M3D-C^1 Simulations of the Plasma Response to n = 3 Magnetic Perturbations applied to the NSTX-U Snowflake Divertor

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in collaboration with

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58th Annual Meeting of the APS - DPP

San Jose - CA, October 31- November 4, 2016

Power exhausted challenges on the road to a fusion reactor

- **Erosion caused by ELM energy bursts can reduce significantly the lifetime of plasma facing components (PFCs) in ITER** [Loarte, PPCF (2003)]
  - Need for ELM control techniques

- **Studies worldwide have demonstrated that ELMs can be suppressed by relatively small non-axisymmetric resonant magnetic perturbations**
  - These studies have led to the addition of ELM control coils to ITER [Evans, PPCF (2015)]

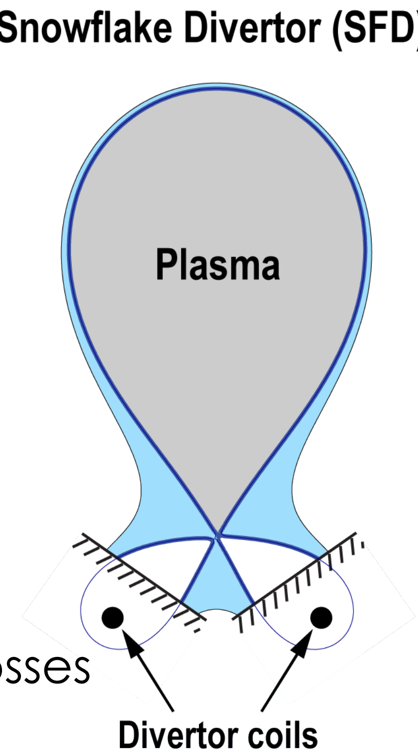
- **ITER has to demonstrate sustained burning plasma operation with Q > 10 while preserving the integrity of the PFCs**
  - More than 60% of the power crossing the LCFS has to be radiated in the divertor [Pitts, Physica Scripta (2009)]

- **In DEMO and future fusion power plants, this fraction must be > 90%**
  - Still unclear if these conditions can be achieved in reactor-sized machines while operating in H-mode [Kotschenreuther, Phys. Plasmas (2007)]

Snowflake (SF) divertor is proposed as an exhausted solution for DEMO

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

- **SF is a 2nd order null-point:** $\mathbf{B}_p = 0$ **and** $\nabla \mathbf{B}_p = 0$
  - In practice always two 1st order null-points
  - Larger region of low B_p near the null-point
    - + Increases connection length $L_{||}$
    - + Increases divertor volume V_{div}

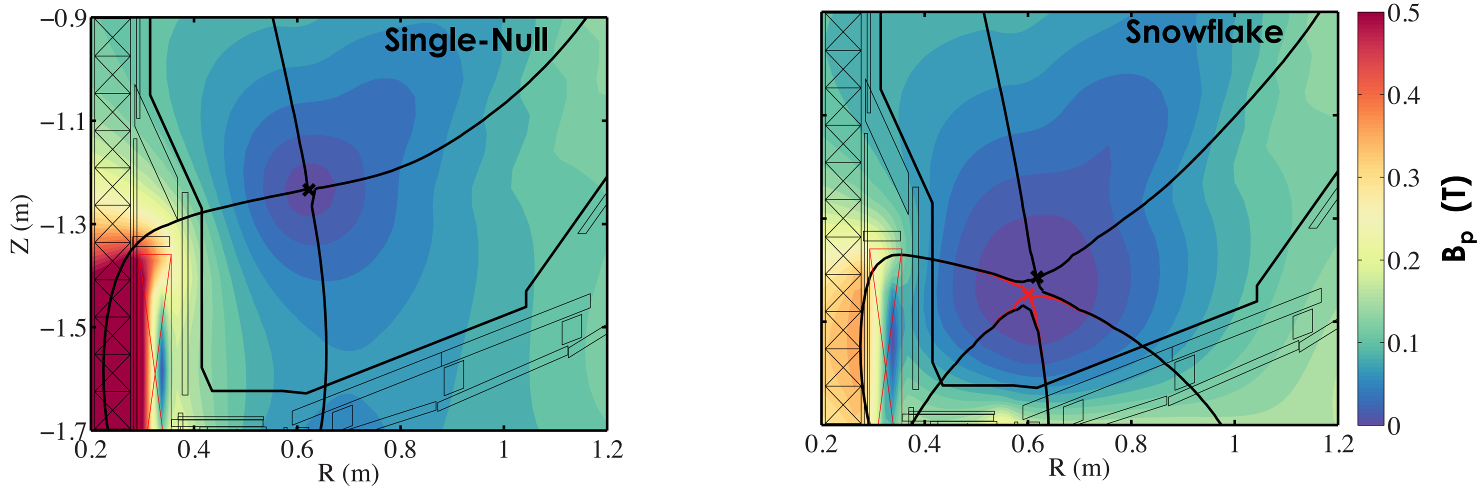


- **Potential advantages**
  - Greater $L_{||}$ decreases target temperature
  - Greater V_{div} may increase power and momentum losses
  - Greater $L_{||}$ broadens the SOL
  - Lower B_p may increase cross-field transport and broaden SOL

ELM control coils and SF divertor will have to operate simultaneously in future fusion power plants

- **ELM control coils and SF divertor are two potential solutions proposed to solve two separate outstanding issues on the road to a fusion reactor**

- **The SF configuration is expected to be more susceptible to non-axisymmetric perturbations due to its lower B_p in the null-point region**



- **In a reactor, these two solutions would have to operate simultaneously**
  - Needs to investigate their compatibility to identify possible conflicts that could prevent them from operating simultaneously

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- **The M3D-C^1 simulations of the NSTX-U snowflake divertor**
  - The M3D-C^1 code
  - The plasma response in the SN and SF configurations
  - The effect of the divertor configuration on the magnetic lobes
  - The use of impurities as a tool to understand the plasma response

- **Interaction between primary and secondary manifolds in the SF divertor**

- **Summary/Conclusions**

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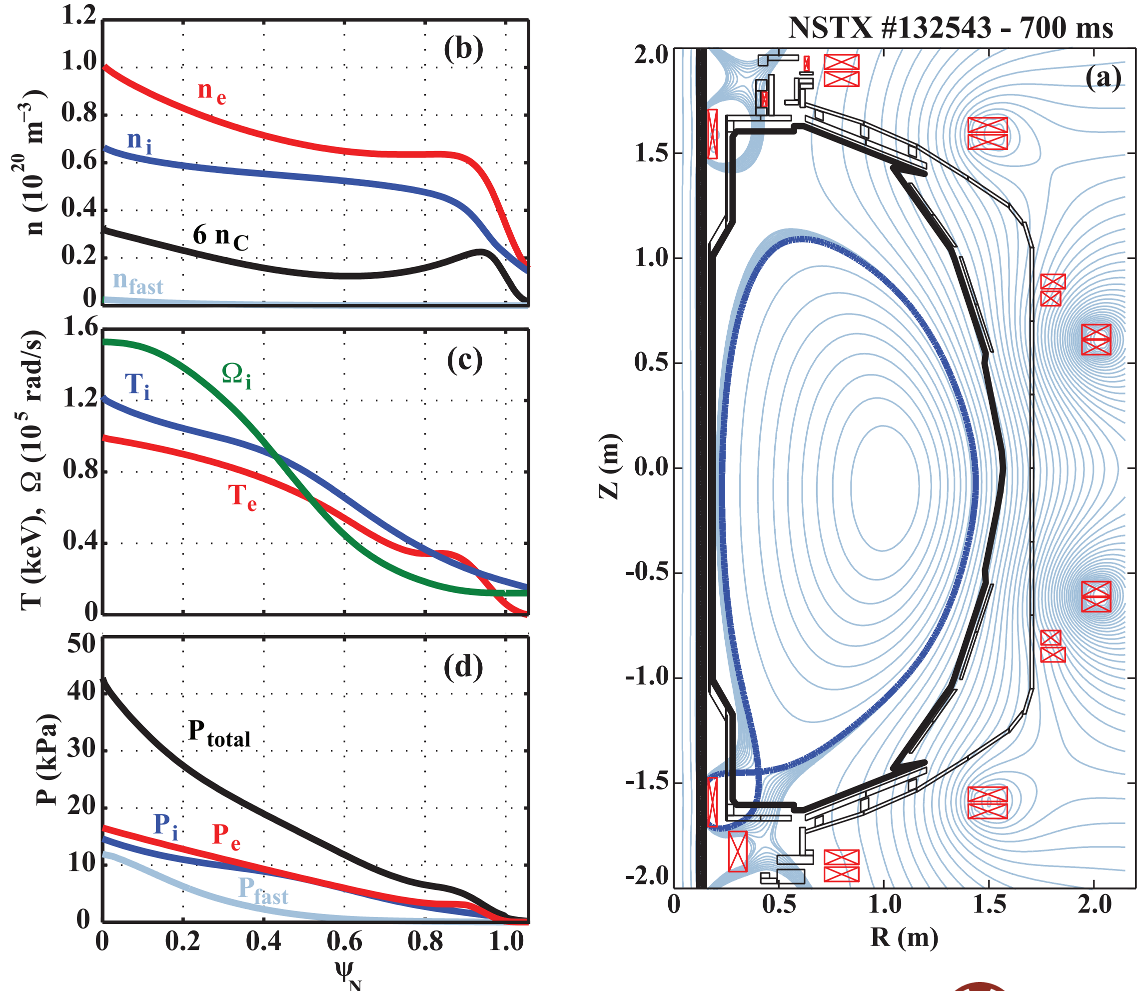
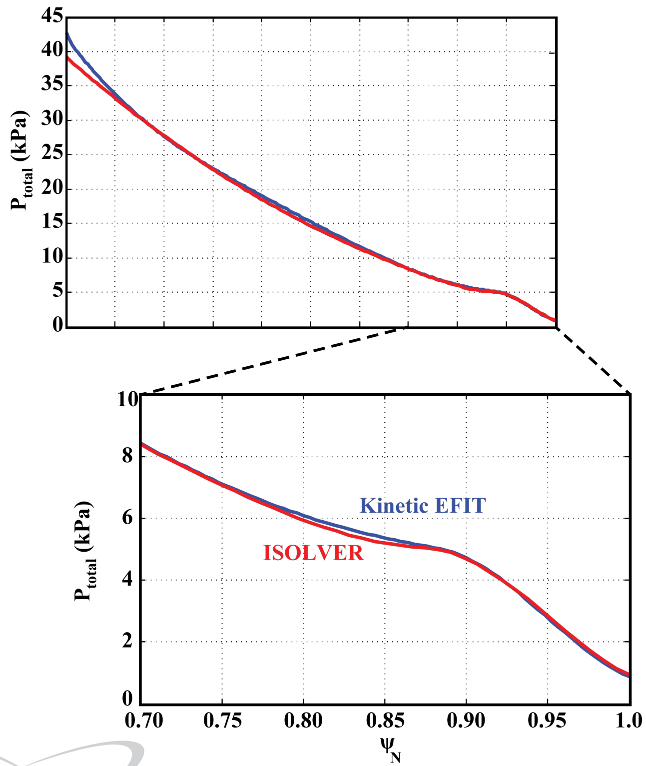
Simulated NSTX-U plasmas are based on equilibrium kinetic profiles from a reference NSTX discharge

- **Plasma parameters from the reference NSTX single-null (SN) discharge**
  - $I_P = 1.0$ MA
  - $B_T = -0.44$ T
  - $P_{NBI} = 6.0$ MW
  - $\kappa = 2.1$
  - $\delta_{top} = 0.37$
  - $\delta_{bot} = 0.71$

