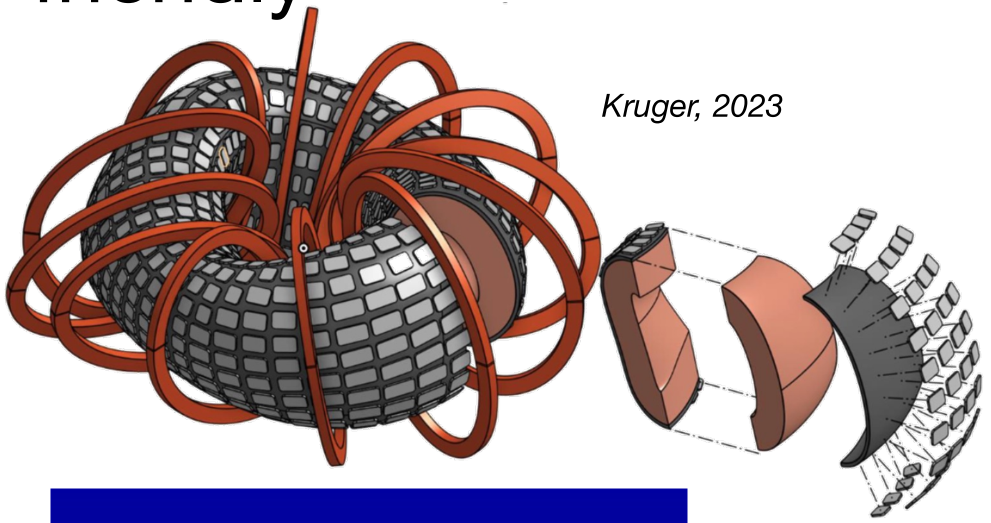
Enhancing Stellarator Accessibility through Port Size Optimization

Or "how to be friends with engineers"

A. Baillod, E. J. Paul

2024-03-20 Simons Team Meeting, Princeton

We need to make stellarator ”engineer friendly”

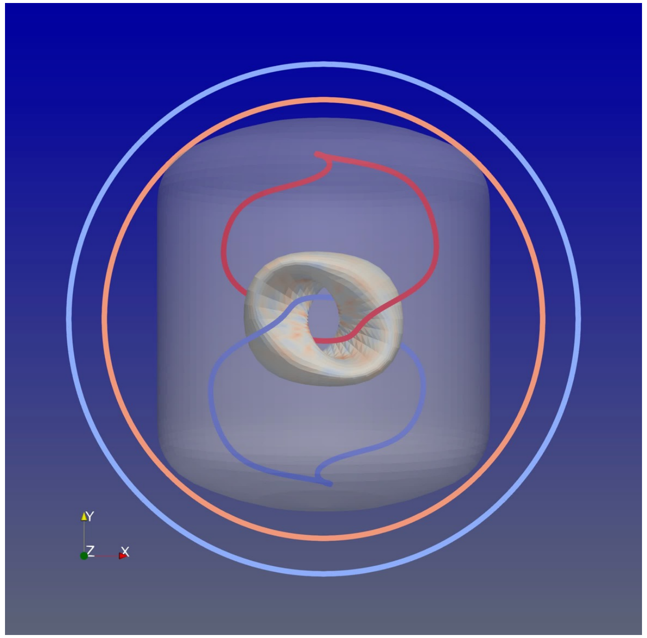


Kruger, 2023

- Stellarators need to be ”engineering-friendly”
  - Buildable (simple coils, robust, satisfy constraints, …)
  - Easy to operate
  - Simple to maintain

- New single-stage optimization techniques allow us to include more engineering constraints *S. Henneberg, 2021*
  - ”Boozer surface approach”, *A. Giuliani 2022, 2023*
  - Fixed-boundary VMEC approach, *R. Jorge 2023*
  - Free-boundary SPEC, *C. Smiet 2023*
  - Others ?

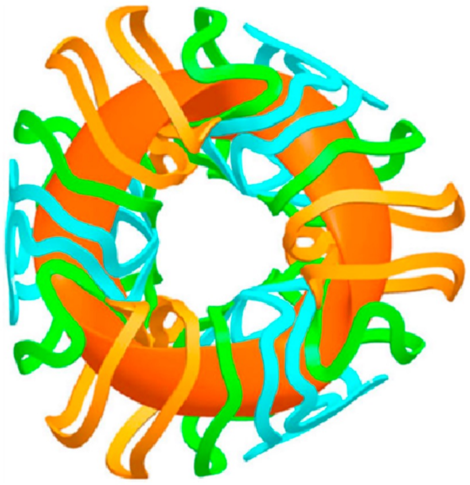
- One such constraint is the accessibility to the device



CSX @ Columbia University

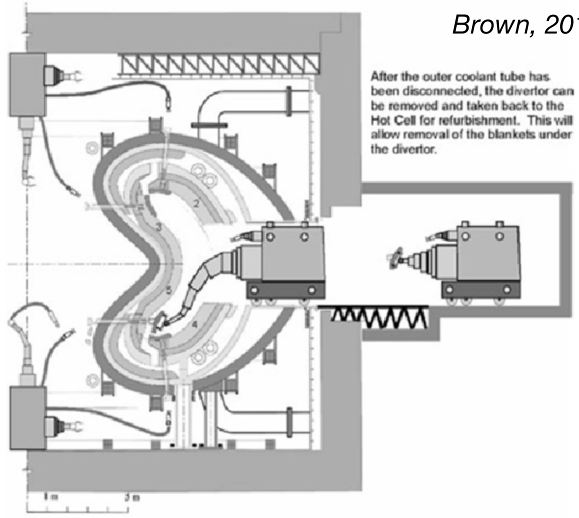
Good accessibility is vital for FPP rentability

- Plasma-facing components need to be periodically replaced
- **Remote handling is required** as strong neutron fluxes activate the machine
- Each element to be replaced is required to
  - Cut at least two pipes
  - Move the element out
  - Position the new element
  - Weld pipes back



ARIES-CS 4.5 AR, 7.75-m R_{axis}

Brown, 2015



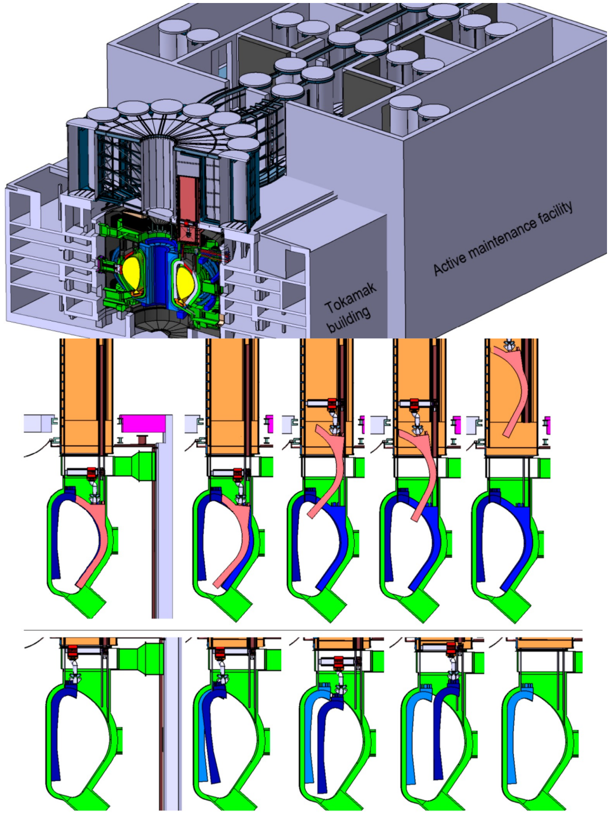
ARIES-CS port maintenance approach

Larger access port sizes → Larger in-vessel components → Smaller number of cuts and weldering → Shorter down-time → Better rentability of the FPP

