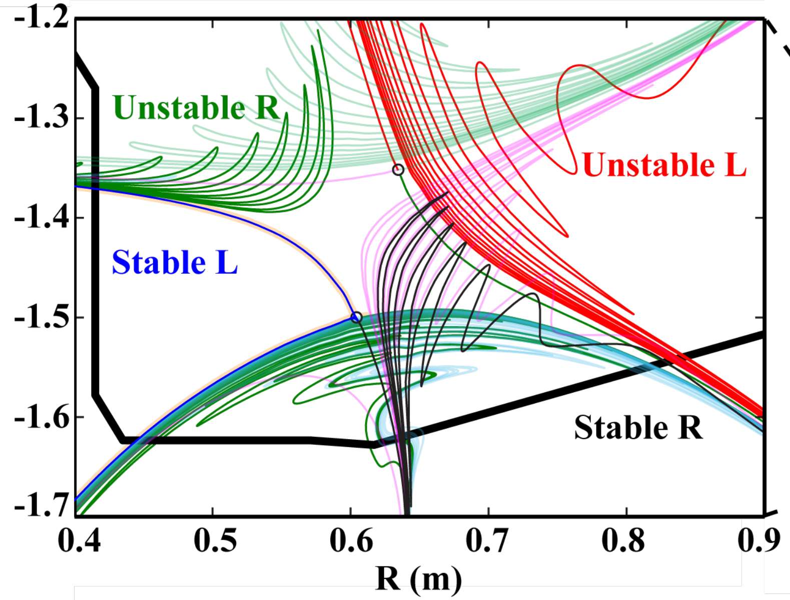
➢ Primary manifolds and left hand secondary manifolds are too far from the perturbation coil

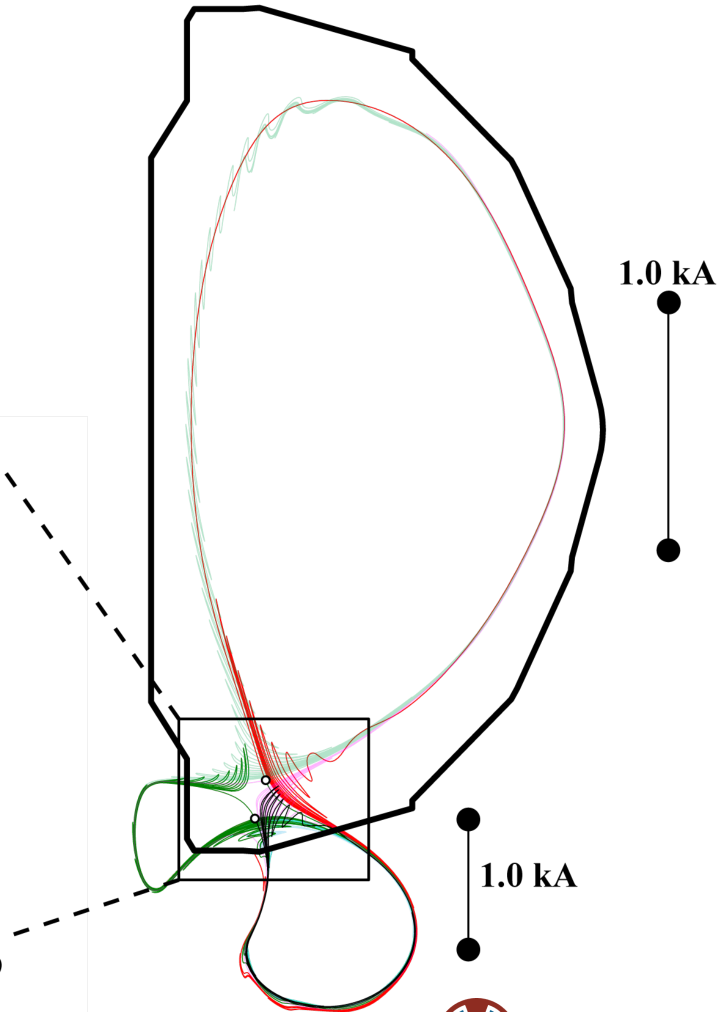




Primary and secondary manifolds are visible when both perturbation coils are used

