MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Stellarator divertor optimisation

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EUROfusion

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Stellarator divertor design and optimisation

What should the **divertor plates** look like?

Divertor design scheme:

- **Low heat loads ✓**

  (using EMC3-Lite (anisotropic heat diffusion))

- **Neutral particle exhaust**

  (using a first-flight neutral model)

What should the **magnetic field** look like?

- **Properties of non-resonant divertors?**

  (i.e. chaotic magnetic fields)

- **Hamiltonian approaches**

EMC3-Lite [1]: Edge Monte Carlo 3D (-Lite)

- Solves a (simplified) anisotropic heat diffusion equation (1) with Bohm target boundary condition (2), to predict heat loads on plasma-facing components

$$\nabla\cdot\left(-\kappa_e\nabla_{||}T-\chi n\nabla_{\perp}T\right)=0 \qquad (1)$$

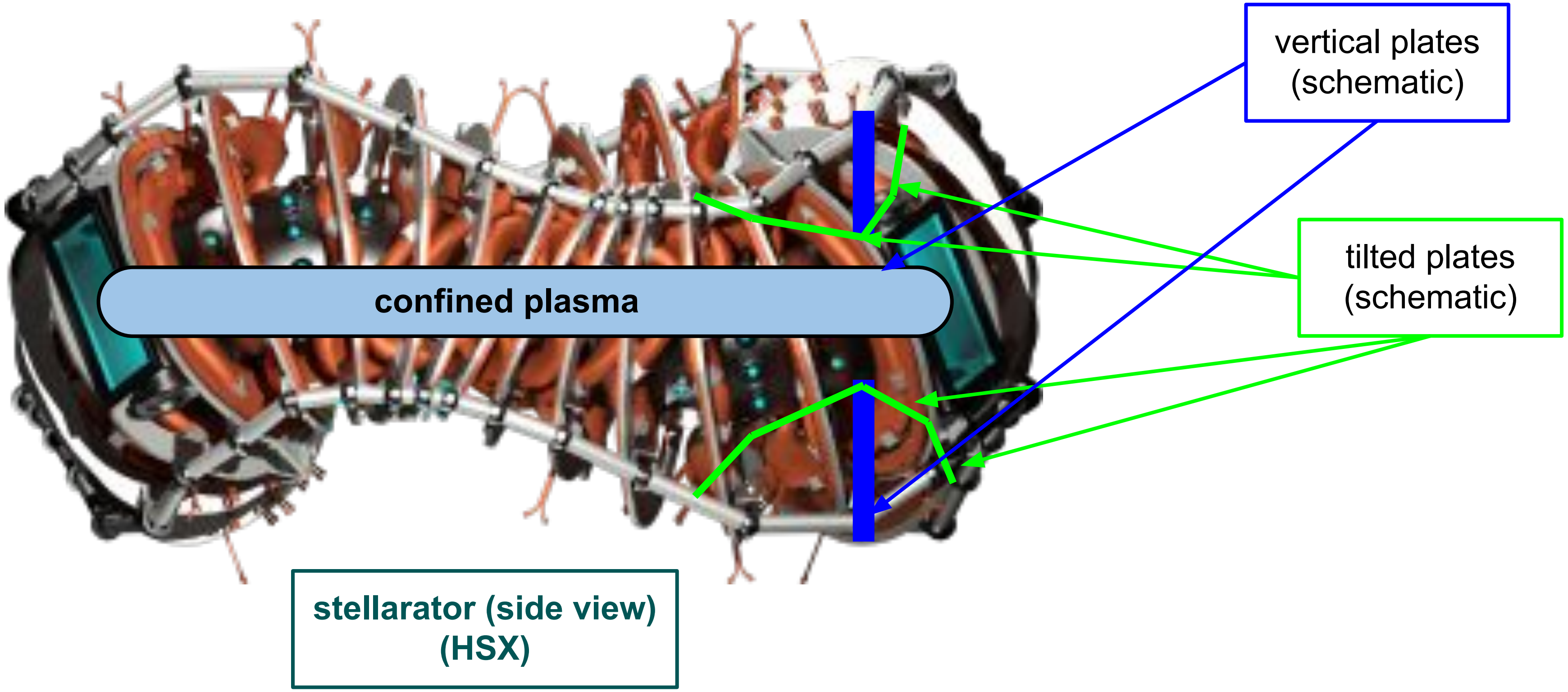
$$-\kappa_e\nabla_{||}T|_{target}=n\cdot C_s\gamma T_{target} \qquad (2)$$

- A Monte-Carlo code, with heat “particles“ diffusing parallel & perpendicular to magnetic field
- Recently upgraded (Y. Feng) to simulate arbitrary stellarators
- Simulation inputs:
  - magnetic geometry
  - Wall geometry
  - Assumed parallel/perpendicular diffusivity

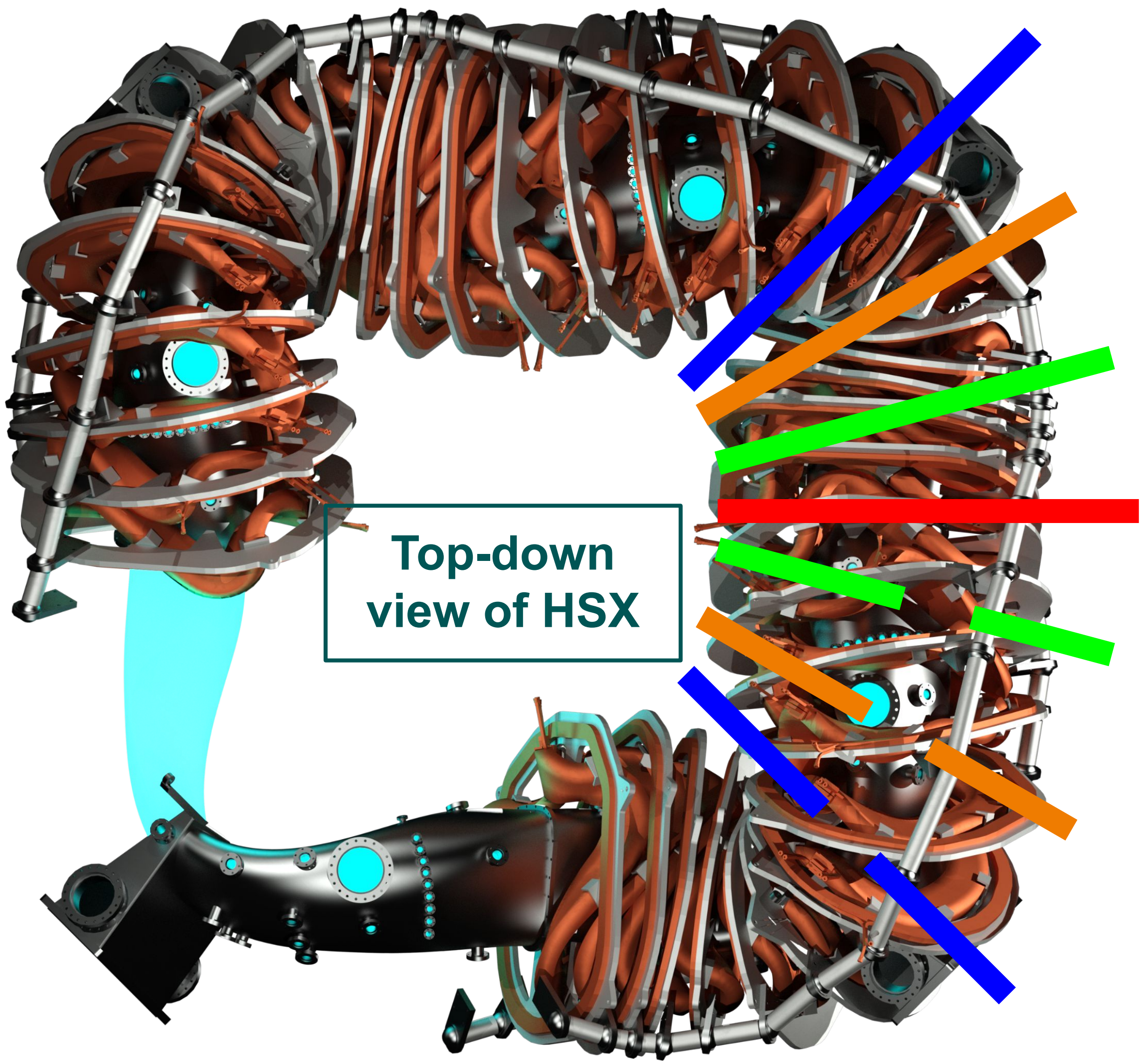
[1] Y. Feng *et al*. *Plasma Physics and Controlled Fusion* 64.12 (2022): 125012

Semi-automated divertor design

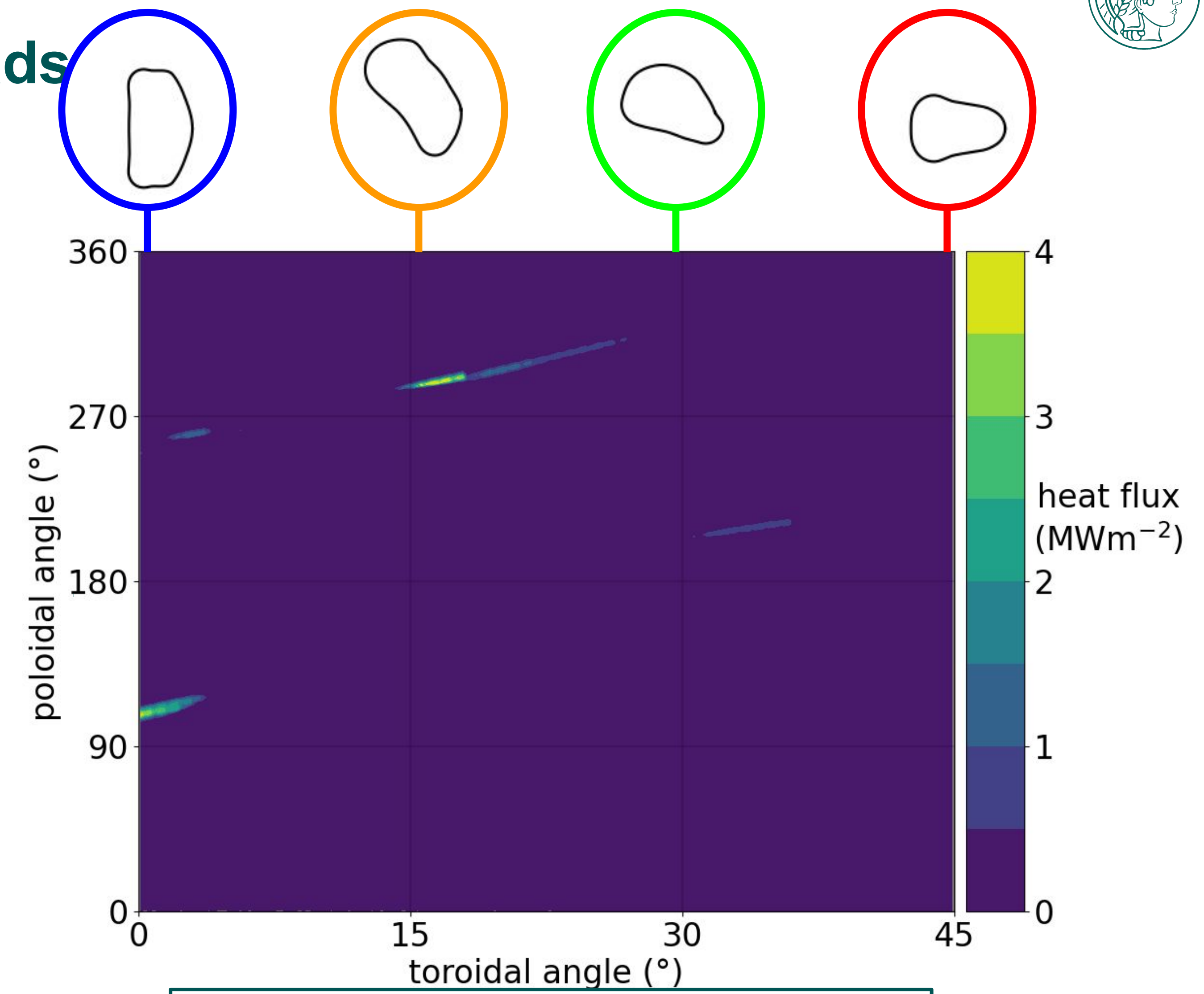
- A systematic scheme to design divertor plates (**not** an optimization algorithm)
- **Step 1**: catch heat load at a given toroidal location using vertically inclined plates
- **Step 2**: Tilt the plate toroidally (following the magnetic field) to ↑ wetted area, ↓ heat loads



Simulated HSX bare wall heat loads



Top-down view of HSX



Simulated heat load on HSX "bare wall"

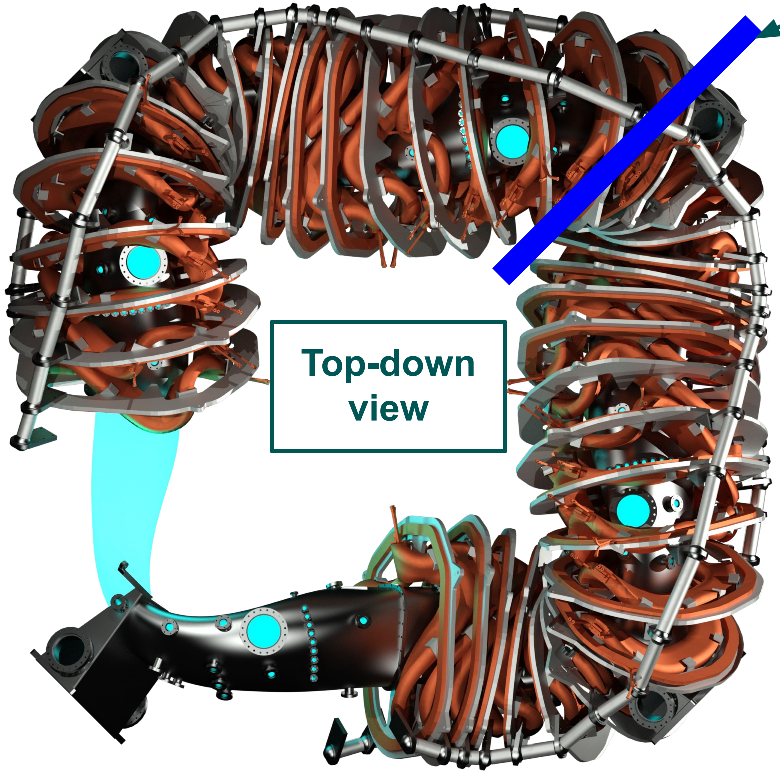
HSX "TEM-optimised" equilibrium
PSOL = 200kW (25kW per half field period)

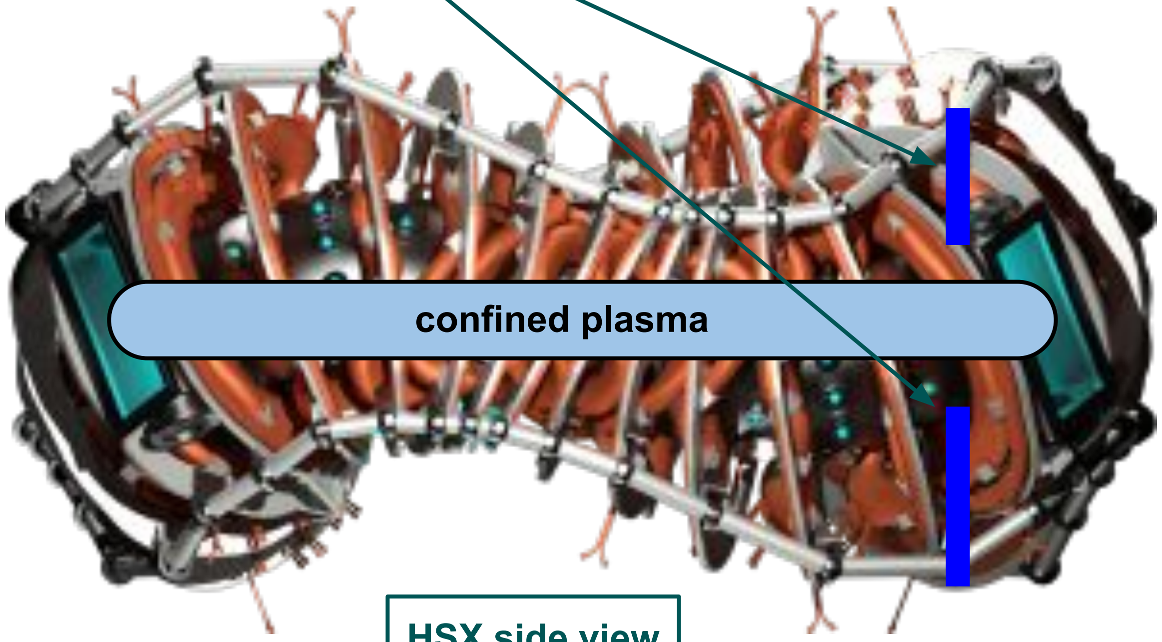
STELLARATOR DIVERTOR DESIGN

Semi-automated divertor design (HSX)

- **Step 1**: catch heat load at a given toroidal location using vertically inclined plates
- Example: use the φ=0° plane

vertical plates at φ=0°

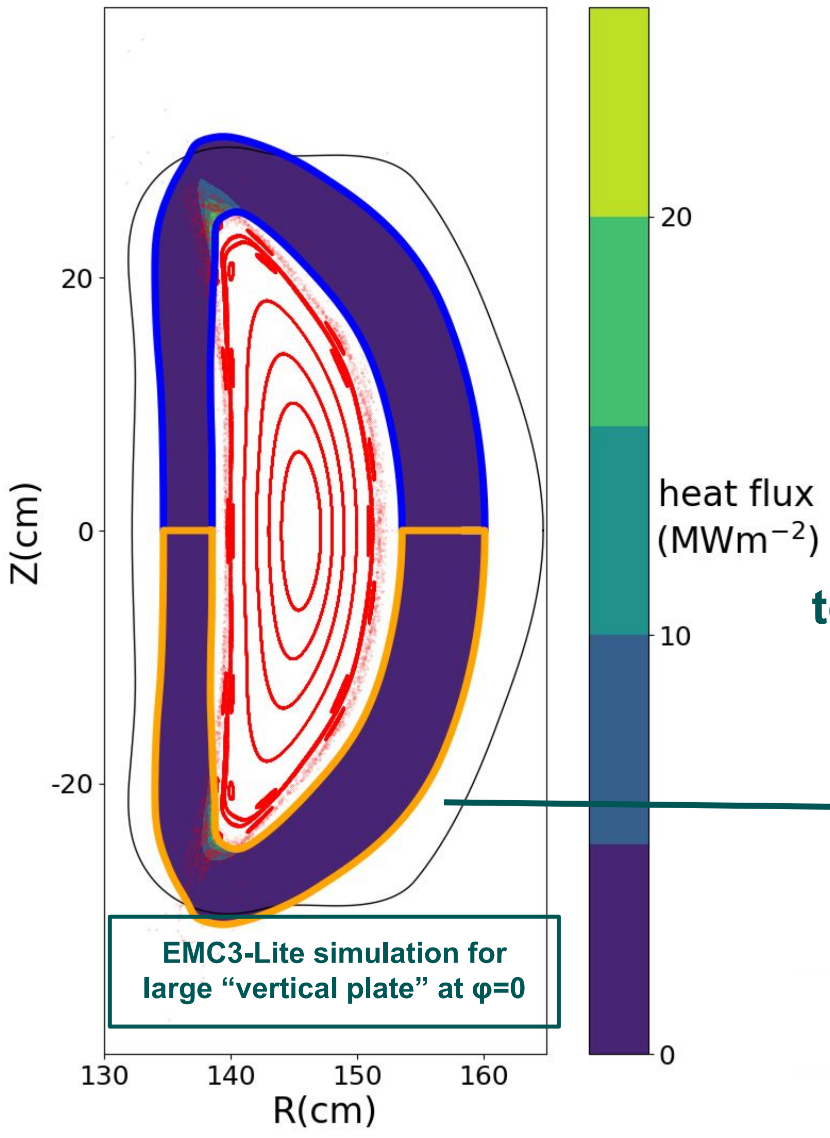


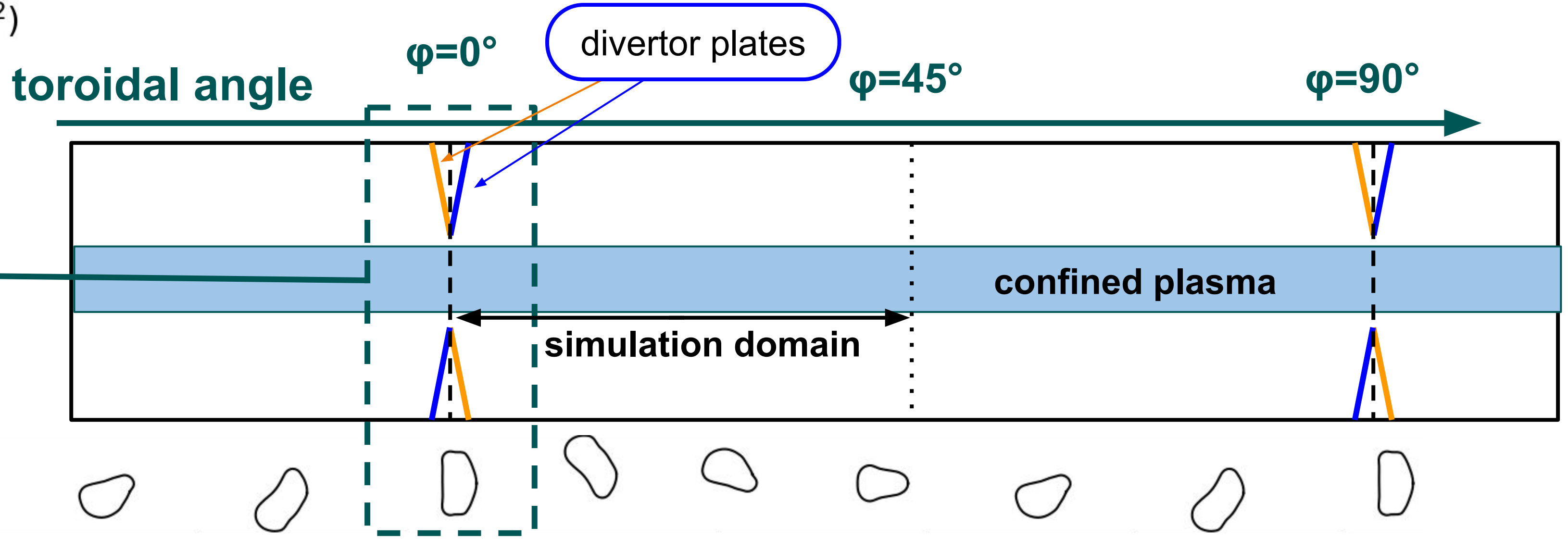


HSX side view

Semi-automated divertor design (HSX)

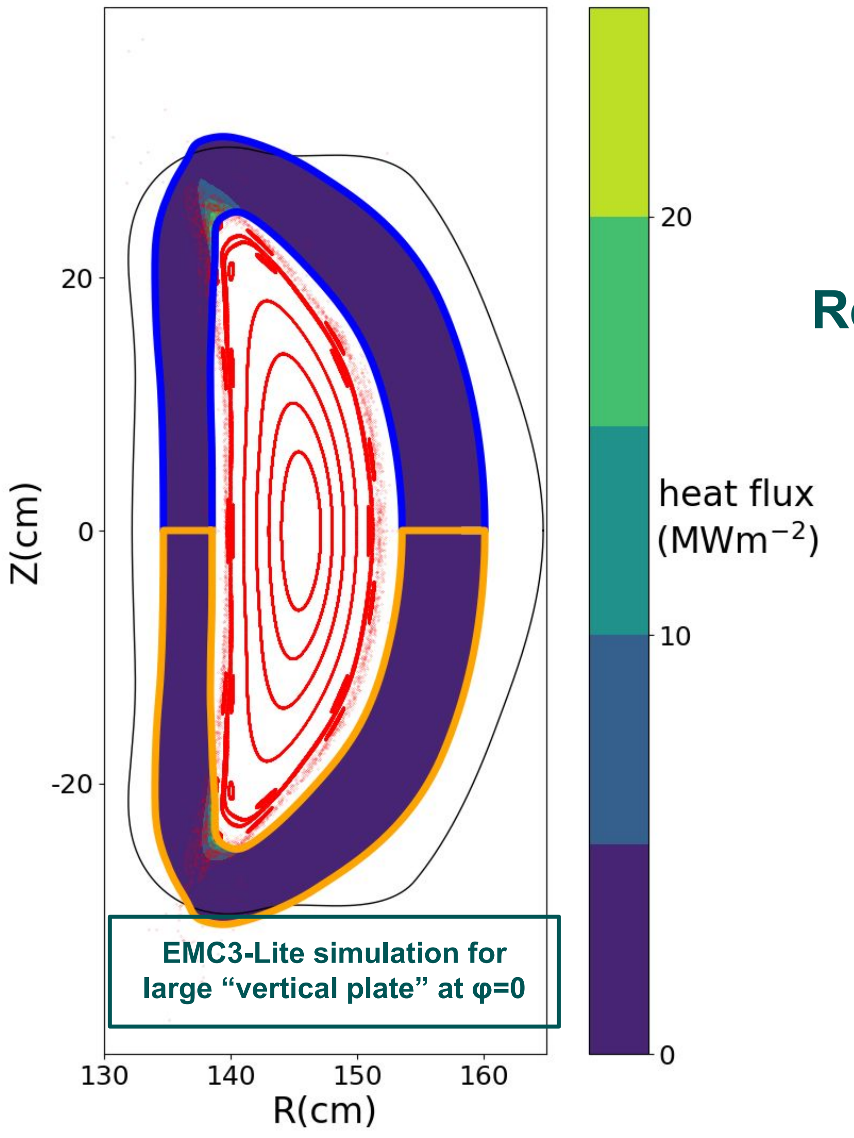
- Example: use the φ=0° plane
- Plate consists of 2 faces, which “see” different incoming flux tubes





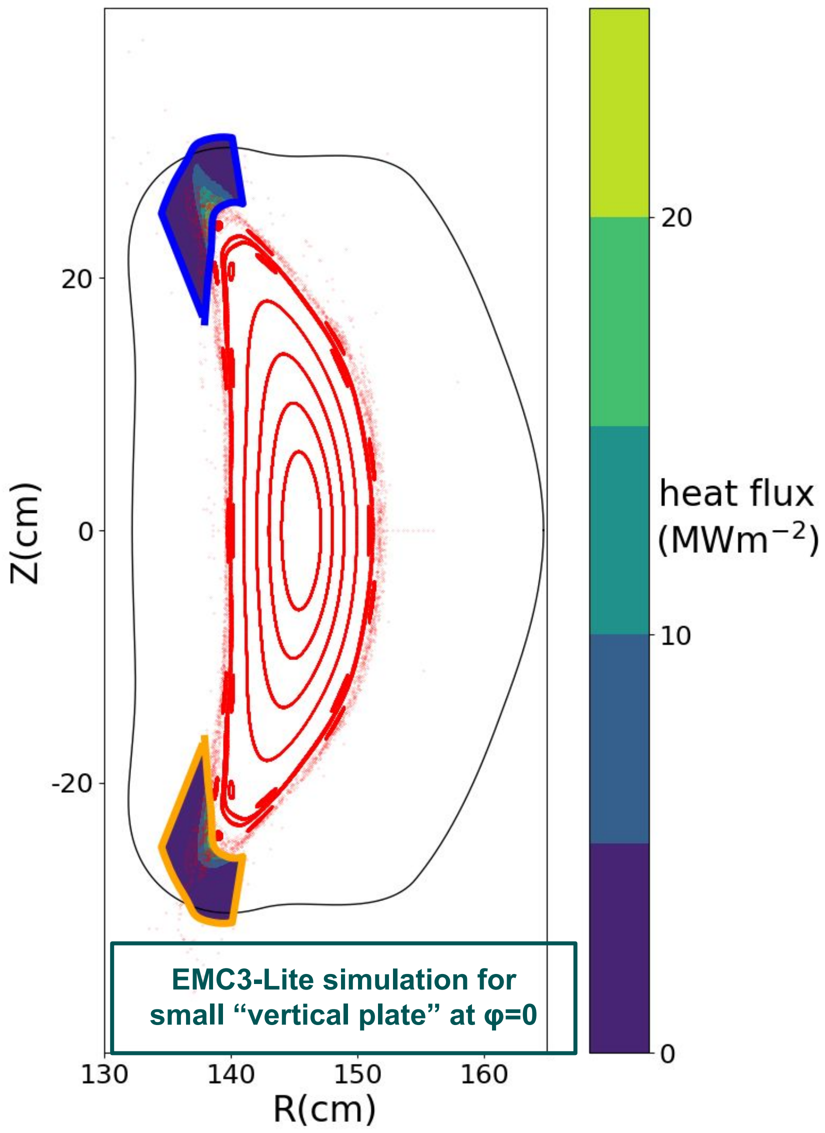
HSX “TEM-optimised” equilibrium
PSOL = 200kW (25kW per half field period)

