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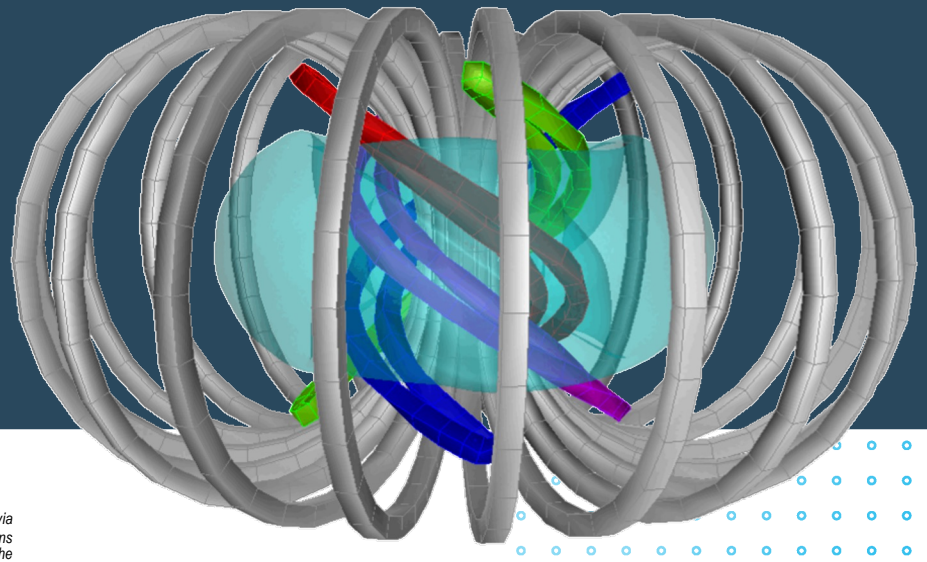
A compact stellarator-tokamak hybrid concept

Sophia A. Henneberg[1]

Tobias M. Schuett[2], Gabriel G. Plunk[1]

[1] Max-Planck-Institut für Plasmaphysik, Greifswald

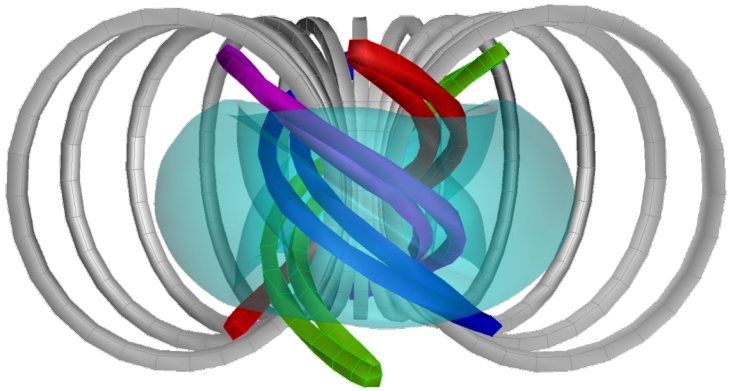
[2] University of York

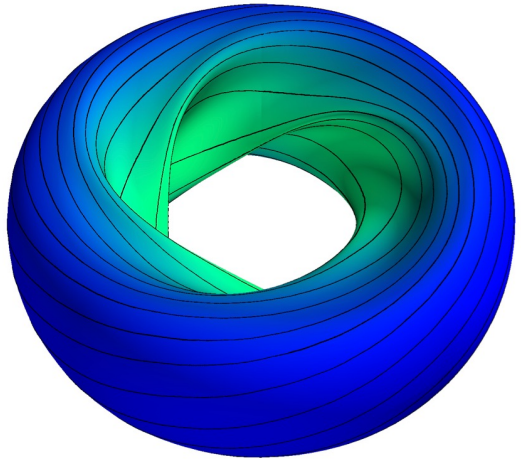


EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Content





Motivation & Background

- **Why are we interested in a stellarator-tokamak hybrid?**
- **Some historic examples of hybrids**
- **What are perturbed axisymmetric quasi-axisymmetric equilibria?**

Hybrid Design

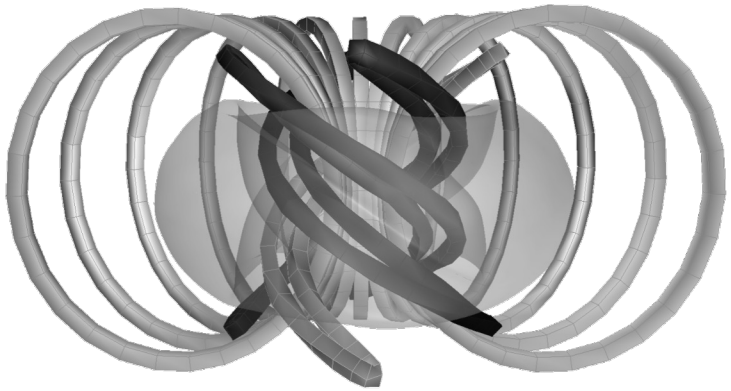
- **Coil set of a compact hybrid**
- **Free-boundary equilibrium**
- **Flux-Surfaces in vacuum**

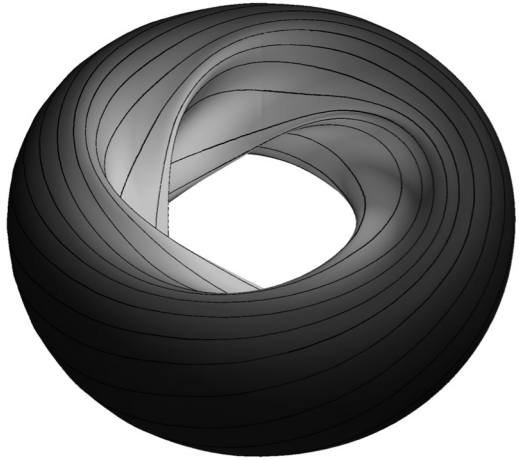
Optimization of the physics properties of these novel compact QA stellarators

- **Optimizing QA**
- **Adding physics targets**
- **Exploring NFP**
- **Coils**

Ongoing & Future work

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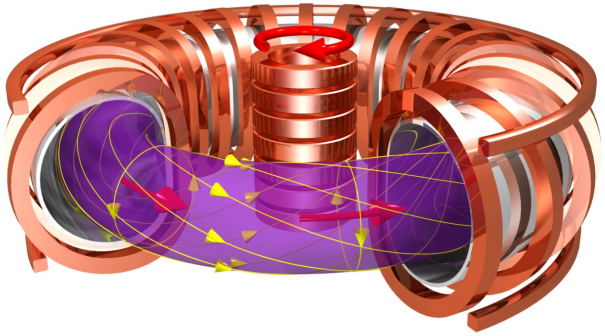
Ongoing & Future work

Combining the strength of tokamaks & stellarators

Tokamaks

+ intrinsic heating (plasma current)
+ compact design (= small aspect ratio)
+ simple coil geometry

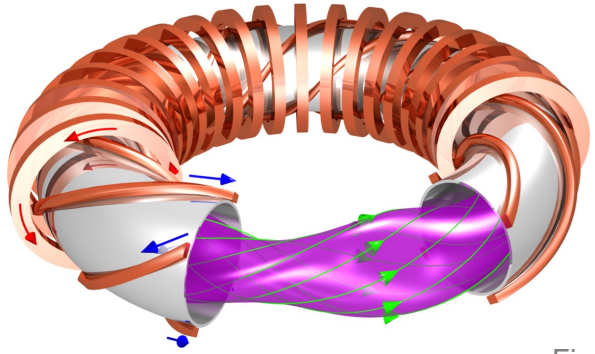
- not intrinsically steady state
- large plasma current (→ disruptions)



Stellarators

+ no need for driving current in the plasma
+ intrinsic steady state
+ more stable (due to reduction of plasma currents)

- more complicated coils
- in general: worse confinement



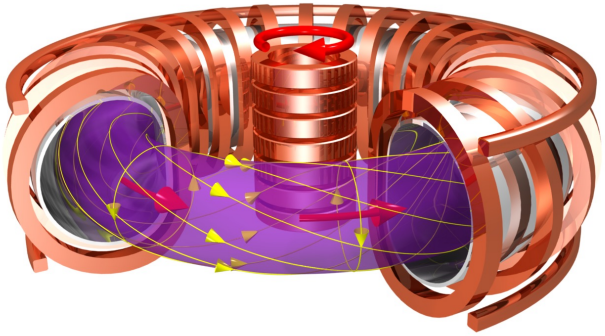
Figs: Brandt, IPP 2011

Combining the strength of tokamaks & stellarators

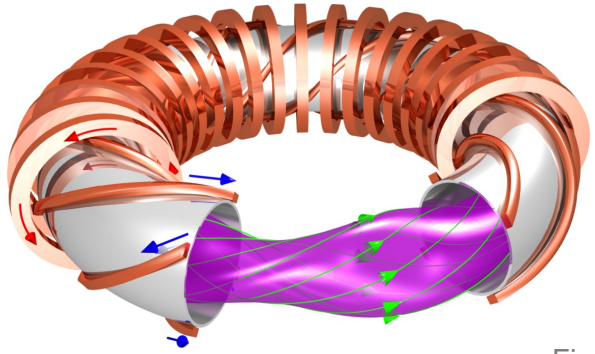
= Ideal Hybrid

+ intrinsic heating (plasma current)	+	+ no need for driving current in the plasma
+ compact design (= small aspect ratio)		+ intrinsic steady state
+ simple coil geometry		+ more stable (due to reduction of plasma currents)

Can we combine all the advantages into one single device?



+

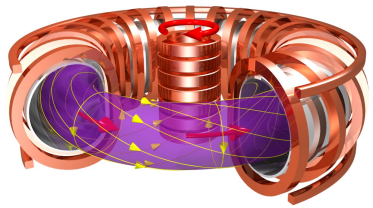


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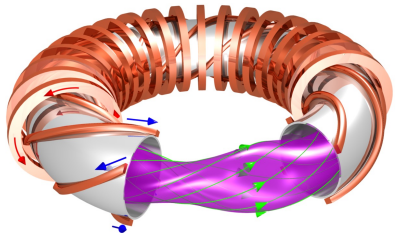
Hybrid concepts:

Hybrid I: (“flexible”) stellarator-tokamak hybrid

- Can run as either a tokamak or stellarator

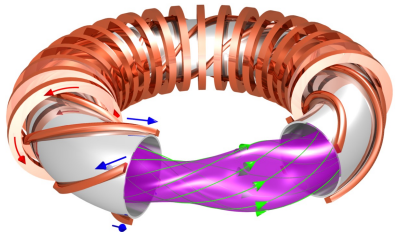


V



Hybrid II: compact stellarator

- Combines benefits of the two designs.
- Typically a compact stellarator.



Hybrid III: compact stellarator-tokamak hybrid

Figs: Brandt, IPP 2011

Let’s learn from the past: Example hybrids

Wendelstein 7-A (1975-1985)

W VII-A Team 1980 Nucl. Fusion

Thanks to valuable insight by Craig Beidler!

- Pre-predecessor of Wendelstein 7-X.
- IPPs first large stellarator.
- “Classical stellarator”
- $A \approx 20$
- Could run as either a stellarator or a tokamak, since it had a transformer.

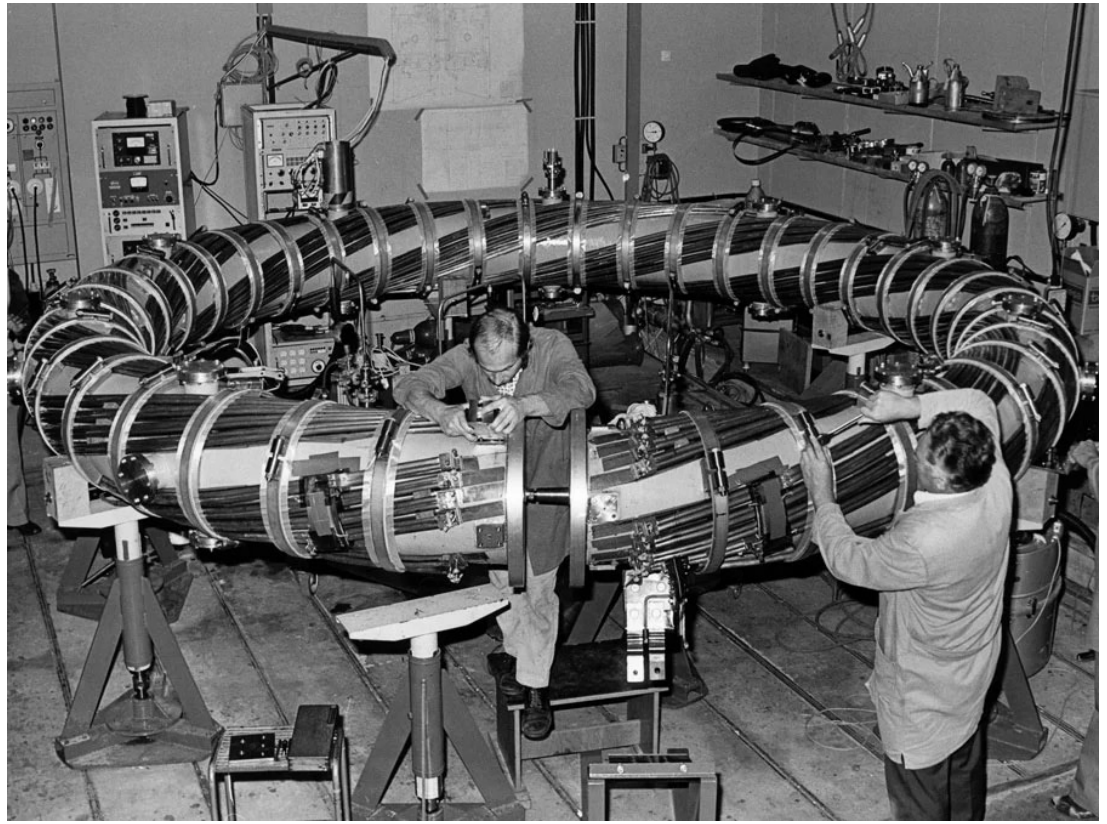


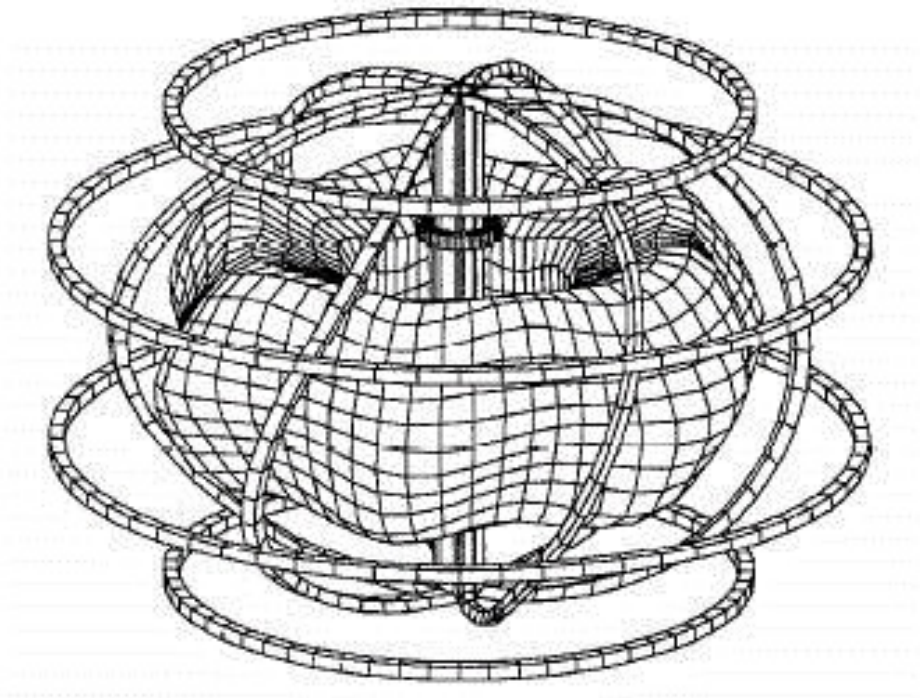
Photo: IPP

Let’s learn from the past: Example hybrids

Spherical stellarator concept

P.E. Moroz, PRL 1996

- Can be very compact (e.g. <2).
- Simple Coils.
- Could be upgraded to also run as a tokamak.

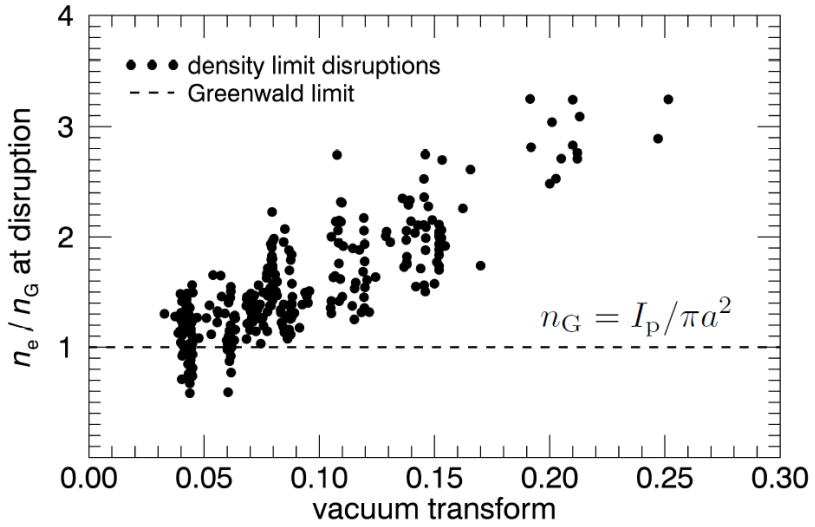


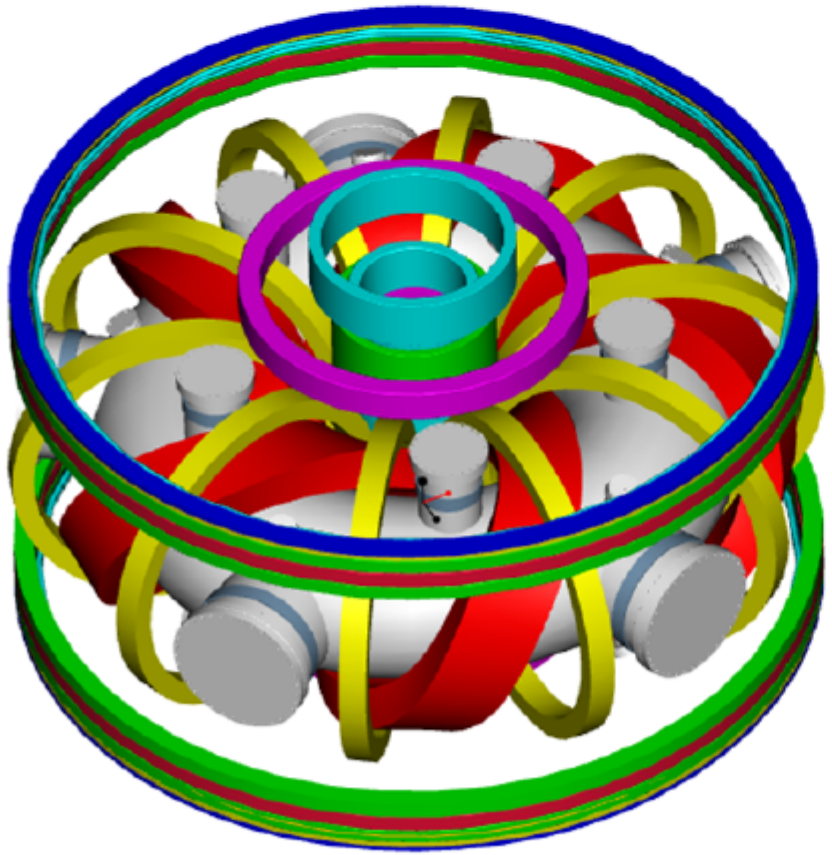
Let’s learn from the past: Example hybrids

Compact Toroidal Hybrid (CTH)

CTH: Maurer, ISHW Greifswald 2015
Hartwell et al. Fusion Sci. Technol. 2017

- Stellarator part: torsatron – helical coil
- Aspect ratio of approximately 4





Let’s learn from the past: Example hybrids

For combining benefits of both, tokamaks and stellarators, we have so far only looked at compactness.

What about good confinement?

→ None of these are “transport optimized” stellarators!

(“transport optimized” = QI, QA or QH)

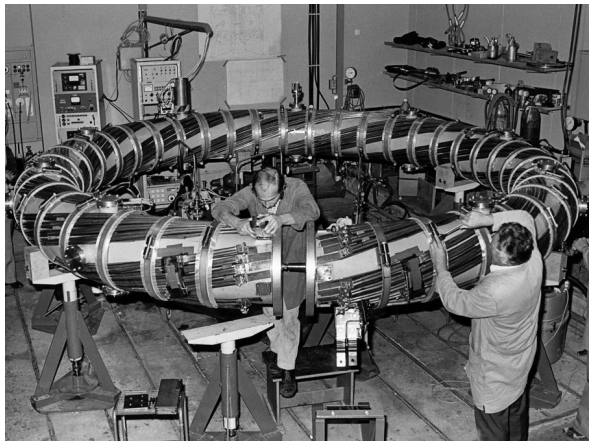
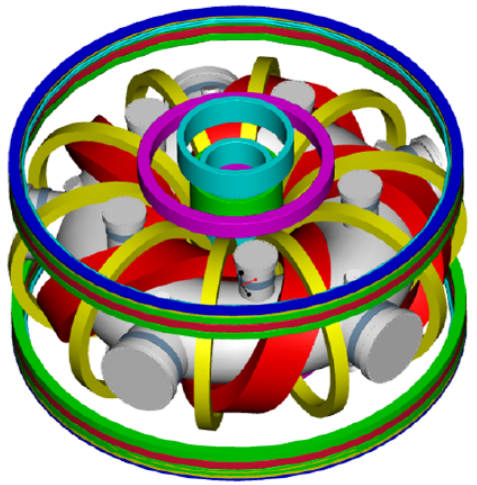
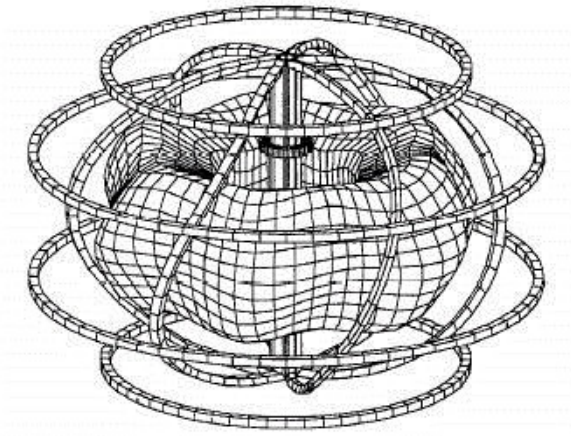


Photo: IPP



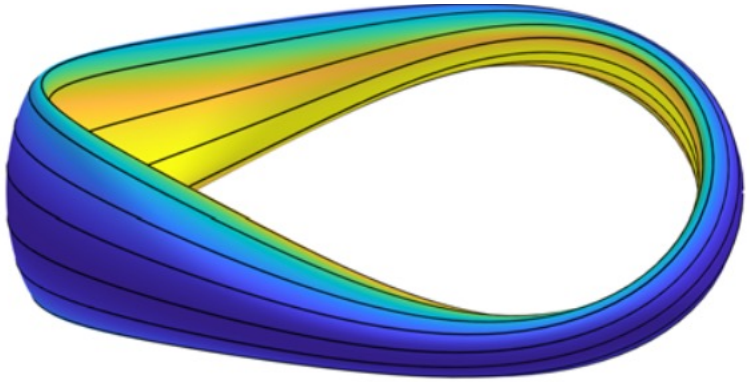
Hartwell et al. Fusion Sci. Technol. 2017

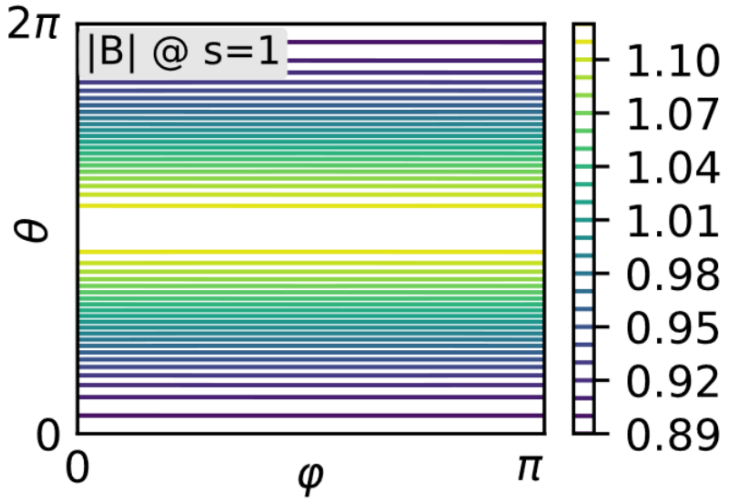


P.E. Moroz, PRL 1996

Can we have a compact hybrid with a transport-optimized stellarator?

