Enhancing Stellarator Accessibility through Port Size Optimization

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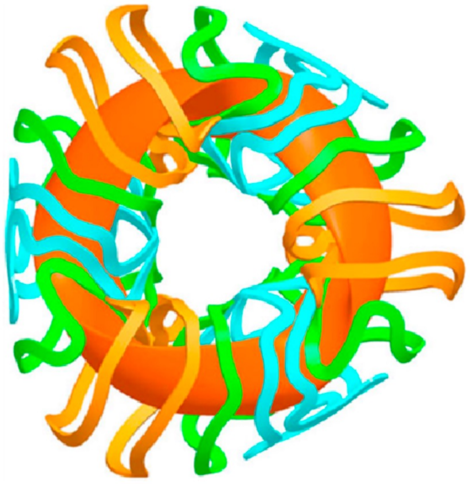
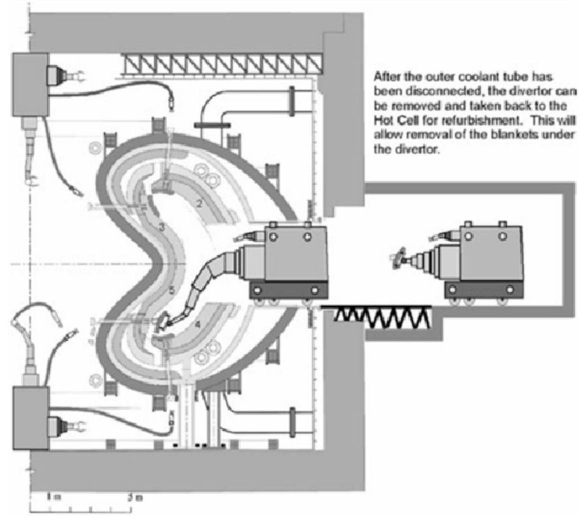
Good accessibility is vital for FPP rentability

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

Brown, 2015



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

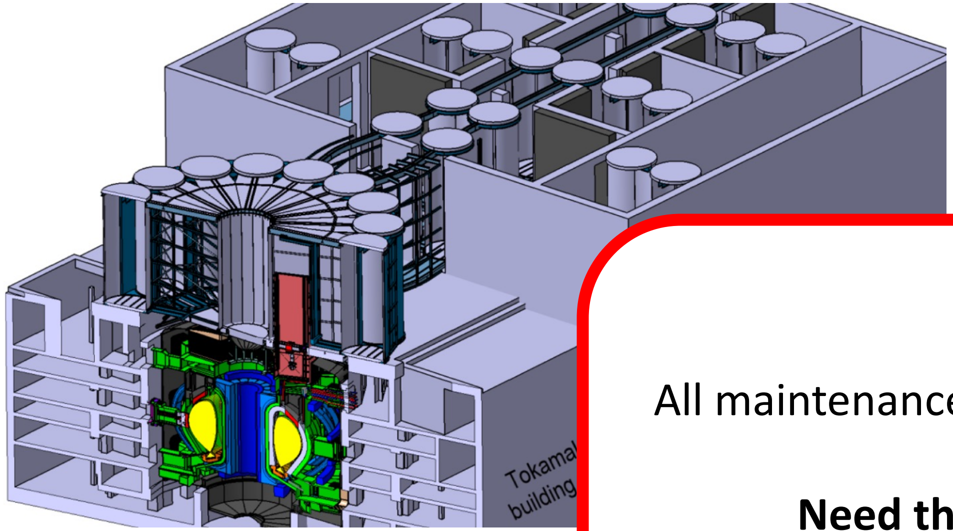


ARIES-CS port maintenance approach

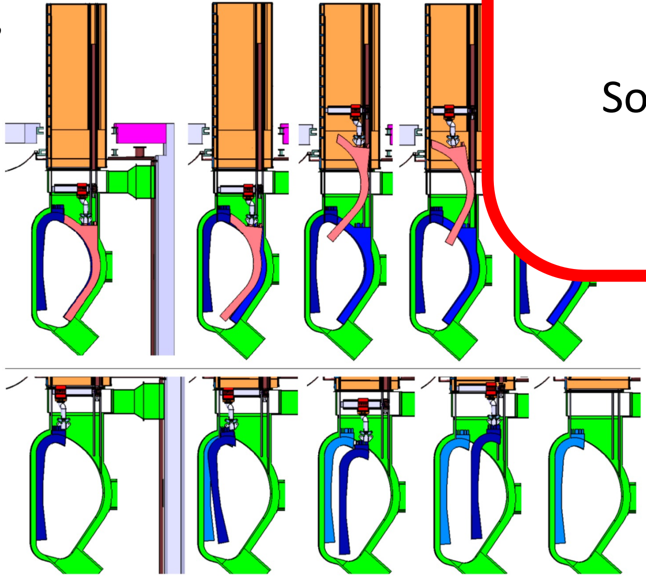
Larger access port sizes → Larger in-vessel components → Smaller number of cuts and soldering → Shorter down-time → Better rentability of the FPP

Remote handling system is not yet chosen for a stellarator

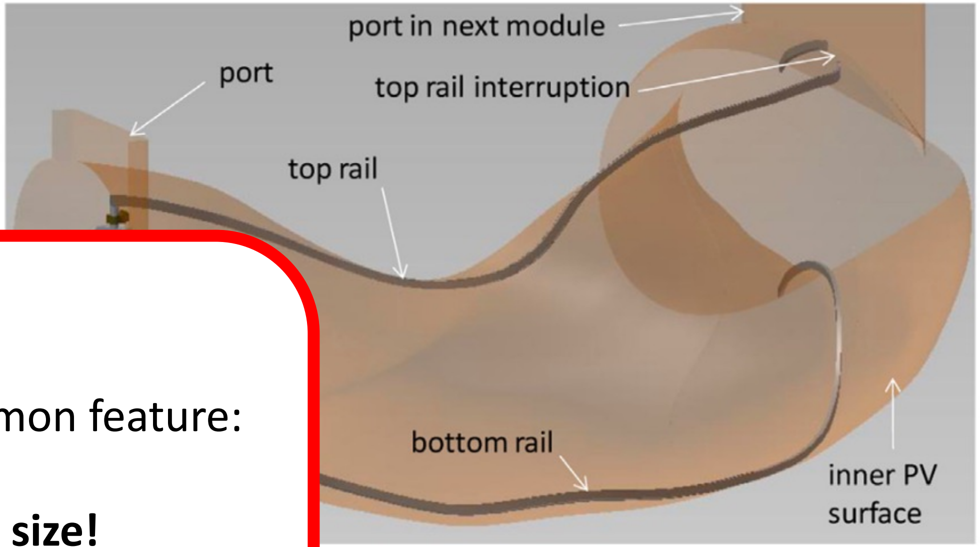
DEMO remote maintenance system



Bachmann, 2022



In-vessel crane on rails

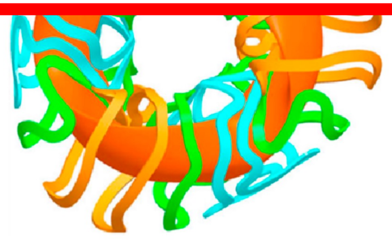


Shauer, 2013

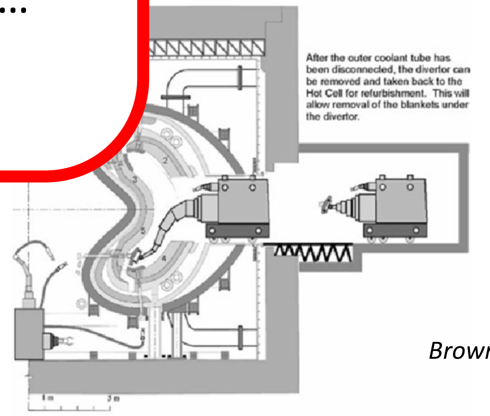
All maintenance schemes have a common feature:

Need the largest possible port size!