There are different approaches to accessibility

Port-based access

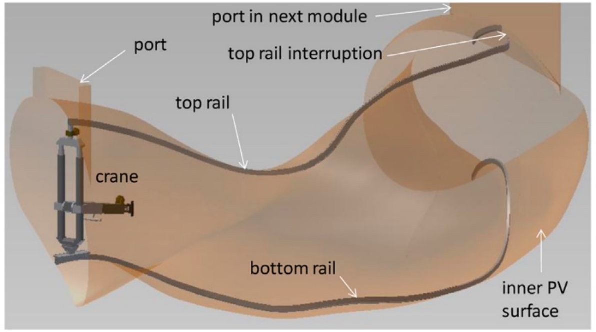
Vertical

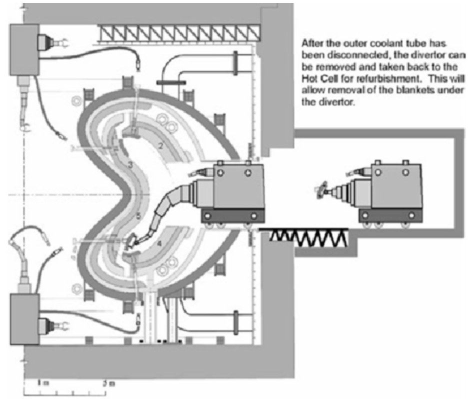


Bachmann, 2022

Horizontal

Schauer, 2013

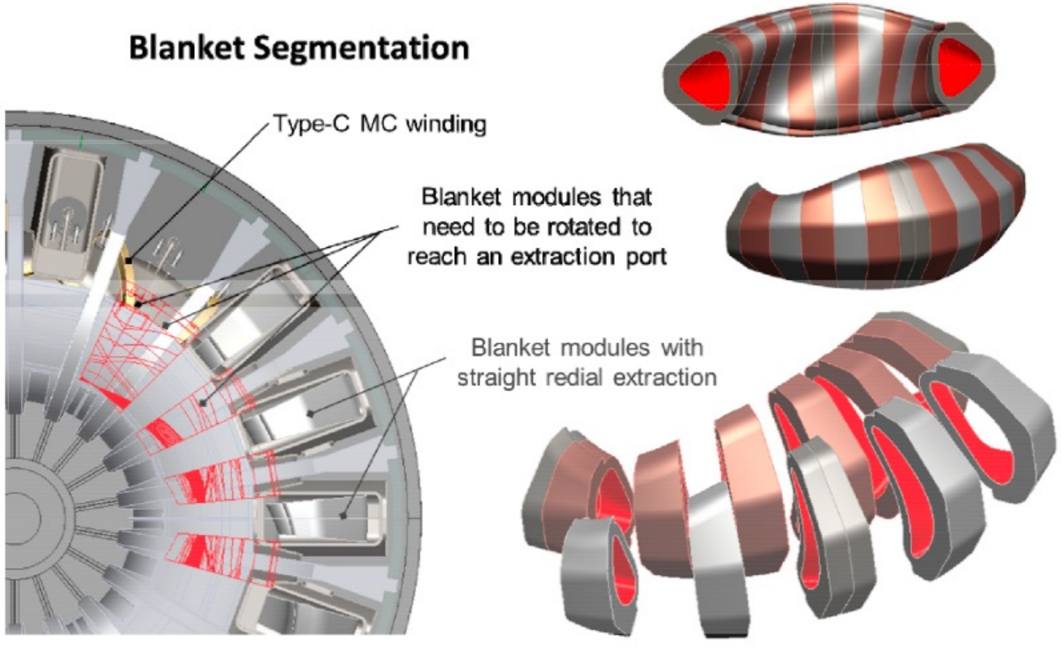




ARIES-CS port maintenance approach

Brown, 2015

Segment-based access



Brown, 2015

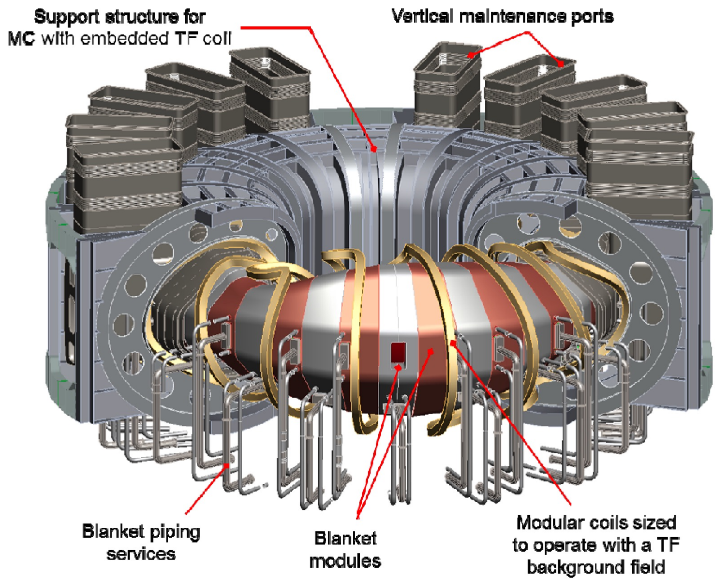
Previous work focused on straightening outer legs of coils

ENGINEERING OPTIMIZATION OF STELLARATOR COILS LEAD TO IMPROVEMENTS IN DEVICE MAINTENANCE

T. Brown[1], J. Breslau, D. Gates, N. Pomphrey, A. Zolfaghari
Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, U.S.A

Recent advances in stellarator optimization

To cite this article: D.A. Gates *et al* 2017 *Nucl. Fusion* **57** 126064

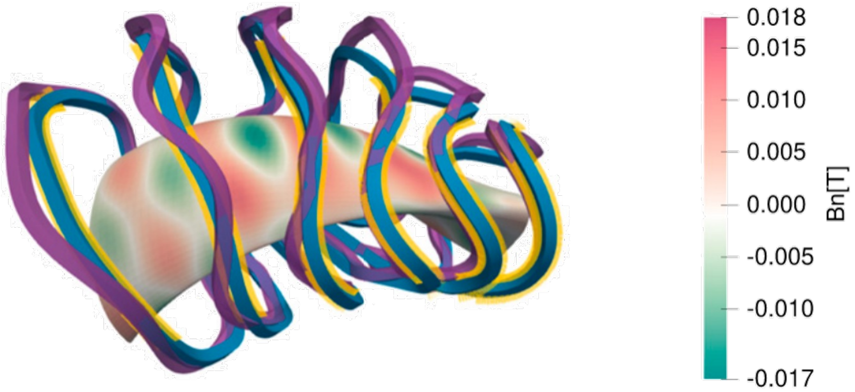


IAEA nuclear fusion

PAPER

Stellarator coil design using cubic splines for improved access on the outboard side

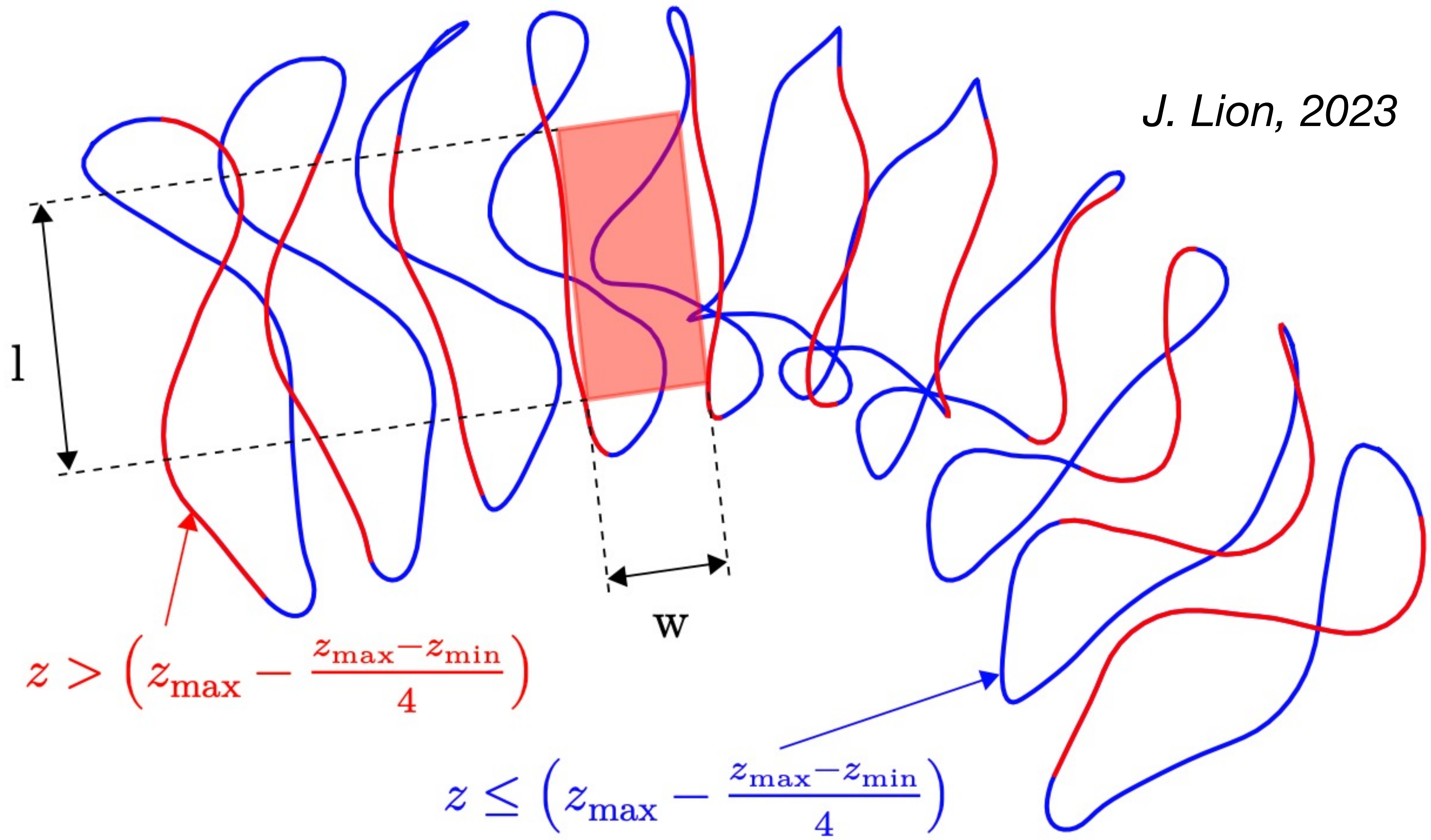
To cite this article: Nicola Lonigro and Caoxiang Zhu 2022 *Nucl. Fusion* **62** 066009