The obvious choice for a stellarator-tokamak hybrid: Quasi-axisymmetry





- The magnetic field strength is nearly independent of the toroidal Boozer coordinate: B≈$B(s,\theta)$. This reduces the radial drift of trapped particles.
- Because of the toroidal symmetry of the magnetic field strength, QA-configurations share many neoclassical properties of tokamaks, such as high bootstrap current.

Boozer, Phys. Fluids, 1983

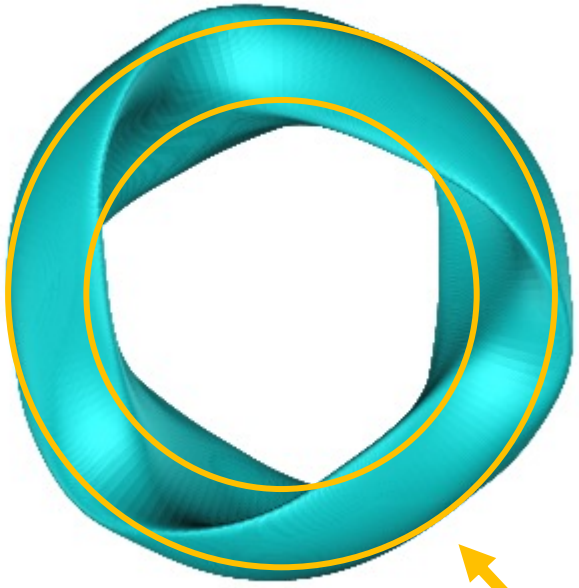
Nührenberg, Phys. Lett. A, 1988

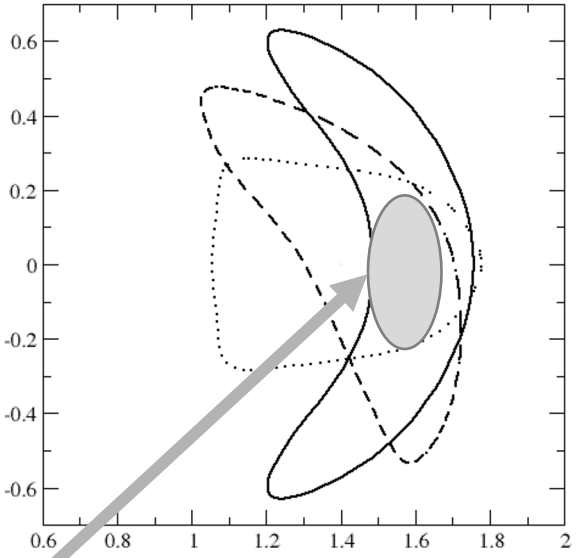
Fig: Landreman and Paul, PRL, 2022

Let’s have a look at previous QA-stellarator designs: How compact would the hybrid be?

NCSX: Zarnstorff et al. PPCF, 2001

Resulting estimated aspect ratio: 11.3



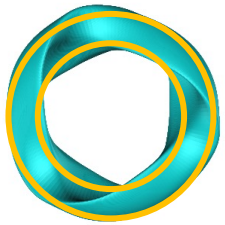


Largest axisymmetric volume within the plasma boundary (assuming elliptical cross section).

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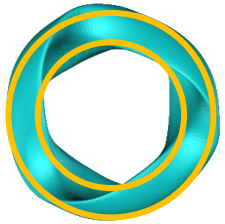
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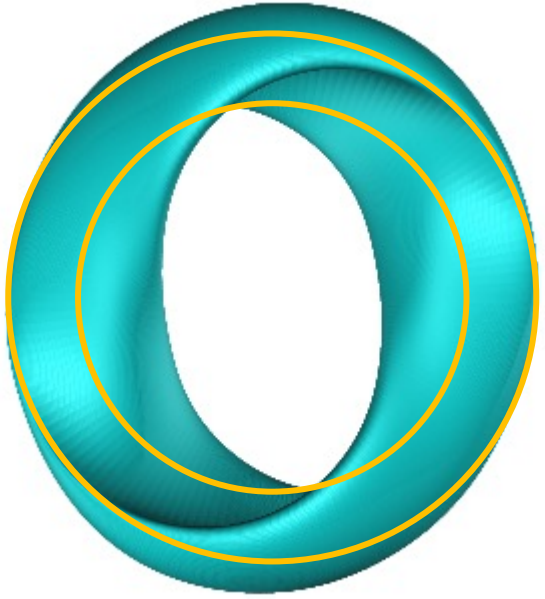
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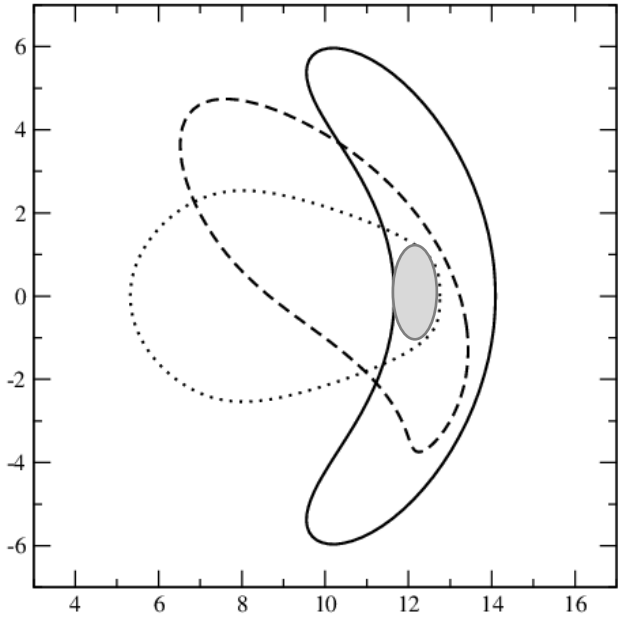
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Henneberg et al., NF, 2019

Resulting estimated aspect ratio: 17

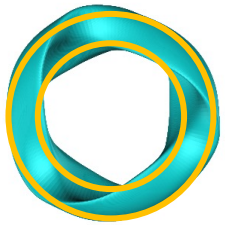




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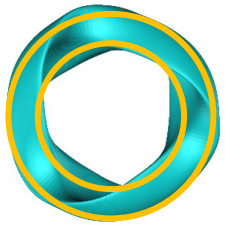
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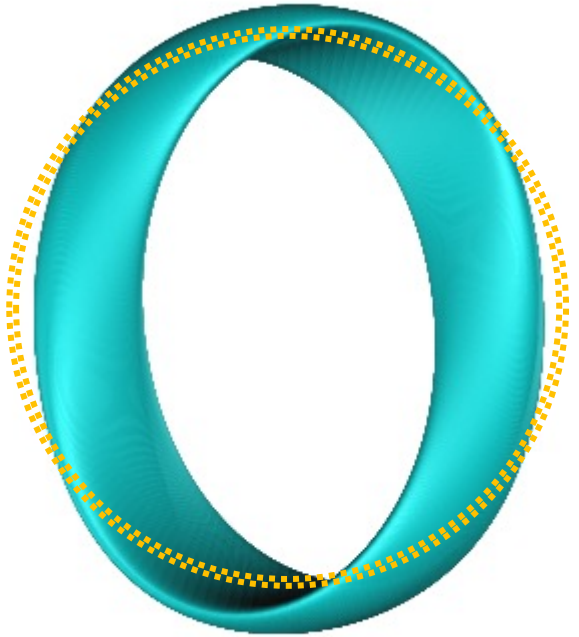
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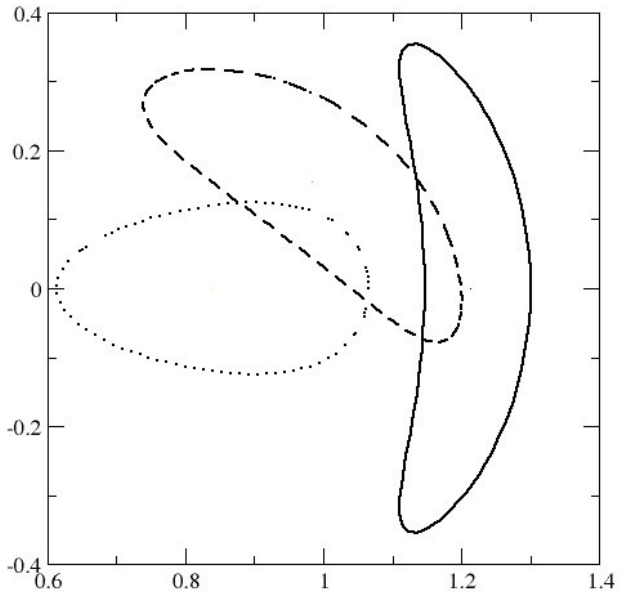
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Landreman and Paul, PRL, 2022

Resulting estimated aspect ratio: -

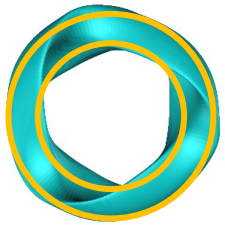




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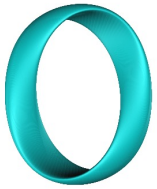
Henneberg et al., NF, 2019

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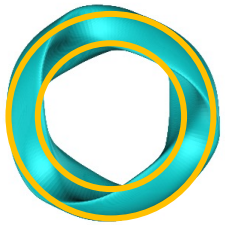
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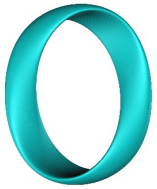
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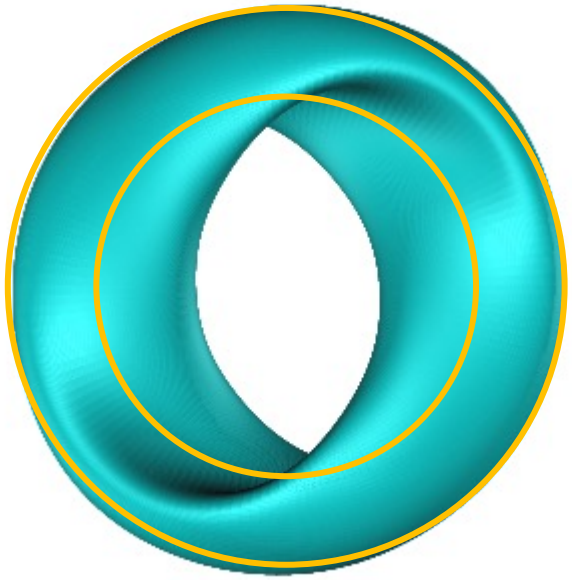
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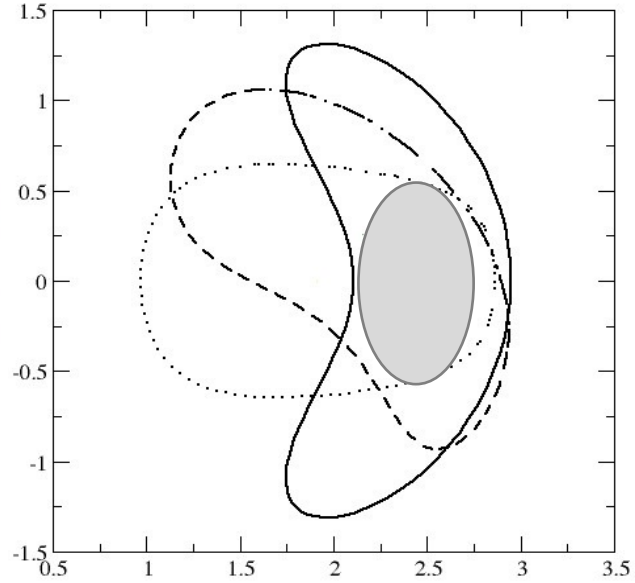


Landreman and Paul, PRL, 2022

Resulting estimated aspect ratio: -







Garabedian and McFadden, J Res Natl Inst Stand Technol. 2009

Resulting estimated aspect ratio: **5.6**

Can the (axisymmetric) design become even more compact?

Perturbed axisymmetric, quasi-axisymmetric equilibria

- Quasi-axisymmetric perturbation of axisymmetric equilibria have been discussed and numerically investigated (e.g. Boozer PPCF 2008; Ku and Boozer, PoP 2009)

- More recently, axisymmetric designs have been analytically perturbed while preserving quasi-axisymmetry
  - **In vacuum** (Plunk and Helander JPP 2018)
  - **And at finite beta** (Plunk JPP 2020)

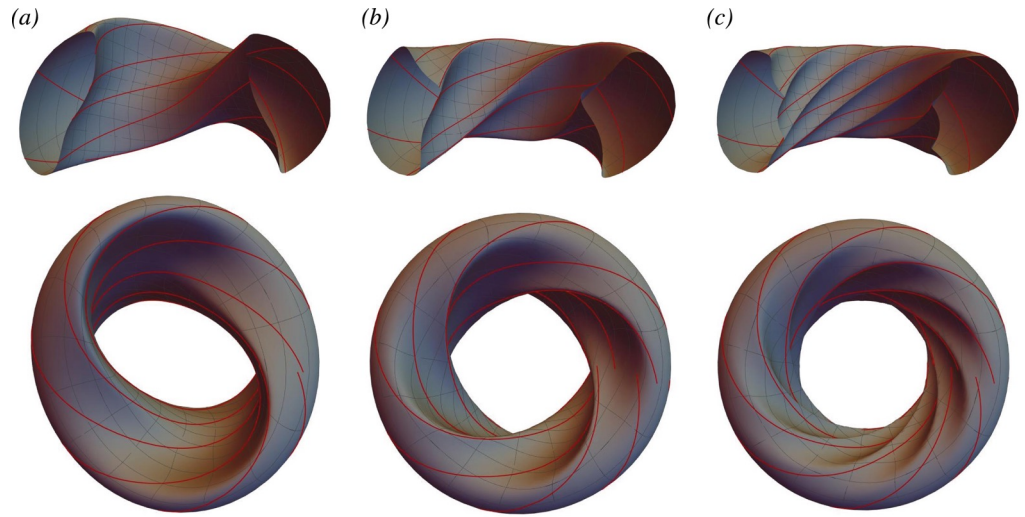


Ku and Boozer, PoP 2009

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The last approach finds very compact QA designs.

How were they found?

Perturbed axisymmetric, quasi-axisymmetric equilibria

- Describing the equilibrium in Boozer coordinates with the toroidal magnetic flux $\psi(\boldsymbol{x})$, and the Boozer poloidal and toroidal angles $\theta(\boldsymbol{x})$ and $\varphi(\boldsymbol{x})$ where $\boldsymbol{x}$ is the location.

- Using the so-called inverse formulation where $\boldsymbol{x}(\psi, \theta, \varphi)$.

- The location and other relevant properties can be perturbed in terms of a small parameter which quantifies the axisymmetric perturbation:

$$\boldsymbol{x} = \boldsymbol{x_0} + \epsilon \boldsymbol{x_1} + \epsilon^2 \boldsymbol{x_2} + \cdots$$

Plunk JPP 2020

Perturbed axisymmetric, quasi-axisymmetric equilibria (cont')

- Now one can obtain different orders of force balance equation $\boldsymbol{J}\times\boldsymbol{B} = \nabla \mathrm{p}$ and the MHD-constraint equation $\boldsymbol{B_{cov}} = \boldsymbol{B_{contra}}$:

$$\frac{\partial \boldsymbol{x}}{\partial \varphi} + \iota \frac{\partial \boldsymbol{x}}{\partial \theta} = G \frac{\partial \boldsymbol{x}}{\partial \psi} \times \frac{\partial \boldsymbol{x}}{\partial \theta} + I \frac{\partial \boldsymbol{x}}{\partial \varphi} \times \frac{\partial \boldsymbol{x}}{\partial \psi} + K \frac{\partial \boldsymbol{x}}{\partial \theta} \times \frac{\partial \boldsymbol{x}}{\partial \varphi}$$

  while enforcing at a given order $\frac{\partial B^2}{\partial \varphi} = 0$.

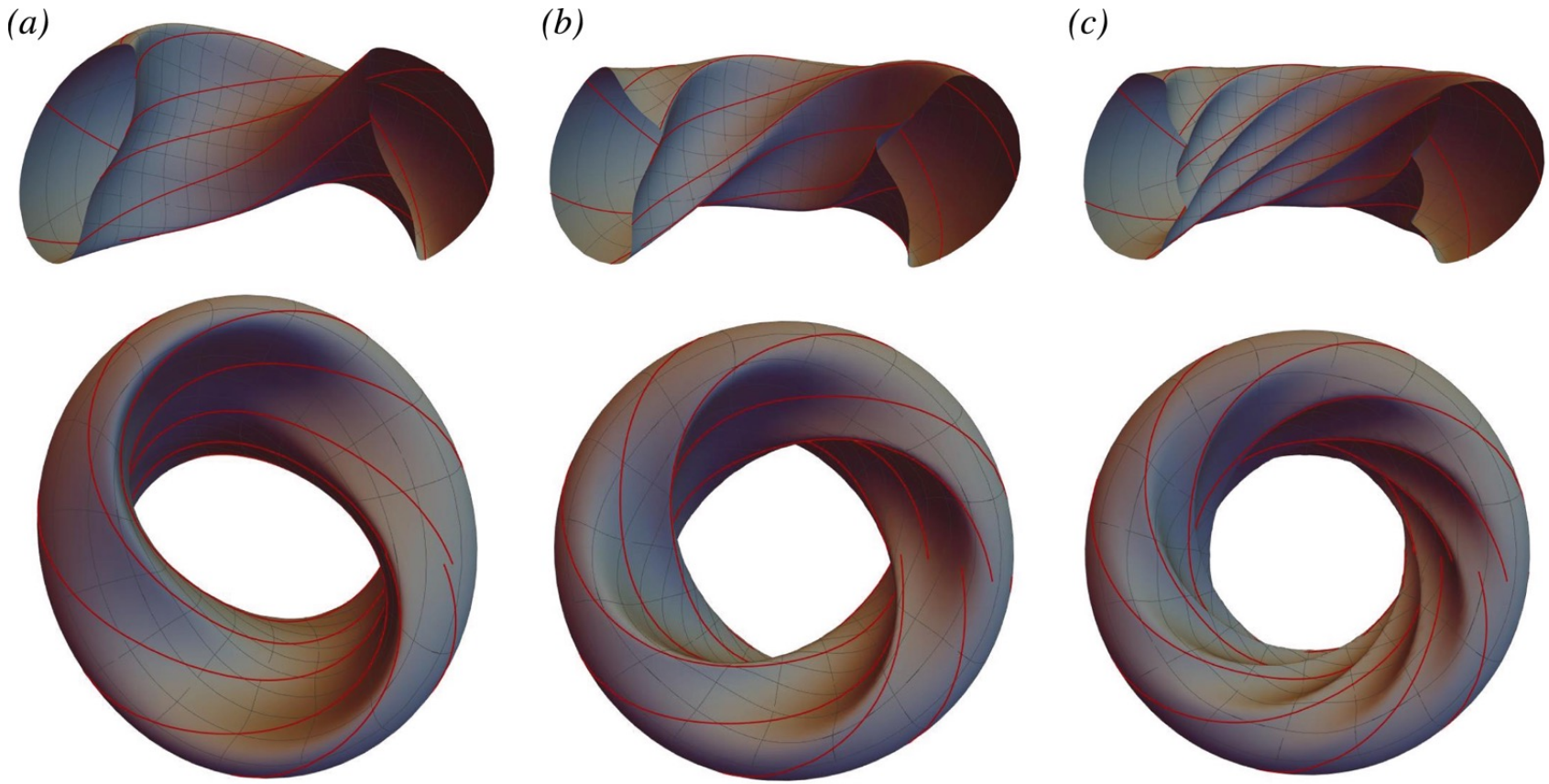
- (currents G, I and pressure p are unperturbed.)

→ 0th order: axisymmetric equilibrium equation: the Grad-Shafranov equation.

→ 1st order: set of four differential equations for the four unknowns $(\boldsymbol{x_1}, K_1)$.

