Assessment of equilibrium field coil misalignments on the divertor footprints in NSTX-U

by

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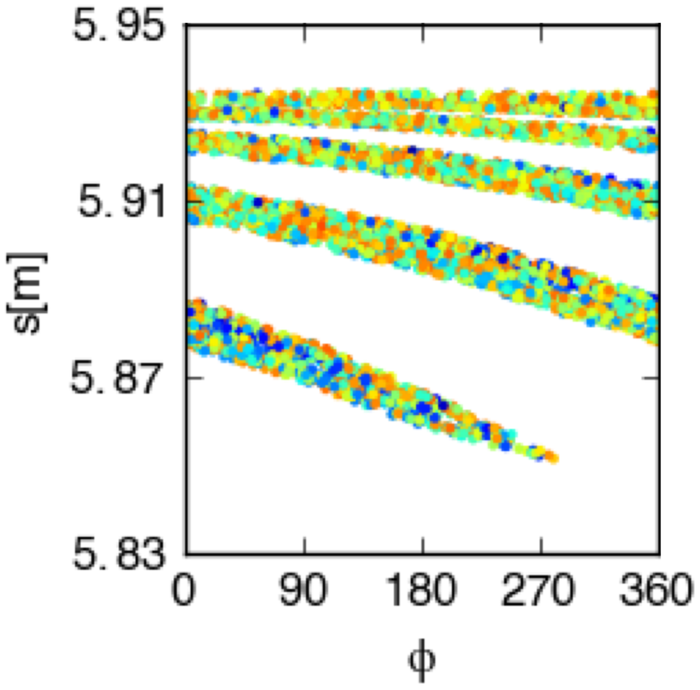

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Motivations

- Non-axisymmetric magnetic field perturbations due to intrinsic field-errors produce complex 3D edge magnetic topologies.

- They significantly alter the properties of the heat and particle flux distributions on the divertor target plates.

- Source of intrinsic field-errors is for example a misalignment of the equilibrium coil.

- Study the precision needed to install the equilibrium coils of NSTX-U in terms of plasma footprints on the divertor plates

Outline

- **Introduction**
  - NSTX-U equilibrium coils
  - MHD simulations with M3D-C1
- **TRIP3D analysis**
  - Workflow
  - Footprints
  - Footprints area
- **Considerations**
  - Plasma contribution
  - Magnetic length vs ψ_N
- **Results**
  - Outermost poloidal field coil (PF5)
  - Innermost poloidal field coil (PF1A)
  - Toroidal field coils (TF)
- **Summary**

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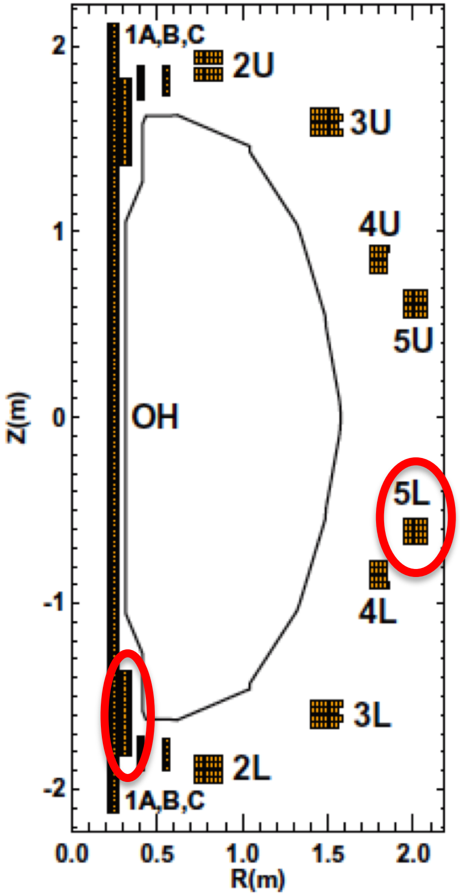
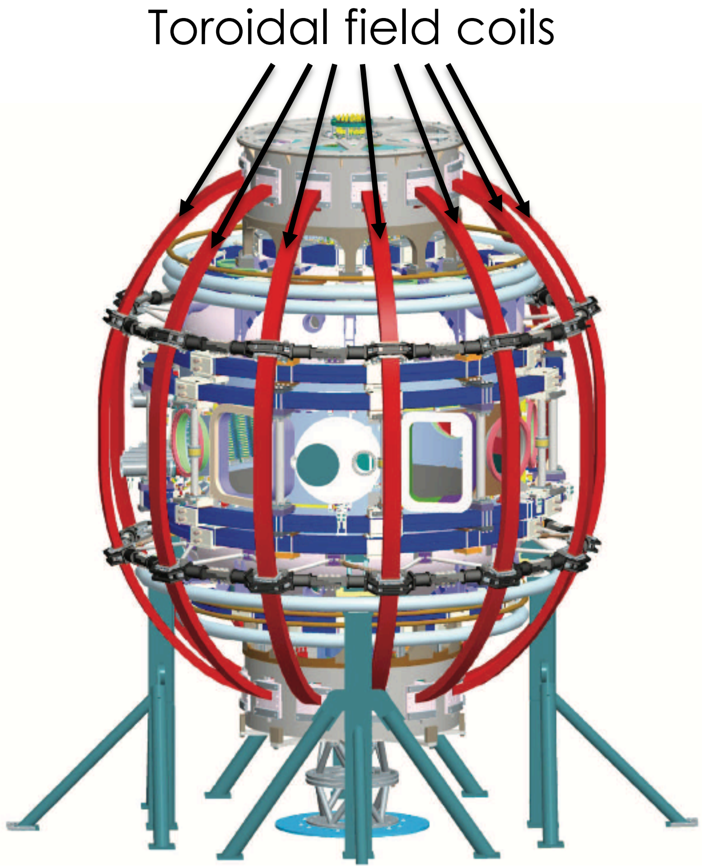
NSTX-U equilibrium coils

NSTX-U equilibrium coils are comprised of:

- 14 poloidal field (PF) coils equally distributed above and below midplane
- toroidal field coils (TF)

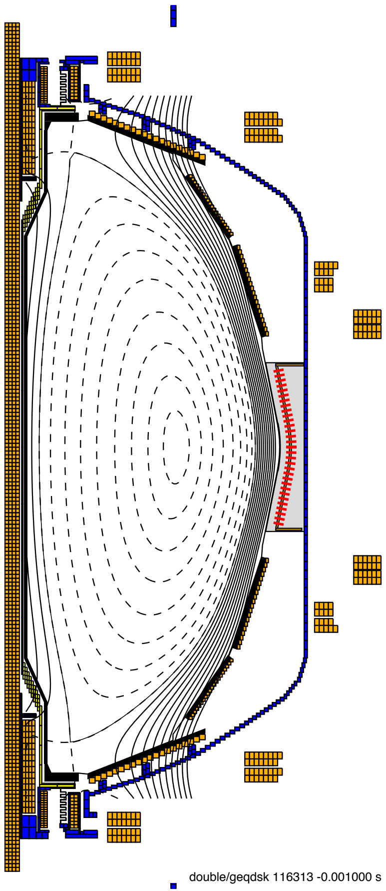
Looking at effect of innermost and outermost lower PF coils and TF coils bundle misalignment