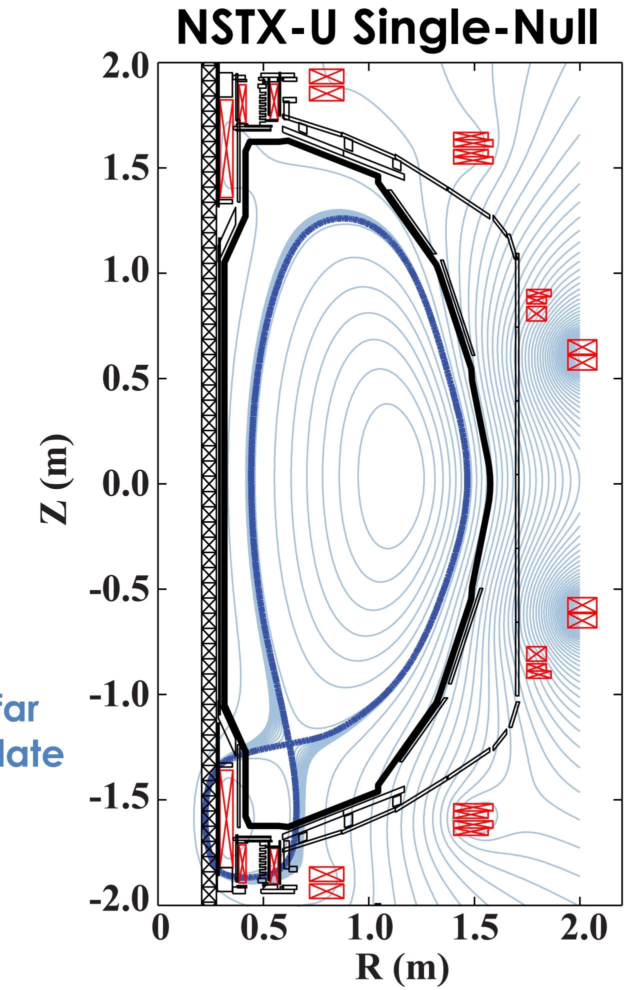


NSTX-U equilibria were generated using the code ISOLVER

- **ISOLVER calculations used P’ and FF’ from the reference NSTX discharge**
  - Total pressure profile assumed to be independent of divertor configuration [Soukhanovskii, *Phys. Plasmas* (2012)]



Primary x-point placed relatively far from targets to isolate null-point region



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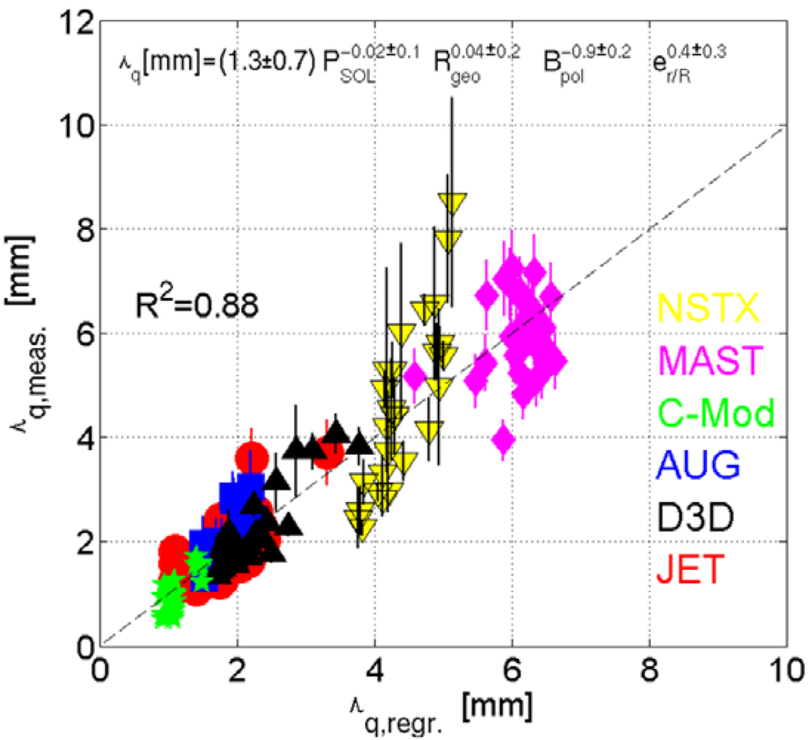
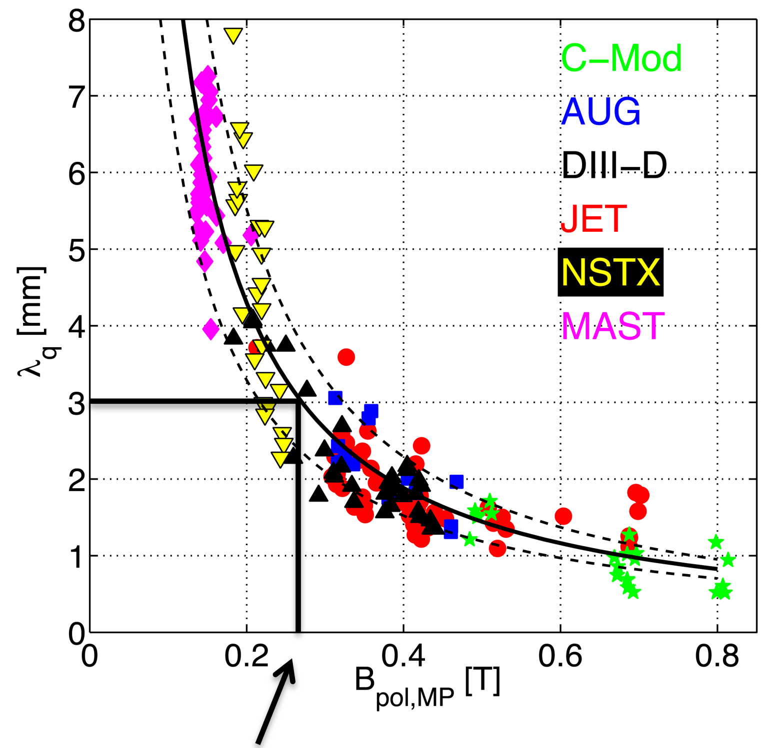
Regression in a multi-machine database provides an estimate for the NSTX-U H-mode SOL power fall-off length

- **Scaling predicts a power fall-off length, λ_q, as low as 3 mm for the plasma parameters used in this work** [T. Eich, *Nucl. Fusion* (2013)]

$$\lambda_q\,(\mathrm{mm}) = 1.35 \cdot P_{SOL}^{-0.02} \cdot R_{geo}^{0.04} \cdot B_{pol}^{-0.92} \cdot \varepsilon^{0.42} \approx 3\ \mathrm{mm}$$

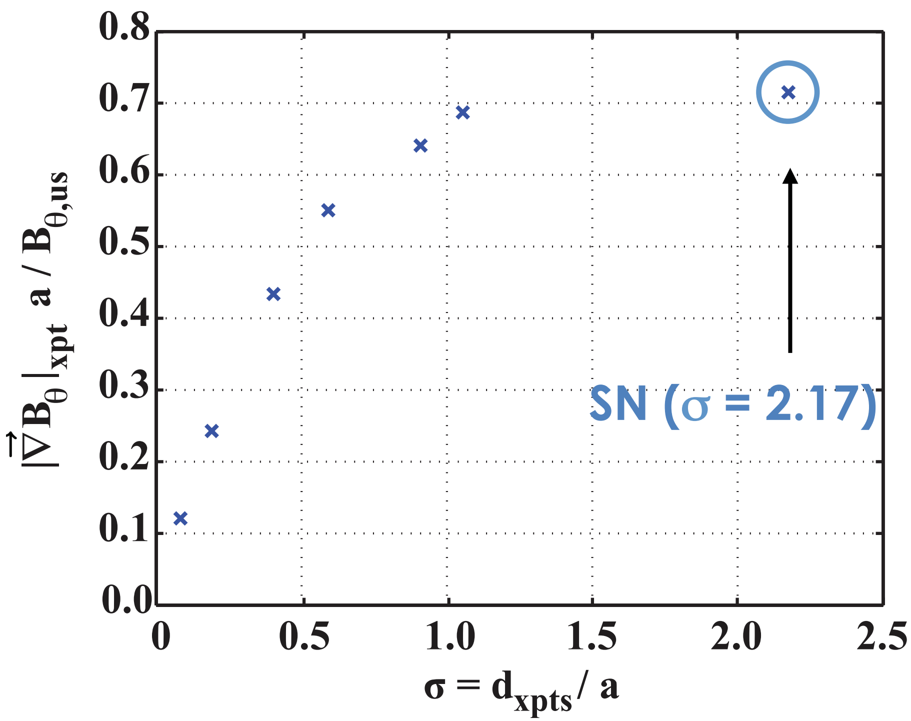


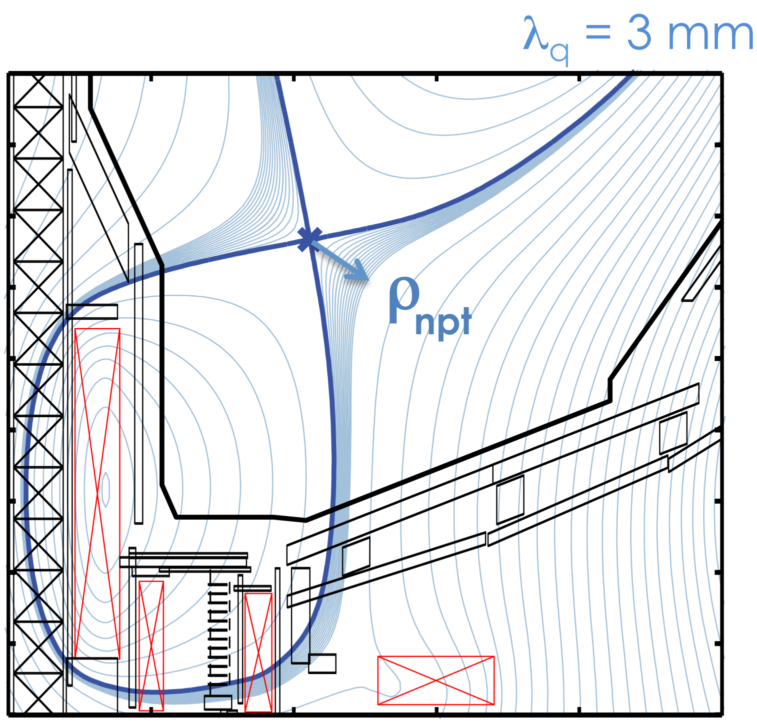


$B_{pol,MP}$ ~ 250 mT

NSTX-U divertor configuration is varied from a SN 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 to an exact SF





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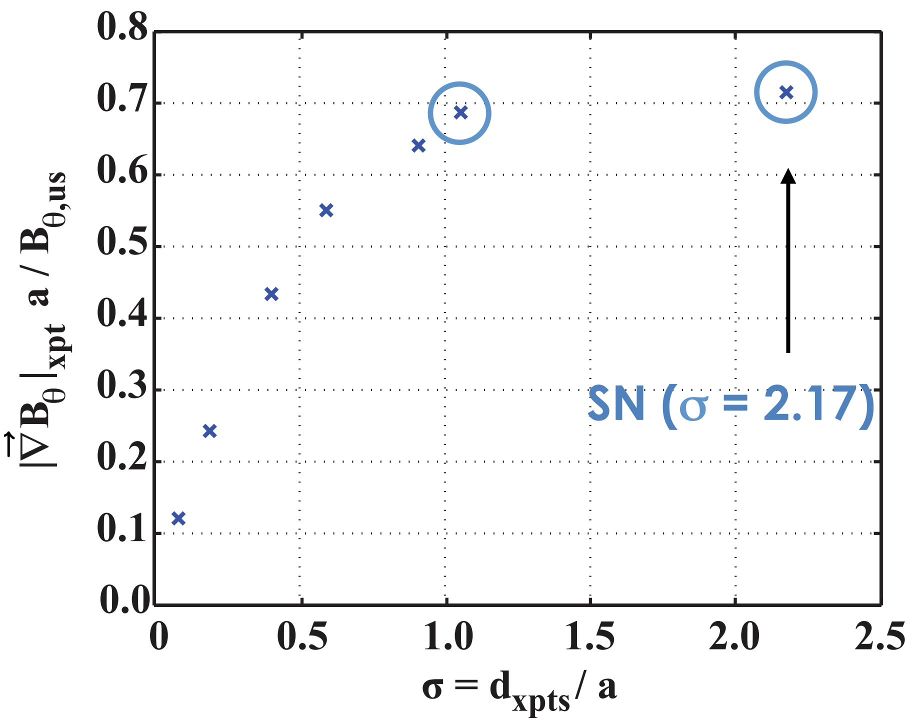