Plunk JPP 2020

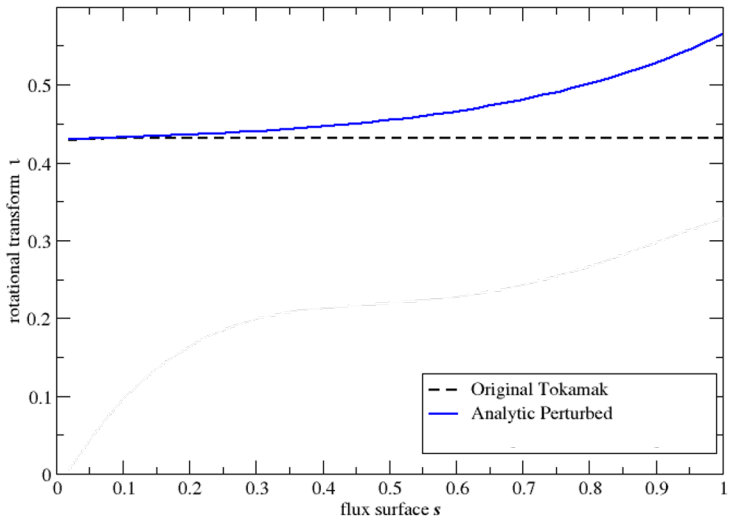
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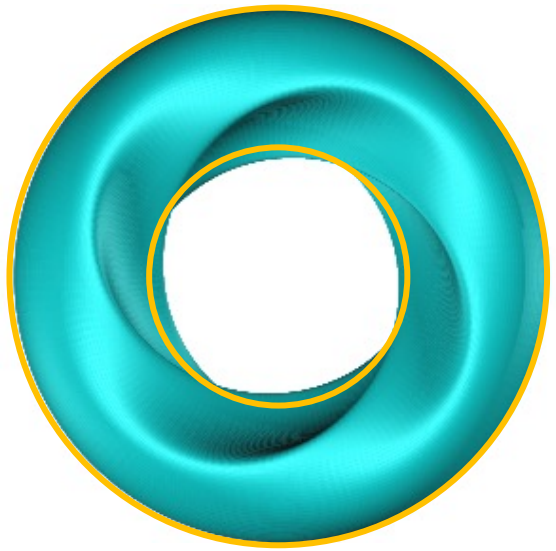


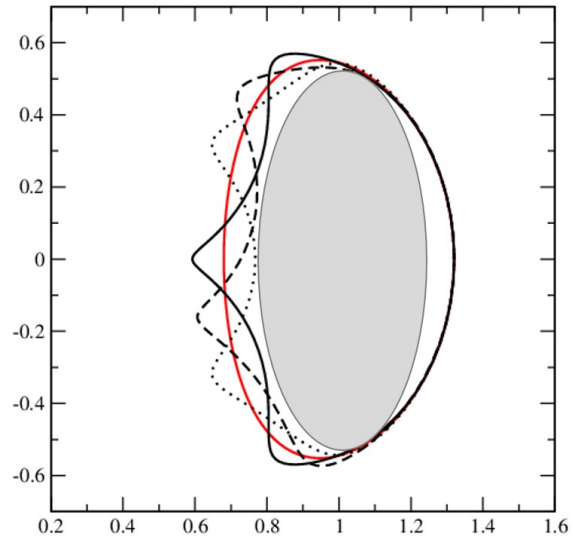
Plunk JPP 2020

The perturbed equilibrium we examined:

- Aspect ratio of 2.4
- NFP=4
- Resulting estimated aspect ratio**: 2.9**



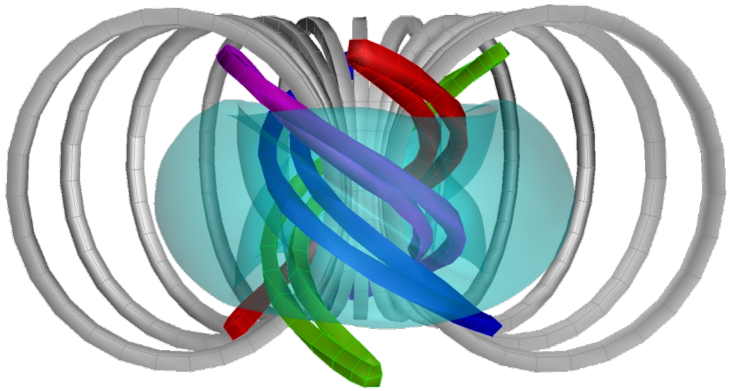


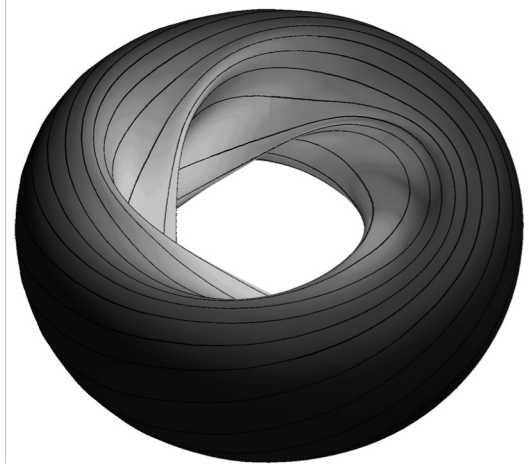


Can we find simple coils for that?

And can we run it purely as a stellarator too?

Content





Motivation & Background

- **Why are we interested in a stellarator-tokamak hybrid?**
- **Some historic examples of hybrids**
- **What are perturbed axisymmetric quasi-axisymmetric equilibria?**

Hybrid Design

- **Coil set of a compact hybrid**
- **Free-boundary equilibrium**
- **Flux-Surfaces in vacuum**

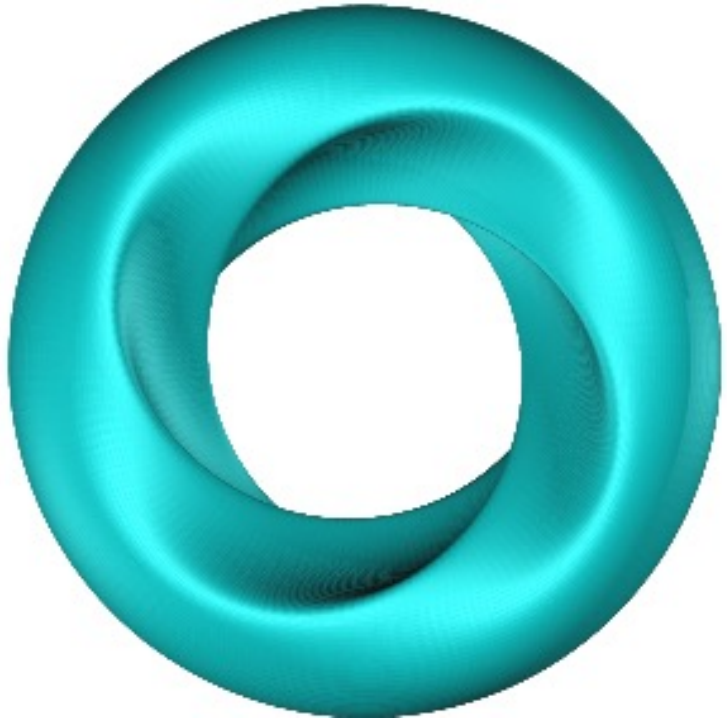
Optimization of the physics properties of these novel compact QA stellarators

- **Optimizing QA**
- **Adding physics targets**
- **Exploring NFP**
- **Coils**

Ongoing & Future work

Coil optimization (2nd stage [1])

- Keeping the targeted surface fixed.
- Searching for coils which can reproduce this boundary shape.
- The independent degrees of freedom are the coil (filament) geometry and coil current.



[1] Henneberg, et al. JPP 2021

Coil optimization (2nd stage)

- Using coil optimization features of simsopt [1]
- Basic coil optimization target:

$$\varphi_2 + \omega(L - L_T)^2$$

Where L is the length of the coils and $\boldsymbol{\varphi_2}$ is the quadratic-flux error functional:

$$\varphi_2 = \frac{1}{2}\int |B_{E,n} - D_n|^2 \mathrm{d}s$$

With

- $\int ds$ is the surface integral,
- $B_{E,n}$ is the normal component of the coil magnetic field,
- And D_n is the targeted normal component of the external magnetic field.

[1] Landreman et al., J. Open Source Softw. 2021

Coil optimization (2nd stage) (cont')

1. Design coils for axisymmetric equilibrium
   - Poloidal field coils (PF) (4)
   - Toroidal field coils (TF) (20)

2. Optimize QA-coils while keeping tokamak coils fixed, with different geometries:
   - Conventional modular coils.
   - Initialize with 8 small circular coils on the inboard side of the torus (linked & non-linked).
   - Initialize with 4 small circular coils on the inboard side of the torus.

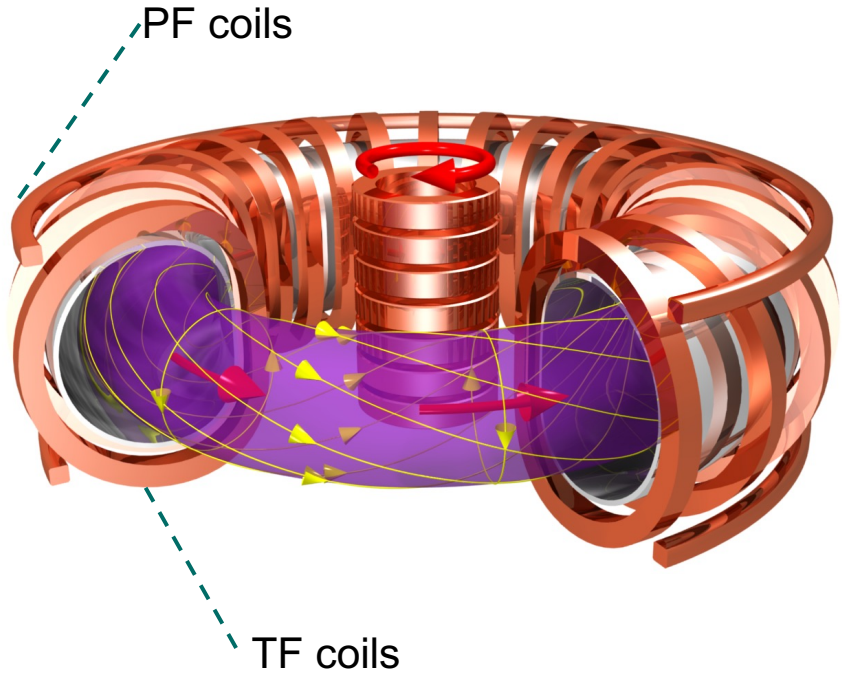
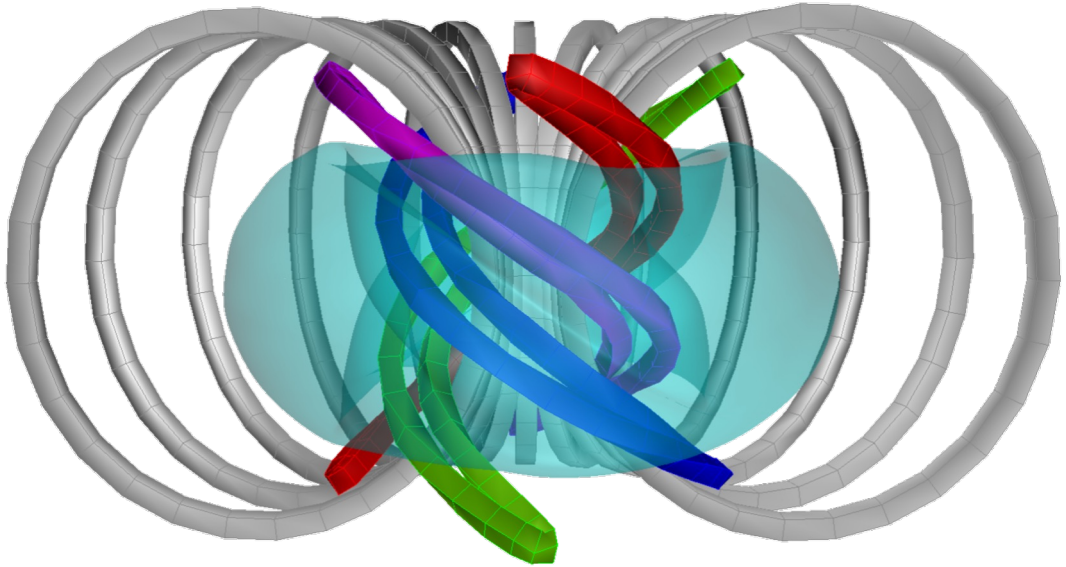


Fig: Brandt, IPP 2011

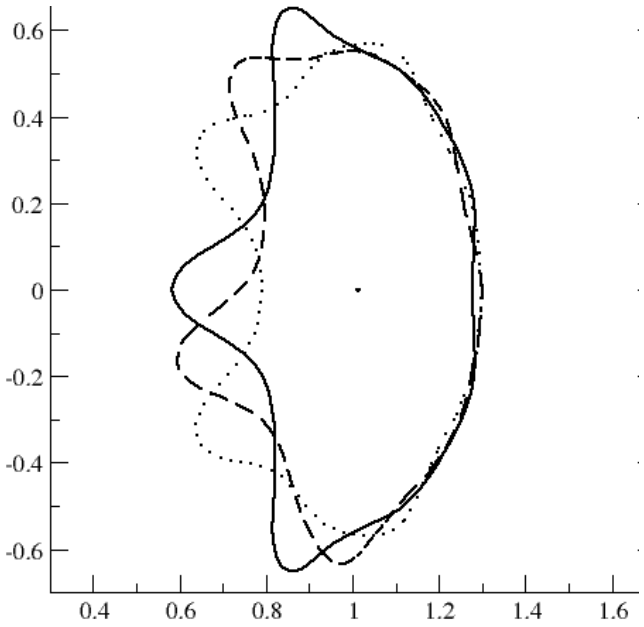
A new type of QA-stellarator-tokamak hybrid

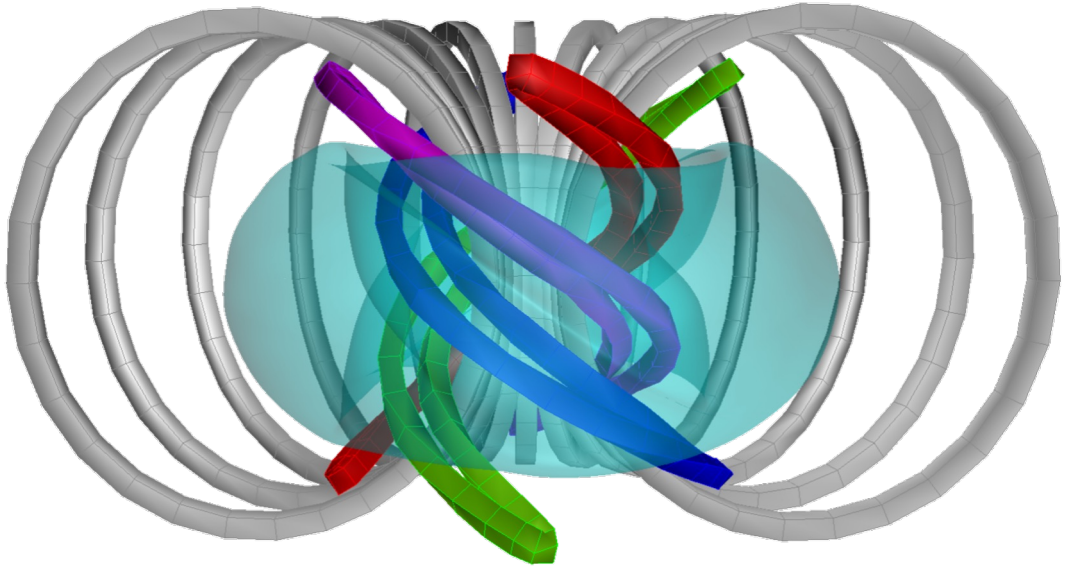
- Aspect ratio is <2.4 for both QA-stellarator & tokamak.
- Only one type of stellarator coil needed in addition to tokamak coils.
- These coils are modular-modular coils in the sense that they are not interlinked with the plasma.
- Can be operated as a tokamak or a QA-stellarator or anything in-between.



A new type of QA-stellarator-tokamak hybrid

- Resulting plasma boundary: main features as from analytic solution.

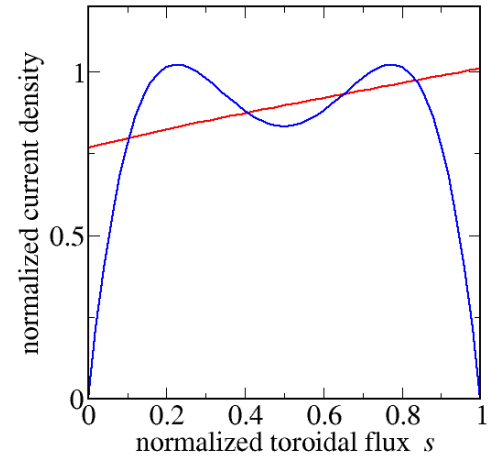


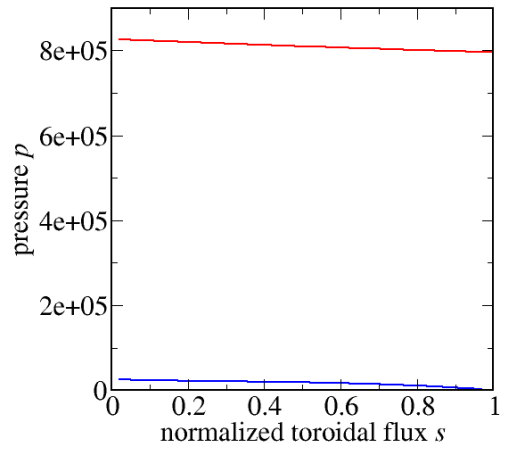


A new type of QA-stellarator-tokamak hybrid

- Resulting plasma boundary: main features as from analytic solution.

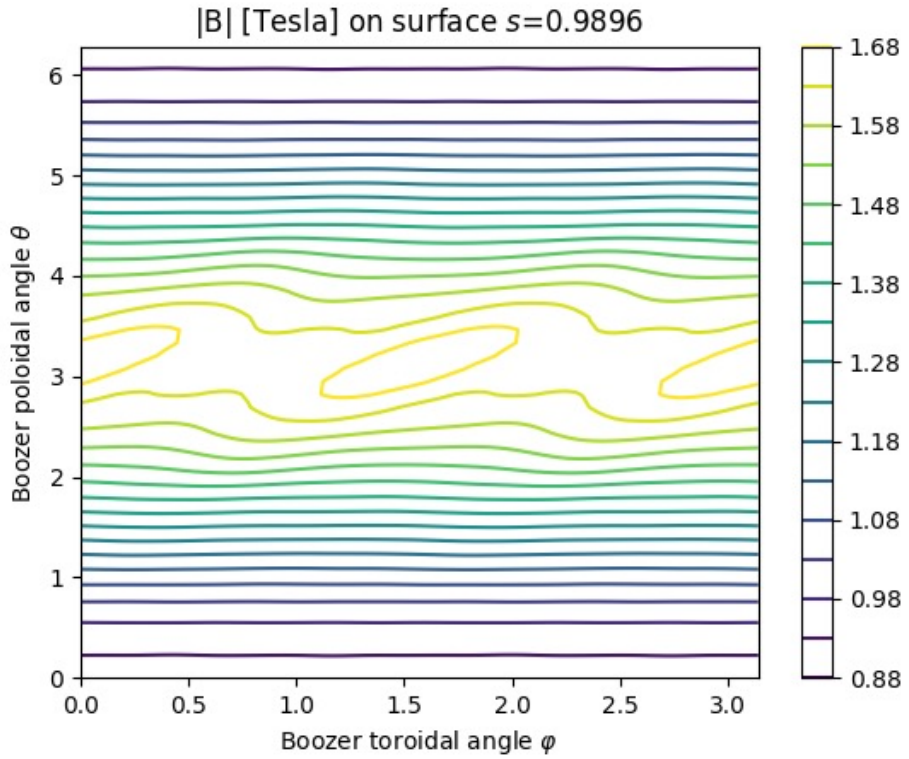
- Let check the properties for different pressure and vacuum:
  - Original
  - Altered pressure and current profiles
  - Zero pressure and current profiles (still VMEC solution)

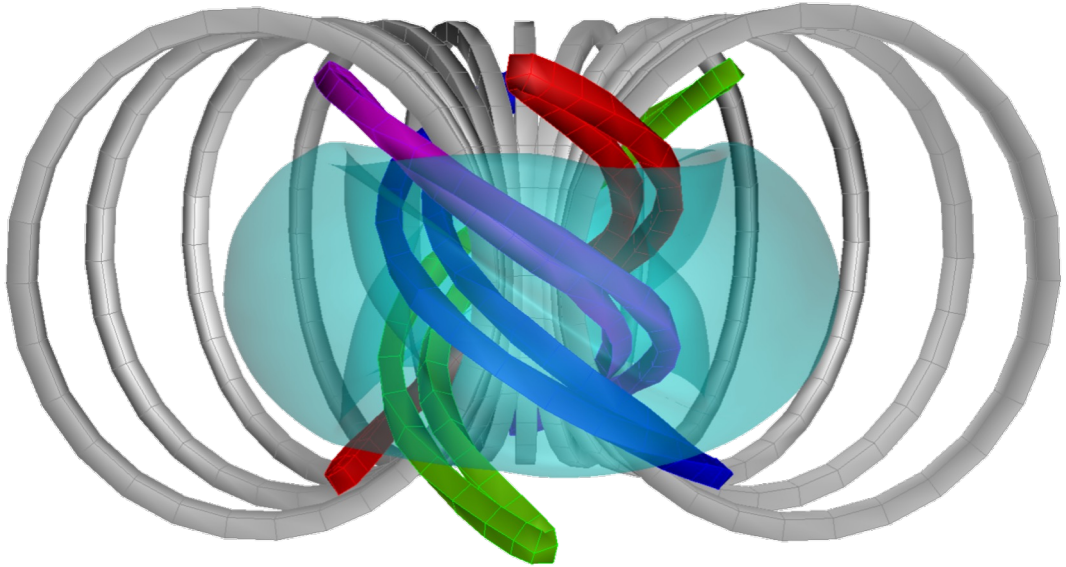




Quasi-symmetry

- Contours of magnetic field strength on the plasma boundary:





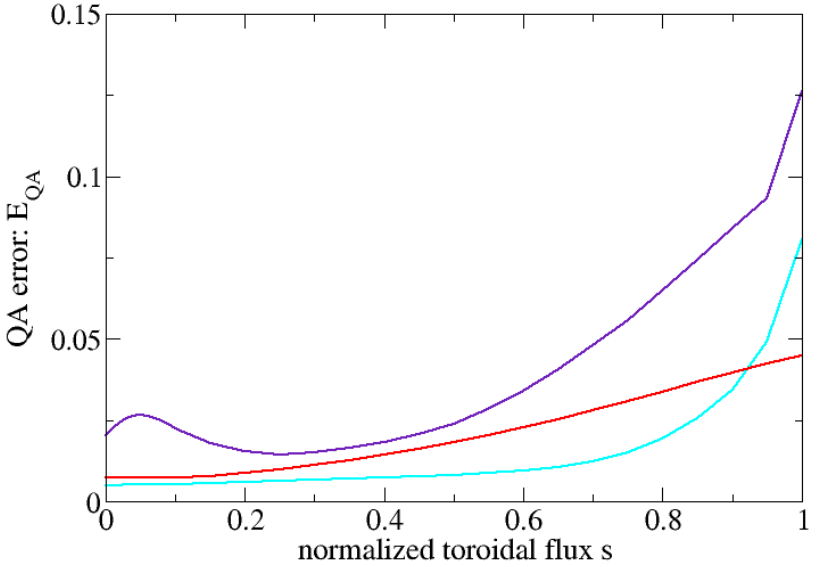
Quasi-symmetry

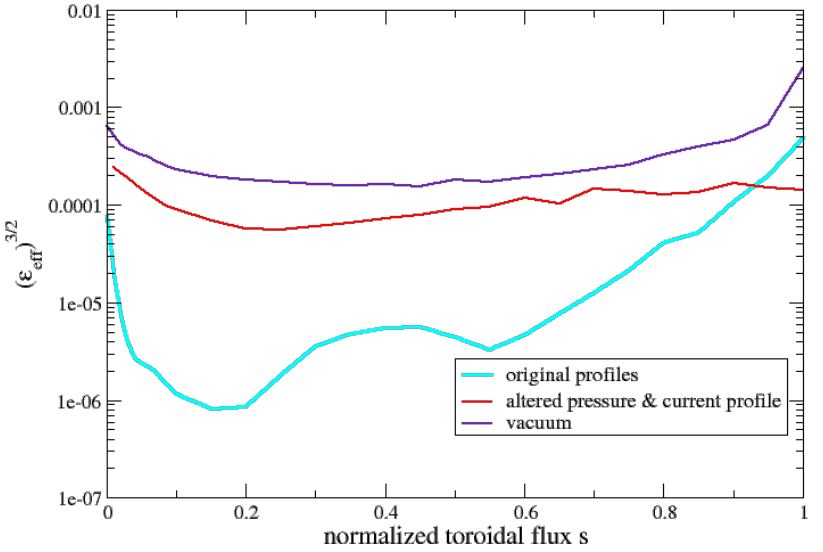
- Quasi-axisymmetric error:

$$E_{QA} = \frac{\sqrt{\sum_{n\neq 0,m} B_{m,n}^2}}{B_{00}}.$$

- Effective ripple ϵ_{eff} is a proxy for neoclassical transform

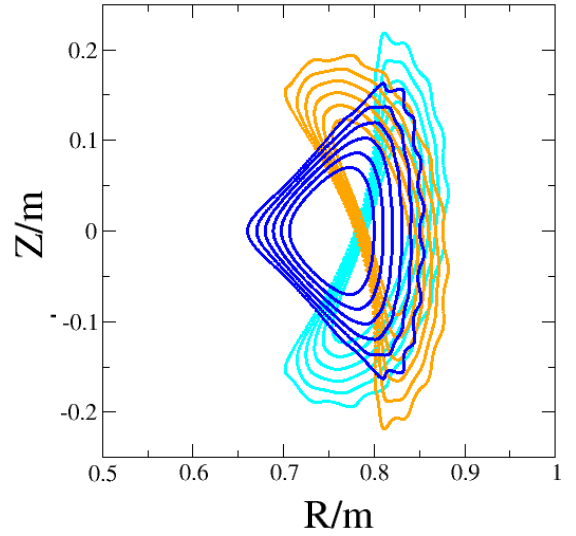
  Nemov et al., PoP 1999

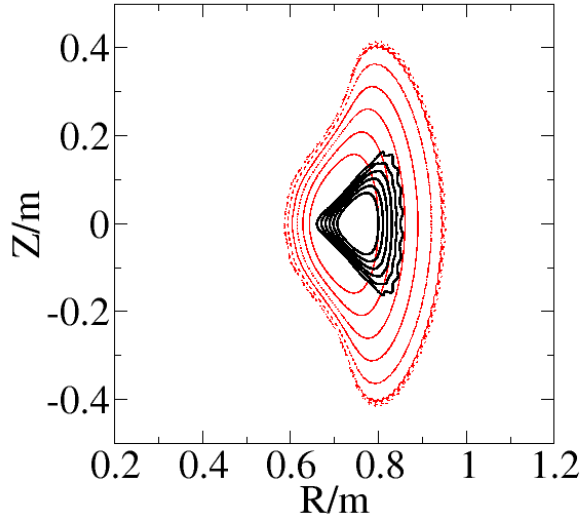




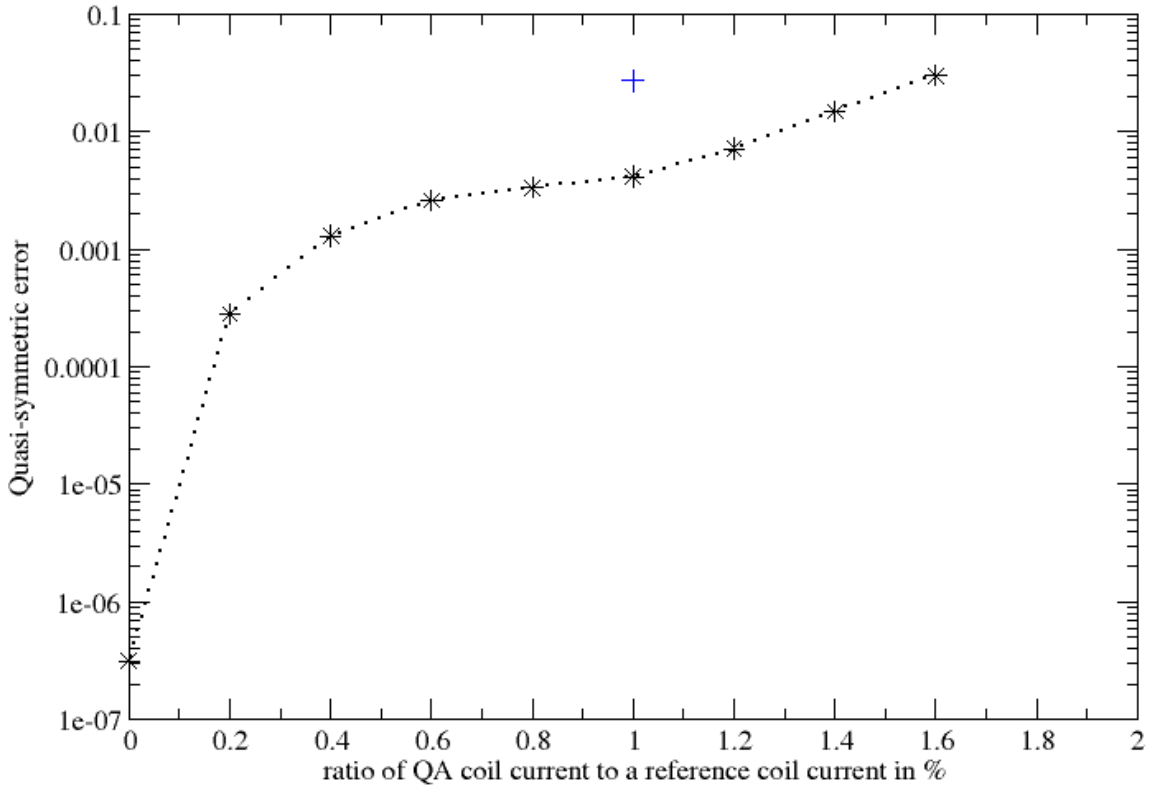
Vacuum flux surfaces & rotational transform

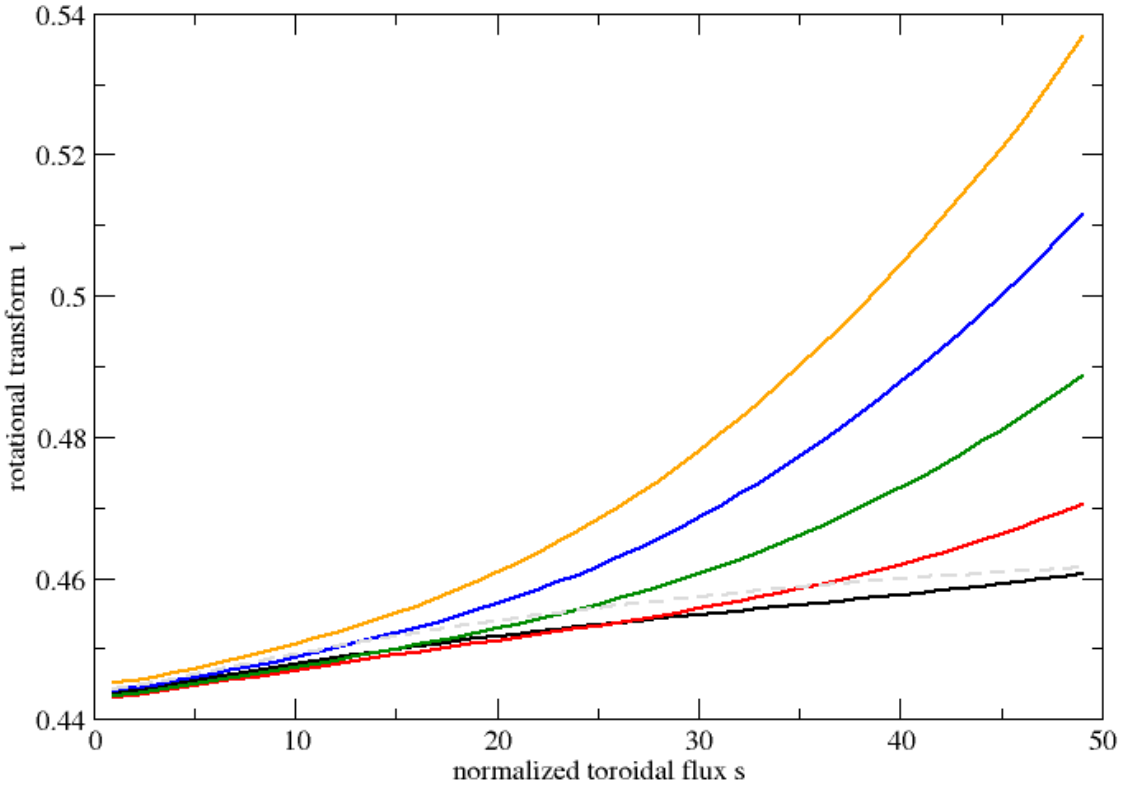
- It is not guaranteed that there are flux surfaces in vacuum for the quasi-axisymmetric solution.
- We have to test → Poincaré Plots
- Less volume because of a low order rational in the iota profile (near 0.308≈ $4/13$)
- We can change the QA current to alter rotational transform (0.13 … 0.1) → changes volume of vacuum flux surfaces.
- Flux surfaces in vacuum could be used for start-up for the tokamak part too!



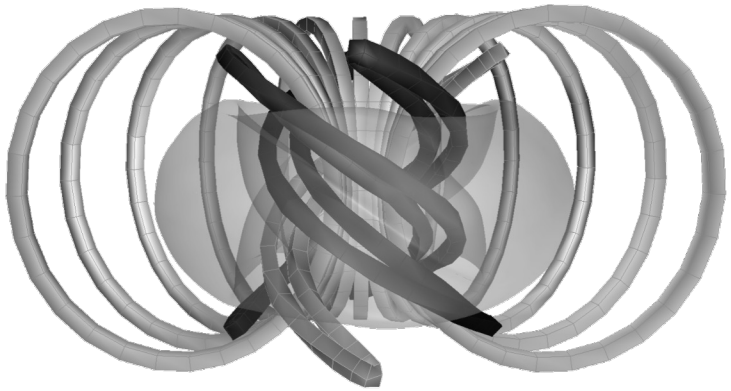


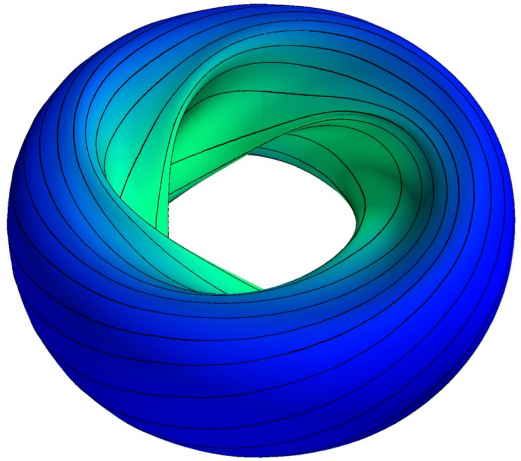
Going from tokamak to QA-stellarator





Content





Motivation & Background

- **Why are we interested in a stellarator-tokamak hybrid?**
- **Some historic examples of hybrids**
- **What are perturbed axisymmetric quasi-axisymmetric equilibria?**

Hybrid Design

- **Coil set of a compact hybrid**
- **Free-boundary equilibrium**
- **Flux-Surfaces in vacuum**

Optimization of the physics properties of these novel compact QA stellarators

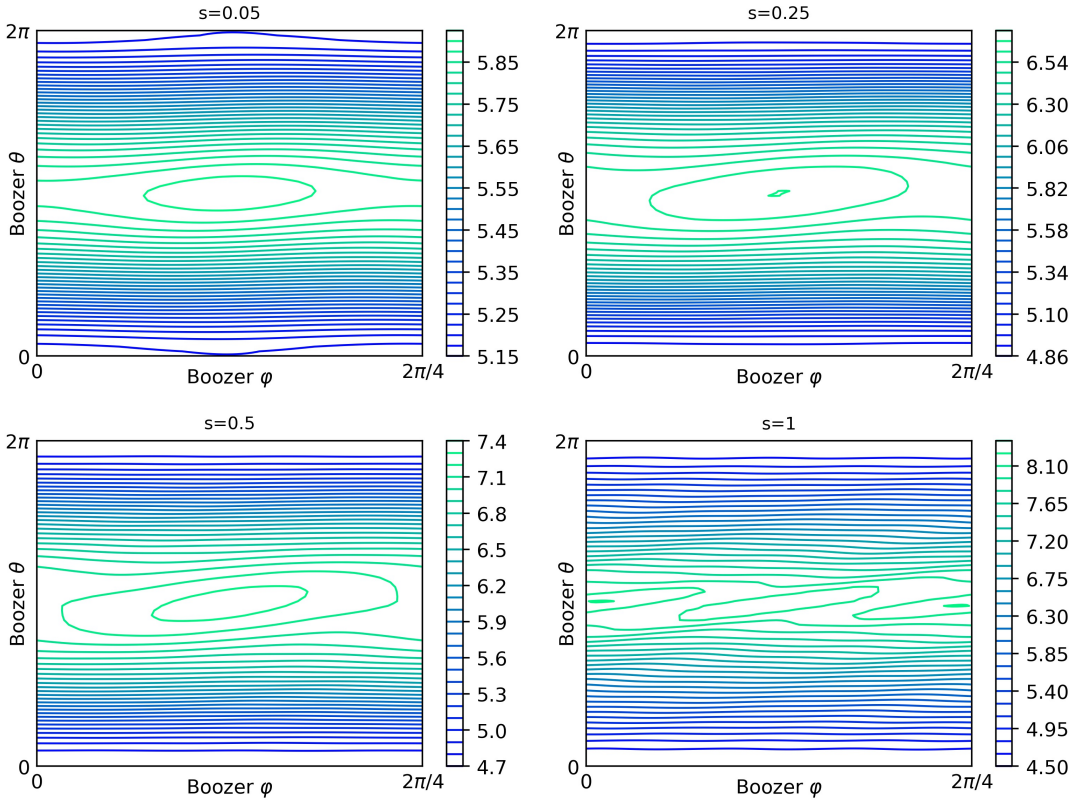
- **Optimizing QA**
- **Adding physics targets**
- **Exploring NFP**
- **Coils**

Ongoing & Future work

Can we optimize these novel types of perturbed axisymmetric equilibria?

- For investigating coil sets, we have used analytic solutions for the plasma boundary.
- Quasi-symmetry isn‘t as high as modern QA designs.

→ Can we improve the quality of quasi-axisymmetry?

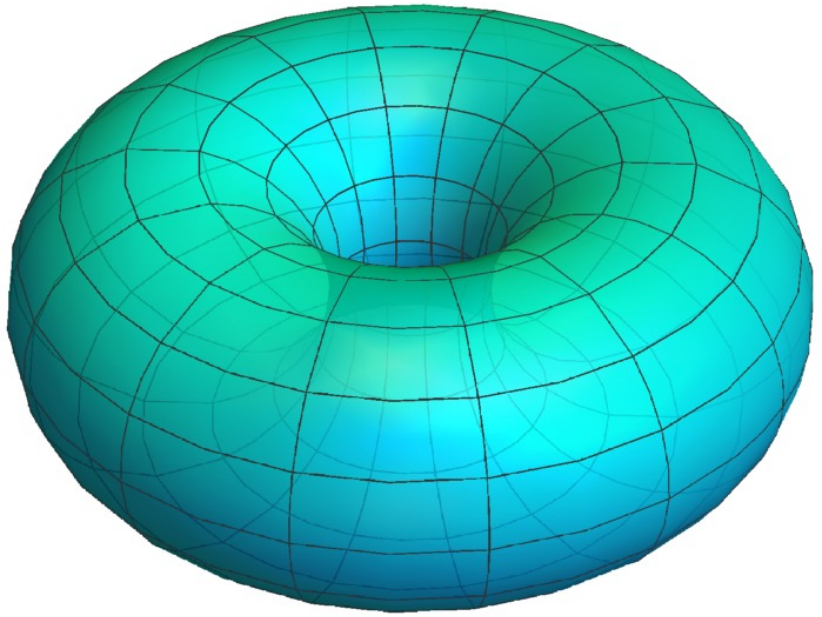


Optimizing perturbed axisymmetric equilibria for QA?

- The only example of a perfectly global quasi-axisymmetric equilibrium we know of, is the *axisymmetric case*.
  So if we start from close to axisymmetry the optimizer will find axisymmetric solutions!

- In the past this has been typically avoided by perturbing the initial equilibrium sufficiently.

→ One has to be careful while optimizing.



Plasma boundary optimization (1st stage [1])

- Independent degrees of freedom: plasma boundary shape:
  (Using the ideal MHD equilibrium code VMEC [2]):

$$R = \sum_{m=0}^{M} \sum_{n=-N}^{N} R_{m,n} \cos(m\theta - N_p n\varphi)$$

$$Z = \sum_{m=0}^{M} \sum_{n=-N}^{N} Z_{m,n} \sin(m\theta - N_p n\varphi)$$

Where φ is the toroidal angle, and θ is a poloidal angle.

We are using the Fourier harmonics as the independent degree of freedom.

[1] Henneberg, et al. JPP, 2021

[2] Hirshman & Whitson, Phys. Fluids, 26, 1983

Plasma boundary optimization (1st stage)

- Using plasma optimization features of simsopt [1].

- Optimization target:

$$f_A + f_{QS} + f_\beta + f_\iota$$

Where

- $f_A = (A - A^*)^2$ targets a certain aspect ratio (here we used typically $A^* \approx 2.4$),
- $f_{QS} = \sum_{s_j} \left\langle \left(\frac{1}{B^3} [-\iota \, \boldsymbol{B} \times \nabla B \cdot \nabla \psi - G \, \boldsymbol{B} \cdot \nabla B] \right)^2 \right\rangle$ [2]
  where ι is the rotational transform and $2\pi G/\mu_0$ is the poloidal current.
- $f_\beta = \max[\beta - 0.05, 0]^2$ to target the plasma beta to stay below 5%.
- f_ι is the new target to ensure that the optimizer finds non-axisymmetric solutions.

[1] Landreman et al., J. Open Source Softw. 2021

[2] Landreman and Paul, PRL, 2022

New external rotational transform target

- Let's define the external rotational transform ι_{ext} as the difference between the rotational transform of a given equilibrium ι and an *equivalent axisymmetric* equilibrium ι_{axi} :

$$\bar{\iota}_{\text{ext}} \equiv \bar{\iota} - \bar{\iota}_{\text{axi}}.$$

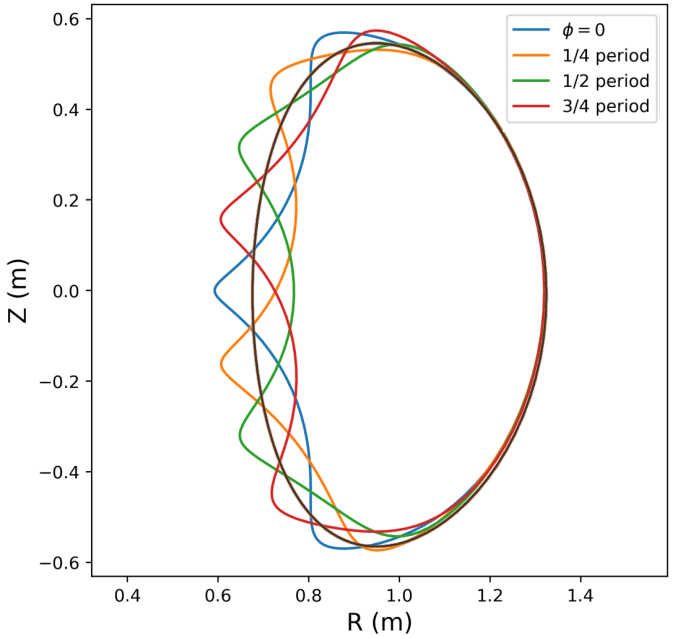
- So to find the equivalent axisymmetric, we simply set all non-axisymmetric Fourier components equal zero:

$$R_{mn} = Z_{mn} = 0 \text{ for } n \neq 0.$$

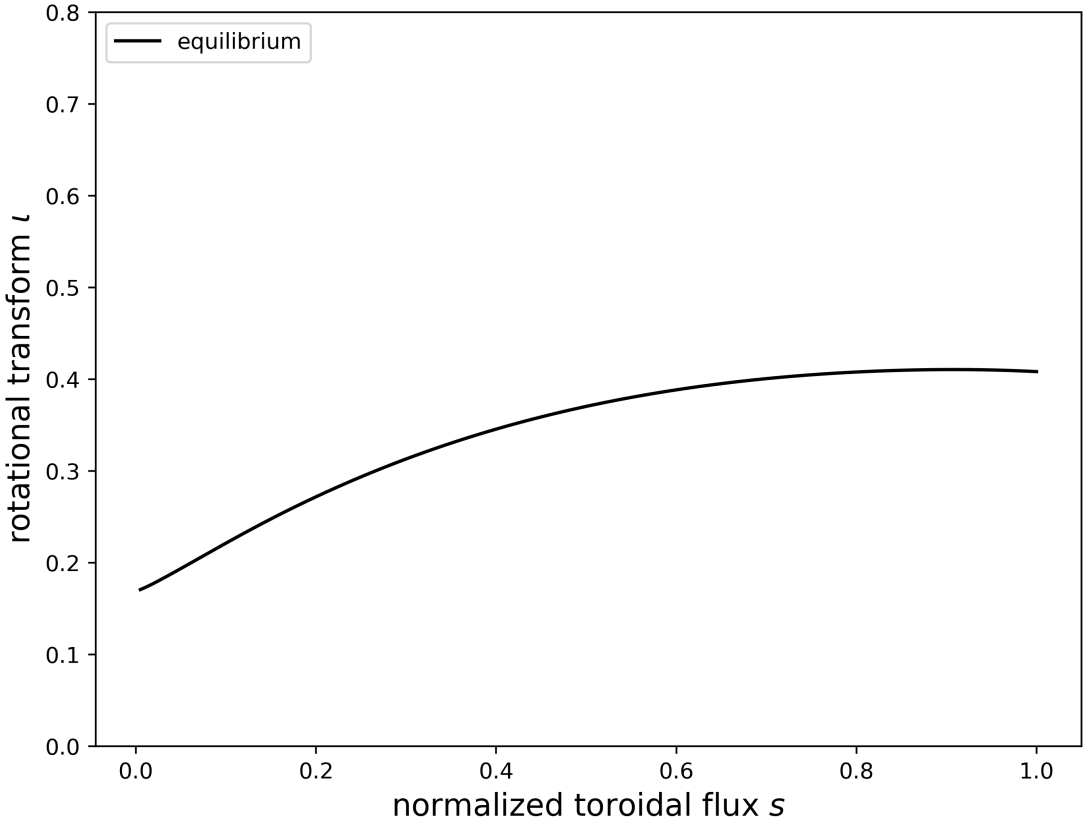
- Our target is now given by:

$$f_\iota = \max[\, \bar{\iota}^*_{\text{ext}} - \bar{\iota}_{ext}, 0]^2$$

with the the targeted mean external rotational transform $\bar{\iota}^*_{\text{ext}}$.