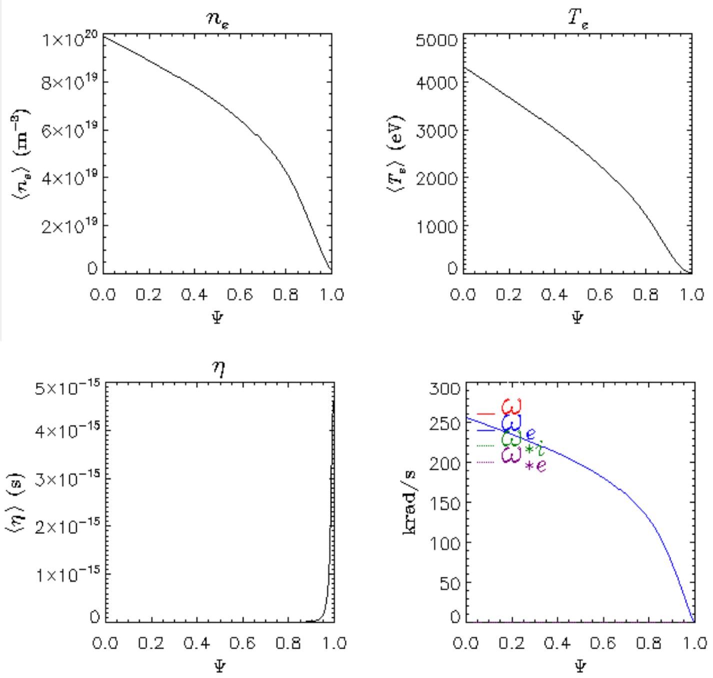




The perturbed equilibrium due to the coil misalignment is computed with the MHD code M3D-C[1]

- For each simulation one coil is shifted (tilted) by 1 mm (1mr)
- The simulations are linear so shift/tilt can be varied in TRIP3D
- Also the current in the coils can be varied in TRIP3D for small changes so that the equilibrium doesn't change
- Discharge analyzed has:
  - $I_p \simeq 2MA$,
  - $\beta_N \simeq 4.7$,
  - $q_{95} \simeq 6.7$





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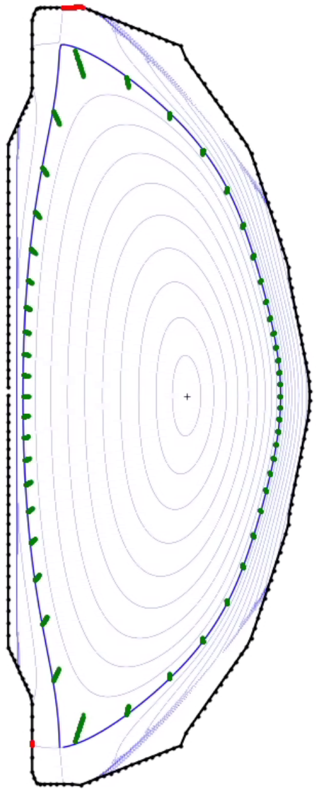
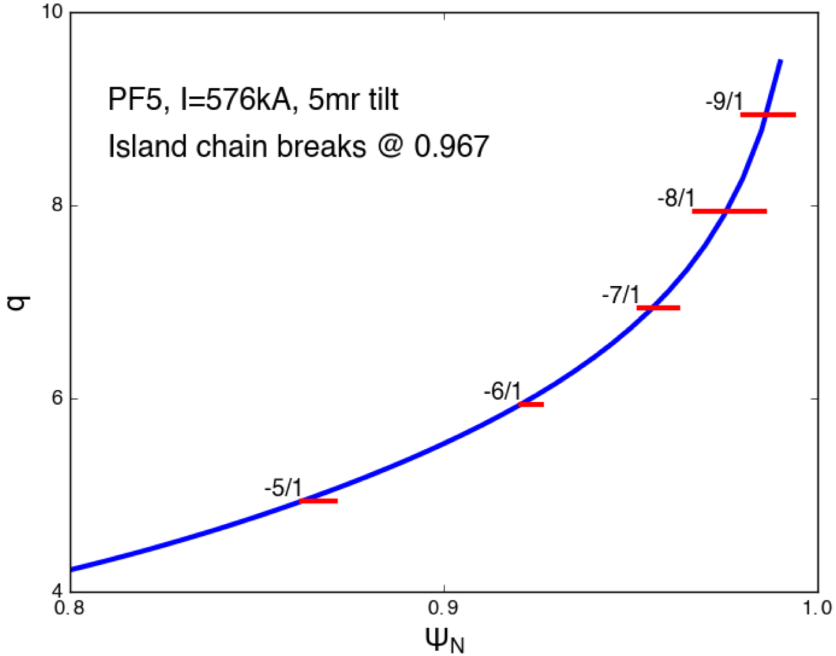
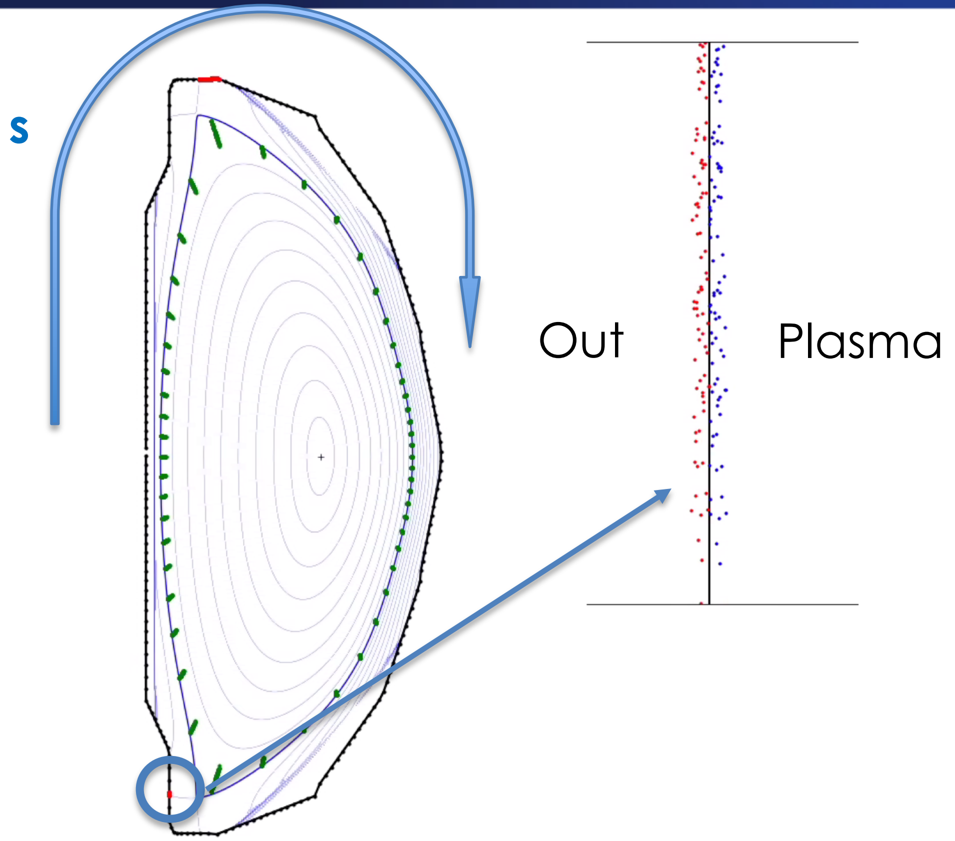
SURFMN is used to identify the outermost island that is not part of the island chain



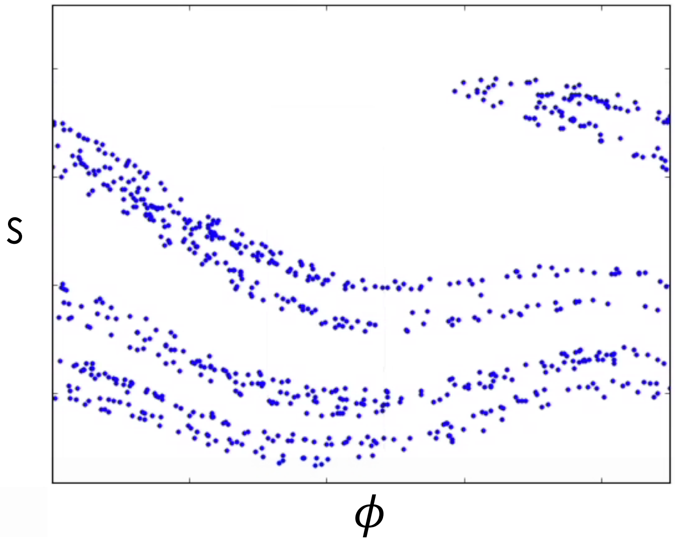
- 15k lines launched, 30 radial points ($0.94 < \psi_N < 1$), 50 poloidal positions, 10 toroidal positions.
- Followed for at least 200 toroidal turns, integration step of 1 toroidal degree in the HFS and 0.1 in the LFS, both positive and negative direction.
- Using the last points inside the limiter as new starting point, re-run the simulations for 20k turns to estimate magnetic length and minimum ψ_N of each line