Port access was studied using system codes

Vertical access port implemented in PROCESS

J. Lion, 2023

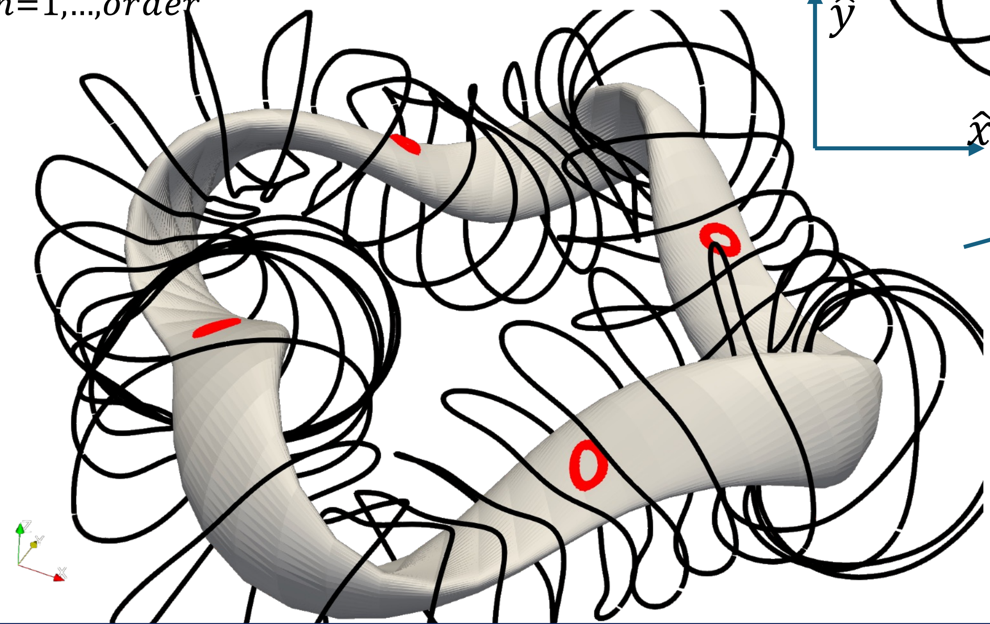


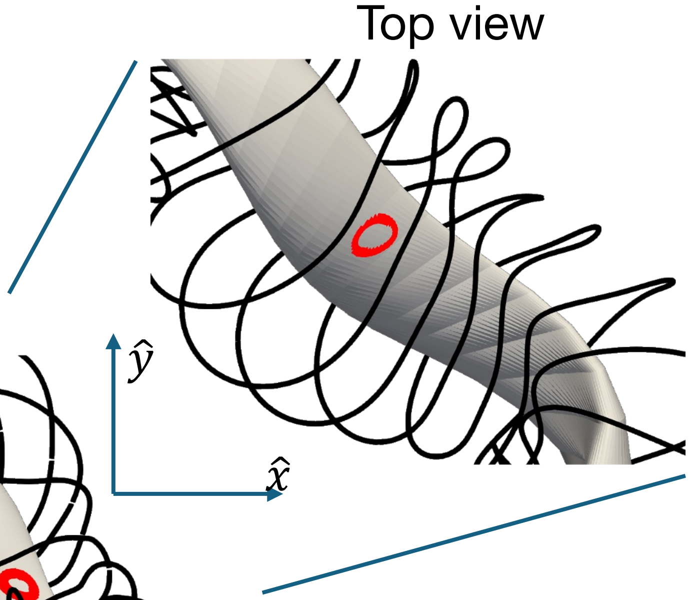
The access port is represented as a curve on the plasma boundary

Surface: $\Gamma(\theta, \phi) \to \mathbb{R}^3$. We target the precise QH surface by Landreman and Paul (2022)

Curve on $\boldsymbol{\Gamma}$ is $C(l) = \Gamma(\theta(l), \phi(l))$, where $\theta(l)$ and $\phi(l)$ are described as Fourier series

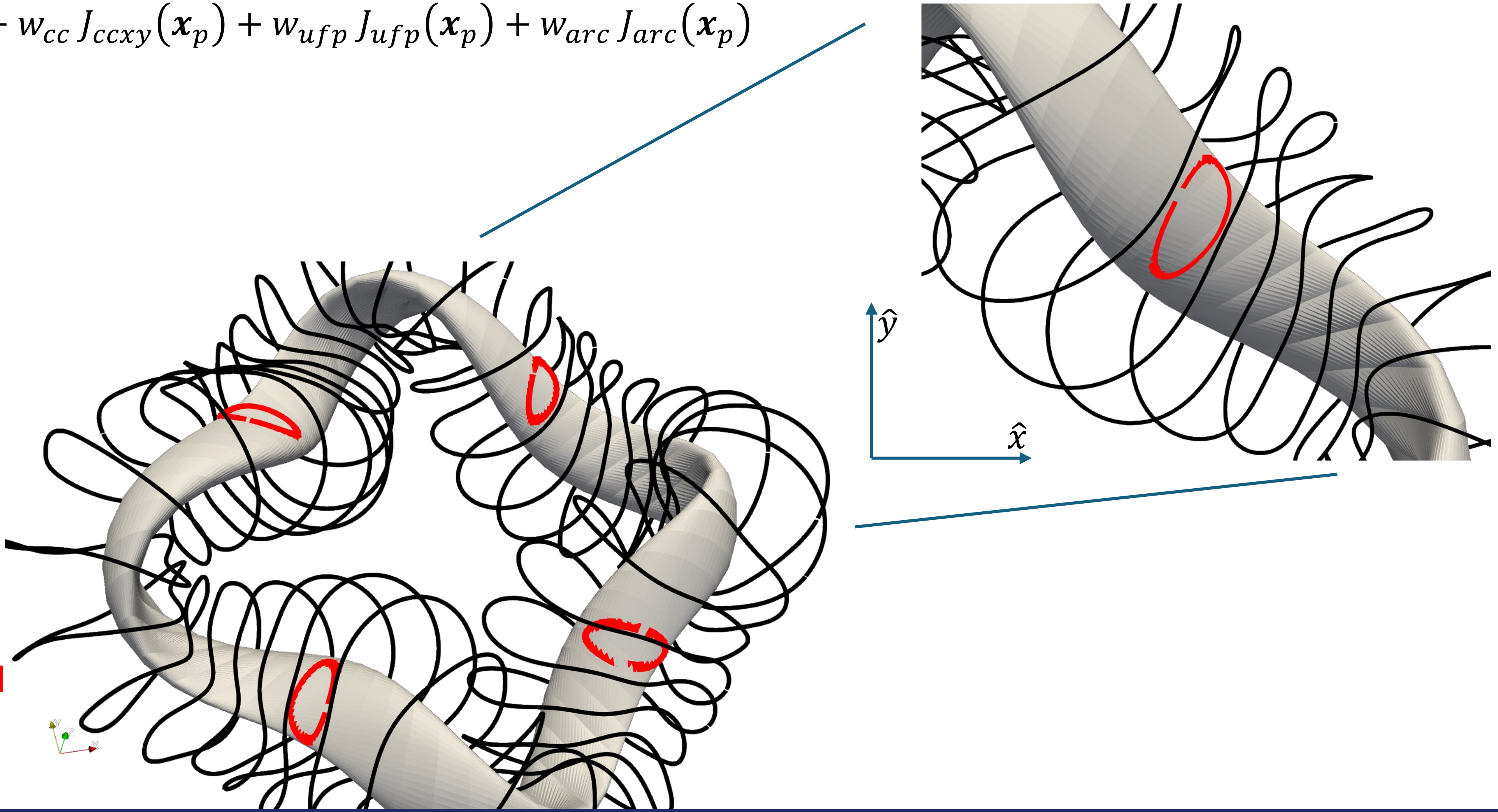
Dofs $\boldsymbol{x}_p$ are $\{\theta_{cn}, \phi_{cn}\}_{n=0,\dots,order}$ and $\{\theta_{sn}, \phi_{sn}\}_{n=1,\dots,order}$





Access port can be optimized to maximize its enclosed area

$$f_{port}(\boldsymbol{x}_p) = -A_{xy}(\boldsymbol{x}_p) + w_{cc}\,J_{ccxy}(\boldsymbol{x}_p) + w_{ufp}\,J_{ufp}(\boldsymbol{x}_p) + w_{arc}\,J_{arc}(\boldsymbol{x}_p)$$

