Impact of error fields and error fields correction on heat fluxes in SPARC

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The presence of 3D fields causes 3D heat fluxes on the divertor

- Presence of error fields is unavoidable in a tokamak
- 2 of the issues with the presence of error fields are:
  - reduced plasma performance
  - generation of 3D heat fluxes at the divertor plates
- Plasma performances can be recovered by superimposing a 3D field that minimize the core resonance of the error field
- How does this impact the heat fluxes?

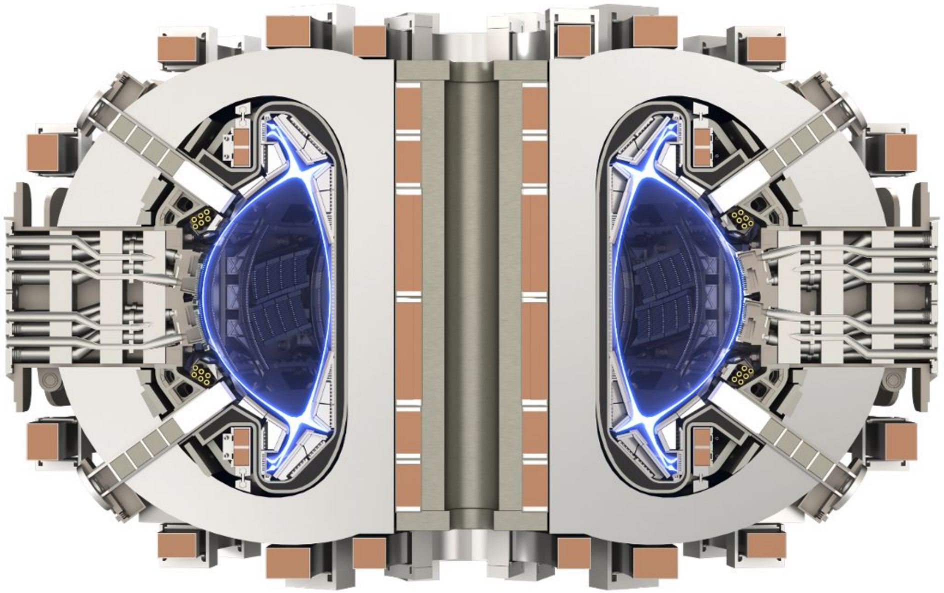
Outline

- Introduction
  - Equilibrium & 3D perturbation
  - Magnetic footprints
  - From magnetic footprints to heat fluxes
- Causes of the 3D magnetic footprints
  - Application of external 3D fields
  - 3D field due to 2D coils misalignments
  - Combination of 3D field sources
- Heat fluxes due to error fields and their correction
  - Database of error fields and their correction with external 3D fields
  - Impact of EFC on the heat fluxes
  - Dependence on parameter choices
- Conclusions and future work

Introduction

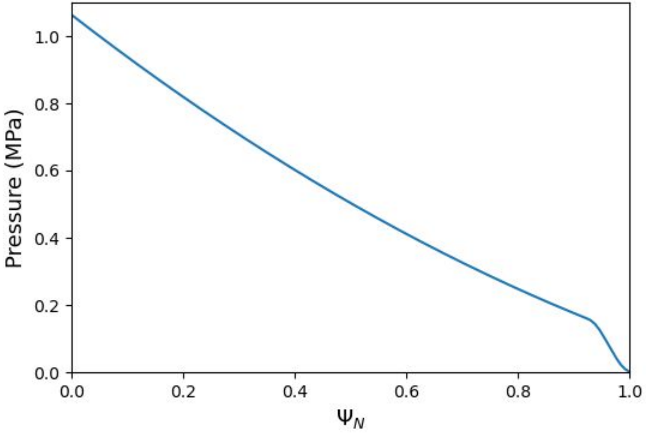
The SPARC tokamak

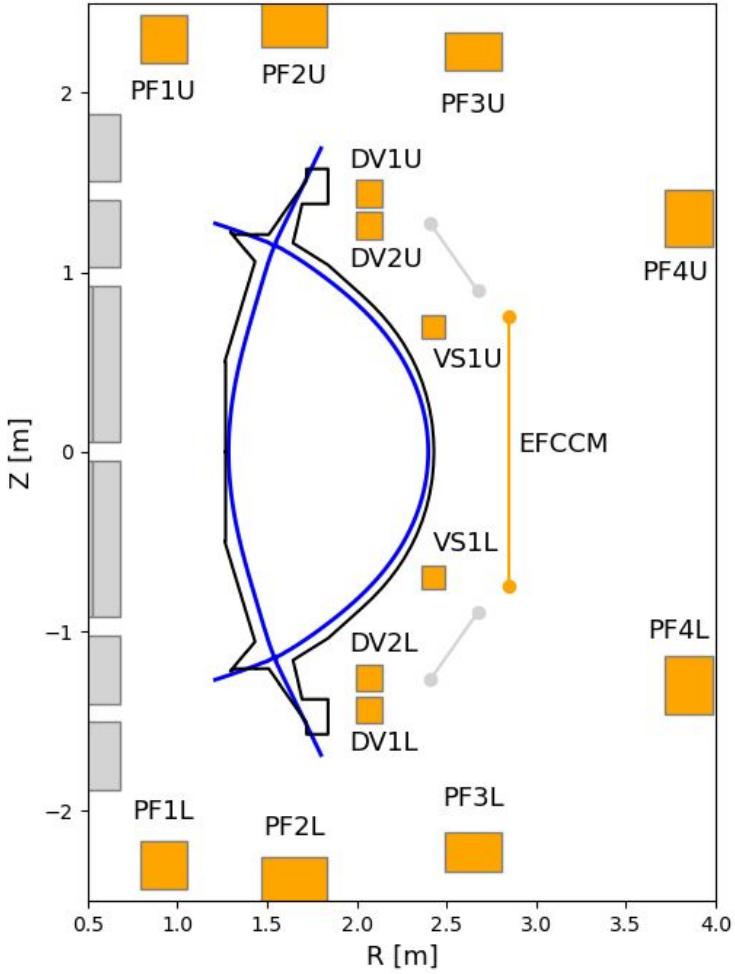
SPARC Primary Reference Discharge		
R	1.85	m
a	0.57	m
B_0	12.2	T
I_p	8.7	MA
q^*	3.05	(q_{95} = 3.4)
κ_{sep}	1.98	
$\langle T_e \rangle$	7.33	keV
$\langle n_e \rangle$	3.13	$10^{20} m^{-3}$
τ_E	0.77	s
f_g	0.37	
P_{ohmic}	1.7	MW
$P_{rf,coupled,operating}$	11.1	MW
P_{fus}	141	MW
Q	11.0	(h-mode)