Footprints are estimated using the last step inside and first step outside the limiter and the limiter itself

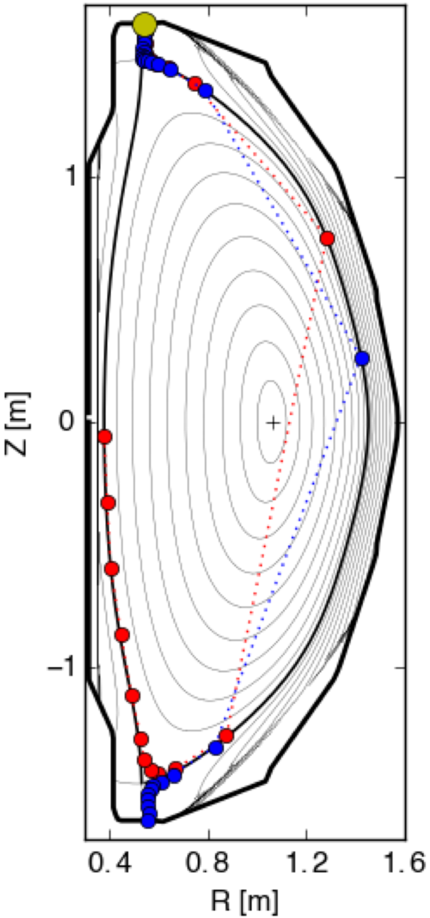


- Hit parameter "s" is defined as the distance from inner midplane along the wall clockwise.



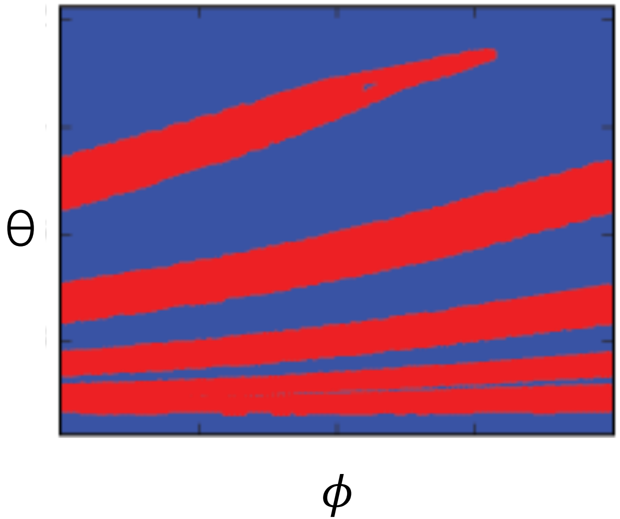
The area is estimated starting from a grid on the limiter

- Area of the footprint = size of one grid element area times number of lines that enter the plasma
- The area of the grid elements is assumed equal to the middle grid one (not accounting for different R)
- Number of turns for the simulation chosen to ensure all the lines either exit the limiter or complete a poloidal turn



The line makes 1 poloidal turn => plasma

The line can't cross the X-point => SOL



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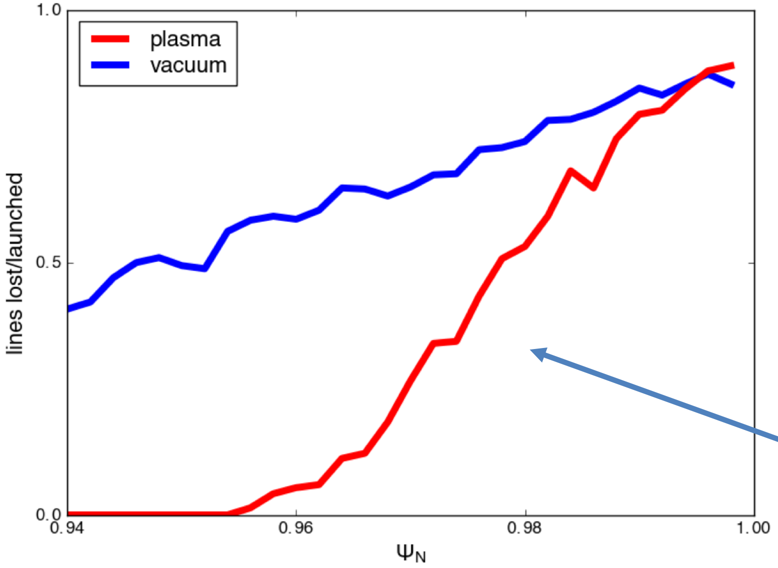
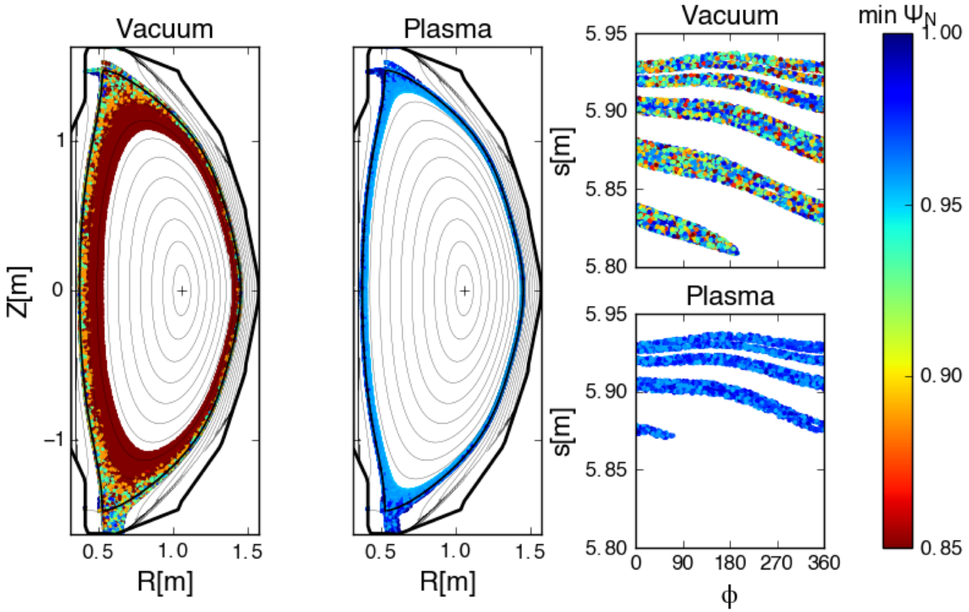
Including the plasma contribution in the simulations, the footprints size is reduced by more than a factor of 2