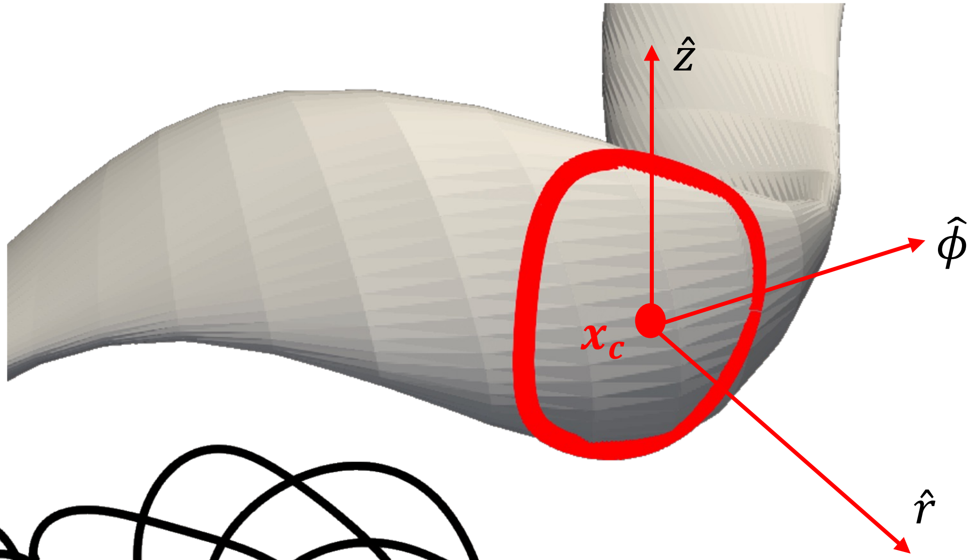


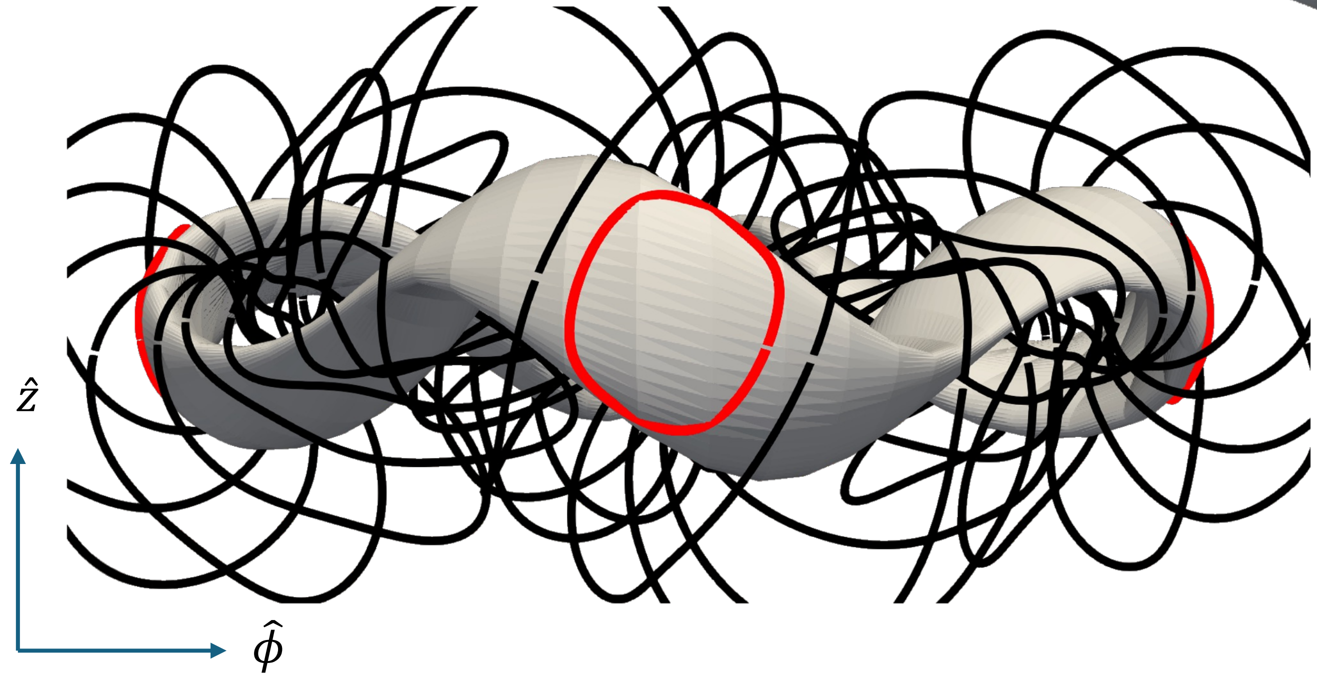
Vertical Access
Plasma boundary: fixed
Coils: fixed
Port: free

Port optimization can be extended to any access direction

1. Given port boundary $C(l)$ on Γ, evaluate centroid x_c
2. Evaluate the cylindrical radial basis $\hat{r}$ vector at x_c
3. Evaluate area and penalty function in the plane $\perp$ to $\hat{r}$.

$$f(\boldsymbol{x}_p) = -A_{z\phi}(\boldsymbol{x}_p) + w_{cc}\, J_{ccz\phi}(\boldsymbol{x}_p) + w_{ufp}\, J_{rfp}(\boldsymbol{x}_p) + w_{arc}\, J_{arc}(\boldsymbol{x}_p)$$



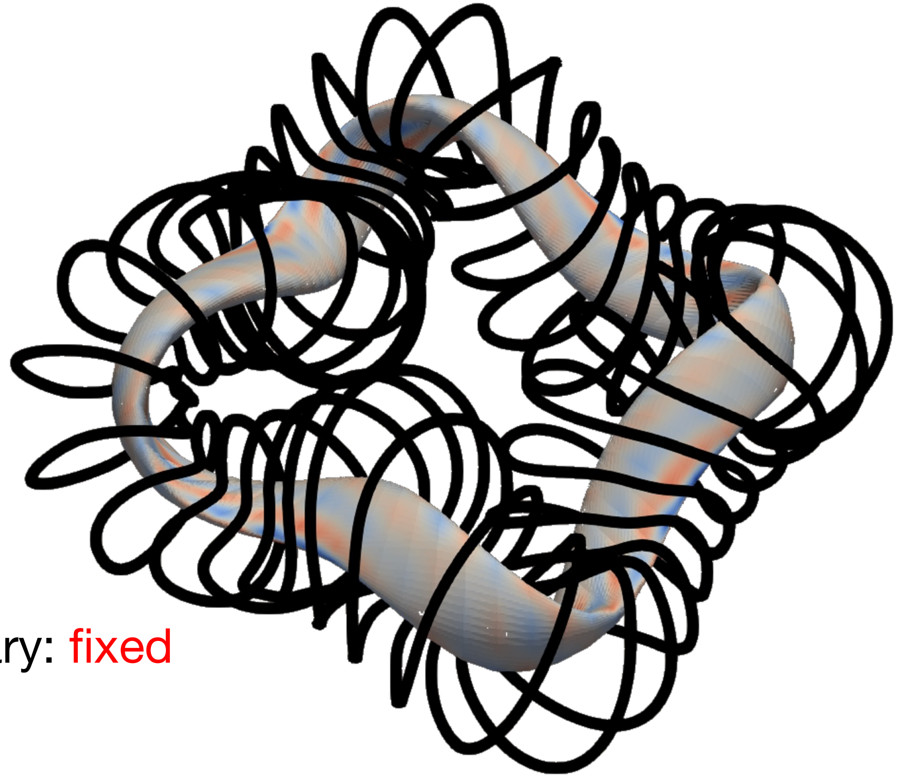


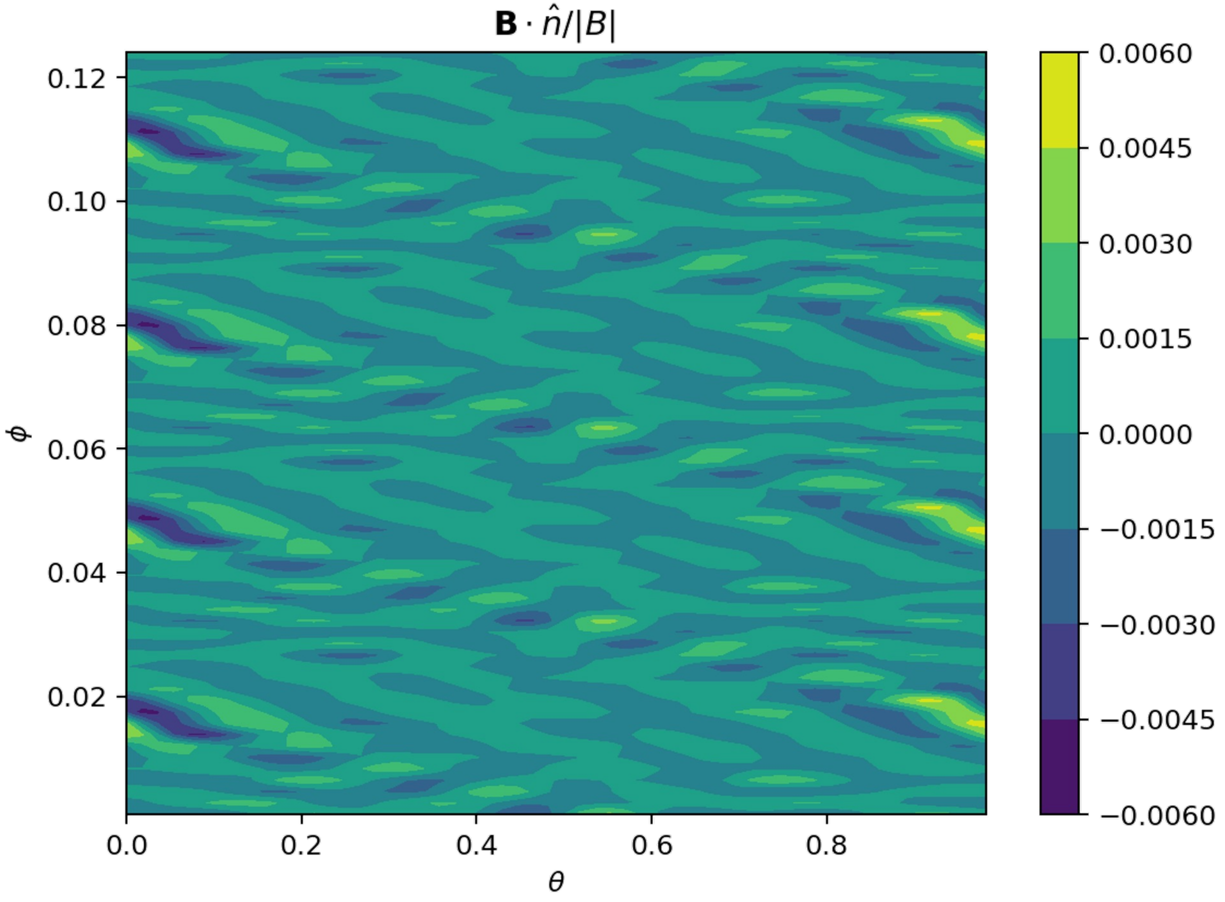
Radial Access
Plasma boundary: fixed
Coils: fixed
Port: free

Port size can be optimized for in a stage II optimization

$$f(\boldsymbol{x}_c, \boldsymbol{x}_p) = f_{II}(\boldsymbol{x}_c) + w_{port}\, f_{port}(\boldsymbol{x}_p)$$

Stage II weights are those published by Wiedman *et.al.* (2023)





