# M3D-C1 Simulations of the Plasma Response to Magnetic Perturbations in the NSTX-U Snowflake Divertor


Gustavo Paganini Canal[1]

in collaboration with

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São Paulo, May 10th, 2018

# Outline: M3D-C$^1$ simulations of the snowflake divertor

- **Introduction**
- **The properties of the NSTX-U snowflake equilibria**
- **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
- **Interaction between primary and secondary manifolds in the SF divertor**
- **Summary/Conclusions**

**For more details see G.P. Canal, Nuclear Fusion (2017) 57 076007**

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# 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)]

- **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)]

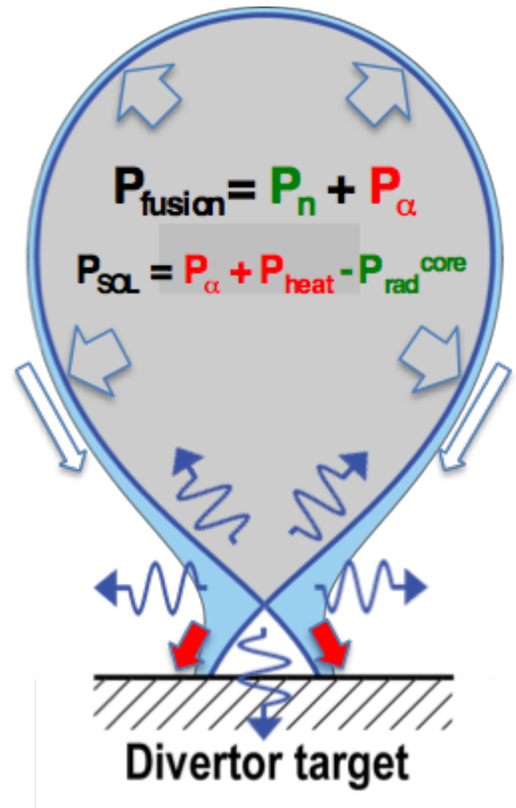
- **In Demo and future fusion reactors, ELMs will not be tolerated**
  - Solution for ELMs come in the form of applied 3D magnetic perturbations [A. Loarte, *Nucl. Fusion* (2014)]
  - The effect of 3D magnetic perturbations in the SF configuration has to be investigated

# High heat flux in a reactor will require a new strategy to reduce the power loads onto the divertor targets

- **Heat flux expected to increase significantly with the toroidal magnetic field**

$$P_{div} \propto (1 - f_{rad})\, R_0^{1.65}\, B_0^{1.65}$$

- **Increase heat flux capability of divertor material**



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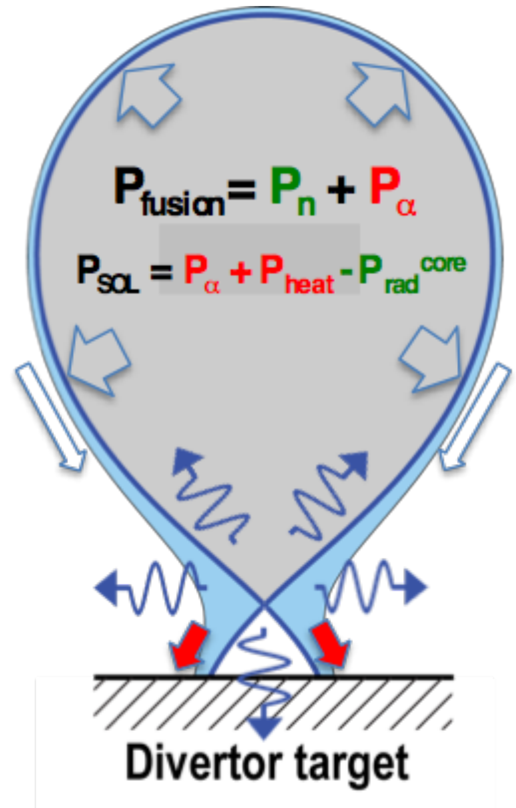
- **Increase heat flux capability of divertor material**
- **Increase the radiation fraction**
  - Impurity seeding, increase divertor volume, connection length
- **Increase the power distribution**
  - Major radius, SOL width, number of legs




**Modify the conventional divertor configuration**

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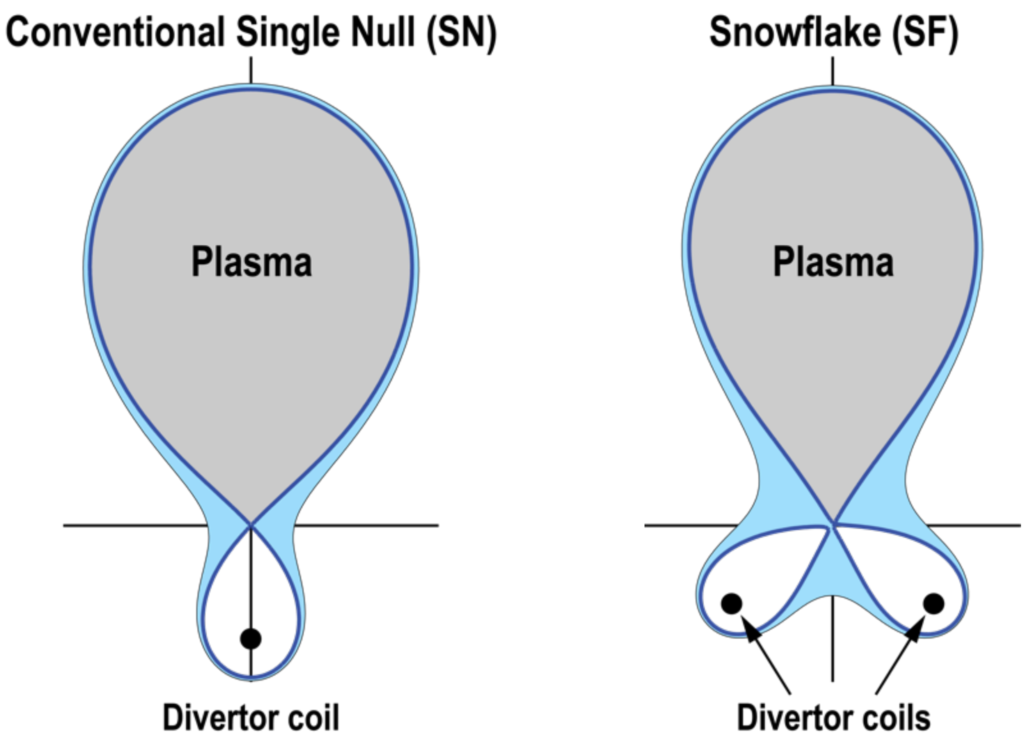
# Snowflake configuration proposed as a possible solution to reduce target power loads

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

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




$$\left|\mathbf{B}_P^{SN}\right| \propto \rho_{npt} \qquad \left|\mathbf{B}_P^{SF}\right| \propto \rho_{npt}^{\ 2}$$

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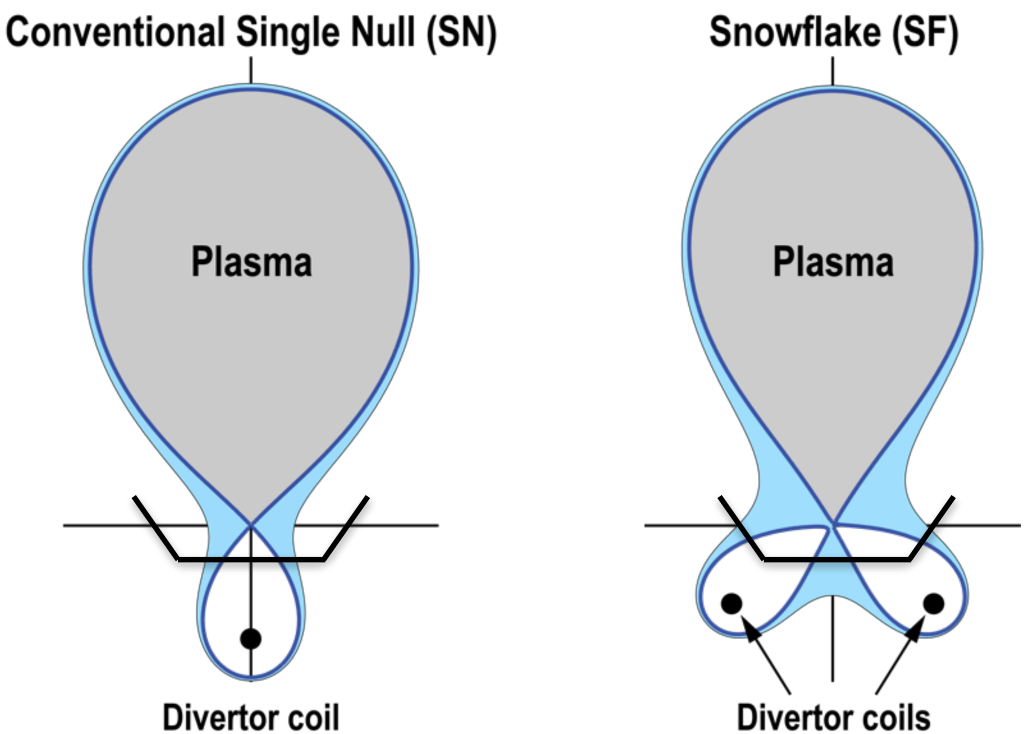


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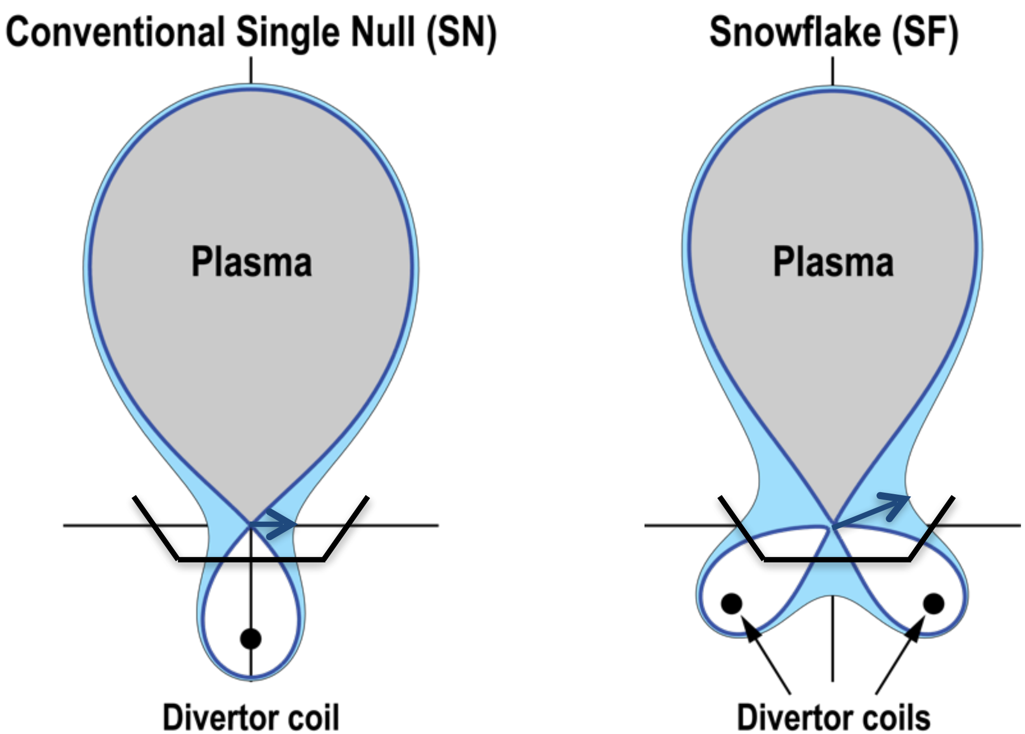
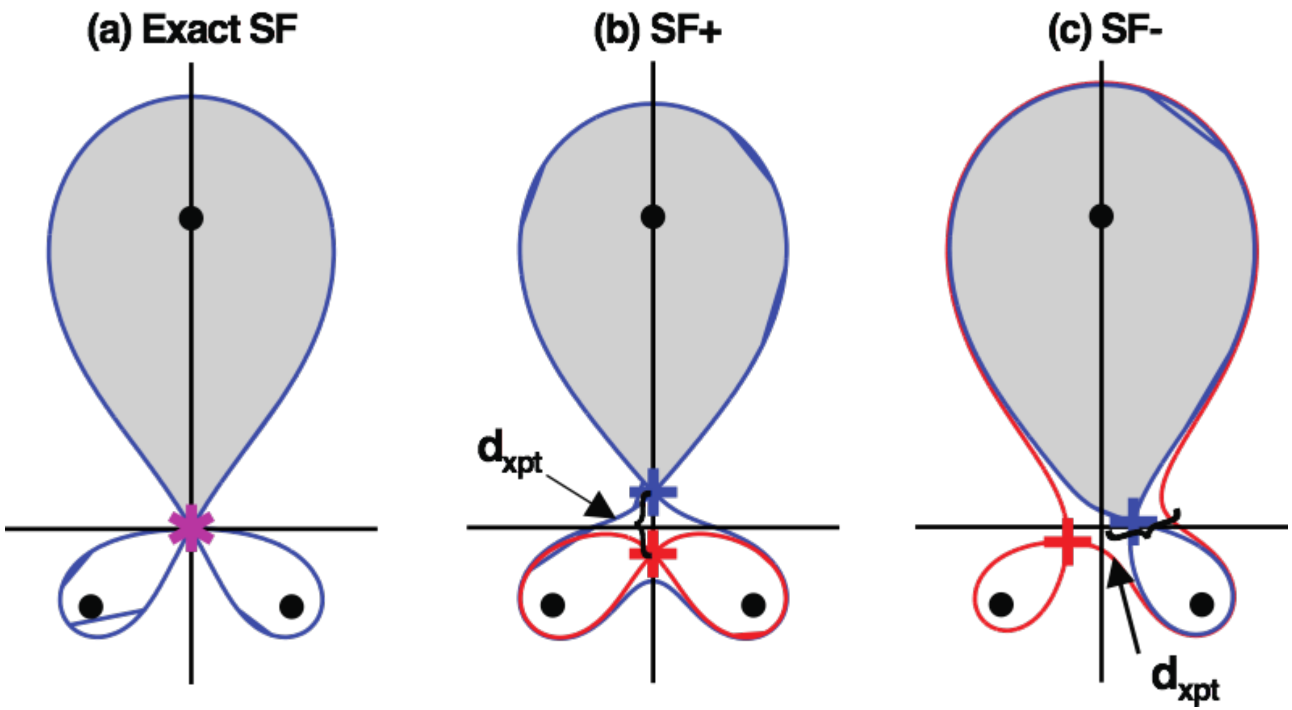



$\left|\mathbf{B}_P^{SN}\right| \propto \rho_{npt}$ $\quad$ $\left|\mathbf{B}_P^{SF}\right| \propto \rho_{npt}^{\;2}$