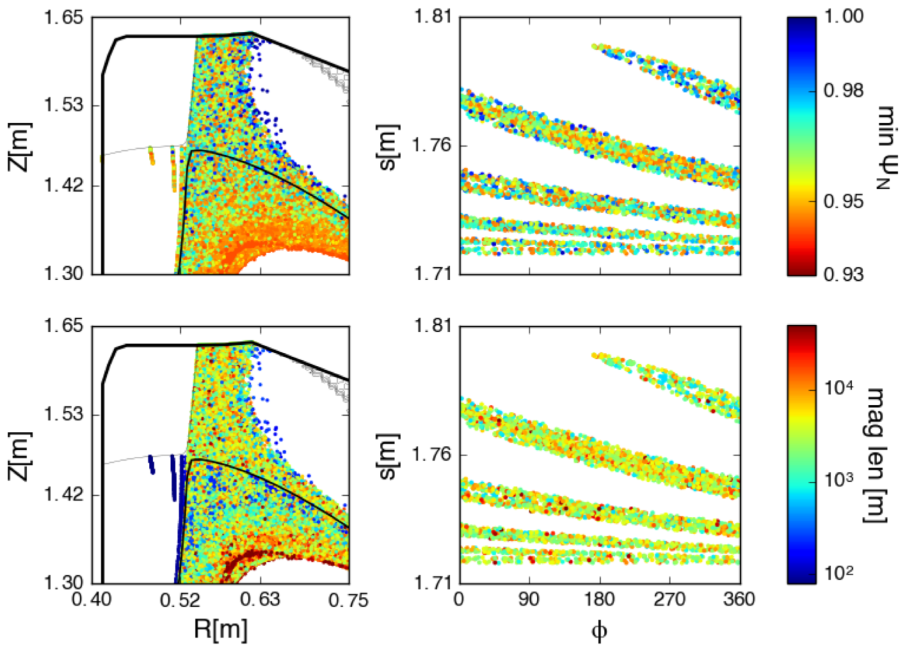
Field lines starting from the same ψ_N go deeper in the plasma when the plasma response is neglected

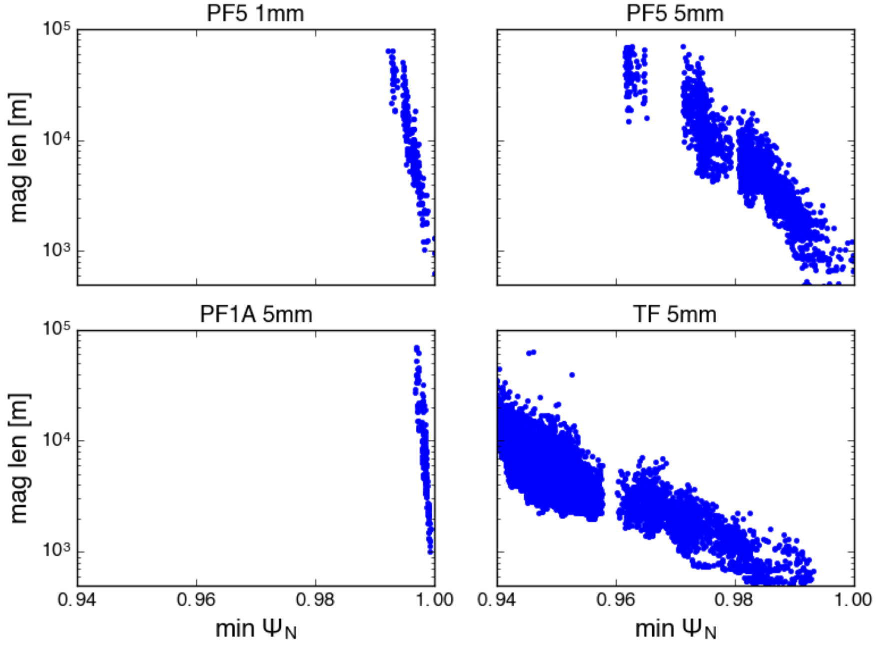




Neglecting the plasma contribution results in a field line loss of 50% at $\psi_N \simeq 0.95$, the inner field line loss boundary when the plasma response is included

ψ_N provides more information than the field line length when comparing different misalignments





- There is an inverse dependence between minimum ψ_N and magnetic length
- While the range of ψ_N changes for the different cases, the magnetic length is between 100 m ($\psi_N \simeq 1$) and 100 km (deepest ψ_N)

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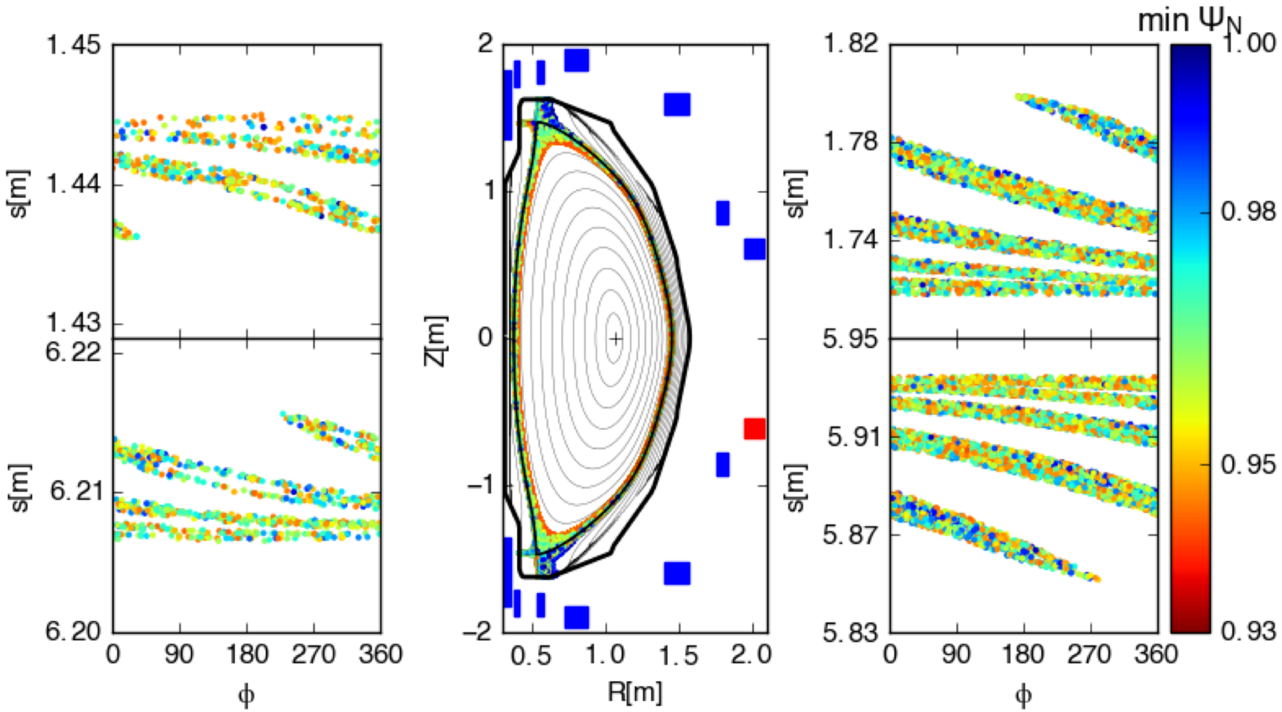
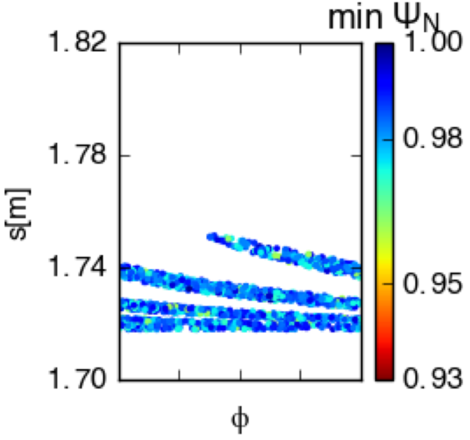
5mr tilt of PF5L produces 8 cm wide footprints on the outer divertor plates