So let's try to make our engineer's life easier…



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



Brown, 2015

ARIES-CS port maintenance approach

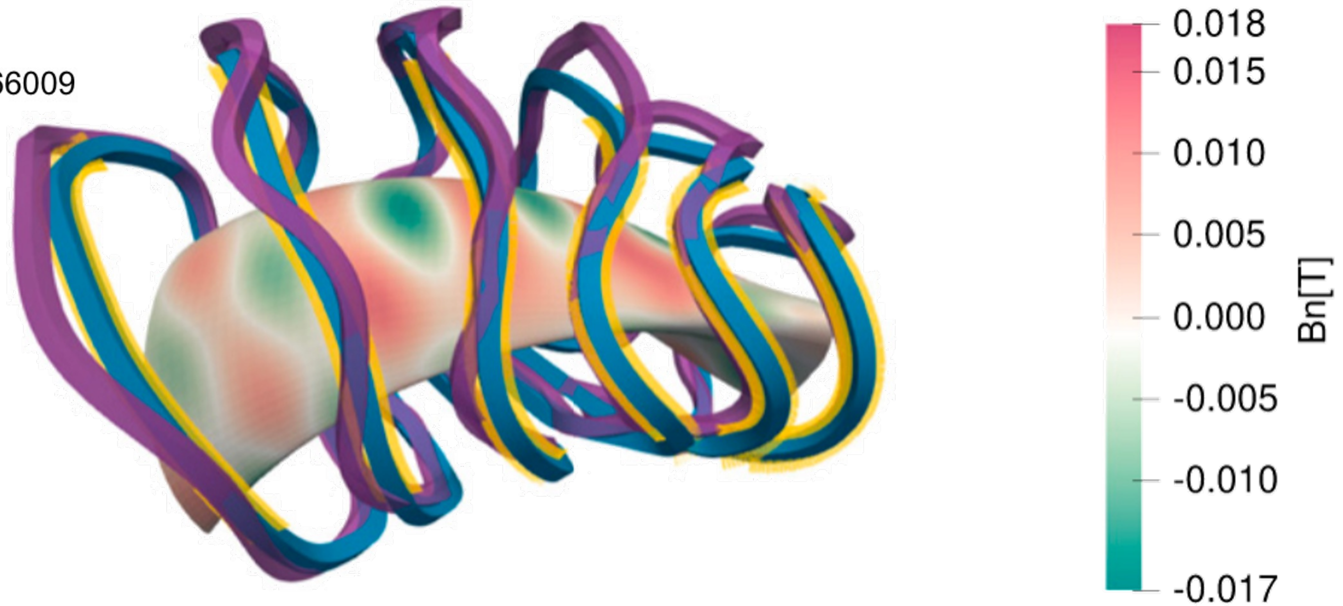
Previous work focused on straightening outer legs of coils

nuclear fusion
IAEA

PAPER

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

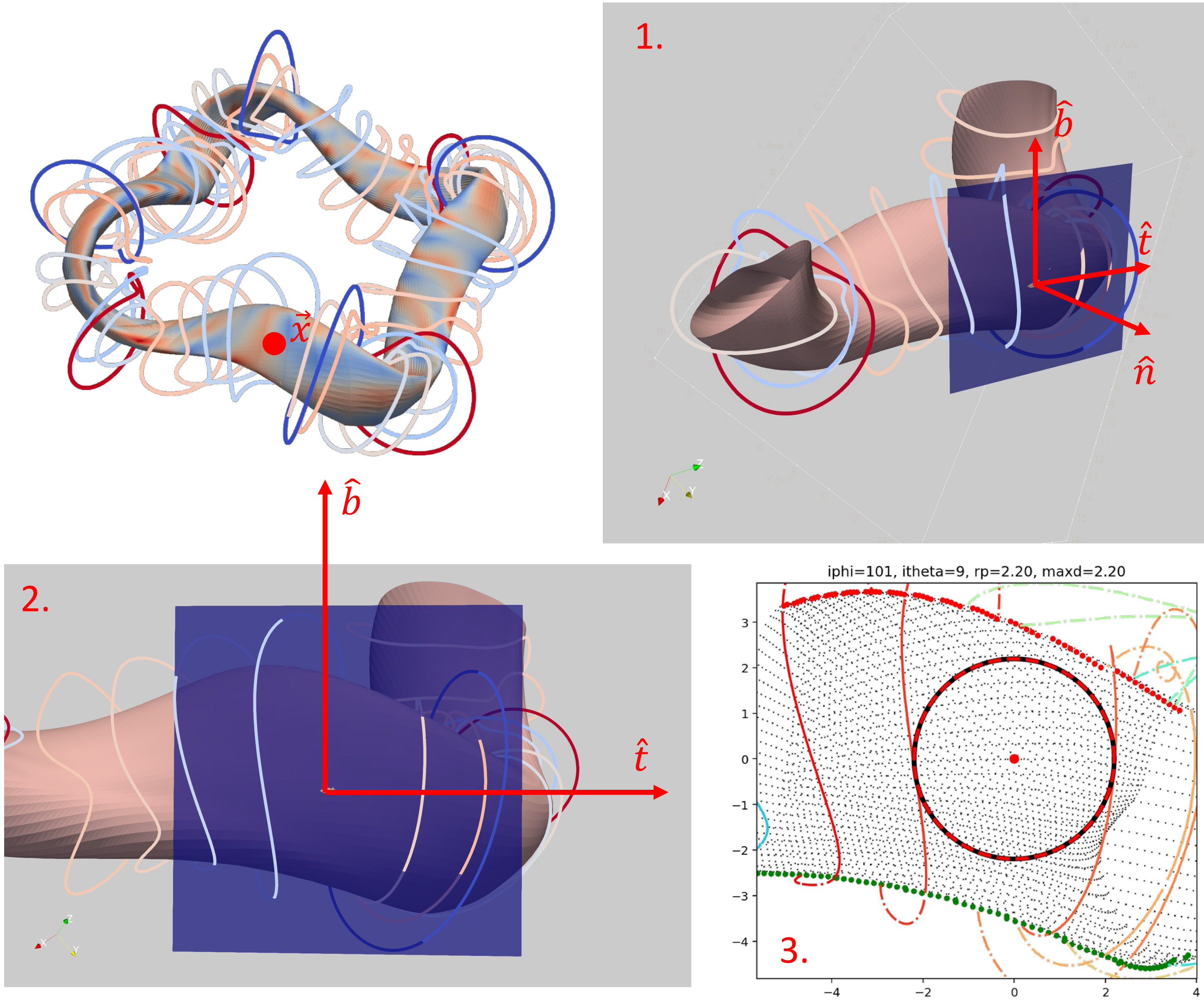
To cite this article: Nicola Lonigro and Caoxiang Zhu 2022 *Nucl. Fusion* **62** 066009