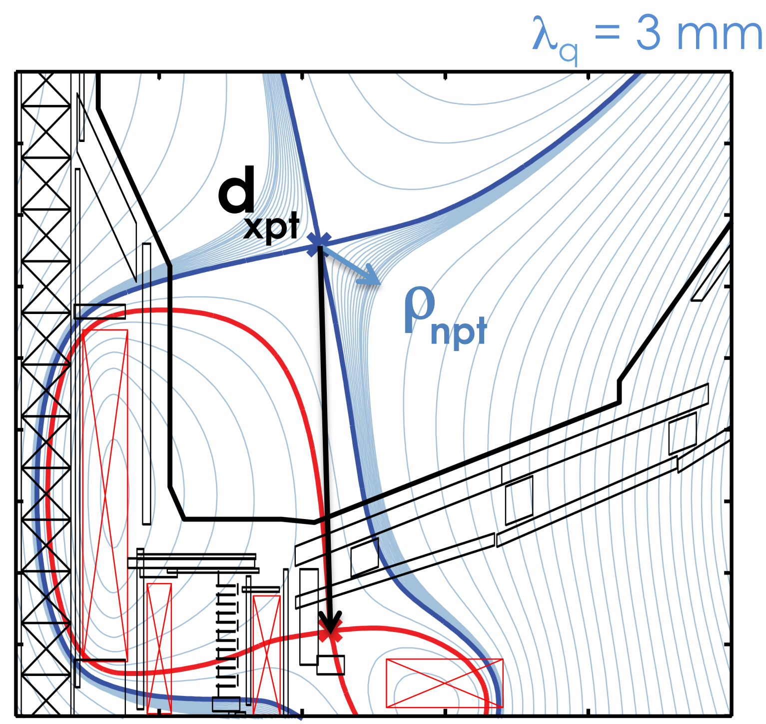

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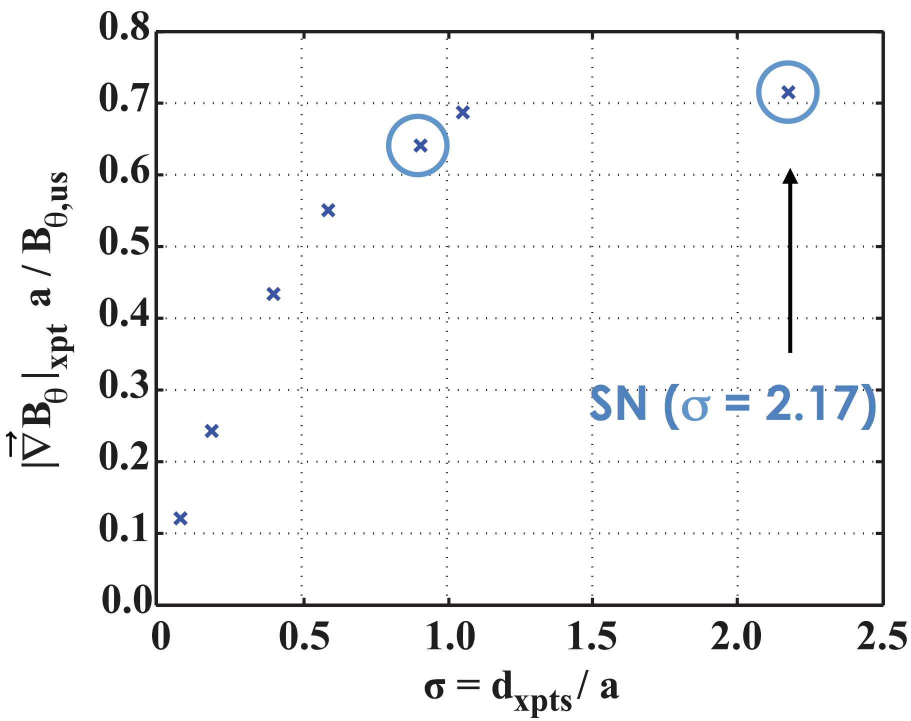

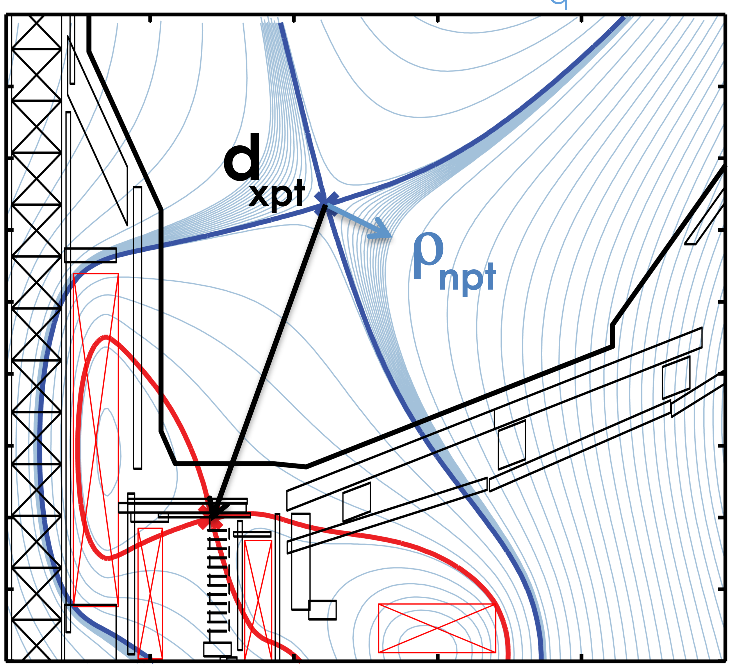

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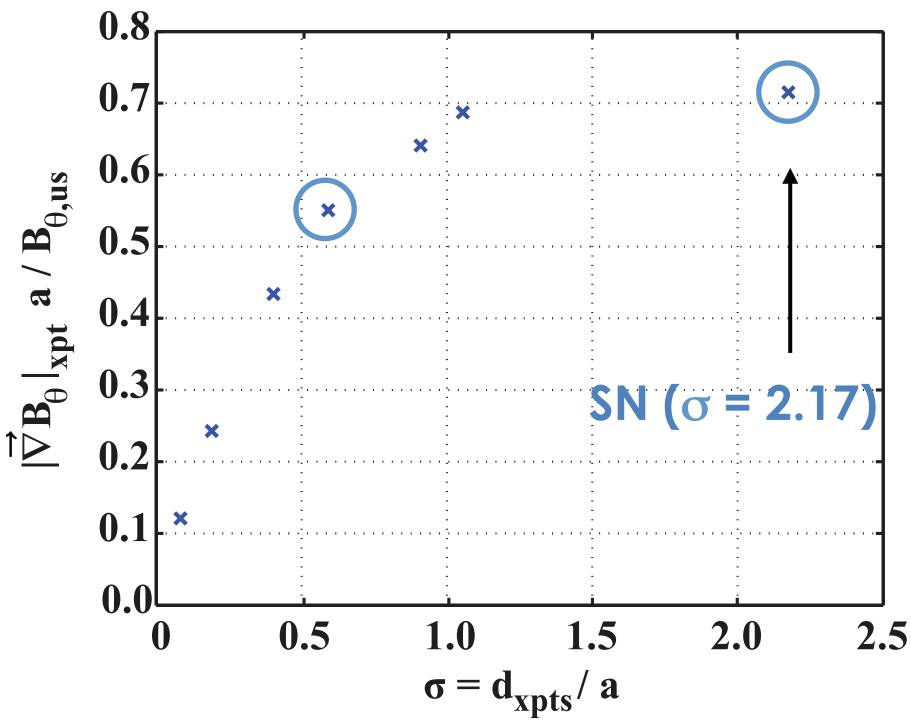

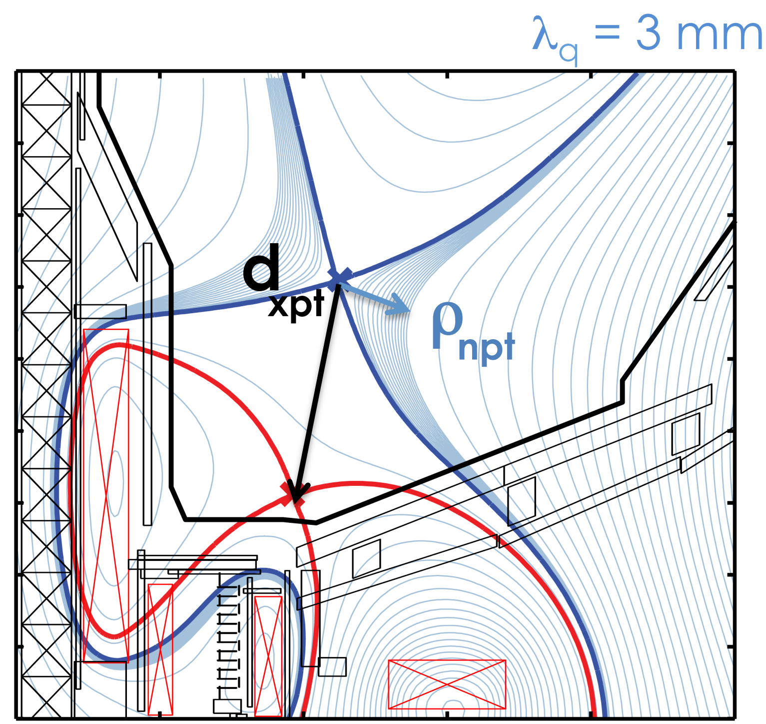

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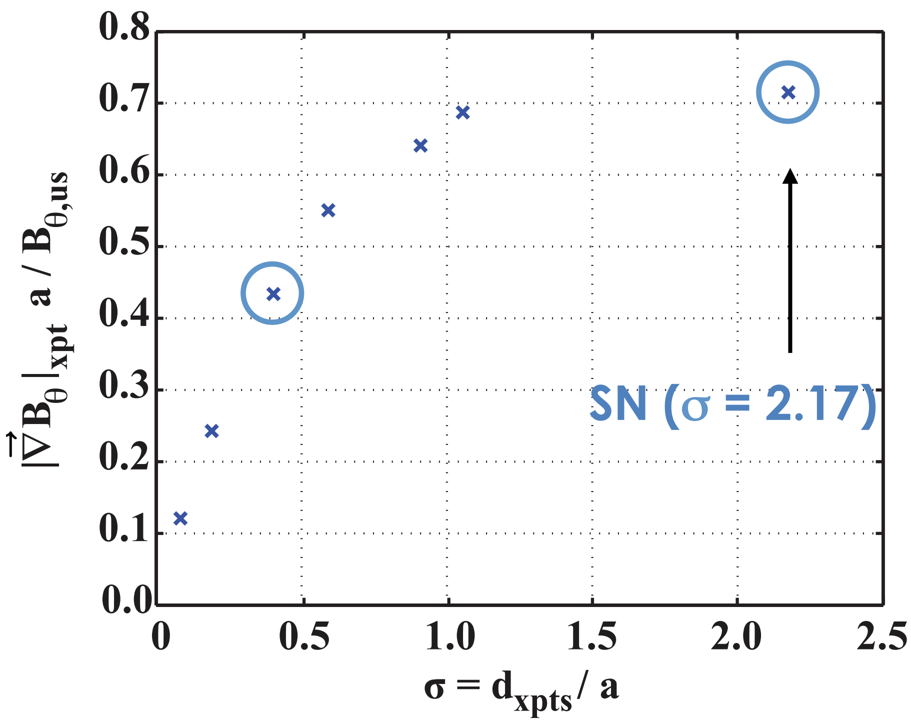