Semi-automated divertor design (HSX)



EMC3-Lite simulation for large "vertical plate" at φ=0

Reducing vertical plate size

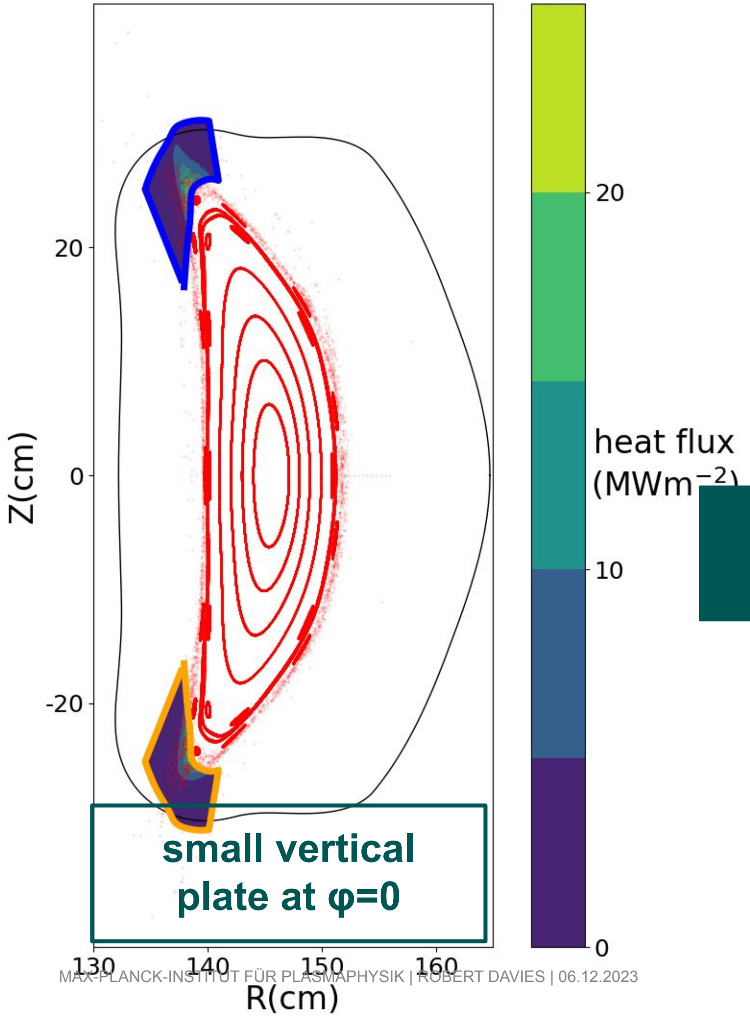


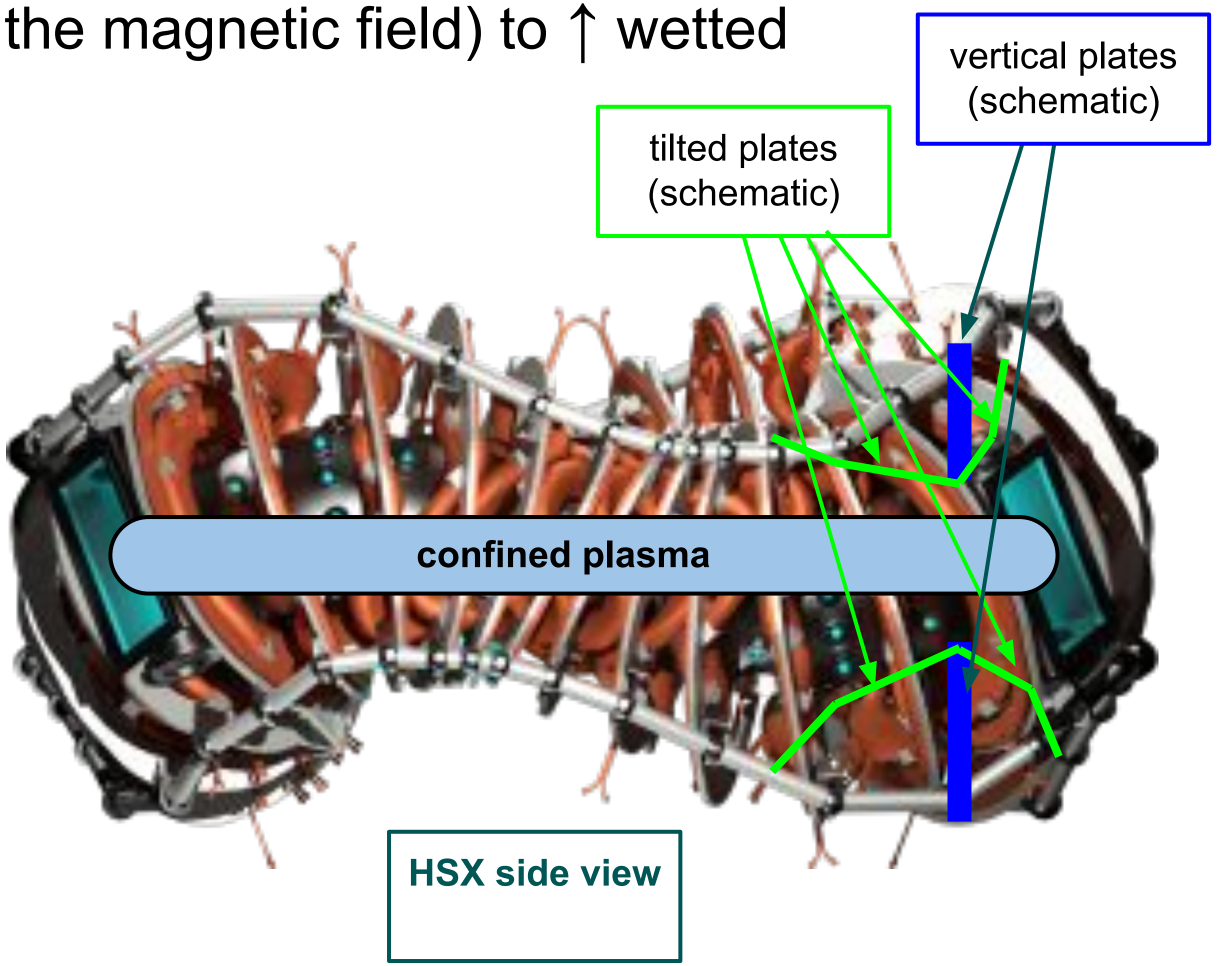
EMC3-Lite simulation for small "vertical plate" at φ=0

HSX "TEM-optimised" equilibrium
PSOL = 200kW (25kW per half field period)

Semi-automated divertor design (HSX)

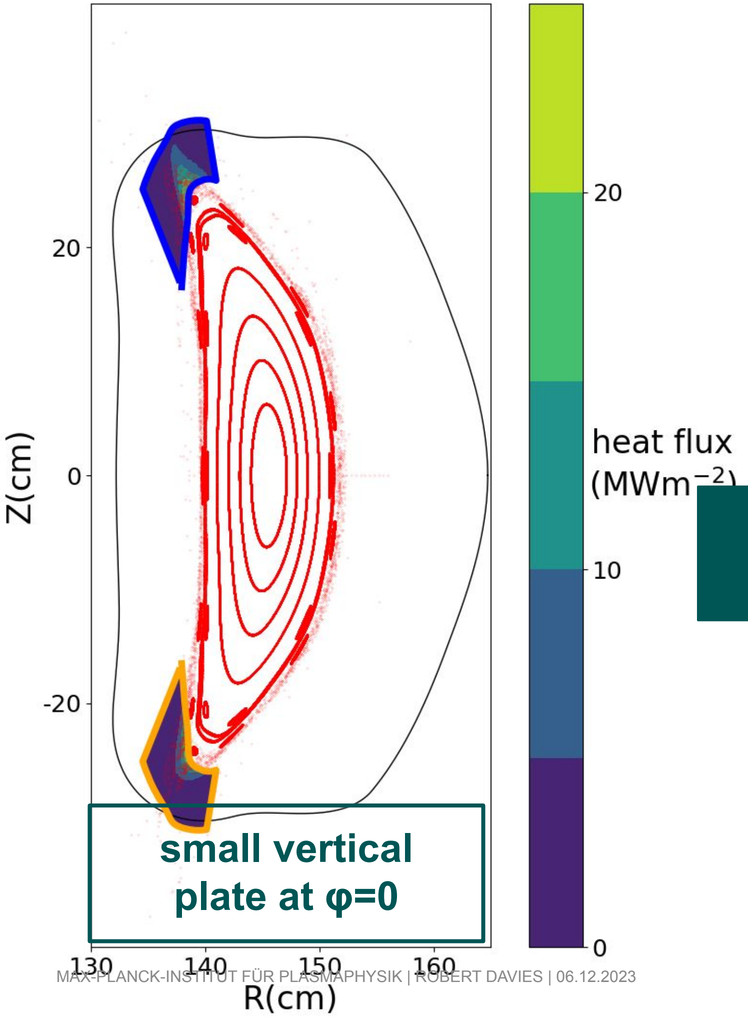
- **Step 2**: Tilt the plate toroidally (following the magnetic field) to ↑ wetted area, ↓ heat loads



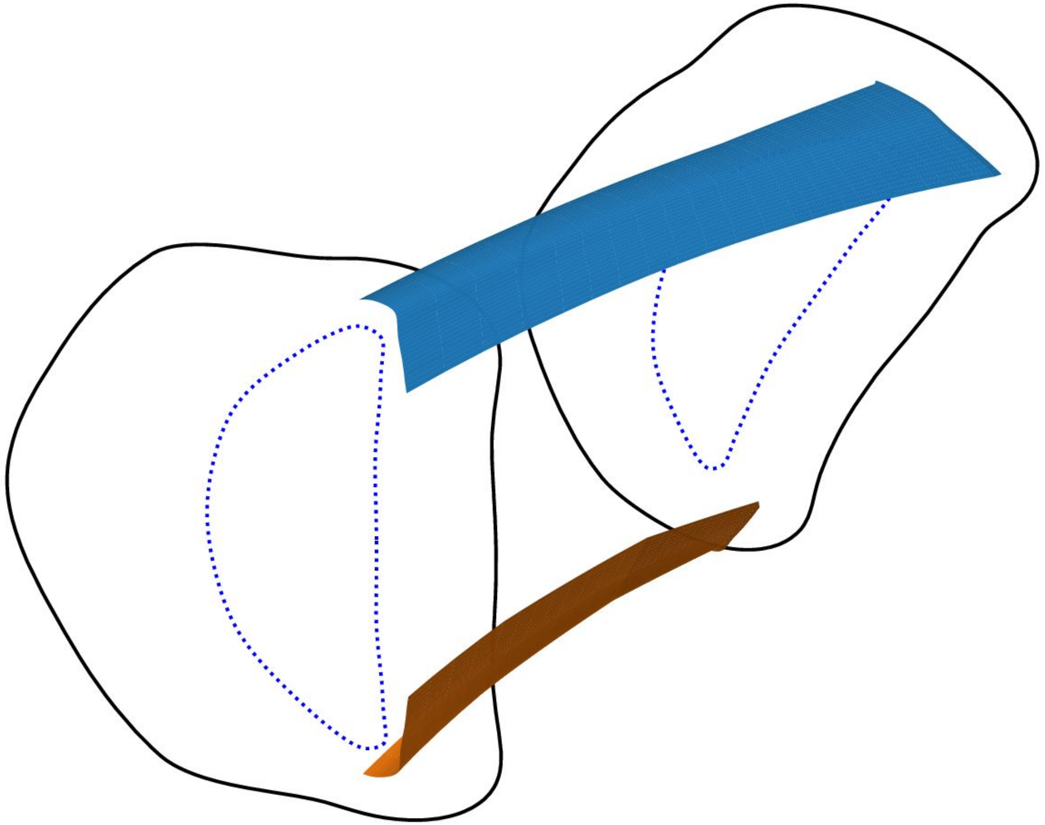


Semi-automated divertor design (HSX)

- **Step 2**: Tilt the plate toroidally (following the magnetic field) to ↑ wetted area, ↓ heat loads



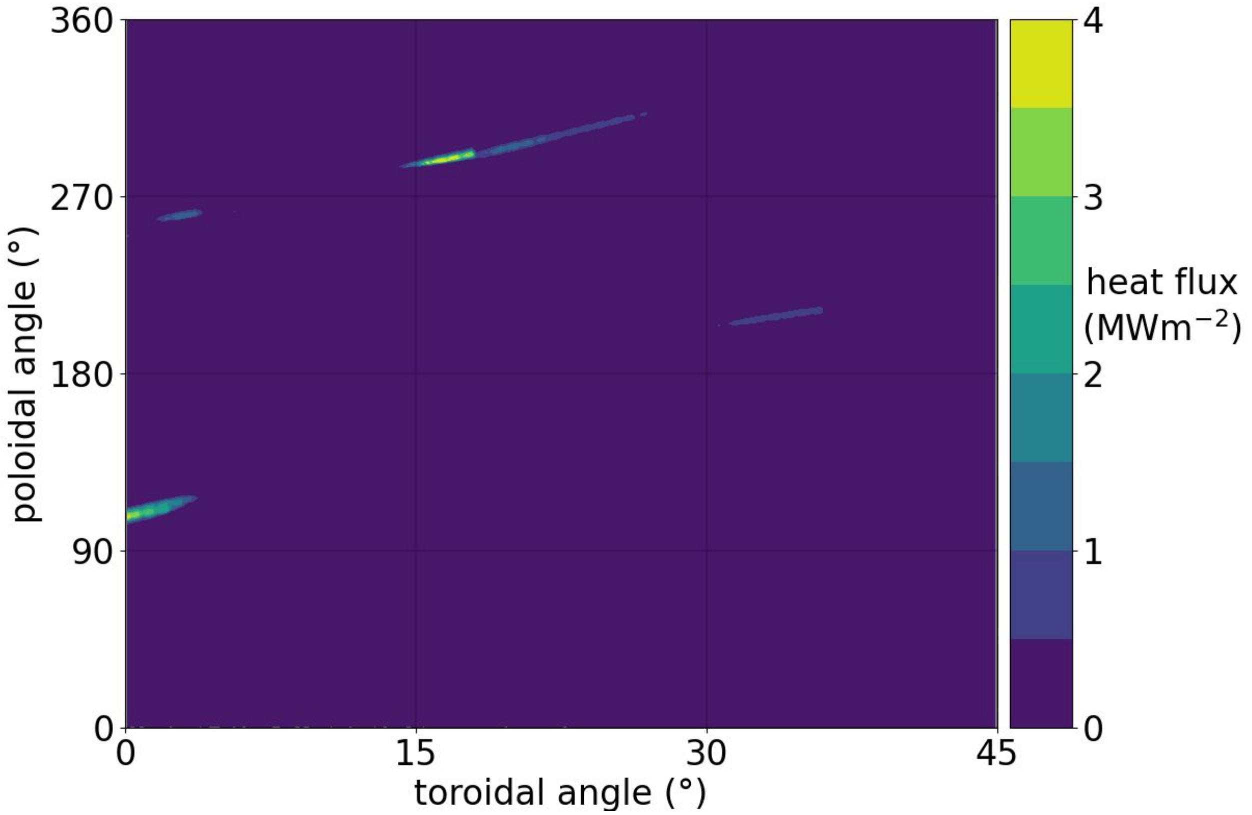
small vertical plate at φ=0



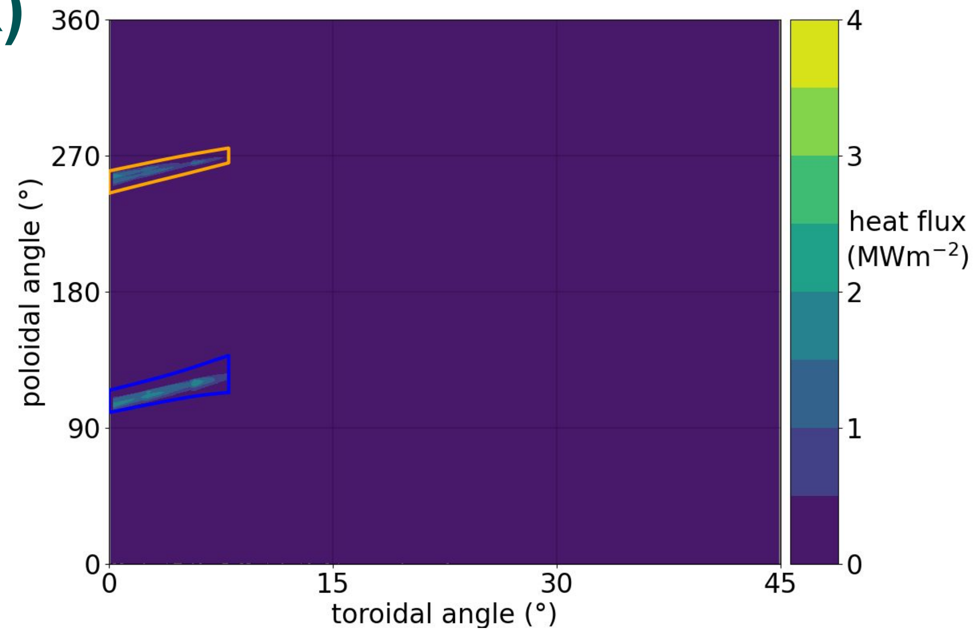
Toroidally tilted plates. NB (x,y,z) axes not to scale

Semi-automated divertor design (HSX)

Simulated heat load on HSX "bare wall"



Simulated heat load on tilted plates



Semi-automated divertor design (HSX)

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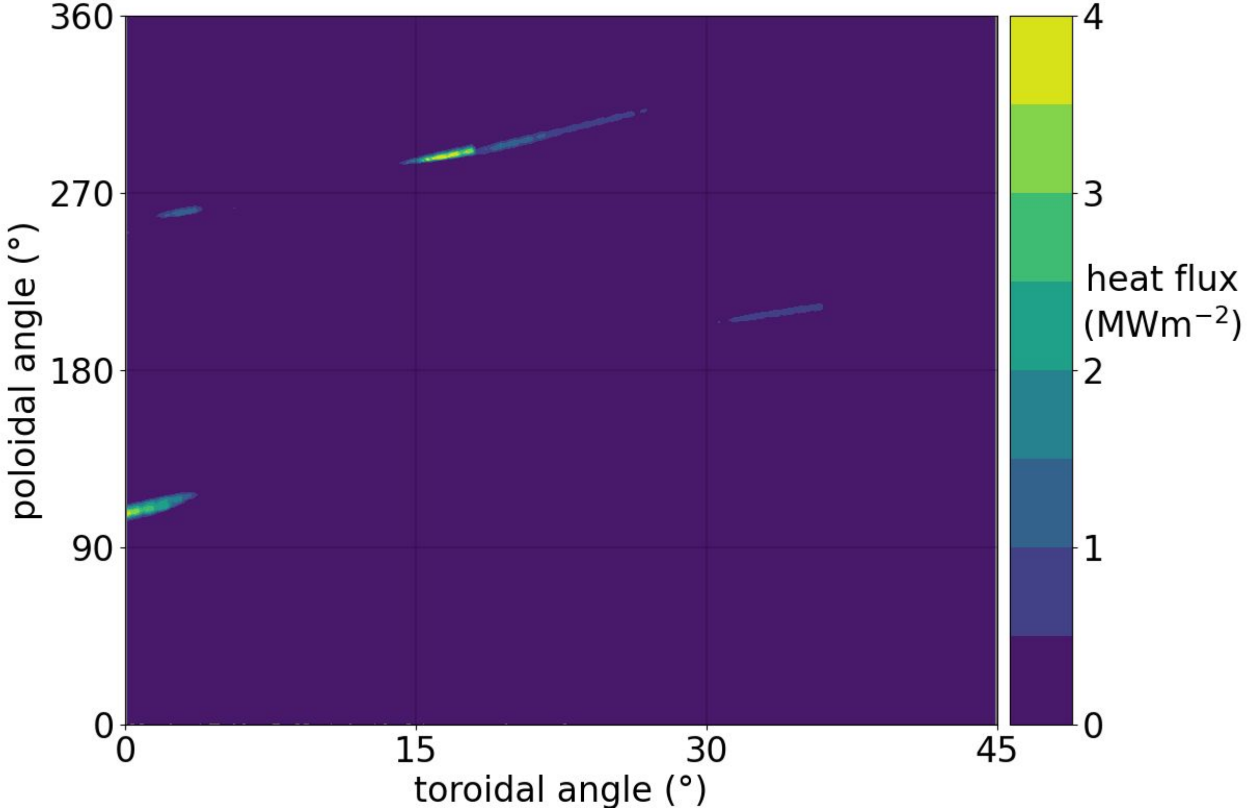
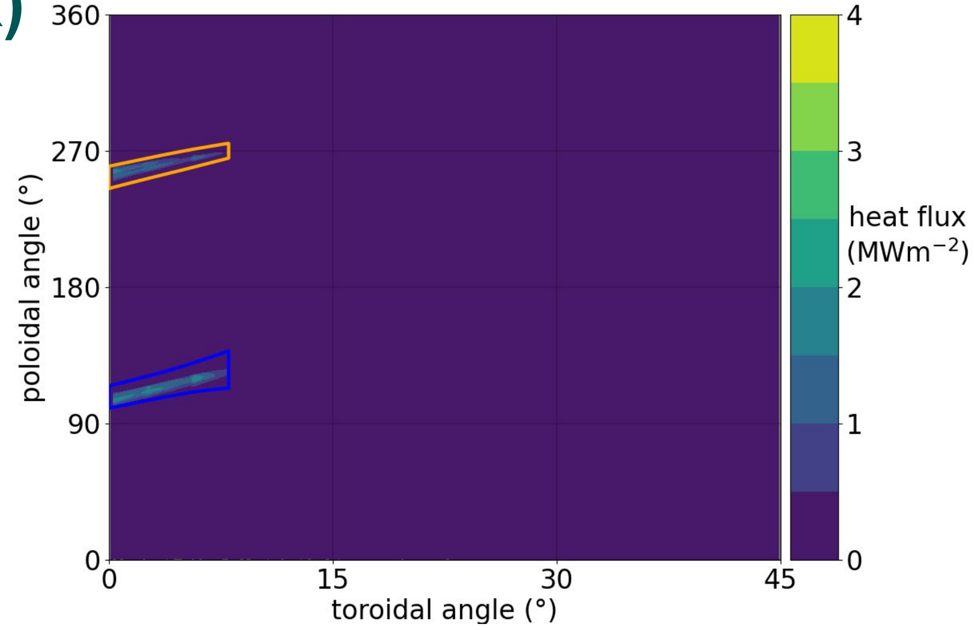
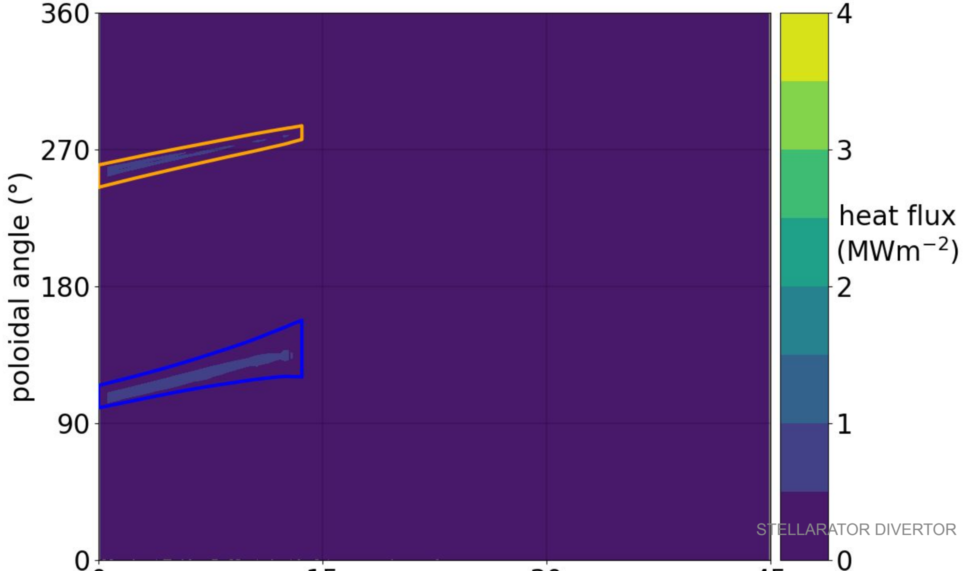


Simulated heat load on tilted plates





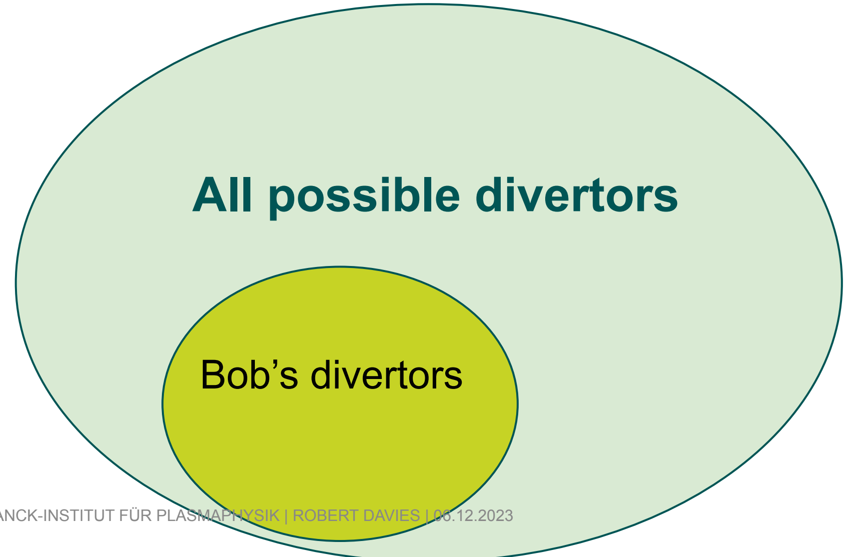
Semi-automated divertor design (HSX)