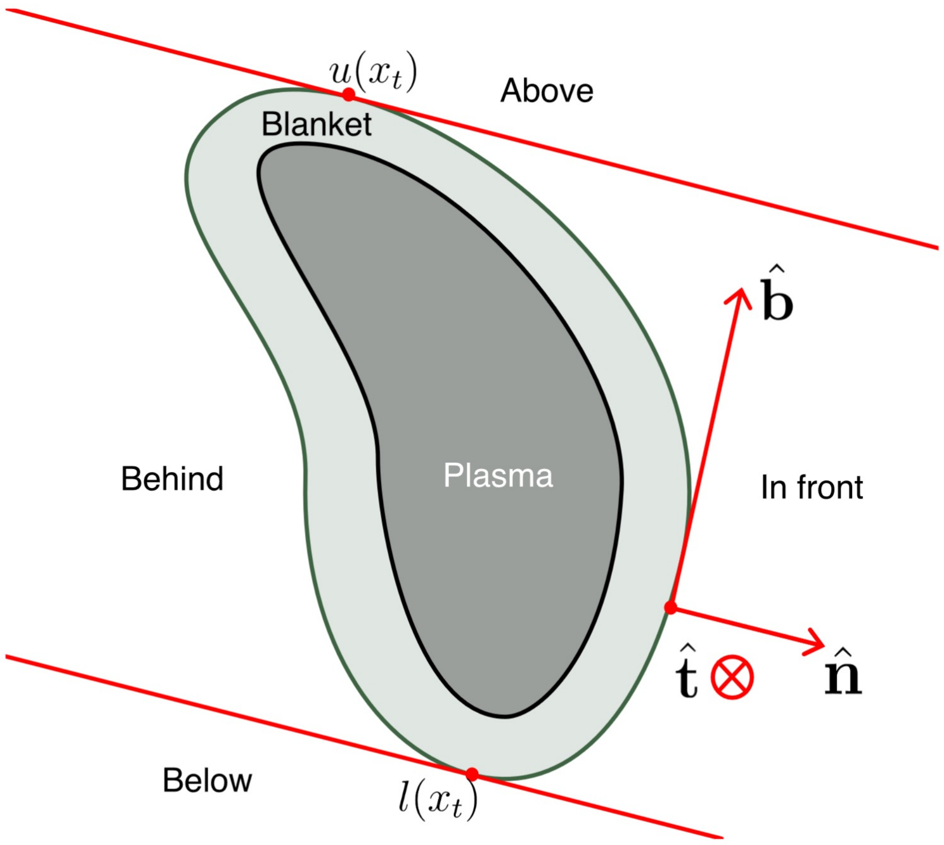
How to evaluate a port size – geometry 101

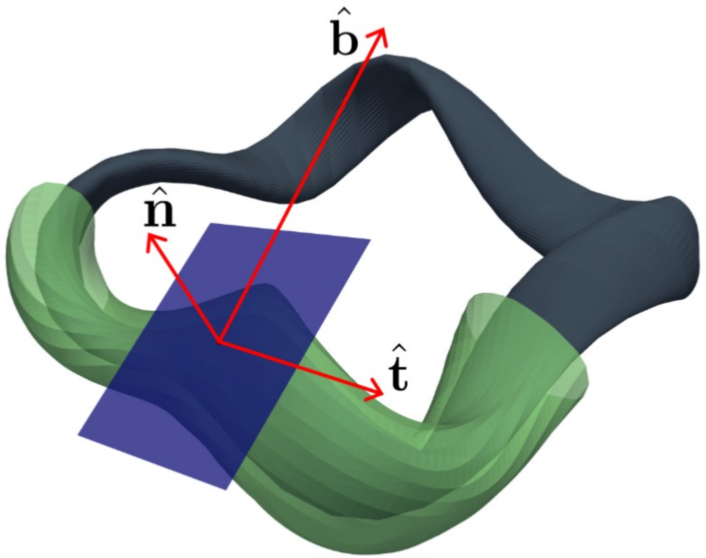
Given a point $\vec{x}(\theta,\phi) \in \Gamma$ and a set of coils C, **we search the maximum circular port size** that provides **normal access** to the vessel:

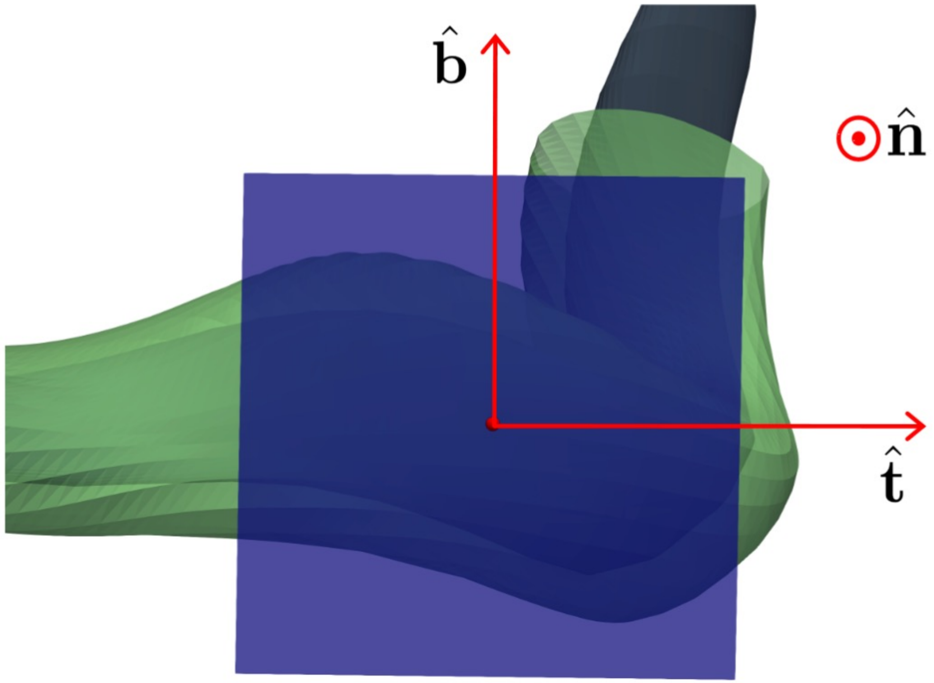
1. Construct coordinate system $(\hat{n},\hat{t},\hat{b})$, where
   - $\hat{n}$ is the unitary normal vector to Γ
   - $\hat{t} = \frac{\partial\vec{x}}{\partial\phi} \Big/ \left|\frac{\partial\vec{x}}{\partial\phi}\right|$ is the unitary tangent vector to Γ
   - $\hat{b} = \hat{n}\times\hat{t}$ is another unitary tangent vector
2. Express all coils position and Γ in the $(\hat{n},\hat{t},\hat{b})$ system
3. Identify maximum circular port size $r_p(\theta,\phi)$ in the $\hat{n}$ direction
   1. Limited by closest coil point in the $(\hat{t},\hat{b})$ plane that is in front of the plasma,
   2. Or by the « envelop » of Γ, projected on the $(\hat{t},\hat{b})$ plane.