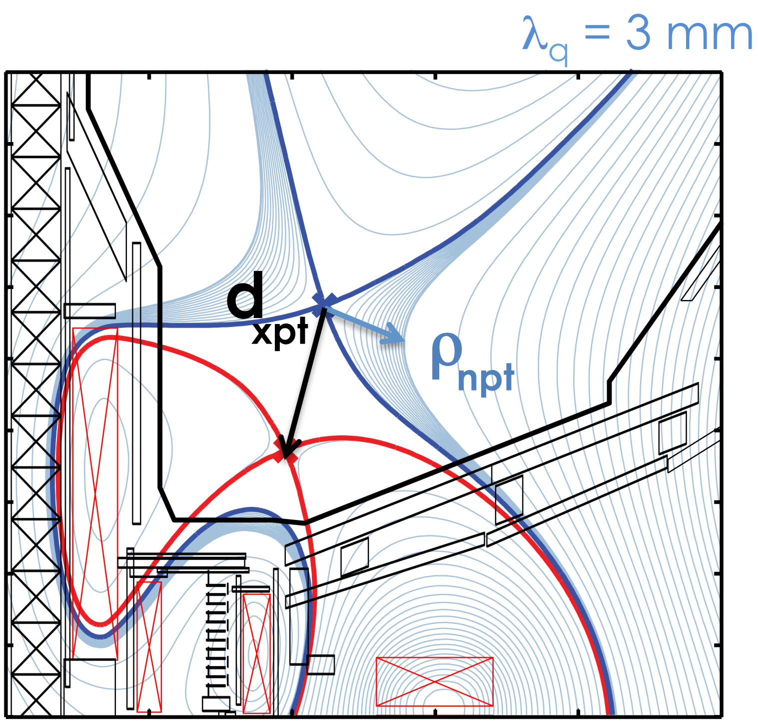

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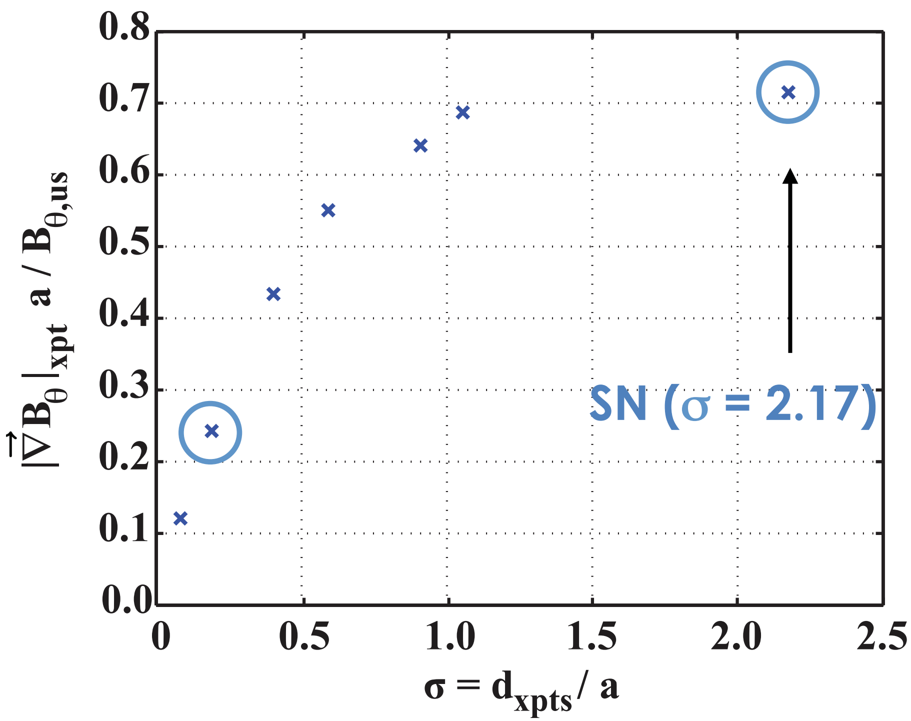

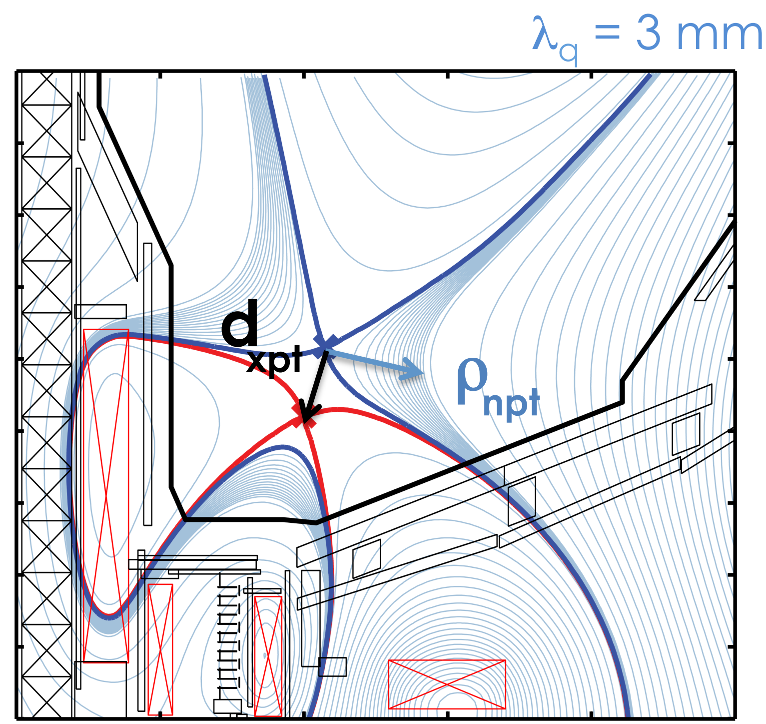

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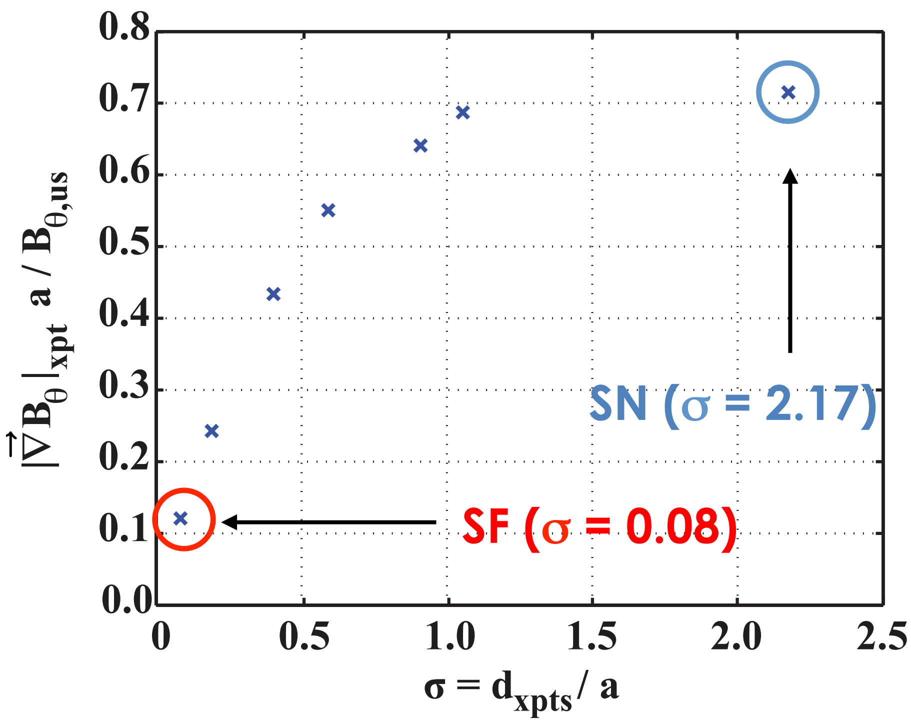
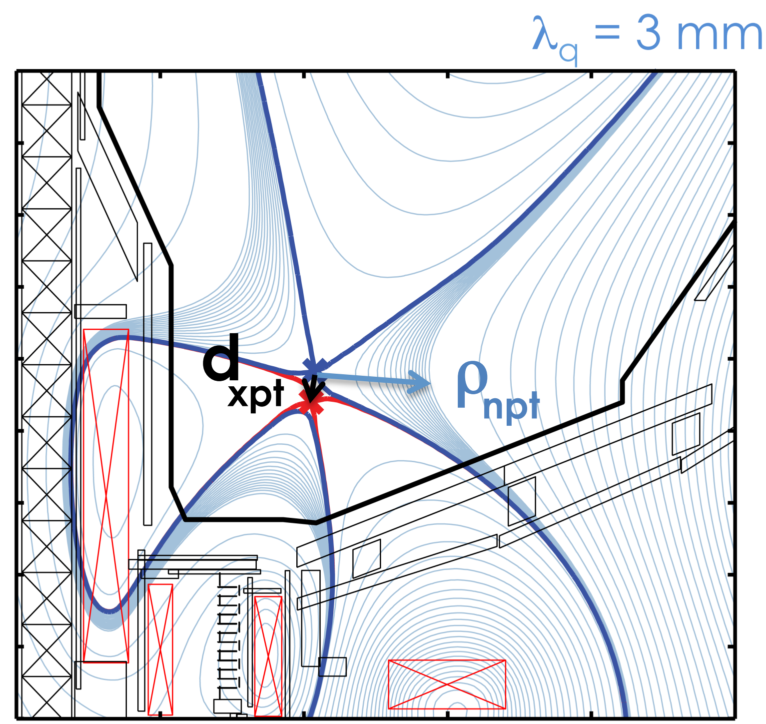
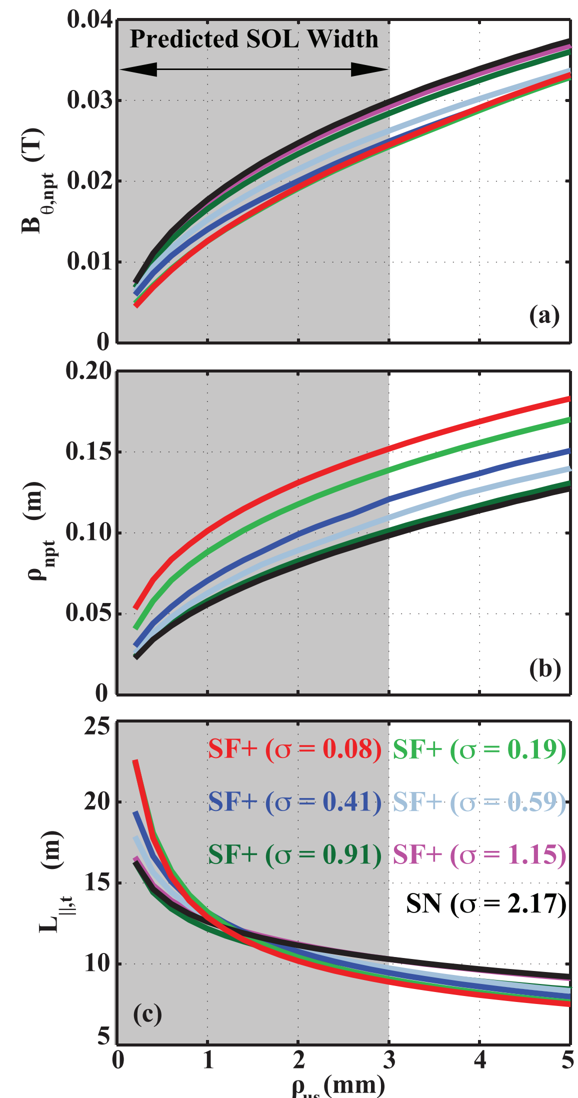