Upside-down symmetric double null equilibrium

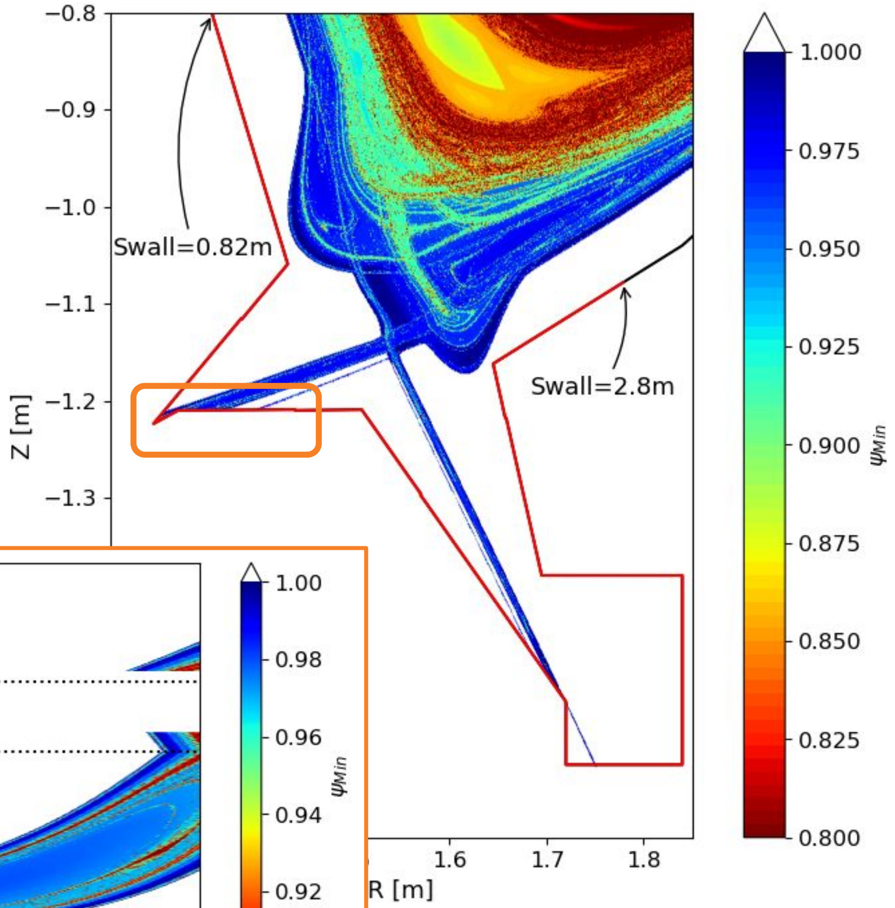
- SPARC equilibrium 1791, Ip=8.7 MA, B_T=12.2 T
- Resistive MHD code M3D-C1 used to calculate the plasma response:
  - Spitzer resistivity
  - no plasma rotation
  - single fluid
  - analytical n_e
  - $n_e=n_i$, $T_e=T_i$

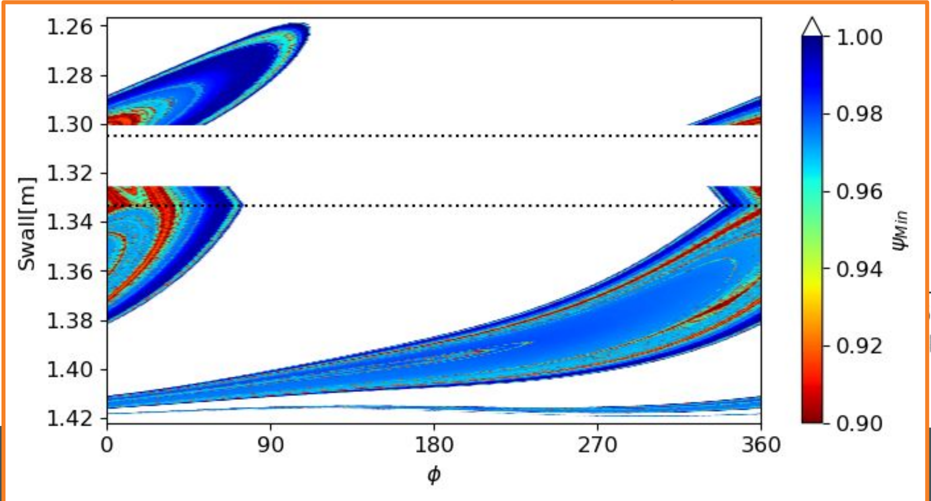




Magnetic footprints

- 3D fields cause field lines otherwise closed to intersect PFC
- Swall is the distance from the HFS midplane along the wall in the counter clock direction
- Create a grid on the divertor and launch field lines toward the plasma
- Consider only those that complete a full poloidal turn (ie, cross the X-point) by setting a minimum connection length
- For each field line, record the minimum unperturbed Ψ_N reached





Converting footprints to heat fluxes

In 2D the heat flux (q) profile can be described as (Eich-profile, *Eich et al, PRL 2011*):

$$q(R(\psi)) = \frac{q_0}{2} exp\left[\left(\frac{S}{2\lambda_q}^2\right) - \frac{R-R_0}{S}\right] \times erfc\left(\frac{S}{2\lambda_q} - \frac{R-R_0}{S}\right) + q_{BG}$$

major radius at the outer midplane as function of normalized poloidal flux

heat flux layer width

private flux region spread

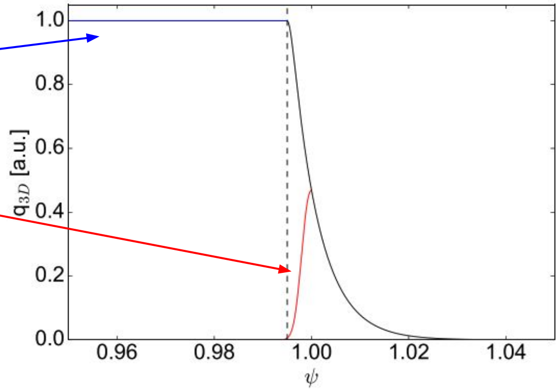
The heat flux profile formulation adapted to the 3D case is (*Wingen et al, NF 2021*):

$$q_{3D}(R(\psi)) = \begin{cases} q(R), \psi \geq \psi_{LCFS} \\ q(R_0), \psi < \psi_{LCFS}, L \geq Lc_{min} \\ q_s q(R)/max(q), \psi < 1, L < Lc_{min} \end{cases}$$

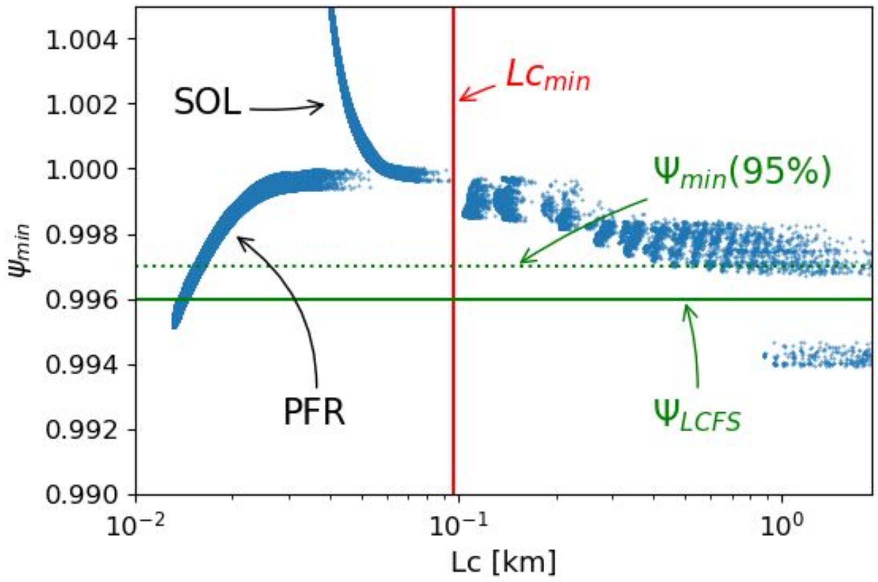
q(R(1))

