Plasma Edge Simulations for Non-Resonant Divertors

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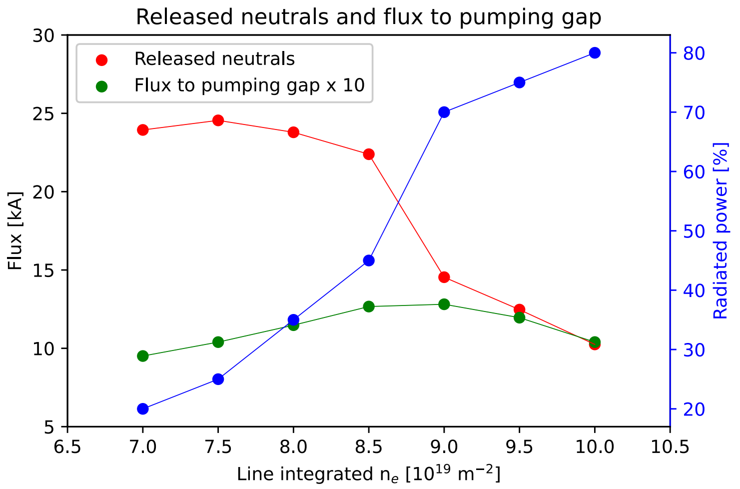
Problems with island divertors

- Experience W7-X:
  - Good for heat exhaust
  - Bad for neutral exhaust
  - Not resilient against changes in equilibrium

  ➔ Check possible alternatives

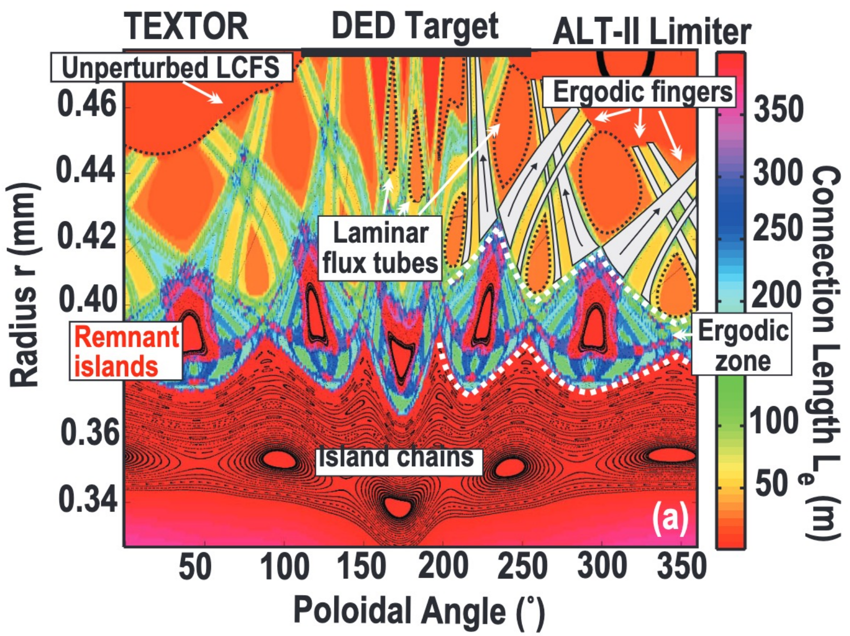


[D. Boeyaert *et al* 2023 *Plasma Phys. Control. Fusion* **66** 015005]

Non-resonant divertors

- Tokamaks with ergodic divertors
  - Flux channels (fingers) coming out of plasma
  - Independent of a specific edge rotational transform

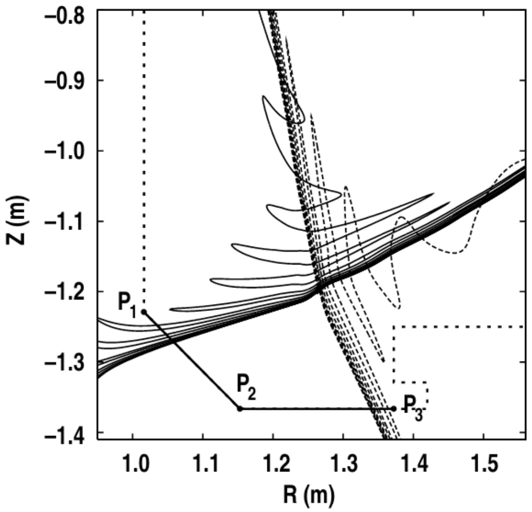
  ➔ Determine if similar structures exist in stellarator



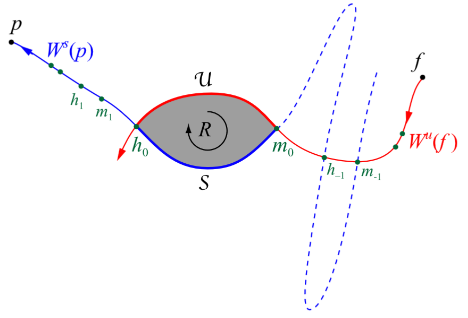
[O. Schmitz *et al* 2012 *Fusion Sci. Technol.* **61.2T** 221-229]

Non-resonant divertors

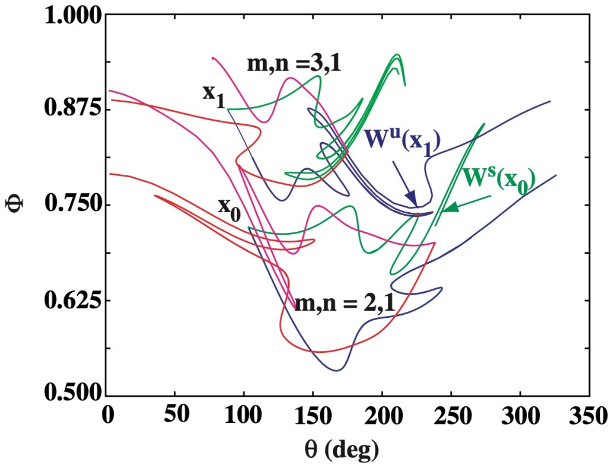
- Tokamaks with ergodic divertors
  - Flux channels (fingers) coming out of plasma
  - Independent of a specific edge rotational transform
- Interaction between stable and unstable manifold
  - ➔Formation of homoclinical tangle – top figure (interaction between stable (blue) and unstable (red) manifold for same resonance)
  - ➔Formation of heteroclinical tangle – bottom figure (interaction between manifolds of different resonances)

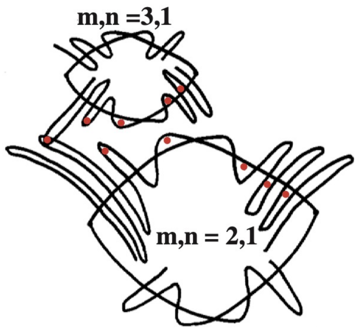


[A. Wingen *et al* 2009 *Nucl. Fusion* **49** 055027]



[J.[D. Meiss 2015 *Chaos* **25** 097602]