Any NSTX-U divertor configuration with σ > 1.0 behaves as a SN

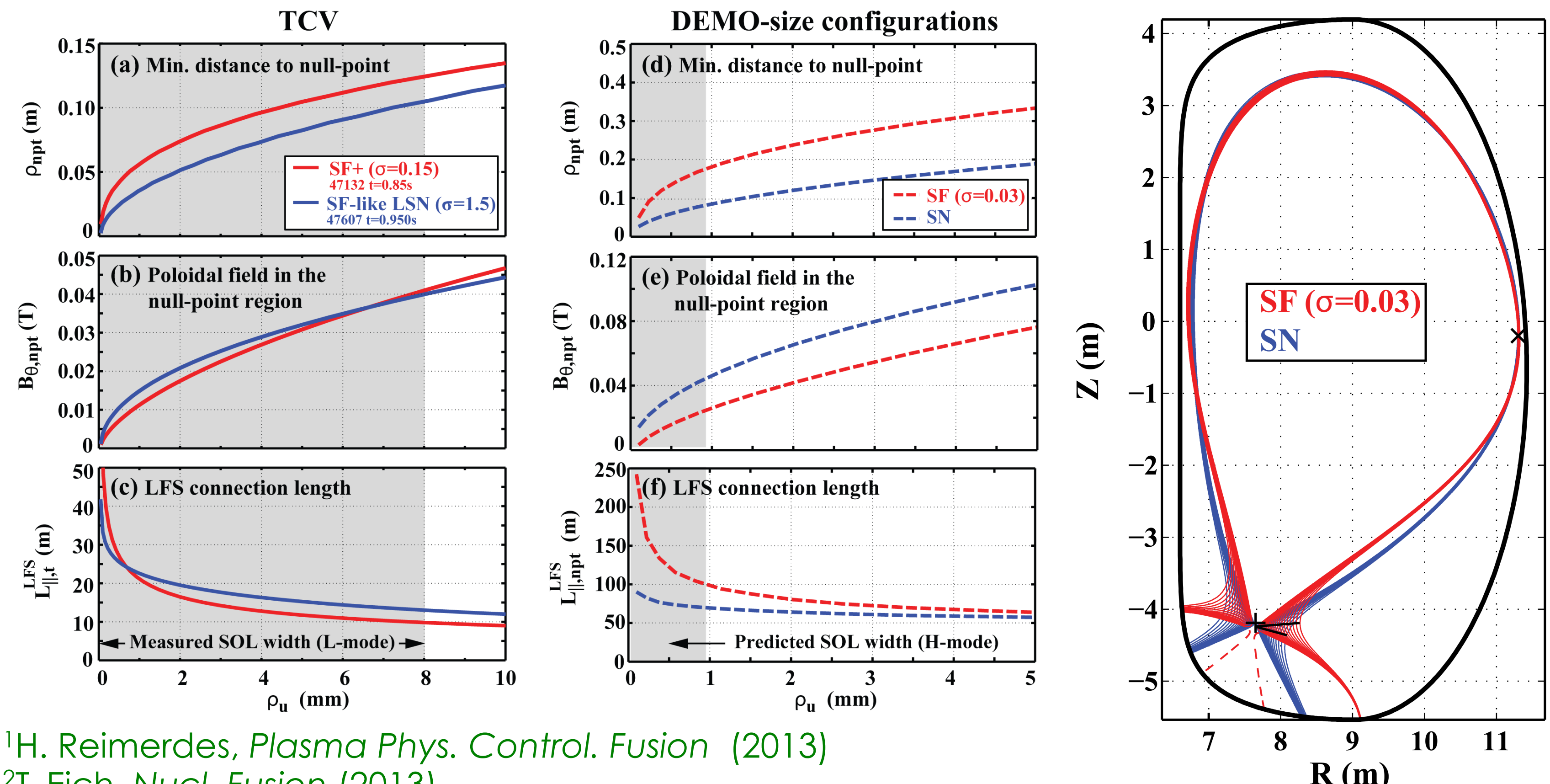
Geometrical properties of the NSTX-U snowflake configuration

- **Larger region of low Bp near the null-point**
  - May increase cross-field transport and broaden SOL
- **Significant increase in ρ_{npt}, which is closely related to the divertor volume**
  - Larger radiative losses
  - Greater energy and momentum transfer to neutrals
- **Only inner part of SOL experiences a longer connection length**
  - Lower electron temperature at the divertor target
  - Easier access to detachment
- **Outer part of SOL behaves as in a SN**
  - It is noteworthy that advantageous effects of the SF are noticeable experimentally



The advantageous properties of the snowflake divertor will be significantly enhanced in DEMO-size devices

- **Enhancement of the SF properties over a SN depends on the width of the SOL with respect to the linear dimensions of the device[1]**
  - SOL width is not expected to increase with the device size[2]



[1]H. Reimerdes, *Plasma Phys. Control. Fusion* (2013)
[2]T. Eich, *Nucl. Fusion* (2013)

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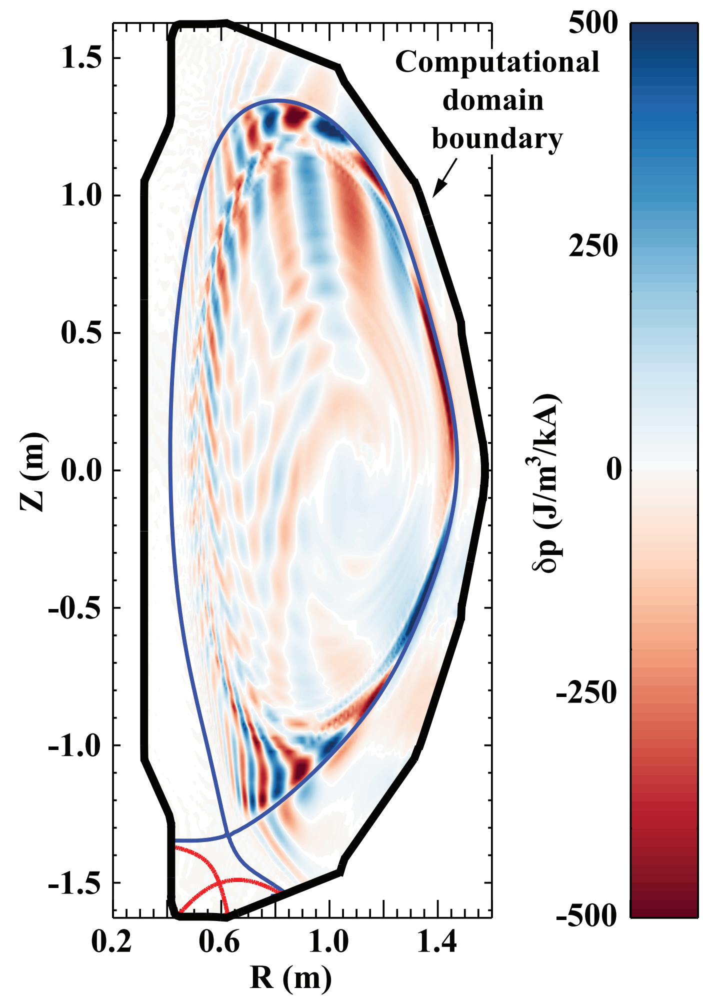
The plasma response to n = 3 magnetic perturbations is estimated using the code M3D-C[1]

- 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



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

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- **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

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

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

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

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

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

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

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

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

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

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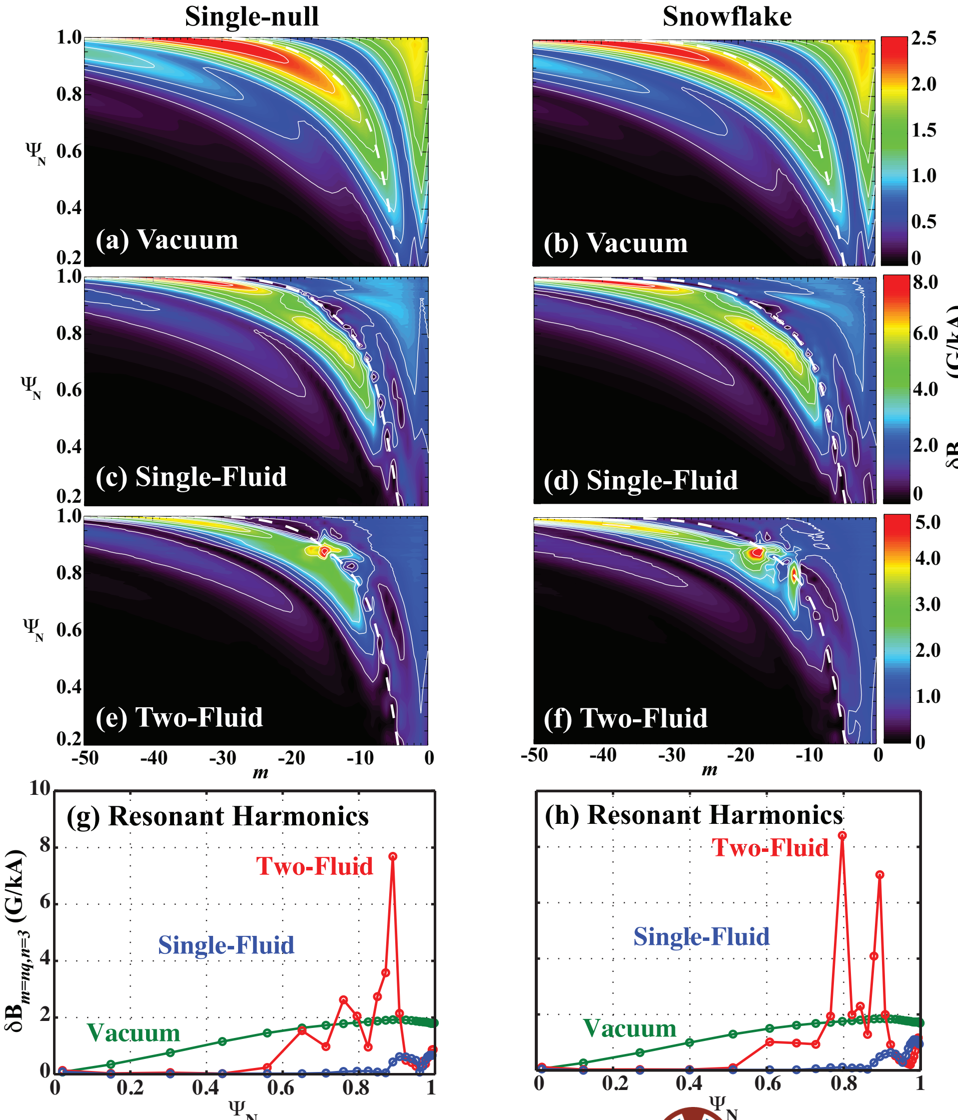
Vacuum approach, single- and two-fluid models provide substantially different results

- **Vacuum approach calculations provide almost identical results for SN and SF**
- **Single-fluid calculations show, for both SN and SF,**
  - Strong screening of resonant (tearing) harmonics
  - Strong amplification of non-resonant (kink) harmonics
- **Two-fluid calculations show**
  - Slightly stronger amplification of tearing harmonics in the SF than in the SN
  - Moderate edge kinks in both SN and SF configurations



The different screening mechanisms in the single- and two-fluid models can provide different plasma responses

- **The vacuum approach has no screening mechanism**

- **In the single-fluid model, the screening is provided only by the E x B rotation**

- **In the two-fluid model, the screening is also affected by the diamagnetic rotation**
  - In these calculations:

$$\vec{v}_\mathrm{i} = R\,\Omega_\mathrm{i}\left(\Psi\right)\hat{e}_\phi$$

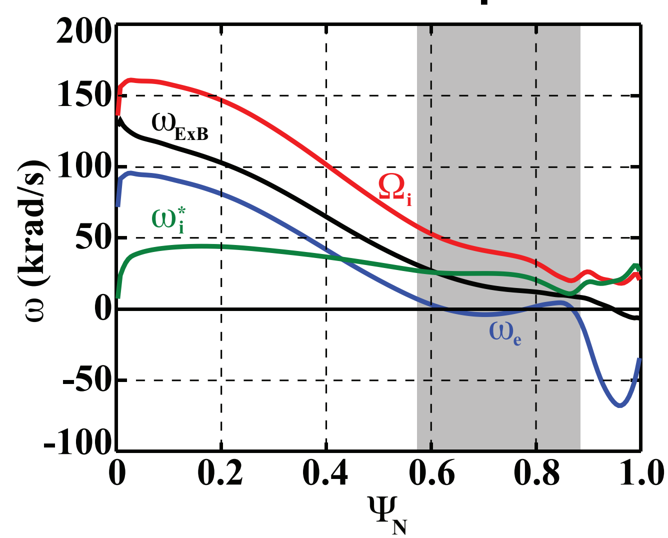
$$\vec{v}_\mathrm{e} = R\,\omega_\mathrm{e}\left(\Psi\right)\hat{e}_\phi + \frac{K\left(\Psi\right)}{n}\vec{B}$$