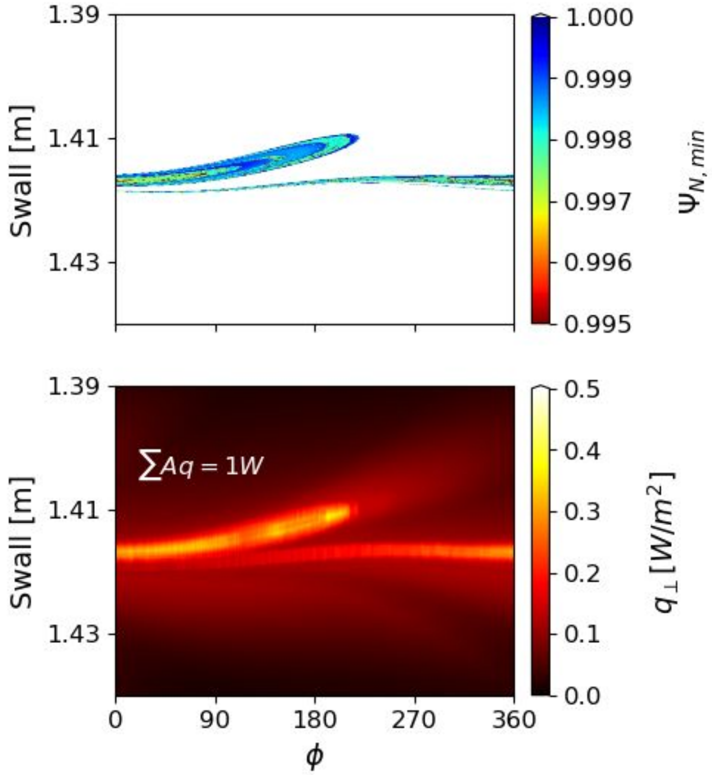
$R(\Psi_{LCFS})$

In 3D, Ψ_N=1 is no longer the LCFS



Lc_{min} and Ψ_{LCFS} are calculated based on the magnetic footprint

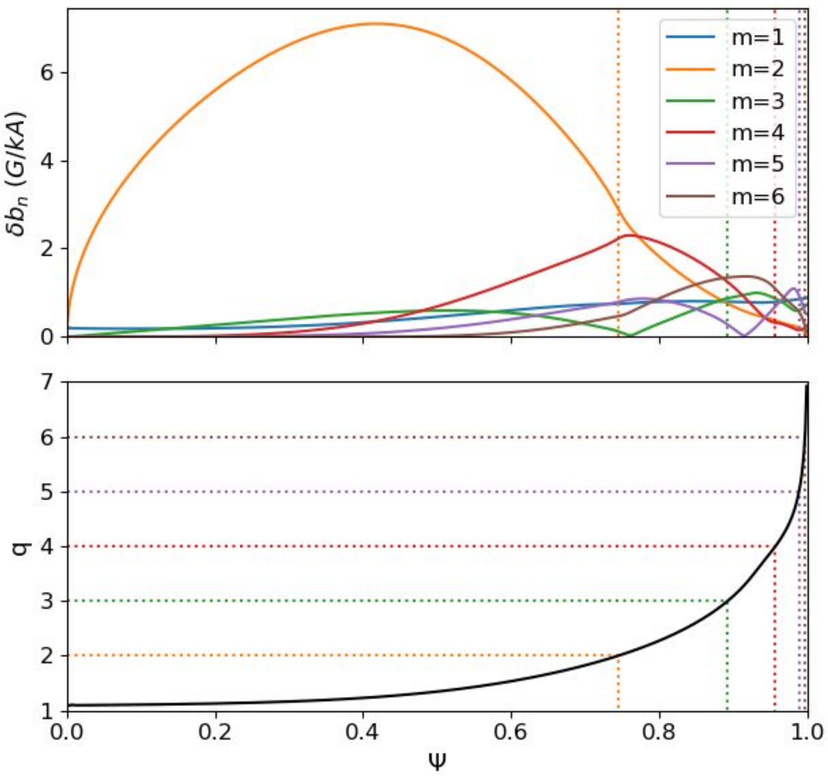




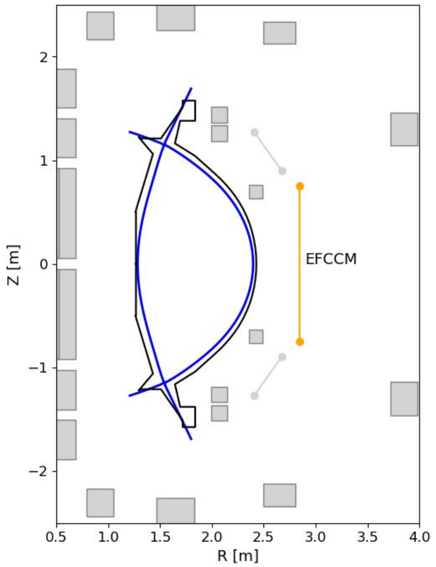
- From Eich scaling #9 (*Eich et al, NF 2013*), $\boldsymbol{\lambda_q}$**=0.6mm** in SPARC
- In SPARC, a reasonable **S=λ_q=0.6mm**

Causes of the 3D magnetic footprints

3D fields can be produced by EFCCM



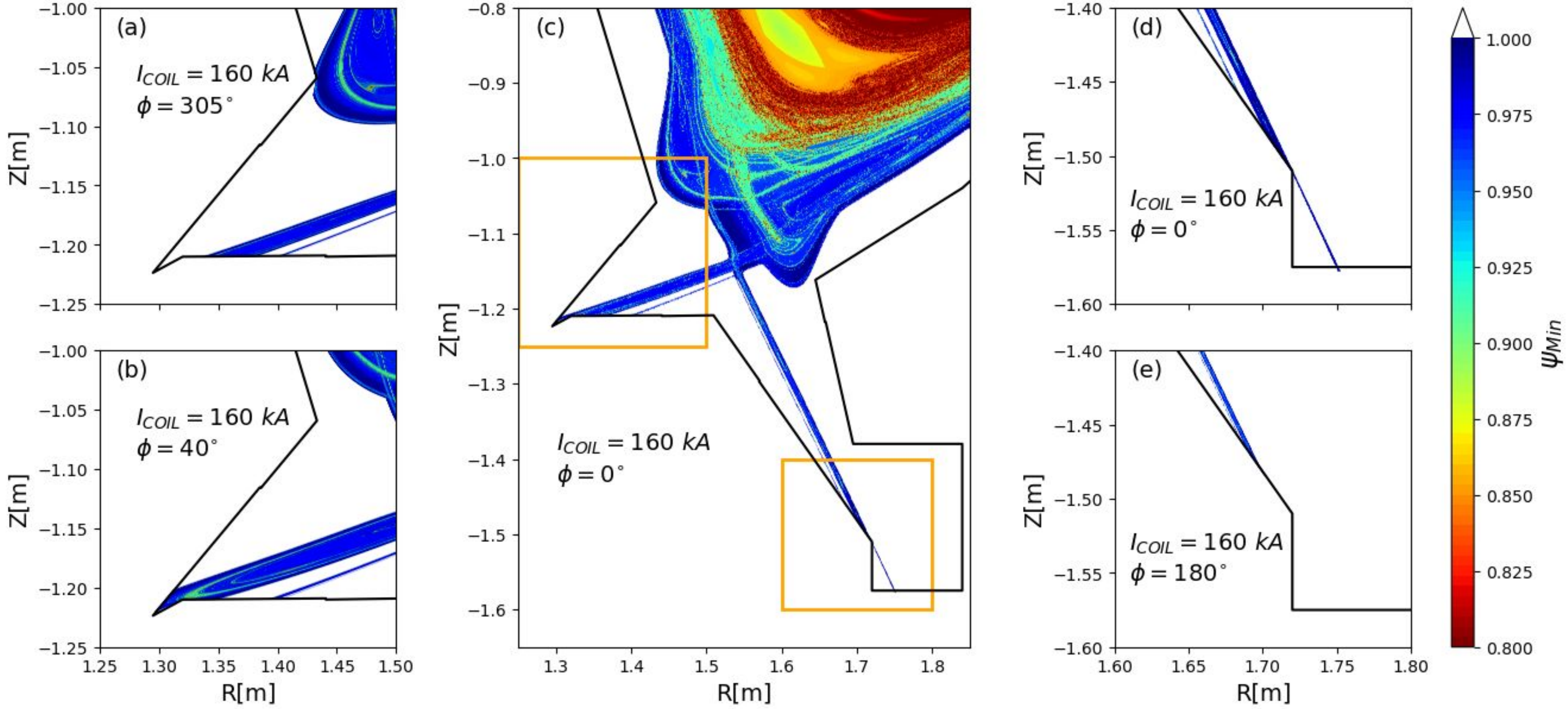
The Error Field Correction Coils - Midplane (EFCCM) are a set of **6** picture frame coils located at R=2.93m, that extend toroidally for about 2m (they are not continuous). Such geometry results in:



$I_{n=1}=0.645 * I_{COIL}$

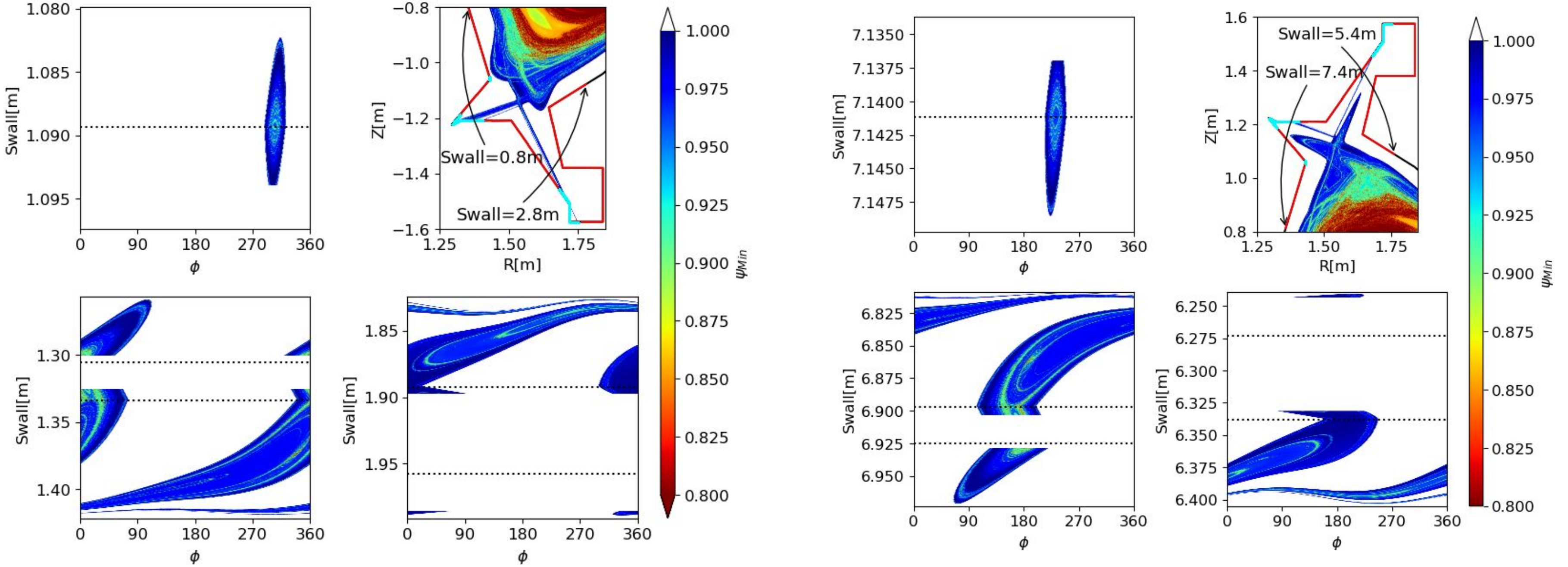
$I_{COIL}=160kA \sim I_{n=1}=103kA$

At the max amplitude, several parts of the wall can be connected with inside the unperturbed separatrix



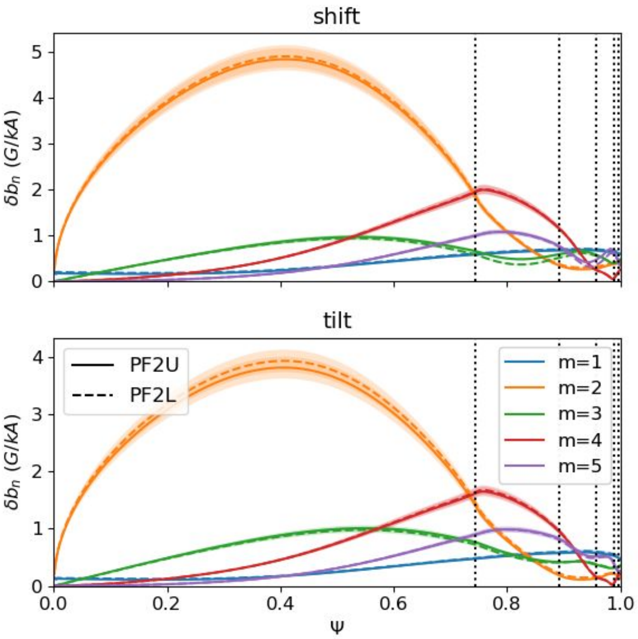
Upper and lower divertor have similar magnetic footprints

Looking for footprints in the divertor area every 1mm in the Swall direction and 1° in the toroidal direction



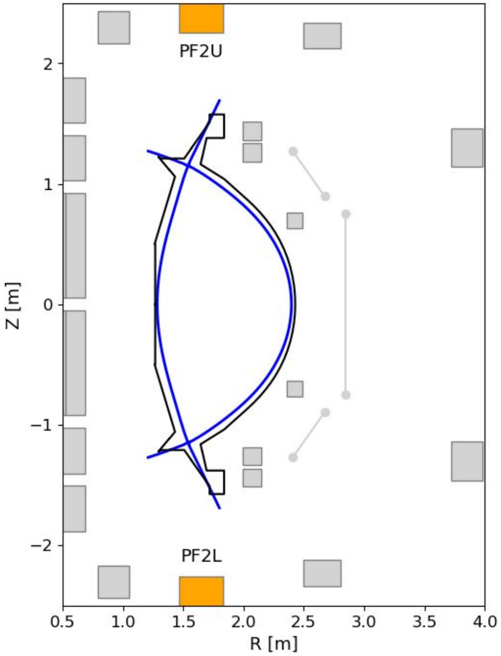
3D fields can be produced by 2D coils misalignment

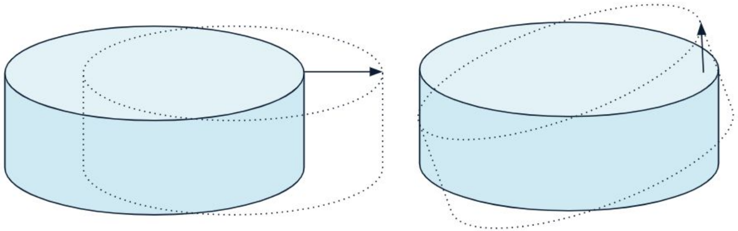
M3DC1 run done with 1 mm shift or 1 mrad tilt