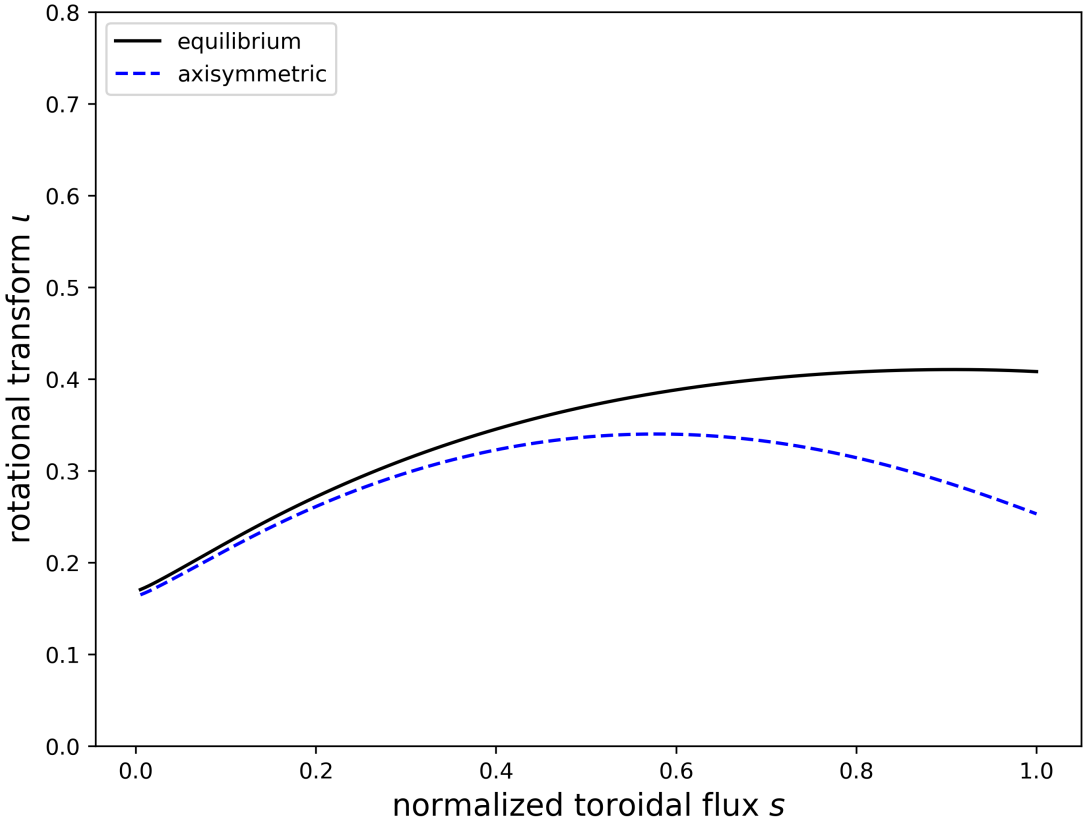
New external rotational transform target



- We construct an equilibrium by setting all the non-axisymmetric Fourier harmonics equal to zero:

$$R_{mn} = Z_{mn} = 0 \text{ for } n \neq 0.$$

New external rotational transform target

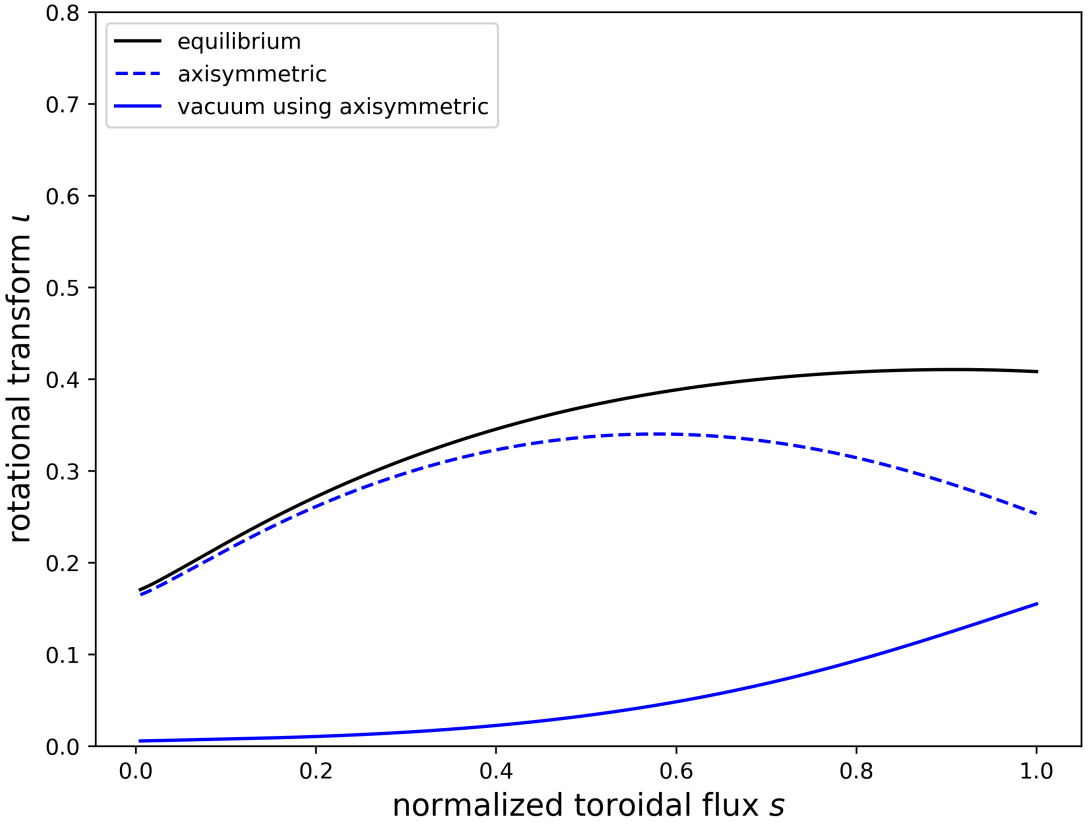


- We construct an equilibrium by setting all the non-axisymmetric Fourier harmonics equal to zero:

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- The external rotational transform can be determined by the difference of the original rotational transform and the constructed one.

New external rotational transform target

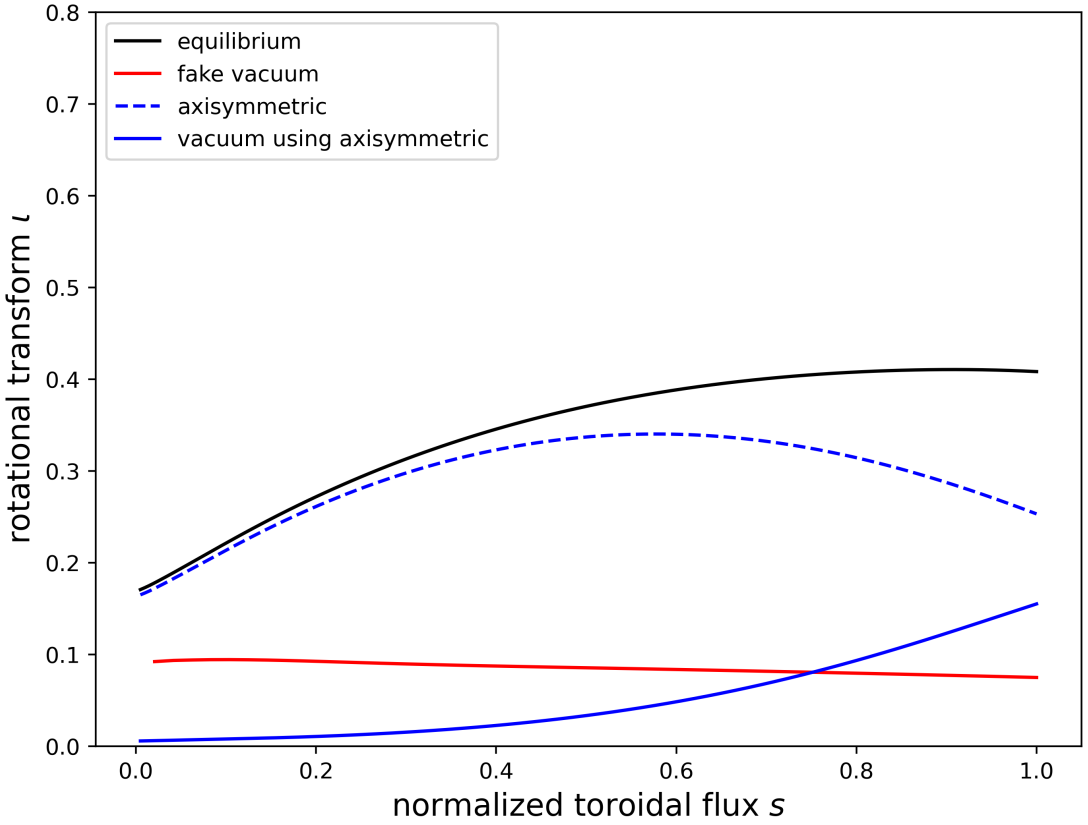


- We construct an equilibrium by setting all the non-axisymmetric Fourier harmonics equal to zero:

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- The external rotational transform can be determined by the difference of the original rotational transform and the constructed one.
- This rotational transform differs from the one of the zero-beta and zero-current equilibrium solution (“fake vacuum”).

New external rotational transform target

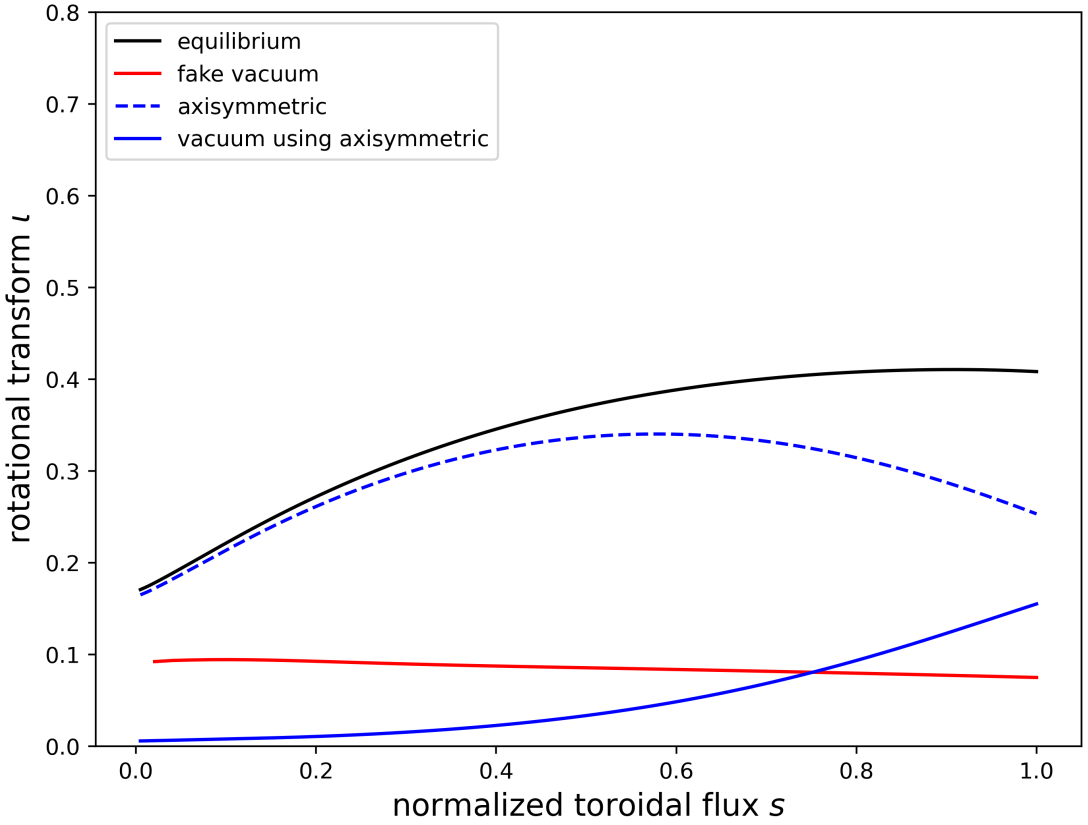


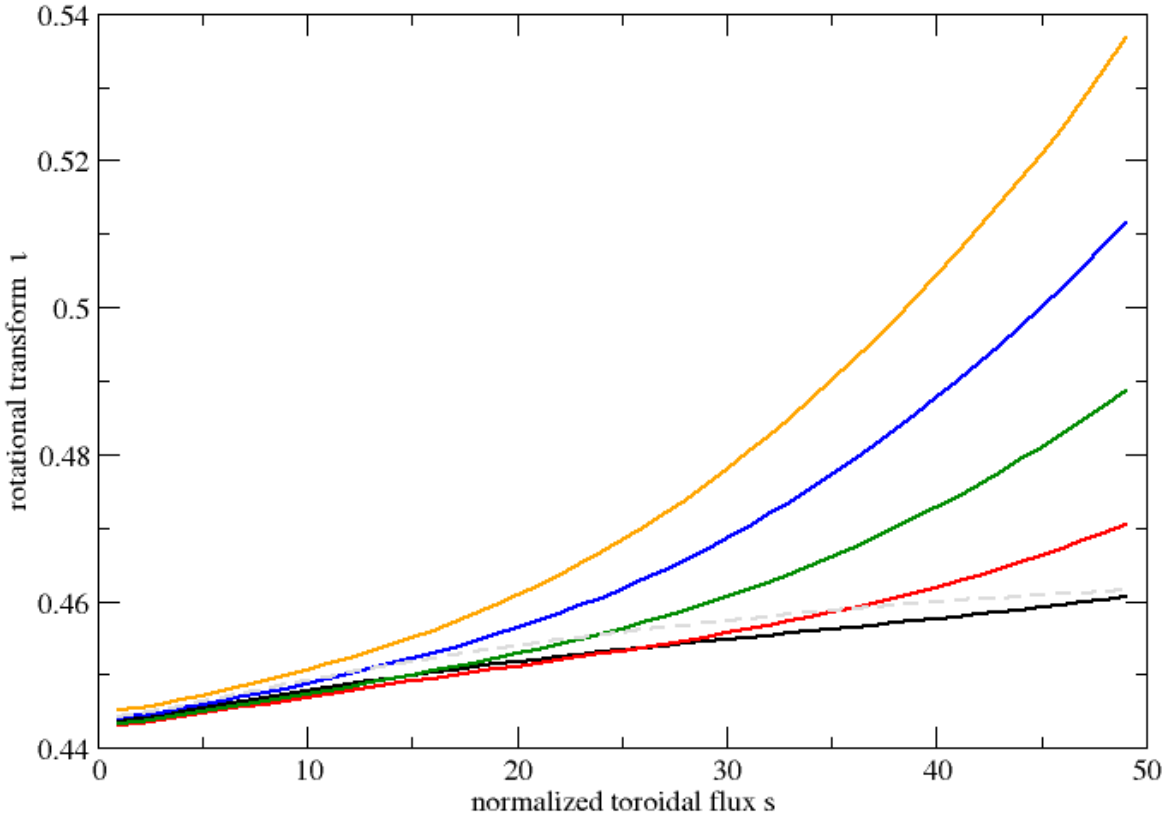
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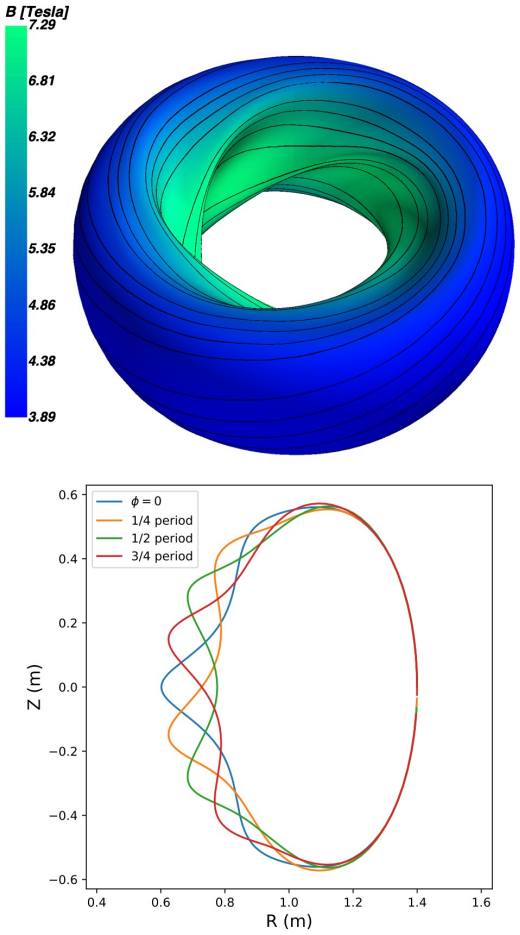
- The external rotational transform can be determined by the difference of the original rotational transform and the constructed one.
- This rotational transform differs from the one of the zero-beta and zero-current equilibrium solution (“fake vacuum”).
- Comparing it to the banana coils results.

New external rotational transform target



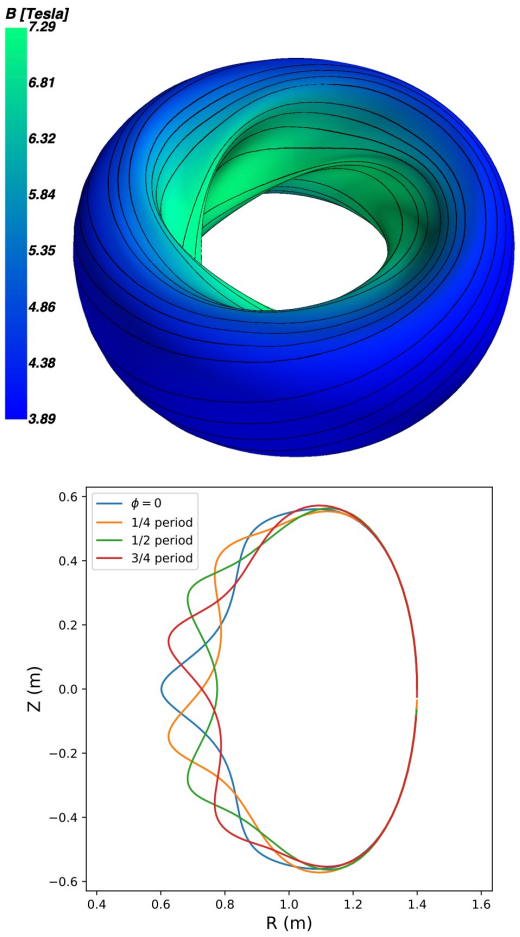


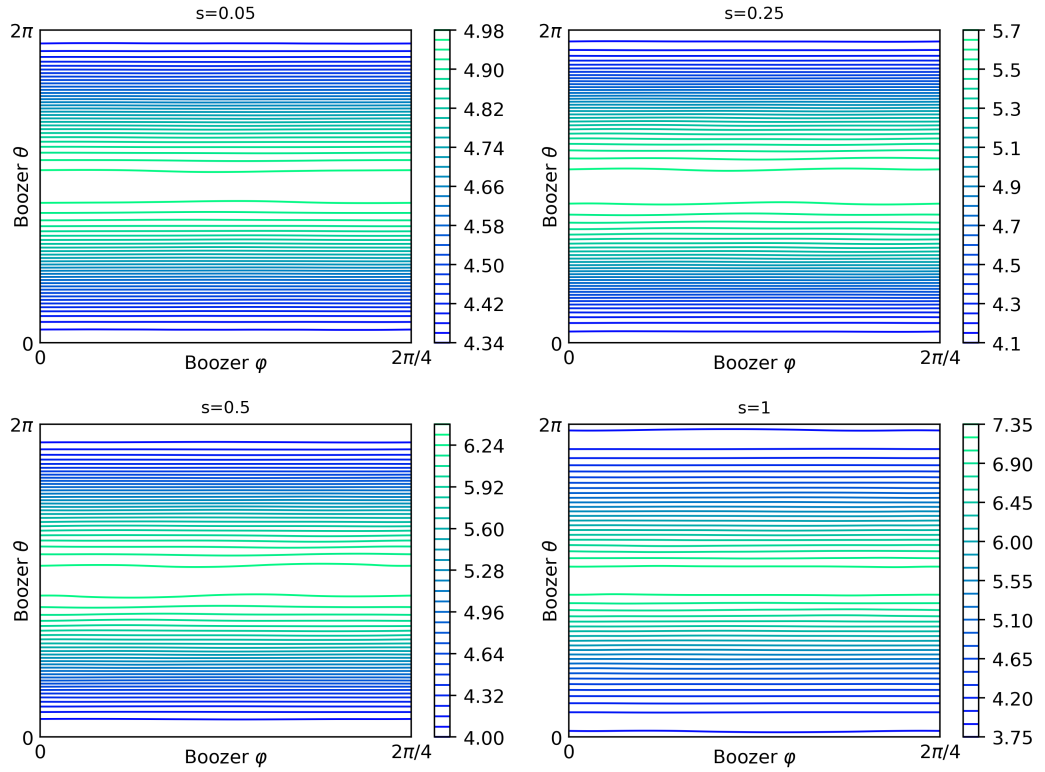
Can we optimize these novel types of perturbed axisymmetric equilibria? Yes!



- Starting point: analytic solution
- $NFP = 4$
- The aspect ratio: fixed to original value = 2.4
- $\bar{l}_{ext,proxy} = \bar{l}^{initial}_{ext,proxy}$

Can we optimize these novel types of perturbed axisymmetric equilibria? Yes!

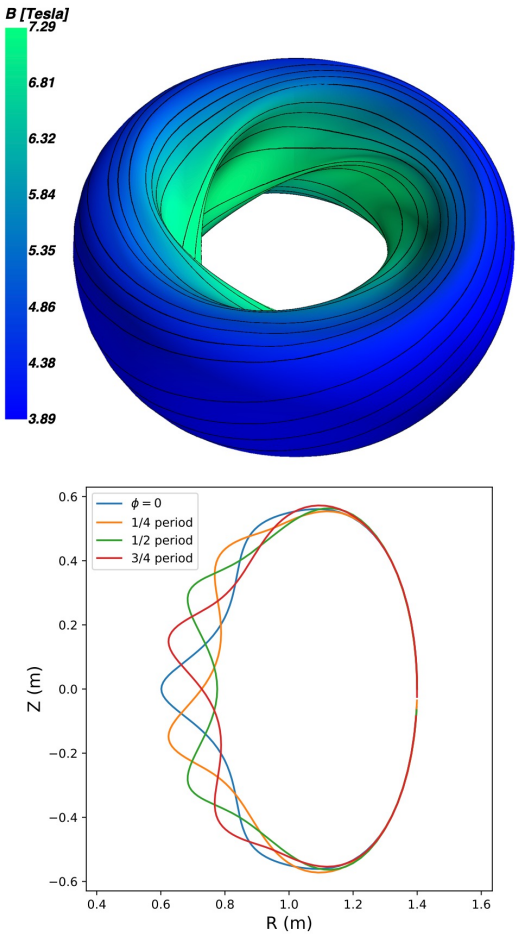




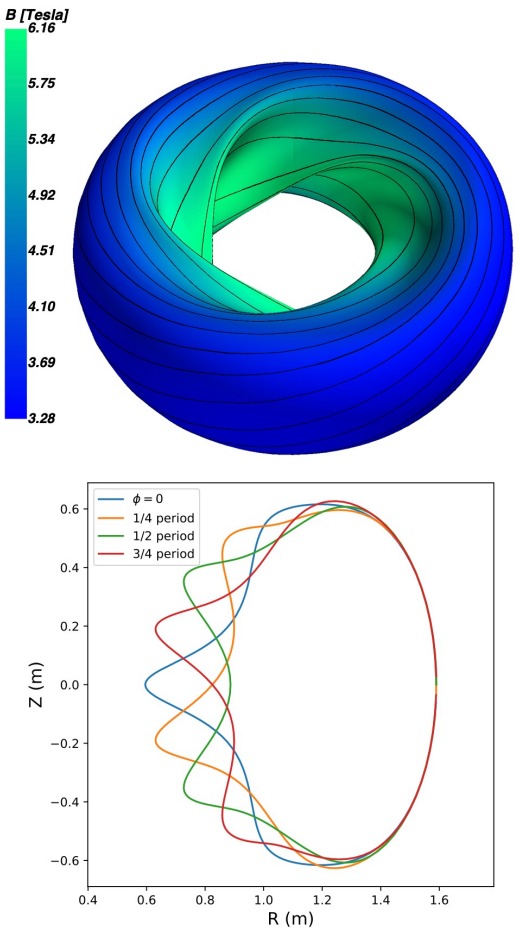
→ What happens when we increase the targeted external rotational transform?