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

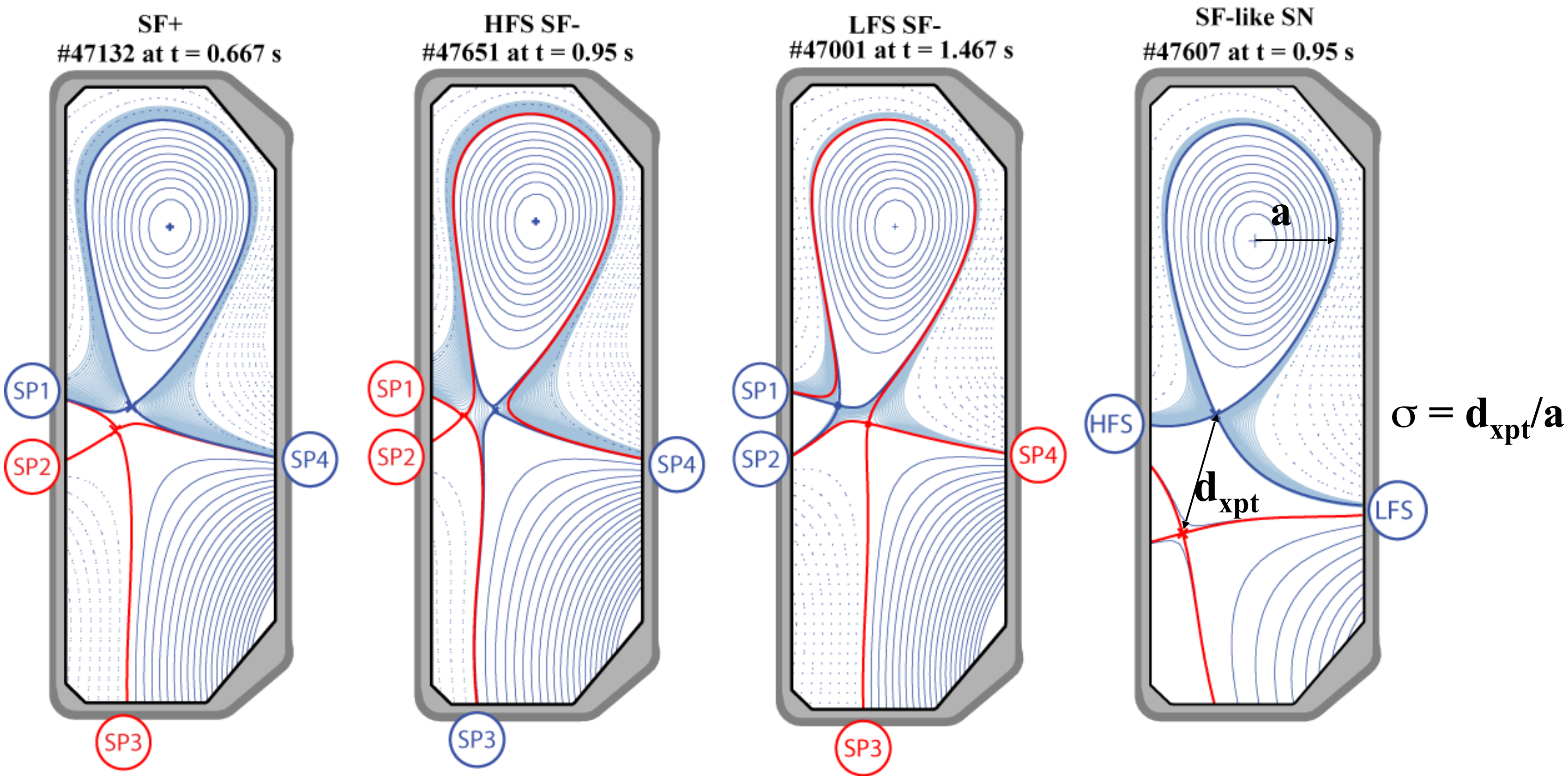
# In practice any snowflake has two nearby x-points




Proximity to SF:
$\sigma = d_{x\text{-pointt}} / a$

- **Snowflake plus (SF+):** Secondary x-point is in the private flux region
- **Snowflake minus (SF-):** Secondary x-point is in the common flux region

# The TCV was the first machine to create and investigate the various snowflake configurations

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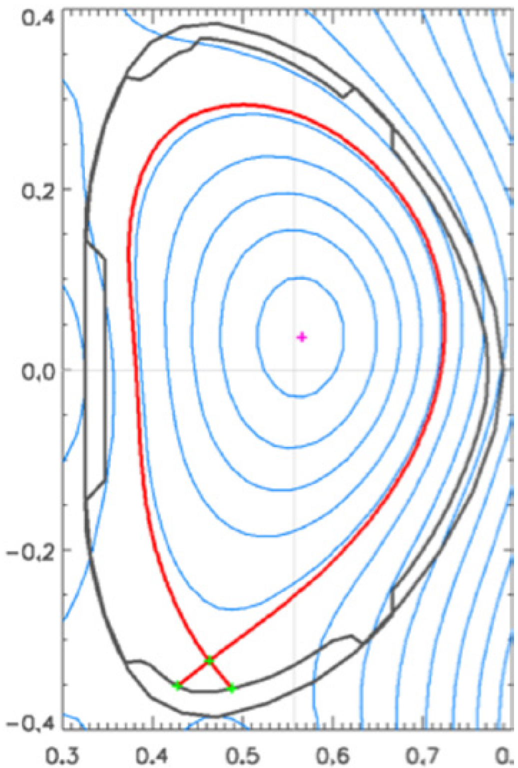
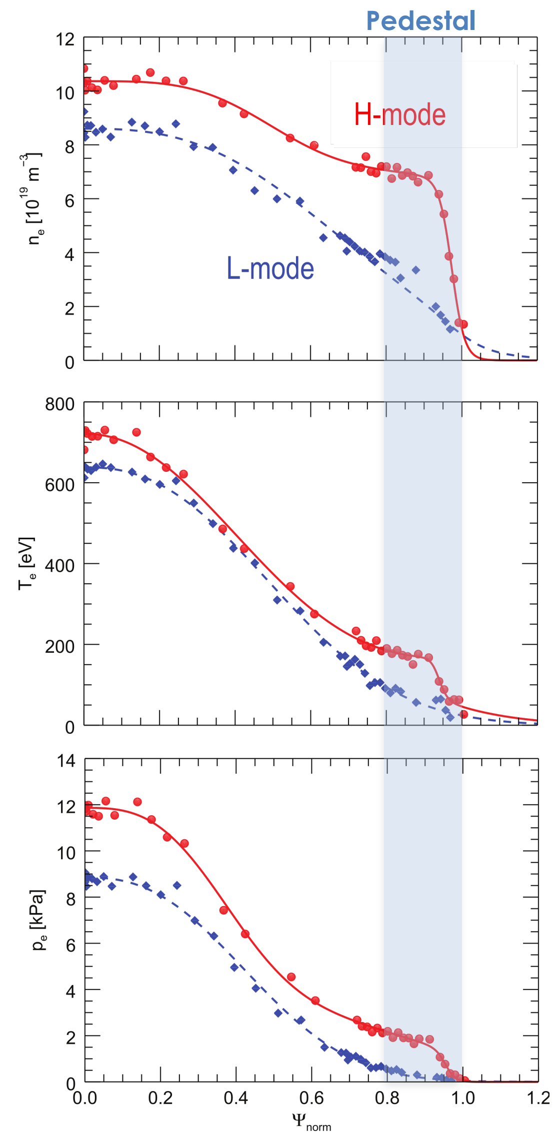
# High confinement mode is the most promising operational mode for achieving thermonuclear fusion

- **Main signature of an H-mode is a transport barrier in the plasma edge causing steeper plasma density and temperature profiles than those in L-mode**



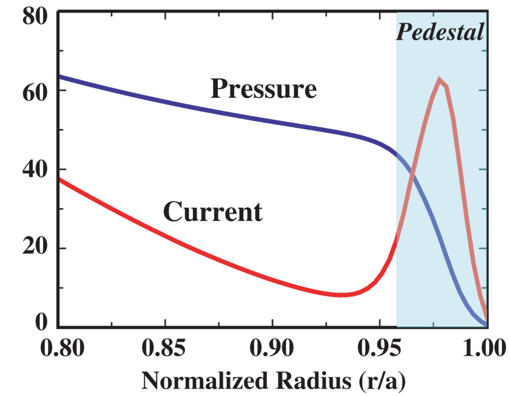

**COMPASS**

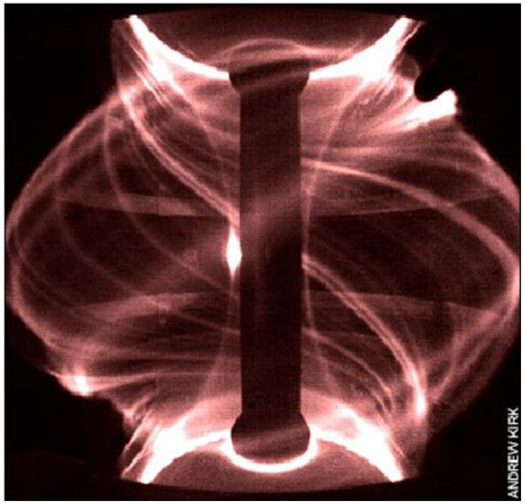
**in the Czech Republic**

[1]R. Pánek, *Plasma Phys. Control. Fusion* (2016)

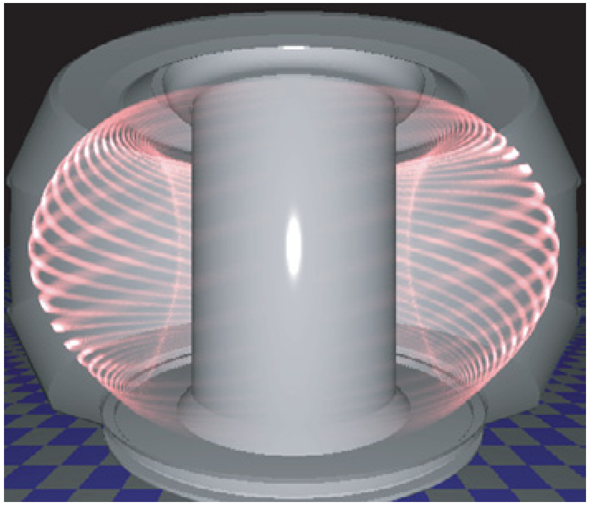
# H-mode plasmas are found to be unstable to Edge Localized Modes

- **Ideal MHD stability calculations show that the observed instabilities (ELMS) are caused by coupled Peelling-Ballooning modes**

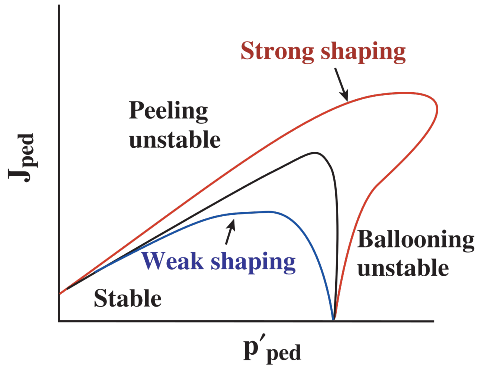


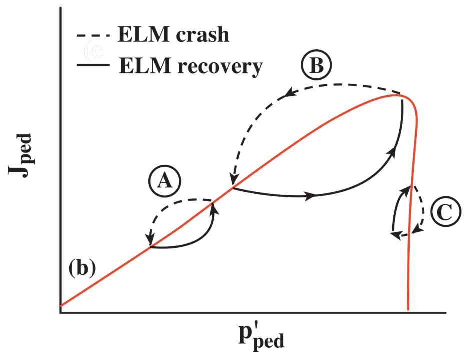




**ELM filaments in MAST**



**Ideal MHD calculations of ELMs in DIII-D**



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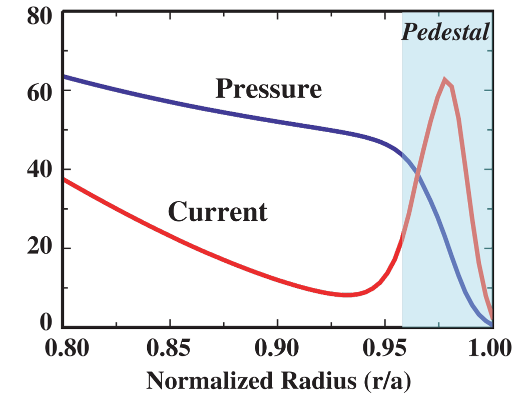
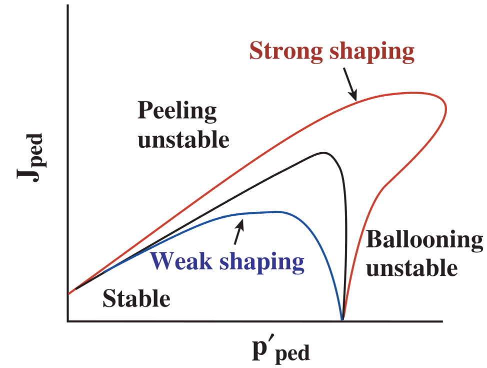
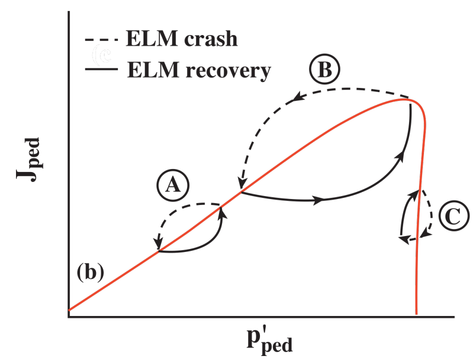
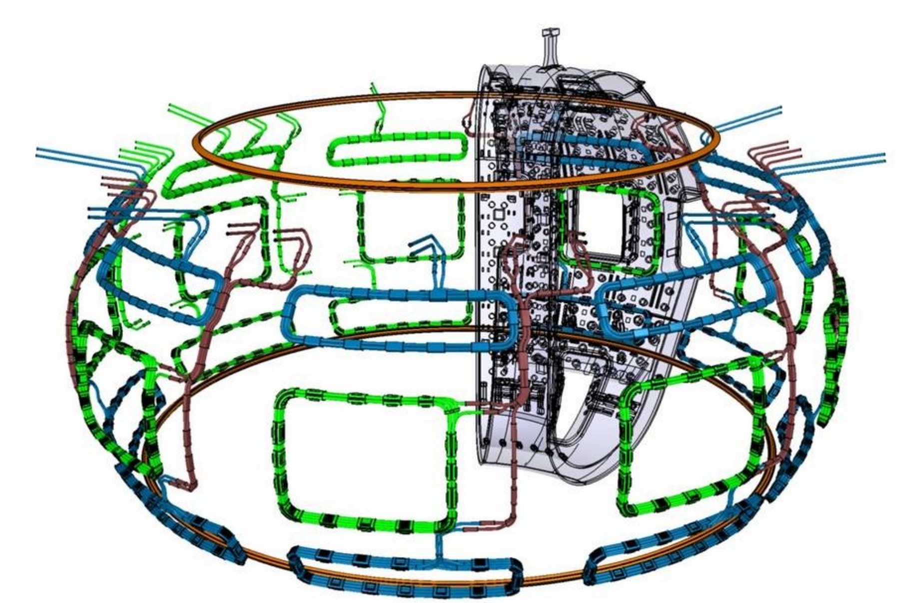