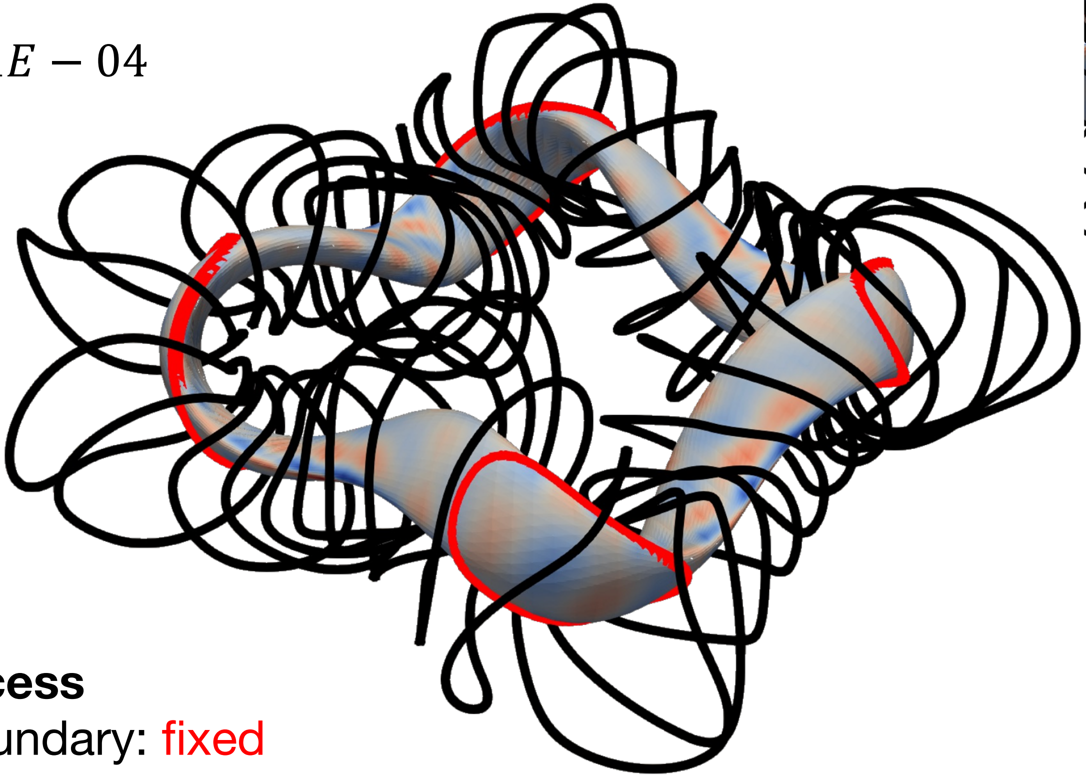
$w_{port} = 0$

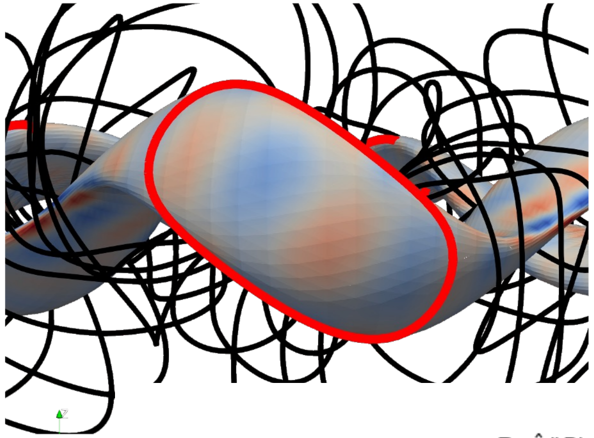
Plasma boundary: fixed
Coils: free
Port: No port

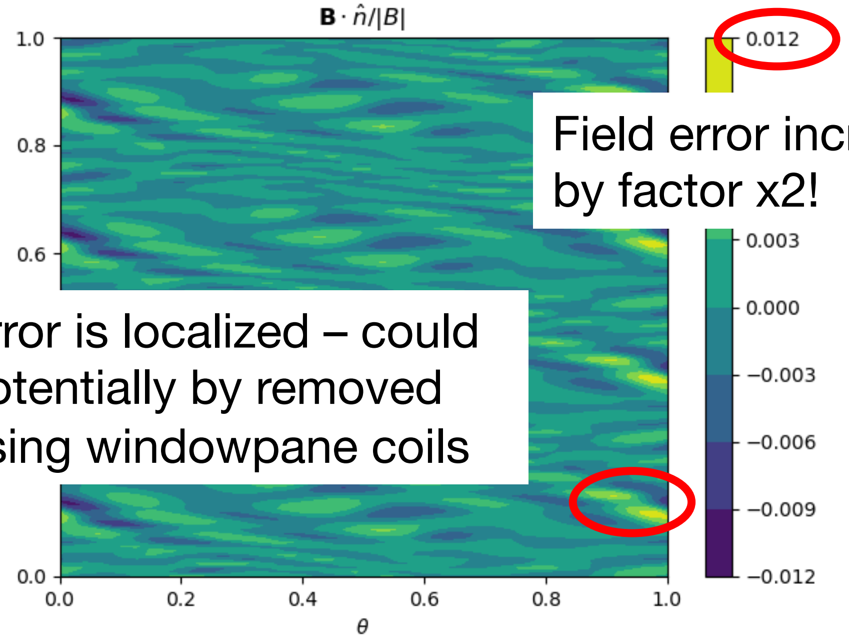
Port size can be optimized for in a stage II optimization

$$f(\boldsymbol{x}_c, \boldsymbol{x}_p) = f_{II}(\boldsymbol{x}_c) + w_{port}\, f_{port}(\boldsymbol{x}_p, \boldsymbol{x}_c)$$

$$w_{port} = 1E - 04$$







Field error increased by factor x2!