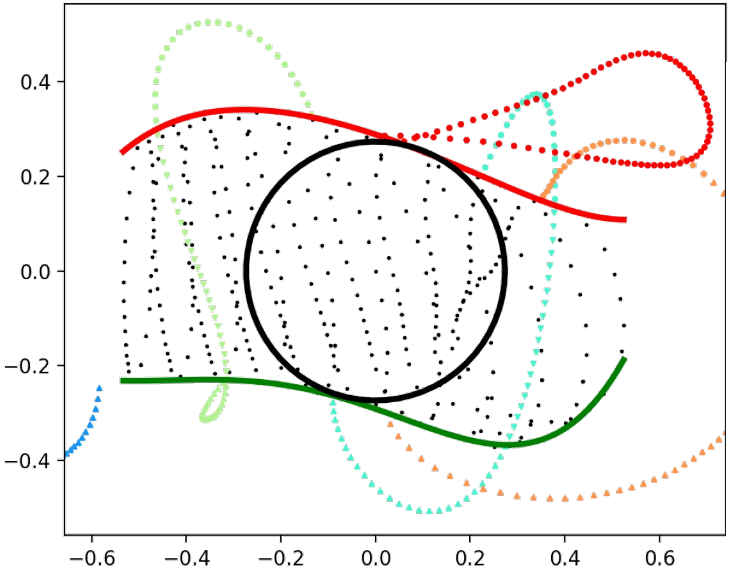
More visualisation…



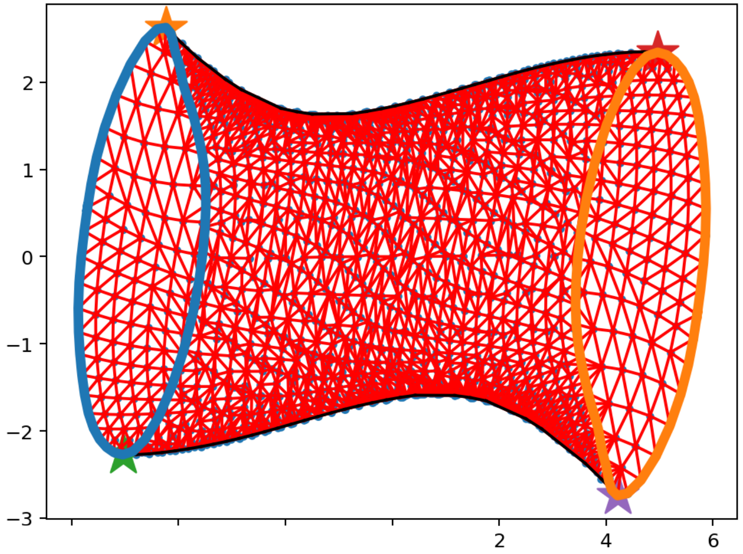




Upper limit to port size is set by the space available on the vessel

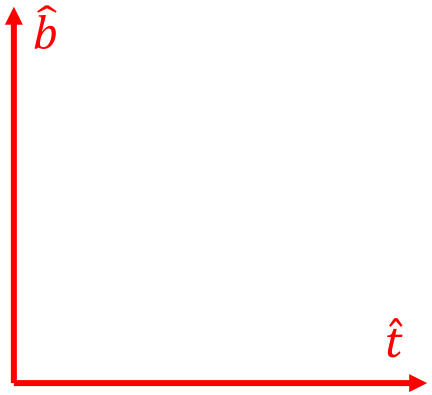


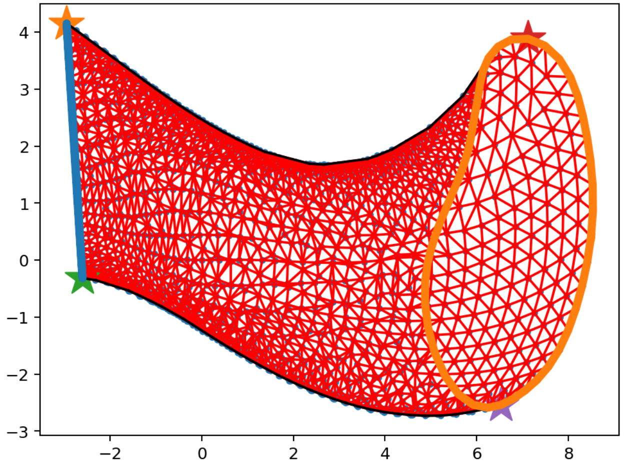
=> need to build the non-convex hull of the projected vessel



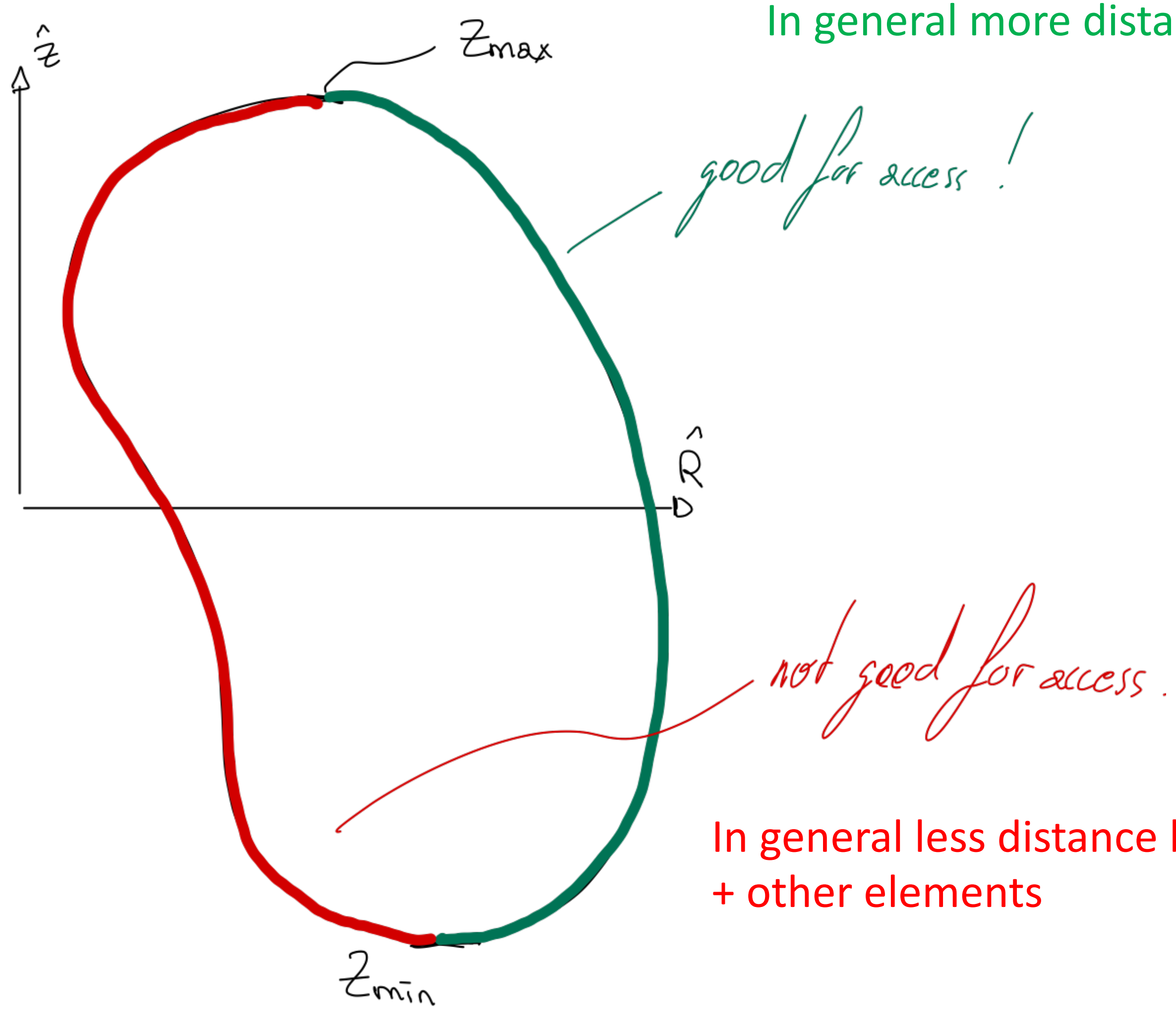
Preprocessing algorithm:

For each point of interest on the surface,
1. Construct tangent plane
2. Project surface
3. Extract upper and lower envelop from the non-convex hull
4. Evaluate maximum possible port size d_{max}





How to evaluate the maximum port size on a field period



In general more distance between coils

In general less distance between coils
+ other elements

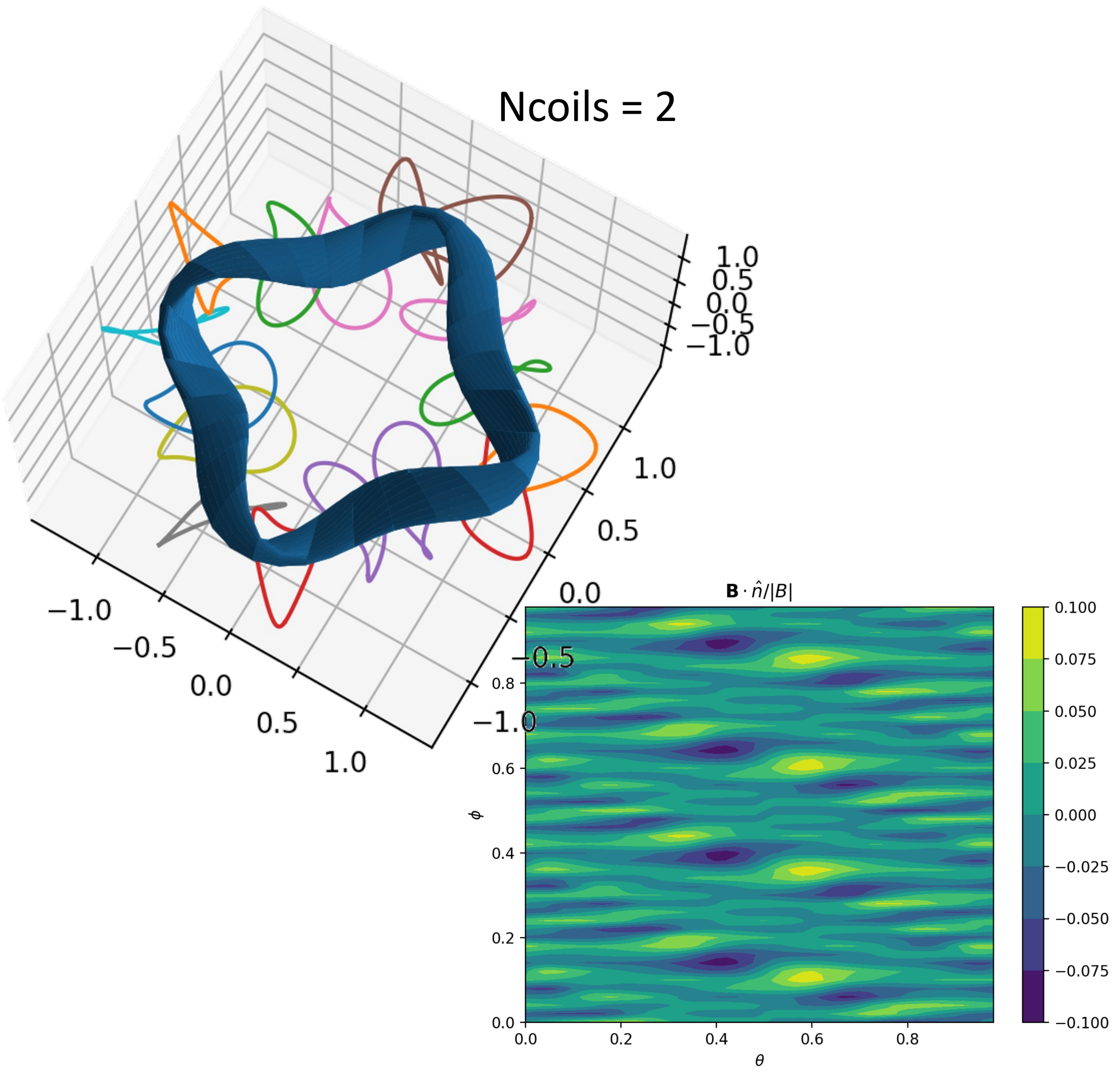
1. Construct grid on the part of $\Gamma(\theta, \phi)$ that you would consider for access ports