5 mr tilt of the PF5L coil



5 mm shift

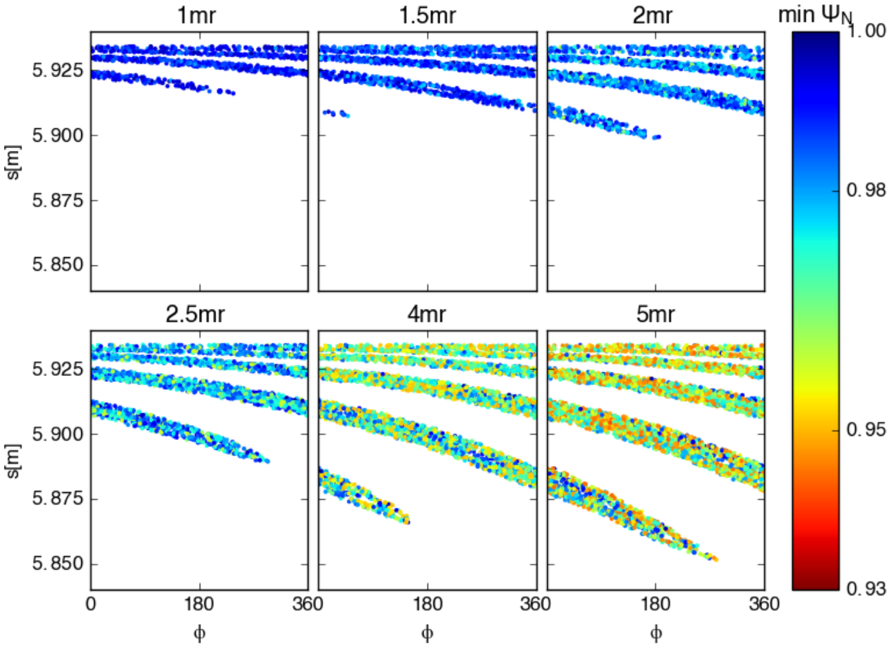


Outer footprints area

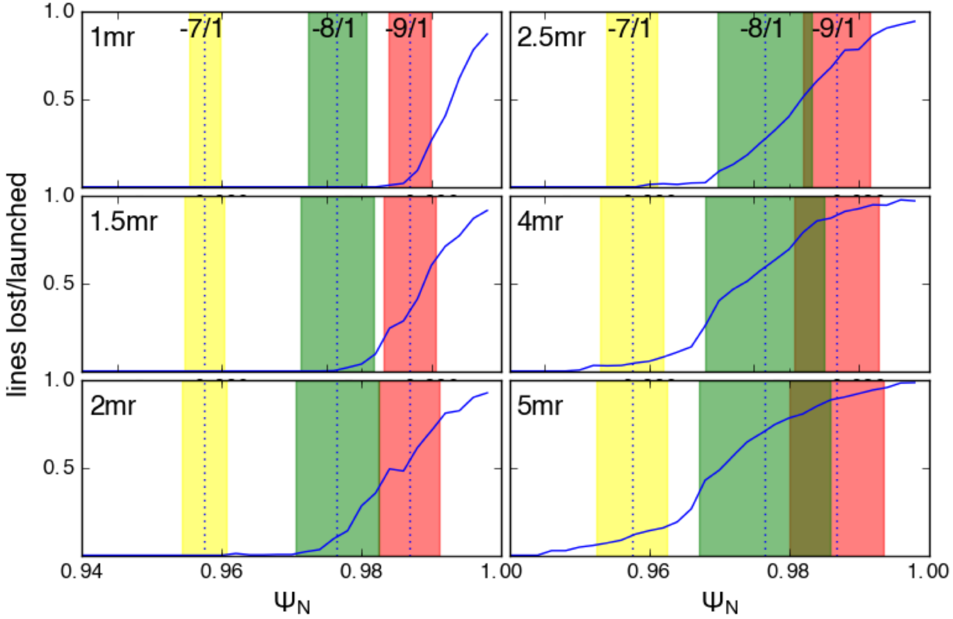
- 5mr tilt:
  - Upper -> 0.0854 m^2
  - Lower -> 0.0876 m^2
- 5mm shift:
  - Upper -> 0.0333 m^2
  - Lower -> 0.0351 m^2

The majority of the lines lost come from the island chain

- For 1 mr tilt the footprint is about 1.8 cm wide, for 5 mr 8 cm wide
- The larger the tilt, the deeper the lines go in the plasma



No overlap   -8/1 & -9/1 overlap



- A step in the fraction of line lost is present in correspondence of the island chain for the larger tilts

The superficial density of power deposition to the divertor is inversely proportional to the tilt magnitude

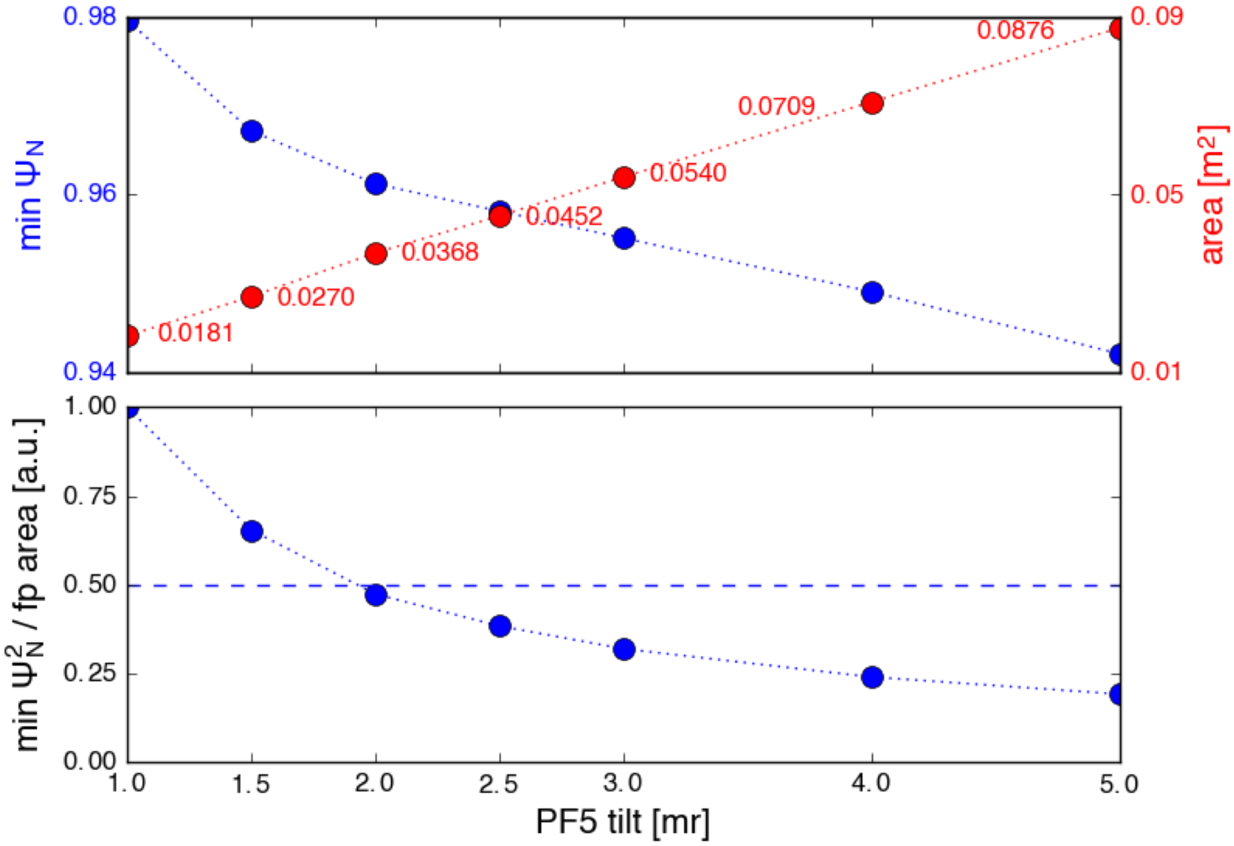
$P_{divertor} = P_{injected} - P_{radiated}$