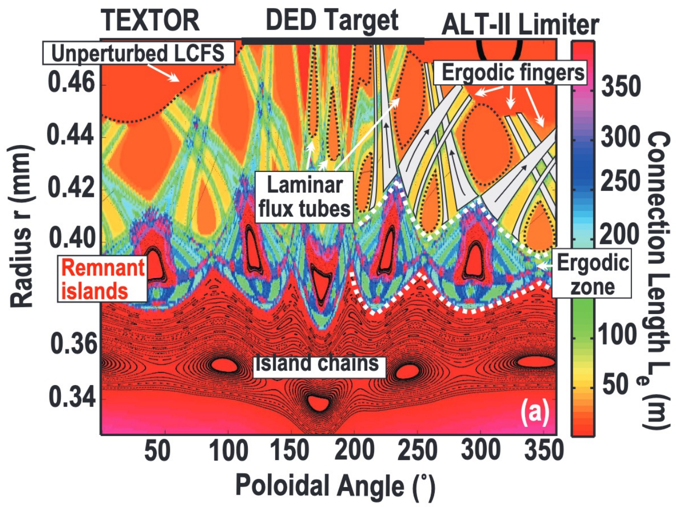


[T. E. Evans *et* al 2005 *J. Phys.: Conf Ser.* **7** 174]

Non-resonant divertors

- Tokamaks with ergodic divertors
  - Flux channels (fingers) coming out of plasma
  - Independent of a specific edge rotational transform
- Interaction between stable and unstable manifolds
  - ➔Formation of homoclinical tangle
  - ➔Formation of heteroclinical tangle
- Turnstiles are flux tubes which deposit particles from the core to the divertor targets (strike line patterns)

[A. Punjabi *et* al 2022 *Phys. Plasmas* ***29*** 012502]



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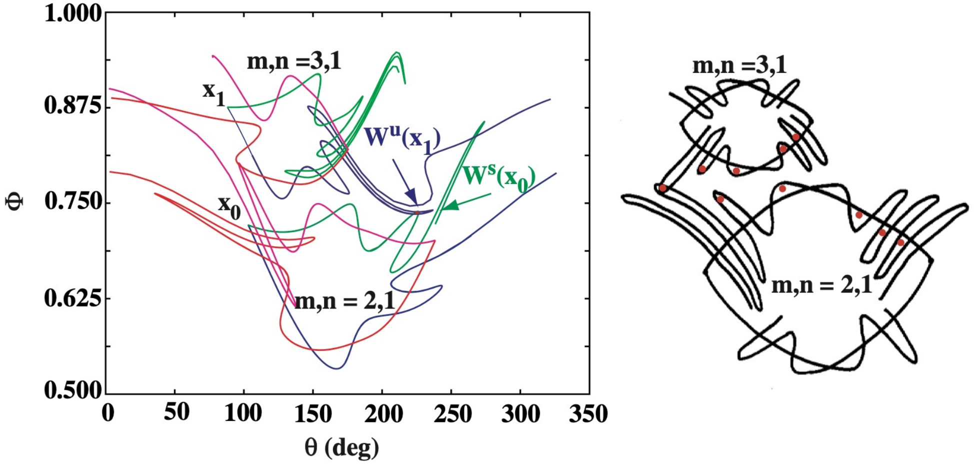

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Non-resonant divertors

- Tokamaks with ergodic divertors
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- Interaction between stable and unstable manifolds
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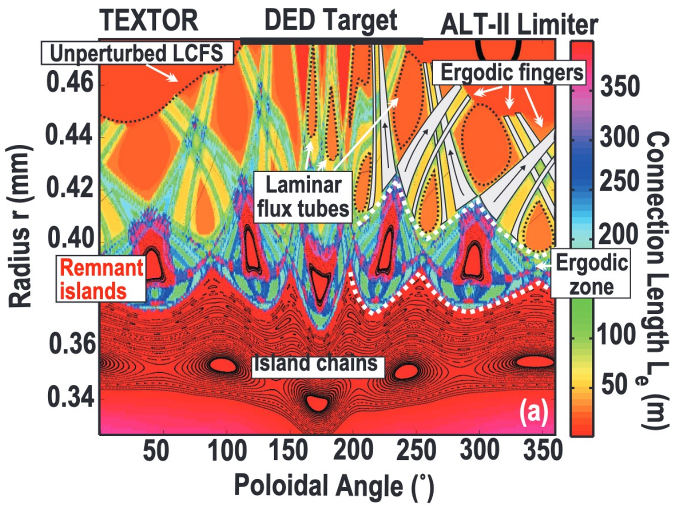
  - ➔Formation of heteroclinical tangle
- Turnstiles are flux tubes which deposit particles from the core to the divertor targets (strike line patterns)
- Similar connection length features observed in stellarators ➔ non-resonant divertor



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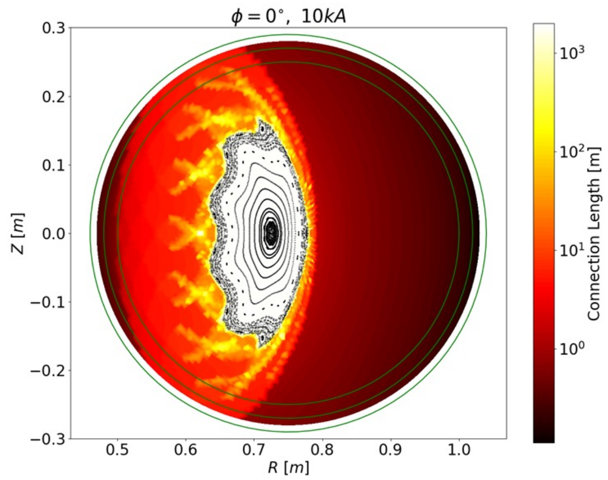


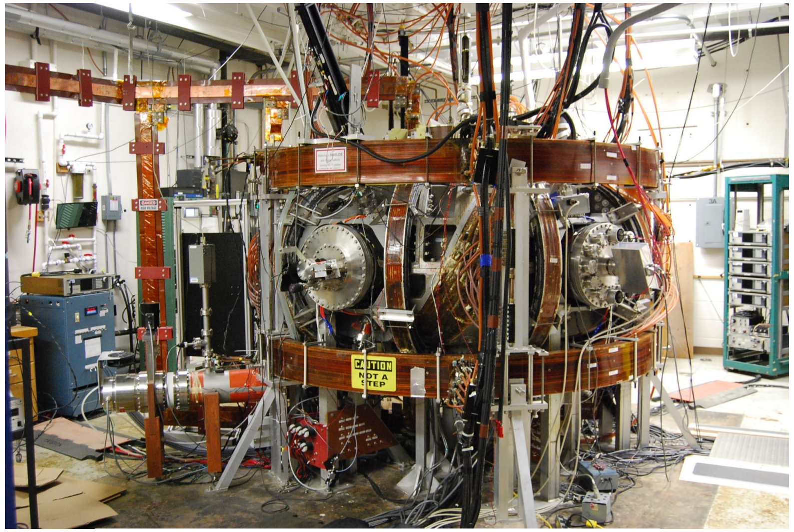
[K.A. Garcia *et al* 2023 *Nucl. Fusion* **63** 126043]