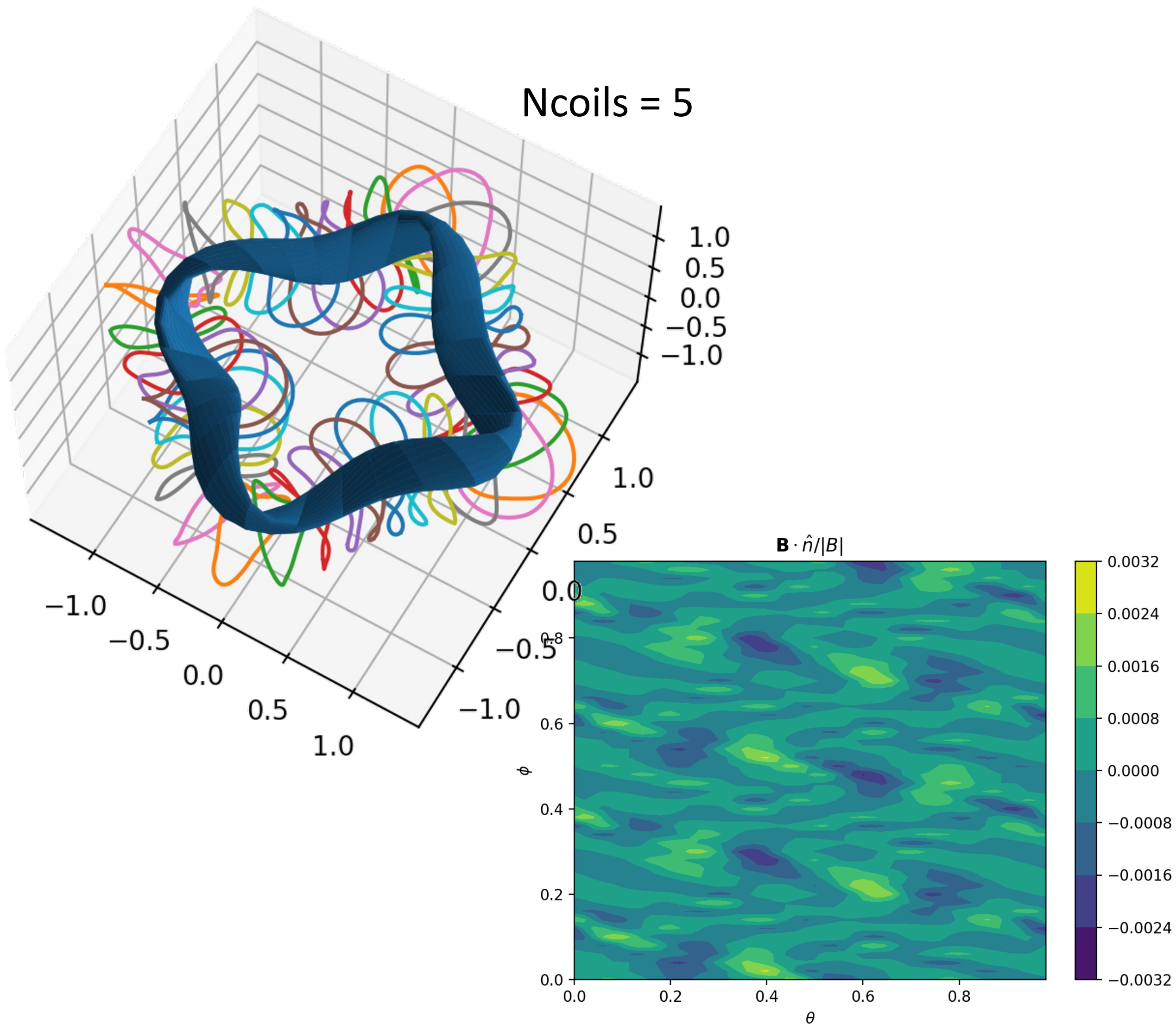
2. Evaluate

$$\mathrm{r}_{\mathrm{p,max}}(\Gamma, C) = \max_{\theta,\phi} r_p(\theta, \phi)$$

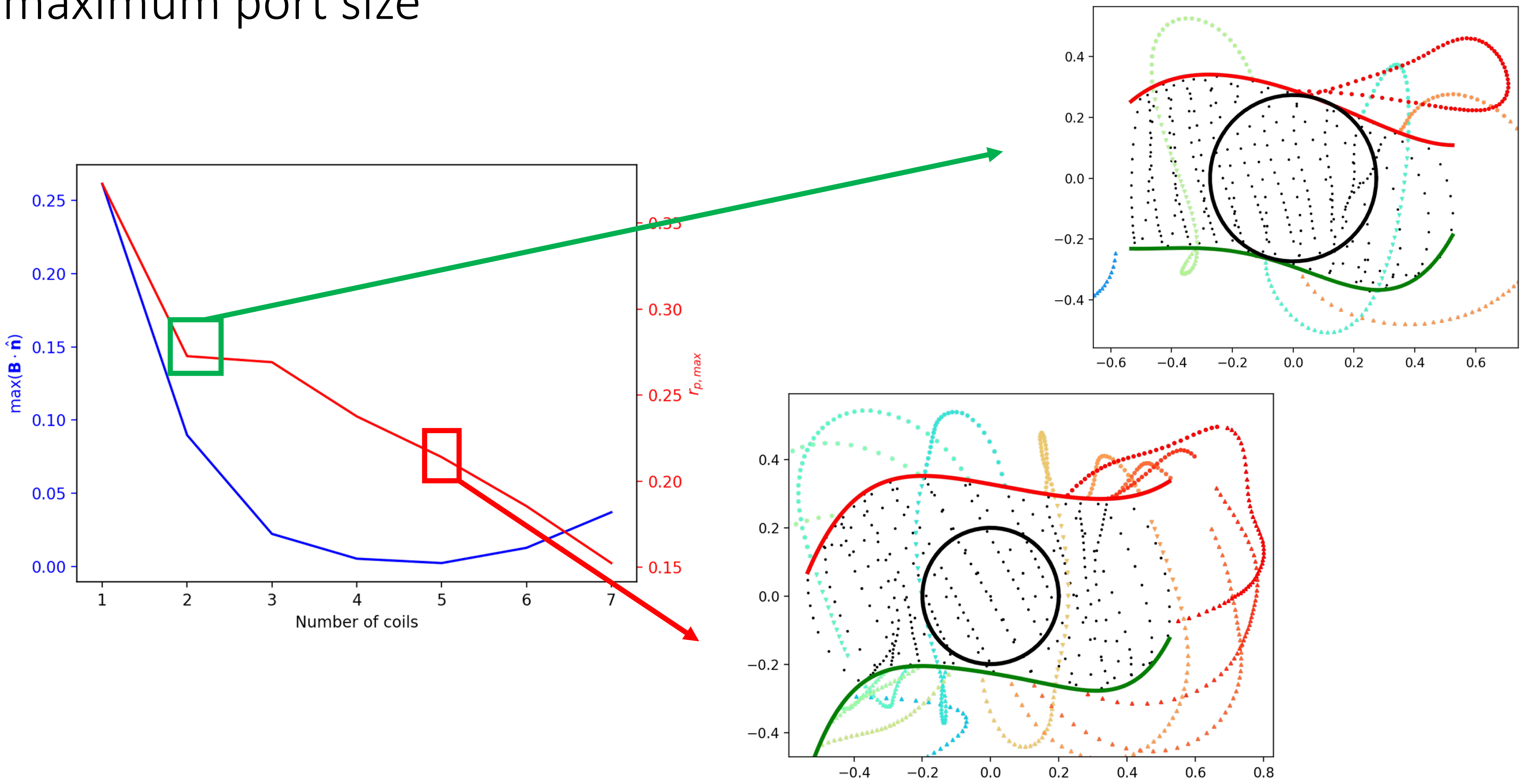
Configuration: precise QH, Landreman and Paul 2022
Coils: using script by Wiedman et al., 2023