Error is localized – could potentially by removed using windowpane coils

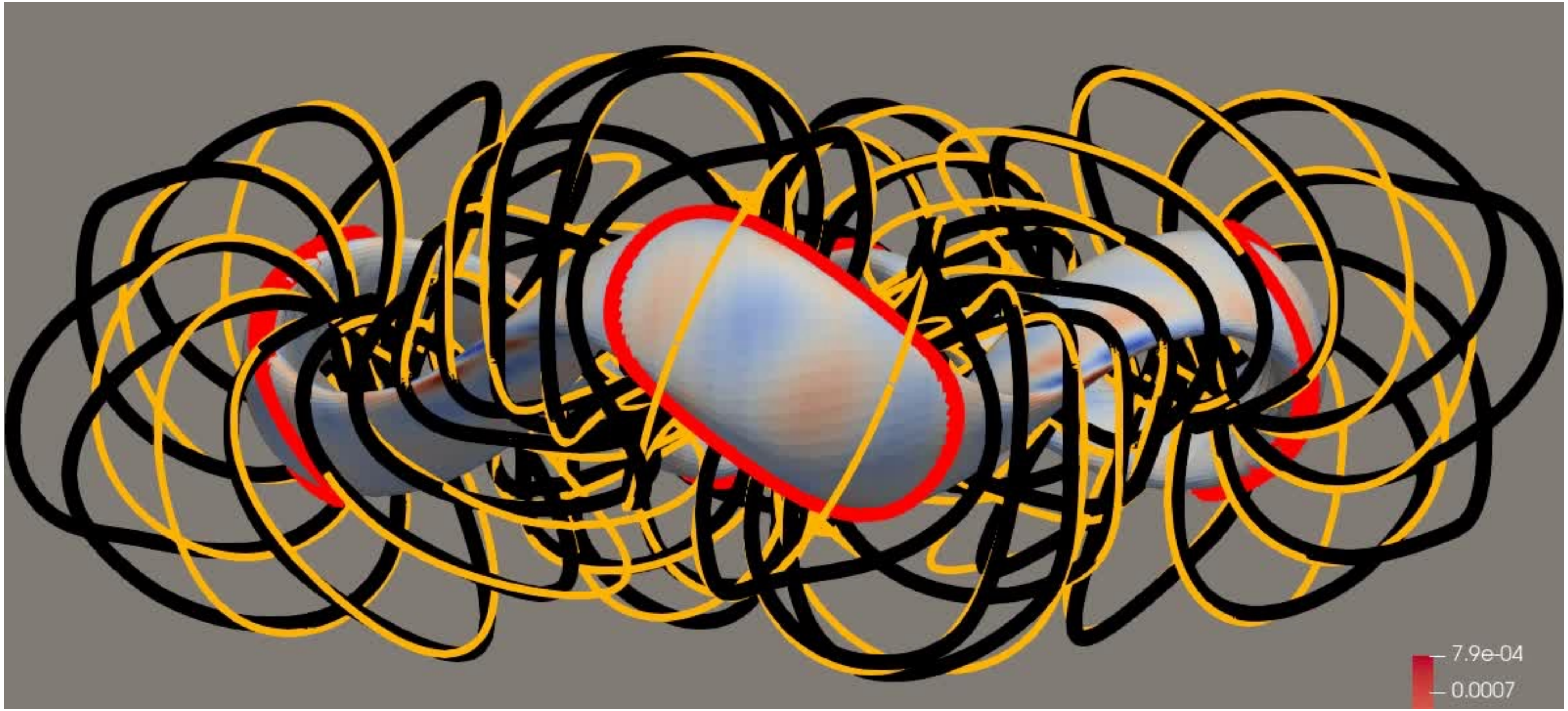
Radial Access

Plasma boundary: fixed

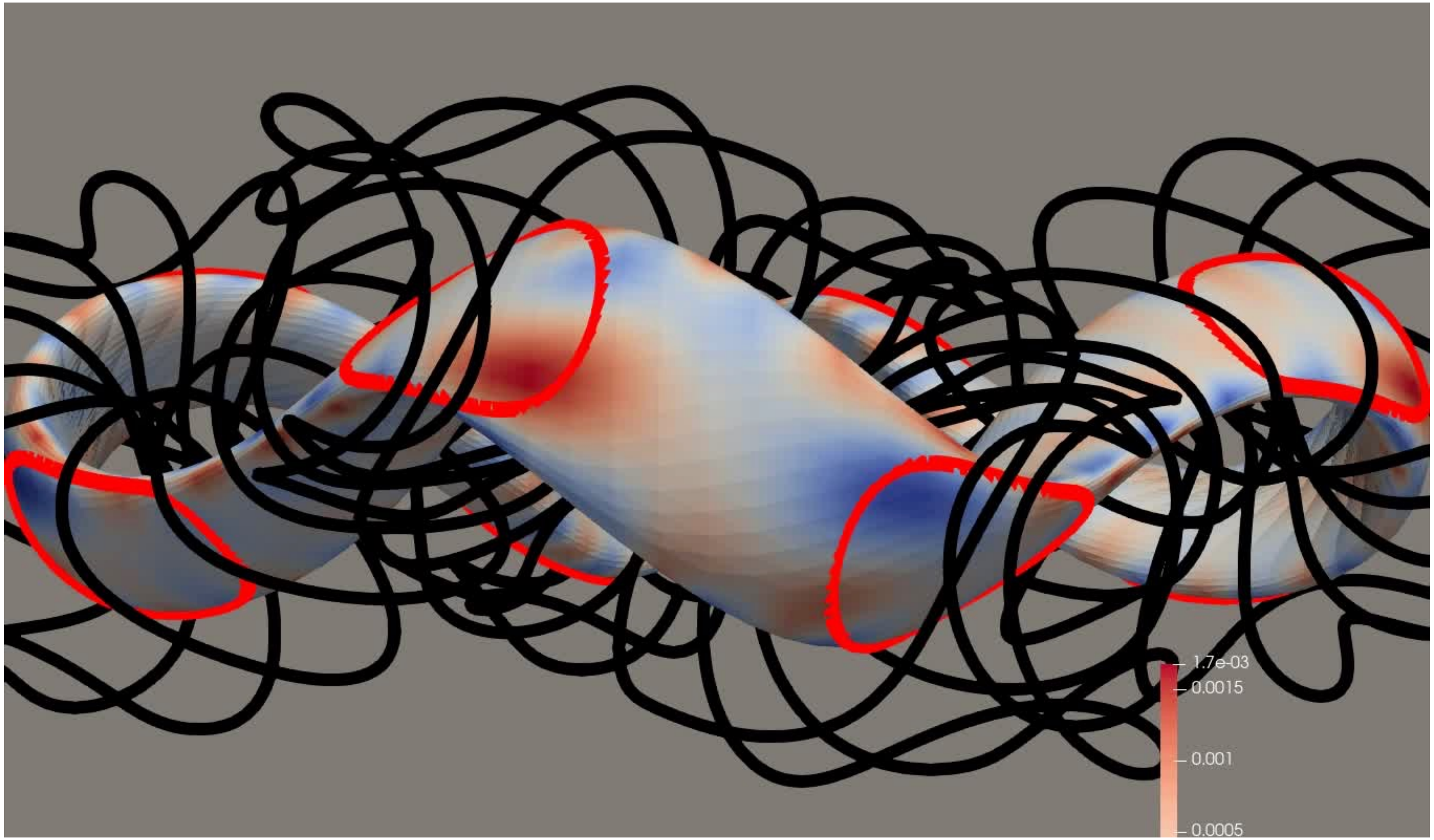
Coils: free

Port: free

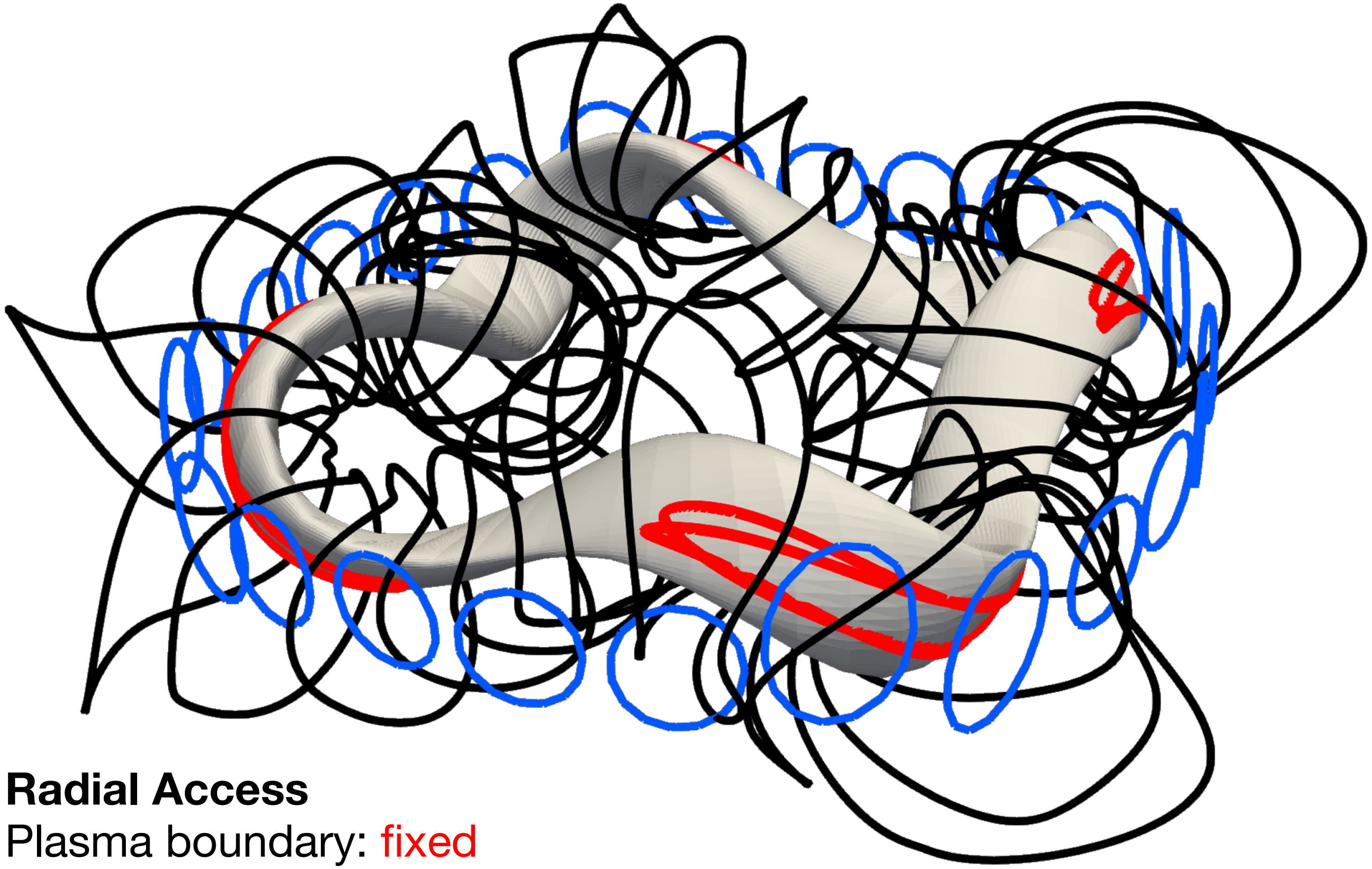
Orange curves: not including the port optimization metric
Black curves: including the port optimization metric