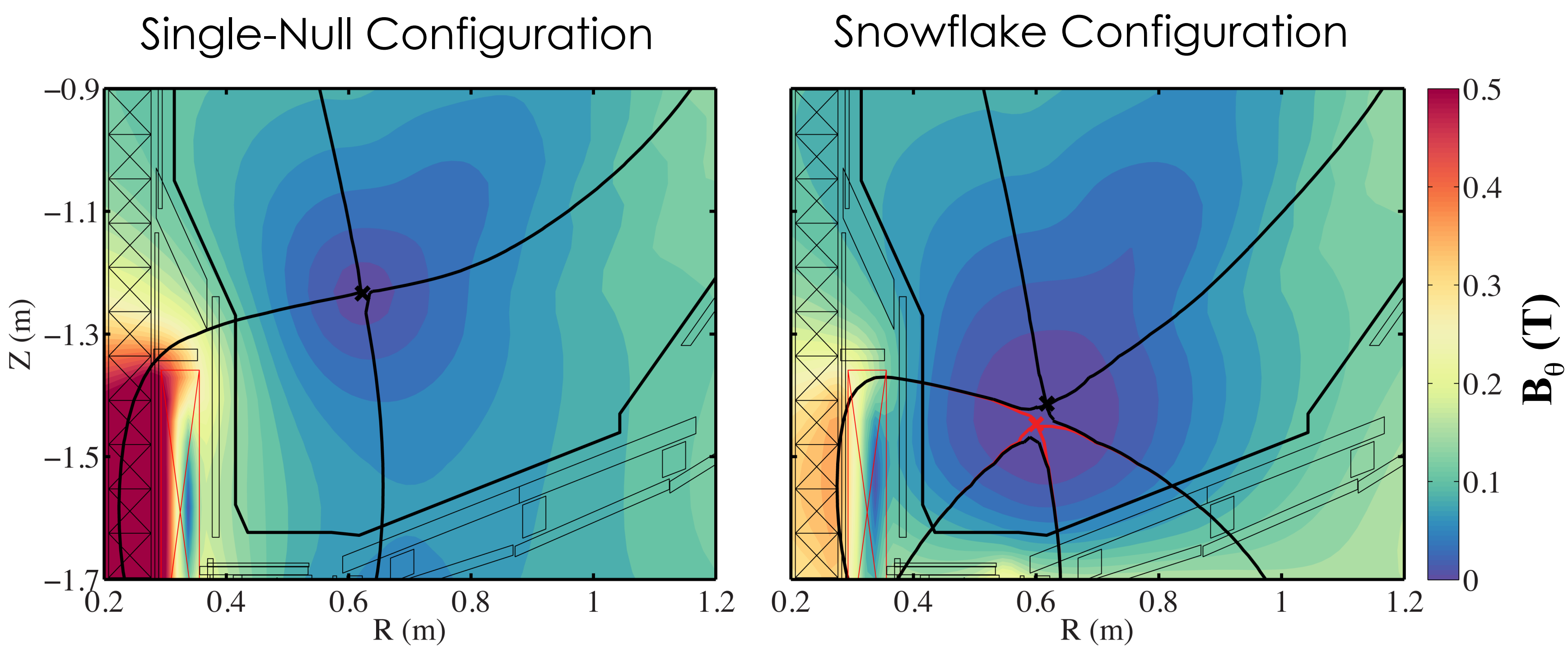



**ITER 3D coils for ELM supression**

# 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 $B_\theta$ near the null-point**




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

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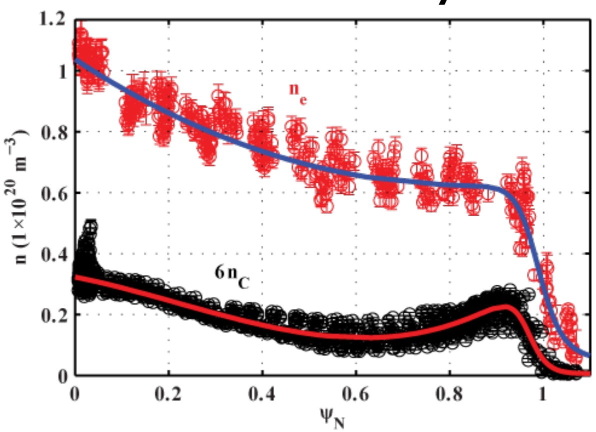
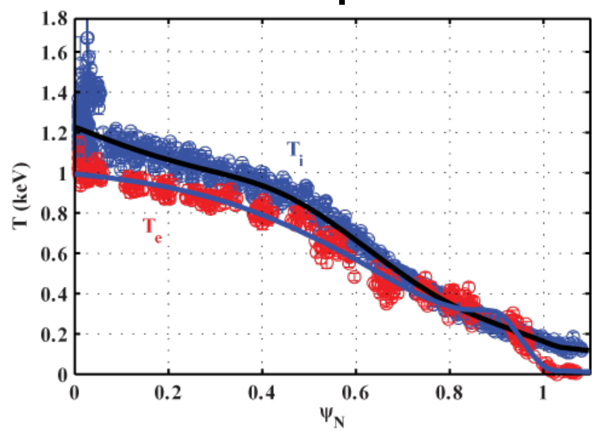
# NSTX discharge provides the equilibrium profiles for the ISOLVER calculations of the NSTX-U SF divertor

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

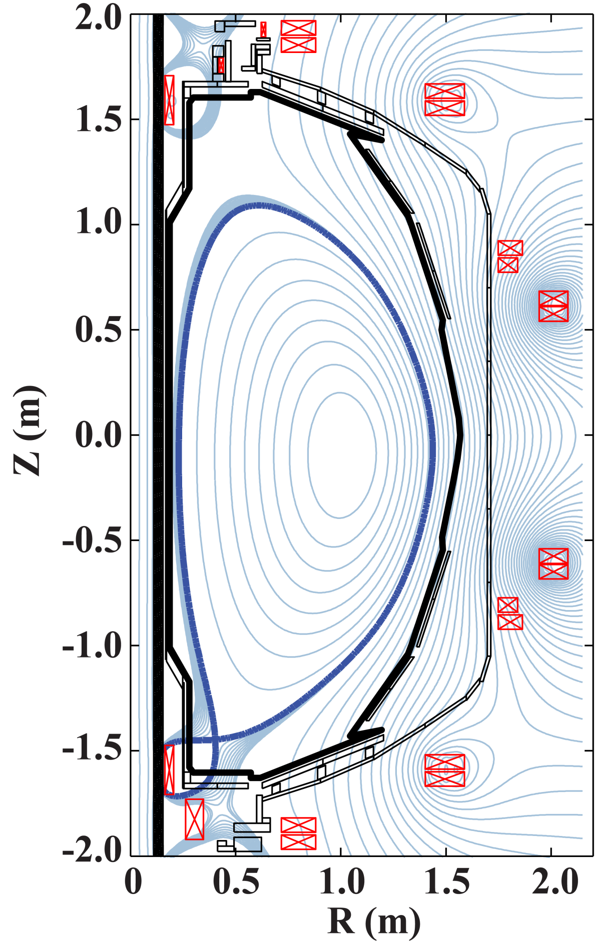
**Plasma density**




**Plasma Temperature**

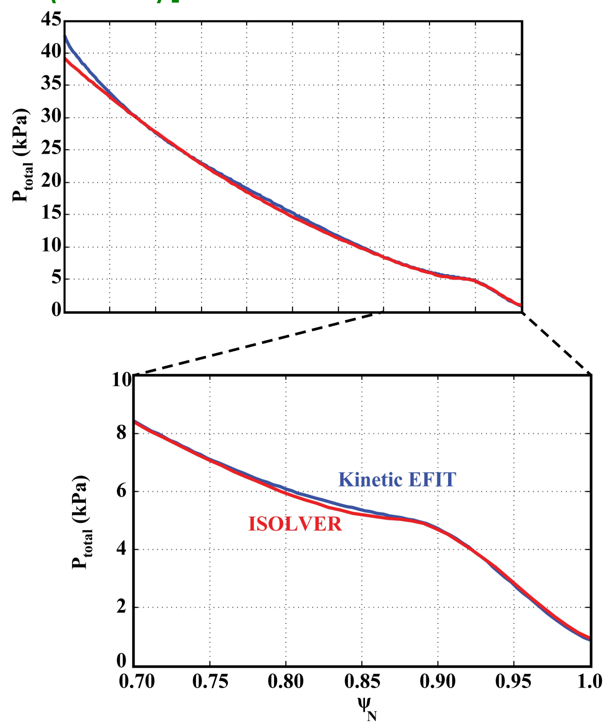


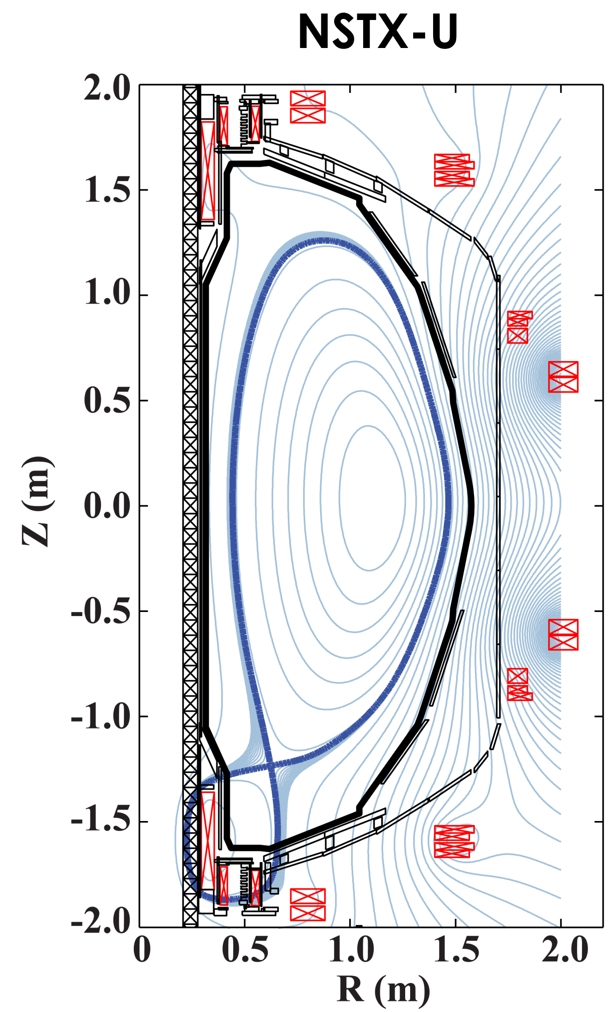

**NSTX**



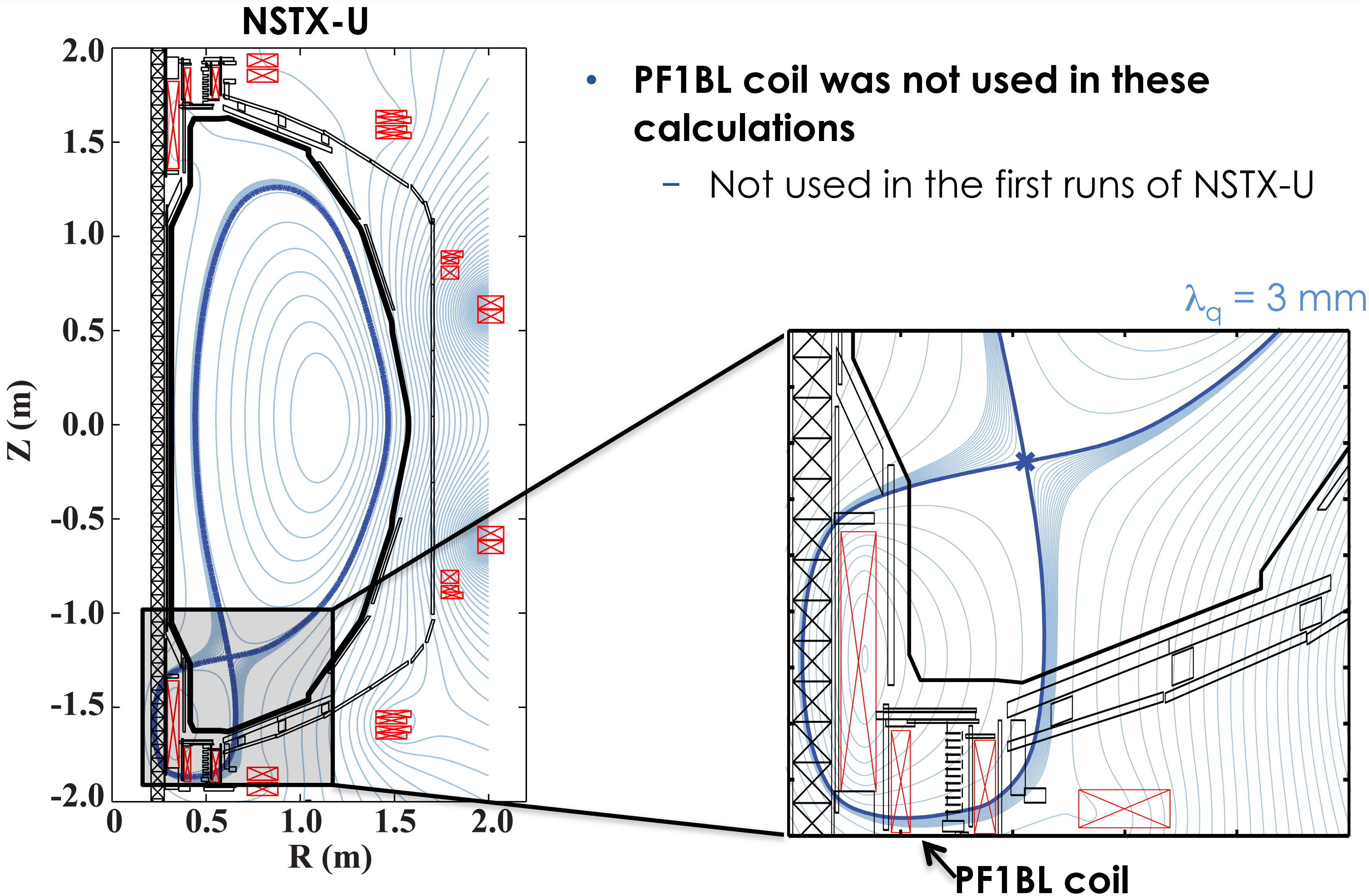
# ISOLVER calculations of the NSTX-U SF divertor assume approximately the same total plasma pressure profile

- **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)]