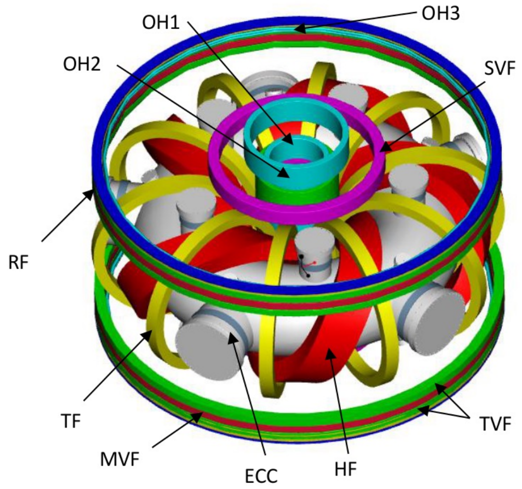
Plasma edge simulations

- Strike line plots to confirm resiliency
  - Performed with FLARE for CTH and HSX
- Connection length plots to study possible turnstiles
  - Performed with FLARE for CTH and HSX
- EMC3-EIRENE simulations to investigate heat patterns and neutral exhaust
  - Solves Braginskii-like equations in plasma edge
  - Field-aligned grid required (made using FLARE)
  - Performed for CTH, challenges for HSX

CTH – Compact Toroidal Hybrid

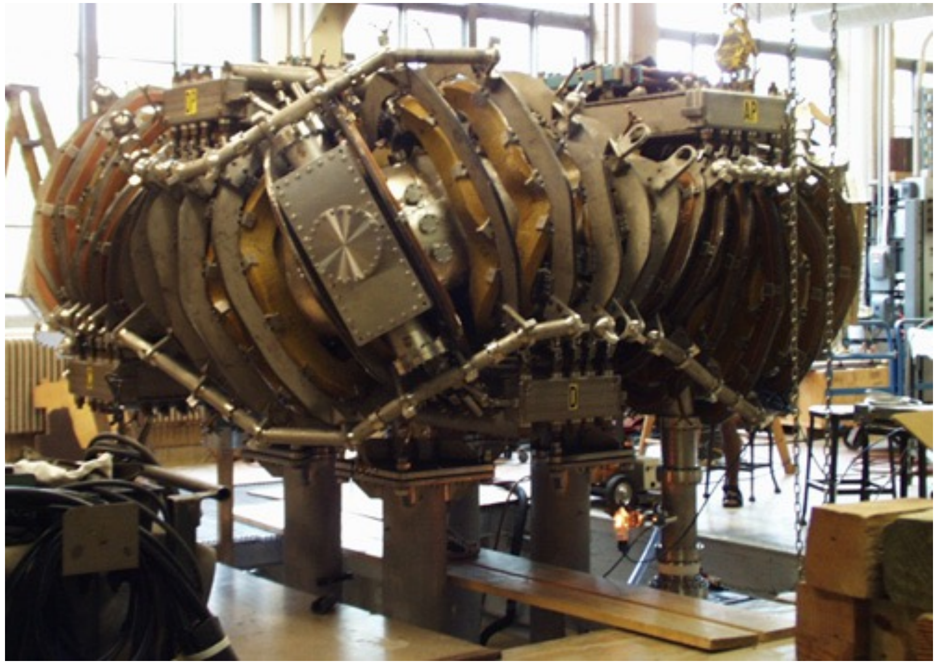
- Located at Auburn University
  - Major radius: 75 cm
  - Minor radius: 29 cm
  - 5-fold symmetry
- Toroidal vessel
  - ➔ Circular cross section