Example: precise QH

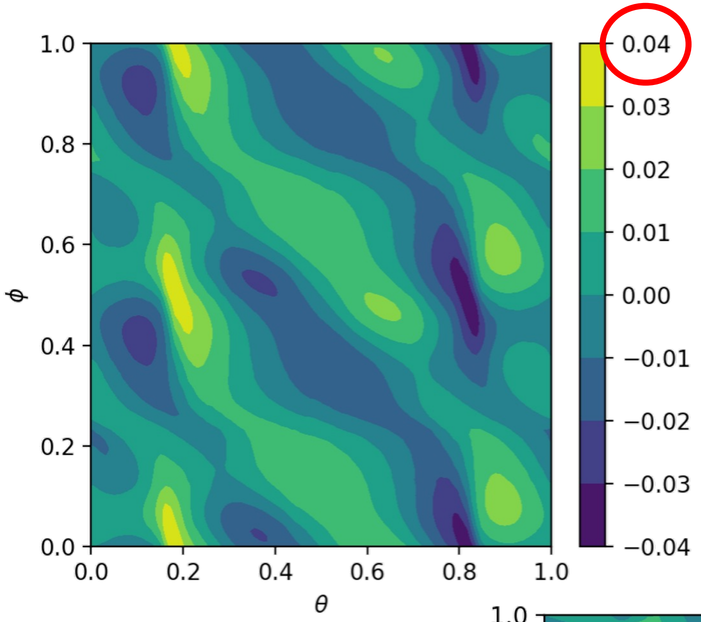




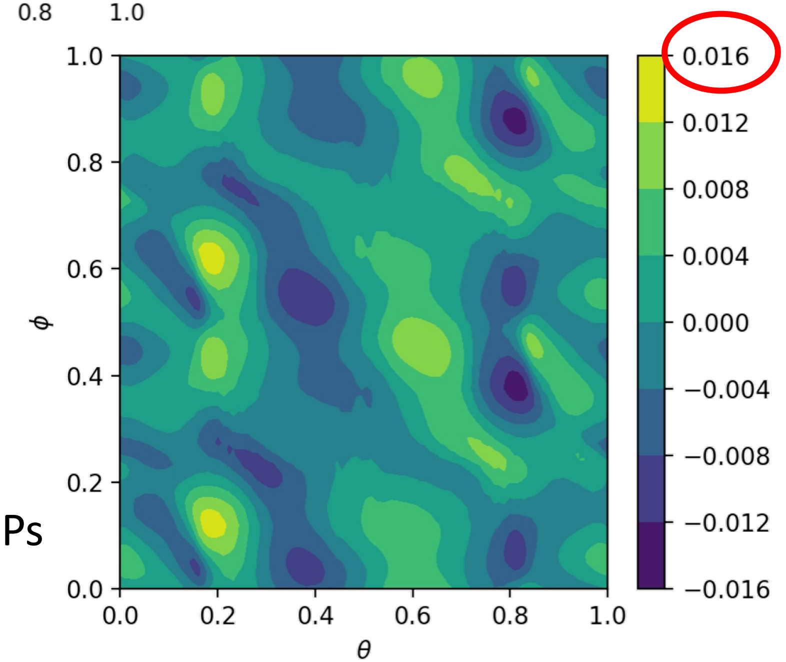
There is a trade-off between the field quality and the maximum port size



Windowpane coils can provide shaping without blocking access

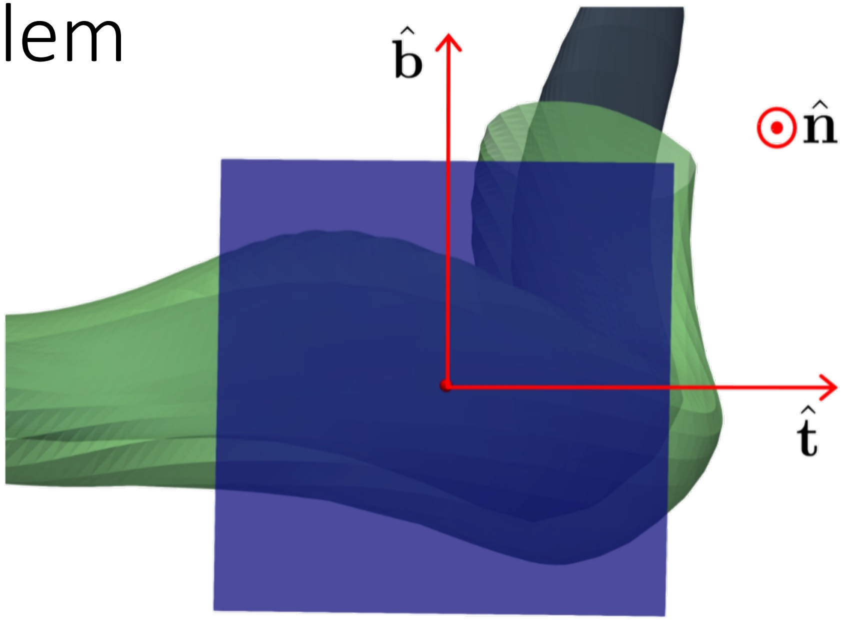


Without WP



With optimized WPs

Port size can be optimized in a stage II problem



- Construct a target function differentiable w.r.t the coils

$$r_{p,max} = \max_{\theta,\phi} r_p(\theta,\phi) \approx \left[\sum_{i=1}^{N_\theta}\sum_{j=1}^{N_\phi} r_p(\theta_i,\phi_j)^p\right]^{\frac{1}{p}}$$

- Use the logistic function to classify curve elements

$$r_k = \sqrt{t_k^2 + b_k^2}$$

$$f_k = f(\boldsymbol{x_k}) = \mathcal{H}(d_{max} - r_k)[\mathcal{H}(b_k)\mathcal{H}(u_k - b_k) + \mathcal{H}(-b_k)\mathcal{H}(b_k - l_k)]$$

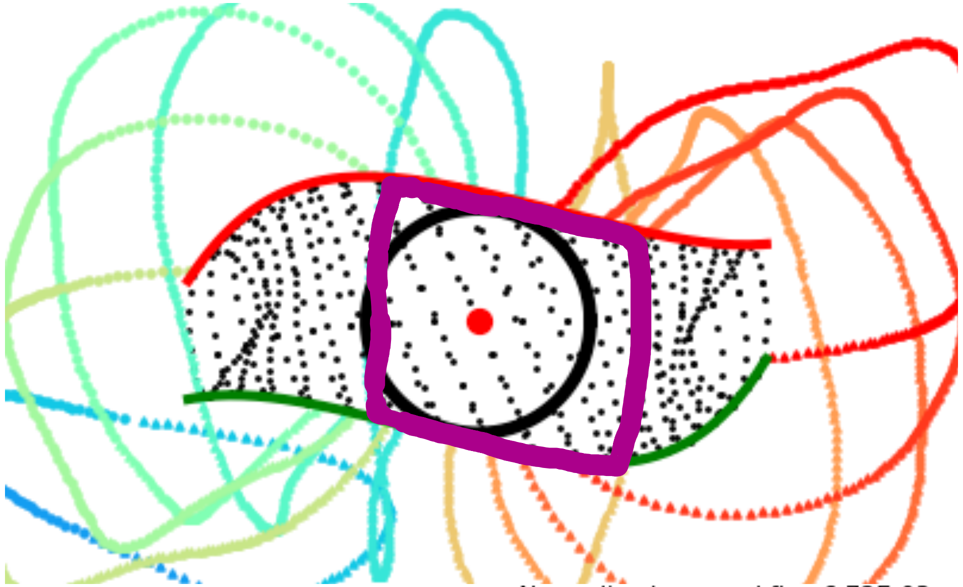
$$r_p = \min_k[N(f_k r_k - 1) + 1], \qquad N \gg 1$$

$$\mathcal{H}(x) \approx \frac{1}{2} + \frac{1}{2}\tanh\frac{kx}{2}, \qquad k \gg 1$$