  - Note that:

$$\Omega_{\mathrm{e},\perp} = \frac{\vec{v}_\mathrm{e}}{R}\cdot\frac{\vec{B}_0\times\vec{\nabla}\Psi}{|\vec{B}_0\times\vec{\nabla}\Psi|} = \frac{B_\theta}{B}\omega_\mathrm{e}\left(\Psi\right)$$

$$\Omega_{\mathrm{e},\phi} = \frac{\vec{v}_\mathrm{e}\cdot\hat{e}_\phi}{R} = \omega_\mathrm{e}\left(\Psi\right) + \frac{B_\phi}{R\,n}K\left(\Psi\right)$$

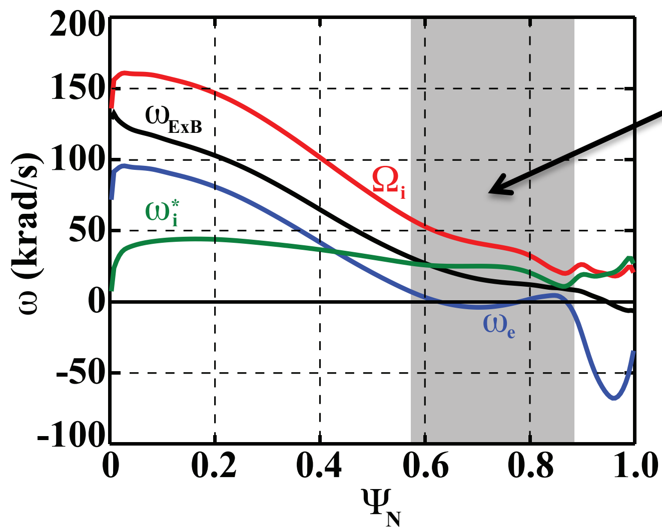
Plasma rotation profiles



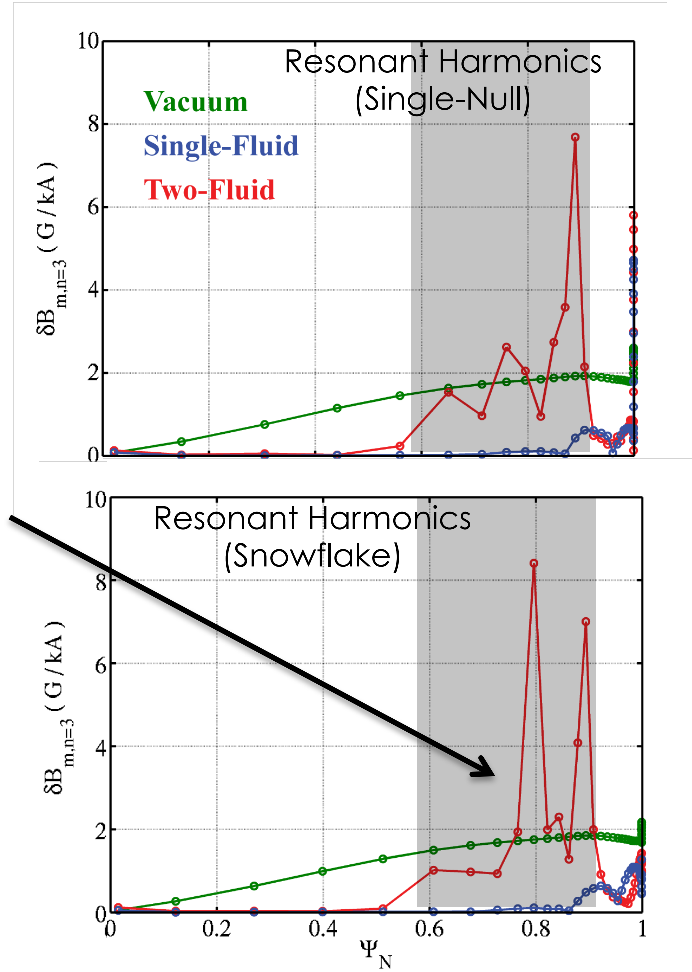
Amplification of tearing harmonics in the two-fluid calculations is caused by low $\Omega_{e,perp}$

- **Penetration of external perturbations into the plasma is determined by the electron perpendicular rotation $\Omega_{e,perp}$** [Ferraro, *Phys. Plasmas* (2012)]

- **Region of enhancement of resonant components coincides with region of low electron fluid rotation**



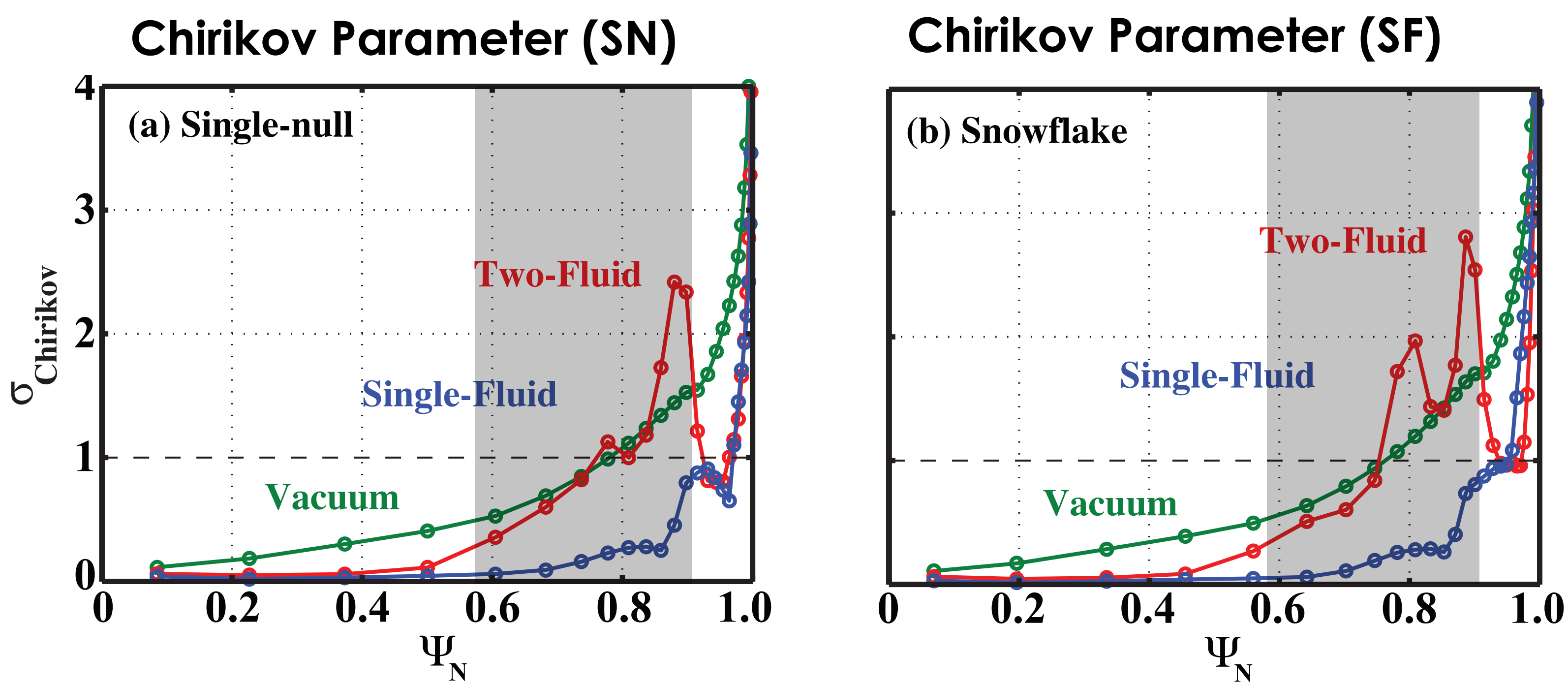
Low $\Omega_{e,perp}$



Coils closer to x-point could be more efficient in suppressing ELMs

Two-fluid model predicts a stochastic region significantly larger than single-fluid model

- **Amplified resonant harmonics in the two-fluid model indicate the formation of magnetic islands and stochastic region**



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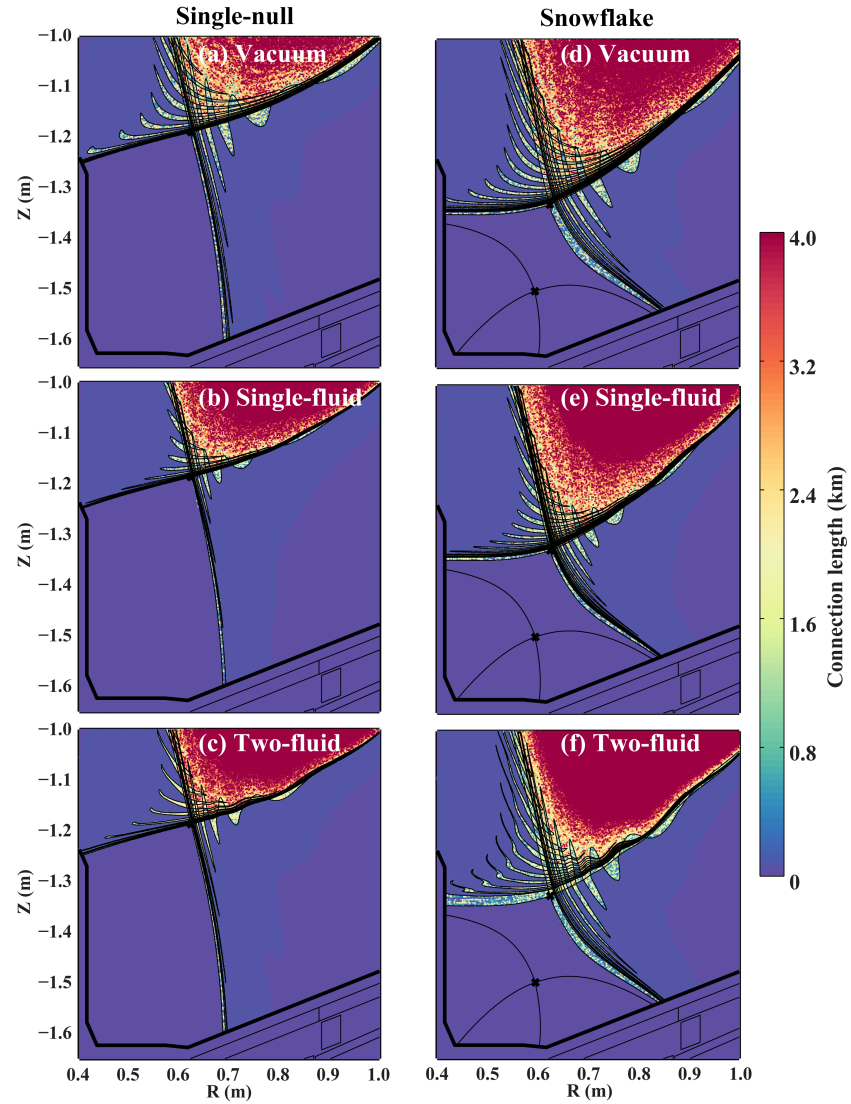
Lower B_p in the null-point region of the SF configuration leads to the formation of longer and additional lobes

- **TRIP3D-MAFOT calculations predict longer and more magnetic lobes in the SF**
  - These effects come from an interplay conservation of magnetic flux through the lobes and the lower B_p in the null-point region