Can we optimize these novel types of perturbed axisymmetric equilibria? Yes!

a.) $\bar{\iota}^{*}_{\text{ext,proxy}} = \bar{\iota}^{\text{initial}}_{\text{ext,proxy}}$

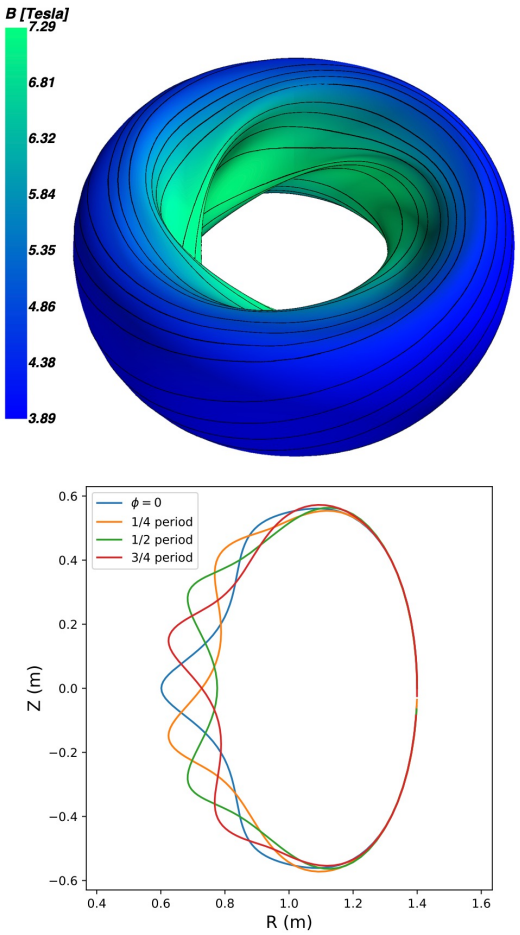


b.) $\bar{\iota}^{*}_{\text{ext,proxy}} = 2\bar{\iota}^{\text{initial}}_{\text{ext,proxy}}$

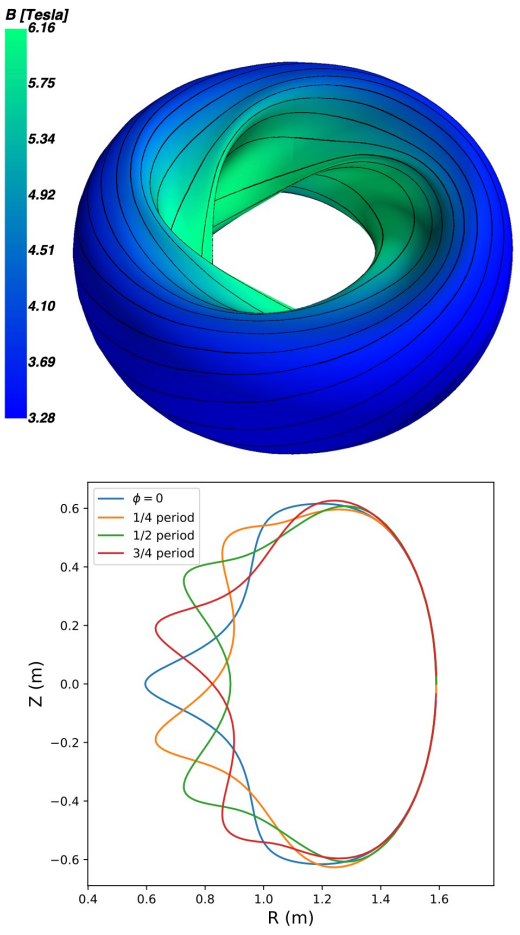


Can we optimize these novel types of perturbed axisymmetric equilibria? Yes!

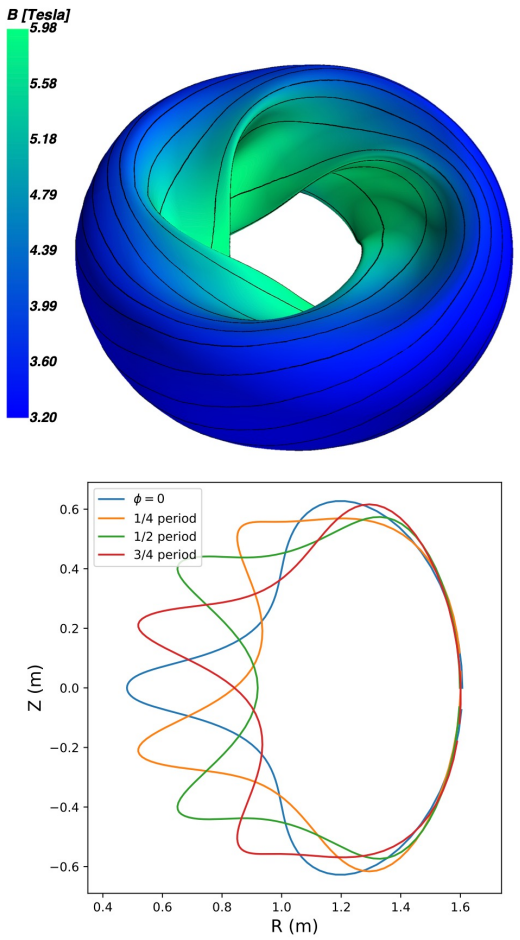
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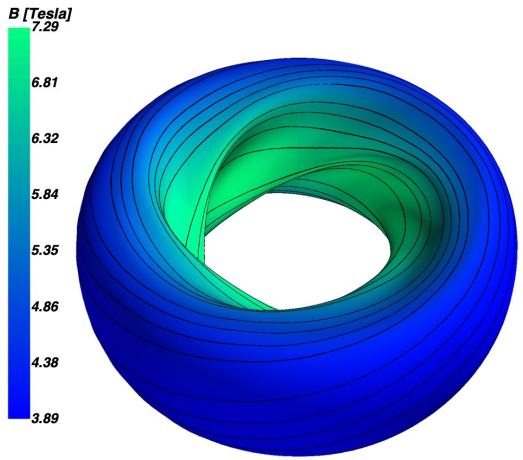


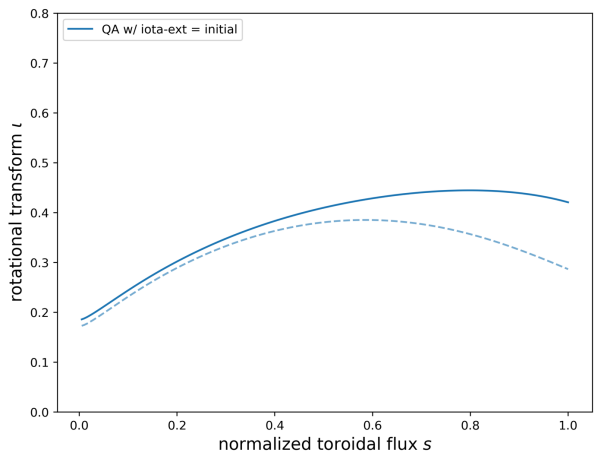
c.) $\bar{\iota}^{*}_{\text{ext,proxy}} = 4\bar{\iota}^{\text{initial}}_{\text{ext,proxy}}$



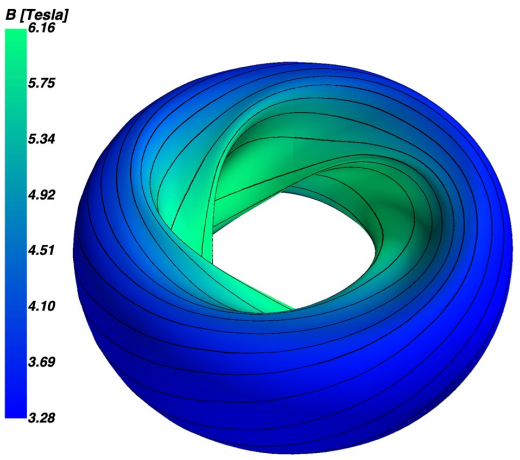
Rotational transform

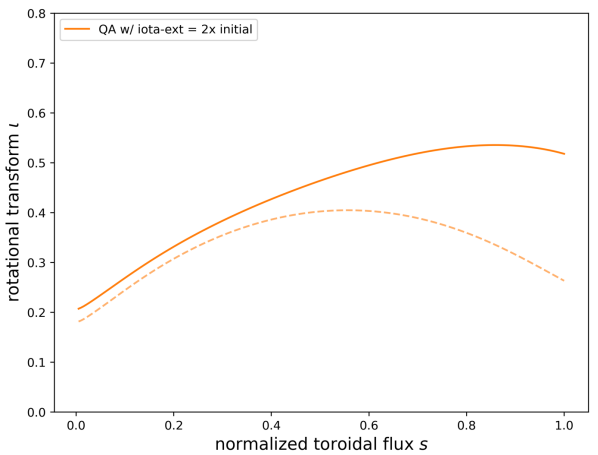
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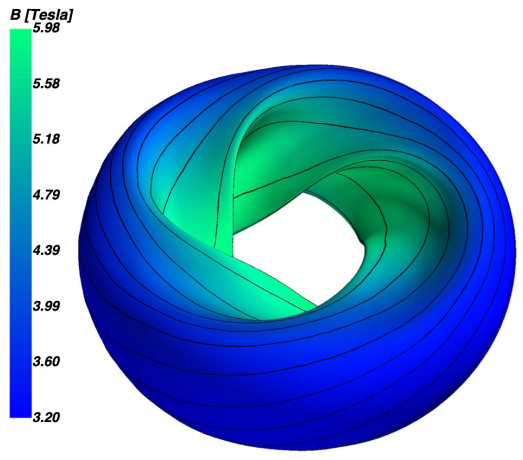


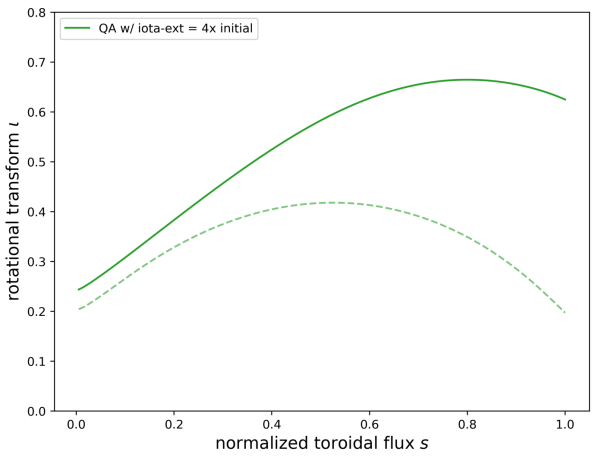
b.) $\bar{\iota}^{*}_{\text{ext,proxy}} = 2\bar{\iota}^{\text{initial}}_{\text{ext,proxy}}$





c.) $\bar{\iota}^{*}_{\text{ext,proxy}} = 4\bar{\iota}^{\text{initial}}_{\text{ext,proxy}}$



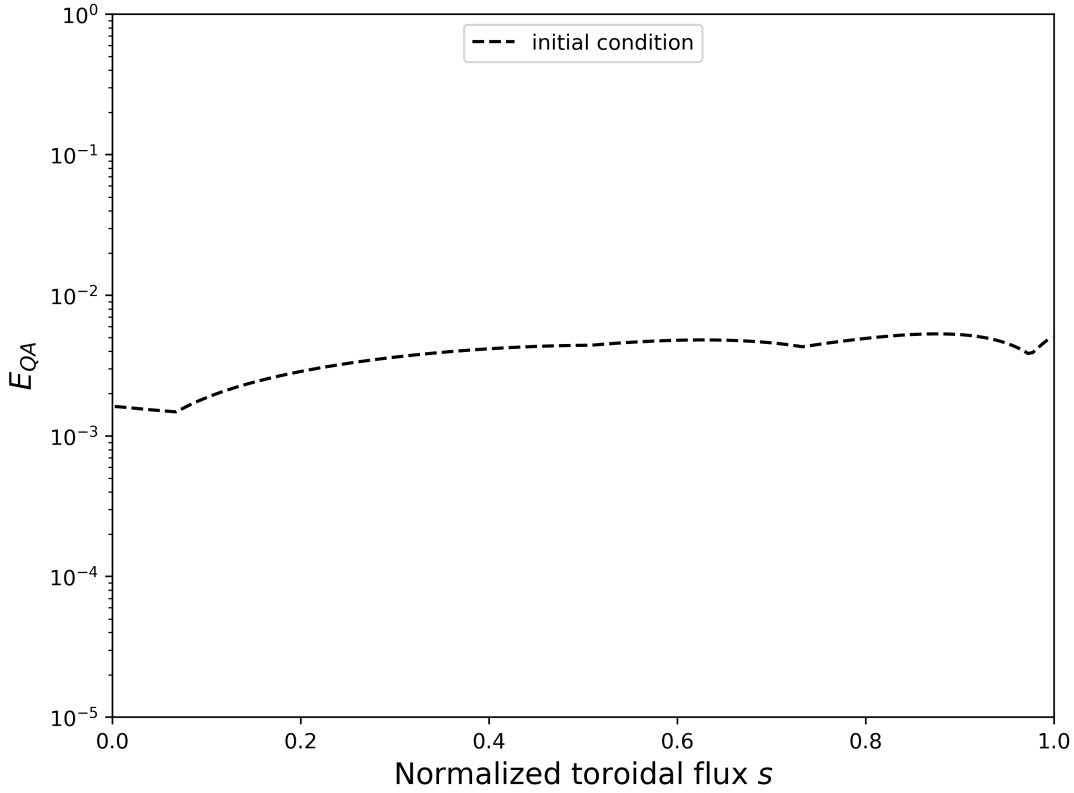


How good is the quasi-symmetry?

Investigating the largest non-quasi-axisymmetric Boozer harmonic of the magnetic field:

$$E_{QA} = \max \frac{|B_{m,n\neq 0}|}{B_{00}}$$

Landreman and Paul, PRL, 2022

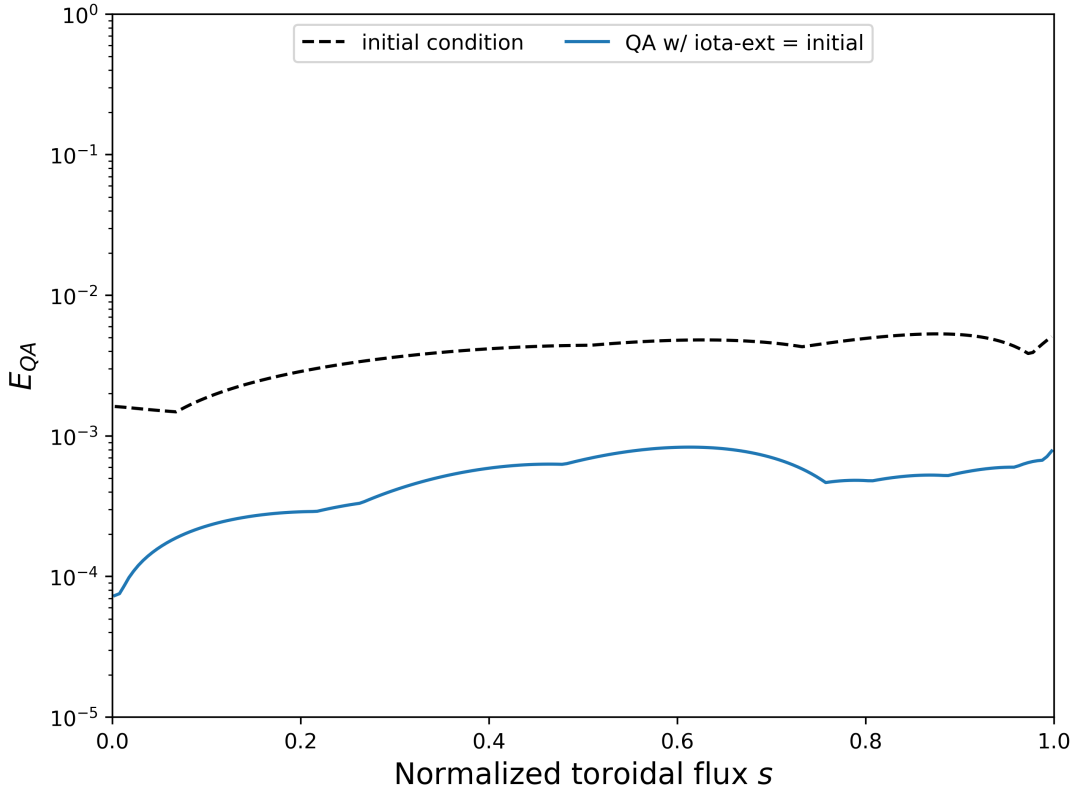


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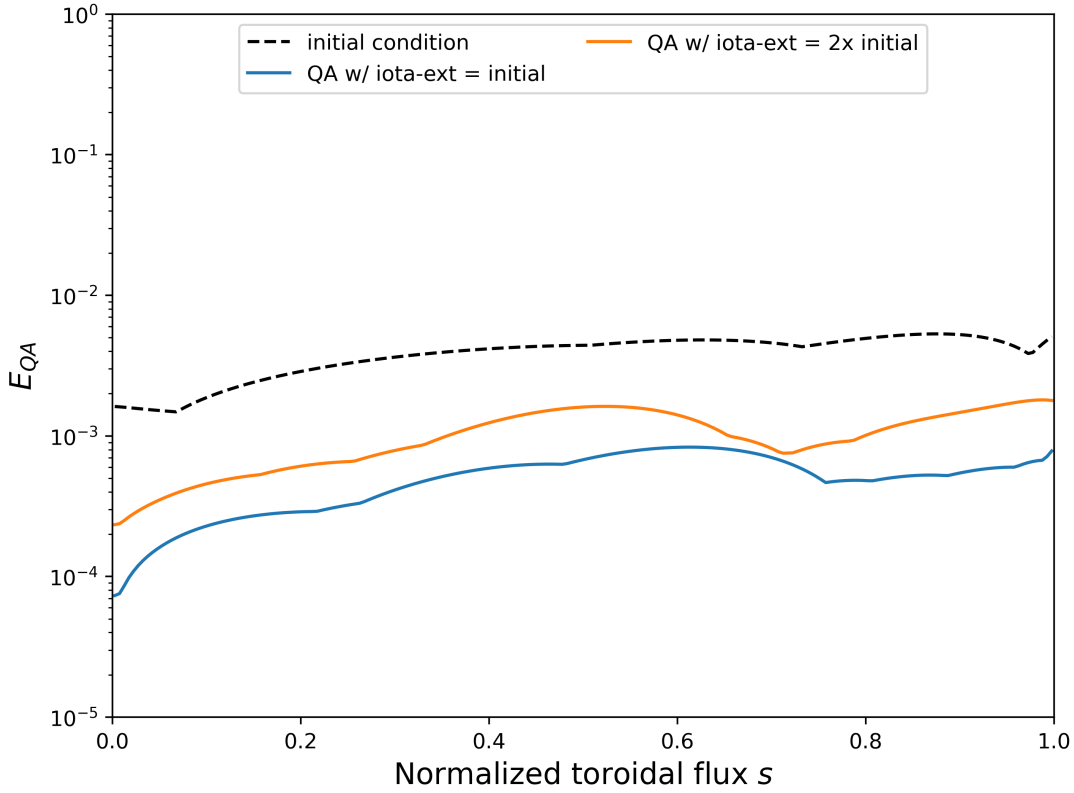


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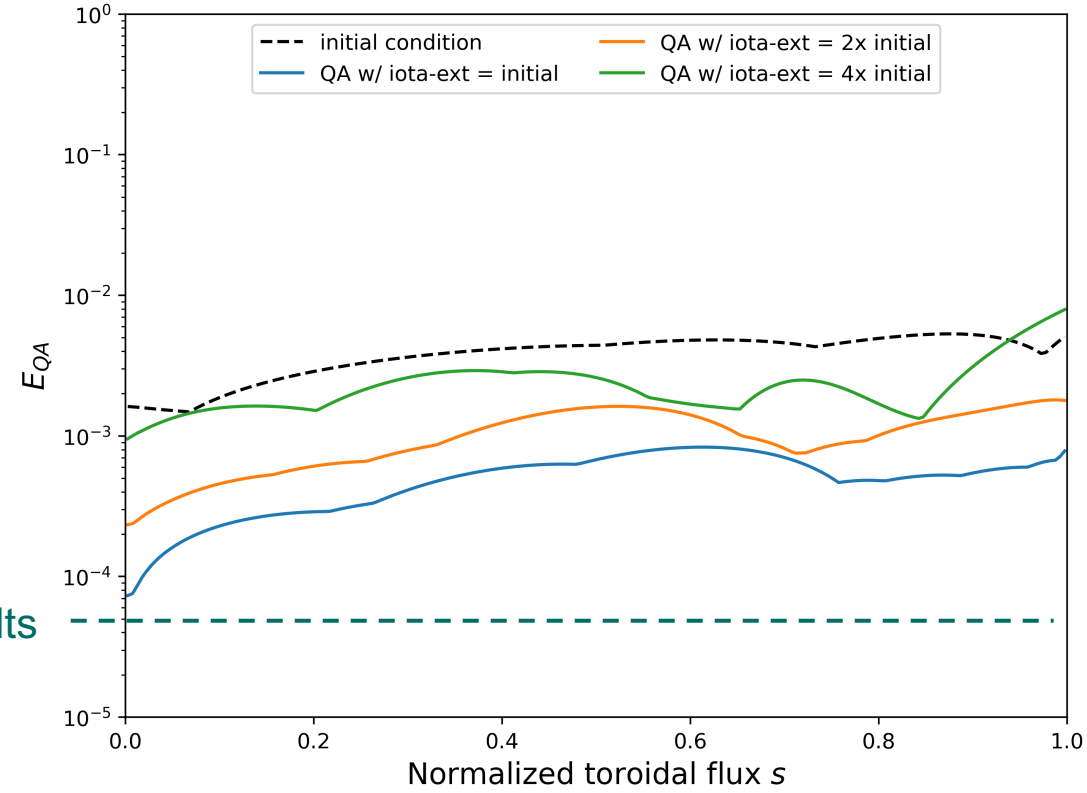
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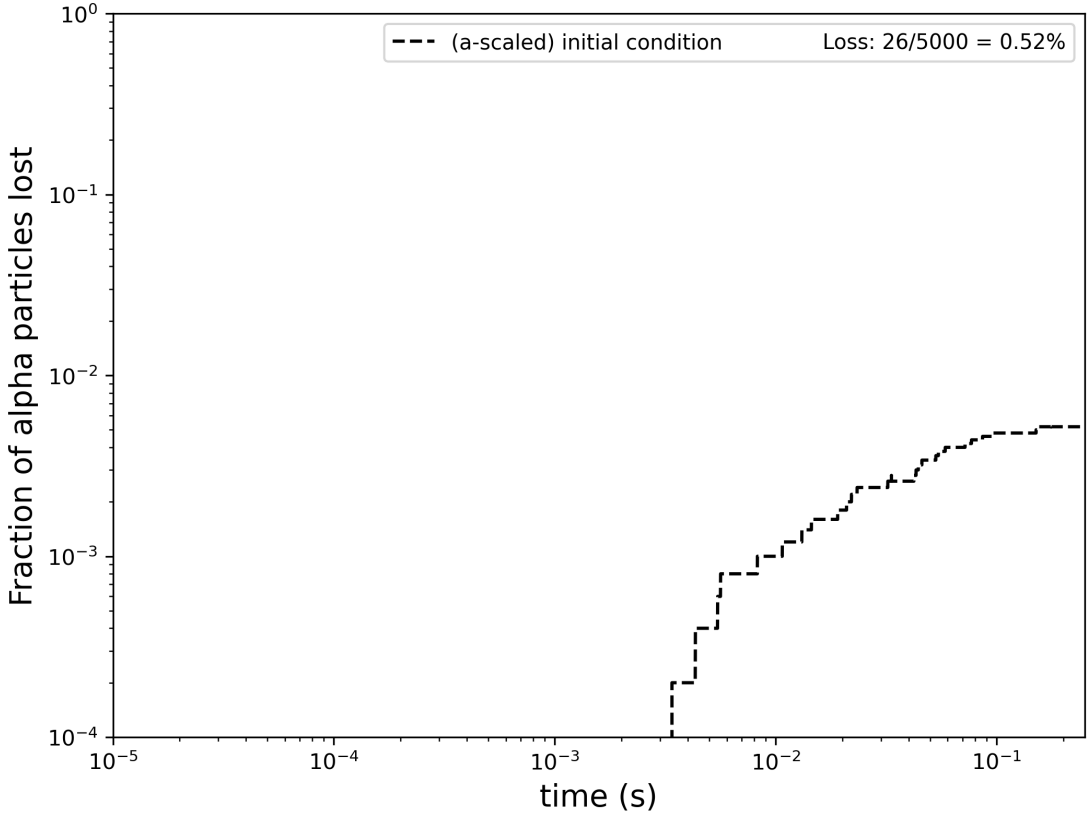
$$E_{QA} = \max \frac{|B_{m,n\neq 0}|}{B_{00}}$$