In the assumption of uniform radial distribution of P_{in}: $P_{rad} \propto V_{stoch}$

therefore

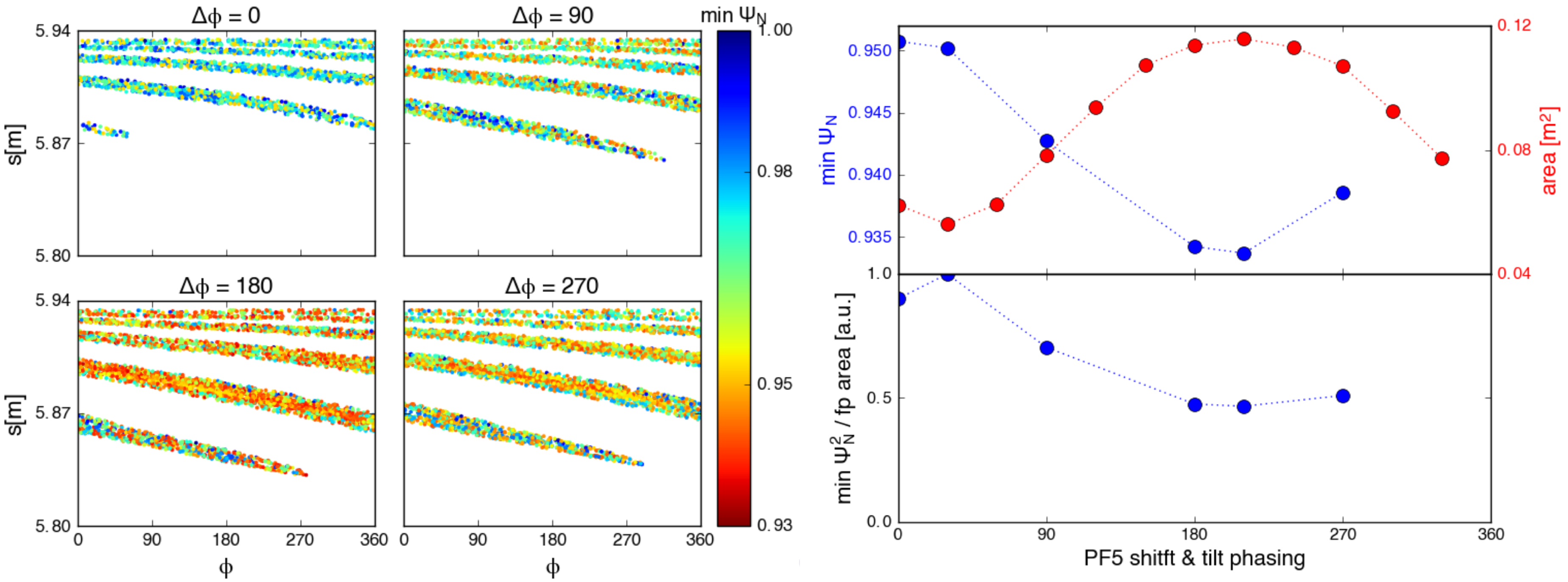
$P_{div} \propto P_{in} * \min \psi_{Nfp}^2$

Double tilt magnitude means less than half power per unit of area



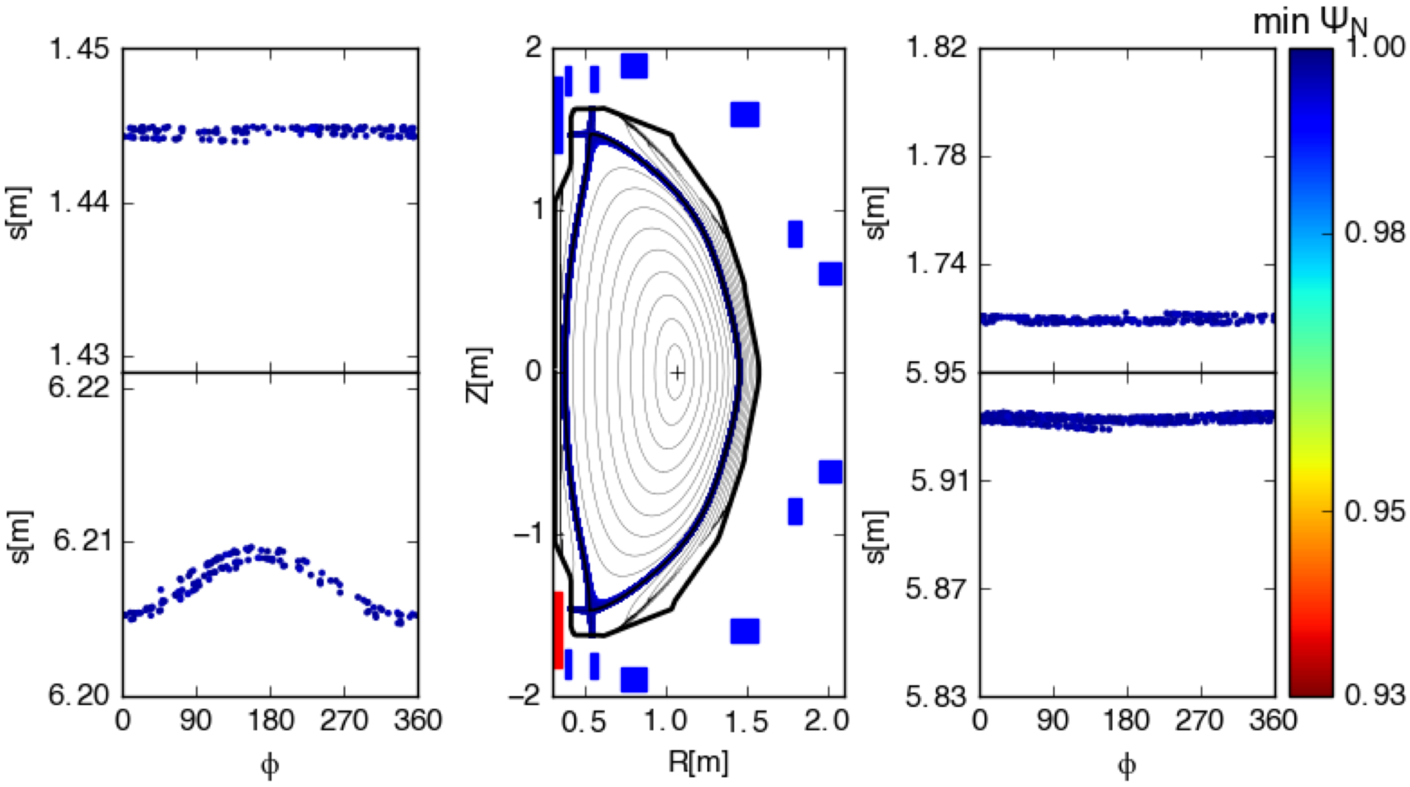
Shift and tilt at 30° have the minimum area, at 210° the maximum

- When combining shift and tilt, only one equilibrium can be used between the shift and the tilt simulation. The difference between footprints is negligible.
- The biggest and deepest footprint is observed when shift and tilt are at 210°
- The smallest footprint is at 30°, while the most superficial one is at 0°