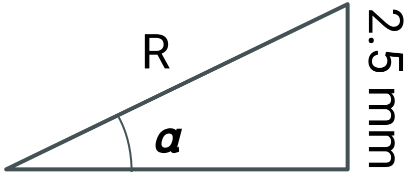


Each coil linearly scaled to the max allowed misalignment (2.5 mm)

Upper and lower coil misalignment produce similar perturbations of the magnetic field within ~10% of each other

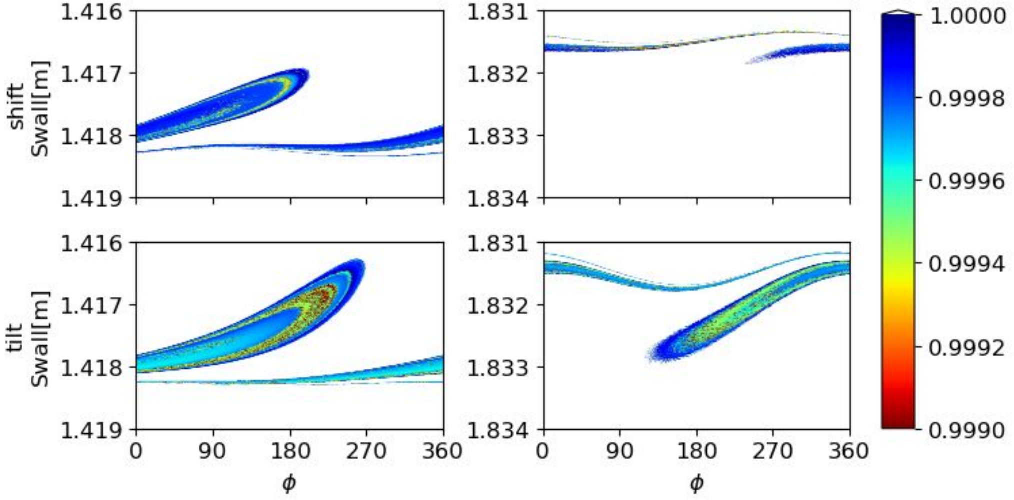


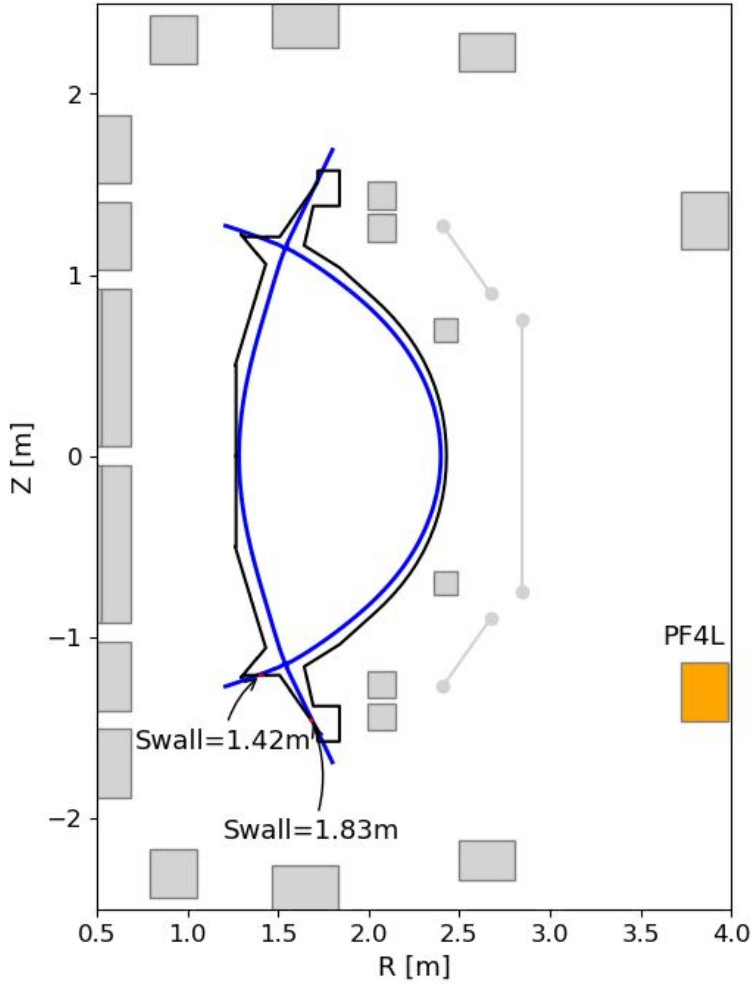




Single coil misalignments produce small 3D footprints

A single misalignment of a single 2D coils produce at most a few mm large footprint

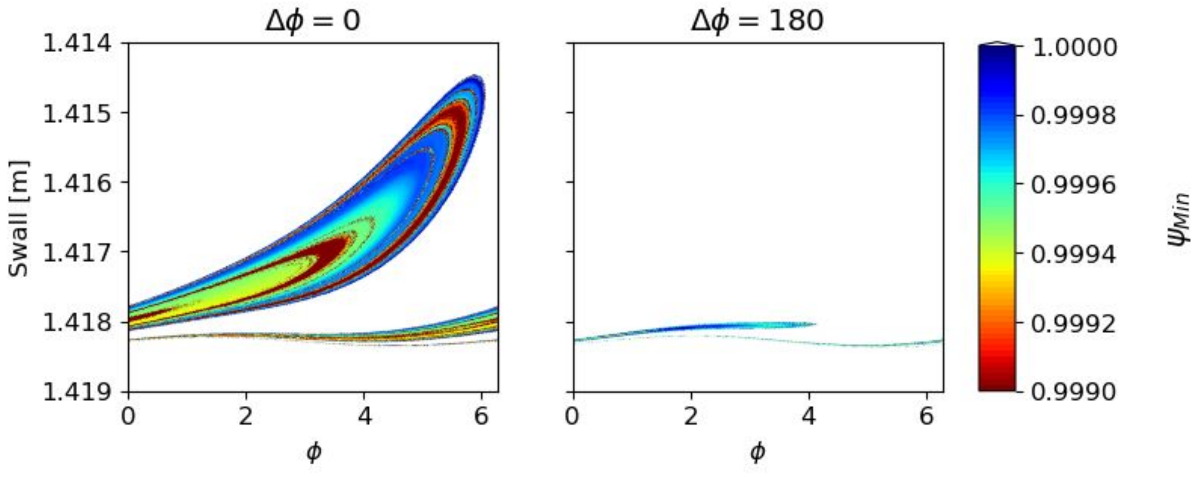


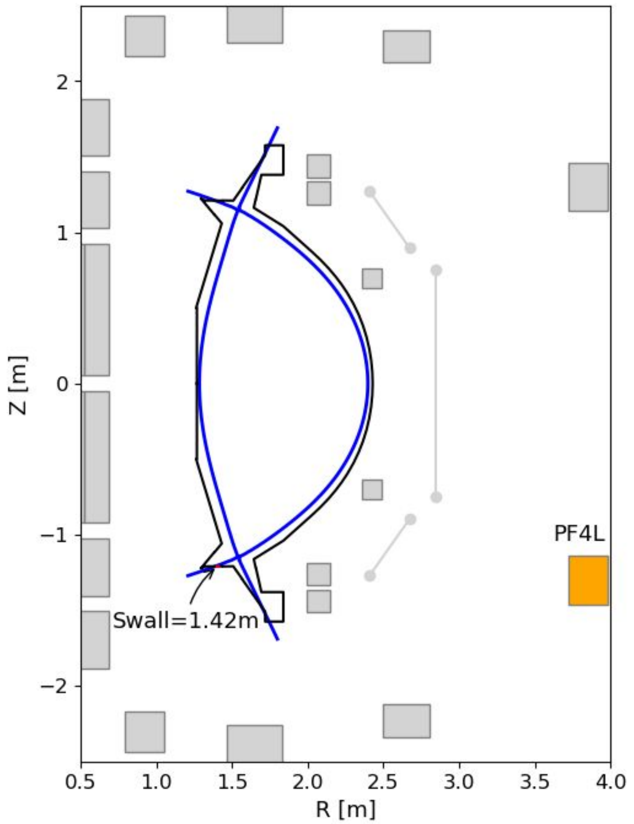


Combining shift and tilt, the relative phase matters

- A combined misalignment of a single 2D coils can produce larger or smaller footprints depending on the relative phase of the misalignments