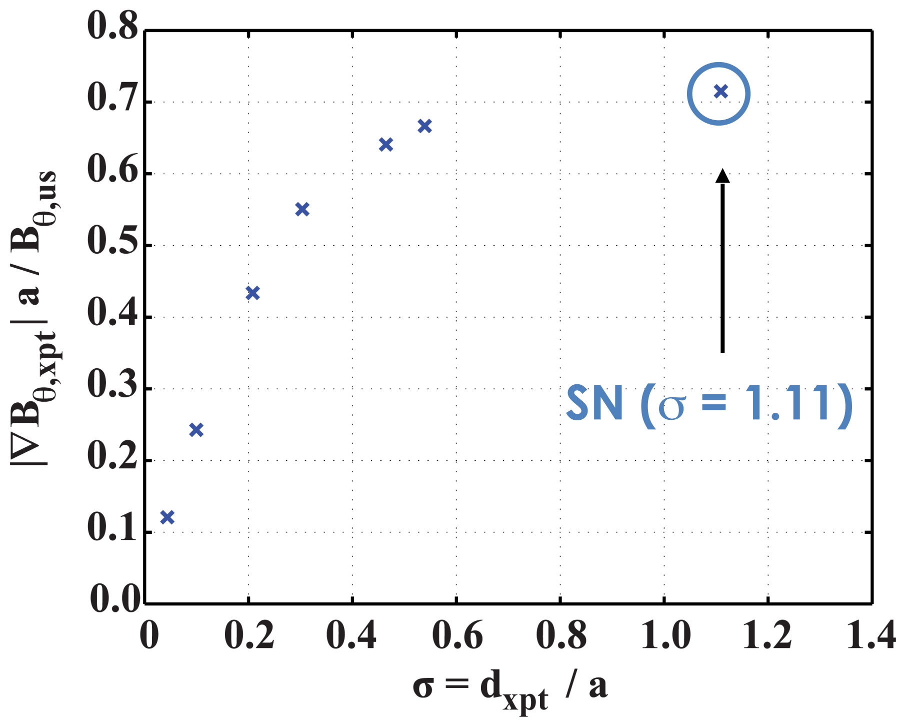
# NSTX-U will operate without the PF1BL coil in the initial run of experiments

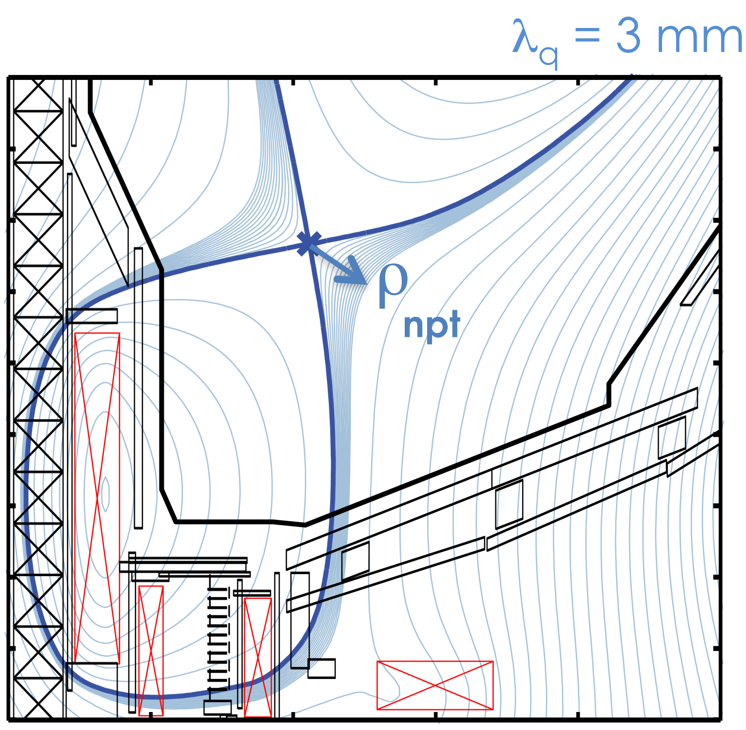



- **PF1BL coil was not used in these calculations**
  - Not used in the first runs of NSTX-U

# Configuration is varied from a SN reference to a SF

- **An exact SF configuration ($\sigma$ = 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



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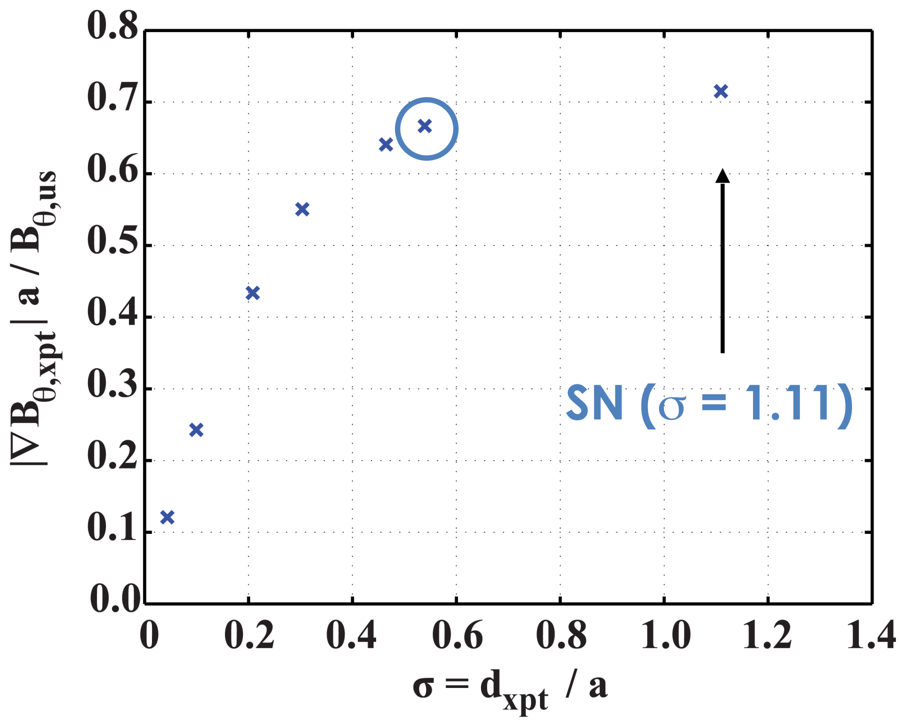


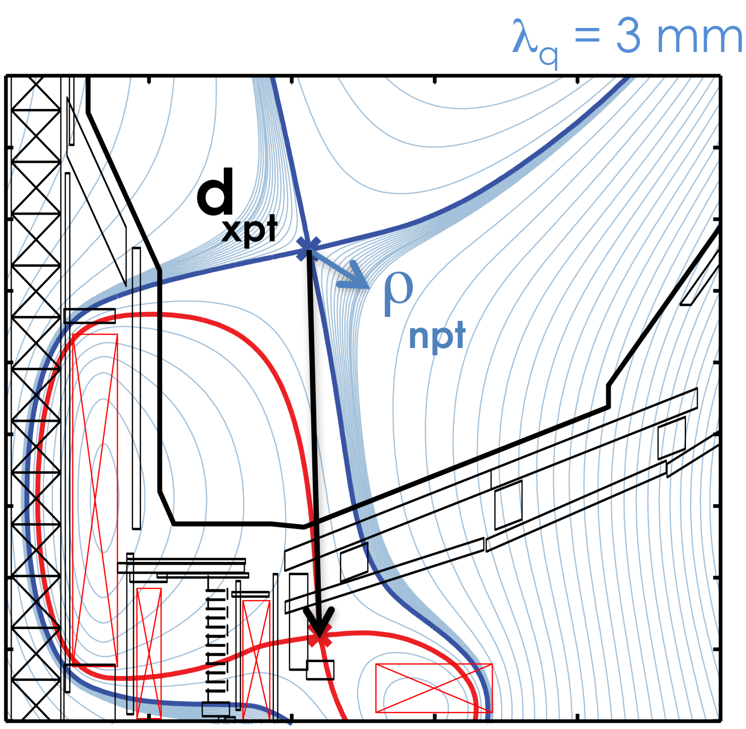

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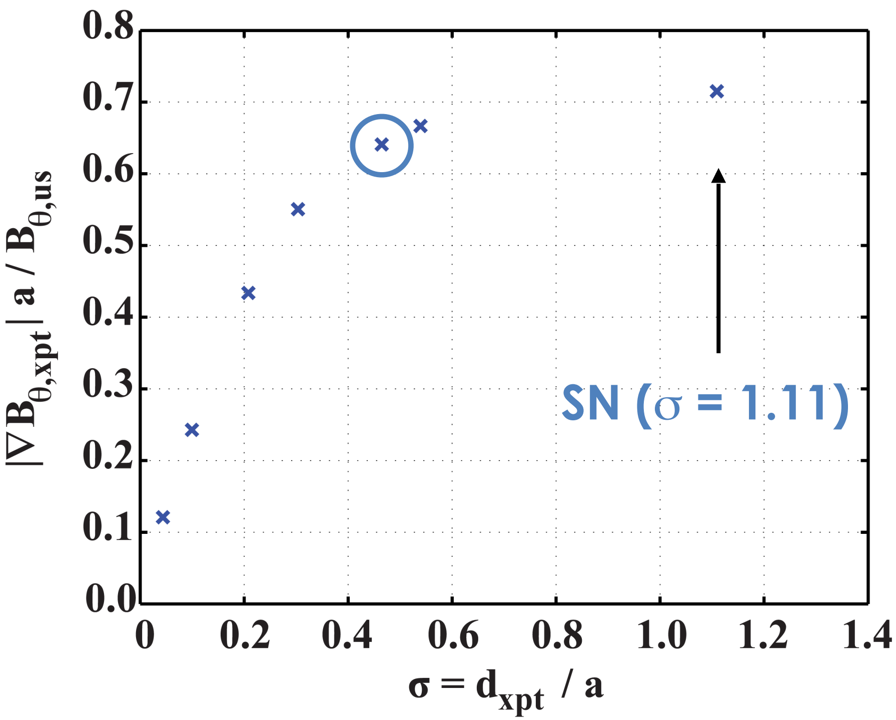


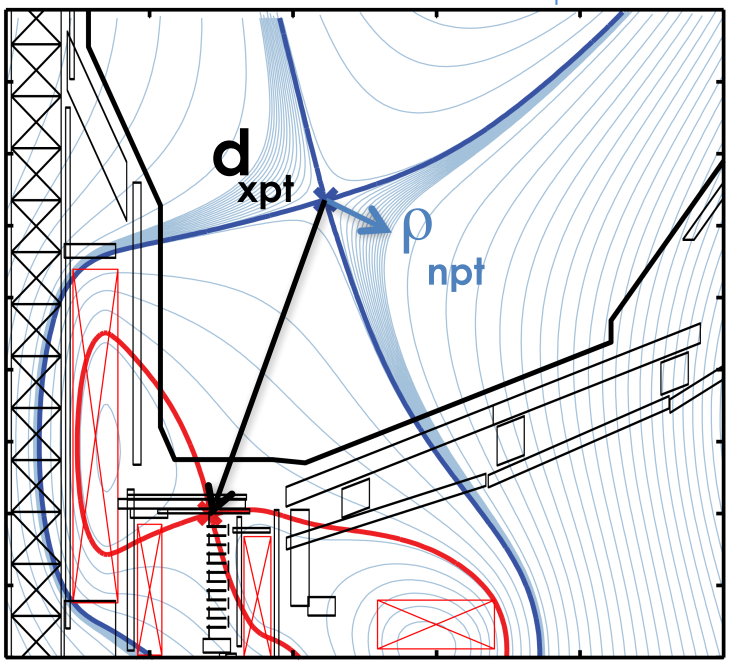

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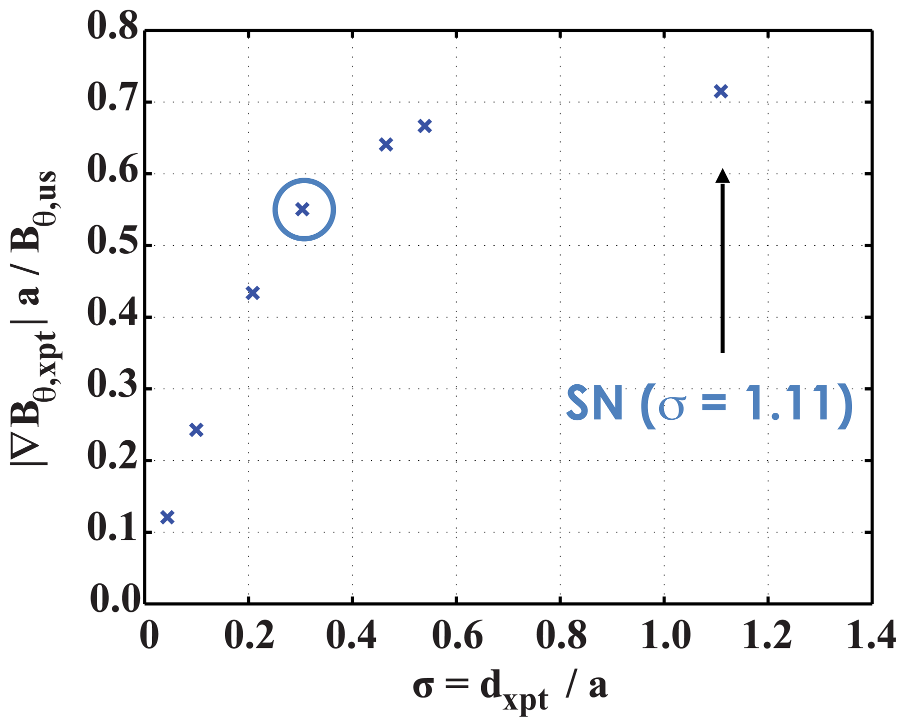


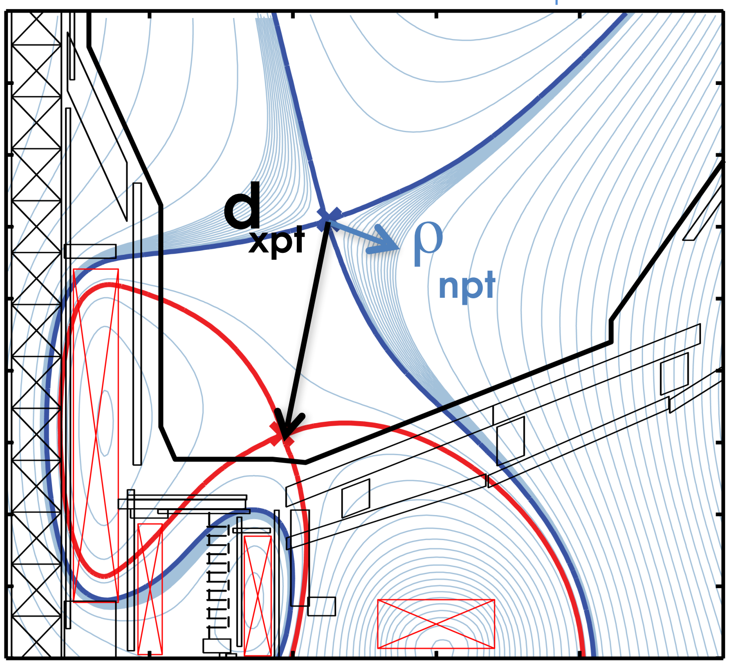

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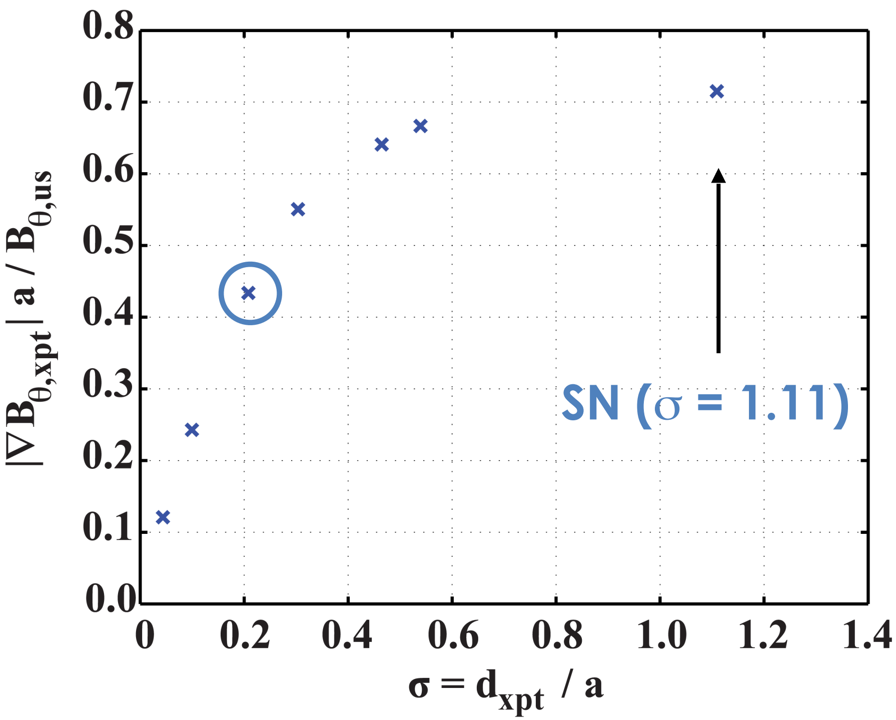