Small misalignment of the PF1A coil produces negligible footprints

5 mr tilt of the PF1AL coil

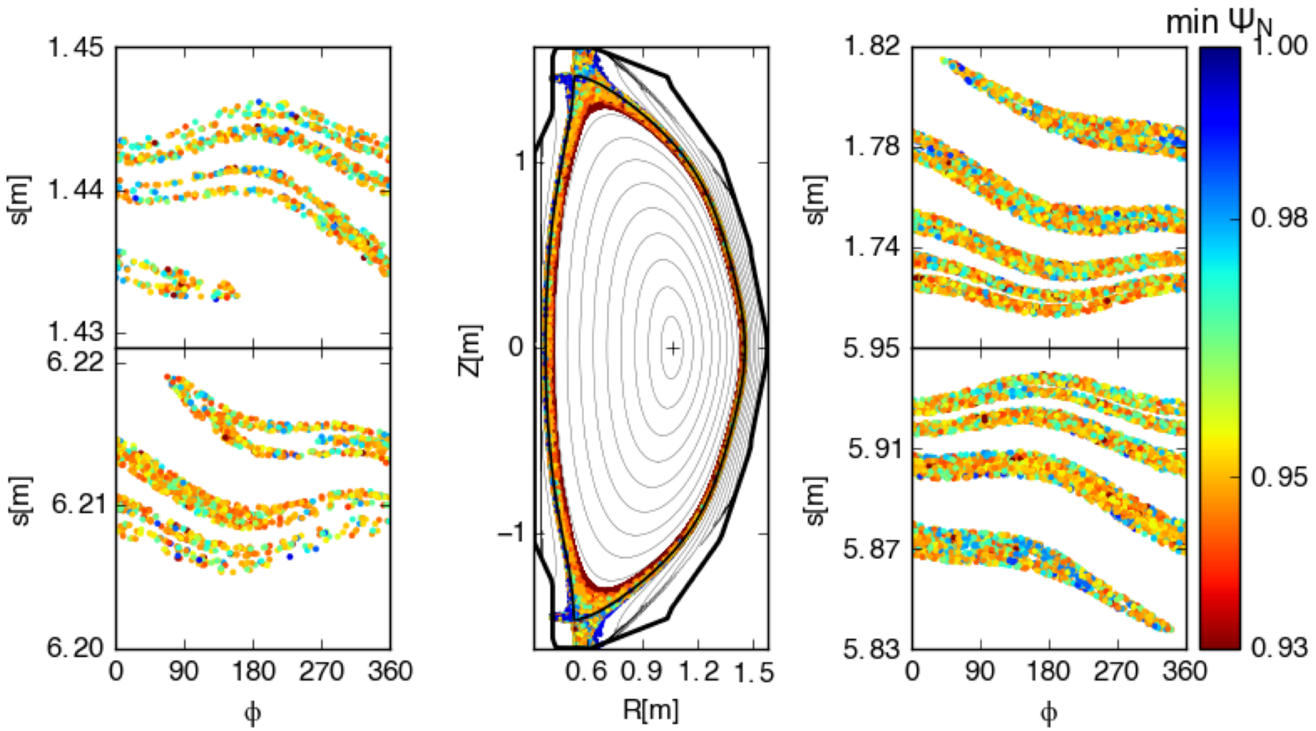


5 mr tilt produces larger footprint than 5 mm shift

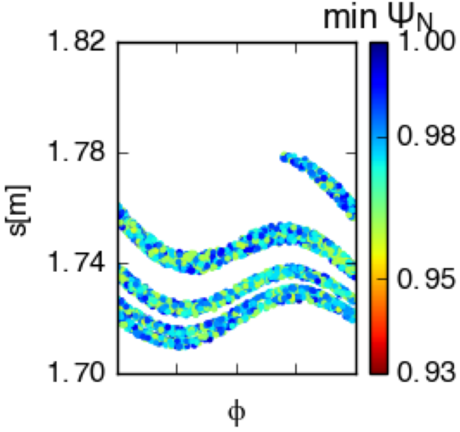
5 mr tilt outer footprint area ~ 0.004 m², an order of magnitude smaller than the PF5 footprints

A 5 mm shift of the TF coils produces 10 cm wide footprints on the outer divertor plates

5 mm shift of the TF coils



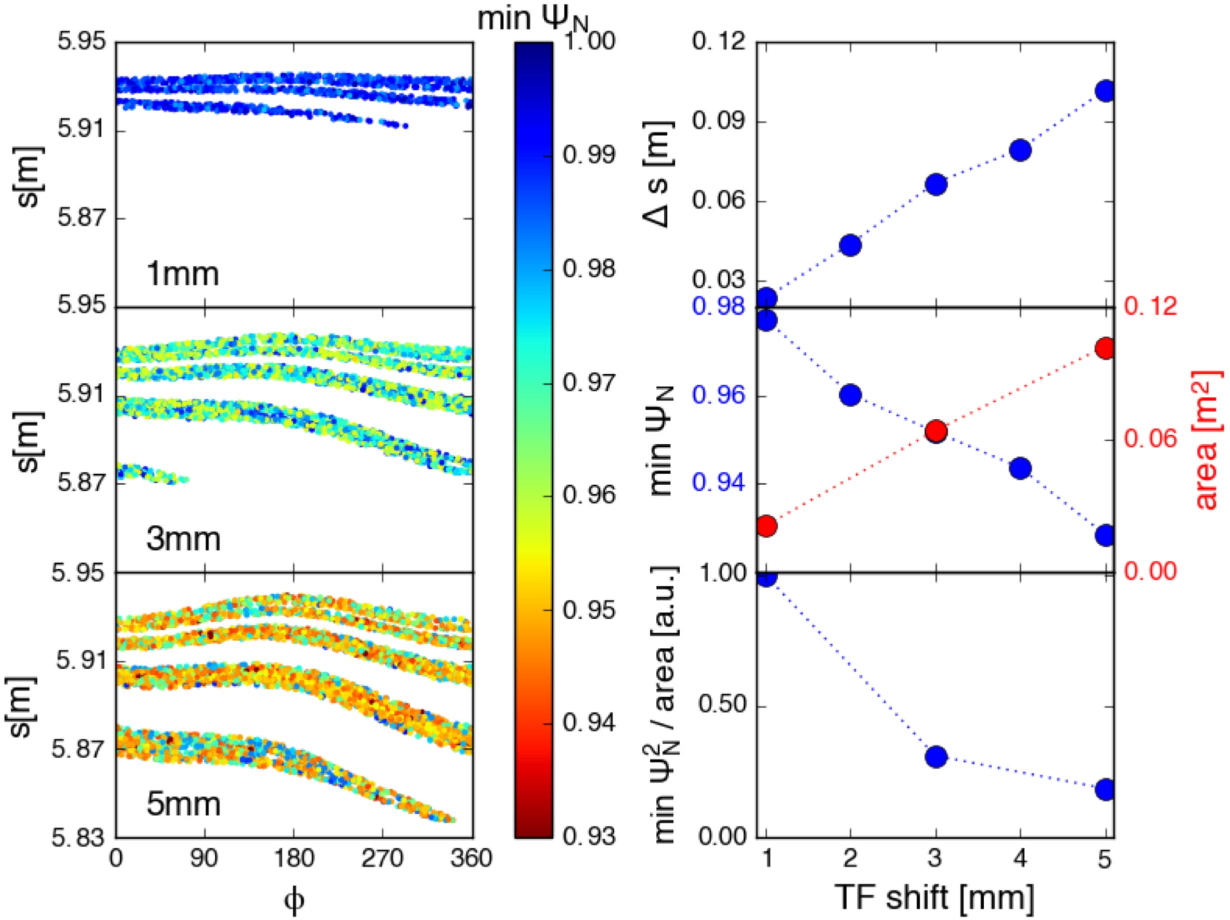
5 mr tilt



Conversely: compared to the PF coils, a shift of the TF coils produces a larger footprint than a tilt