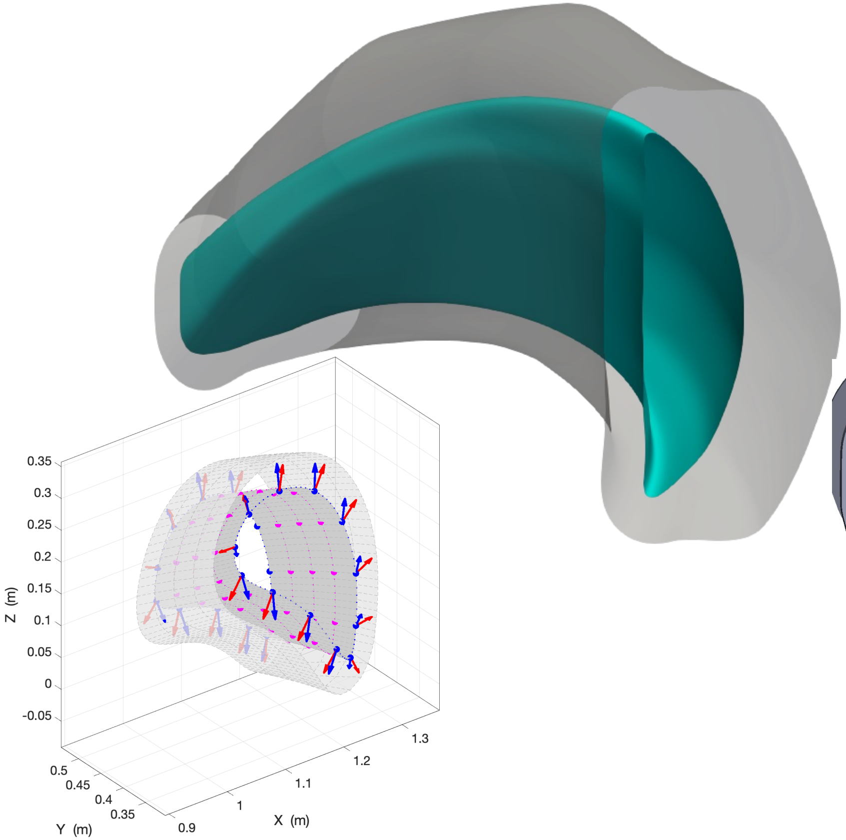


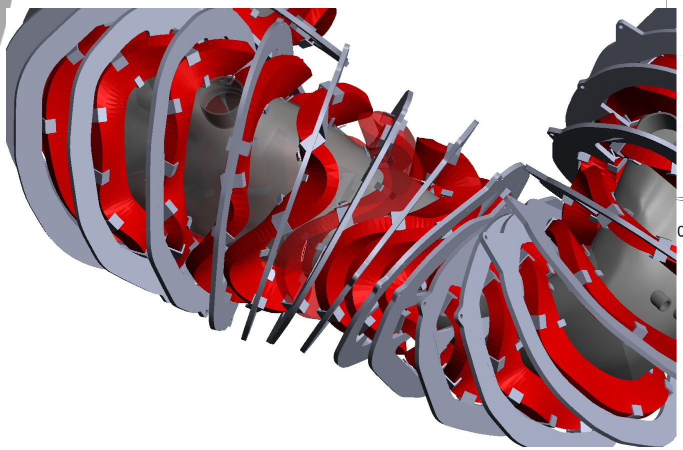
HSX – Helically Symmetric eXperiment

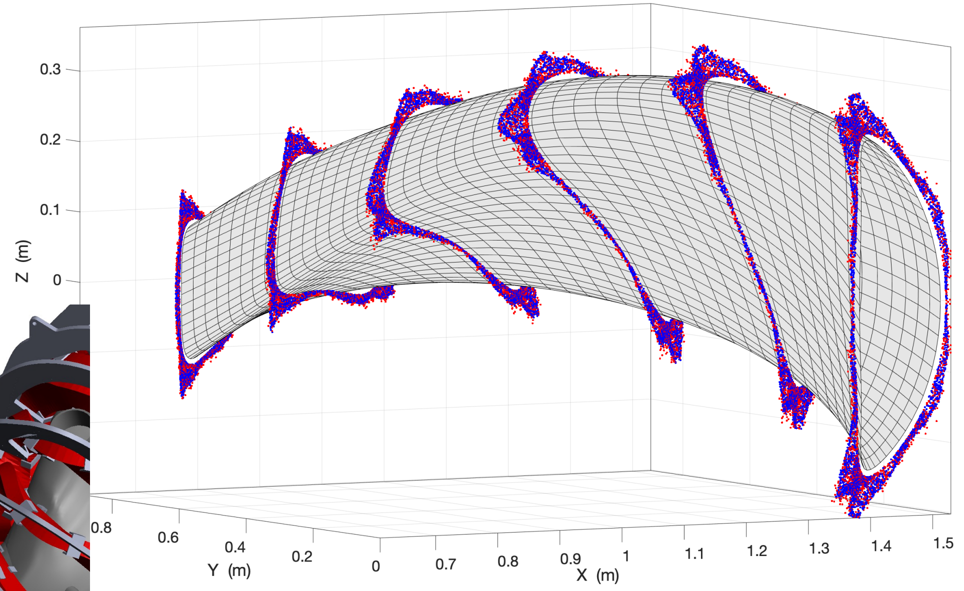
- HSX: quasi-helically symmetric stellarator
  - First stellarator optimized for neo-classical transport
  - Vessel which is ~ 3 cm from LCFS
  - Major radius: 1.2 m
  - Minor radius: 0.12 m
- Upgrade of HSX
  - High ion temperature studies
    - Installation of upgraded ECRH and NBI
    - Protection of first wall required
  - Develop divertor concept for HSX
    - Testbed for non-resonant divertor solutions
    - Flexibility in design: advanced 3D printing



HSX – Helically Symmetric eXperiment





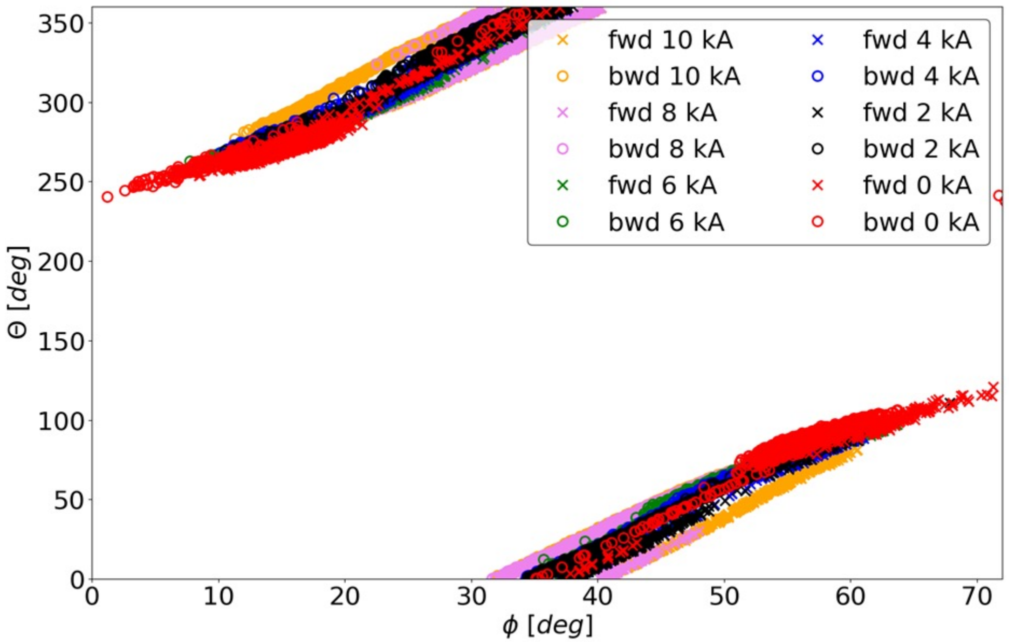


- Start from LCFS
- Move LCFS out as far as possible without interacting with coils
- Maximal possible vessel

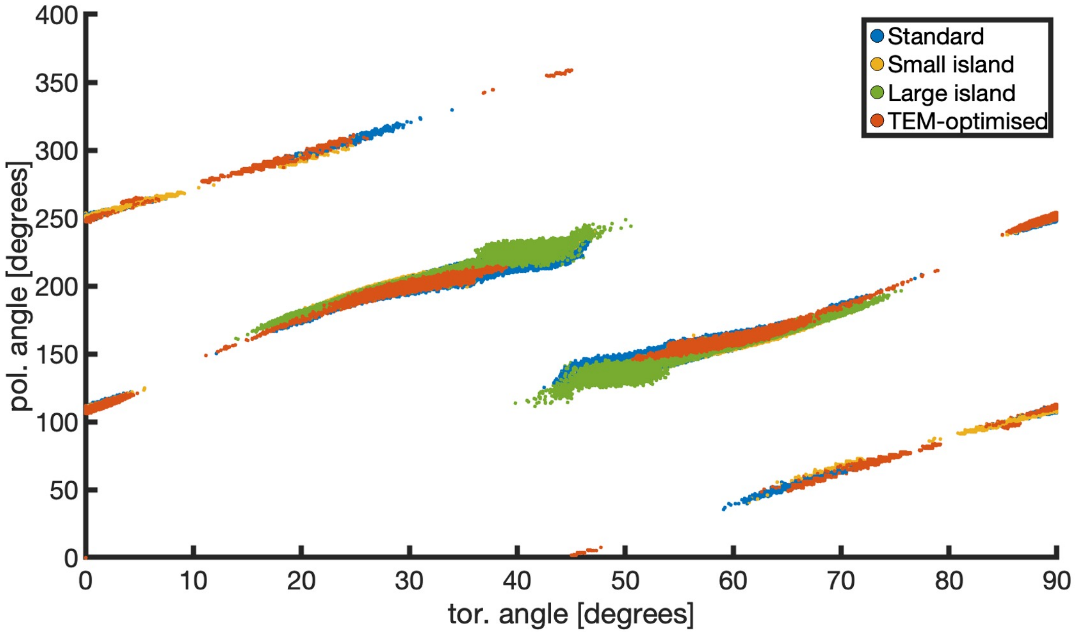
- Check which vessel region is covered by plasma (field line tracing)
- Determine which locations available in vessel