Port size strongly depend on initialization



Error can be reduced using windowpane coils

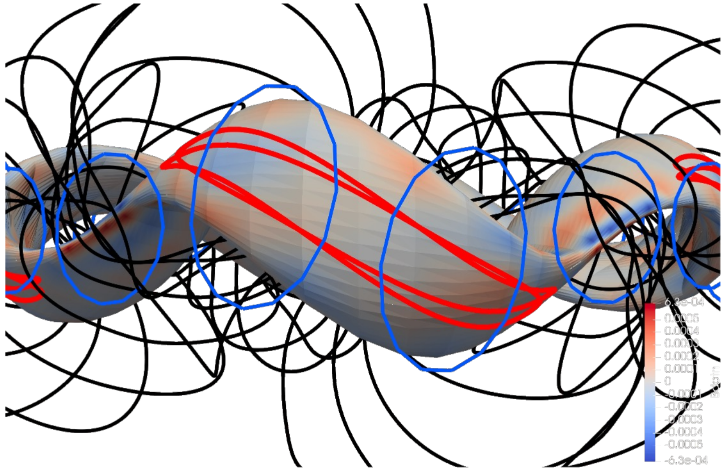


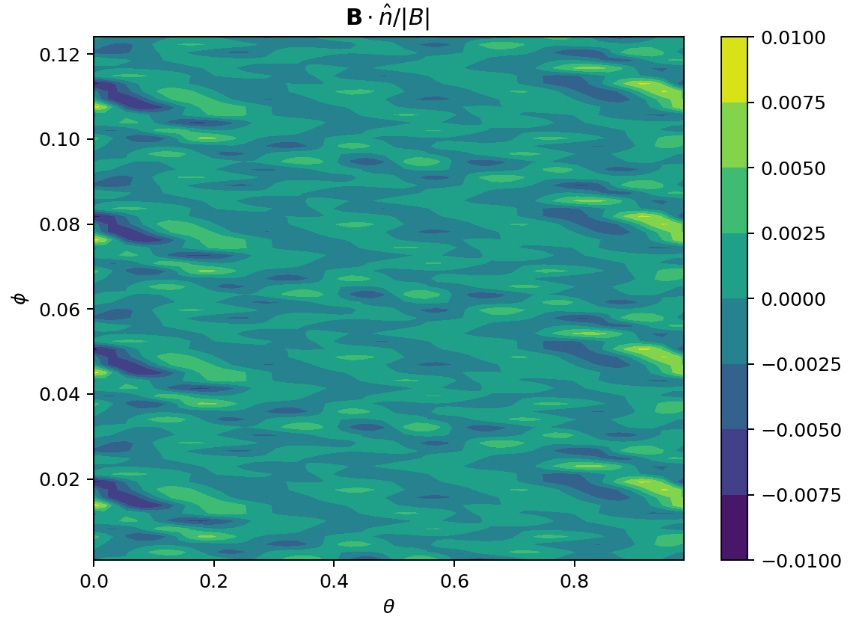
Radial Access

Plasma boundary: fixed

Coils + WPs: free

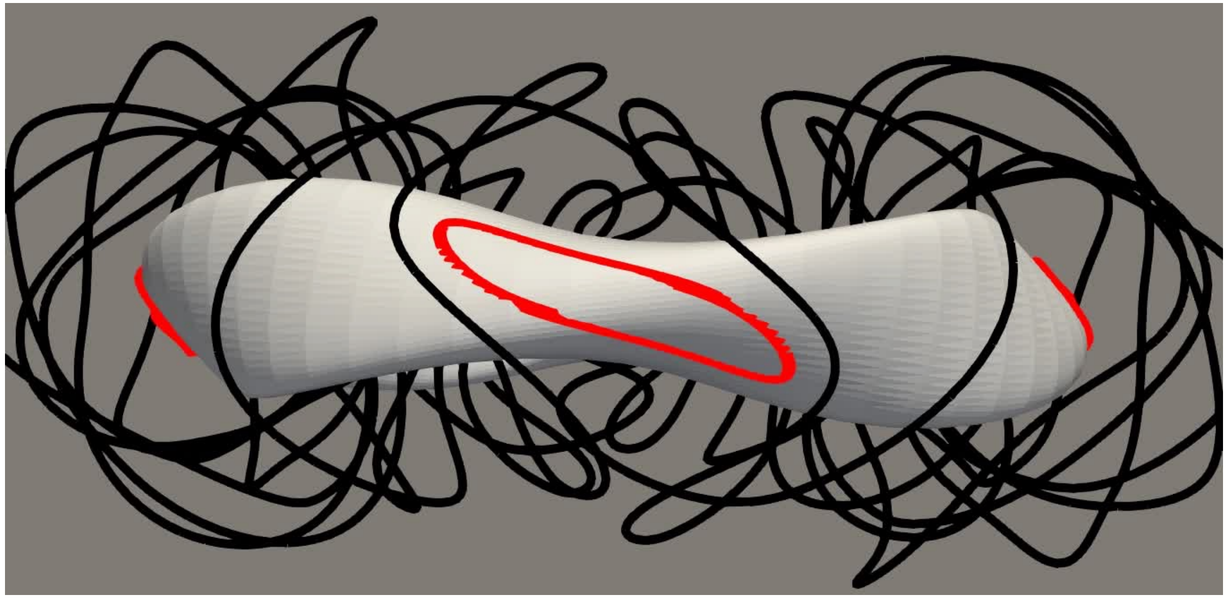
Port: free

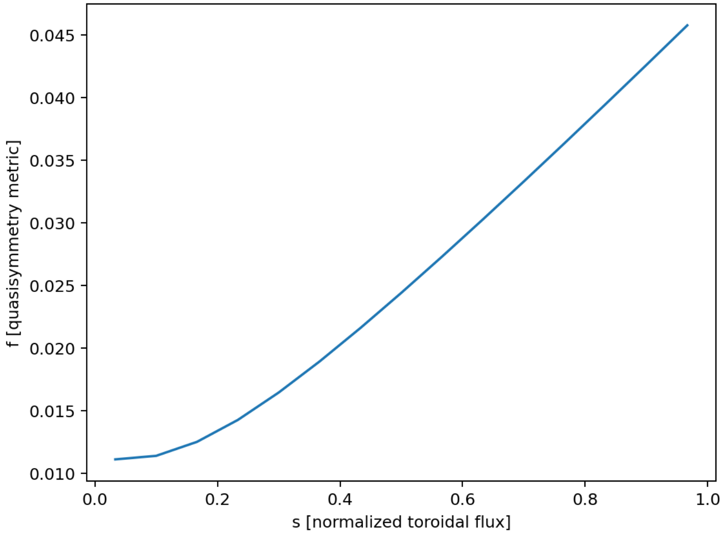


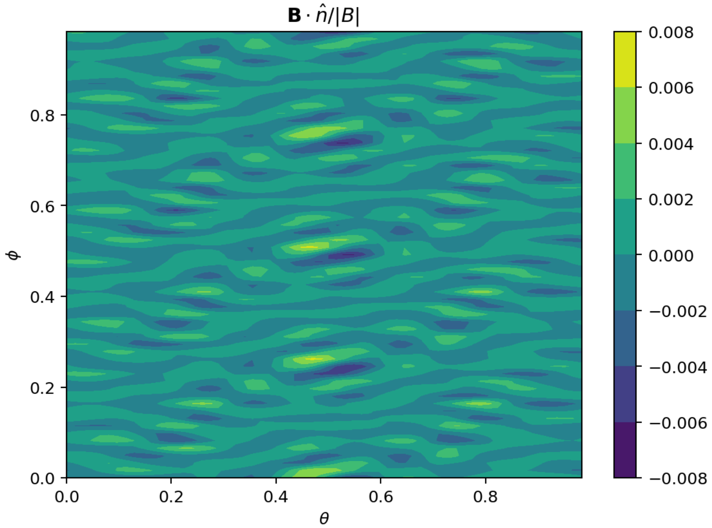


Single stage optimization leads to QS stellarator with good access

$$f(\boldsymbol{x}_c, \boldsymbol{x}_p) = w_{port}\, f_{port}(\boldsymbol{x}_p, \boldsymbol{x}_c, \boldsymbol{x}_s) + f_I(\boldsymbol{x}_s) + w_{II}\left[f_{II}(\boldsymbol{x}_c) + \sum_i \left(\boldsymbol{B}(\boldsymbol{x}_c)\cdot \hat{n}(\boldsymbol{x}_s)\right)_i\right]$$







Radial Access
Plasma boundary: free
Coils: free
Port: free

Issues:
Lots of dofs (155) for low order surface (M=N=1)
Lots of user-supplied weights (12)

Conclusions and take-home messages

- Stellarators need to be ”engineering-friendly”, aka buildable
- New single-stage optimization techniques allow us to include more engineering constraints
- One such constraint is the accessibility
- Using simsopt, access ports can be described as closed curves on the plasma boundary, and their enclosed area can be maximized, with minimal impact on the field

Topic for further discussion

- Is port-based maintenance scheme still relevant?
- Penalty-based, or mathematical constraint?
- Is there any alternative “accessibility” objectives?

Backup slides

Access port can be optimized to maximize its enclosed area

$$f_{port}(\boldsymbol{x}_p) = -A_{xy}(\boldsymbol{x}_p) + w_{cc}\, J_{ccxy}(\boldsymbol{x}_p) + w_{ufp}\, J_{ufp}(\boldsymbol{x}_p) + w_{arc}\, J_{arc}(\boldsymbol{x}_p)$$

$$A_{xy} = \int_C x \frac{dy}{dl} dl \approx \sum_i x_i \frac{dy_i}{dl} \Delta l_i$$

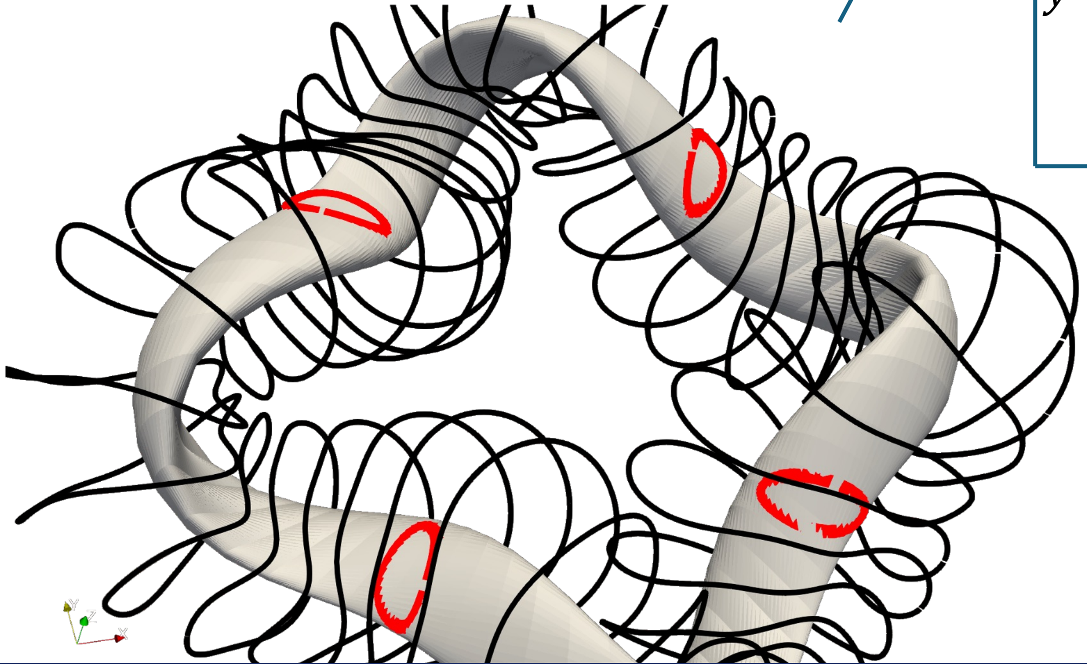
$$J_{ccxy} = \sum_i \sum_j \max(z_i - z_j, 0)^2 \max\left(d_{min} - \left[(x_i - x_j)^2 + (y_i - y_j)^2\right]^{\frac{1}{2}}, 0\right)^2$$