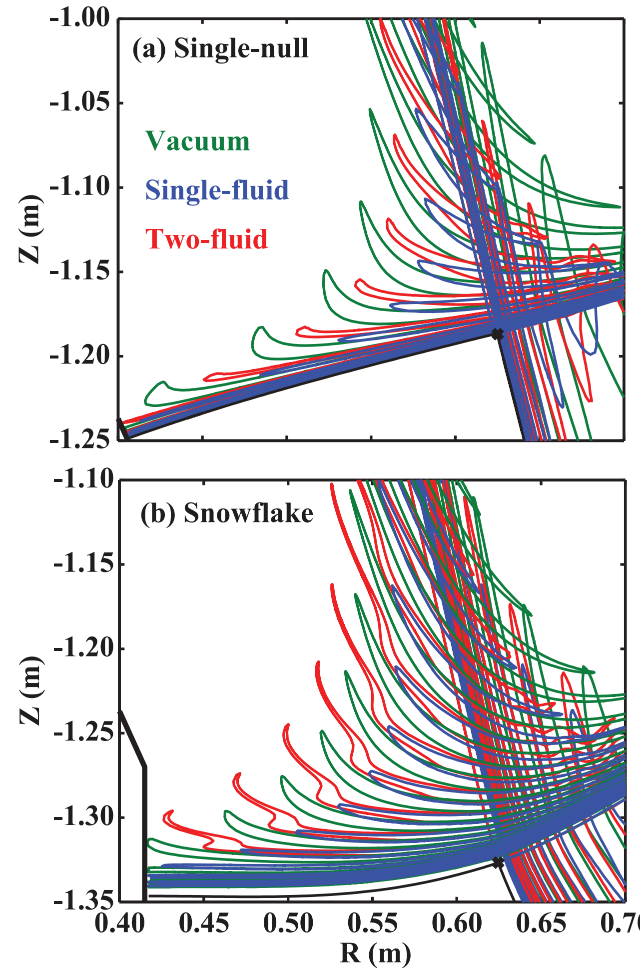
- **The intersection of these longer and additional lobes with the divertor plates is expected to cause additional striations in the particle and heat flux target profiles** [Frerichs, Phys Plasmas (2016)]



The size of the magnetic lobes seems to be more sensitive to resonant than to non-resonant harmonics

- **Two-fluid calculations predict longer lobes than in single-fluid for both SN and SF**
  - Result correlates with amplified resonant (tearing) harmonics in the two-fluid model and screened tearing harmonics in the single-fluid model
  - Non-resonant kink harmonics does not seem to affect the magnetic lobes size

- **Note that a toroidal phase from the plasma response affects the location of the lobes**
  - This should cause a toroidal shift in the predicted particle and heat flux target profiles



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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}**

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

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

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

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

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

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

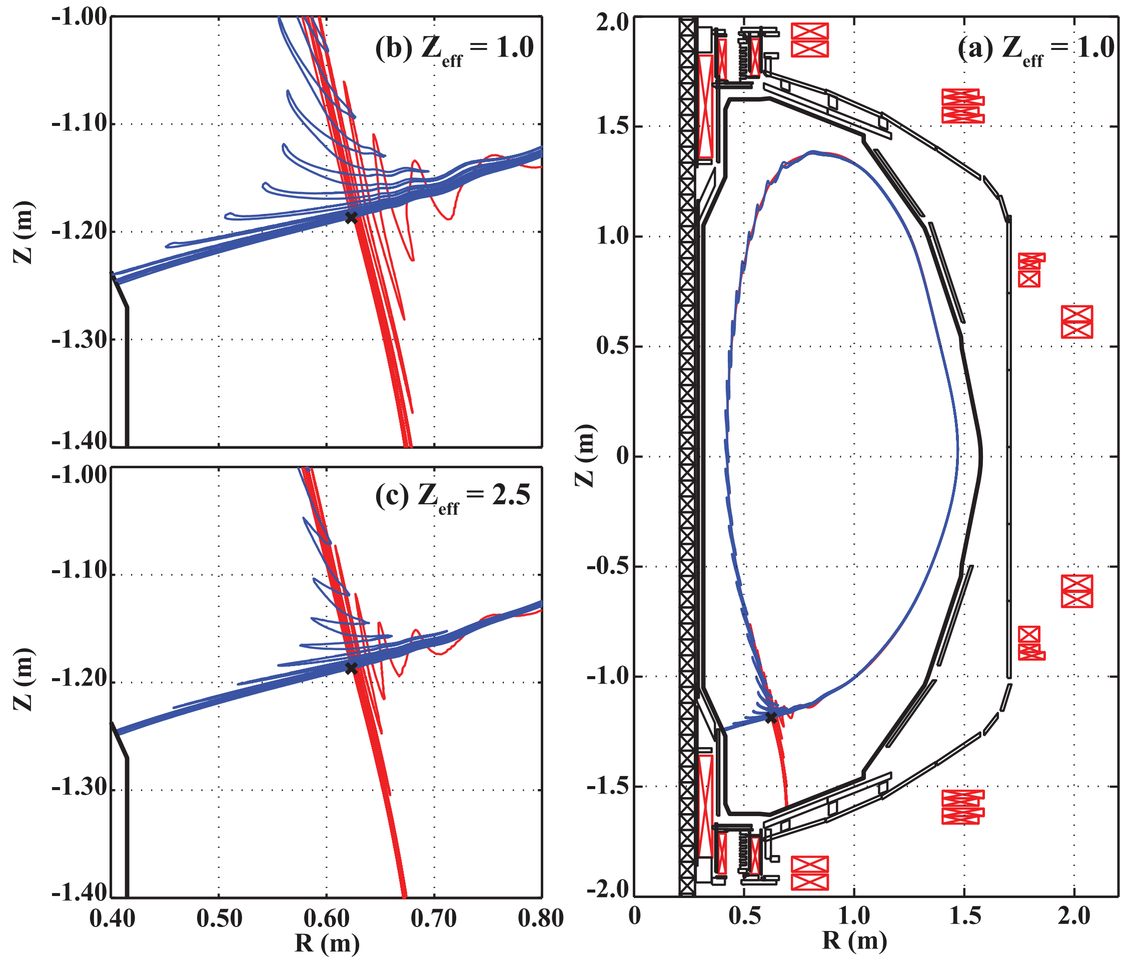
$$\mathbf{q} = -\kappa\nabla\left(\frac{p}{n}\right) - \kappa_{\|}\mathbf{b}\mathbf{b}\cdot\nabla\left(\frac{p_e}{n}\right)$$

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

M3D-C[1] calculations predict longer lobes in plasmas with lower Z_{eff}

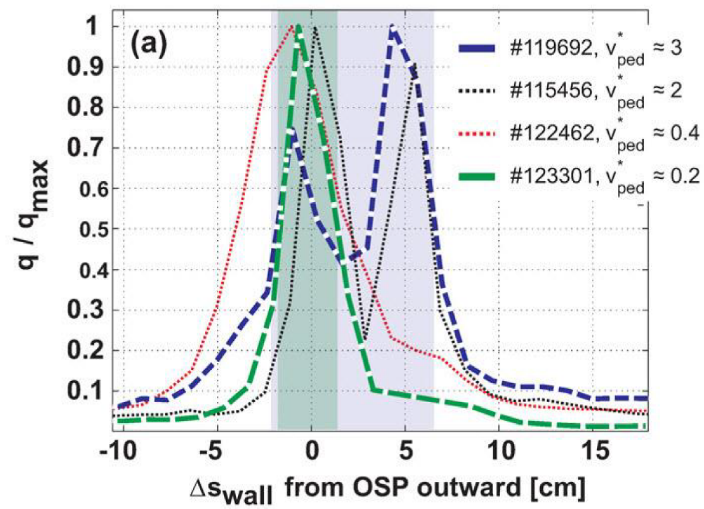
- **Impurities tend to reduce the importance of two-fluid effects**
  - Plasma responds as a single-fluid model

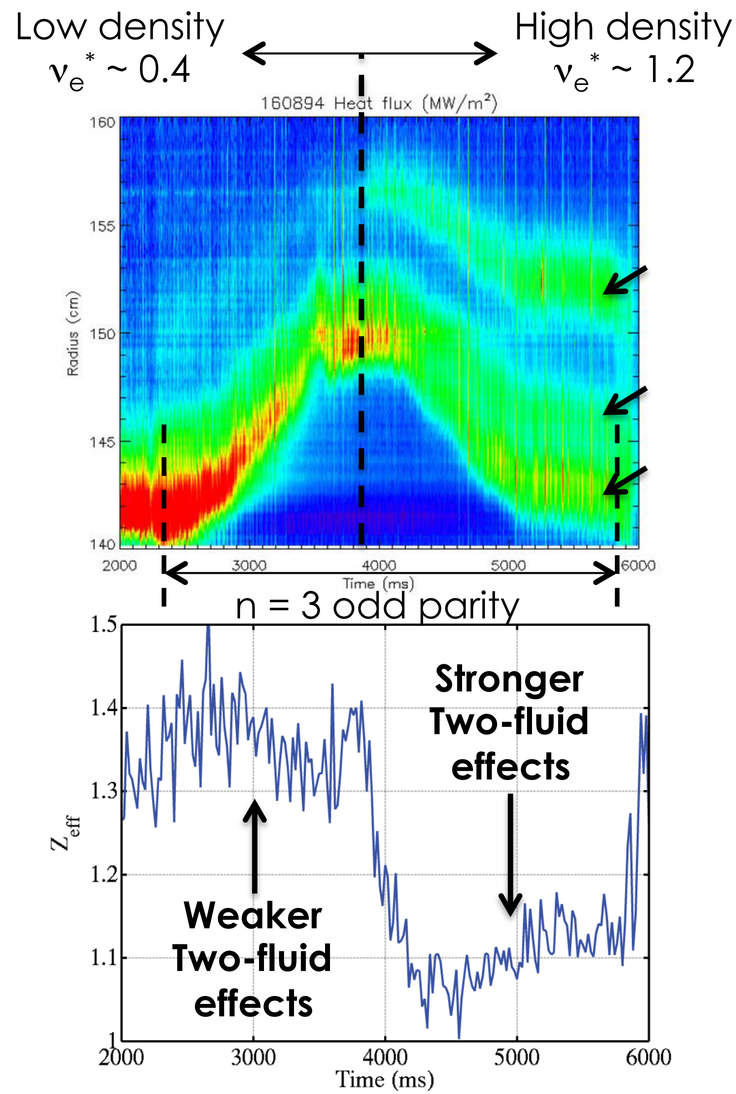
- **Setting Z_{eff} to more realistic values could decrease discrepancies between single- and two-fluid plasma response models**



Impurities might be used as an actuator to probe the importance of two-fluid effects in the plasma response

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





Outline: M3D-C^1 simulations of the plasma response to n = 3 magnetic perturbations applied to the NSTX-U snowflake divertor

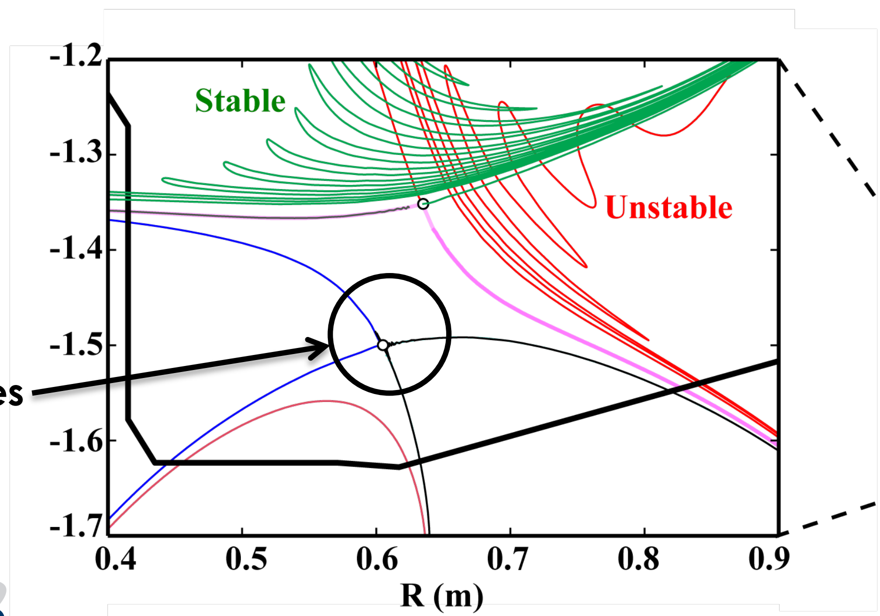
- Introduction
- The equilibrium properties of the NSTX-U snowflake configuration
- The M3D-C^1 simulations of the NSTX-U snowflake divertor
  - The M3D-C^1 code
  - The plasma response in the SN and SF configurations
  - The effect of the divertor configuration on the magnetic lobes
  - The use of impurities as a tool to understand the plasma response
- **Interaction between primary and secondary manifolds in the SF divertor**
- Summary/Conclusions