→ More information, J. Schmitt et al., in preparation

Strike line calculation

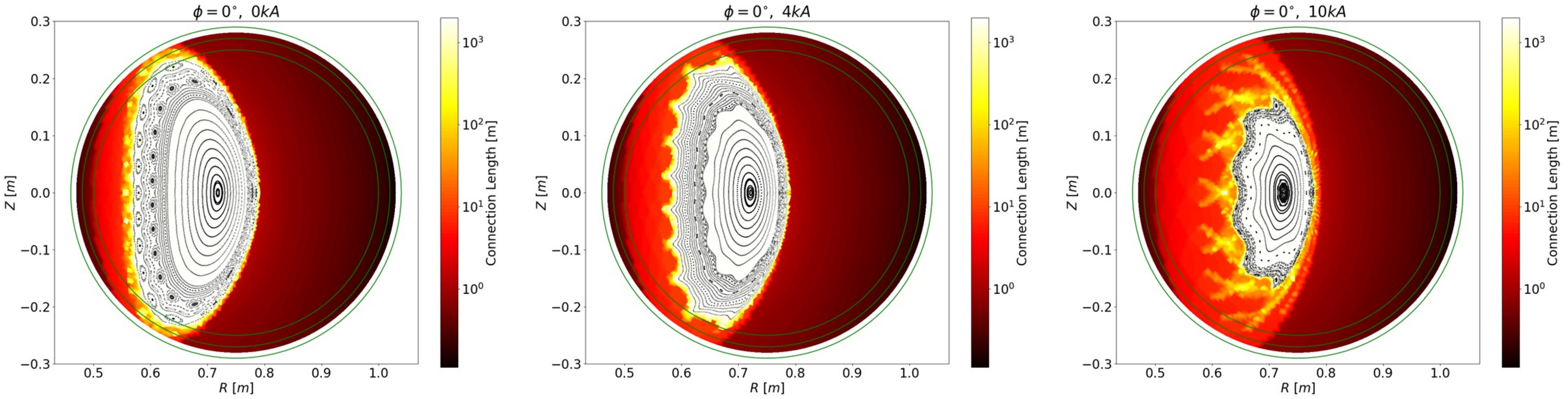


[K.A. Garcia *et al* 2023 *Nucl. Fusion* **63** 126043]



- Divertor resilient against changes in magnetic equilibrium

Connection length calculation - CTH



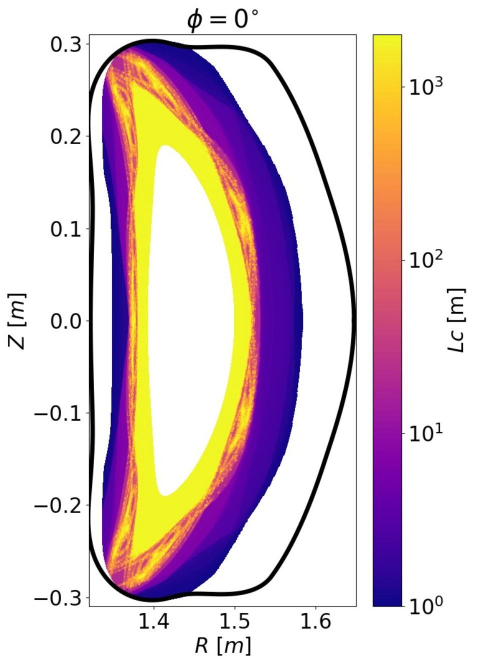
[K.A. Garcia *et al* 2023 *Nucl. Fusion* **63** 126043]

- Increasing the current shrinks the core and increases the edge
- Especially at large currents, turnstiles ('ergodic' fingers) clearly present

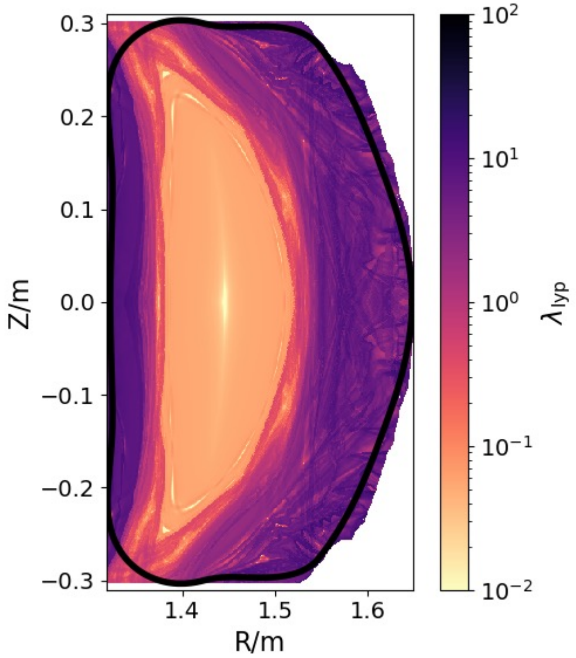
Connection length calculation - HSX

- So far, only QHS configuration investigated
  - NRD behavior not that clear as in 10 kA case CTH
- 2 methods to investigate chaotic behavior in edge:
  - Connection length
  - Lyapanov exponent → Kolmogorov length

  ➔ Combination of both helps to determine critical path for turnstiles
- Both techniques show different behavior neighboring flux channels
- Location where long connection lengths interact with vessel wall qualify for divertor