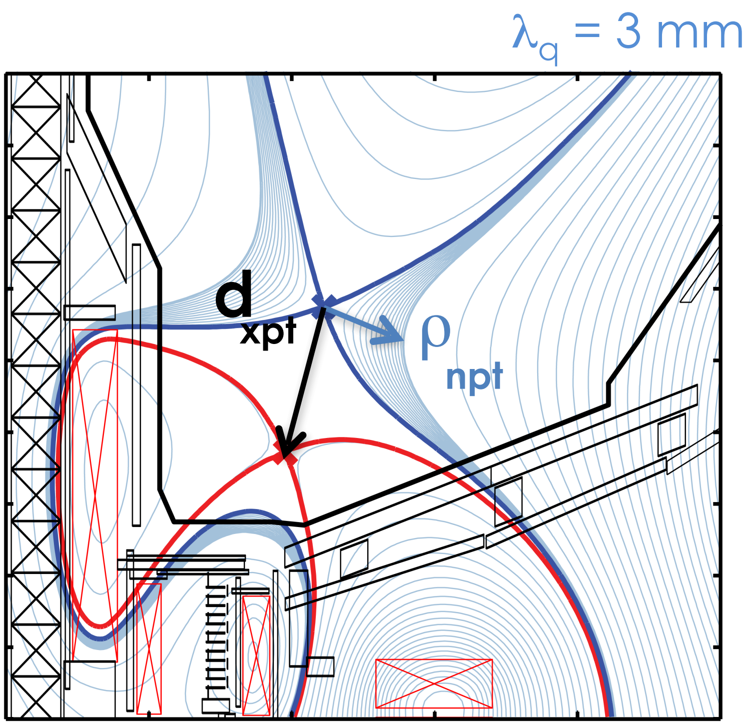

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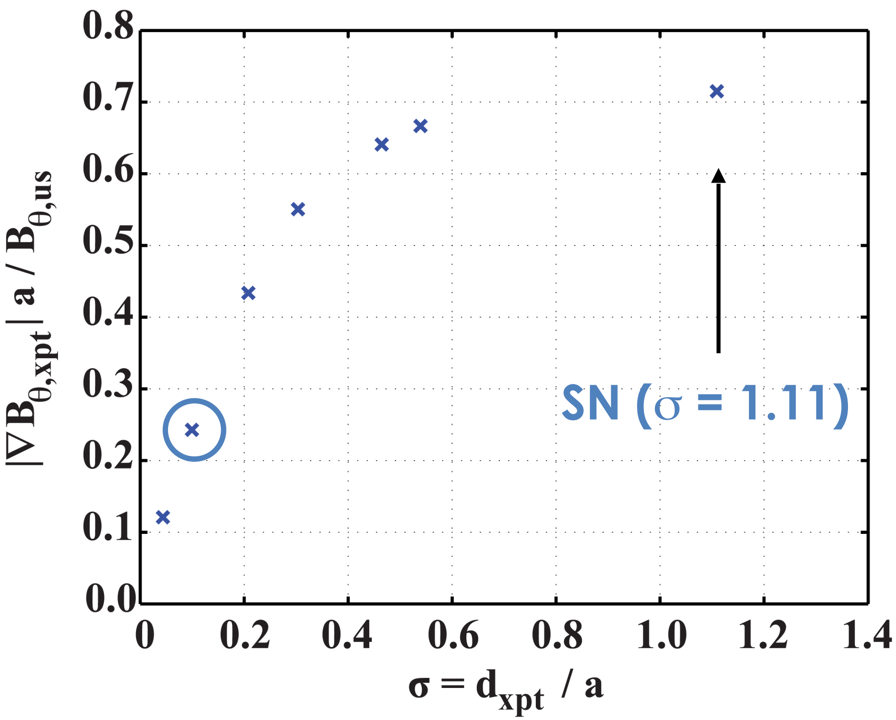


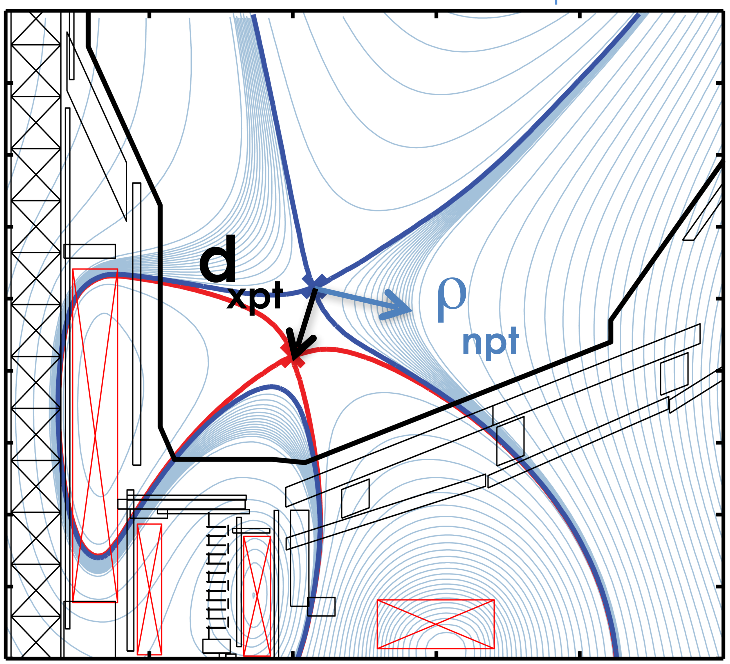

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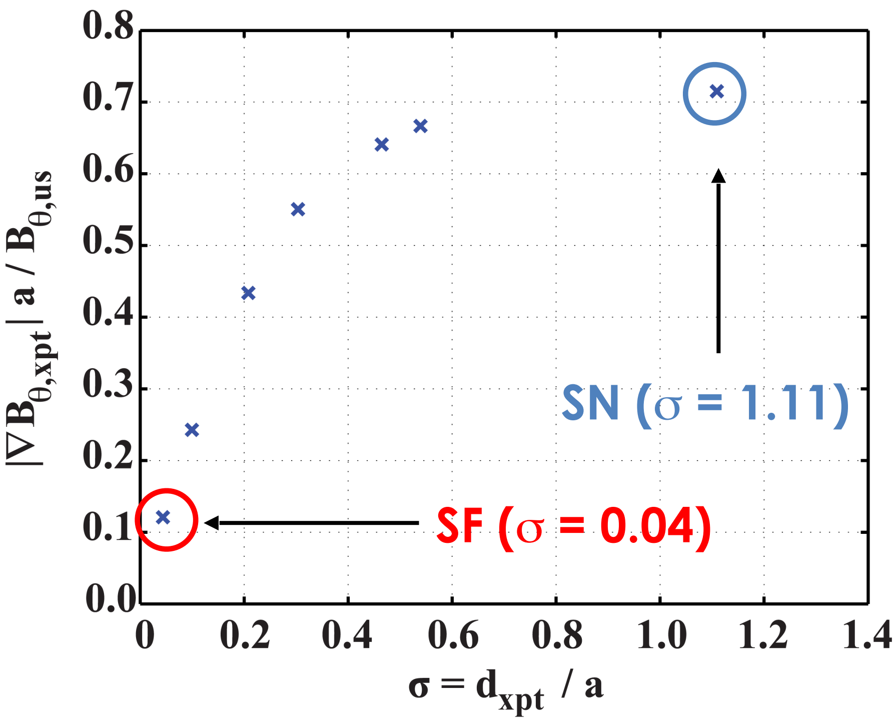


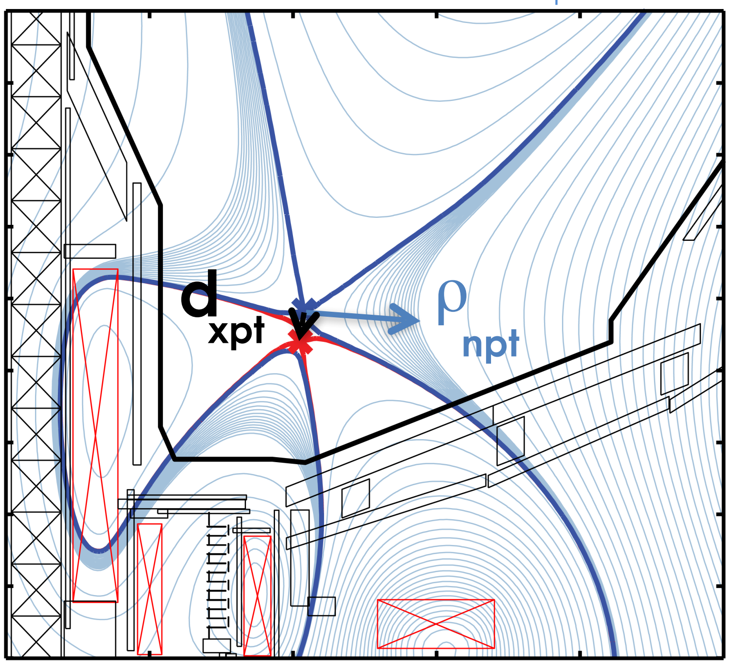

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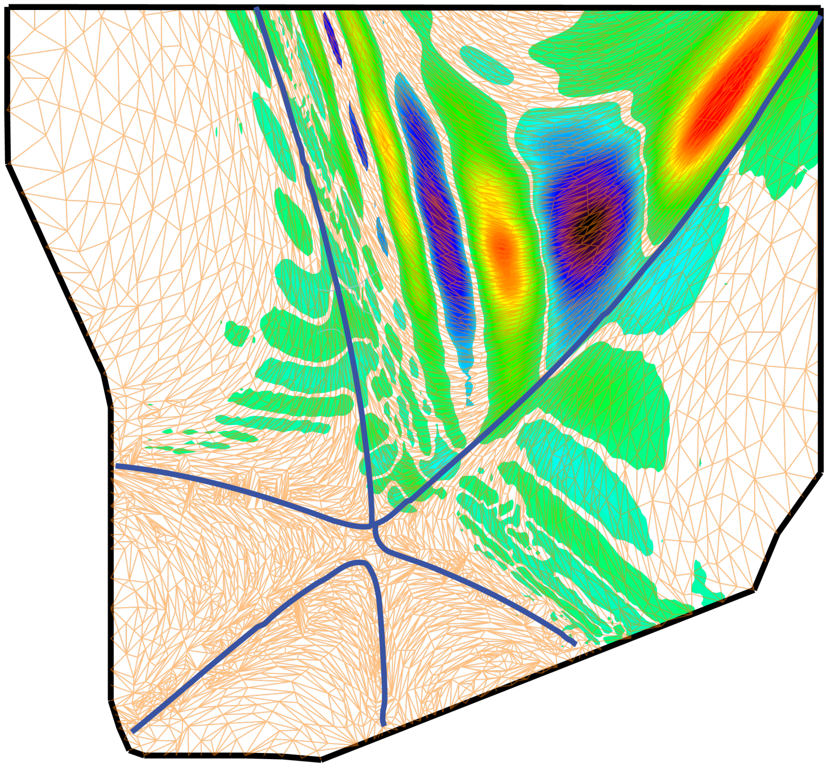
# Estimate the Plasma Response to Externally Applied Non-Axisymmetric Magnetic Fields Using Modelling

- **The M3D-C1 code is a two-fluid, resistive MHD code[1]**
- **The M3D-C1 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. Ferraro, *Phys. Plasmas* (2010)

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- **Two-fluid effects governed by ion inertial length, $d_i$**
  - Electron and ion fluids decouple at finite $d_i$

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

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

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

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

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

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

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

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

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

# Outline: M3D-C1 simulations of the snowflake divertor

- Introduction
- The properties of the NSTX-U snowflake equilibria
- **The M3D-C1 simulations of the NSTX-U snowflake divertor**
  - The M3D-C1 code
  - The plasma response in the SN and SF configurations
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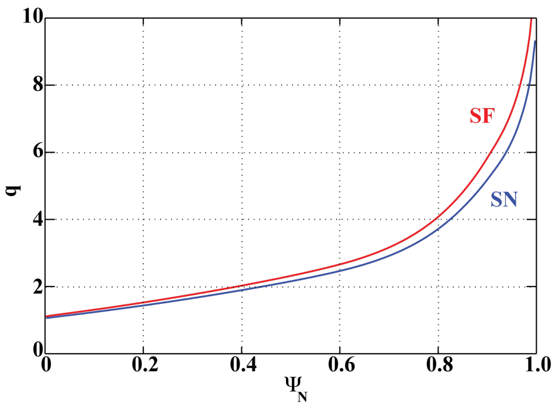
- Summary/Conclusions