Future work

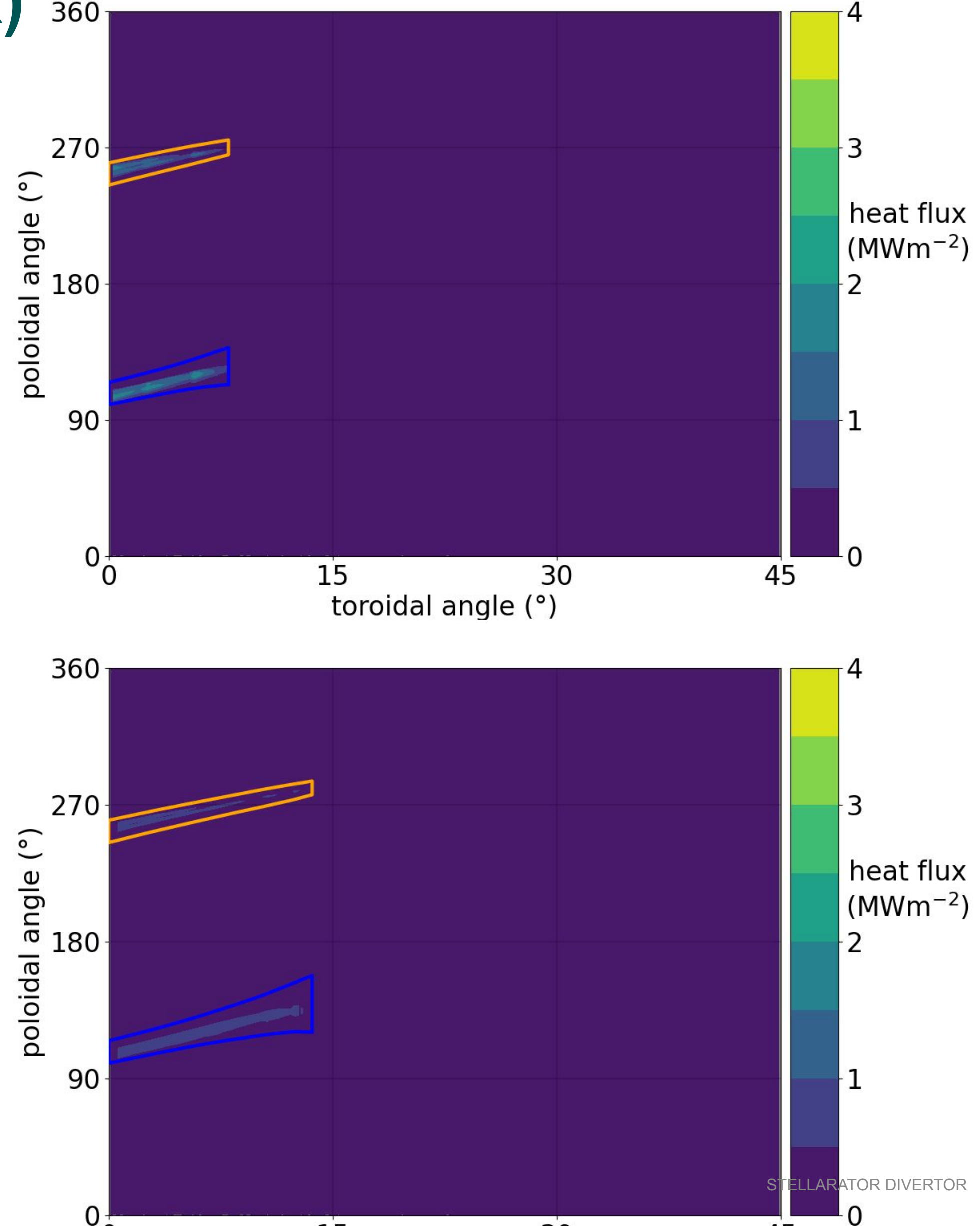
- First-flight neutral model -> divertors designed for heat loads & neutral exhaust

Open question

- *Is there a "general representation" of a divertor plate? (with O(100) controllable parameters?)*
  - … could be used in "black box" optimisation schemes



Simulated heat load on tilted plates

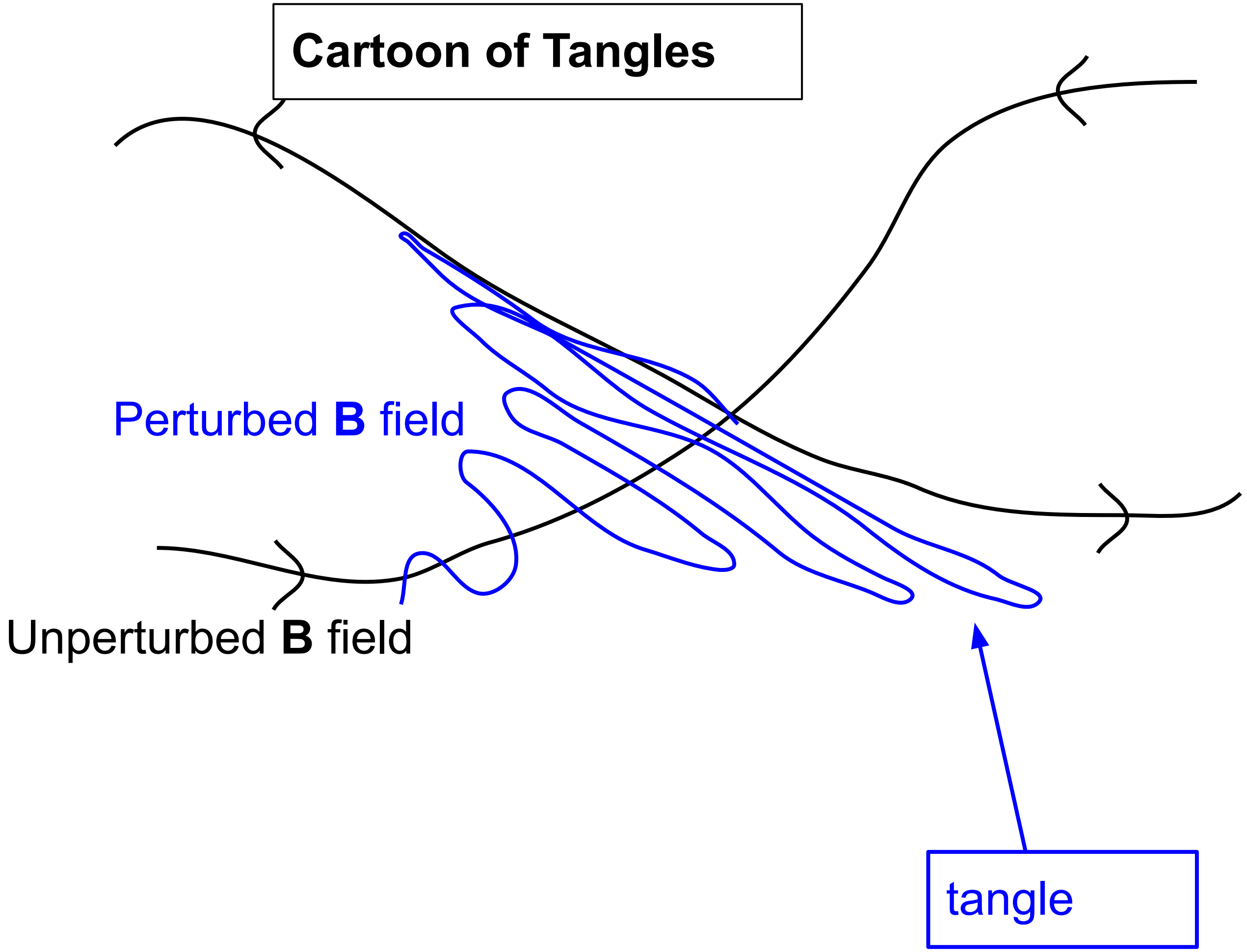


What should the magnetic field look like?

- The island divertor (e.g. W7-X) is currently the most-researched stellarator divertor concept
- Other options are available e.g. “non-resonant divertors”
  - How “good” is heat & particle exhaust for a chaotic edge field?
  - CWGM “joint action” investigating commercial viability of non-resonant divertors (*more info on final slide*)
- Example: A search for **heteroclinic tangles** in W7-X magnetic fields

  (and are they experimentally relevant?)

Tangles - a brief explanation

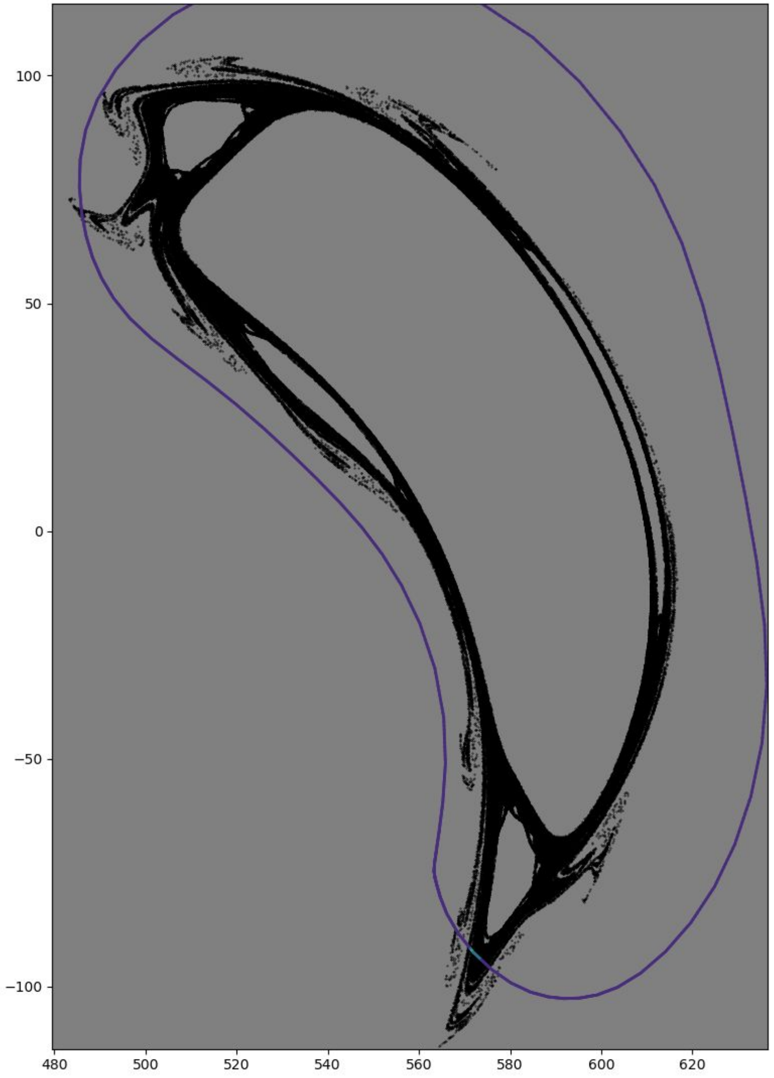


Tangles observed in e.g.

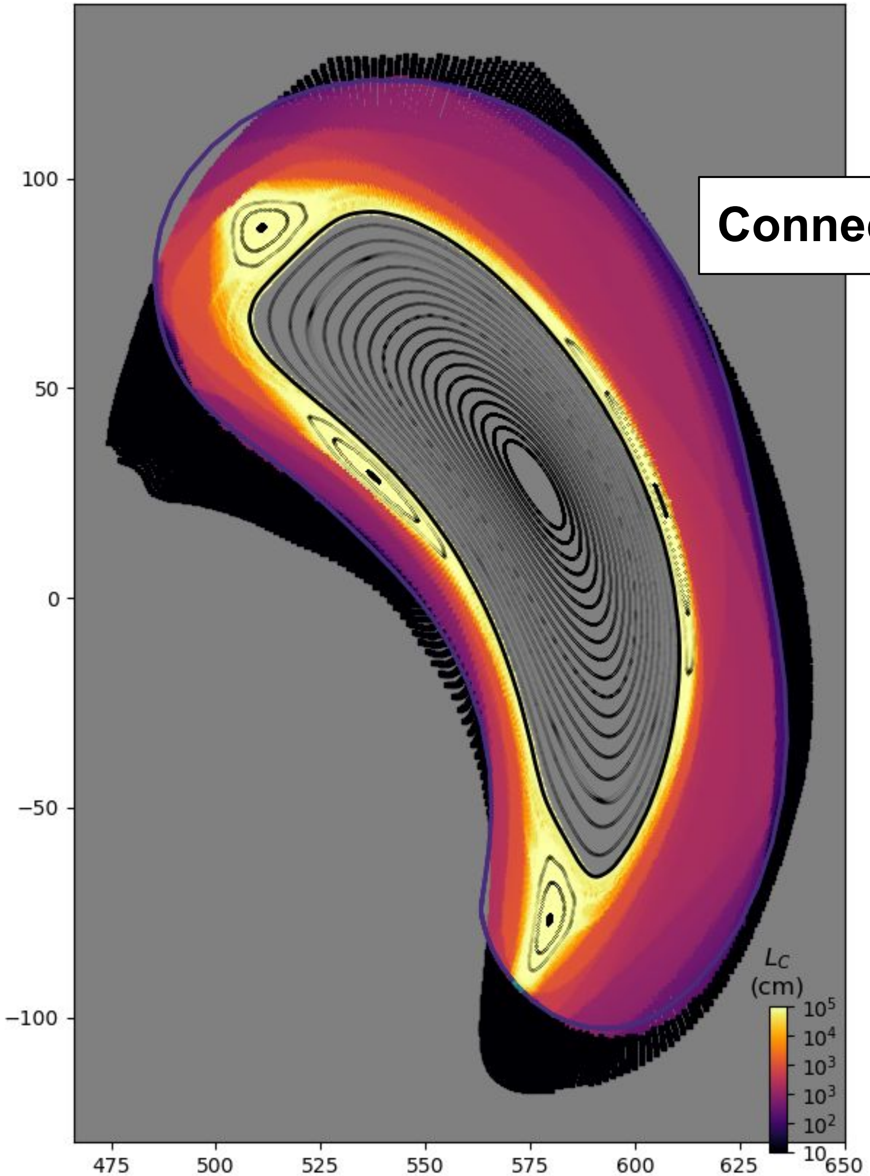
- TEXTOR simulations [1] & experiment [2]
- CTH simulations [3] & (possibly) experiment

[1] O. Schmitz *et al* 2008 *Nucl. Fusion* **48** 024009 **DOI** 10.1088/0029-5515/48/2/024009
[2] M. Jakubowski, M. W., et al. *Journal of nuclear materials* 363 (2007): 371-376.
[3] K.A. Garcia *et al* 2023 *Nucl. Fusion* **63** 126043 **DOI** 10.1088/1741-4326/ad0160

“High iota”configuration in W7-X (vacuum magnetic field)

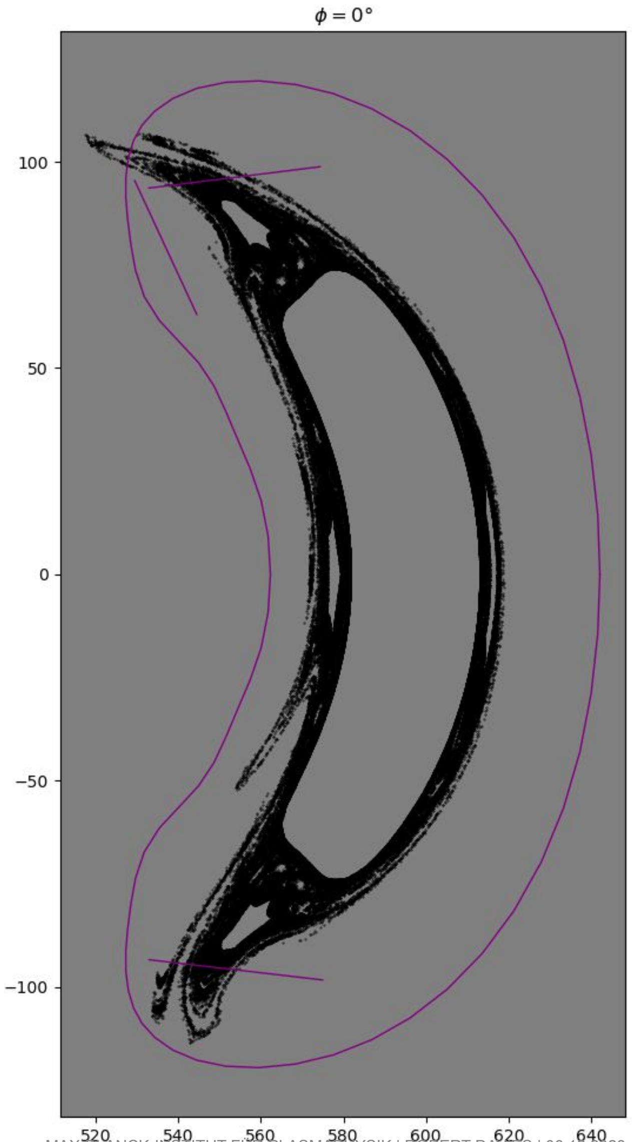


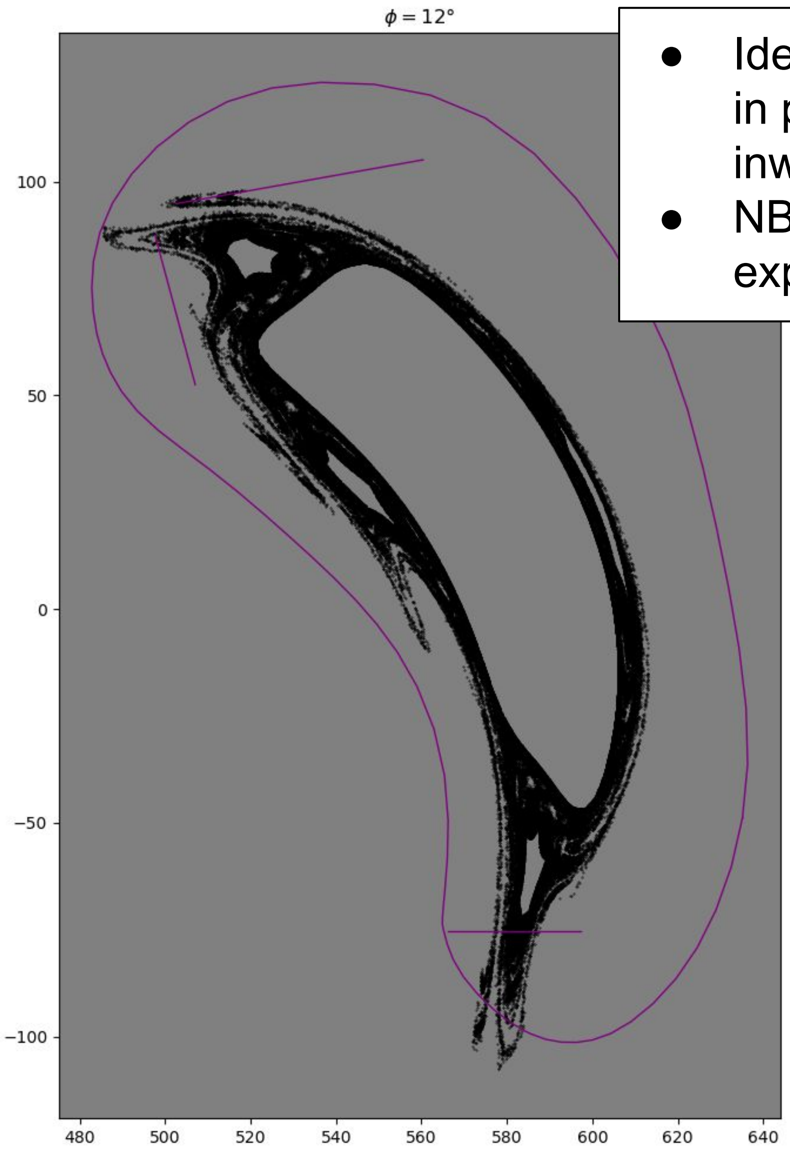
φ=12°



Connection length plot

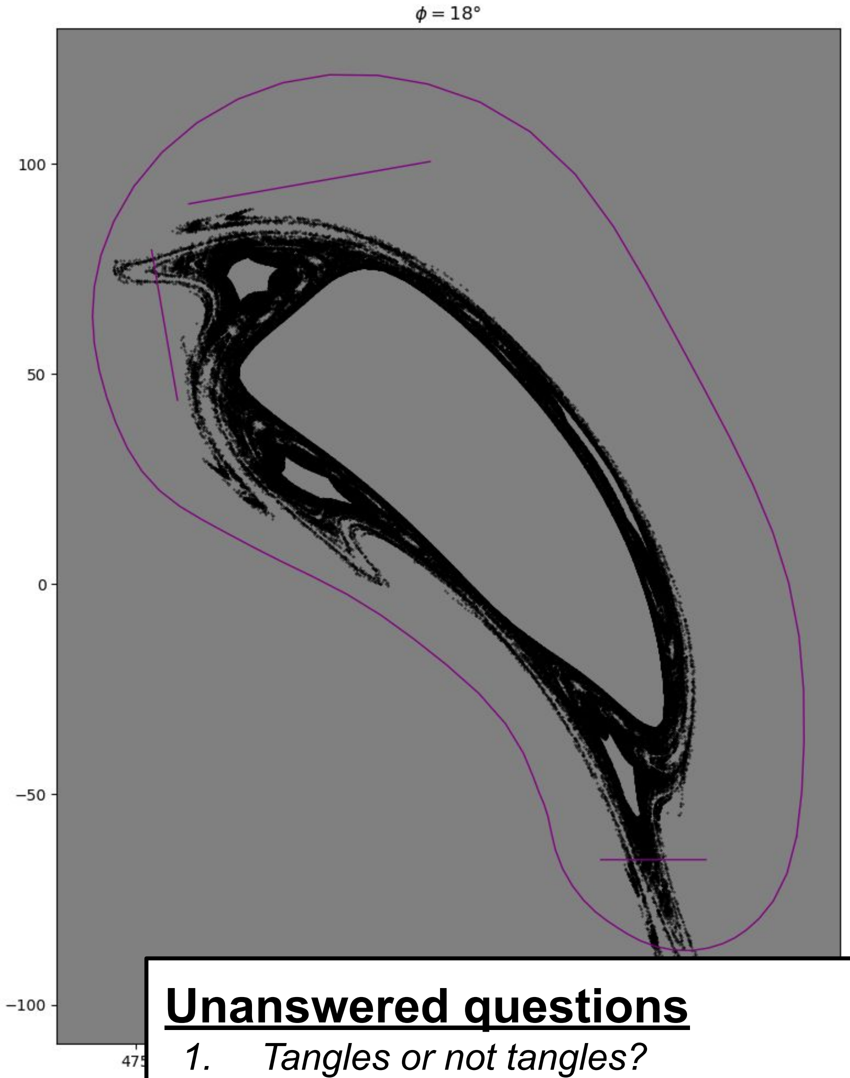
“Very high iota”configuration in W7-X (vacuum magnetic field)

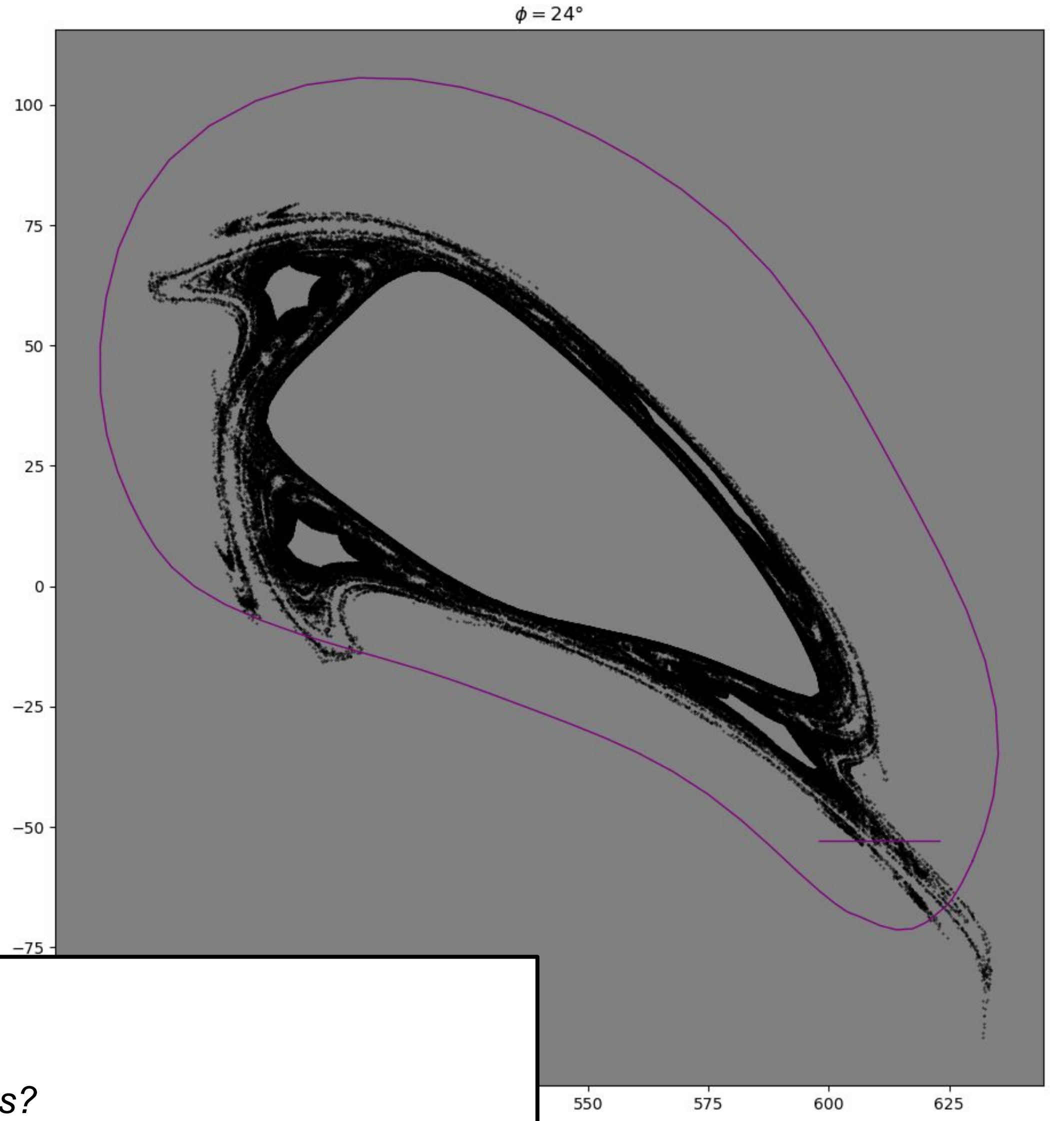




- Idea: increase “high iota” by increasing current in planar coils. Seems to push the islands inwards
- NB these coil currents are (probably) not experimentally realisable

“Very high iota”configuration in W7-X (vacuum magnetic field)



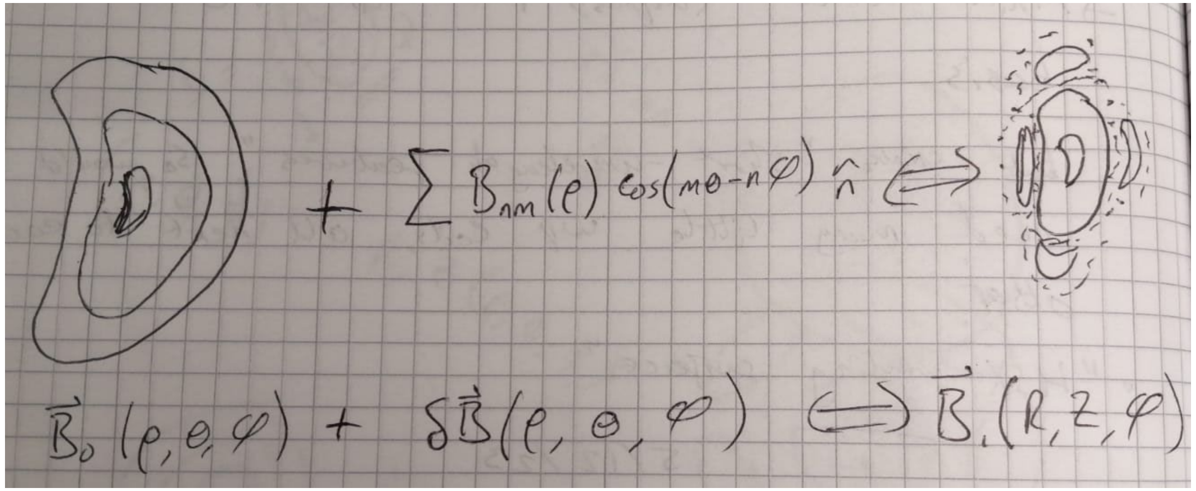


Unanswered questions

1. *Tangles or not tangles?*
2. *Do these manifest in heat strike locations?*
3. *Can we relate these structures to (e.g.) features in the Hamiltonian?*

Systematic investigation of edge topologies & their performance

- *Is there a systematic way to scan the topologies of realistic stellarator edge magnetic fields?*
- *Is there a robust way to identify (e.g.) heteroclinic tangles for a given magnetic field?*
- Vacuum magnetic field generated by coils: easy to scan coil currents, but relation to magnetic field structures is non-trivial
- Equilibrium codes, optimisation suites: Good at creating nested surfaces
  - Is there a way to systematically create islands & chaos? (e.g. add a perturbing field to an equilibrium?)