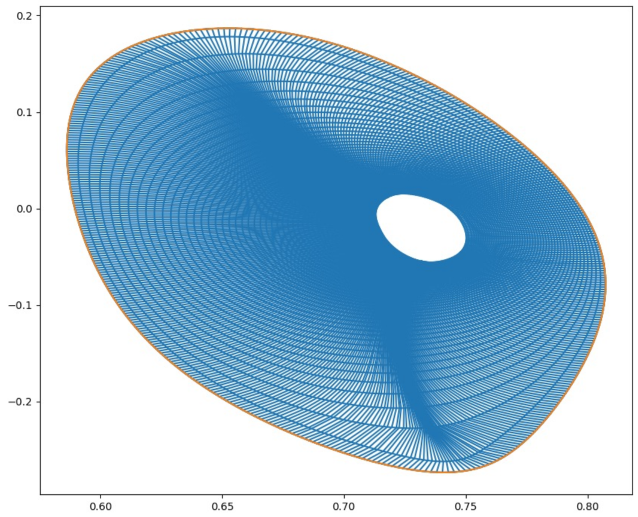


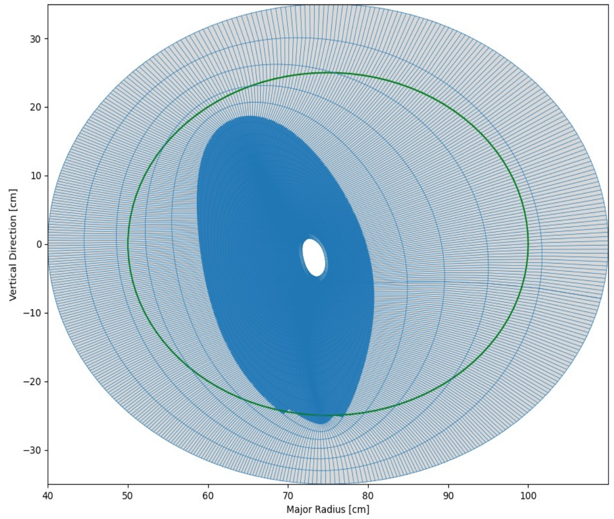
HSX
Helically Symmetric eXperiment



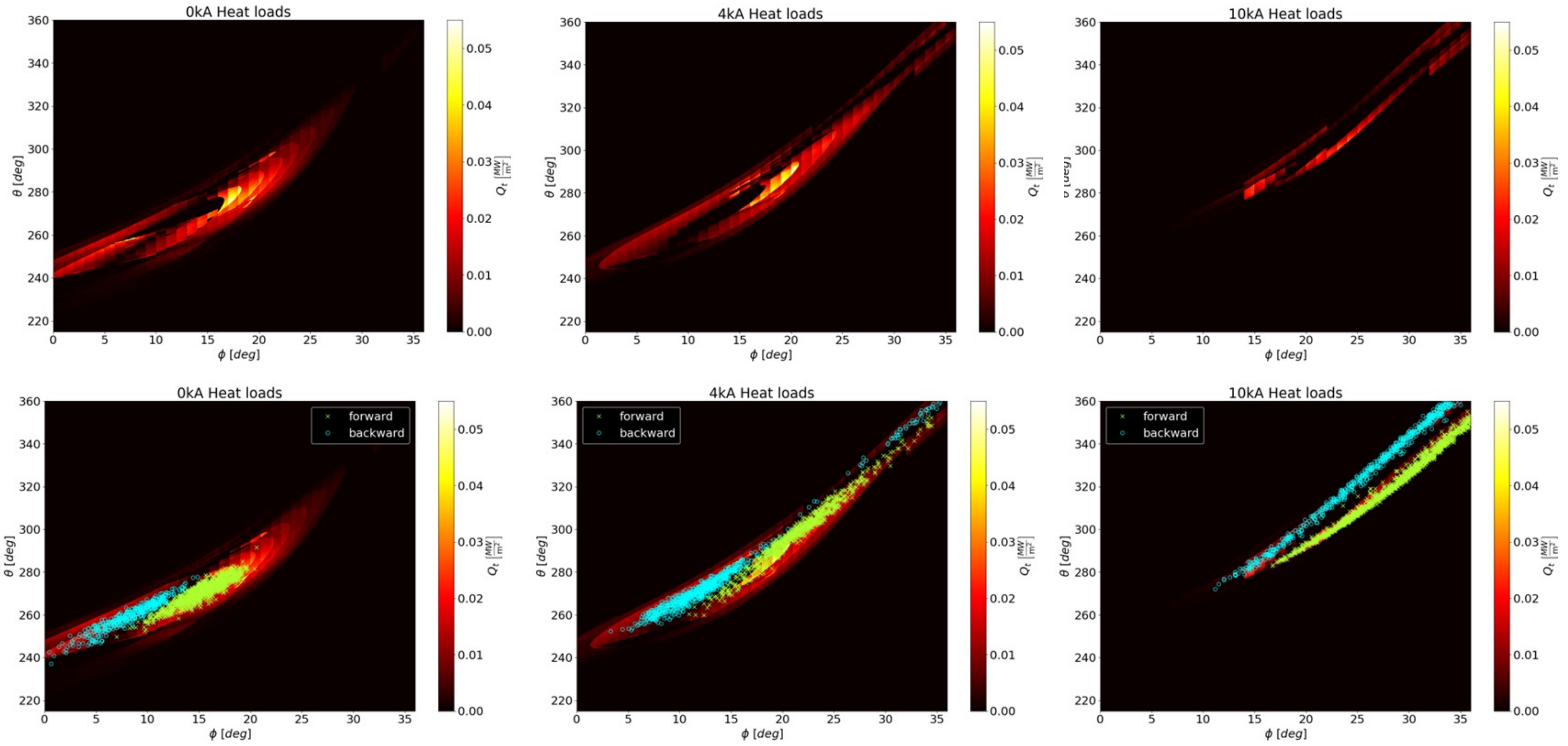
EMC3-EIRENE simulations – grids for CTH

- 5 fold symmetry and absence of drifts in EMC3
  - Grid should cover 36°
- EMC3-EIRENE requires flux conservation
  - Two toroidal sections required due to chaotic edge:
    - Base mesh at 9° (see figures) and 27°
  - FLARE follows fieldlines and generate 2 subgrids (0°-18° and 18°-36°)
- Neutral grid extends outside plasma grid
- Grids generated for 0kA, 4kA and 10kA cases in CTH



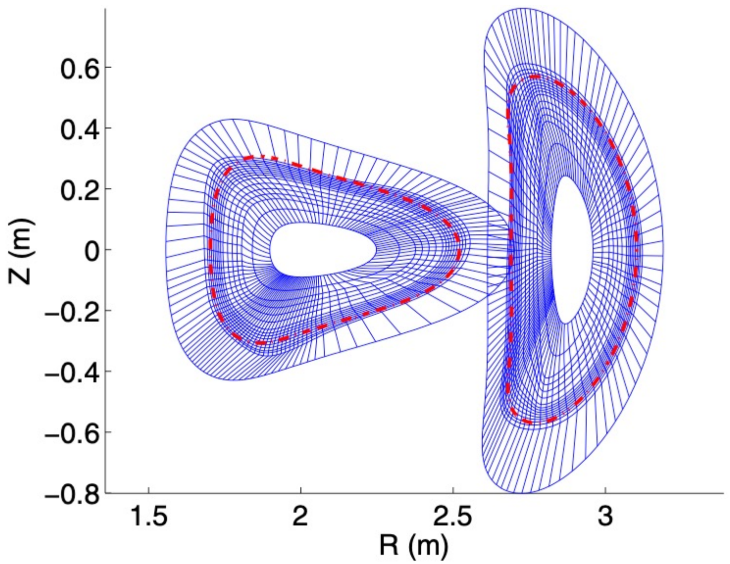


EMC3-EIRENE simulations – simulation results CTH

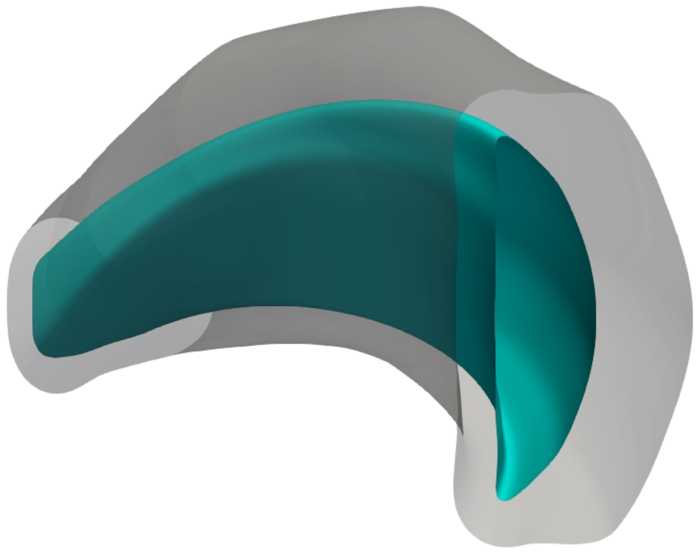


EMC3-EIRENE simulations – grids for HSX

- Experience HSX grids: Aaron Bader
  - Uniform extension of LCFS as plasma boundary (similar to current HSX wall)
  - Five toroidal sections needed
- New proposed vessel:
  - Maximized inside coils ➔ different shape
  - Five toroidal sections taken as starting point
  - How to define plasma boundary?