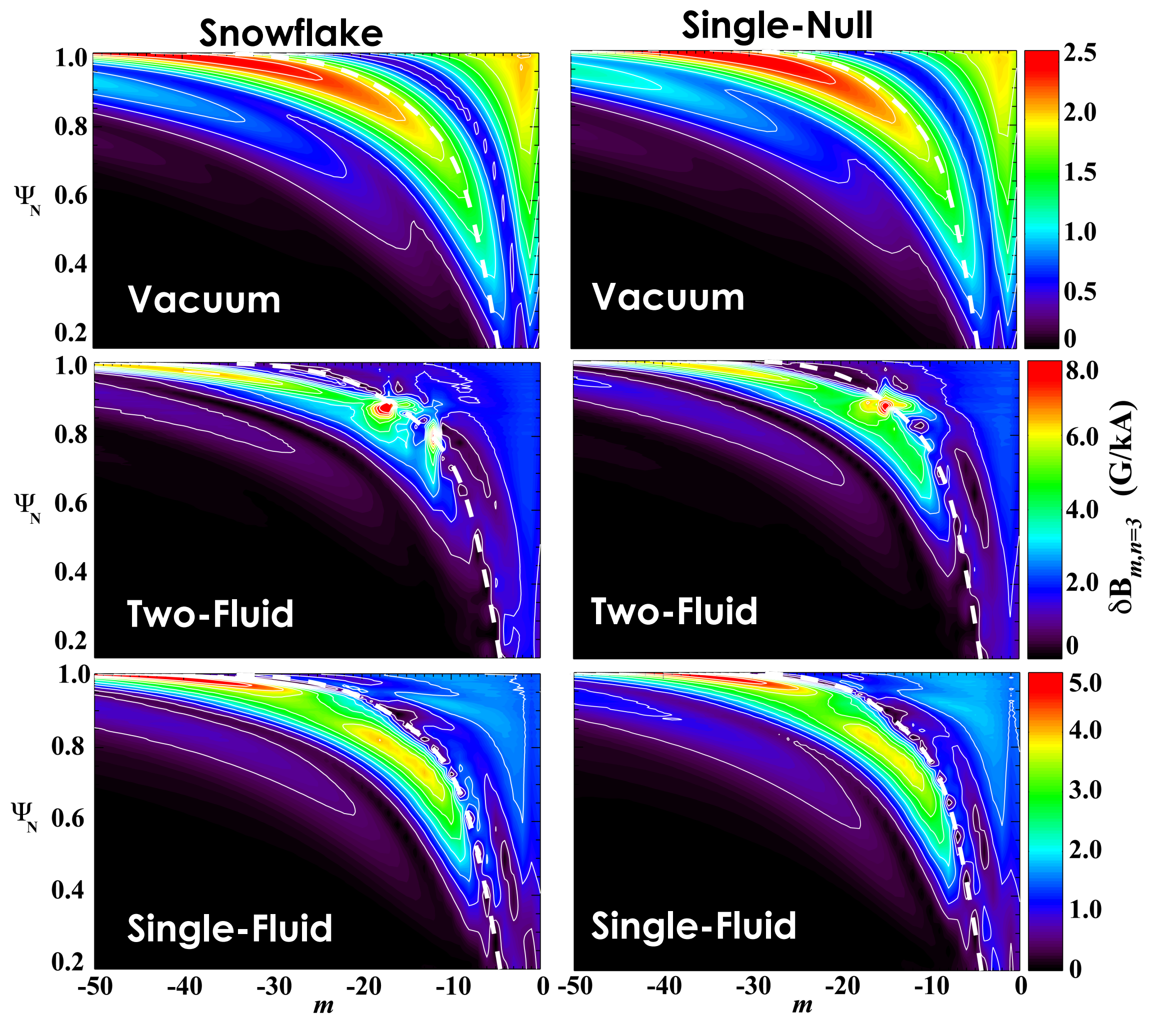
# Two-fluid effects significantly enhance resonant field components in the plasma edge of the SF configuration

- **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

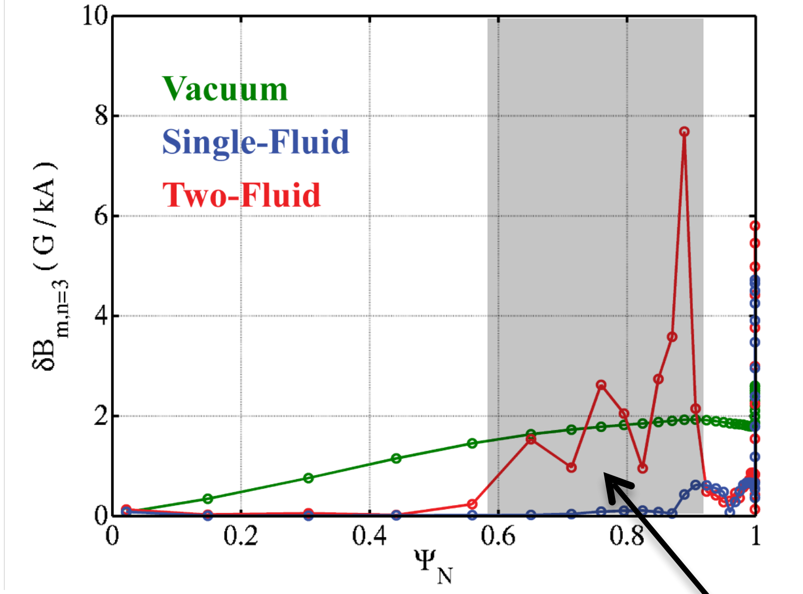
$$J_\theta = \frac{dF}{d\psi} B_\theta$$



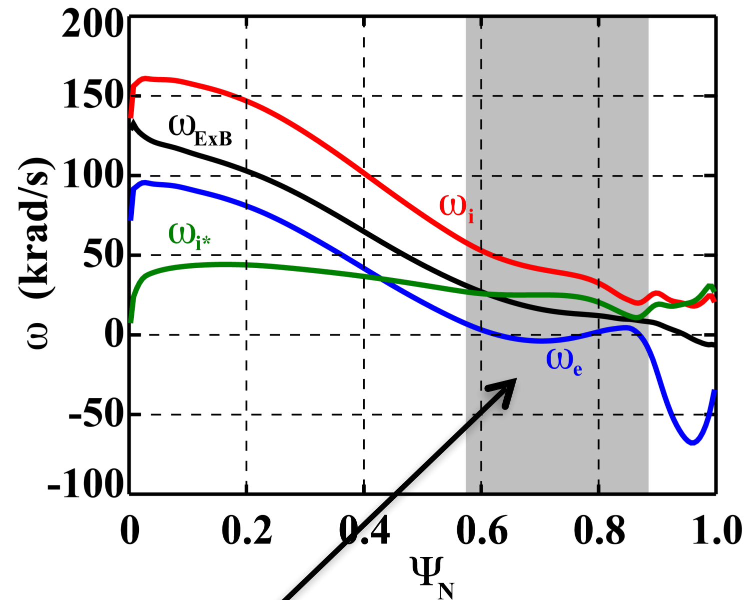
# Enhancement of resonant field components is caused by low electron fluid rotation in the plasma edge

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

**Resonant Magnetic Perturbation (Single-Null)**




**Plasma Rotation Profiles**




**Low electron fluid rotation**

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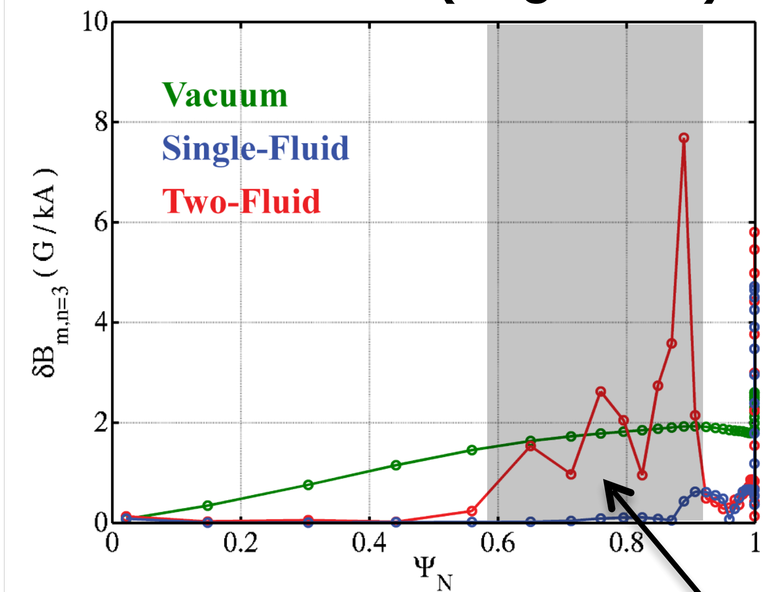
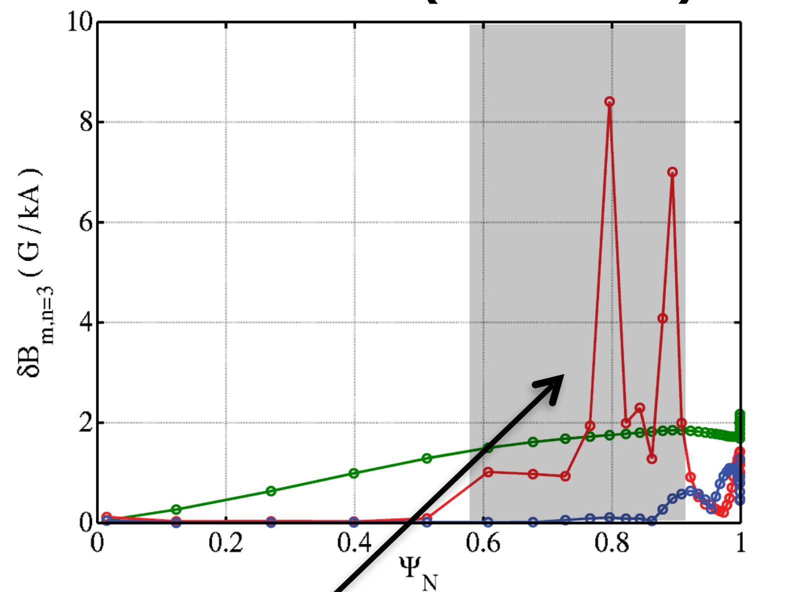



**Resonant Magnetic Perturbation (Snowflake)**

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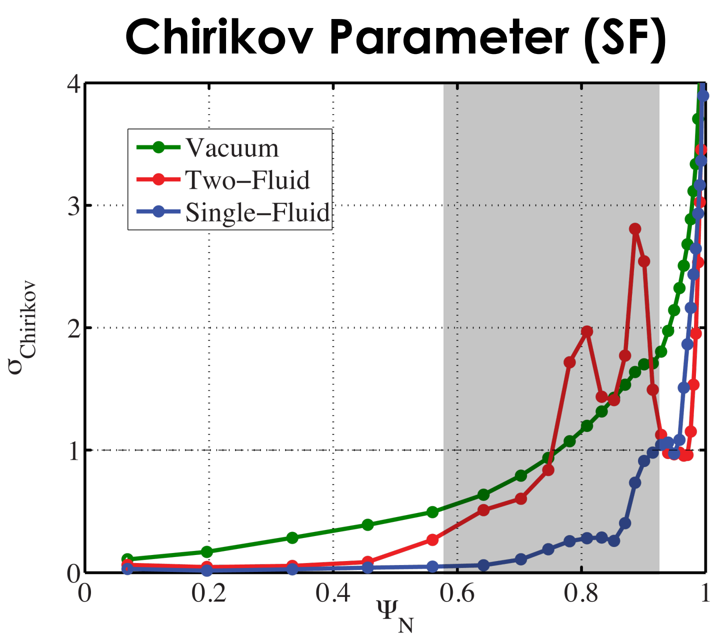
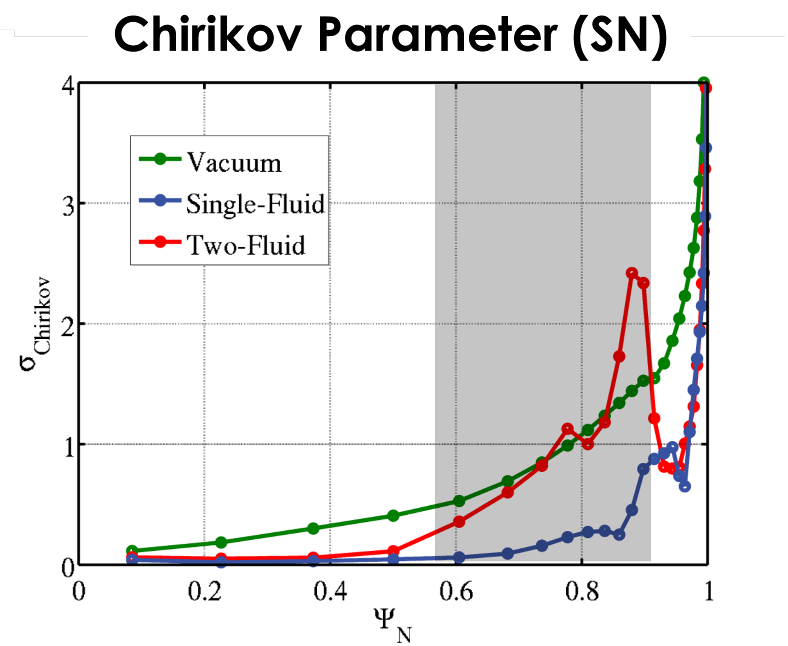
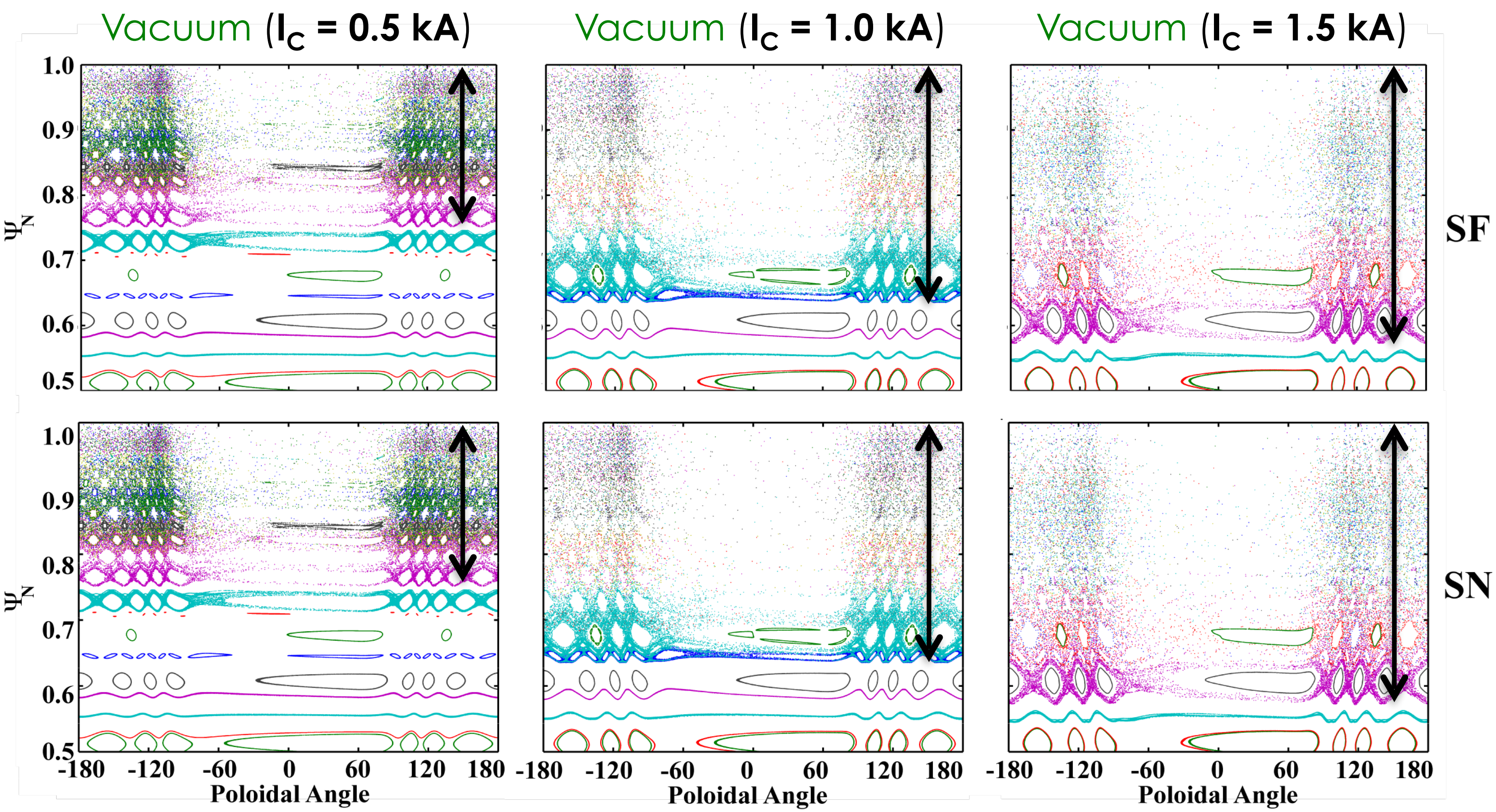