Summary & future work

- Divertor **plate** optimisation: Scheme for constructing "first guess" divertor plates with low heat loads. **Future work**: fast neutral model
- Divertor **magnetic field**: Tools in development for magnetic topology studies (W7-X, HSX). **Future work**: fast assessment of divertor performance for given topologies.

Open questions

1. *Is there a "general representation" of a stellarator divertor plate? (with O(100) controllable parameters?)*
2. *Is there a systematic way to scan the topologies of realistic stellarator edge magnetic fields?*
3. *Is there a robust way to identify (e.g.) heteroclinic tangles for a given magnetic field?*

The Coordinated Working Group Meeting non-resonant divertor joint action ("CWGM NRD JA")

Scientific questions the working group hopes to address:

0. What are the desirable features of a non-resonant divertor (NRD)?

1. NRD properties: understanding the fundamental features

2. NRD plasma transport characterization in HSX, W7-X, CTH

3. Is the NRD a viable exhaust concept?

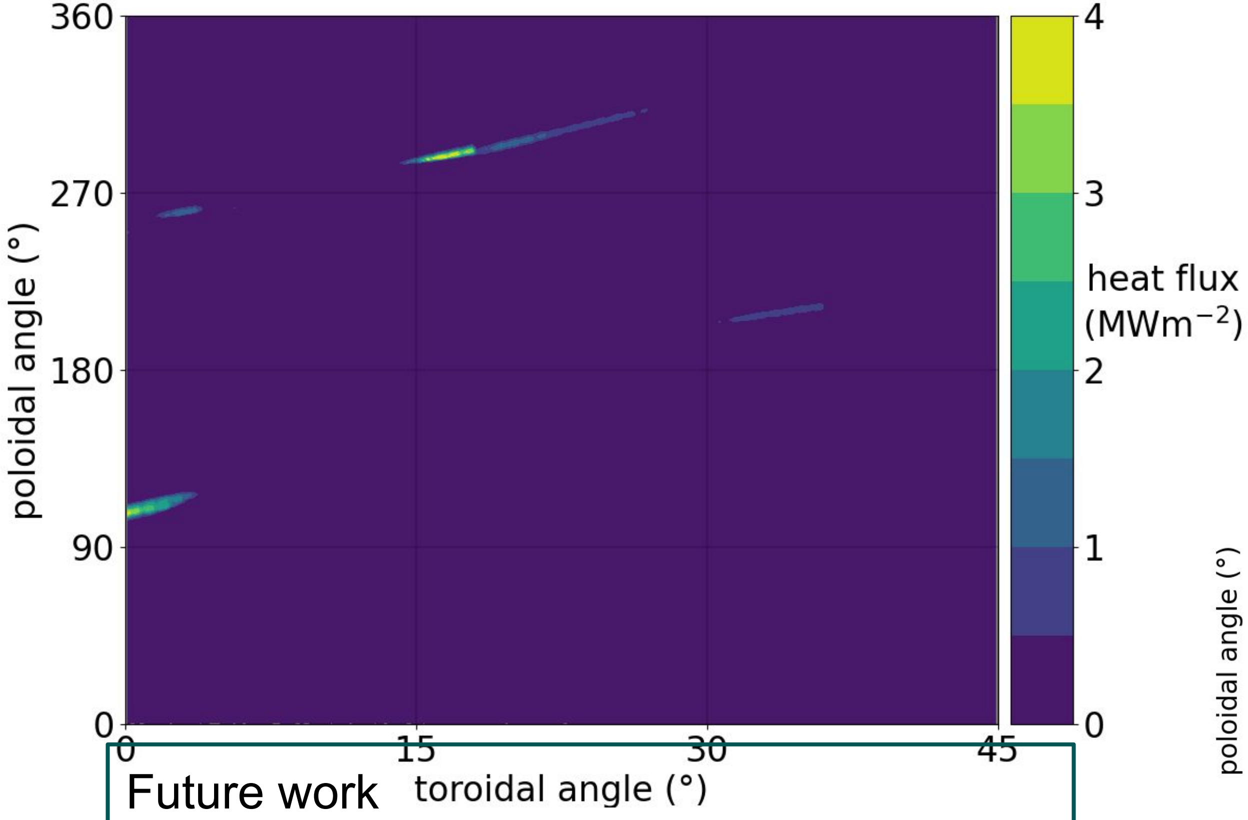
***What the group does**: No specific work commitment. Group meetings every 2 weeks, rotating in theme ("NRD fundamental features", "NRD transport modelling", "NRD experiments"), with pre-announced presentations + general discussion. Bob collates the group's activities and reports to CWGM. The CWGM meets September 2024 & the NRD JA will present at this (format TBD). **Email Bob** to join mailing list.*

email: robert.davies@ipp.mpg.de

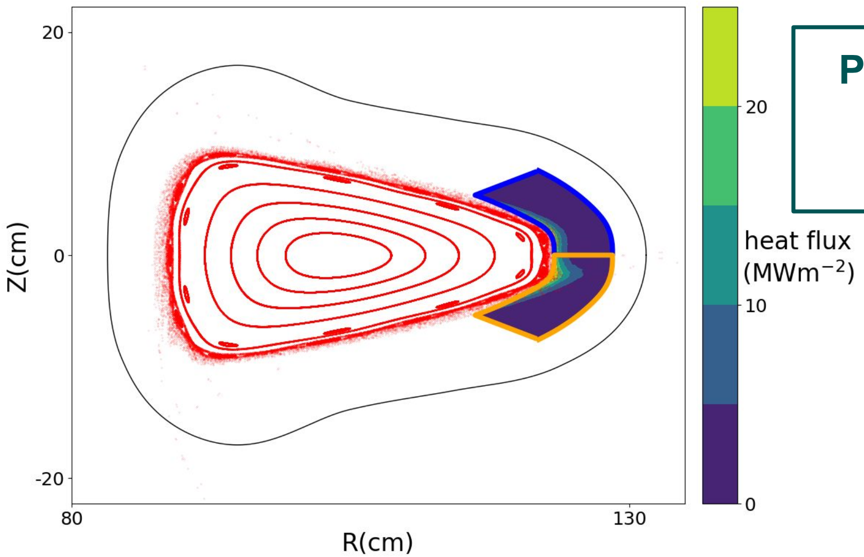
APPENDIX

Divertor design for HSX

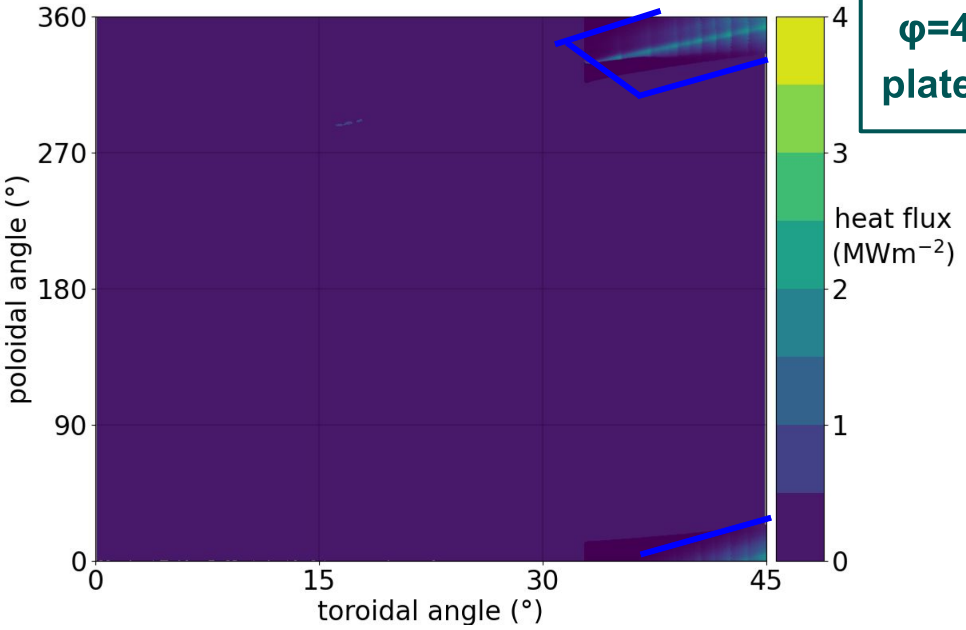
Simulated heat load on HSX "bare wall"



Future work



Plates centered at φ=45°. Step 1: vertical plates



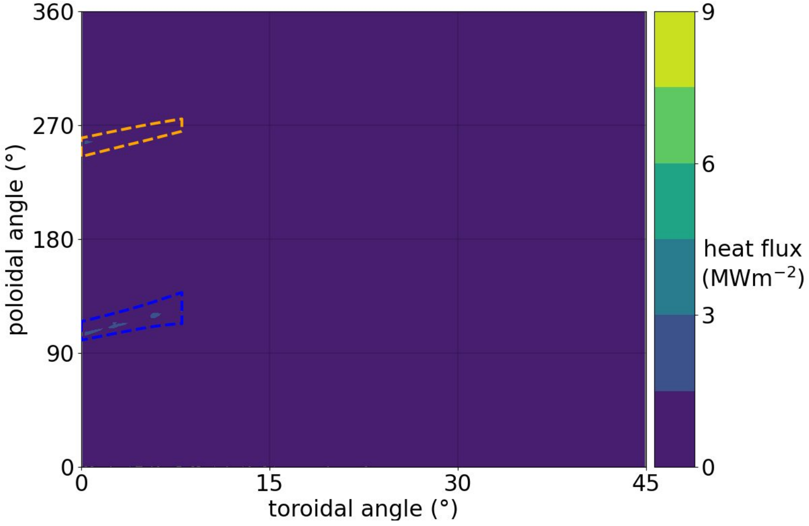
Plates centered at φ=45°. Step 2: tilted plates to ↓ heat loads

HSX divertor plates: different magnetic configurations

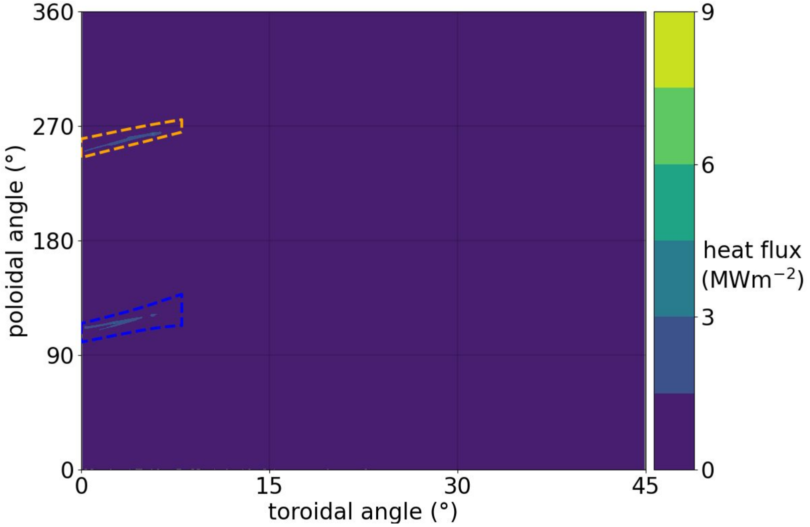
- Low heat load solutions easily achieved for a given magnetic geometry
- Resiliency of divertor to different magnetic configurations more difficult
  - Greatest difficulty for very different magnetic field configurations (e.g.“large island”)
- Future work: optimise plates for multiple configurations simultaneously

heat loads simulations: fixed divertor plates, varying magnetic configuration

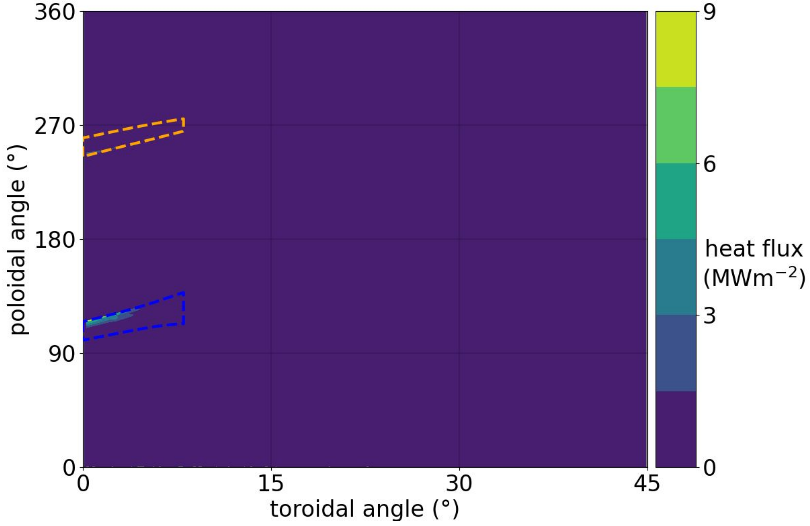
“TEM-optimised” configuration



“standard” configuration

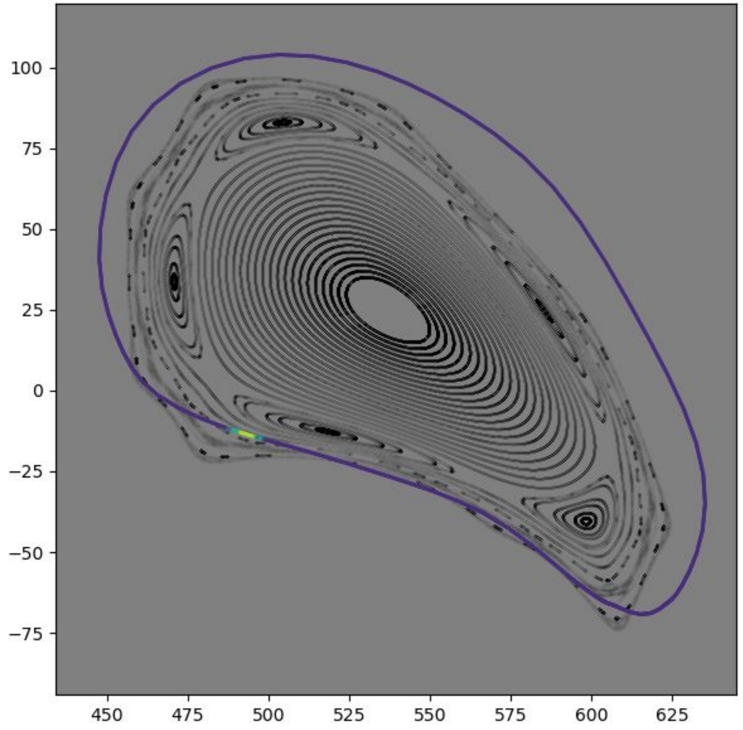


“large islands” configuration

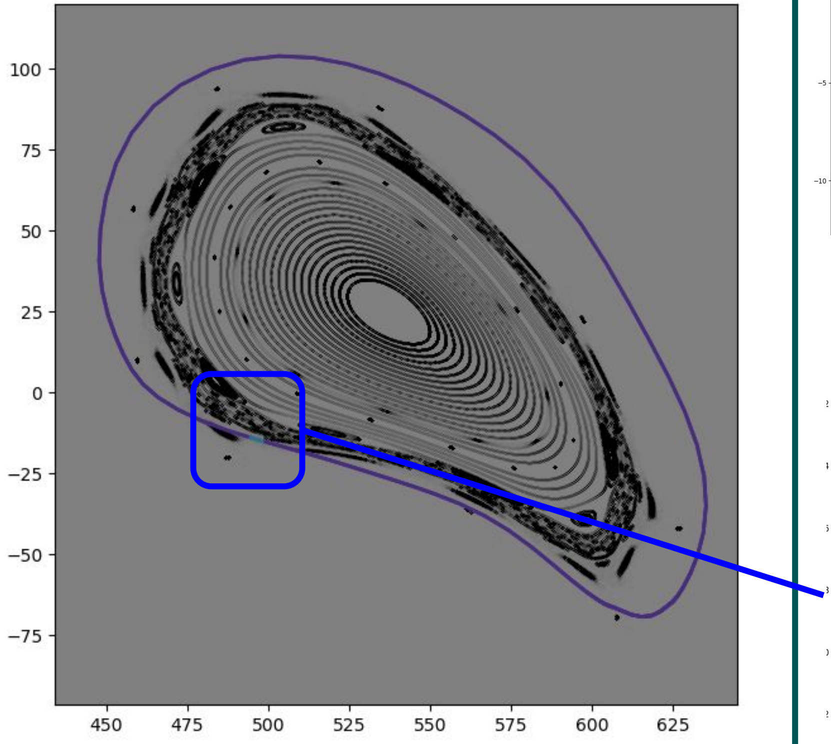


W7-X magnetic field studies: adding chaos

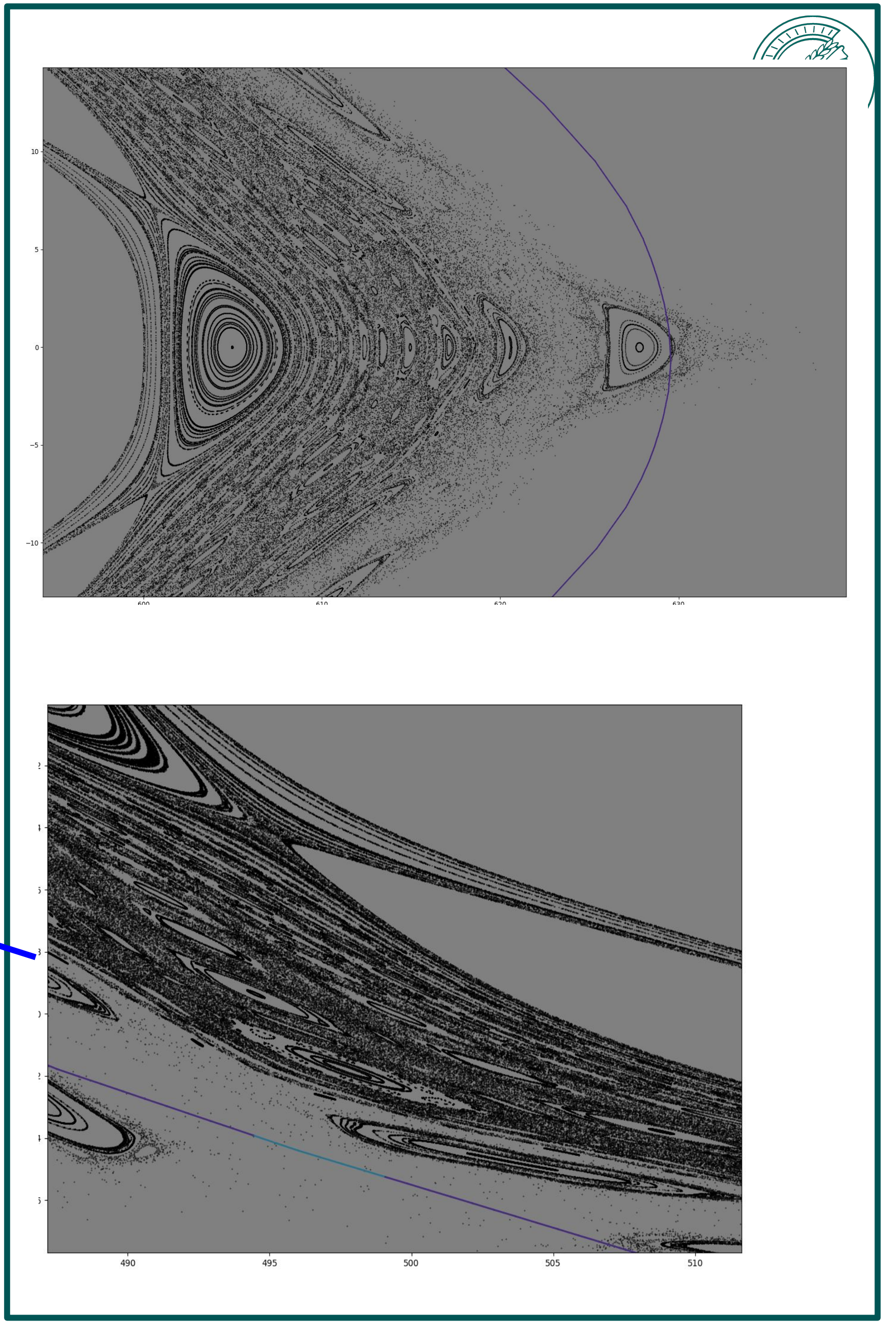
W7-X: Poincare sections + simulated heat loads on “bare wall”



“standard” configuration

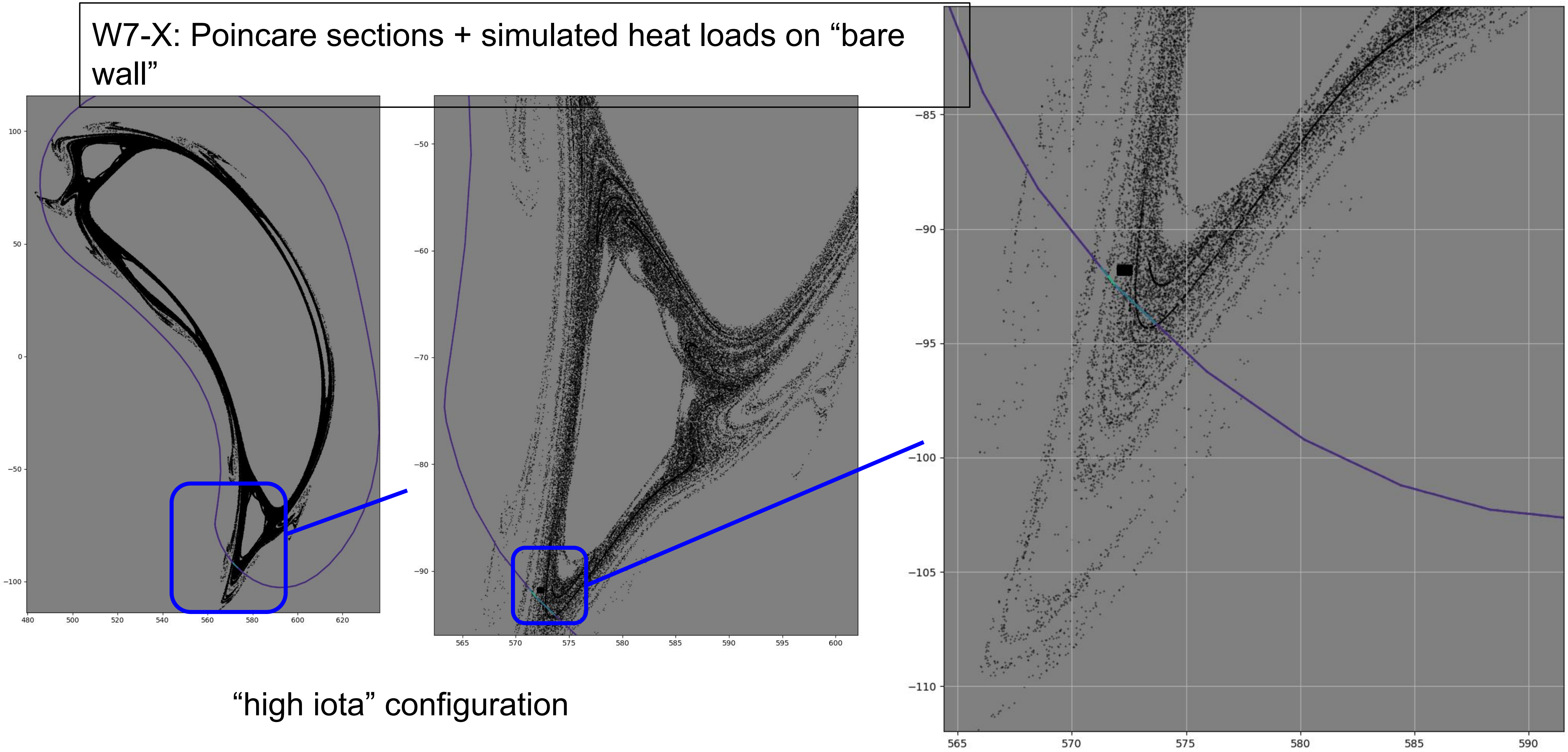


“standard” configuration, slightly chaotic



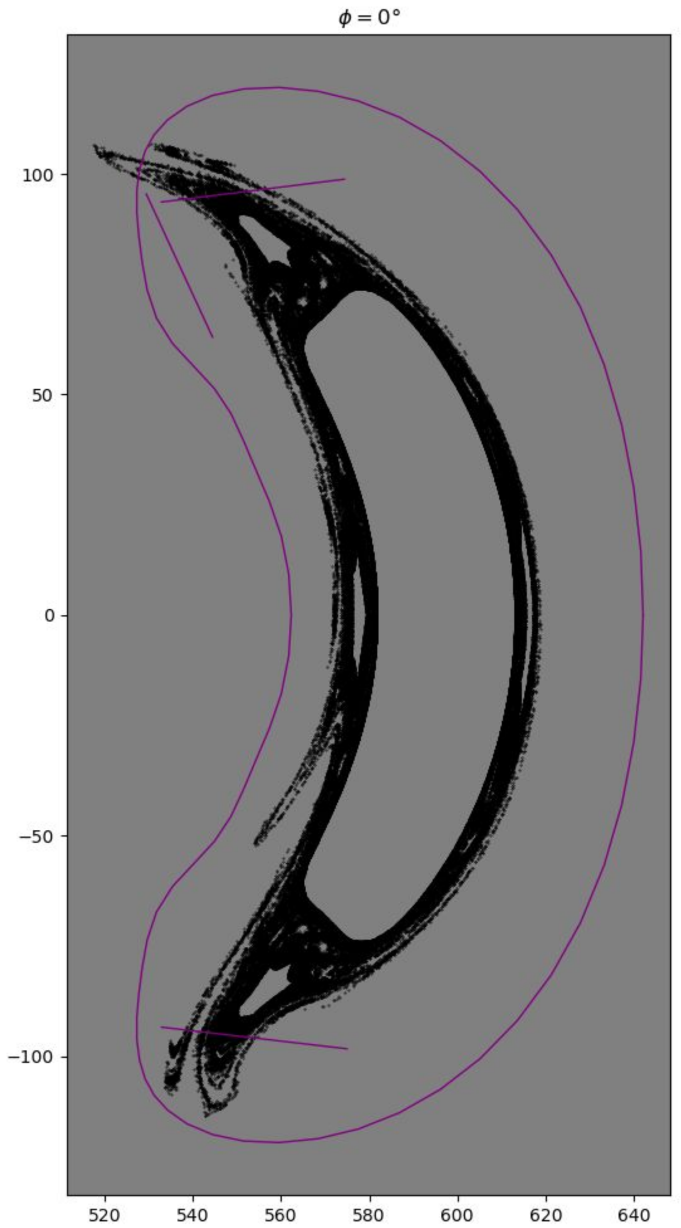
W7-X magnetic field studies: adding chaos