Landreman and Paul, PRL, 2022

“Precise QA” - results



What we care about: particle confinement



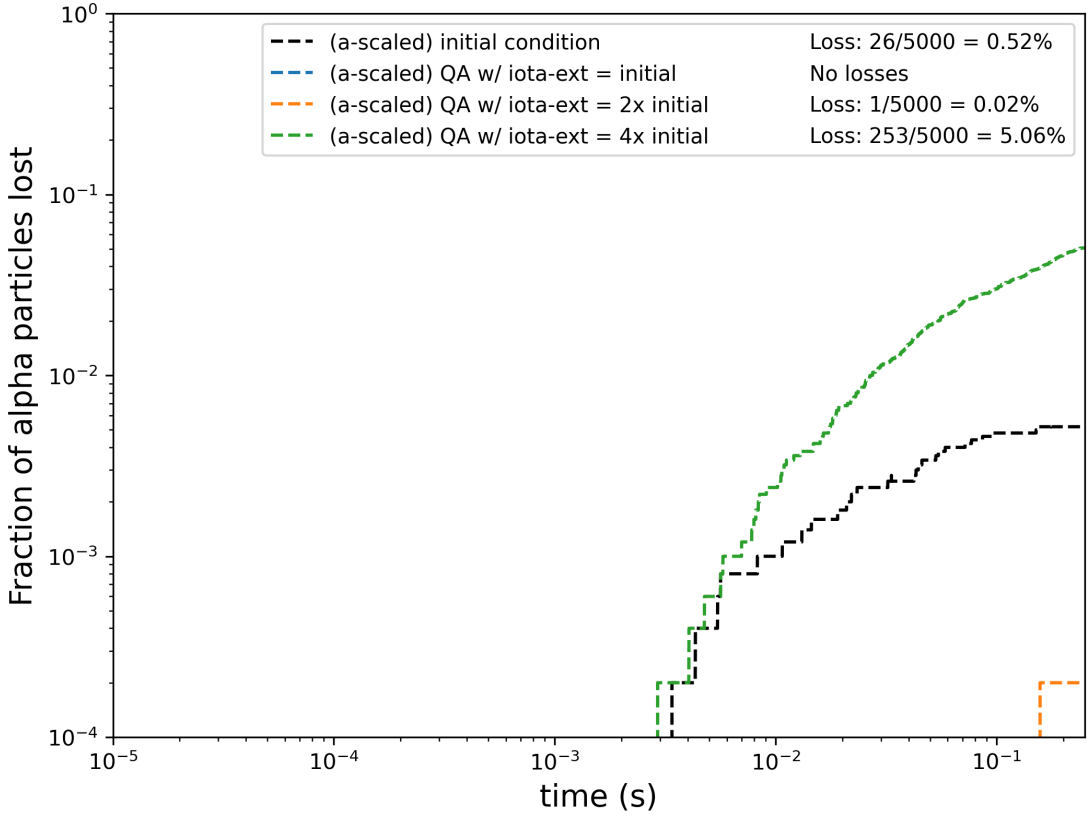
- Using fast particle code SIMPLE [1,2].
- 5000 test particle were followed for 250ms.
- Test particles where launched at $s = 0.25$.

- Losses in analytic solution already very small.

- We are able to reduce this even further down to zero losses.

[1] Albert et al, JPP, 2020
[2] Albert et al, J Comp Phys, 2020

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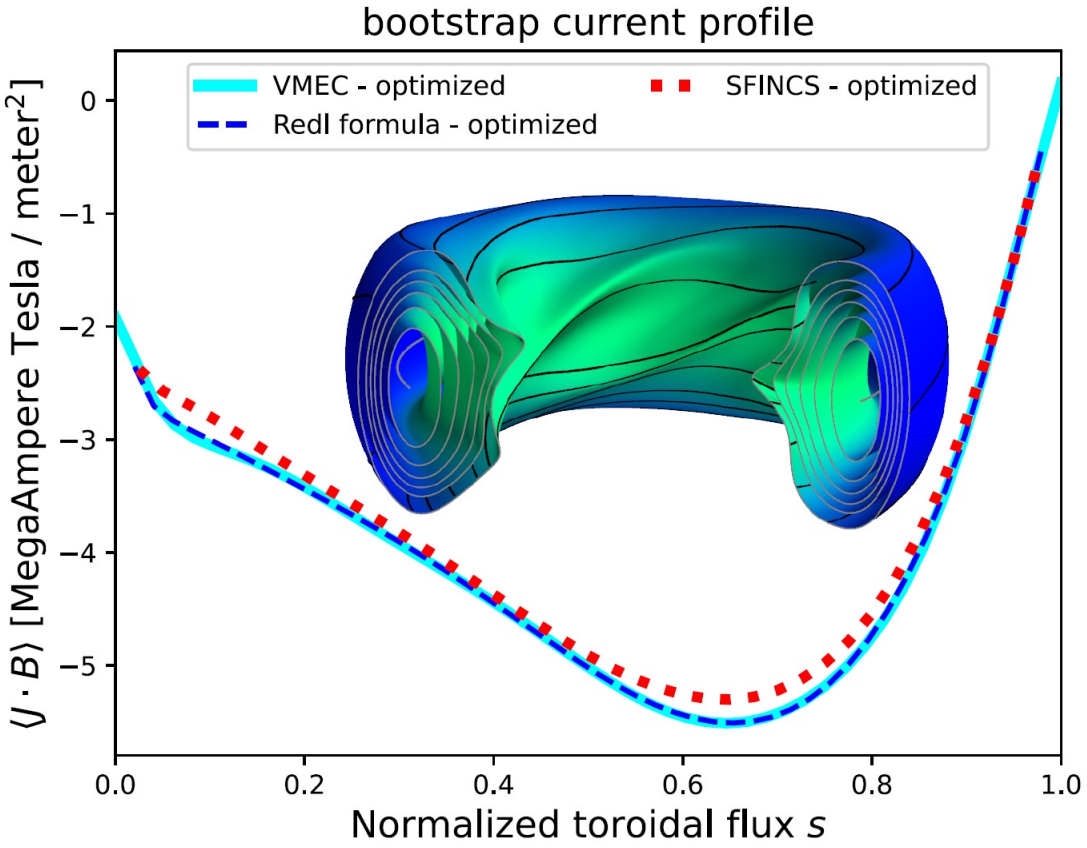
- We are able to reduce this even further down to zero losses.

- The higher the external rotational transform the larger the losses.

[1] Albert et al, JPP, 2020
[2] Albert et al, J Comp Phys, 2020

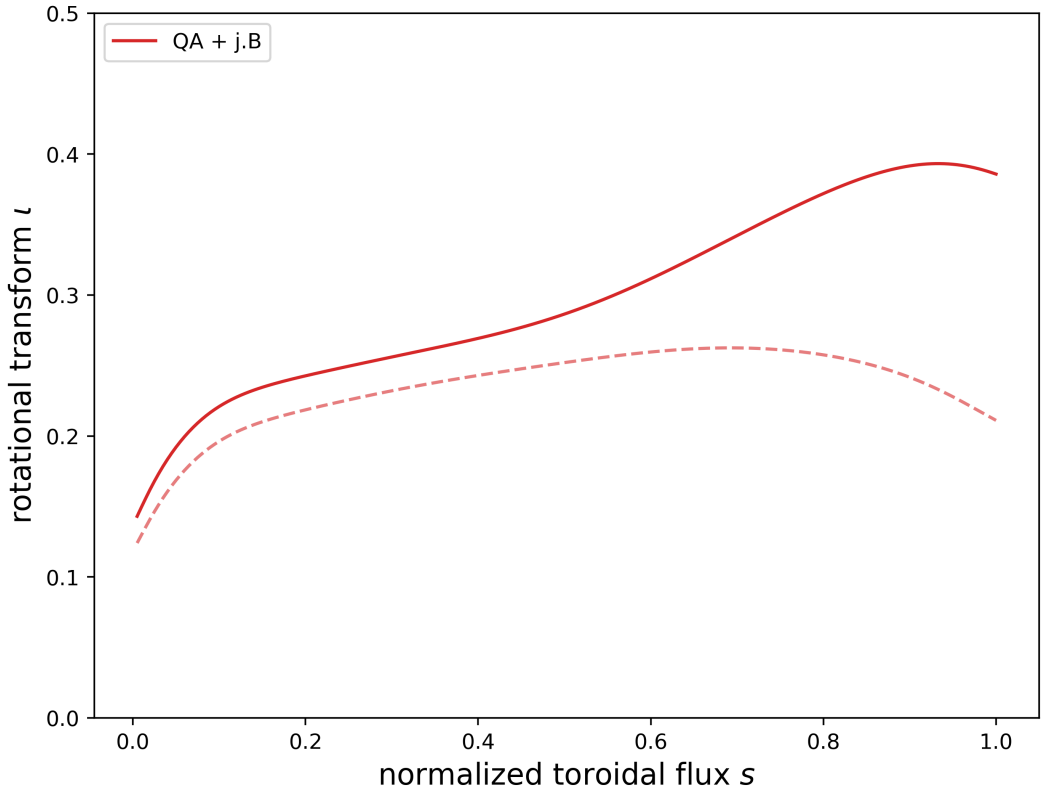
We can add other targets, like self-consistent bootstrap current

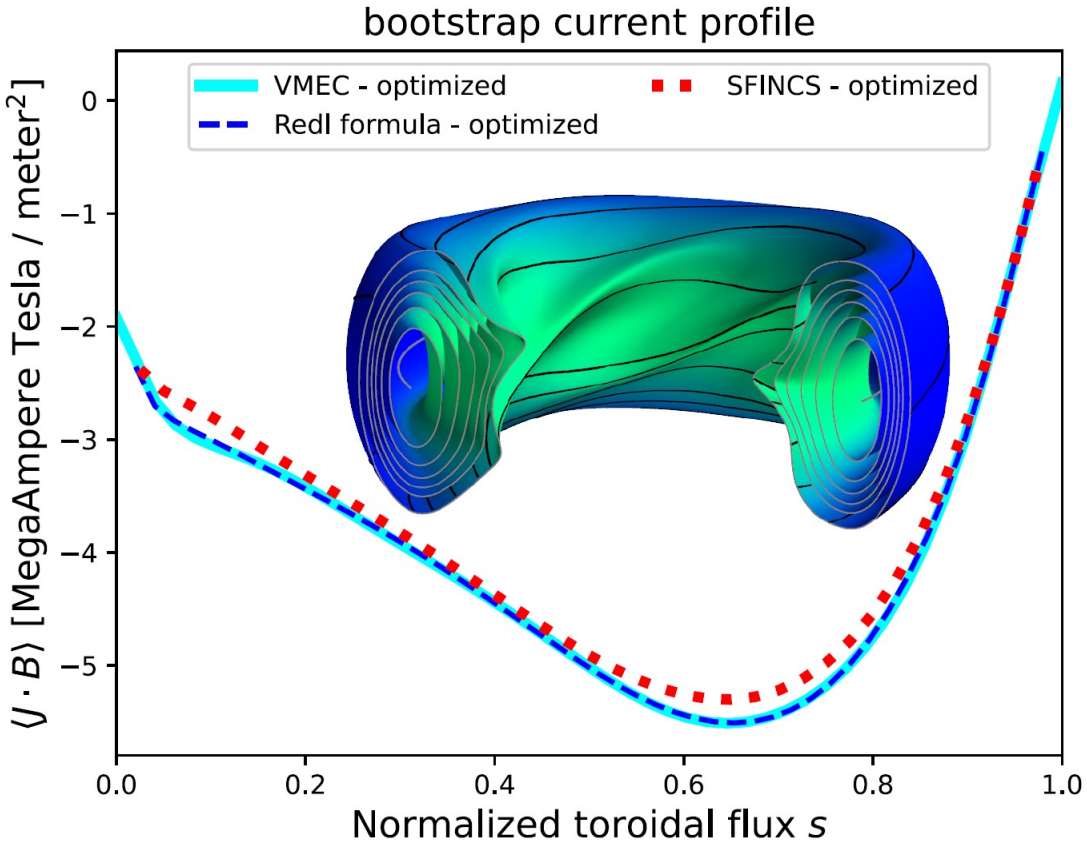
- Similar to [1] we include target for a self-consistent bootstrap current which is based on the Redl et al. [2] formular.
- We also checked with SFINCS [3].
- The resulting rotational transform ranges from 0.15 and 0.4.



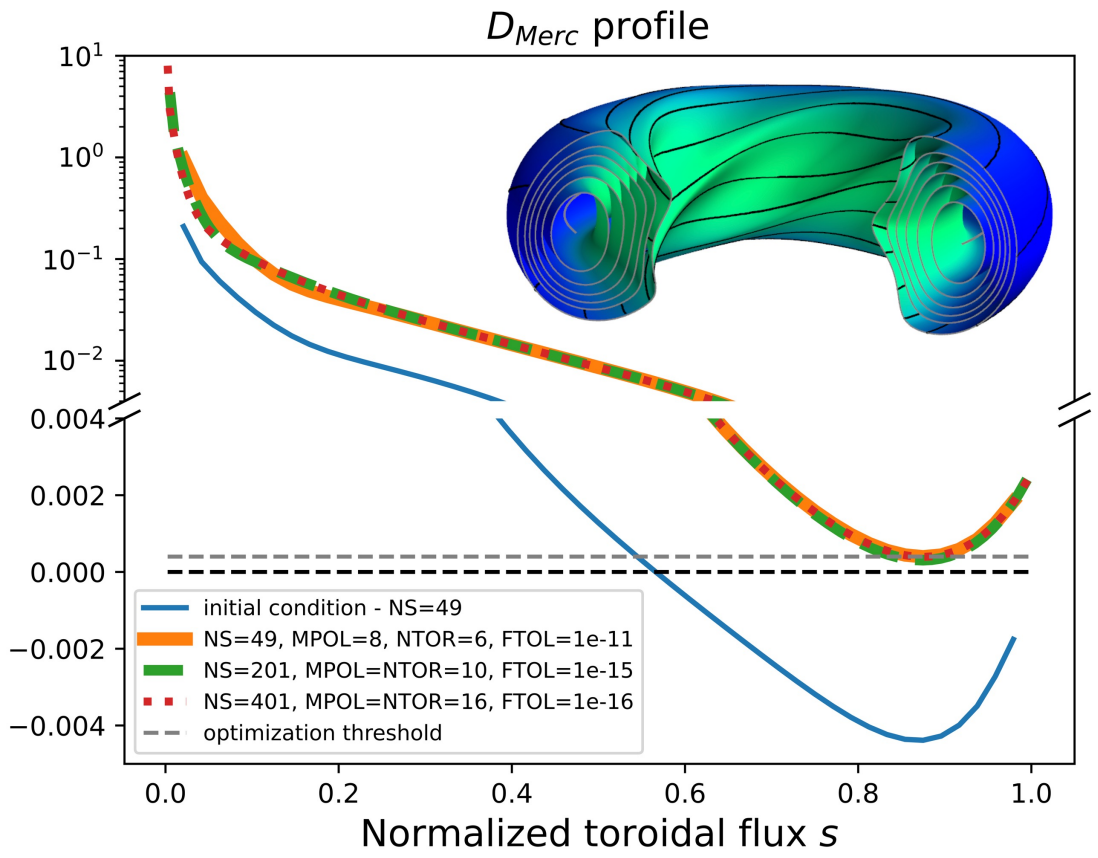
[1] Landreman et al. PoP (2022)
[2] Redl et al., PoP (2021)
[3] Landreman et al., PoP (2014)

We can add other targets, like self-consistent bootstrap current





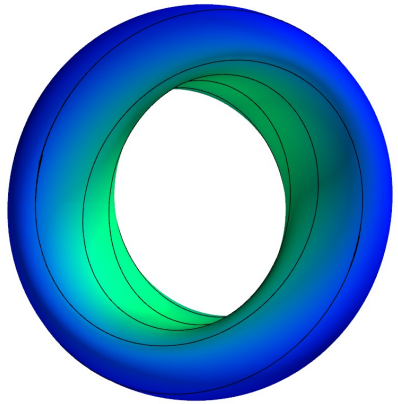
We can add other targets, like self-consistent bootstrap current and yes magnetic well!

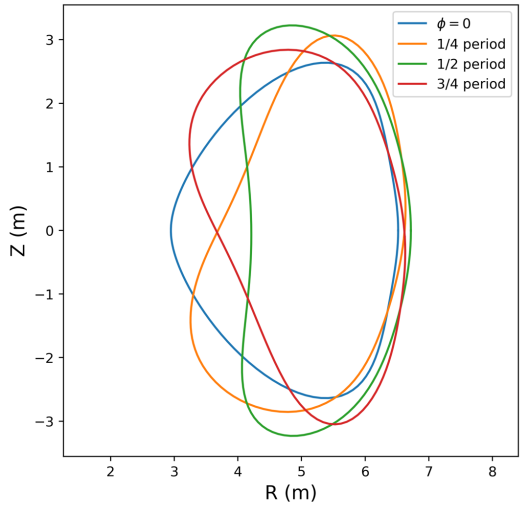


- One might expect that one destroys magnetic well, since the QA perturbation live on the inboard side of the boundary.
- But it is possible to optimize for Mercier stability!
- And still maintain sufficient quasi-axisymmetry, with zero losses for $s = 0.25$.

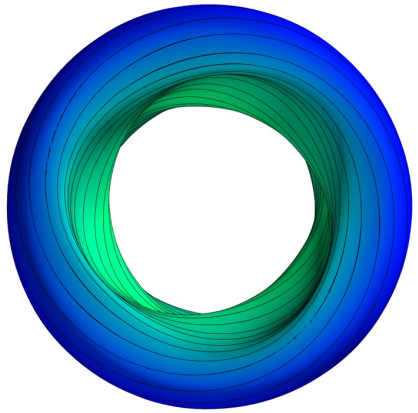
We can explore perturbed tokamaks, e.g. with a wide range of number of field periods (here with A=2.4):

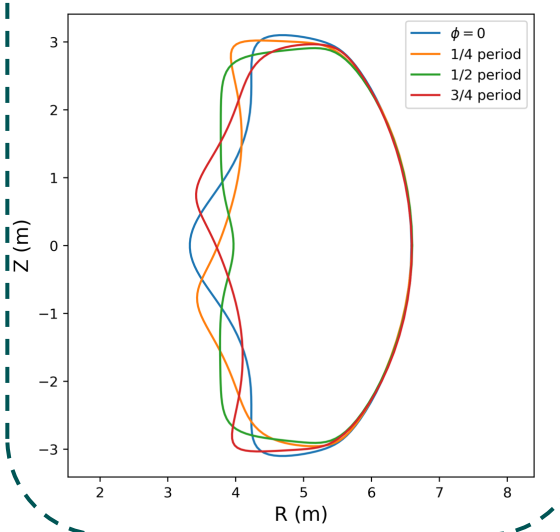
NFP=2



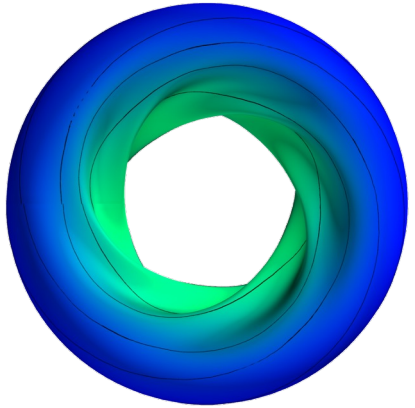


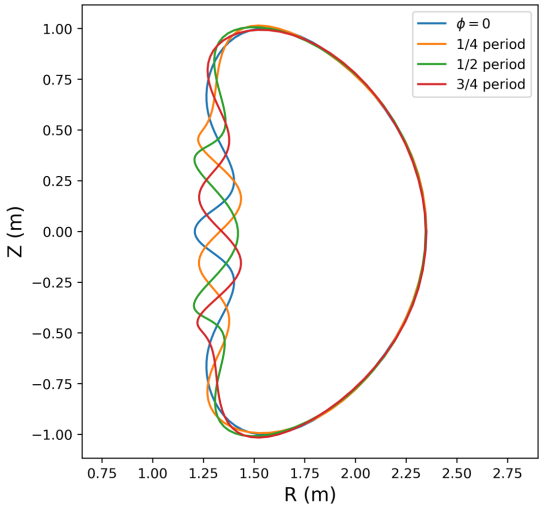
NFP=3



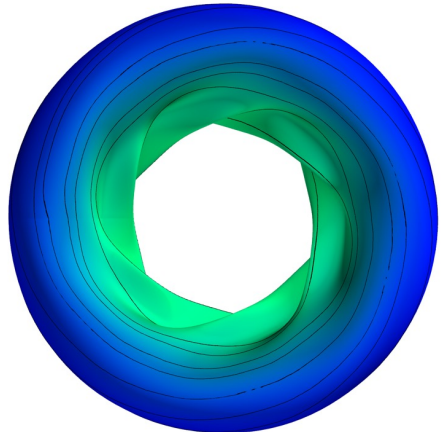


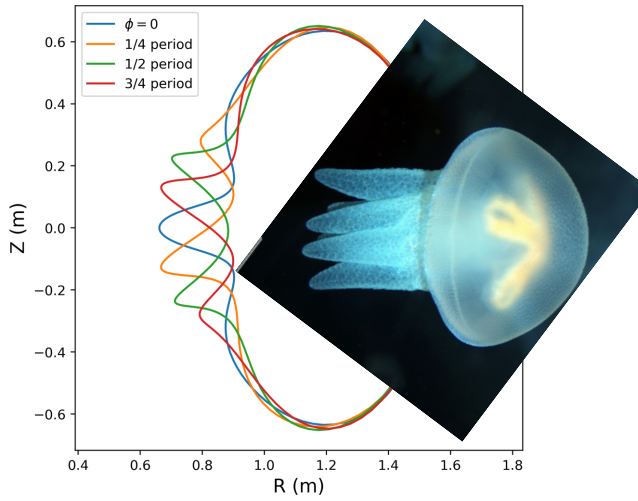
NFP=5





NFP=6
→ “Jelly fish” QA

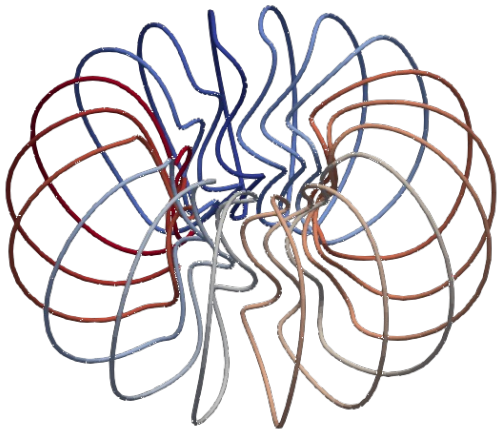




What about coils for optimized configurations?