- **Enhanced resonant fields indicate the formation of magnetic islands**
  - Two-fluid calculations predict stochastic layer in the plasma edge as large as in the vacuum field approach

# 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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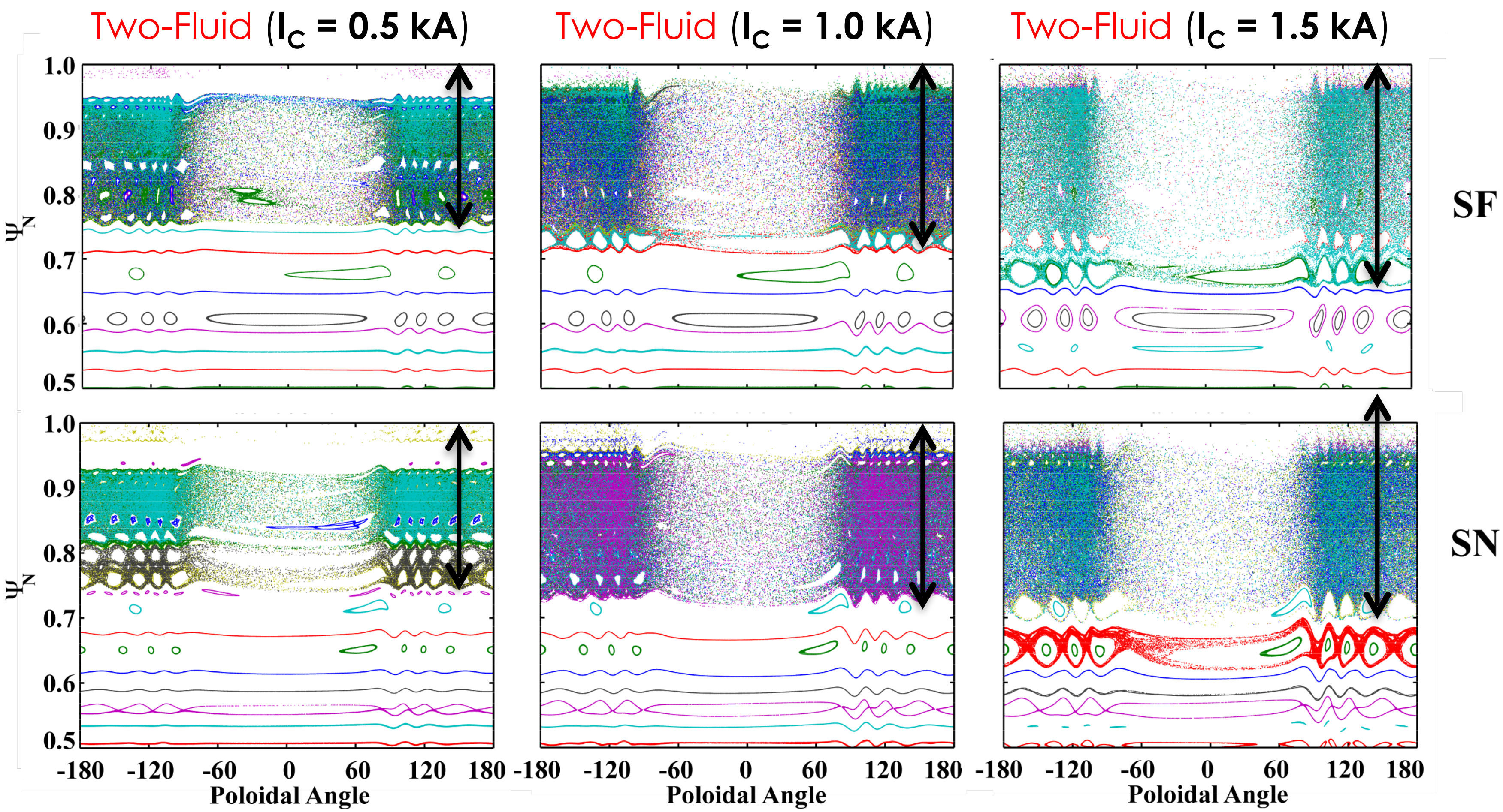

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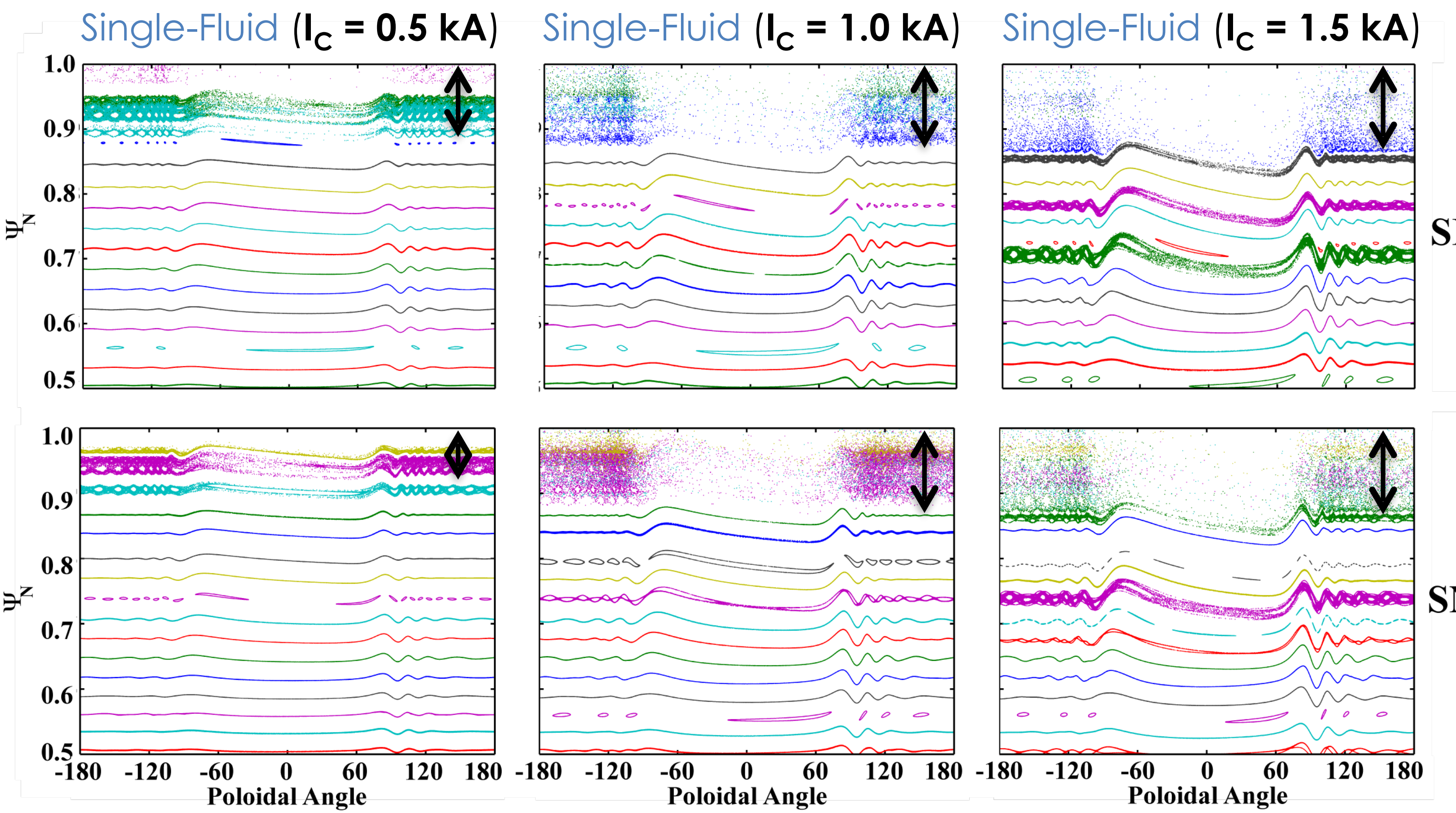
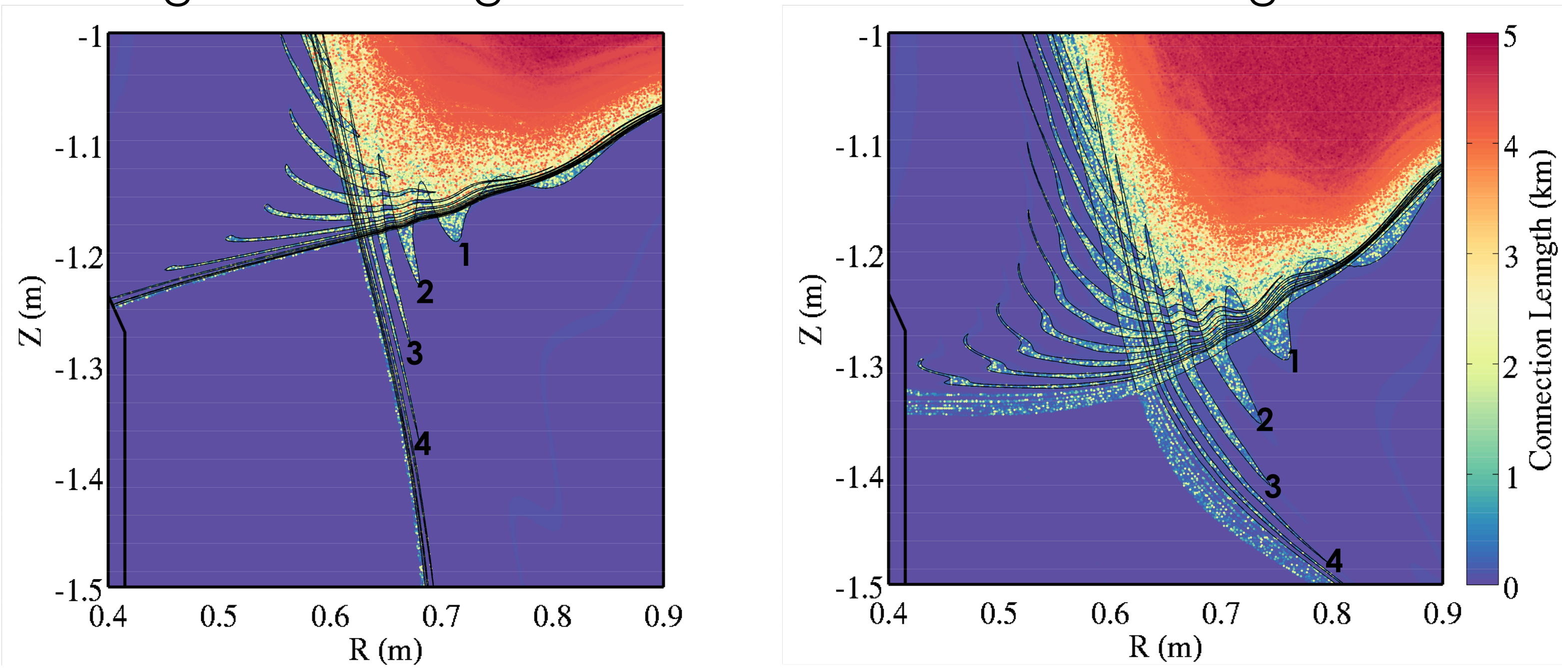


# Lower poloidal field in the null-point region of the SF configuration leads to the formation of longer lobes

- **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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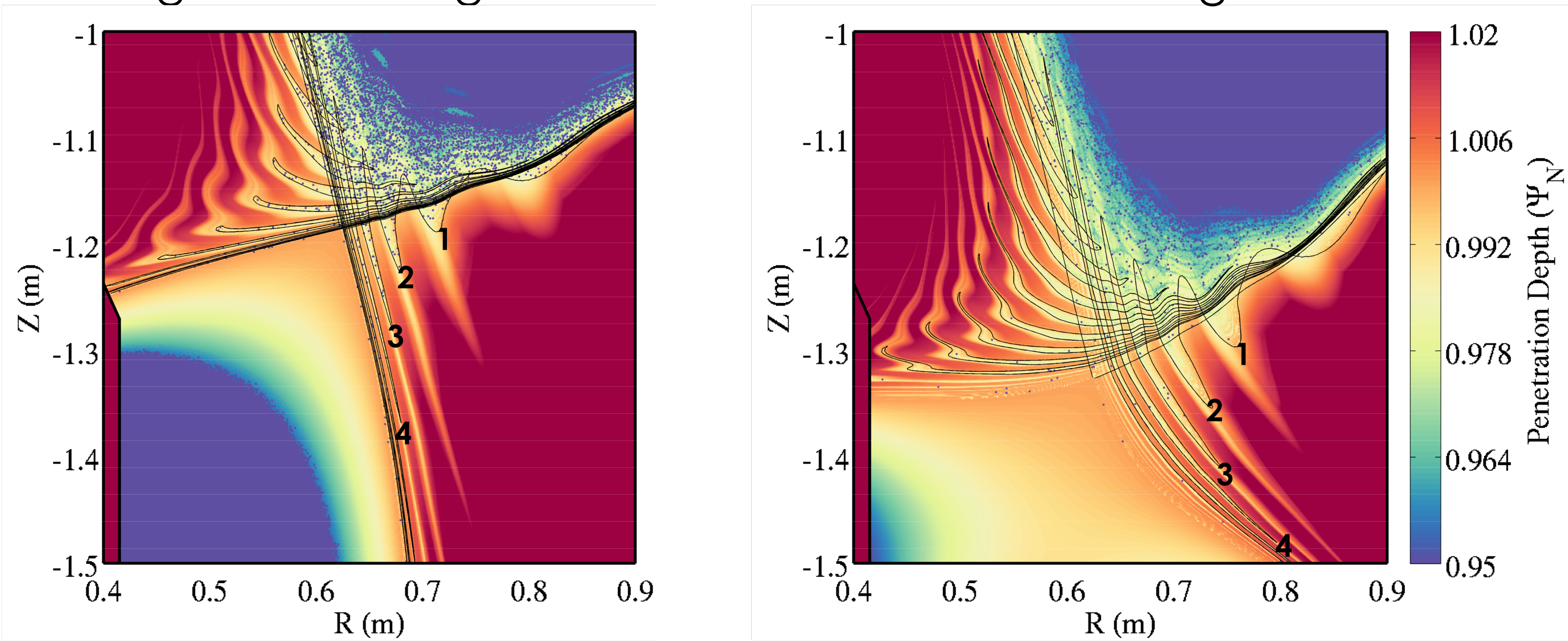


Magnetic field lines in the null-point region of the SF divertor remain close to the edge