- **Calculations show that, for a sufficiently close perturbation coil, both primary and secondary manifolds can be manipulated**
    - Left hand secondary manifolds are still too far from the perturbation coil

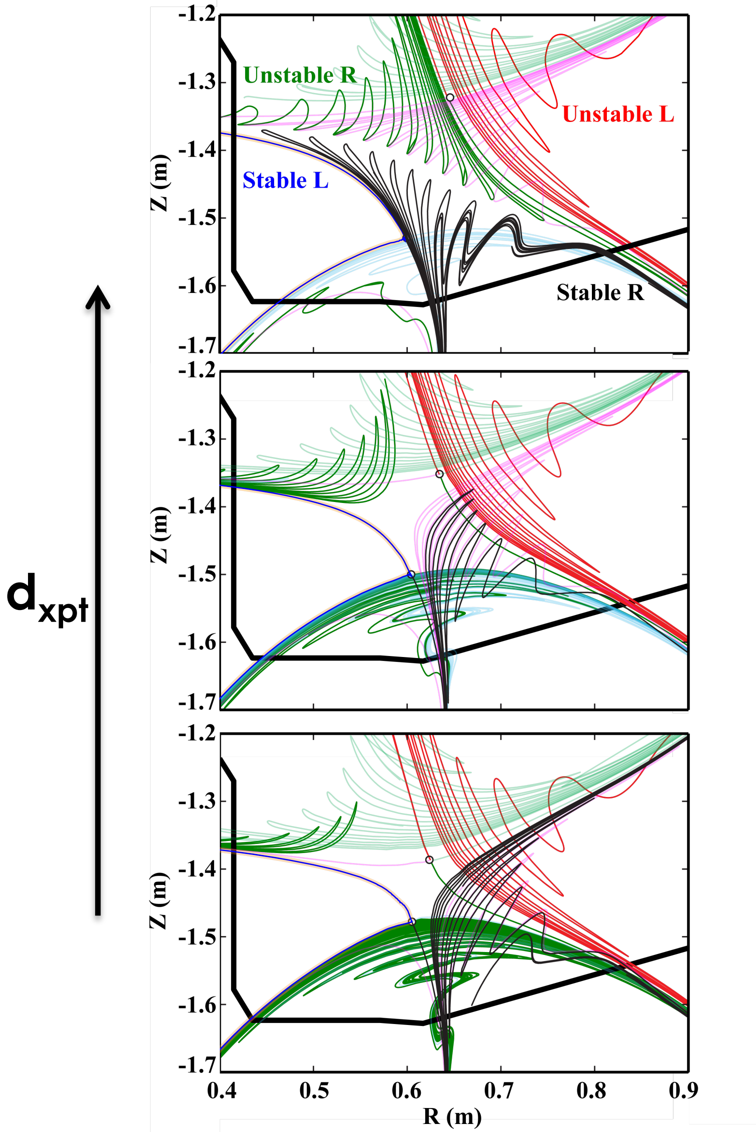




Primary and secondary manifolds interact at sufficiently short distance between x-points

- **Vacuum approach calculations show that primary and secondary manifolds may interact at**
  - sufficiently close perturbation coils
  - sufficiently large perturbation coil currents
  - small distance between x-points

- **Interaction between manifolds may**
  - affect the edge plasma transport
  - improve the power repartition between plasma legs (reduction of peak heat flux)
  - increase divertor volume (radiated power fraction and easier access to detachment)



Summary: Improved physics understanding & modeling of 3D fields in the SF divertor are needed to extrapolate towards larger devices

- **M3D-C[1] calculations predict a strong stochastization of the plasma edge with increasing perturbation coil current in both SN and SF configurations**
  - Plasma lobes in the SF are longer than in the SN configuration

- **Impurities can be used as a tool to manipulate the contribution of two-fluid effects to the plasma response**
  - Plasmas with higher Z_{eff} have shorter lobes and more stochastic edge

- **Interaction between primary and secondary manifolds may have a significant impact on**
  - plasma edge transport
  - improve power repartition between plasma legs
  - increase divertor volume