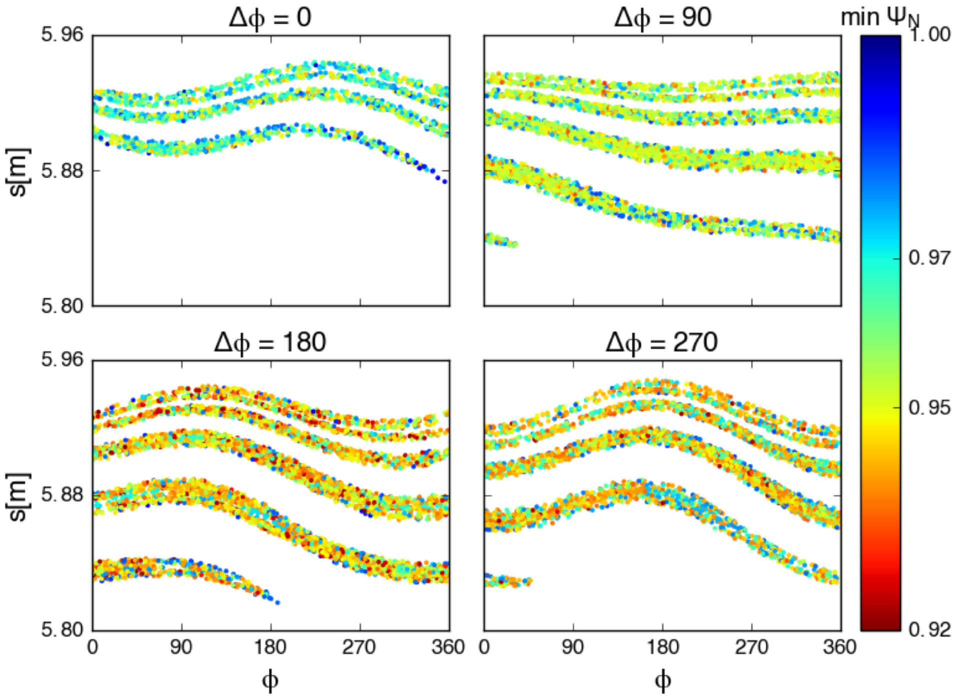
A 1mm shift of the TF produces a 0.021 m² footprint, a 5mm shift a 0.102 m² footprint

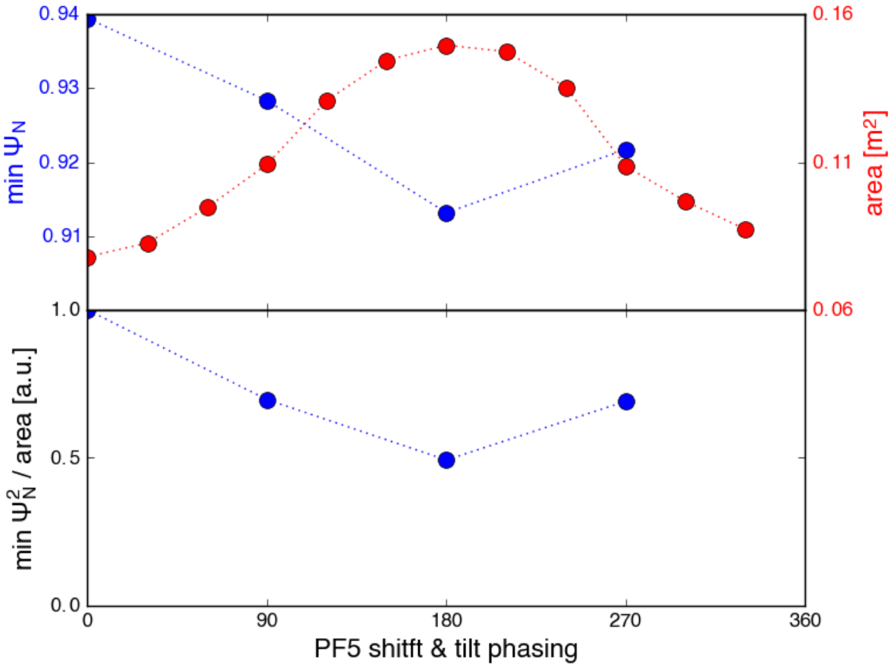
- For 1 mm shift the footprint is about 3 cm wide, for 5 mm 10 cm wide
- The larger the shift, the deeper the lines go in the plasma
- Shift magnitude is inversely proportional to the power deposited per unit of surface



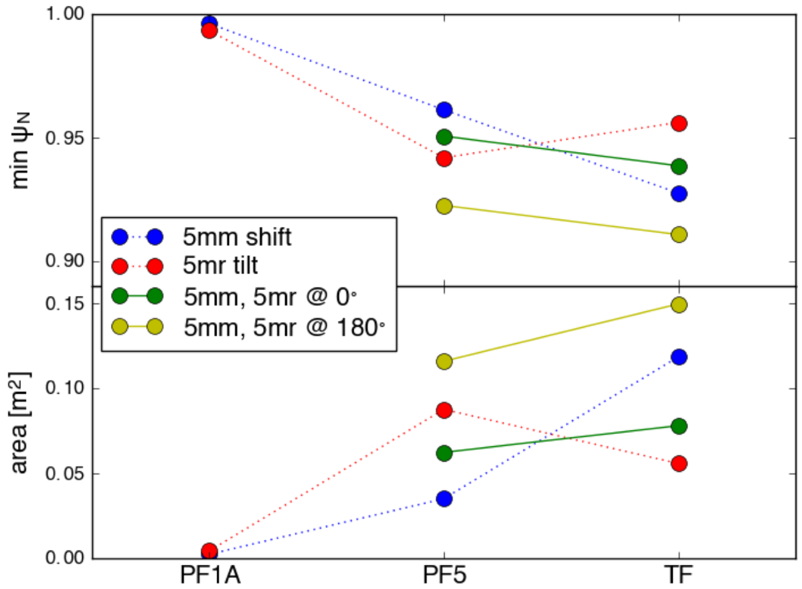
Combinations of TF shift and tilt give similar results to PF5

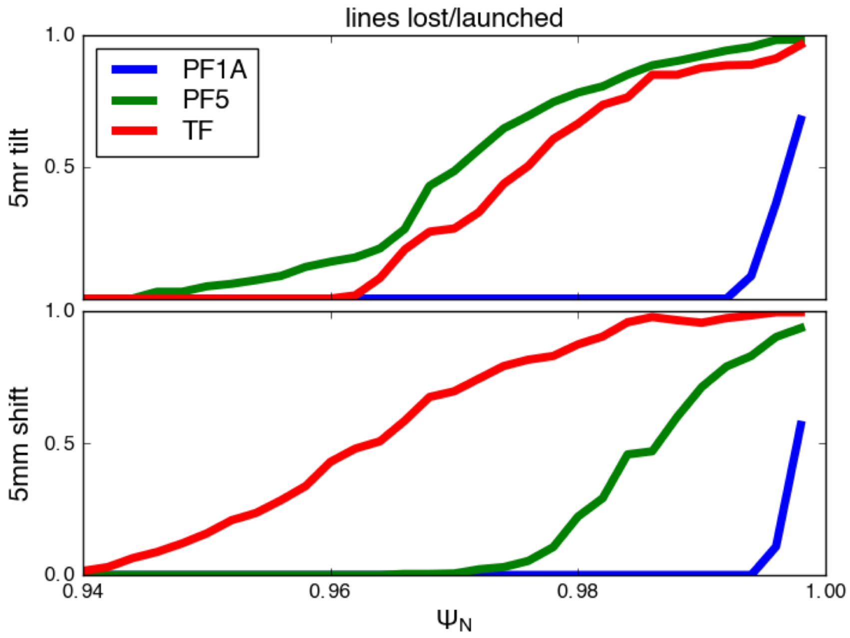
- The biggest and deepest footprint is observed when shift and tilt are at 180°
- The smallest and most superficial footprint is at 0°





TF coils misalignment produces the largest perturbation





- PF1A misalignment negligible compared to the other
- Shift and tilt at 180° produces the largest footprints
- Tilt of the PF5 is comparable to a shift of the TF and vice versa
- The fraction of lines lost due to TF misalignment is bigger than for PF coils

Summary

- 1mm/1mr misalignment of the equilibrium coils simulated with M3D-C[1] and then scaled to max current and desired shift with SURFMN/TRIP3D.
- A tilt of the PF5 coils has a bigger impact on the footprints than their shift.
- Conversely, a shift of the TF coils has a bigger impact on the footprints than their tilt.
- A 5mr tilt of the PF1A coils has negligible effects on the footprints.
- The footprints size is linearly proportional to the misalignment magnitude.
- Shift and tilt combinations reduce the footprint when in phase, increase it when at 180°.
- Power deposition estimations suggest that at a larger footprint correspond a smaller power load per unit of area, although the field lines go deeper in the plasma. These estimations will need to be validated against experimental data.

Disclaimer