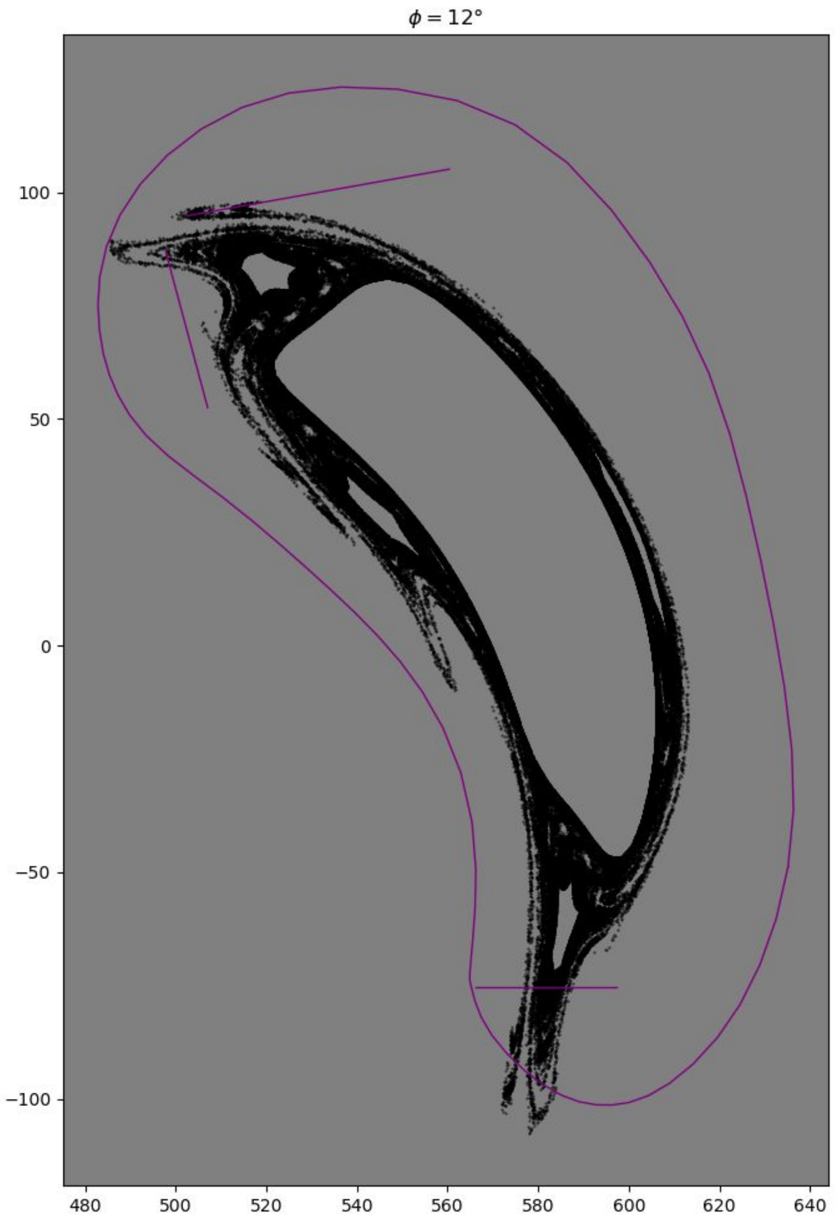
W7-X: Poincare sections + simulated heat loads on “bare wall”



“high iota” configuration

"Very high iota"configuration in W7-X (vacuum magnetic field)

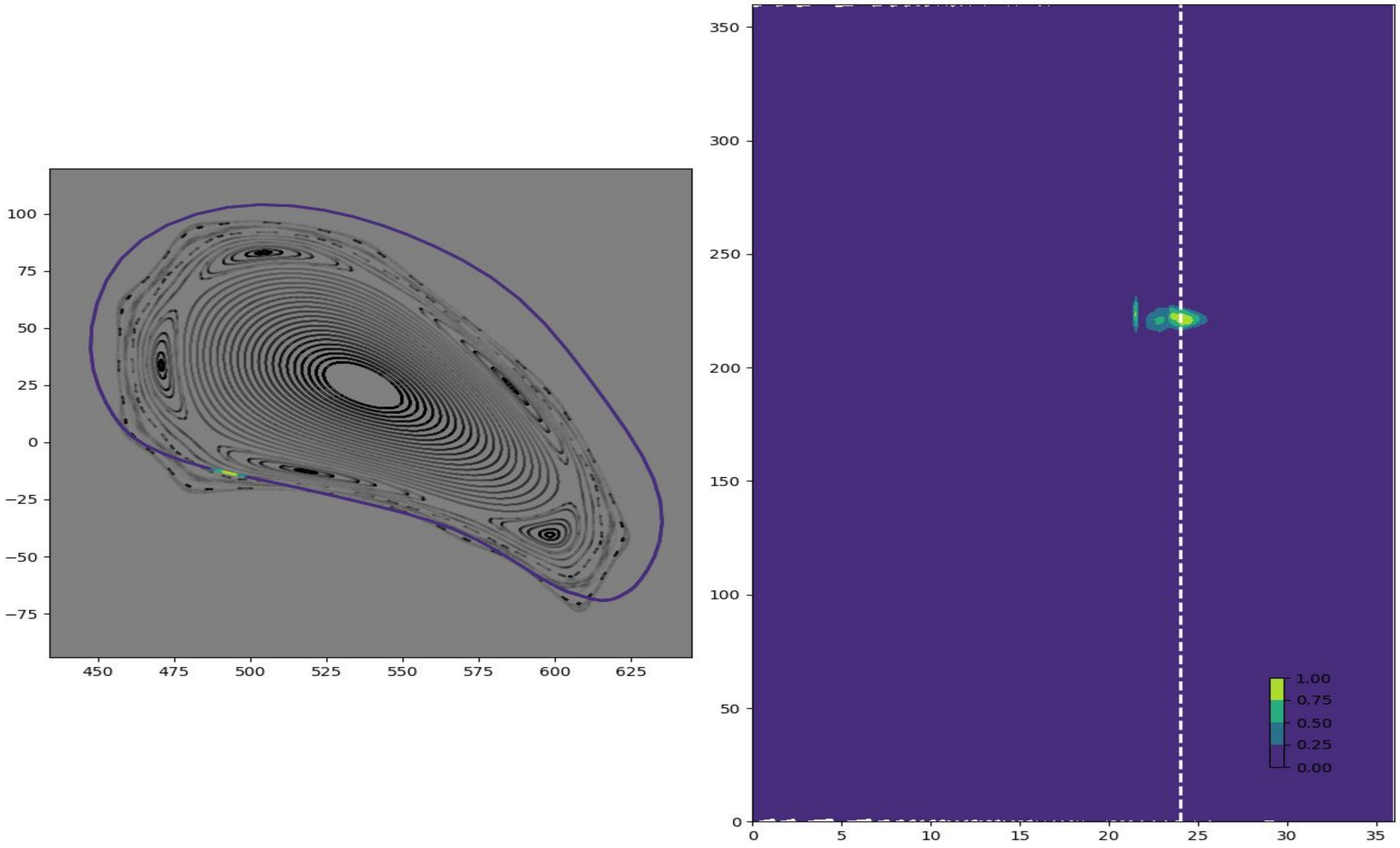




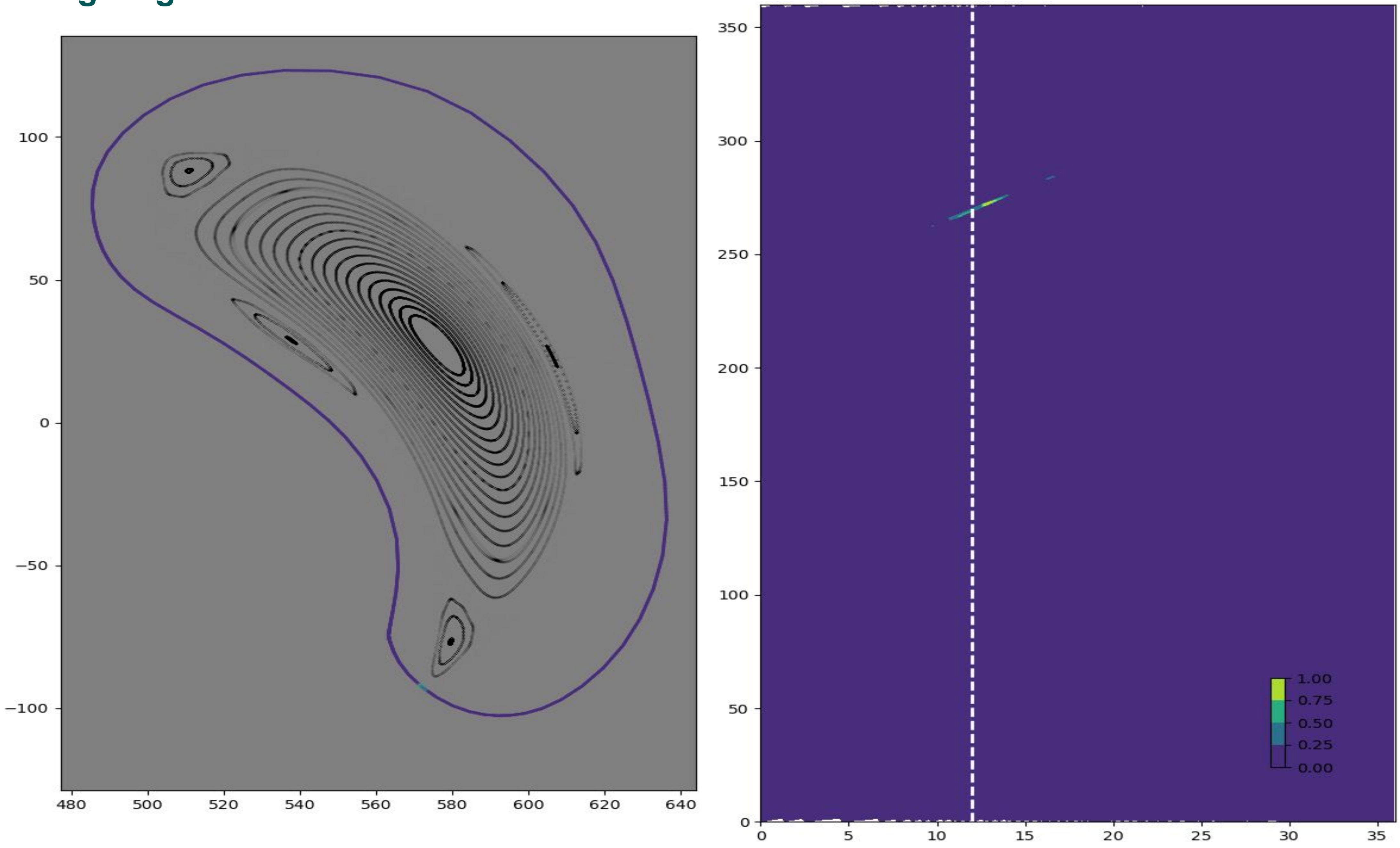
e "high iota" by increasing current in planar coils.
o push the islands inwards

These plots: poincare, only keep trajectories which have survived **200 field periods** (before exiting the magnetic field domain) (>~1km)

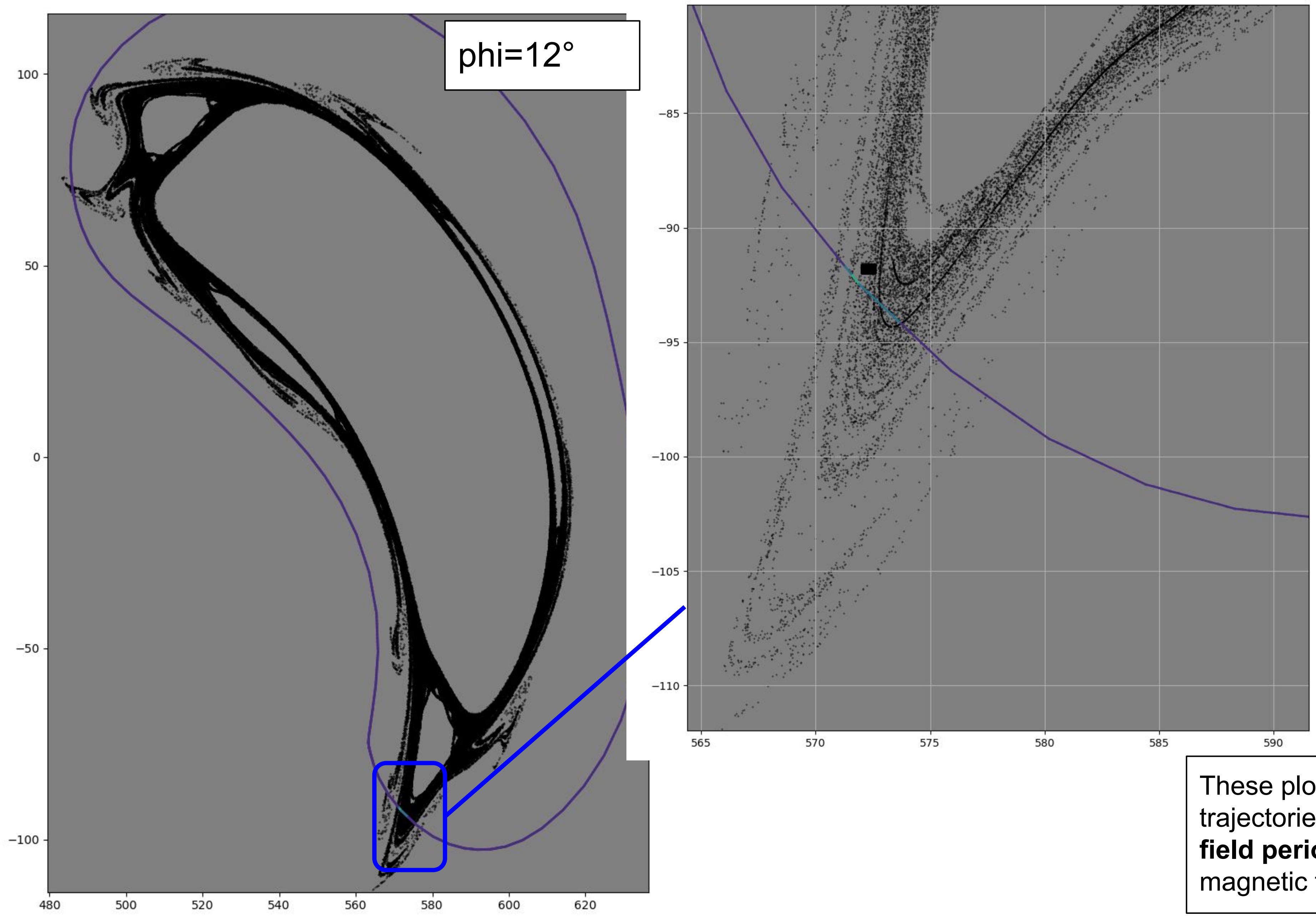
Explaining "standard"



Explaining “high iota”



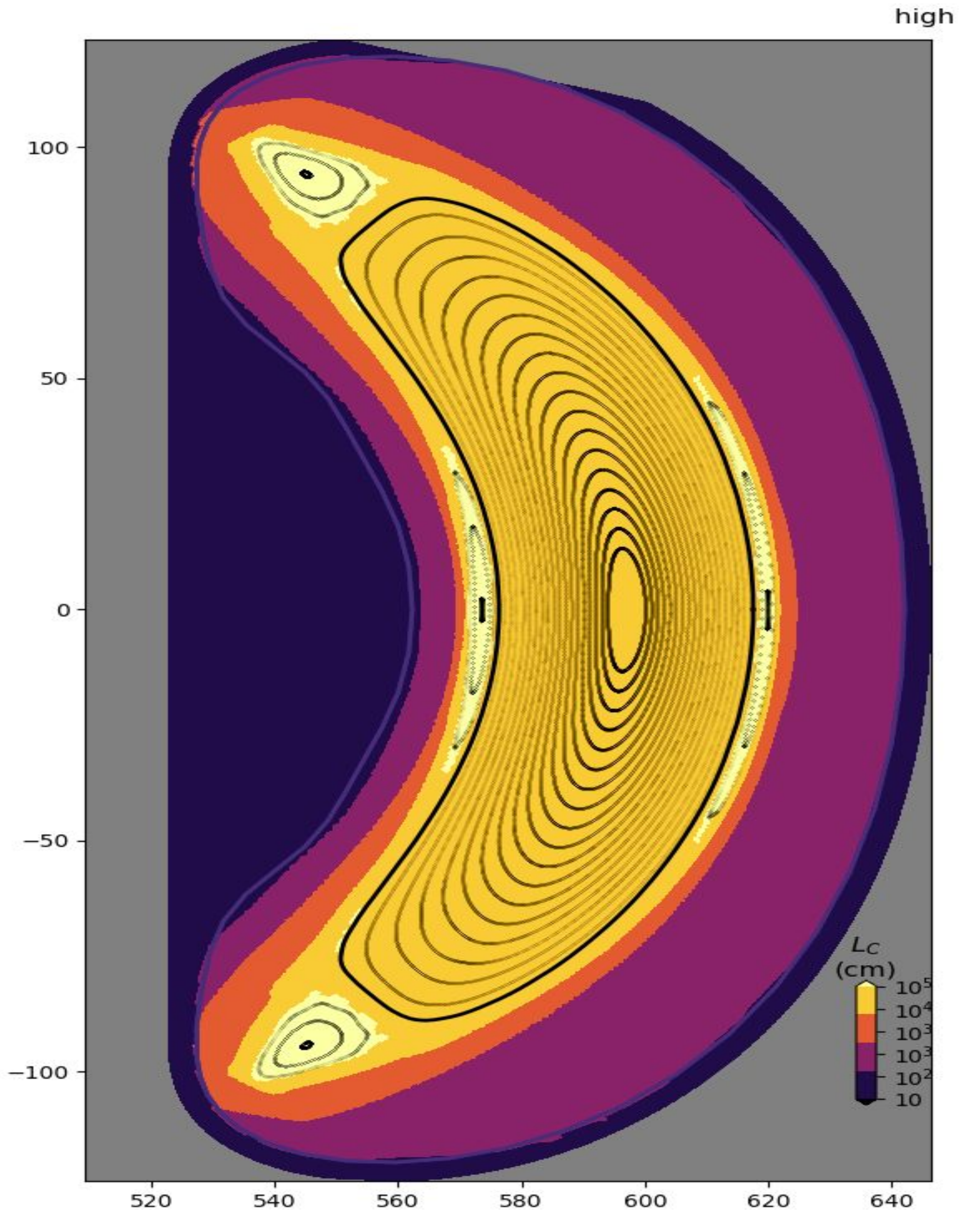
“High iota”configuration in W7-X (vacuum magnetic field)

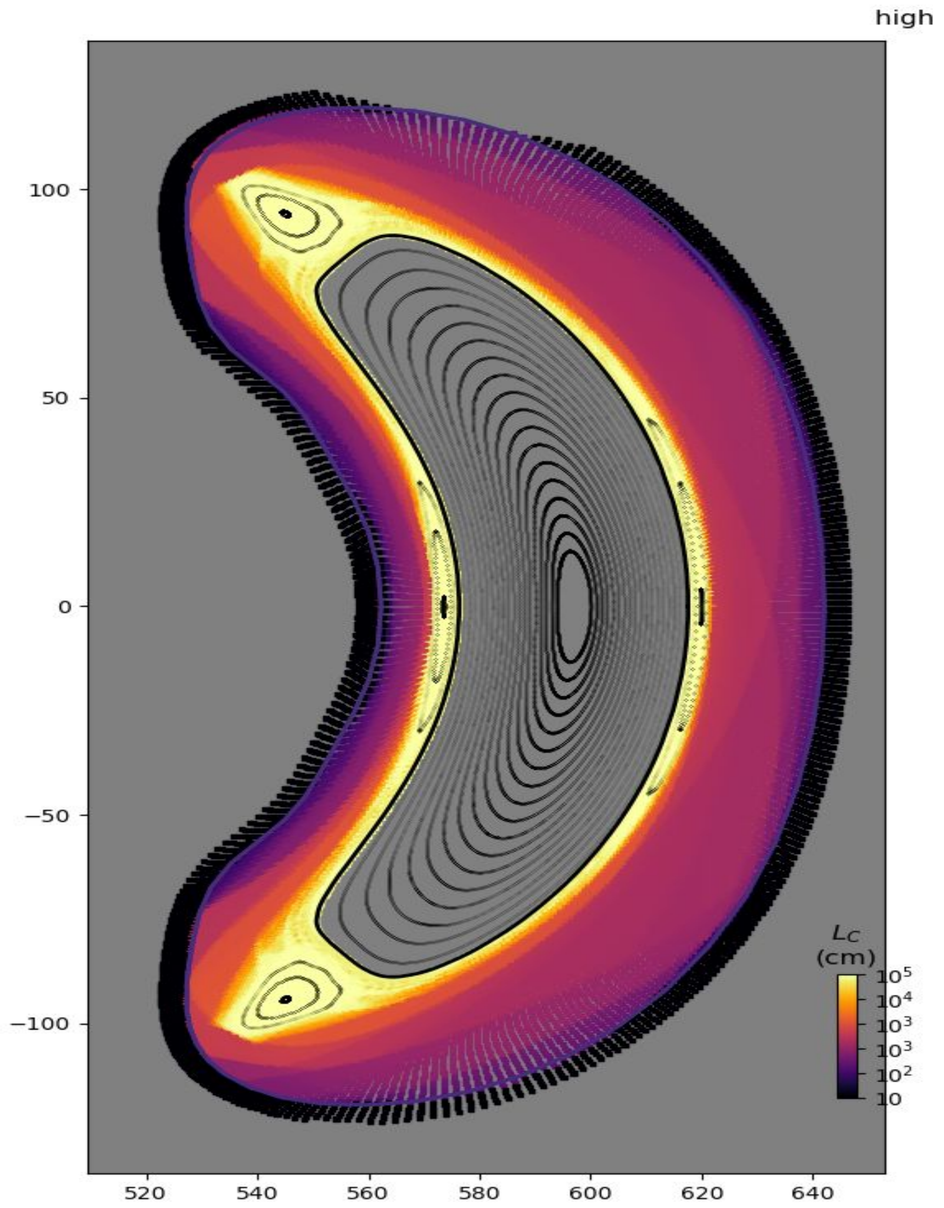


These plots: poincare, only keep trajectories which have survived **200 field periods** (before exiting the magnetic field domain) (>~1km)

Explaining “high iota”