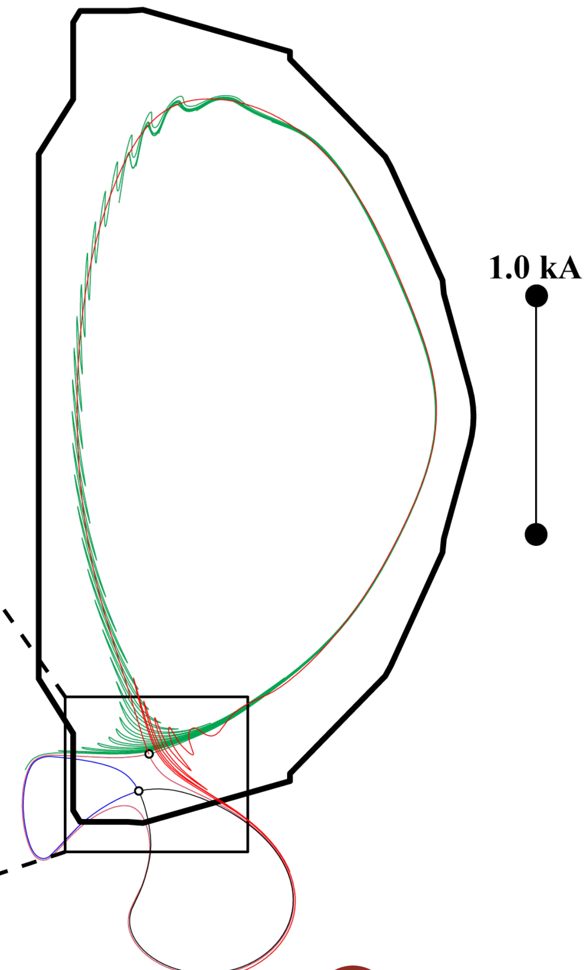
Effect of 3D magnetic perturbations on secondary manifolds is negligible

- **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

Very short lobes





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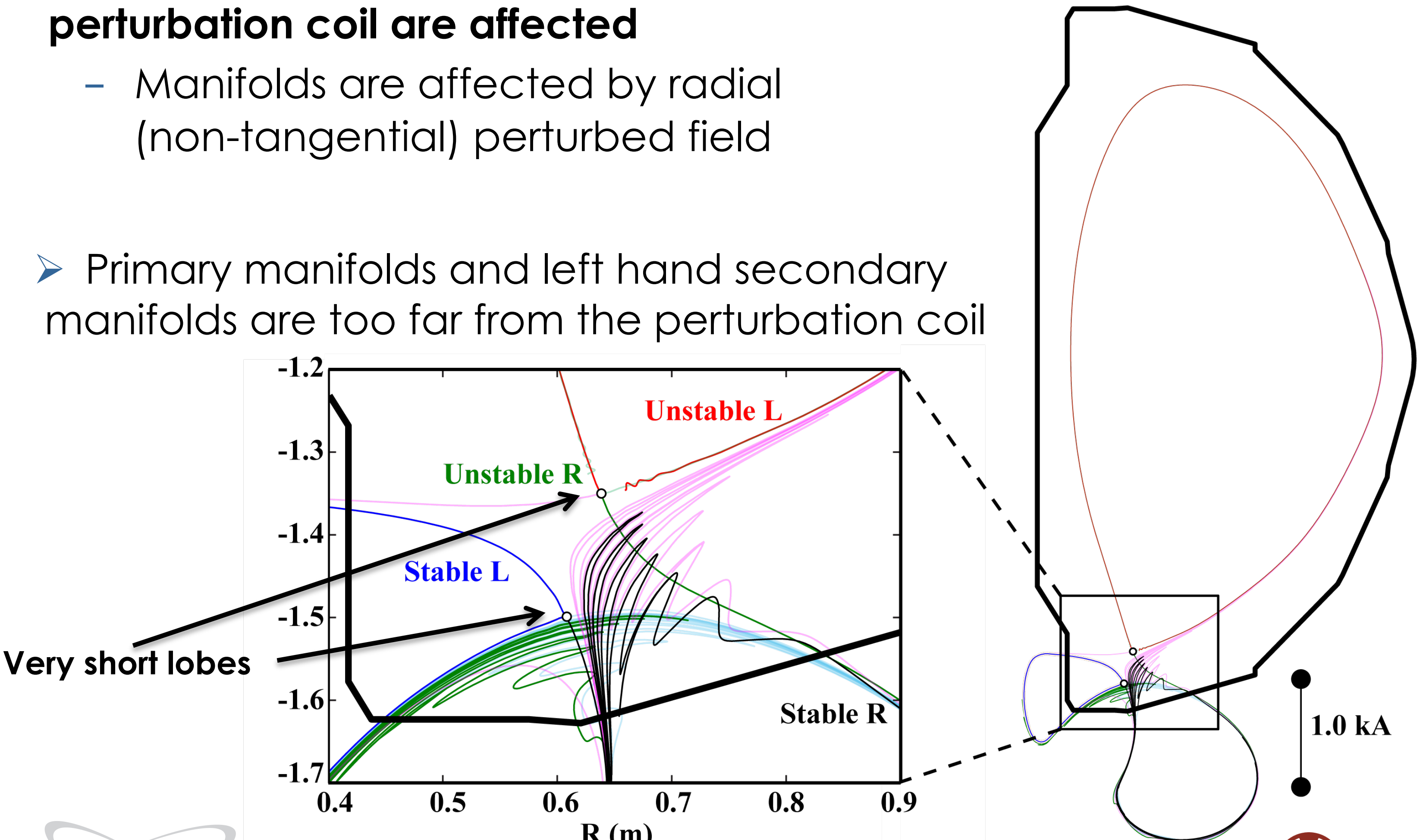
NSTX-U

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

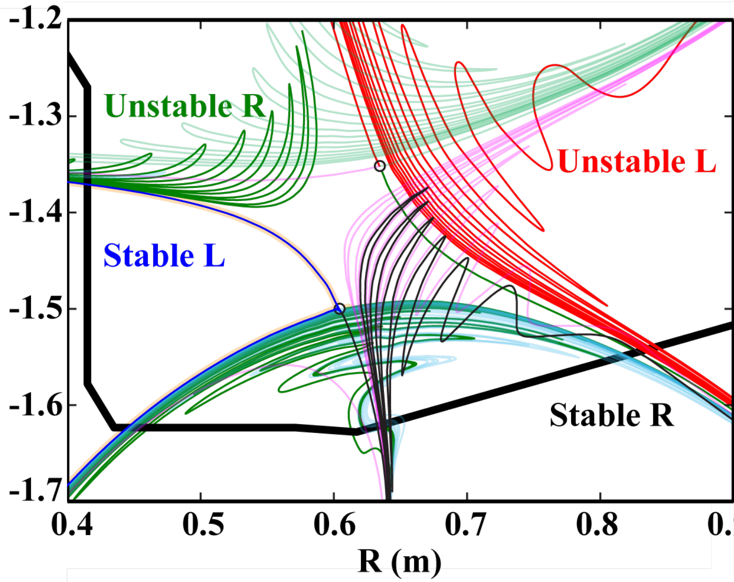


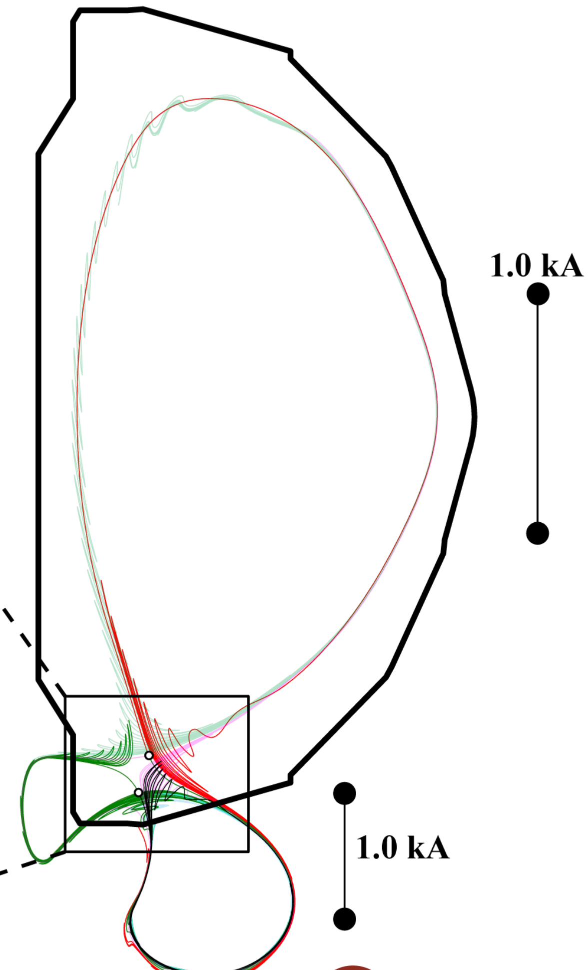
Primary and secondary manifolds are visible when both perturbation coils are used

- **Calculations show that, for a sufficiently close perturbation coil, both primary and secondary manifolds can be manipulated**

EMC3-Eirene transport simulations are in progress

  - Left hand secondary manifolds are still too far from the perturbation coil

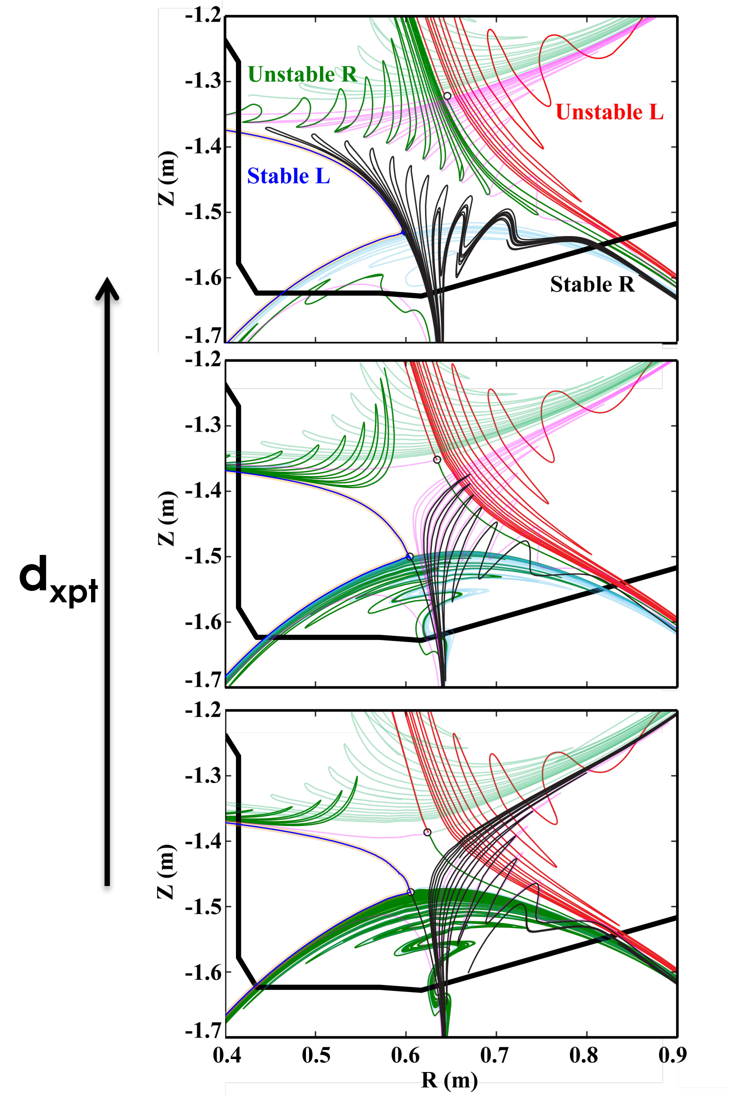




Primary and secondary manifolds interact at sufficiently short distance between x-points

- **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



Summary: No significant differences are expected between the plasma response from SN and SF

- **Equilibrium properties of the NSTX-U SF have been studied**
  - SOL properties are enhanced in the inner part of the SOL

- **Vacuum approach, single- and two-fluid models predict quite different plasma responses**
  - Differences caused by different screening mechanisms of each model
  - ELM control coils closer to the 1st x-point might be more efficient in suppressing ELMs: effect is enhanced in the SF 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 beneficial impact on plasma edge transport**