[A. Bader *et al* 2023 *Nucl. Fusion* **53** 113036]



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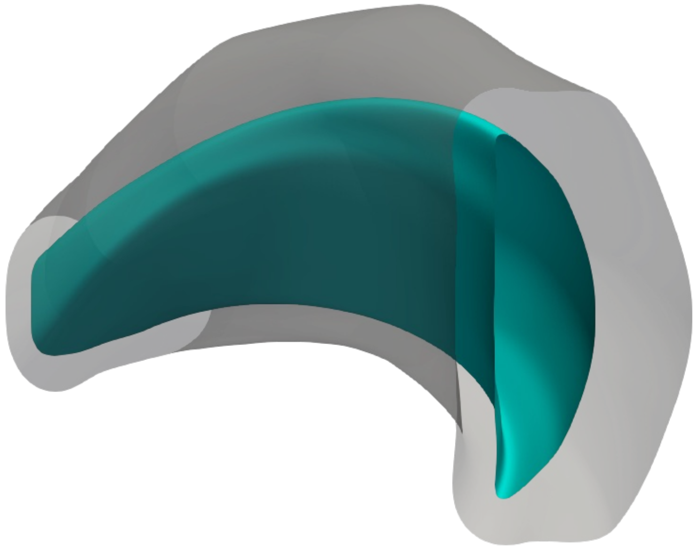
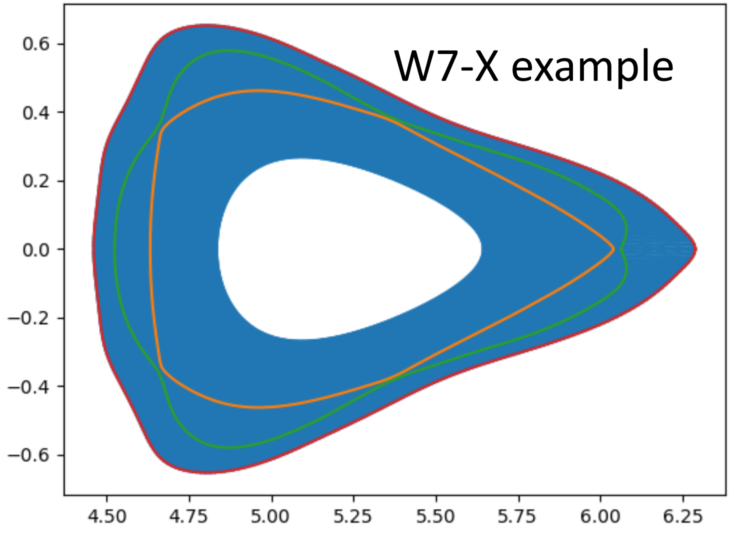
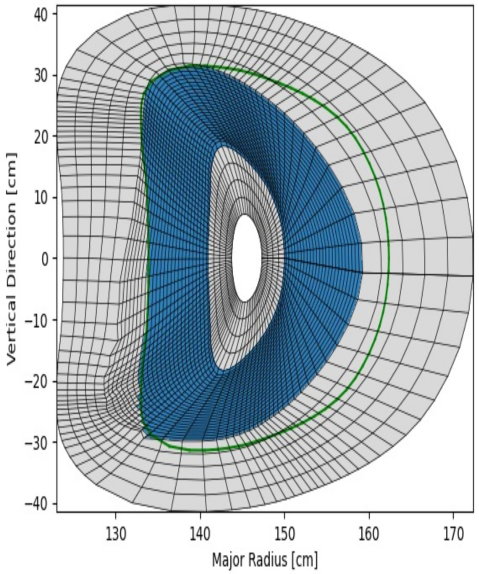
- New proposed vessel:
  - Maximized inside coils ➔ different shape
  - Five toroidal sections taken as starting point
  - How to define plasma boundary?
    - Internal guiding contours required?

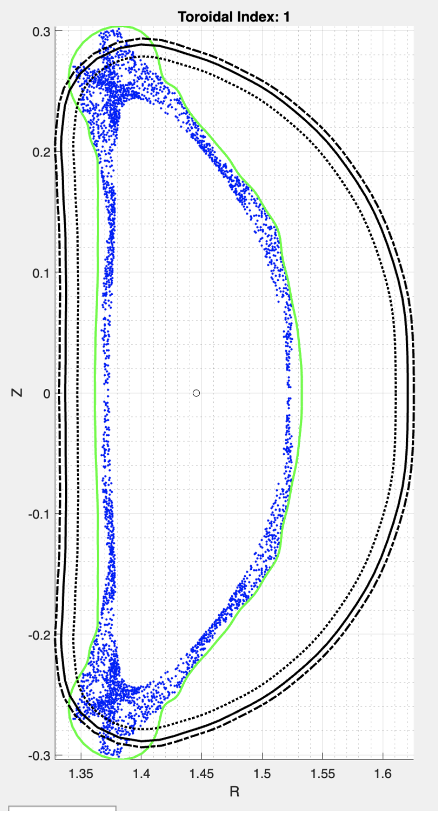


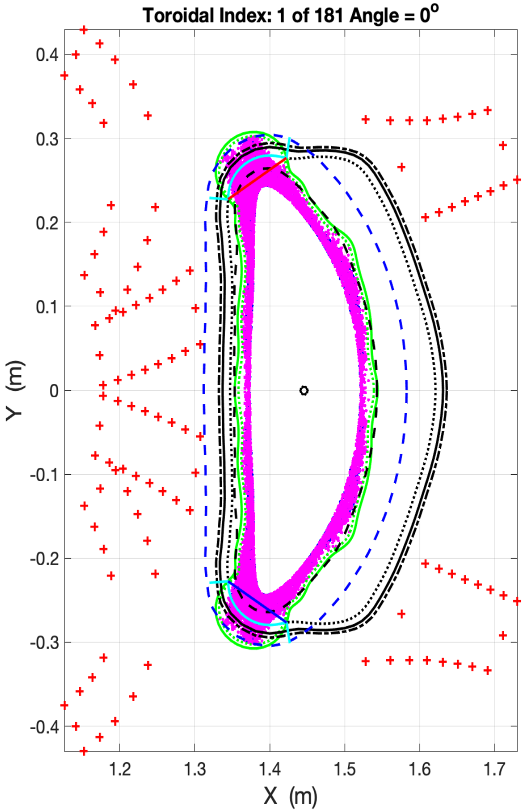


EMC3-EIRENE simulations – grids for HSX

- Examined methods for plasma boundary:
  - Fourier curve around field-line-traced particles [J. Schmitt *et al* in preparation]:
    - Particles traced with FLARE
    - Trajectories stored and plotted
    - Smooth curve for one diffusion coefficient (left)
      - Grid generation possible
    - Less smooth curve for different diffusion coefficients (right)
      - Grid generation not possible