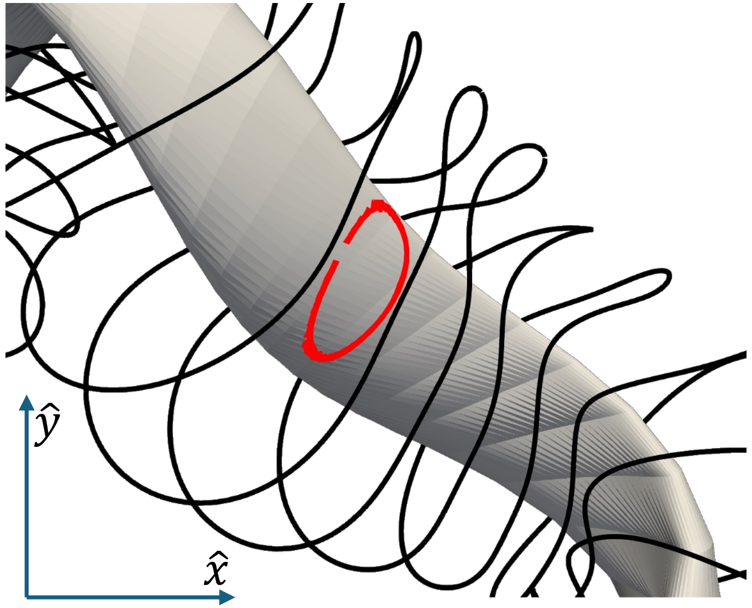
$$J_{ufp} = \sum_i \max(-n_z, 0)^2$$

$$J_{arc} = Var(\{l_i\})$$

Vertical Access

Plasma boundary: fixed
Coils: fixed
Port: free





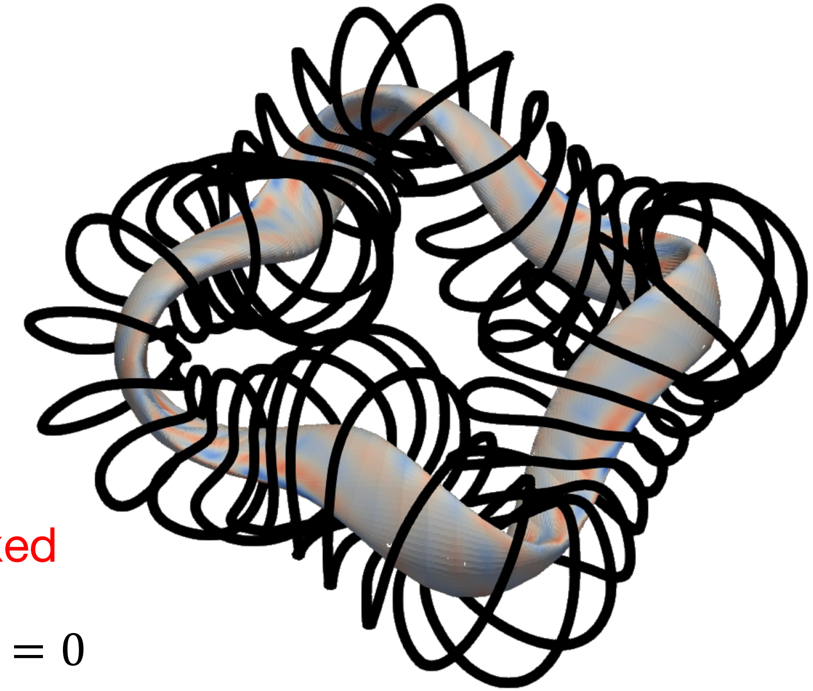
Port size can be optimized for in a stage II optimization

$$f_{port}(\boldsymbol{x}_p) = -A_{z\phi}(\boldsymbol{x}_p) + w_{cc}\, J_{ccz\phi}(\boldsymbol{x}_p) + w_{ufp}\, J_{rfp}(\boldsymbol{x}_p) + w_{arc}\, J_{arc}(\boldsymbol{x}_p)$$

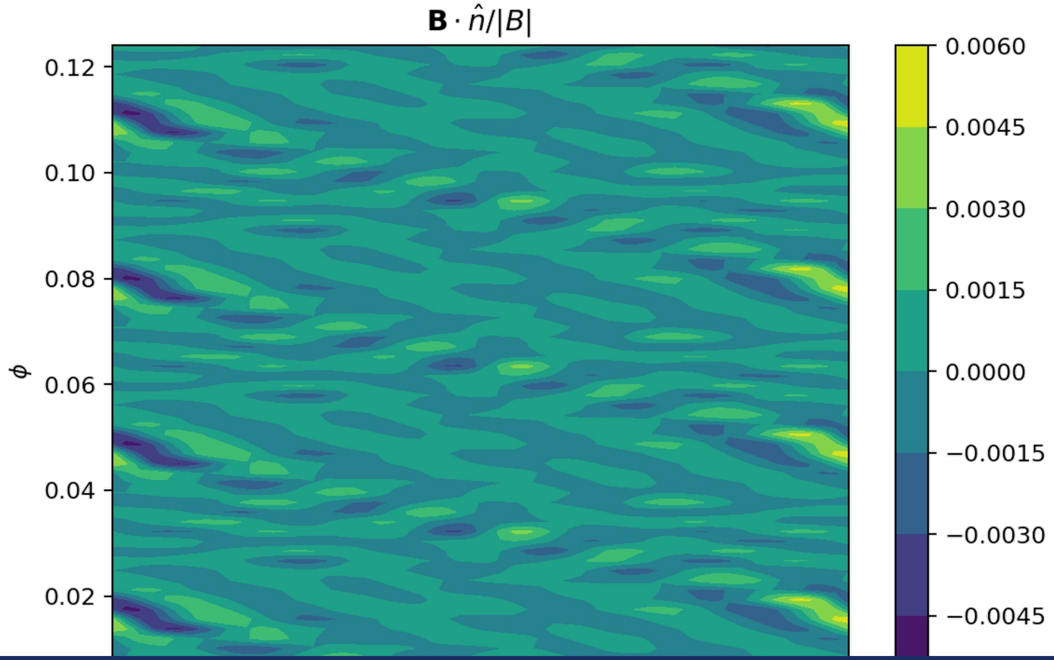
$$f_{II}(\boldsymbol{x}_c) = J_{quadflux}(\boldsymbol{x}_c) + w_L\, L(\boldsymbol{x}_c) + w_{cc}\, J_{cc}(\boldsymbol{x}_c) + w_{cs}\, J_{cs}(\boldsymbol{x}_c) + w_\kappa\, J_\kappa(\boldsymbol{x}_c) + w_{\bar{\kappa}}\, J_{\bar{\kappa}}(\boldsymbol{x}_c) + w_{GL}\, J_{GL}(\boldsymbol{x}_c)$$

$$\boxed{f(\boldsymbol{x}_c, \boldsymbol{x}_p) = f_{II}(\boldsymbol{x}_c) + w_{port}\, f_{port}(\boldsymbol{x}_p)}$$

Stage II weights are those published by Wiedman *et.al.* (2023)



Plasma boundary: fixed
Coils: free
Port: No port $\quad w_{port} = 0$



Single stage optimization leads to QS stellarator with good access

$$f_{port}(\boldsymbol{x}_p, \boldsymbol{x}_c, \boldsymbol{x}_s) = -A_{z\phi}(\boldsymbol{x}_p, \boldsymbol{x}_s) + w_{cc}\, J_{ccz\phi}(\boldsymbol{x}_p, \boldsymbol{x}_c, \boldsymbol{x}_s) + w_{ufp}\, J_{rfp}(\boldsymbol{x}_p, \boldsymbol{x}_s) + w_{arc}\, J_{arc}(\boldsymbol{x}_p)$$

$$f_{II}(\boldsymbol{x}_c) = J_{quadflux}(\boldsymbol{x}_c) + w_L\, L(\boldsymbol{x}_c) + w_{cc}\, J_{cc}(\boldsymbol{x}_c) + w_{cs}\, J_{cs}(\boldsymbol{x}_c) + w_\kappa\, J_\kappa(\boldsymbol{x}_c) + w_{\bar{\kappa}}\, J_{\bar{\kappa}}(\boldsymbol{x}_c) + w_{GL}\, J_{GL}(\boldsymbol{x}_c)$$

$$f_I(\boldsymbol{x}_s) = f_{QS}(\boldsymbol{x}_s) + w_\iota\, (\iota_t - \bar{\iota})^2 + w_A\, (A_t - A)^2$$

$$\boxed{f(\boldsymbol{x}_c, \boldsymbol{x}_p) = w_{port}\, f_{port}(\boldsymbol{x}_p, \boldsymbol{x}_c, \boldsymbol{x}_s) + f_I(\boldsymbol{x}_s) + w_{II}\left[f_{II}(\boldsymbol{x}_c) + \sum_i \left(\boldsymbol{B}(\boldsymbol{x}_c) \cdot \hat{n}(\boldsymbol{x}_s)\right)_i\right]}$$

Radial Access

Plasma boundary: free

Coils: free

Port: free