- The footprint is still small (<5mm)





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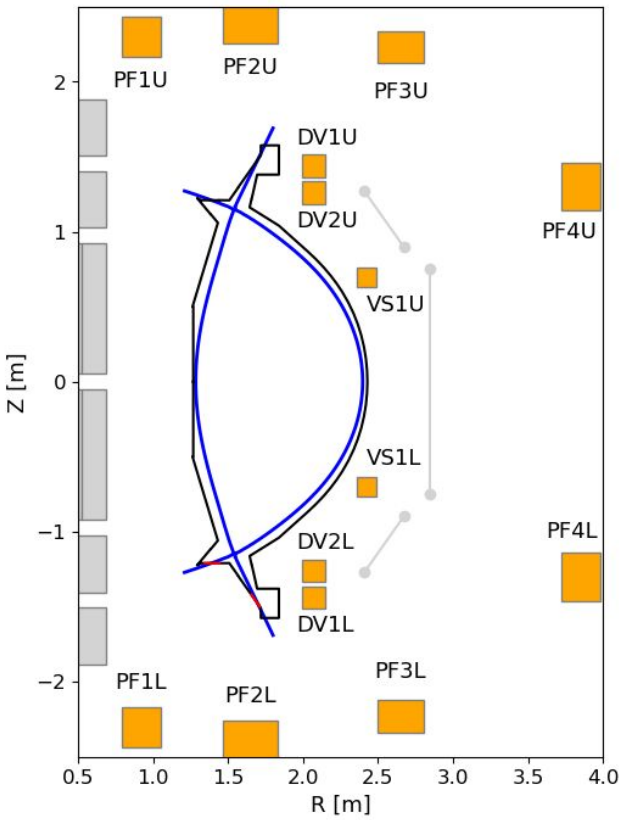
Heat fluxes due to error fields and their correction

Combining all possible misalignment

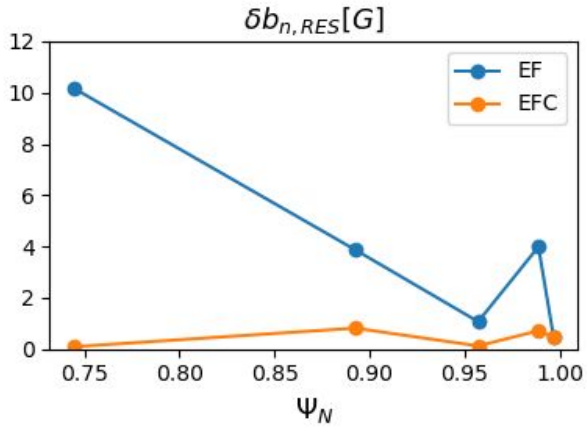
- There are infinite ways to combine the coil misalignments

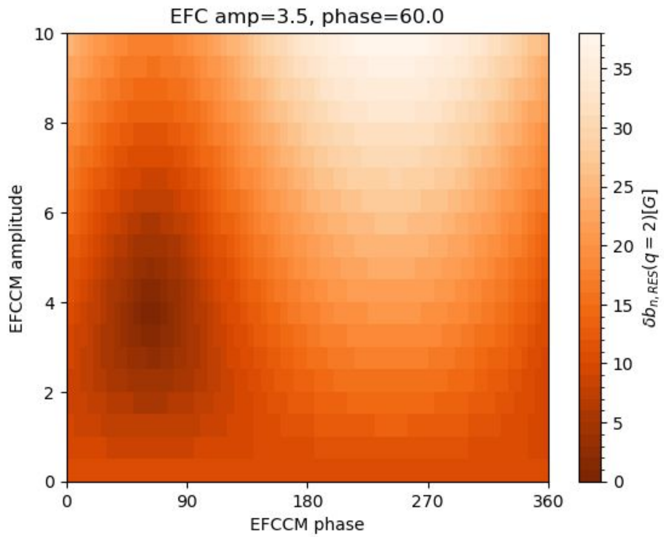
- A MonteCarlo approach is adopted where the coils are randomly misaligned, with some limitations:
  - Each coil is shifted and tiled by 2.5 mm (fixed amplitude)
  - Phase of PF1U shift is fixed, the other are varied randomly (focusing on relative phases)
  - Phase variations limited to step of 15 degrees

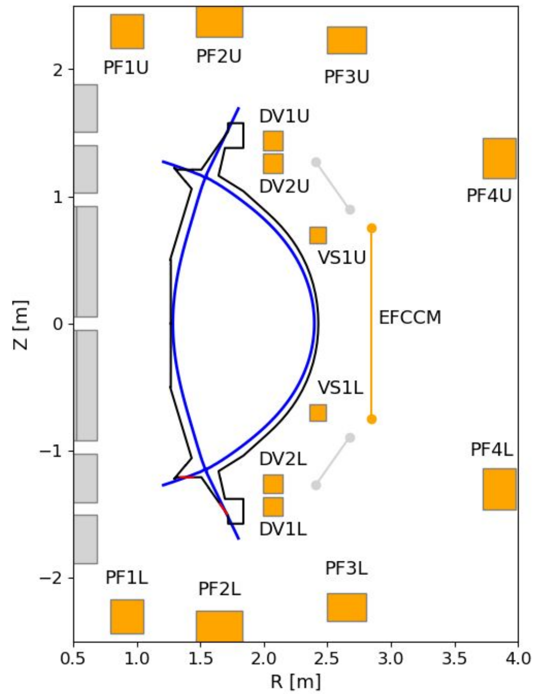


Find the best error field correction for each case

- For each case, the EFCCM was applied
- EFCCM amplitude scanned form 0kA to 10kA with steps of 0.5kA
- EFCCM phase scanned form 0 to 360 deg with steps of 5 deg
- Select the EFCCM amplitude and phase that minimize the resonant field at q=2