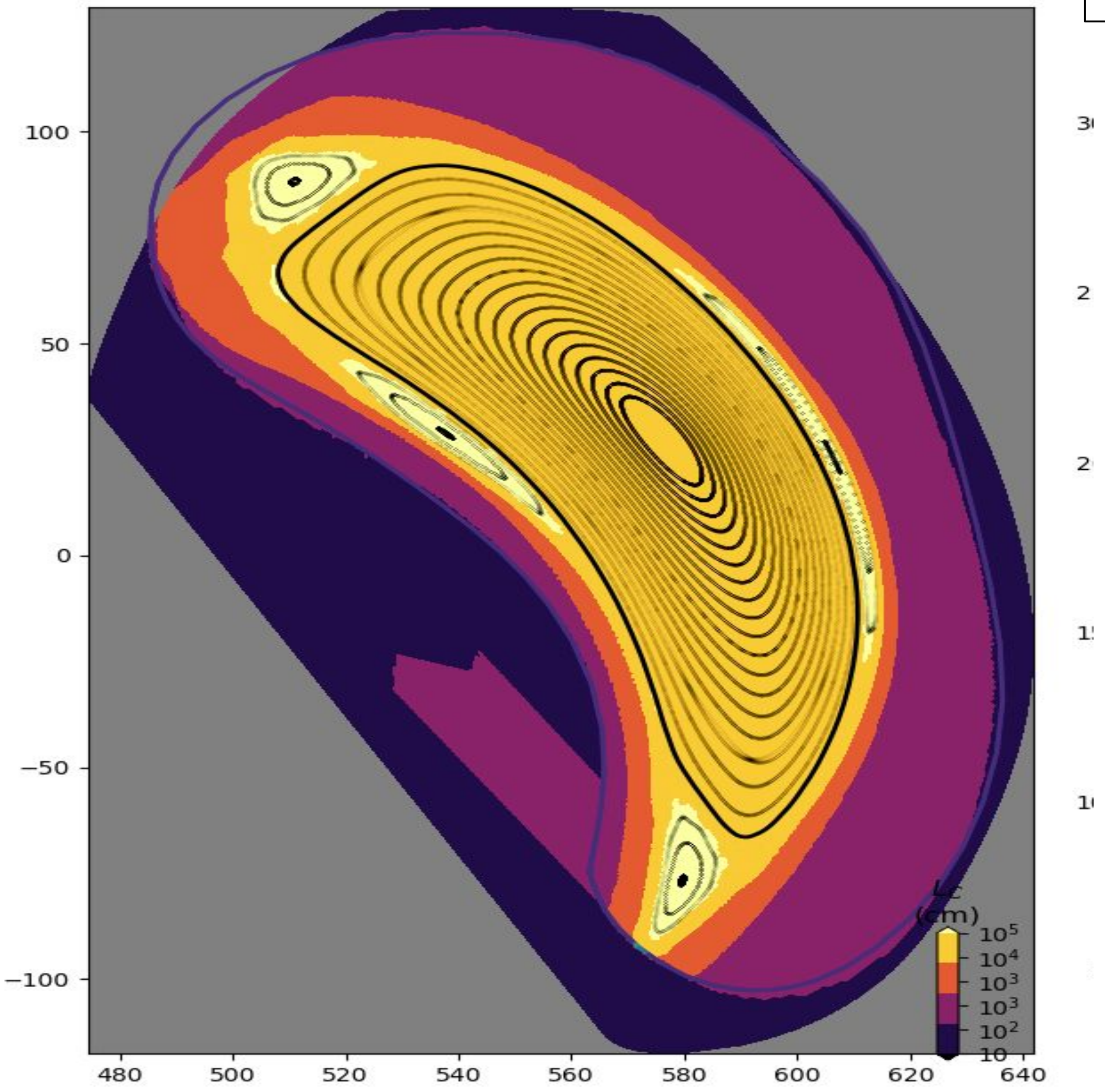
phi=0°

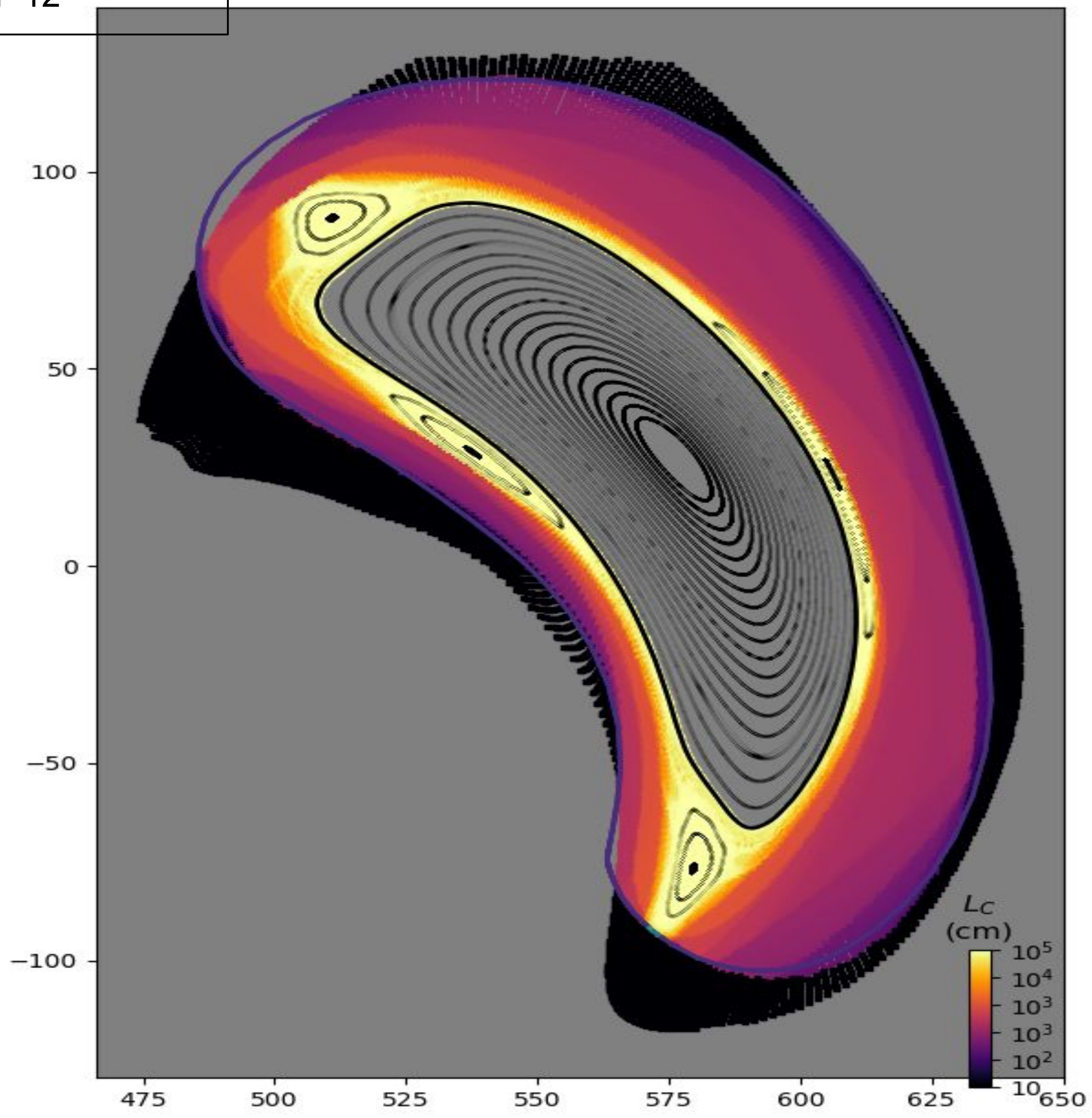




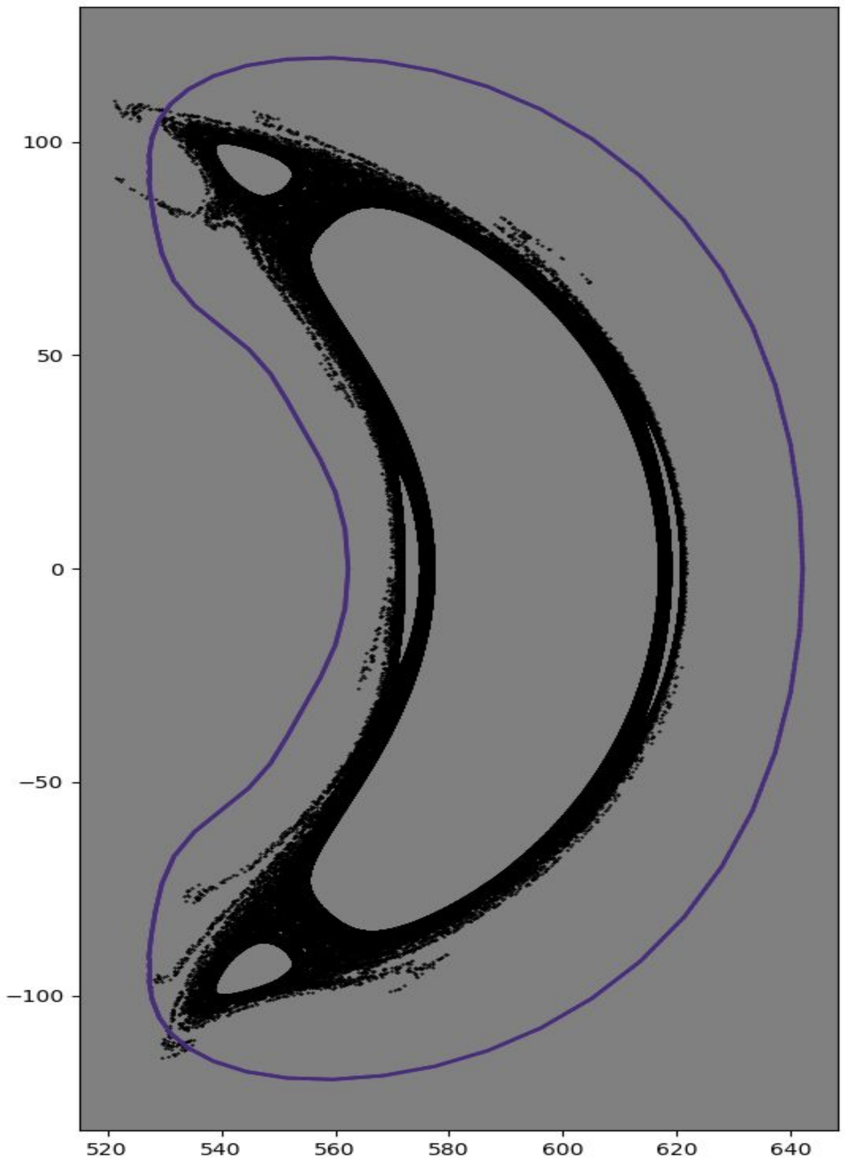
Explaining “high iota”

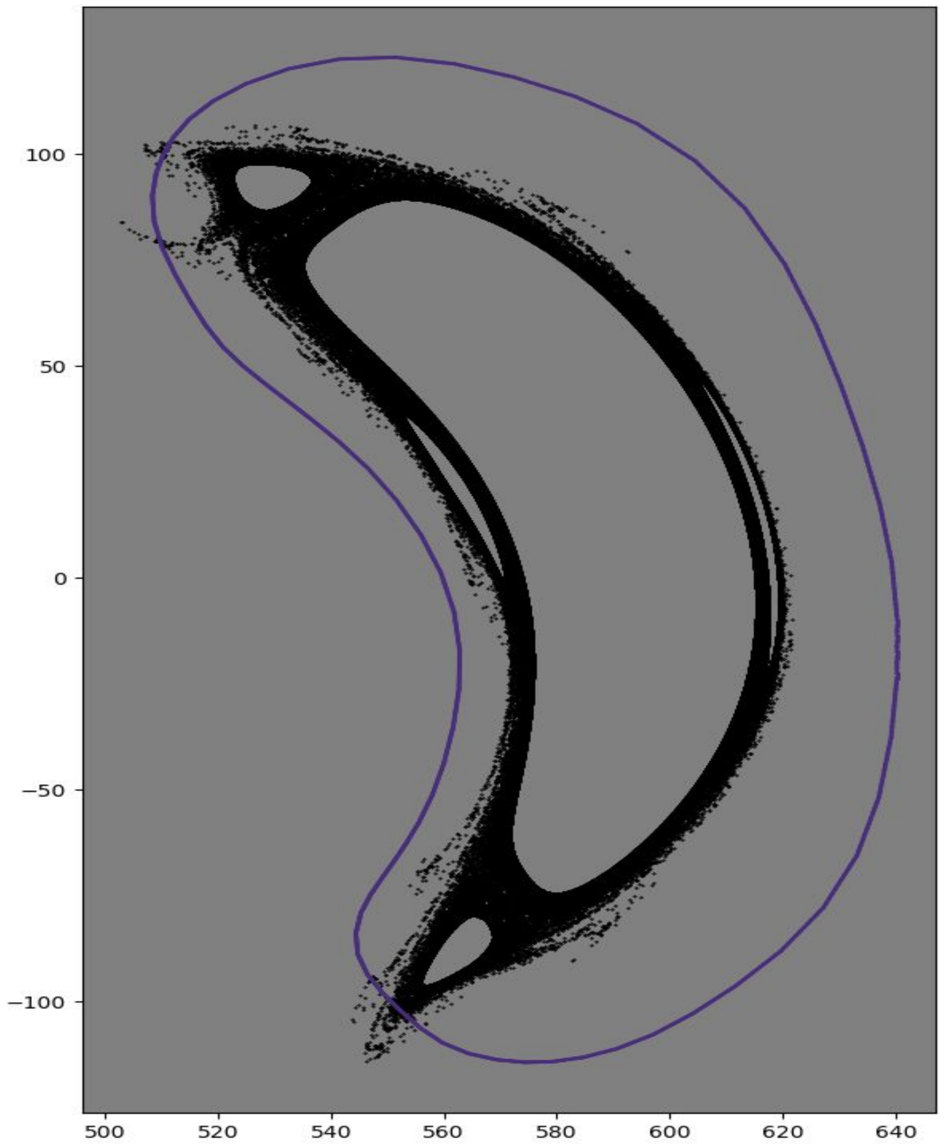
phi=12°





Explaining “high iota”





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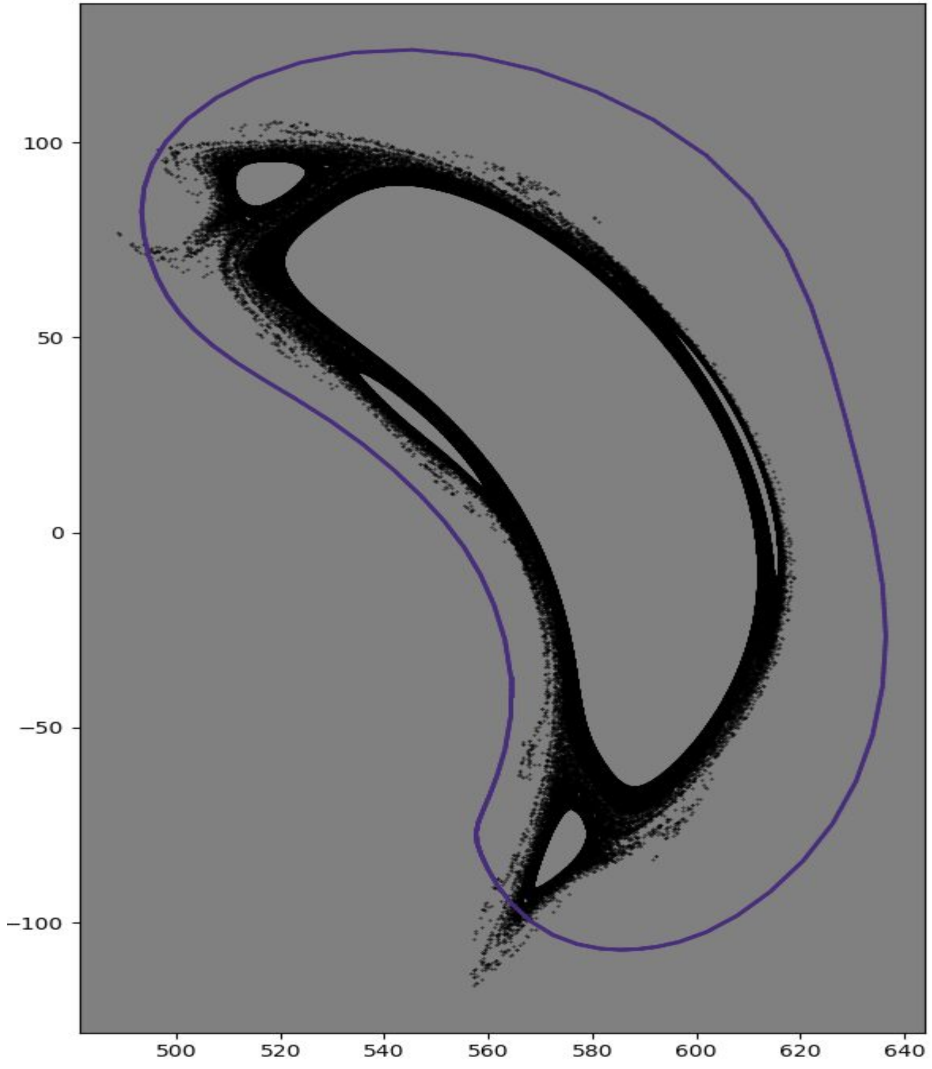

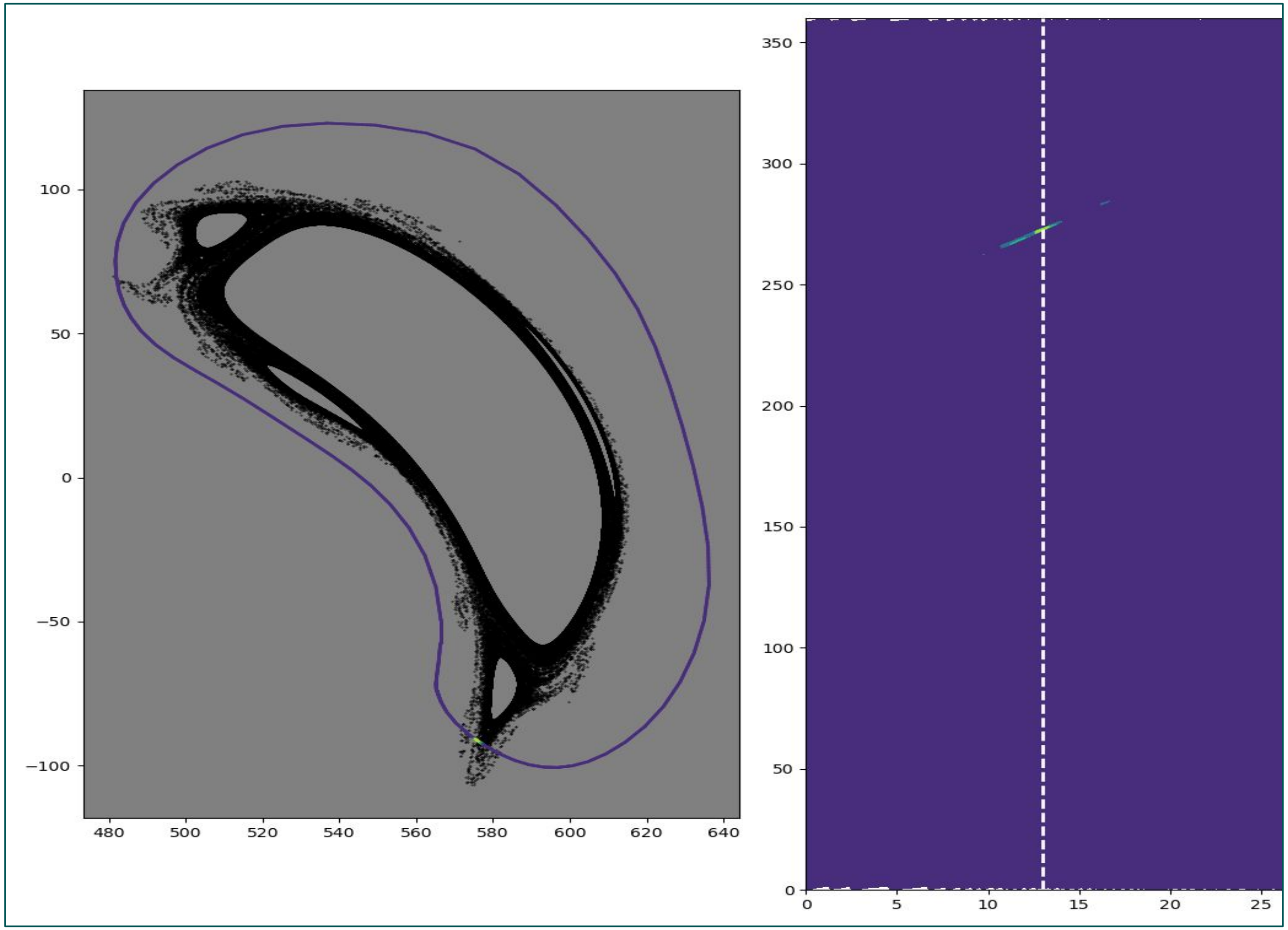

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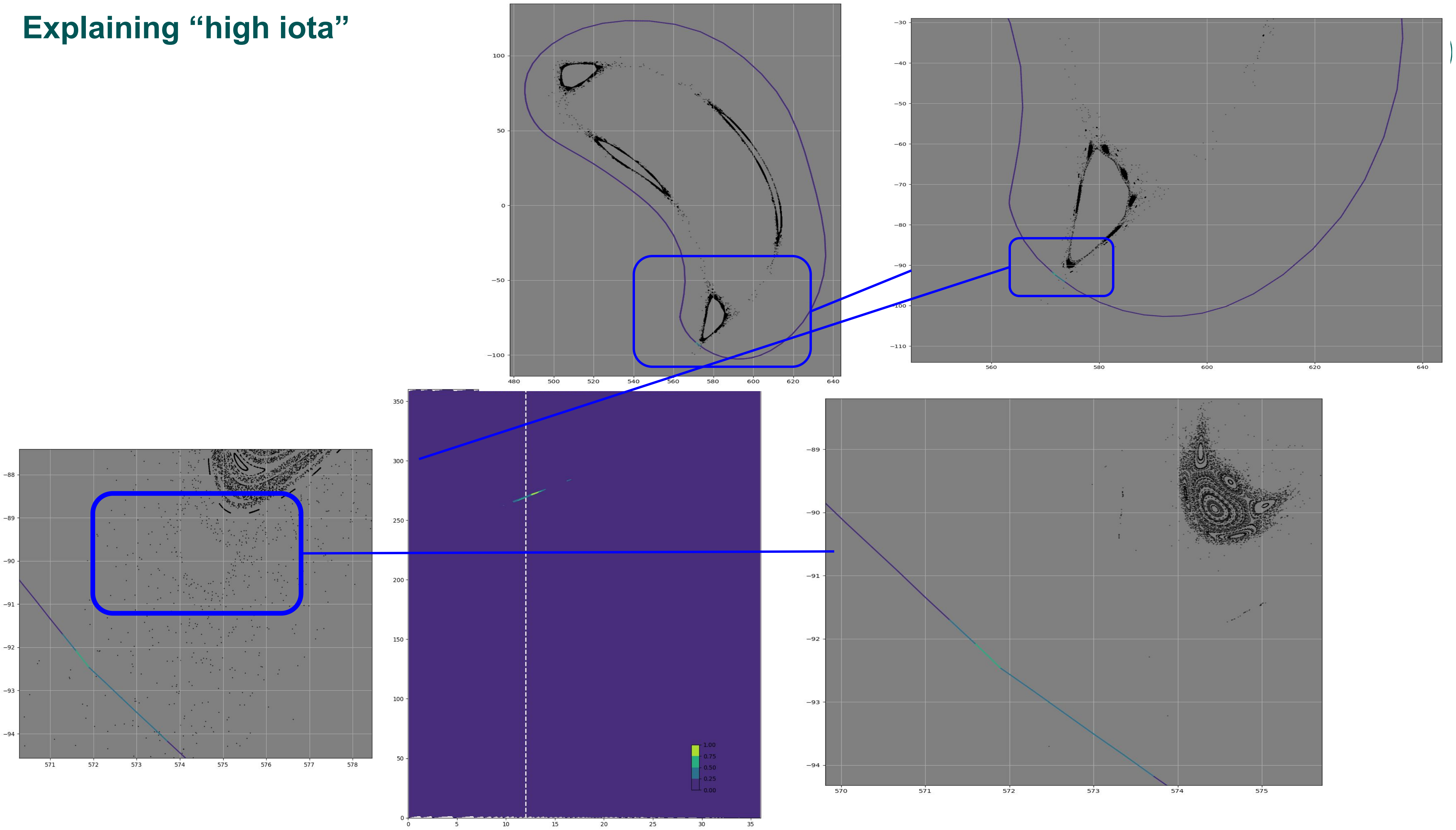
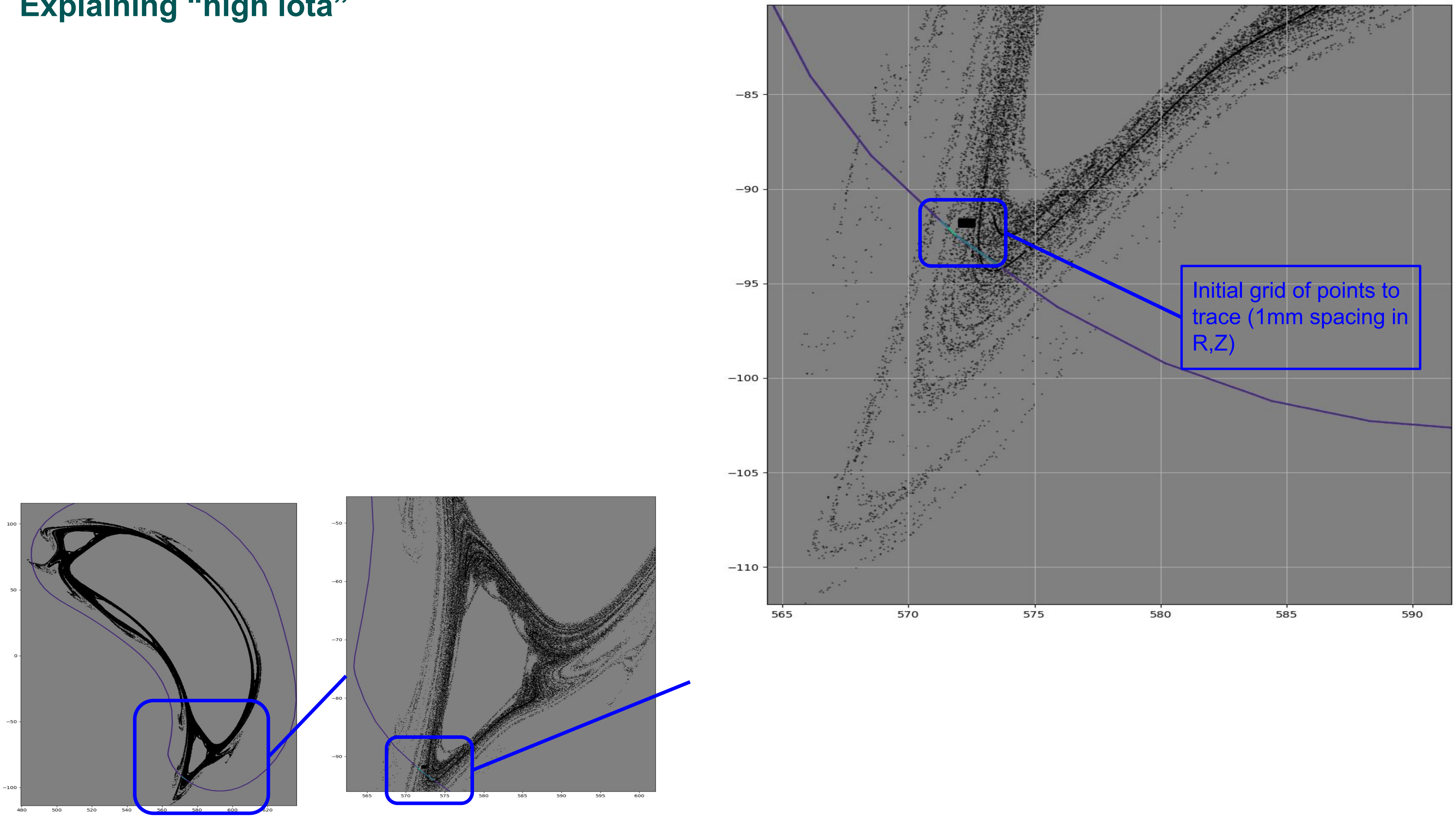
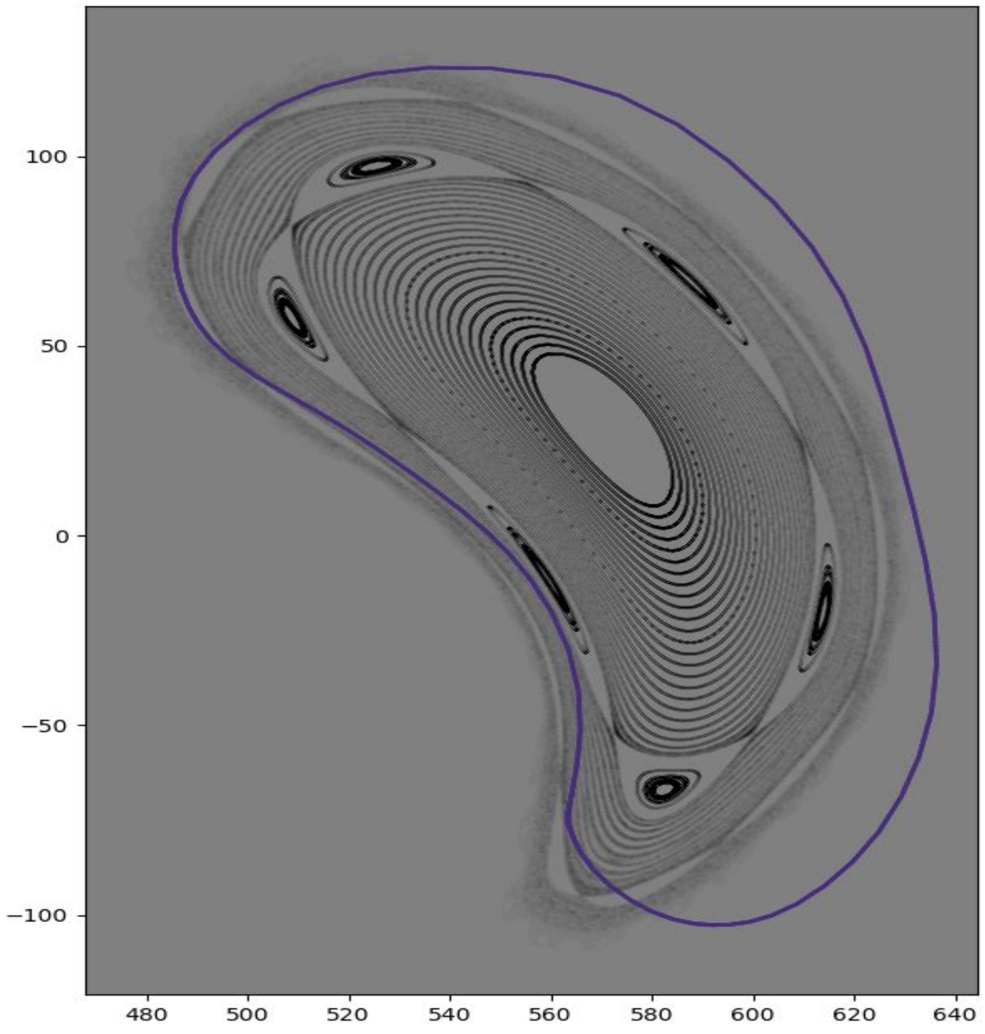
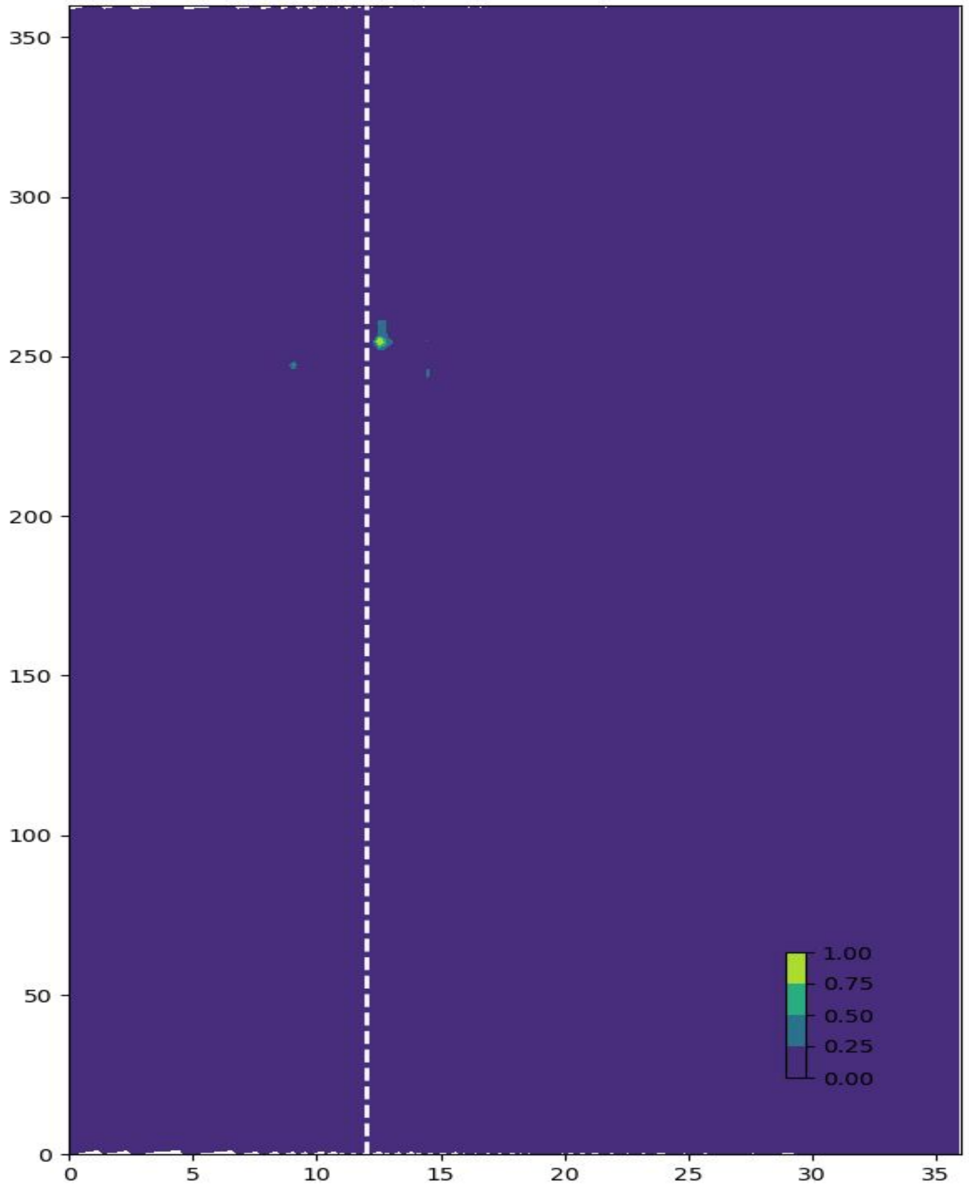