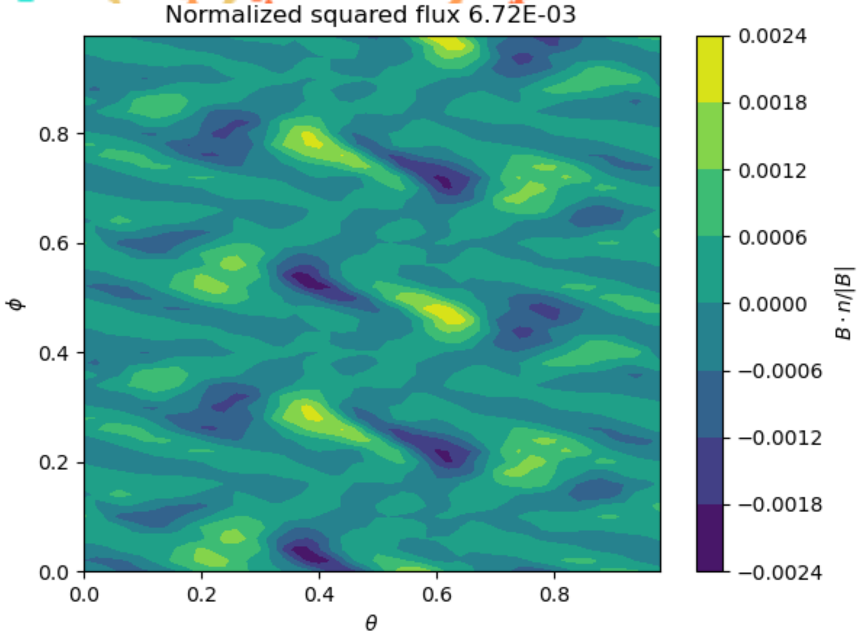
$\mathcal{H}(x)$ is the Heaviside function

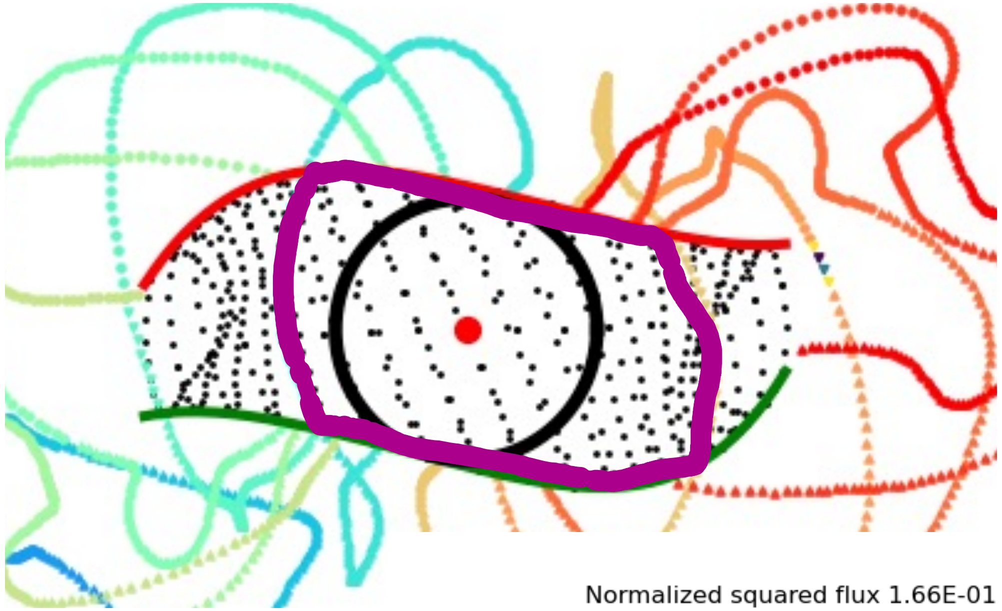
$$f_k = \begin{cases} 1 & \text{if coil is in front of the plasma} \\ 0 & \text{otherwise} \end{cases}$$

Port size is significantly increased at minimal cost on field error

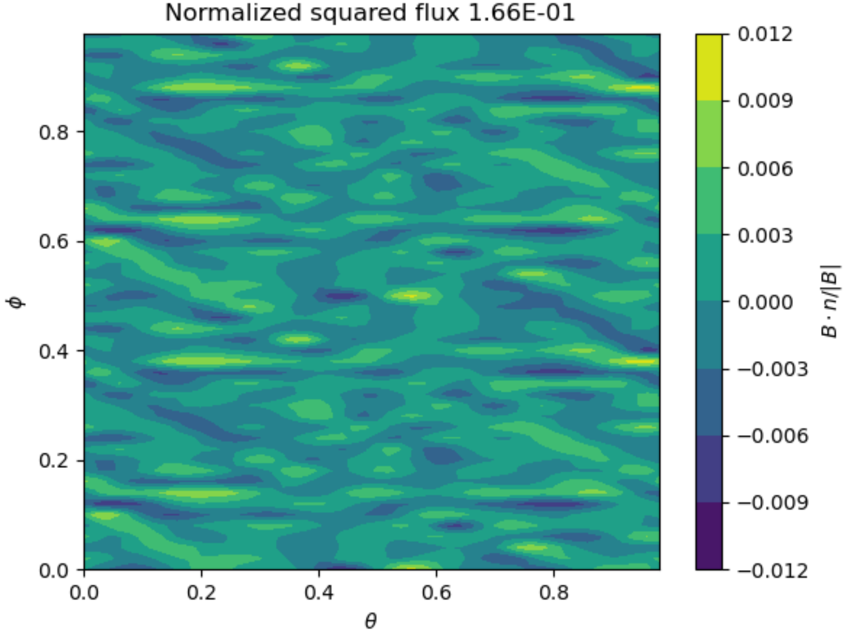


INITIAL





OPTIMIZED



Open questions / future work

- Stage II optimization with WPs
- Extend to rectangular ports
- Focus on vertical access ports
  - No need for projection / new coordinate system
  - Differentiable function with respect to the boundary?
  - Can we do **combined optimization** ?
- Smarter way to write the target function?
  - Only consider one point per region delimited by coils?
  - Define the port edge as a curve; use curve-curve distance penalty; maximize its encircled area while keeping it convex
- How can we optimize for other kind of access?
  - Rail access – need plasma made of straight sections