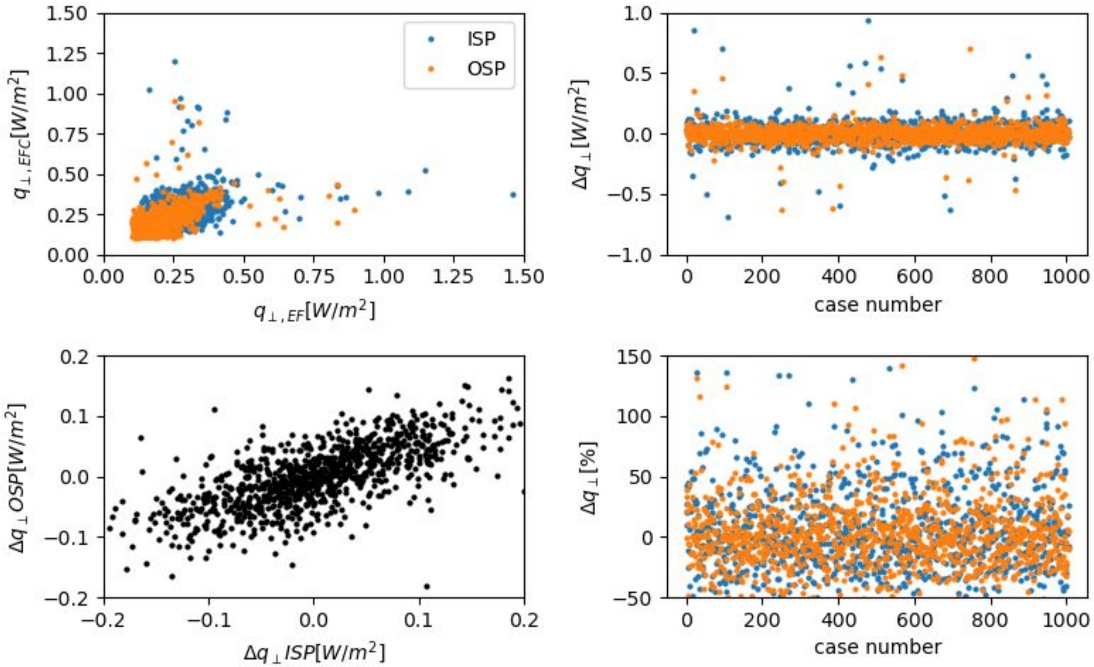






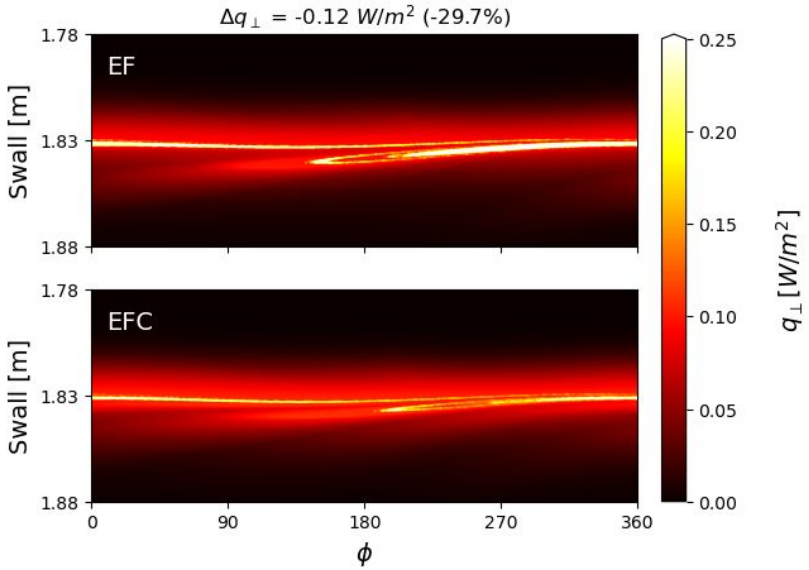
EFC can lead to an increase of more than 100% in the peak perpendicular heat flux

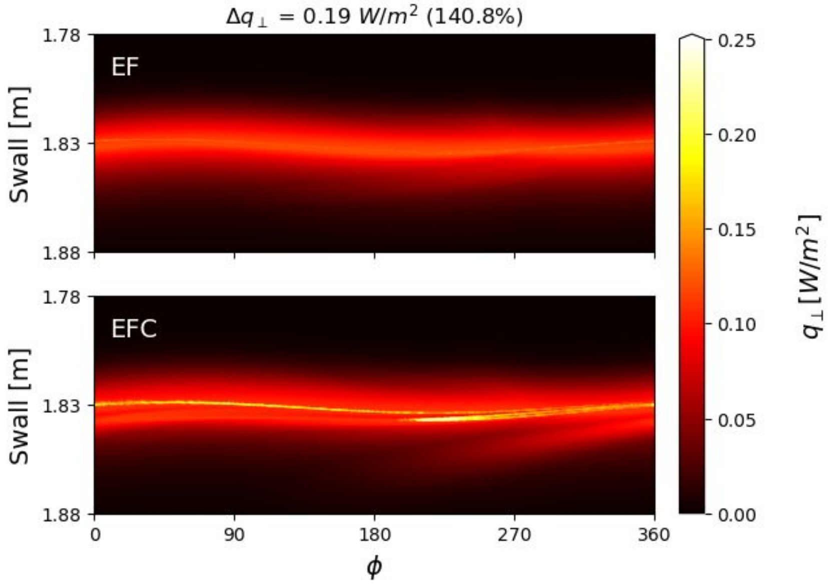
- Looking at more than 1k cases
- For each case, looking at the max perpendicular heat flux ($q_\perp$)
- A convergence study showed that grid elements 0.1mm high and 32 deg large for the OSP provide a max $q_\perp$ within 10% of finer grids (=> following 10k field lines instead of 360k)



3D heat fluxes calculated on a detailed grid highlight the changes in local $q_\perp$

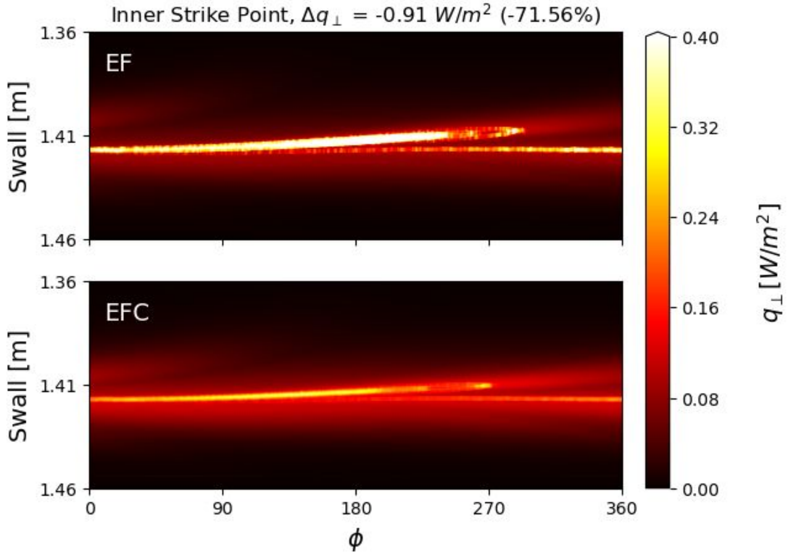
- Grid elements are 0.1mm x 1deg
- EFC can increase or decrease the local $q_\perp$
- The heat flux stays within a few cm from the unperturbed strike point location