Explaining “high iota”



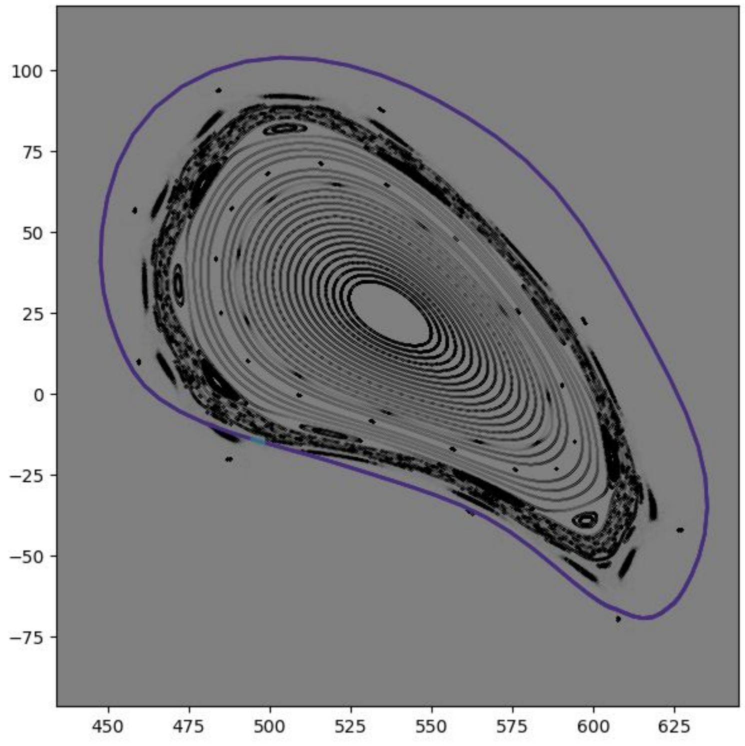
Explaining “low iota”

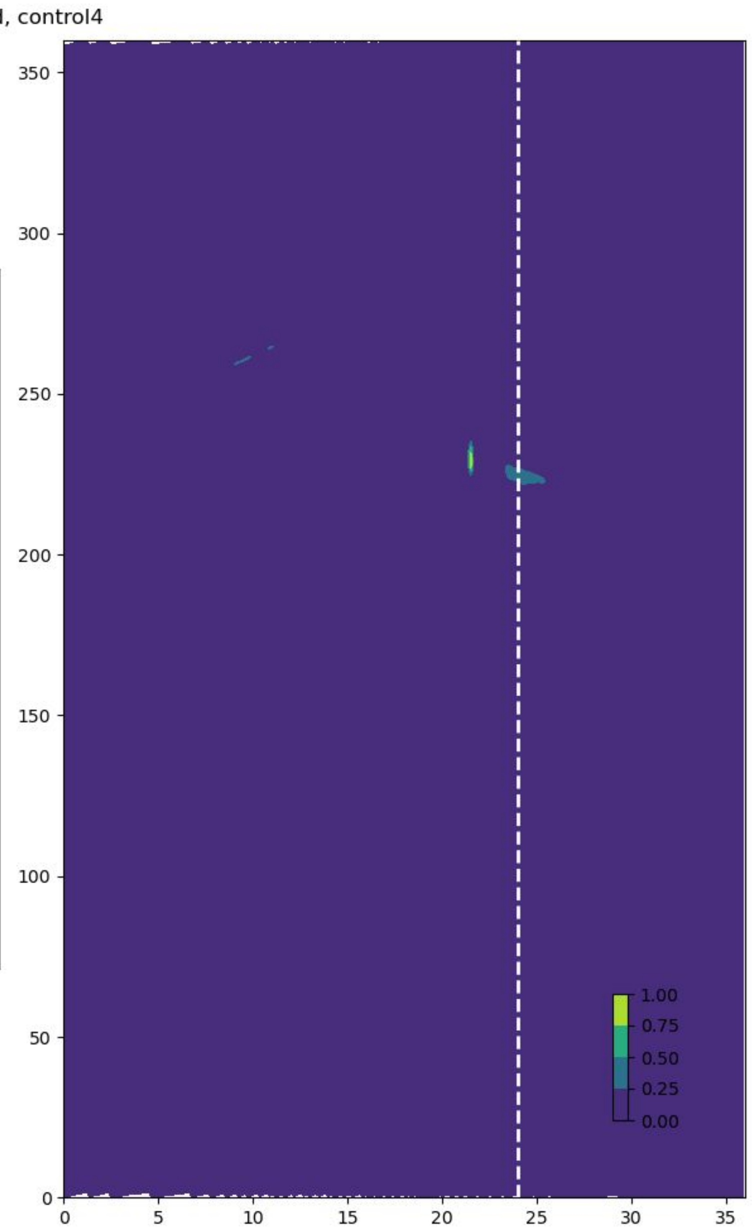




Explaining “standard + small control coil current”

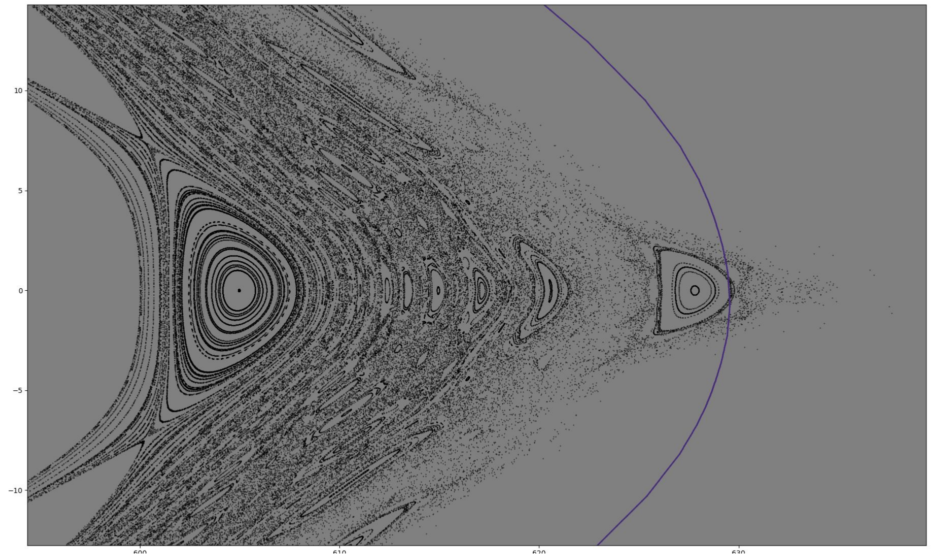
Wall depo >99.9%

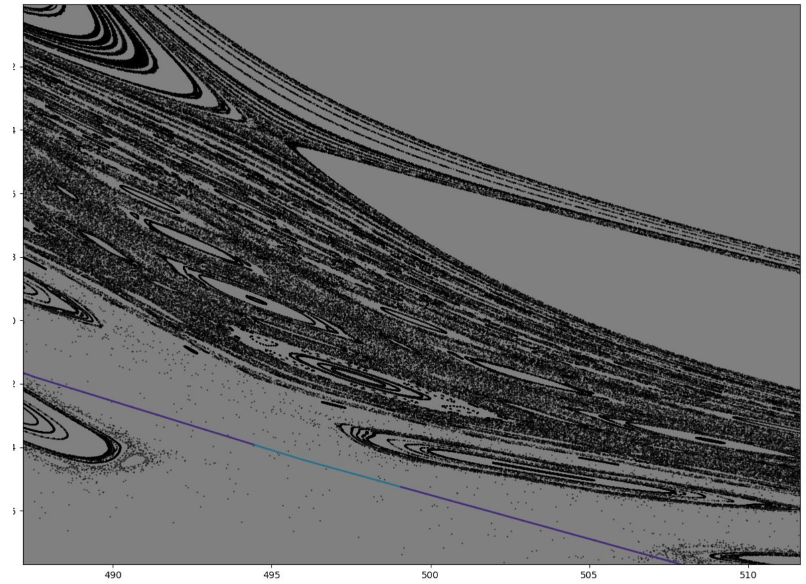




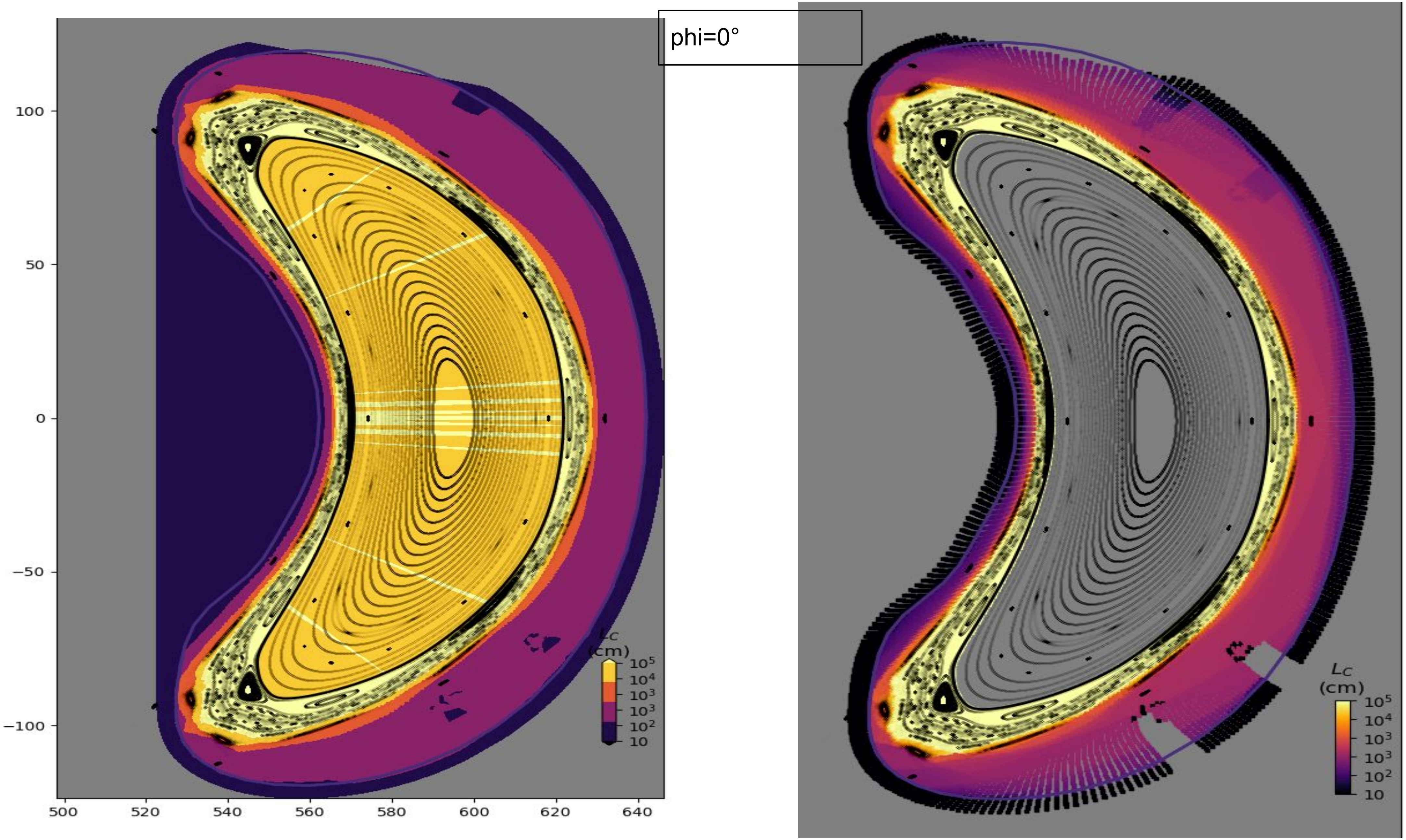
“Control4”
Coil current 2% of main currents

Explaining “standard + small control coil current”

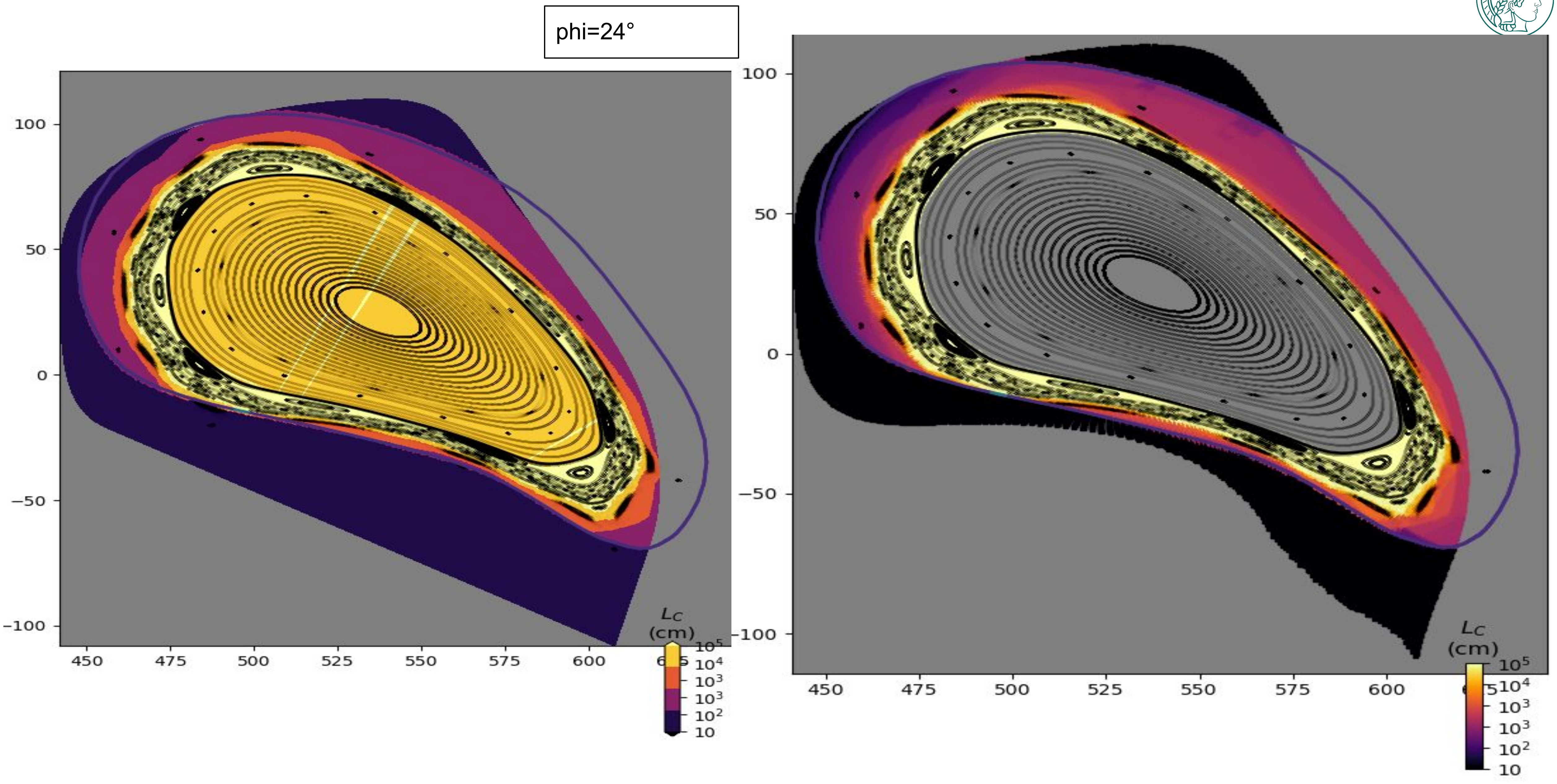




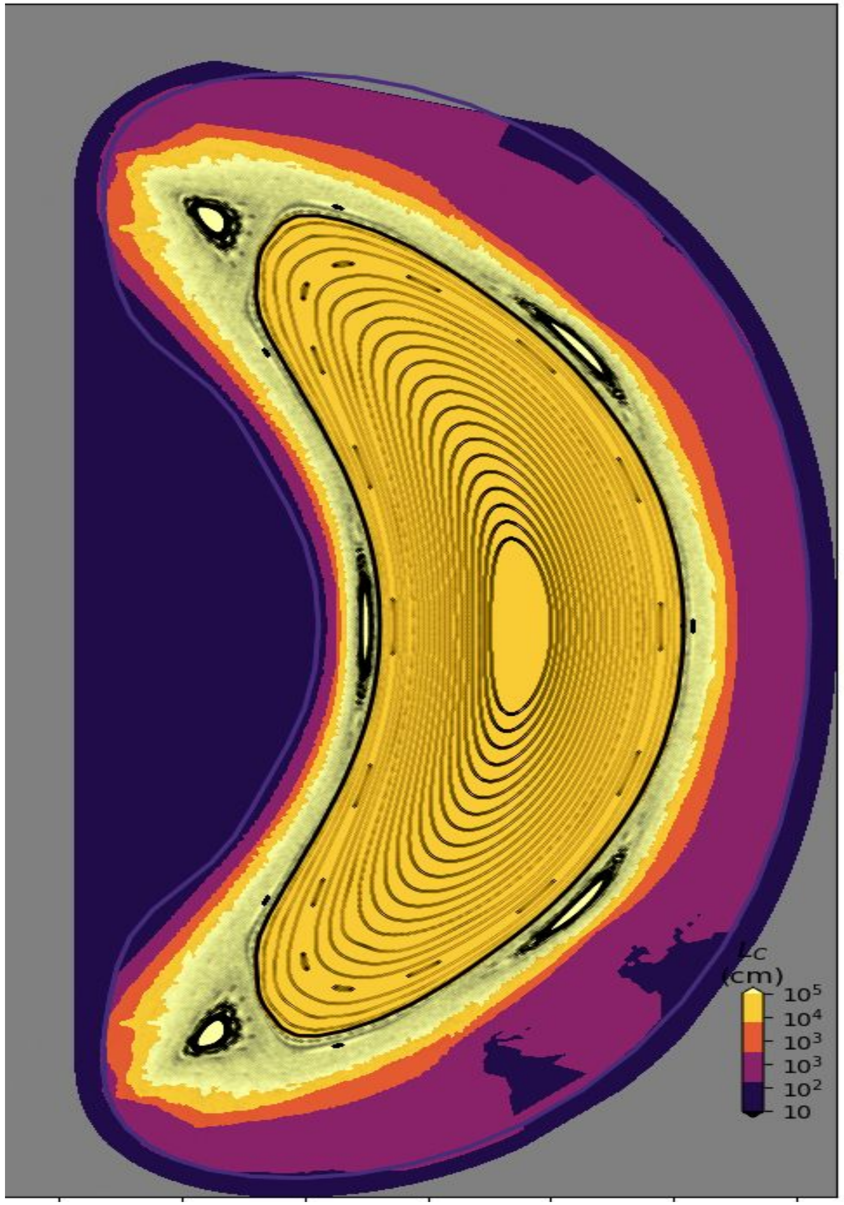
Explaining “standard + small control coil current”



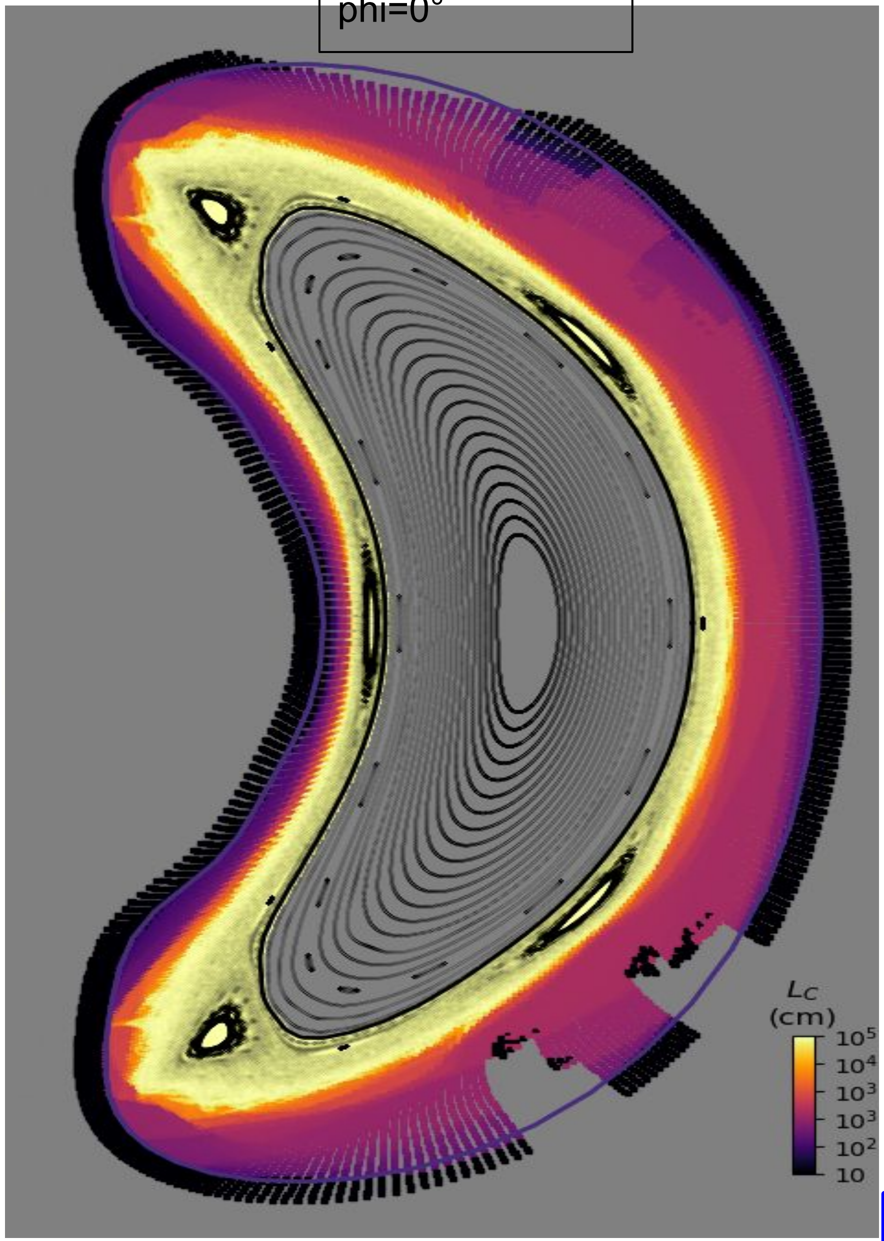
Explaining “standard + small control coil current”



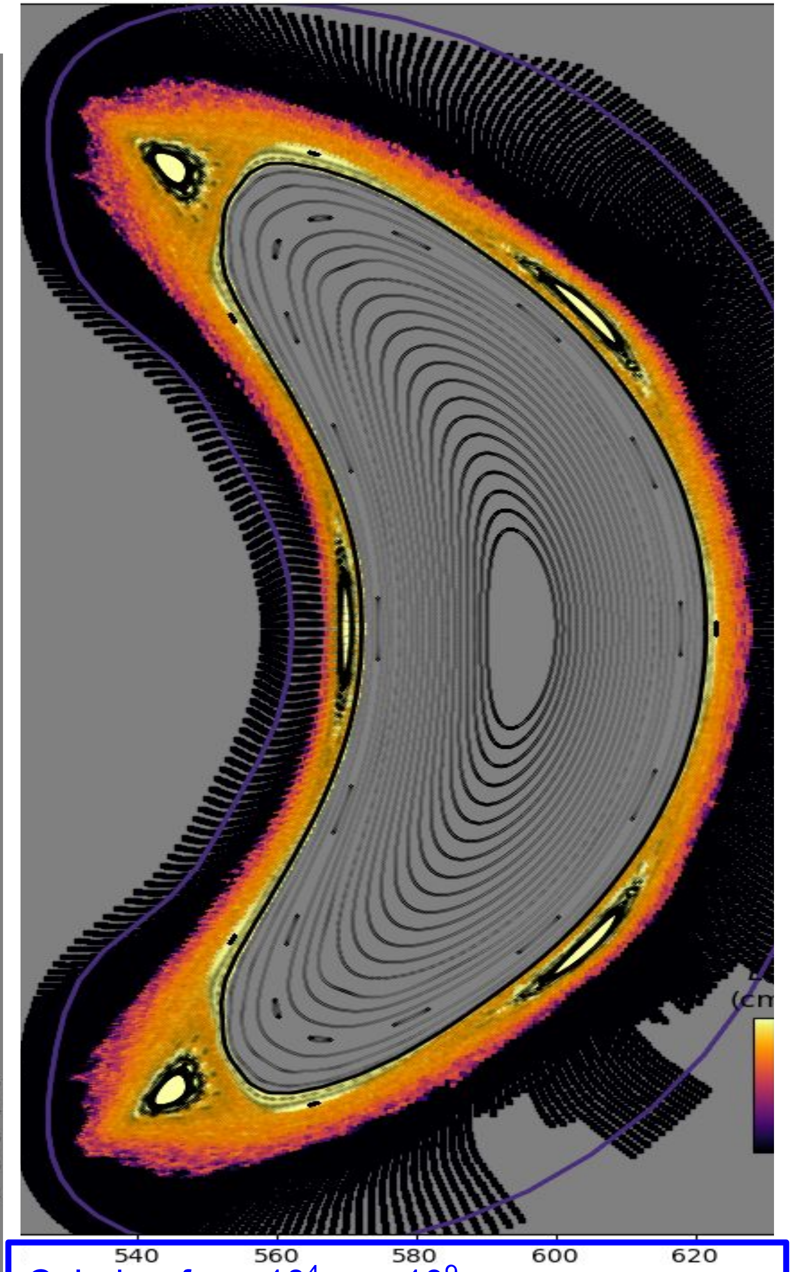
Explaining “standard + larger control coil current”



phi=0°



Wall depo =95%

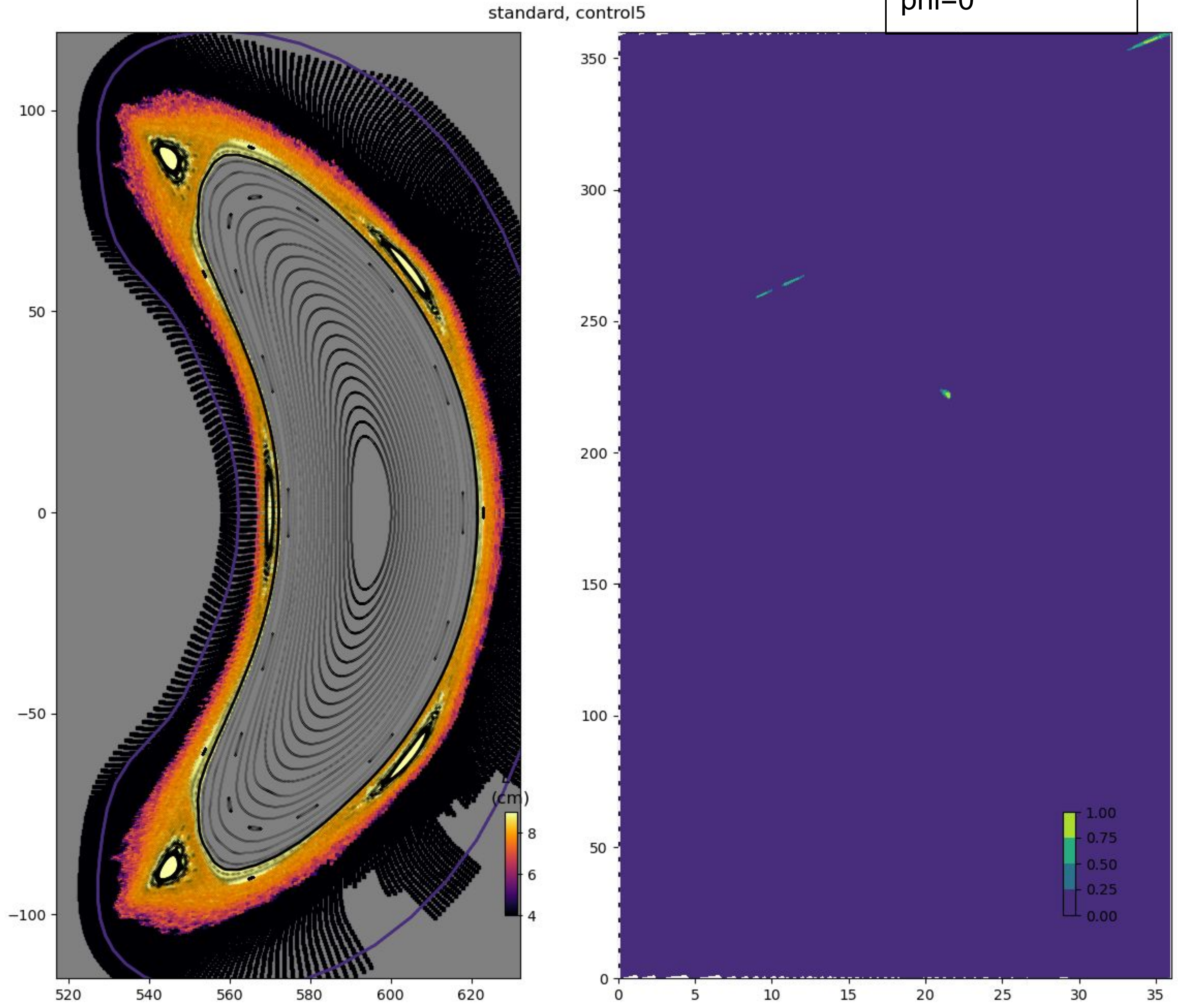


Colorbar from 10^4cm - 10^9cm

Explaining “standard + larger control coil current”