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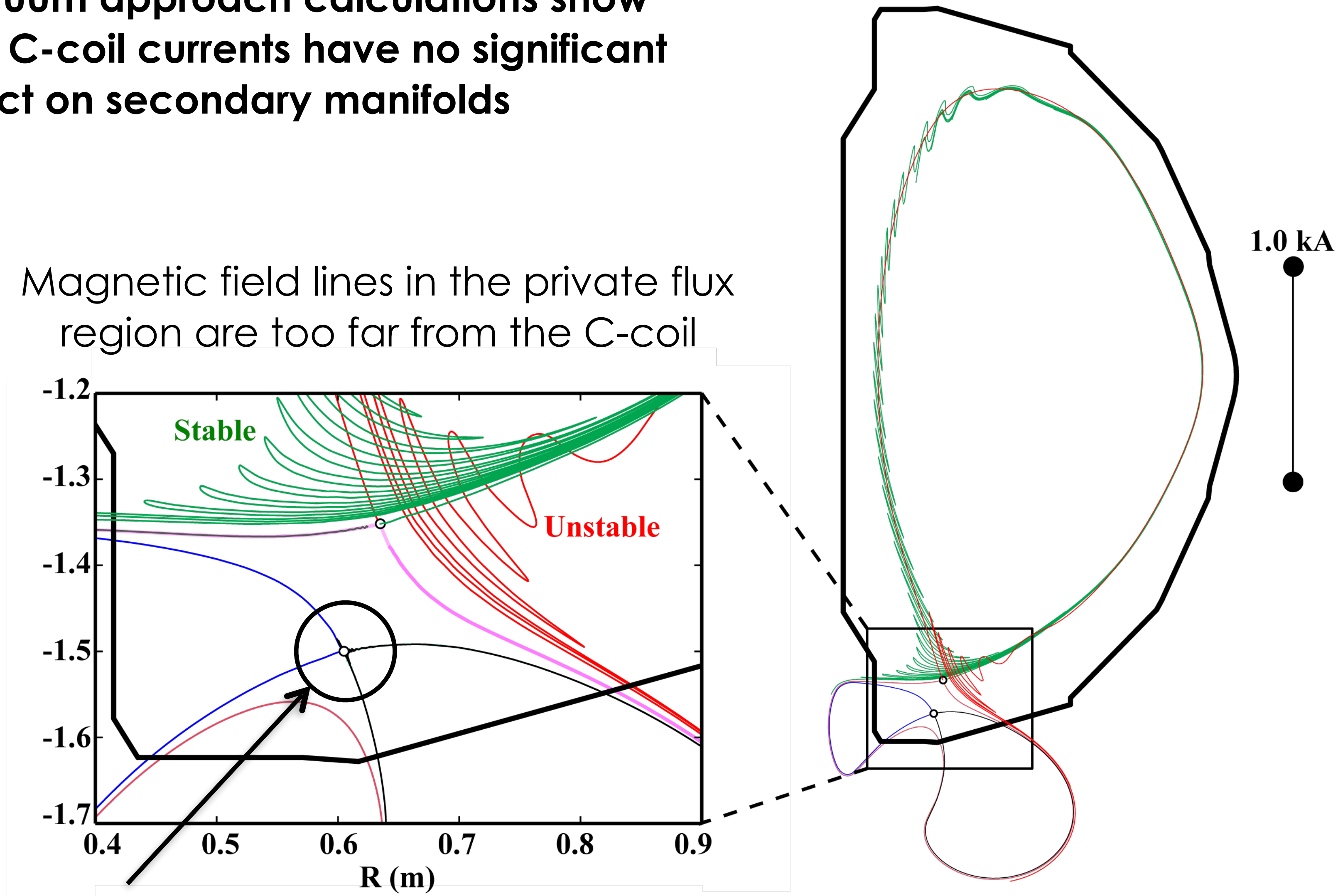
# Effect of 3D magnetic perturbations on secondary manifolds is negligible

- **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

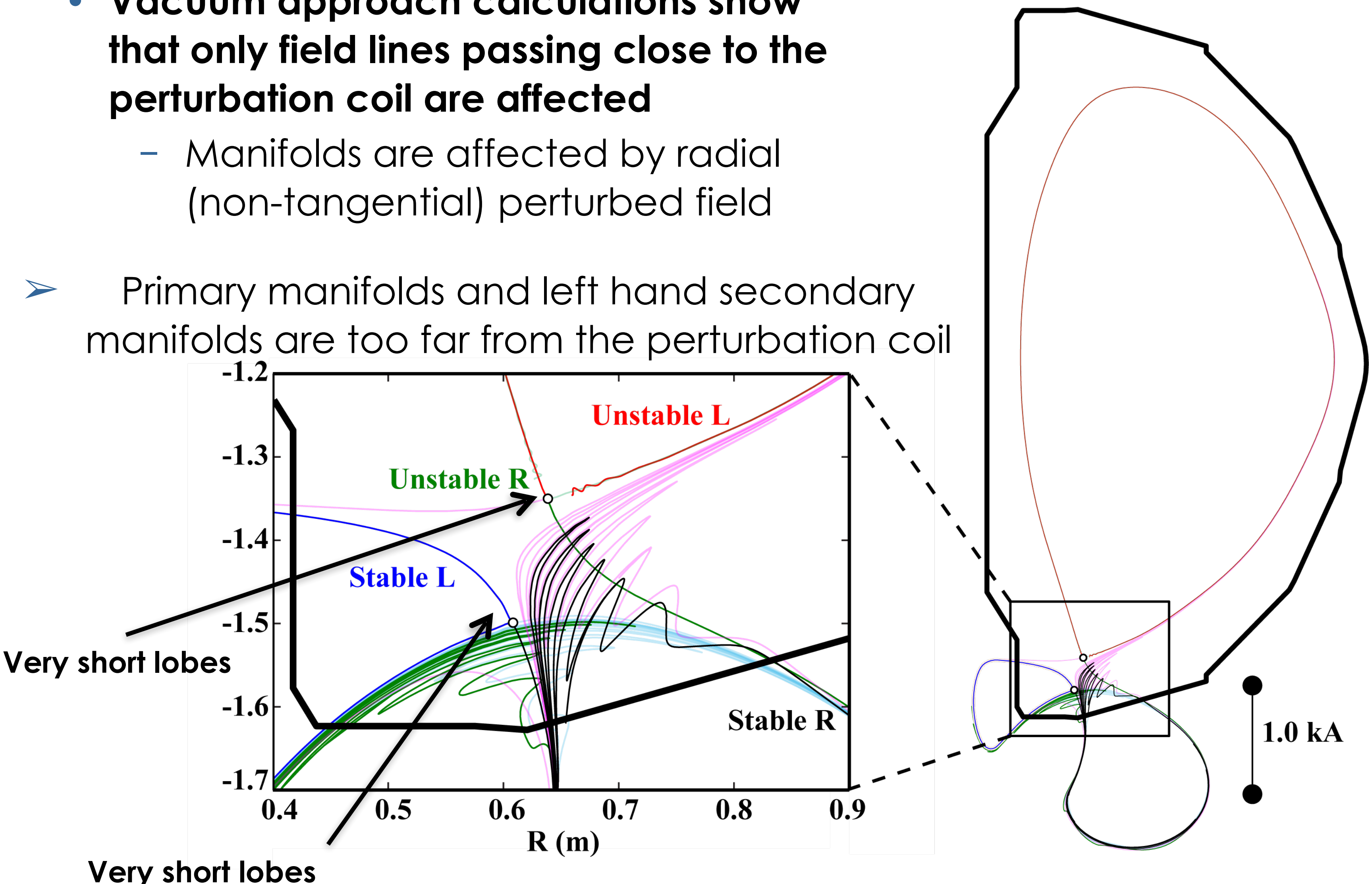



Very short lobes

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

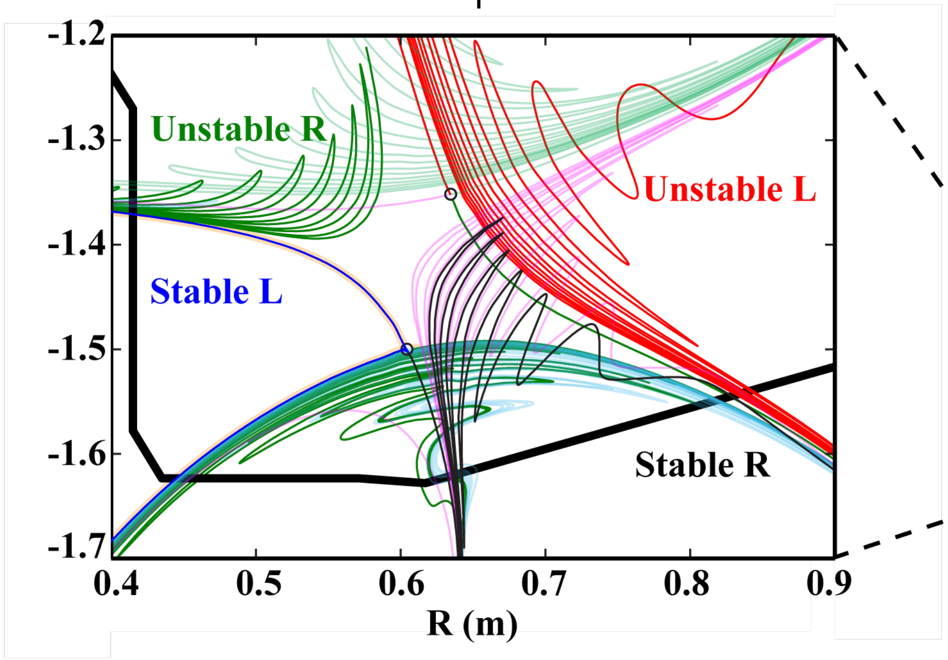
- **Vacuum approach calculations show that only field lines passing close to the perturbation coil are affected**
  - Manifolds are affected by radial (non-tangential) perturbed field

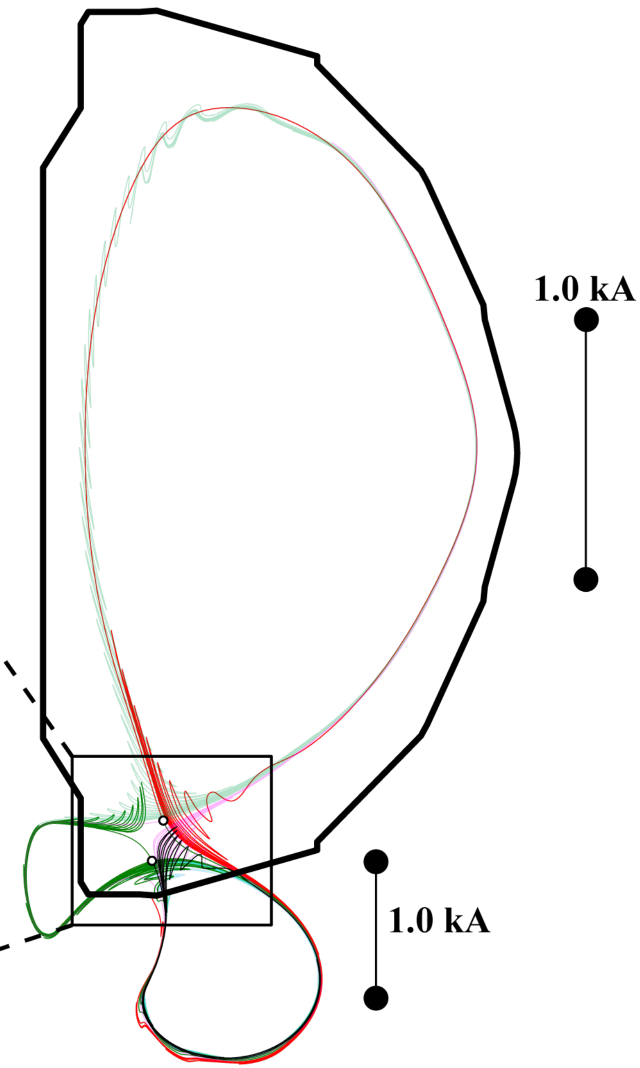
➢ Primary manifolds and left hand secondary manifolds are too far from the perturbation coil



# 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

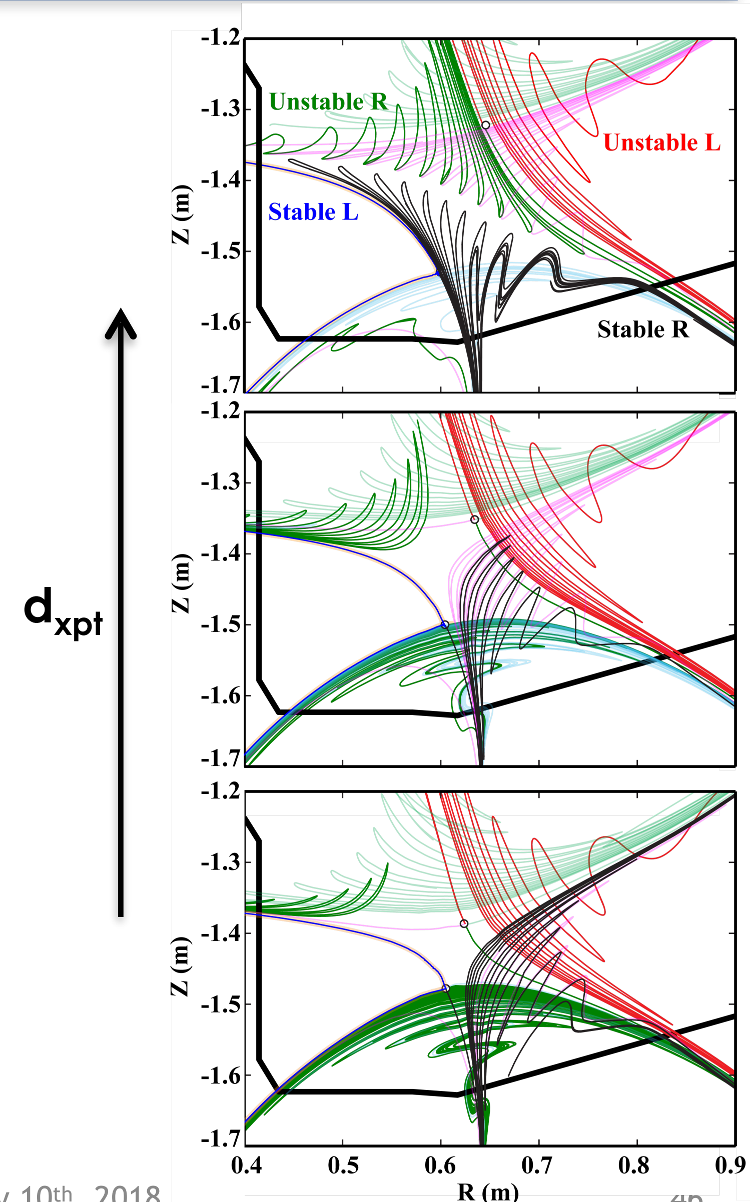


# Primary and secondary manifolds interact at sufficiently short distance between x-points

- **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

- No significant differences are observed between the SN and SF plasma responses (Good News!!!!)
- Plasma lobes in the SF are longer than in the SN configuration
- Interaction between primary and secondary manifolds may have impact on plasma edge transport and, therefore, on the divertor heat flux deposition