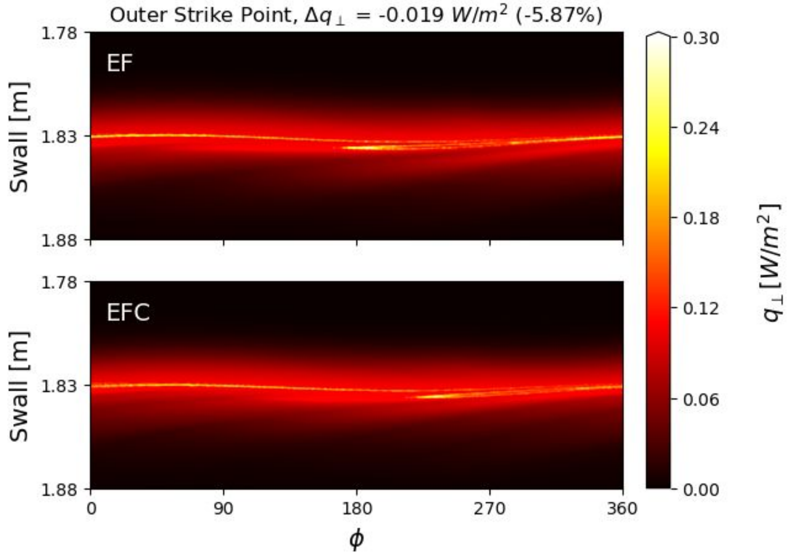




The change in peak heat flux in the OSP can be very different from that in the ISP

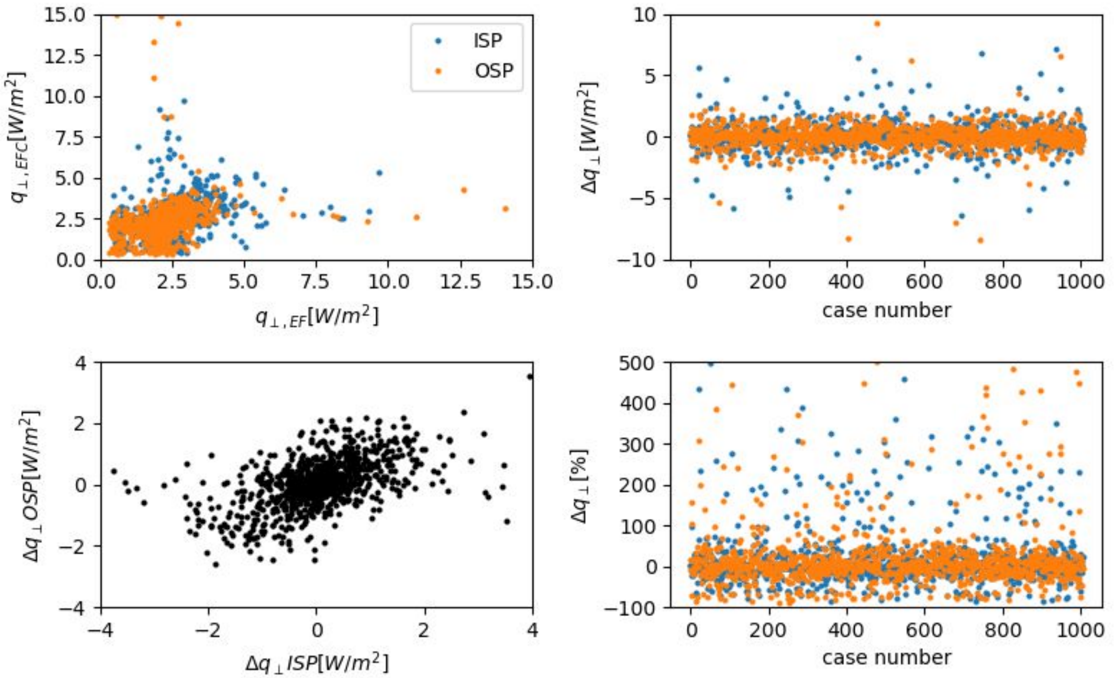
- In this case the EFC reduces the peak $q_\perp$ by about 70% at the ISP, but only by almost 6% at the OSP
- There are a few cases where the peak $q_\perp$ increases on one side and decreases on the other





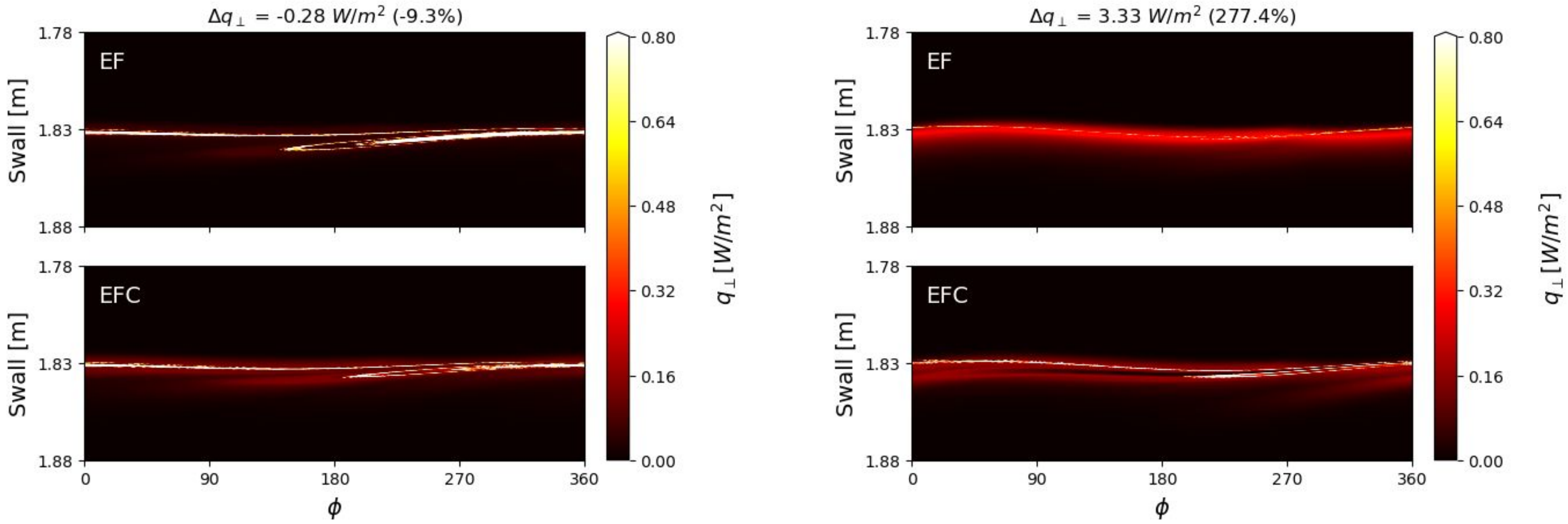
A more unfavorable (smaller) λ_q increases by an order of magnitude the peak heat flux

- Eich scaling #15 predicts λ_q=0.3mm in SPARC
- A stricter choice for S is S=λ_q/2=0.15mm
- The peak heat flux increases by an order of magnitude
- The variation in peak heat flux also increases



A smaller λ_q leads to heat deposition on a smaller area

- A smaller λ_q and S lead to a smaller deposition area and therefore a higher peak heat flux
- EFC can still increase or decrease the peak heat flux and ISP and OSP can still have different behaviour
- The SOL width remains transport dominated for such small 3D perturbations



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Conclusions and future work

Conclusions

- The presence of error fields is unavoidable in tokamaks, and they modify the heat flux deposition on the divertor
- Correcting the core component of the error fields can lead to an increase of the peak heat flux by more than 2 times
- An increase/decrease of the peak heat flux on the Outer Strike Point does not always correspond to an increase/decrease on the Inner Strike Point
- The possible range of peak heat fluxes due to error fields is not affected by the error field correction
- Transport still plays an important role on determining the SOL width for such small 3D perturbations

What is next?

- Can we minimize both the resonant field and the peak heat flux using also EFCCU and EFCCL?

- Is there any dependence on the equilibrium chosen?

- How would this change if we consider the realistic 3D PFC instead of a 2D PFC?