Wall depo =95%

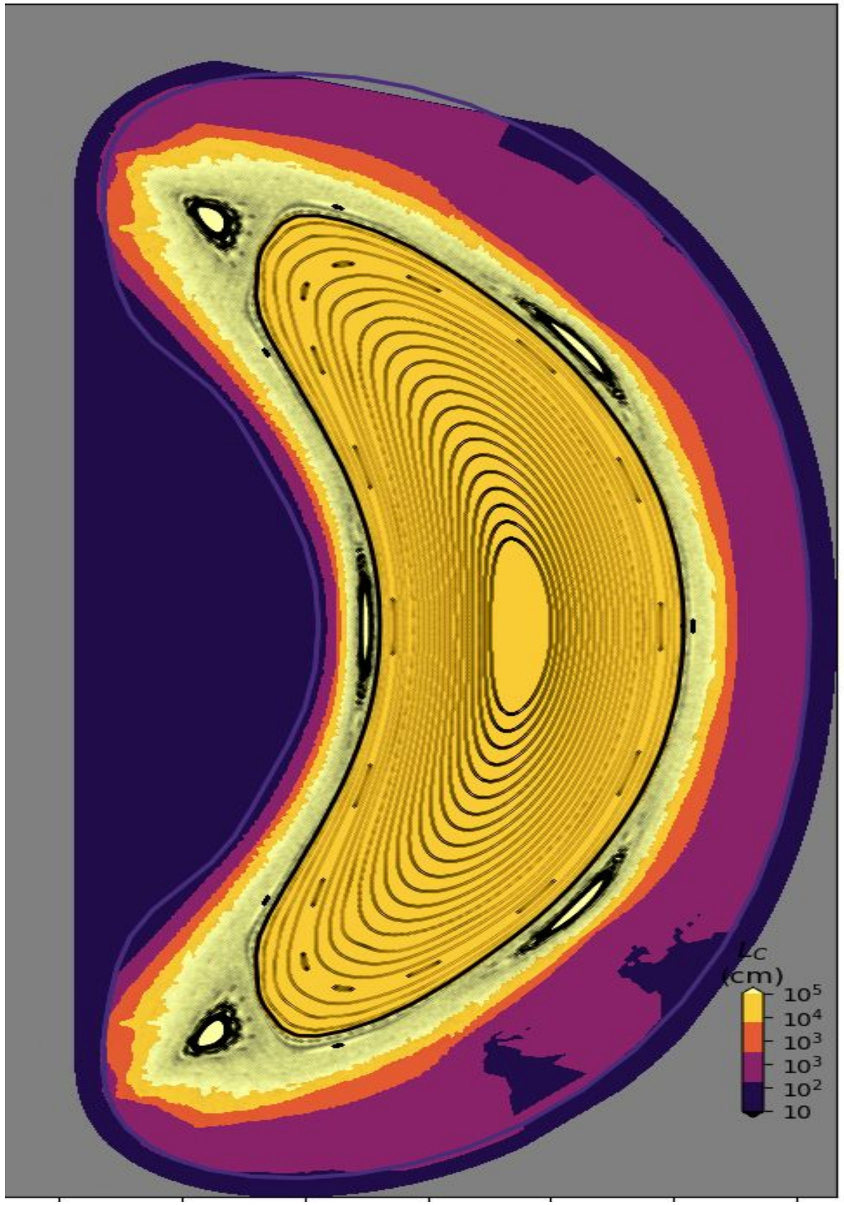
phi=0°



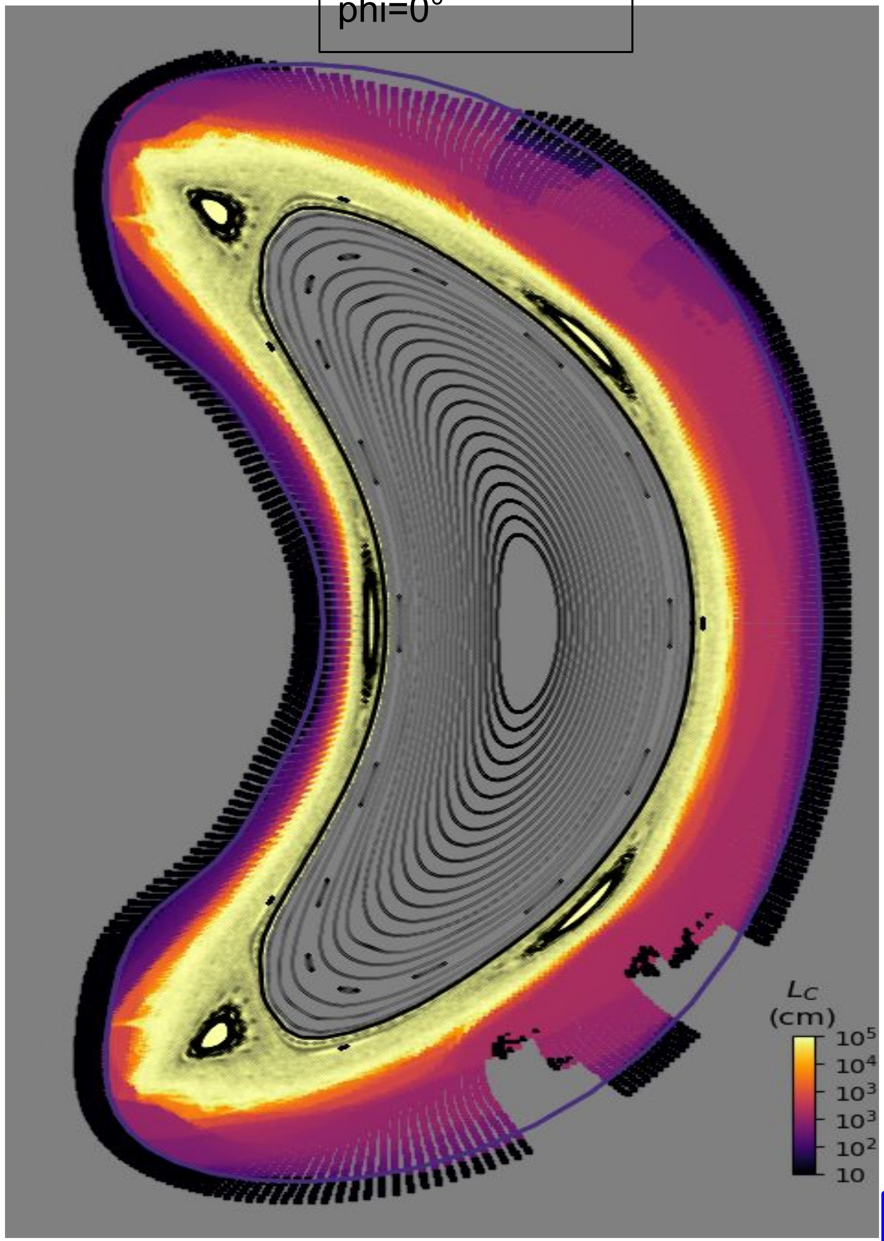
“Control5”
Coil current 2% of main currents

Colorbar from 10^4cm - 10^9cm

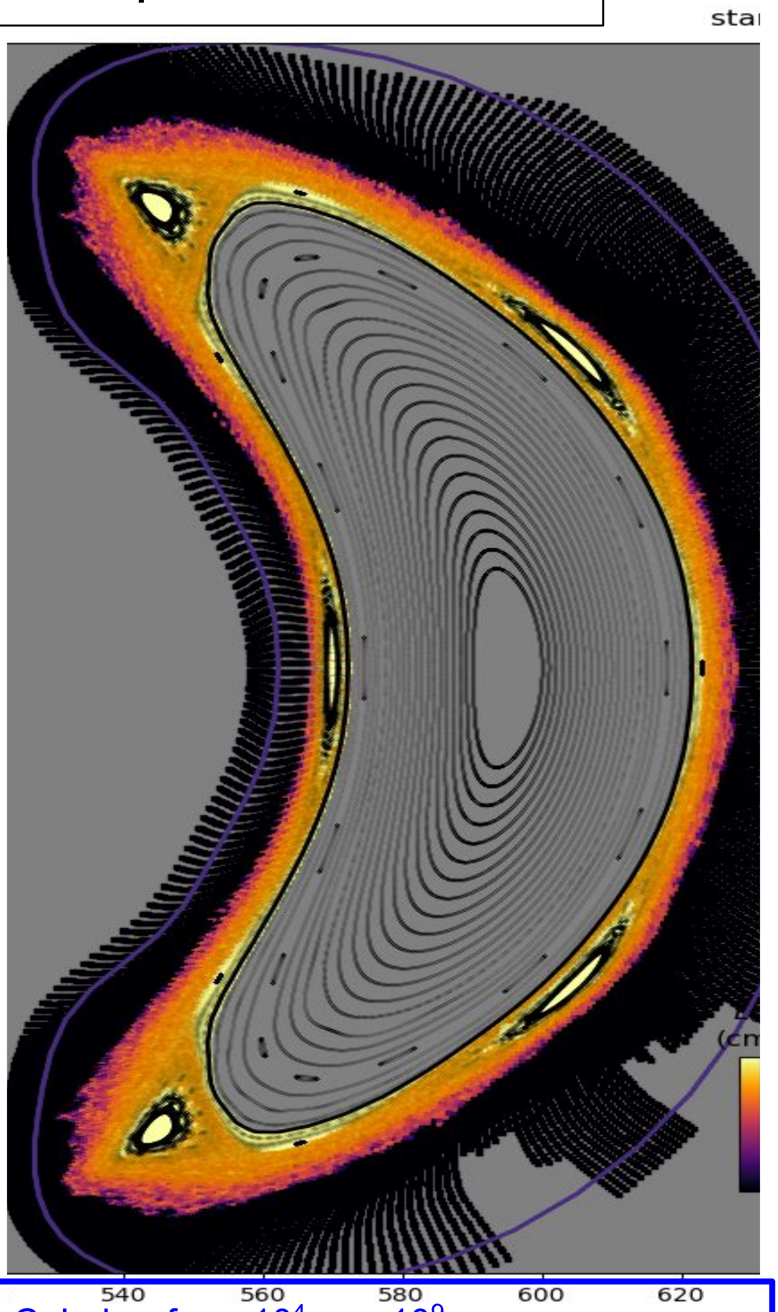
Explaining “standard + larger control coil current”



phi=0°



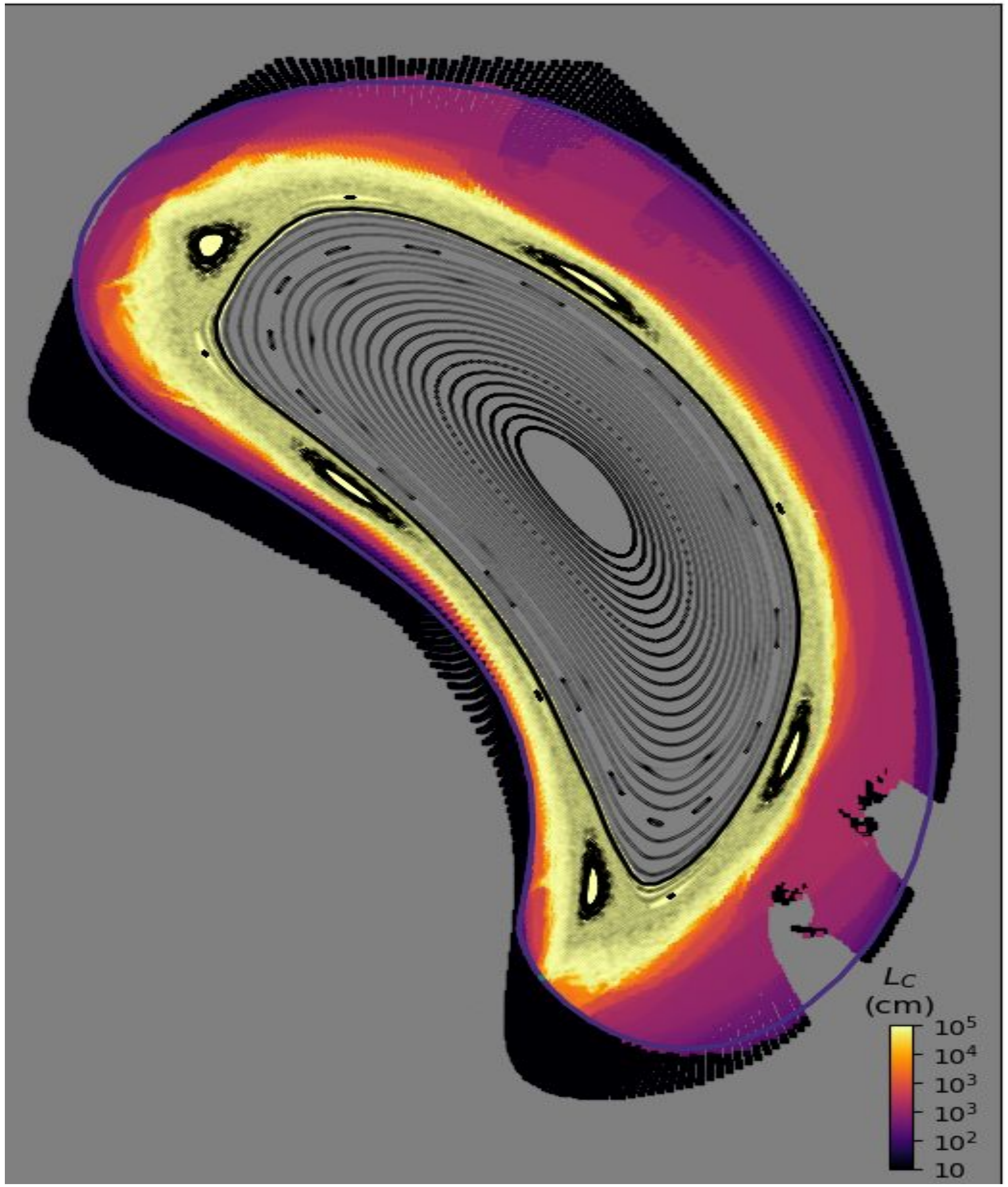
Wall depo =95%

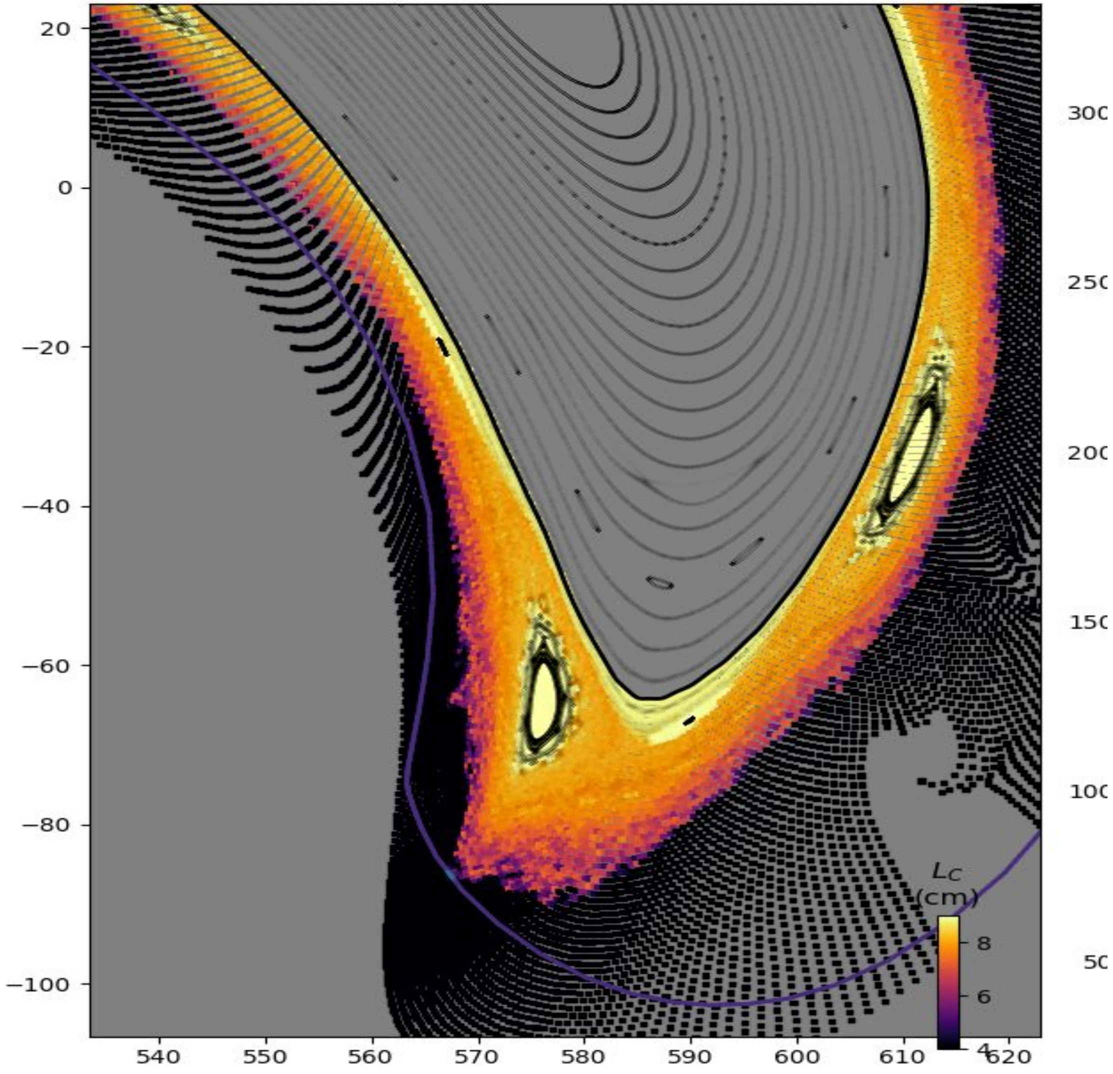


Colorbar from 10^4cm - 10^9cm

Explaining “standard + larger control coil current”

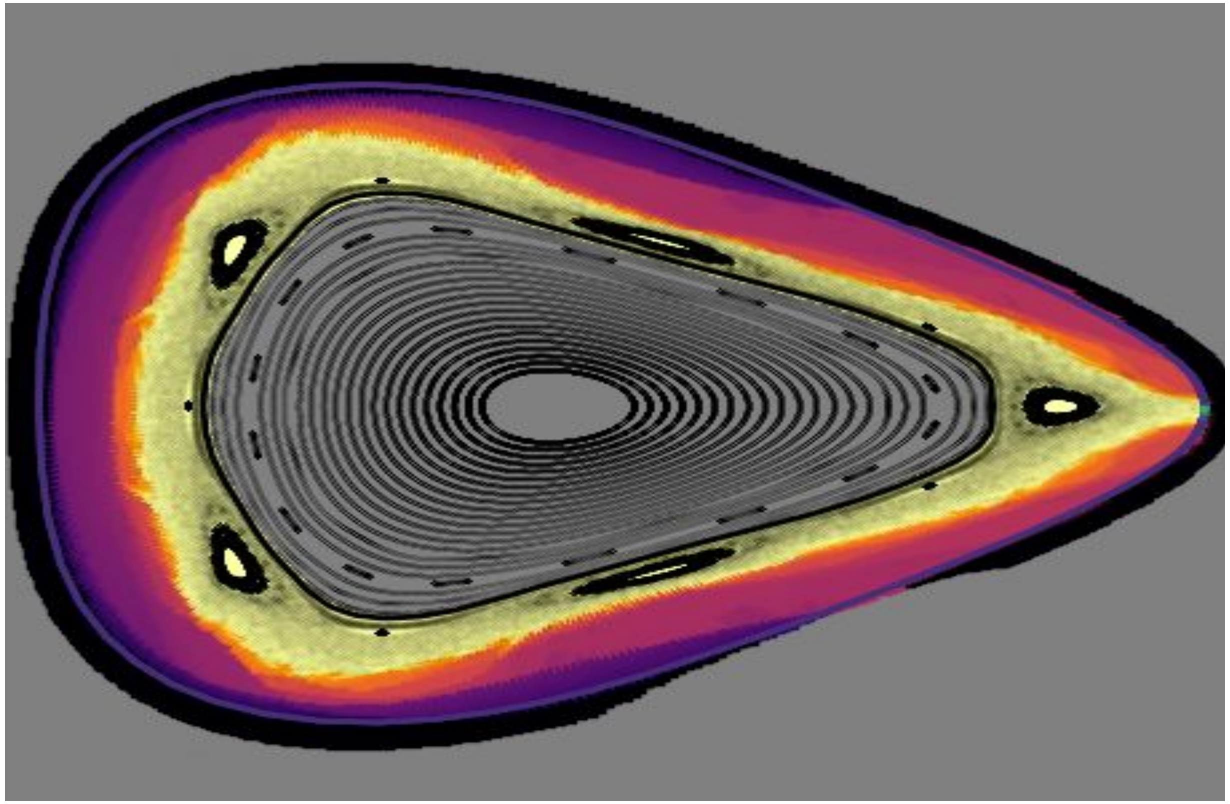
phi=12°



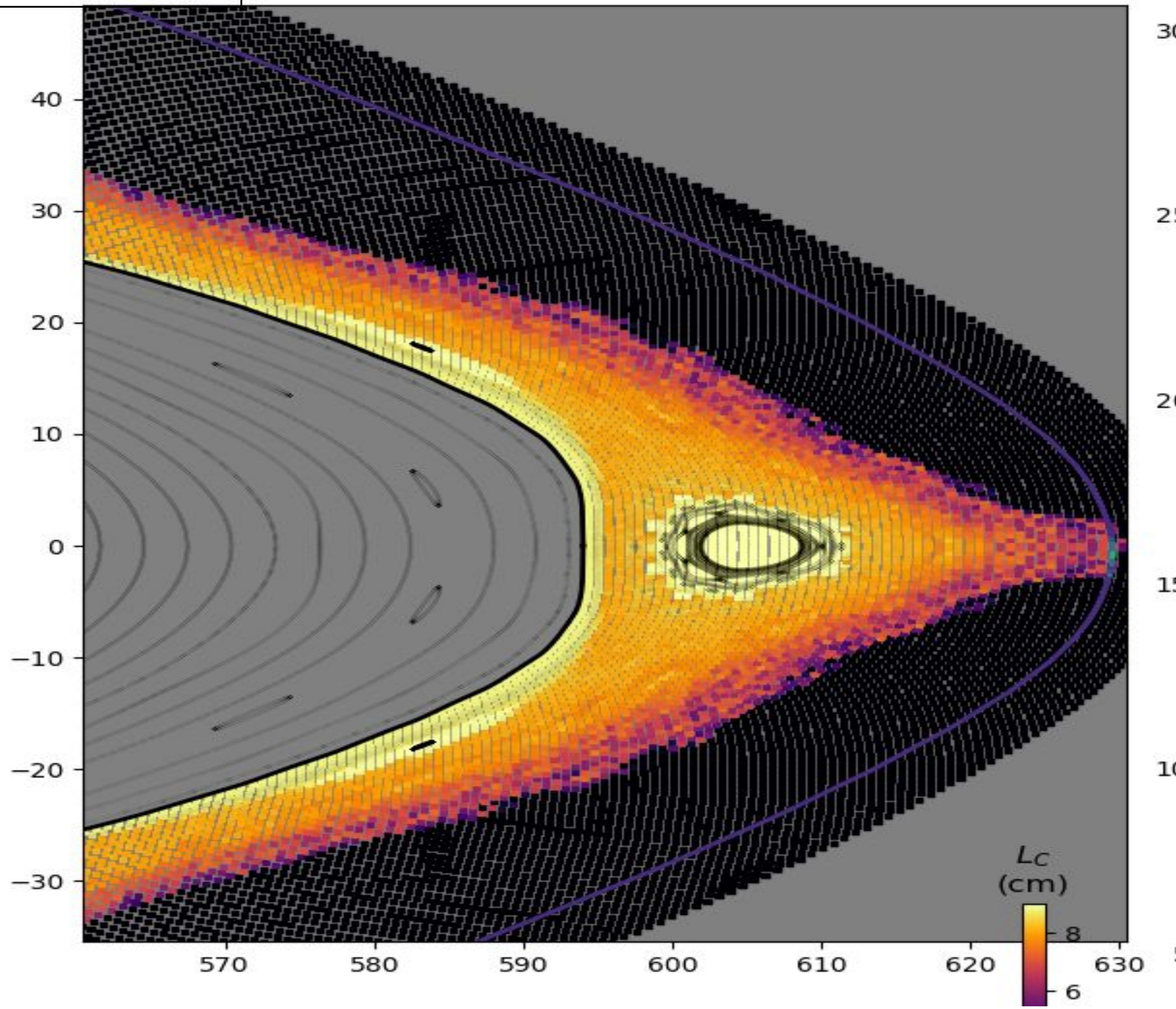


Colorbar from 10^4cm - 10^9cm

Explaining “standard + larger control coil current”



phi=36°



Colorbar from 10^4cm - 10^9cm