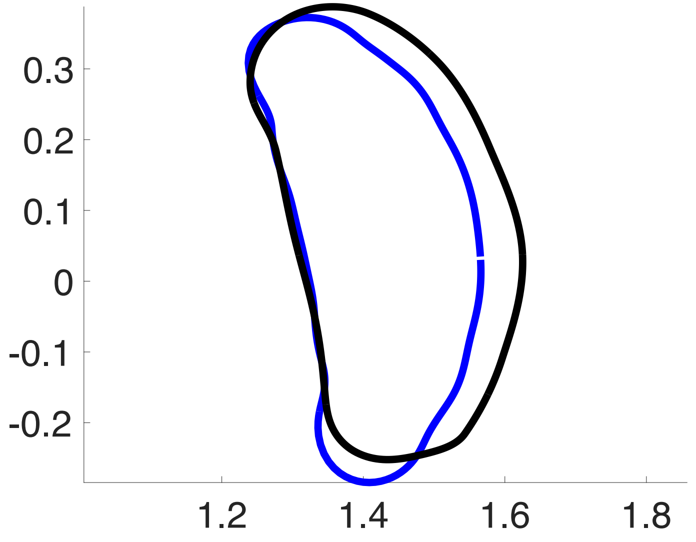


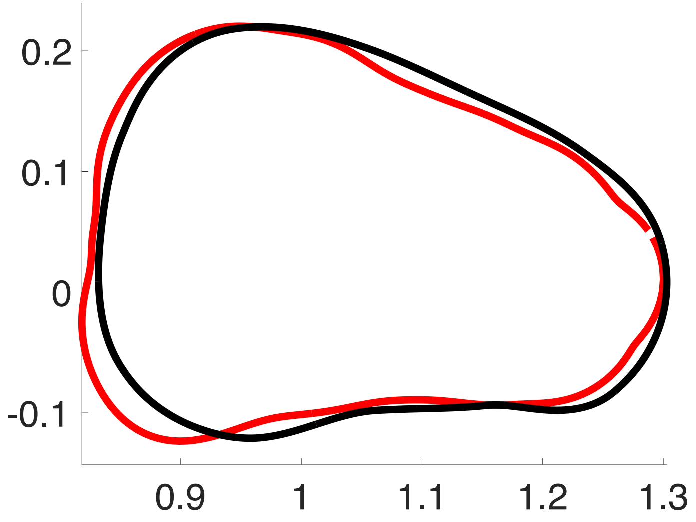




EMC3-EIRENE simulations – grids for HSX

- Examined methods for plasma boundary:
  - Fourier curve around field-line-traced particles
  - **α***Δ* expansion of LCFS [Aaron Bader]:
    - **α** defines how expansion relates to flux (larger expansion in regions with larger flux)
    - *Δ* defines how far outside LCFS surface is expanded
    - If similar parameters are used everywhere:
      - Too few expansion in certain toroidal sections
      - Too large expansion in other toroidal sections
      - ➔Currently investigated if it is possible to use different expansion parameters in different regions



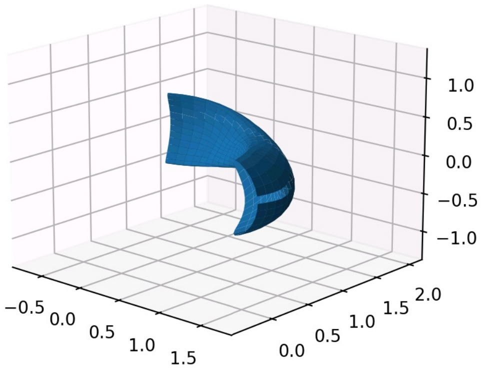


EMC3-EIRENE simulations – grids for HSX

- Examined methods for plasma boundary:
  - Fourier curve around field-line-traced particles
  - $\boldsymbol{\alpha}\Delta$ expansion of LCFS
- Possible other methos:
  - Combine larger "artificial" VMEC LCFS with $\boldsymbol{\alpha}\Delta$ expansion
  - Quadratic-flux minimizing surfaces SIMSOPT
    - Aims to minimize objective function f which is subject to constraint on surface S (such as volume, area, flux)

$$f = \frac{\int_s dx^2\, (\boldsymbol{B} \cdot \hat{\boldsymbol{n}})^2}{\int_s dx^2\, B^2}$$

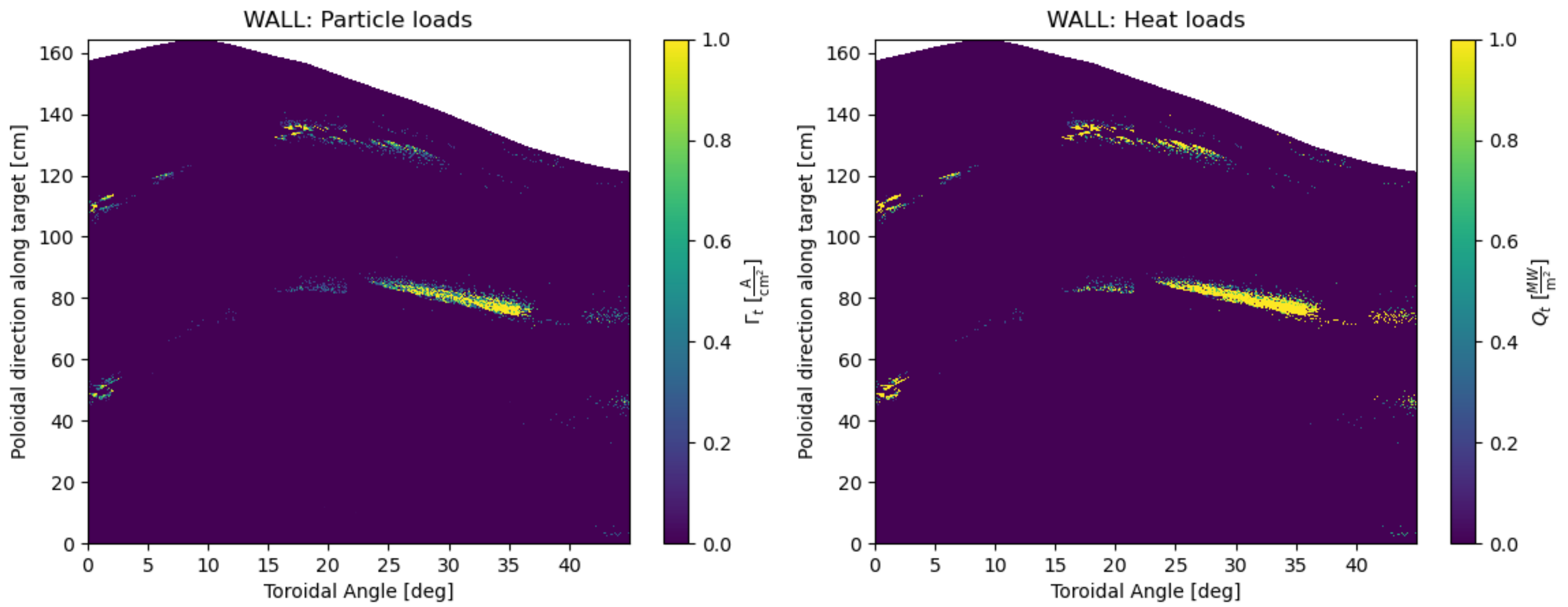
    - Example NCSX:
    - Can this help for HSX?



https://simsopt.readthedocs.io/en/latest

EMC3-EIRENE simulations – simulation results for HSX

- Preliminary simulations
  (with grid which does not cover entire plasma)
- Strike line patterns from field line tracing are covered



Summary

- Plasma edge of HSX and CTH investigated
- Strike lines show resiliency towards changes in magnetic field
- Connection length plots indicate turnstiles if edge is large enough
- EMC3-EIRENE simulations:
  - CTH: strong connection between heat load deposition and particle deposition demonstrated
  - HSX: challenge to construct good grids
  - Neutral behavior should be investigated!