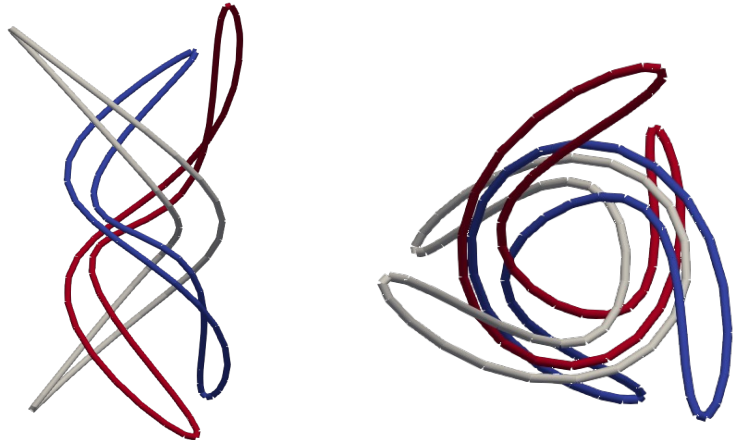
Modular coils (3 types of coils -> 2*3*NFP=18)

- $\max|\boldsymbol{B}\cdot\boldsymbol{n}| \approx 0.7\%$
- $\mathrm{mean}|\boldsymbol{B}\cdot\boldsymbol{n}| \approx 0.2\%$
- For 1900m^3 → 1.21m plasma coil distance
  → 73cm min. radius of curvature



QA (“banana coils”) + tokamak coils (TF + PF)

- $\max|\boldsymbol{B}\cdot\boldsymbol{n}| \approx 3\%$
- $\mathrm{mean}|\boldsymbol{B}\cdot\boldsymbol{n}| \approx 0.7\%$
- For 1900m^3 → **1.75m** plasma coil distance
  → **1m** min. radius of curvature



Hidden symmetry:
A new class of QA stellarators

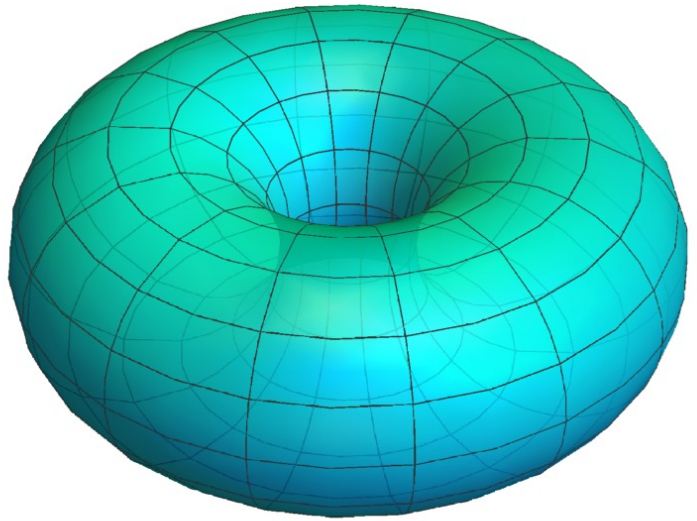
Numerically:

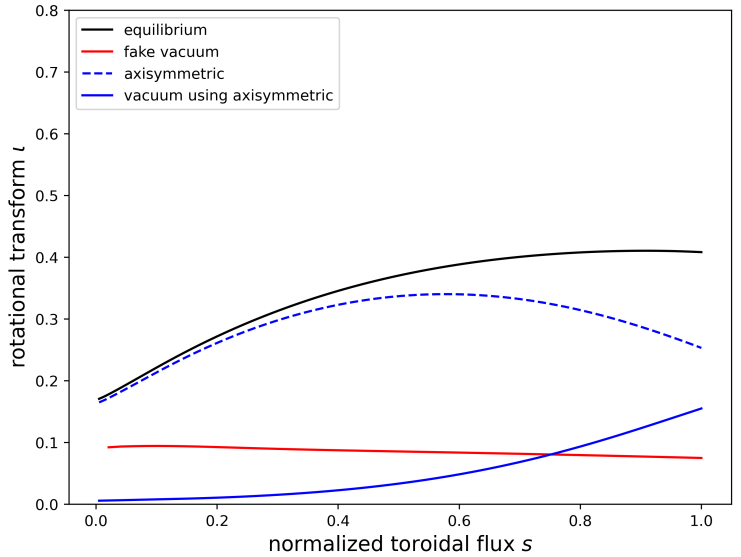
→ One has to be careful how to avoid finding axisymmetric equilibria.

Near-axis expansion:

→ The axis of these QA stellarators almost doesn't deviate much from axisymmetry.

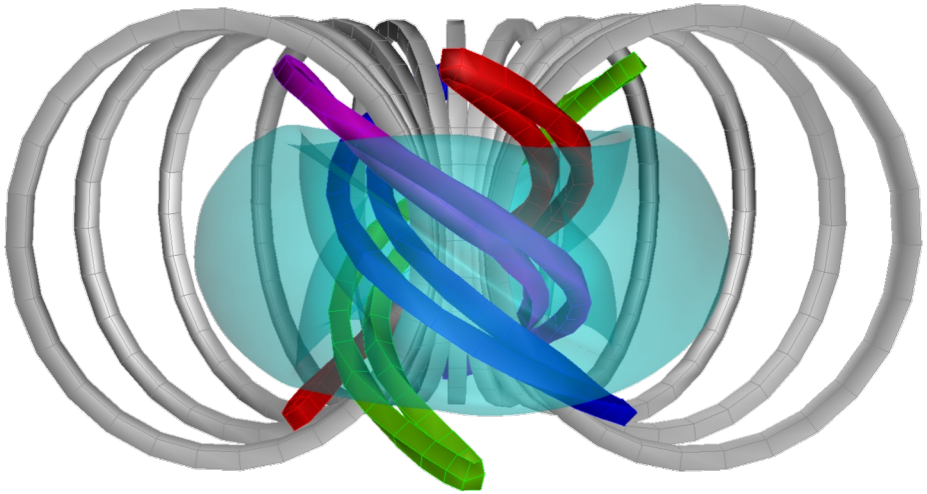
→ Very little external rotational transform near the axis.





Summary & Discussion

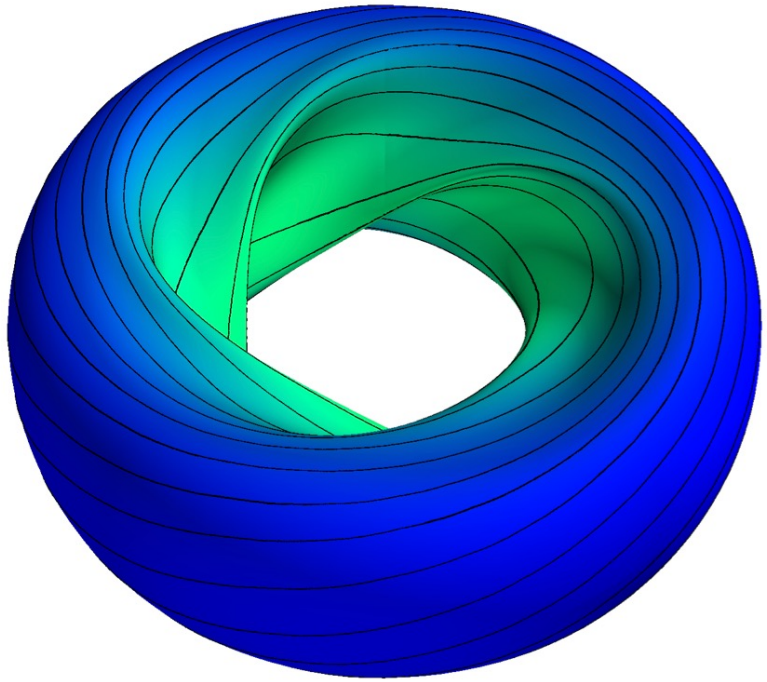
- We found a compact QA-stellarator-tokamak hybrid concept,
- Which can be operated as a tokamak or QA-stellarator or anything in-between.
- It has flux surfaces in vacuum → could be used for tokamak start up! No need for expensive solenoid!
- This type of device could check how physics properties (stability, turbulence…) change from 2D → 3D.
- Could potentially mitigate disruptions!



S. Henneberg & G. Plunk, EUROfusion pinboard ID 35444, 36001

Summary & Discussion (Part 2)

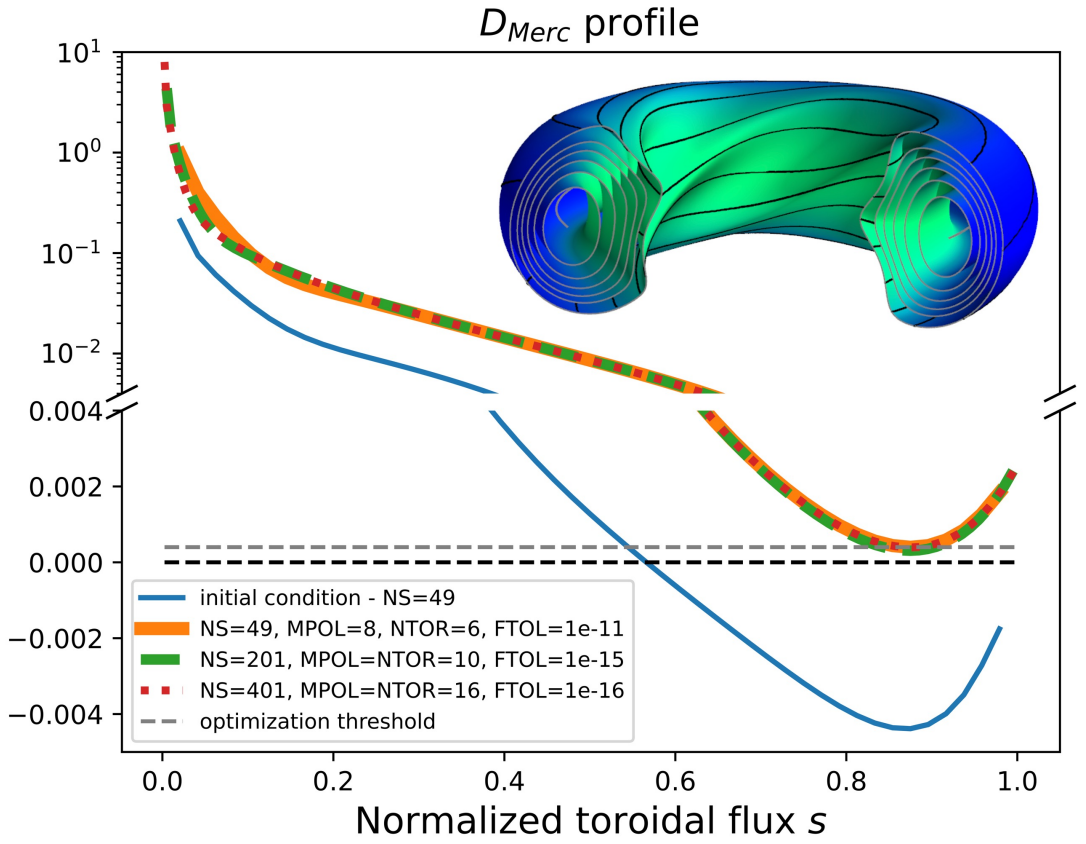
- We optimized the boundary shape to achieve even better starting plasma boundary.
- We also added optimizing for self consistent bootstrap current.
- We investigated the fast particle losses and found that they are sufficiently small.
- We also optimizing for stability, by enforcing a magnetic well.
- We optimized coils for improved plasma boundary.



T. Schuett, S. Henneberg in preparation
→ **Poster by Tobias Schuett**

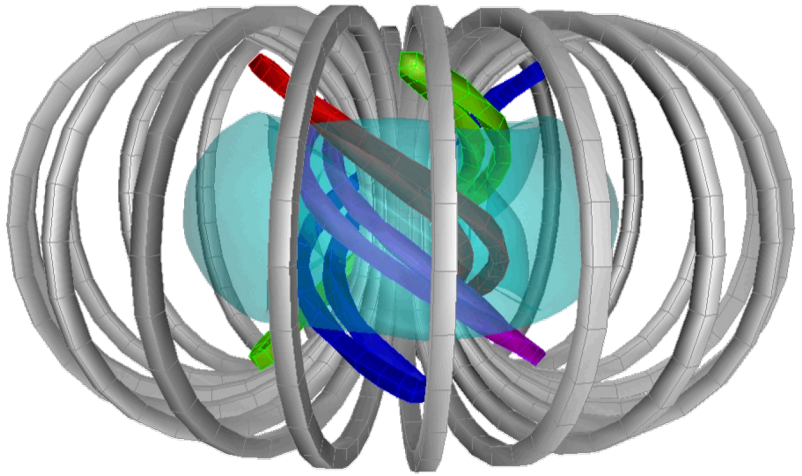
Ongoing & selected future work

- Investigating stability properties (linear, nonlinear, ideal…)
  (Sophia Henneberg, Carolin Nürenberg, Gabriel Plunk).
- Studying (turbulence) confinement (Tobias Schuett).
- Investigating divertor concepts for such an hybrid (**Robert Davies → Poster**).
- Calculating SPEC solution to check for good flux surfaces (Stuart Hudson).
- Investigating if we can upgrade a tokamak (Sophia Henneberg).
- Checking permanent magnets for the perturbed tokamak equilibria.
- Investigating engineering constraints, like forces and stresses.
- Single-stage optimization.



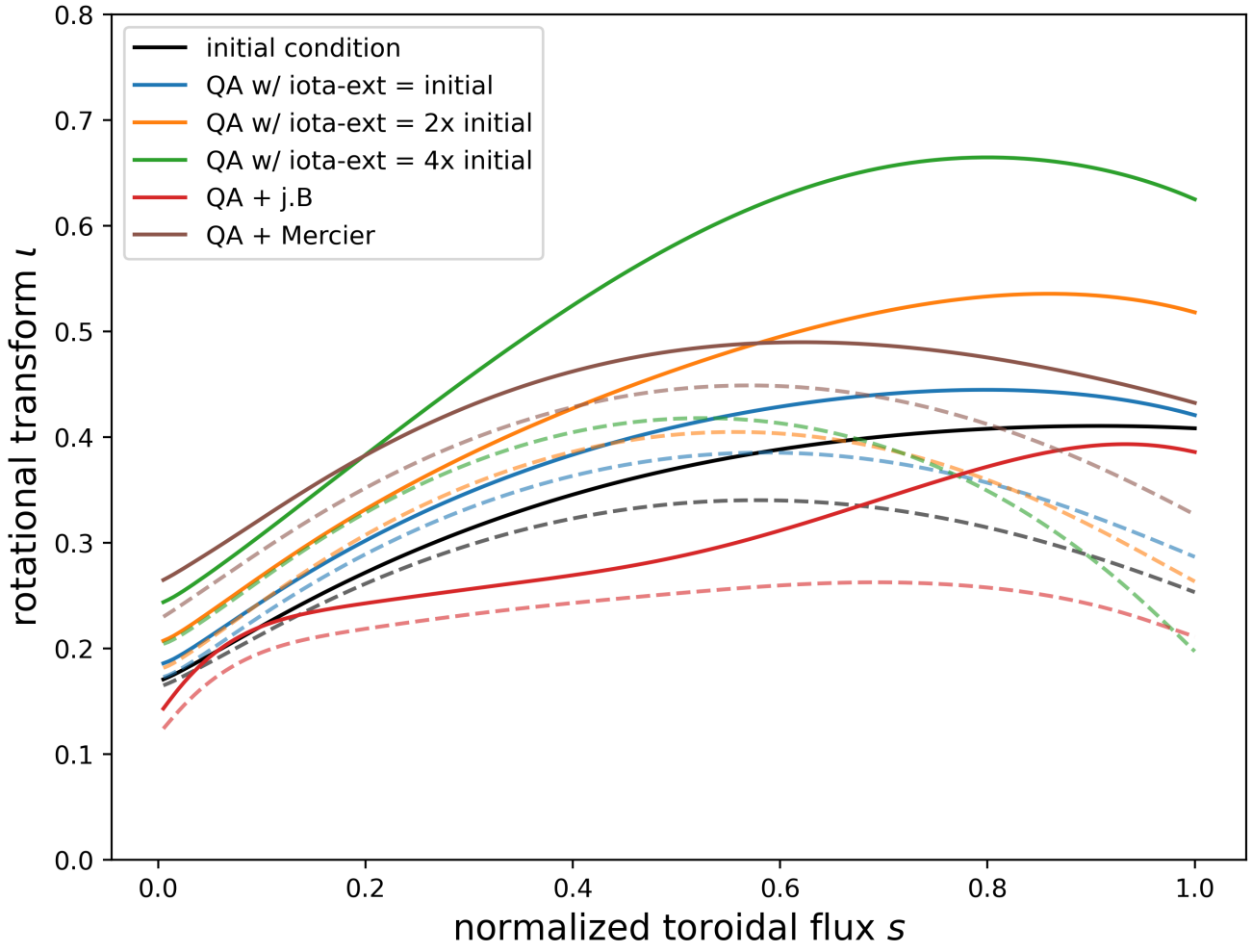
Thanks to the ***Simons collaboration*** for providing tools like simsopt and the amazing support from the simsopt developers!!

Thank you all for listening!



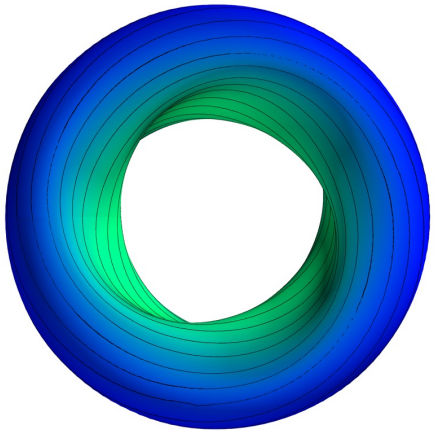
Extra slides

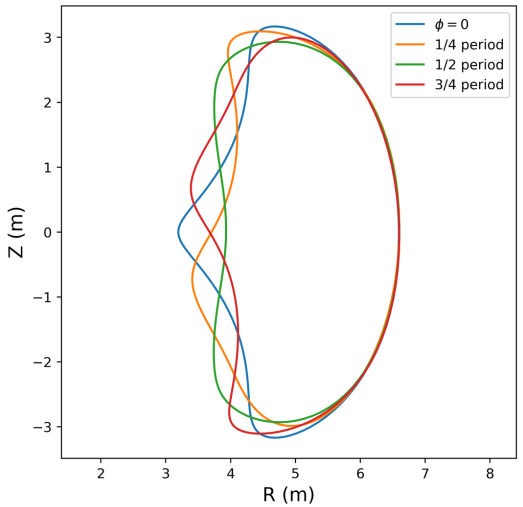
Overview rotational transform plot



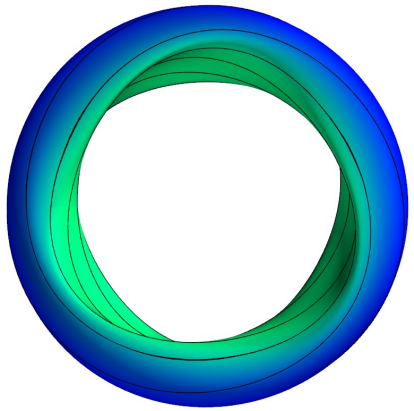
Increasing aspect ratio makes things easier

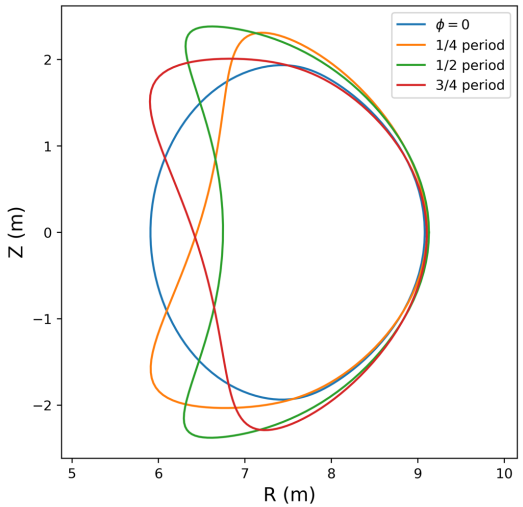
A=2.4



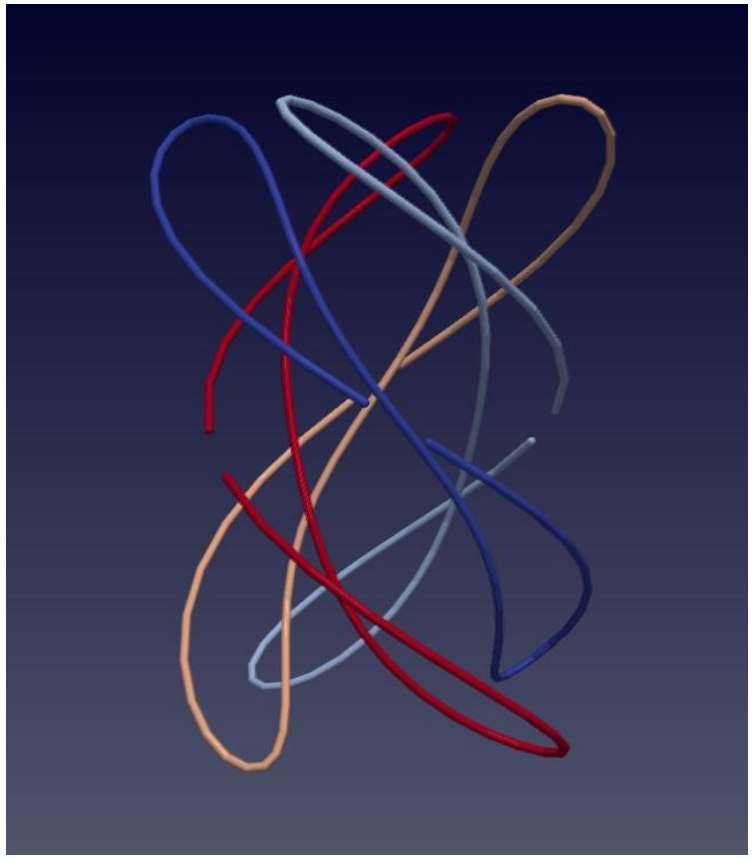


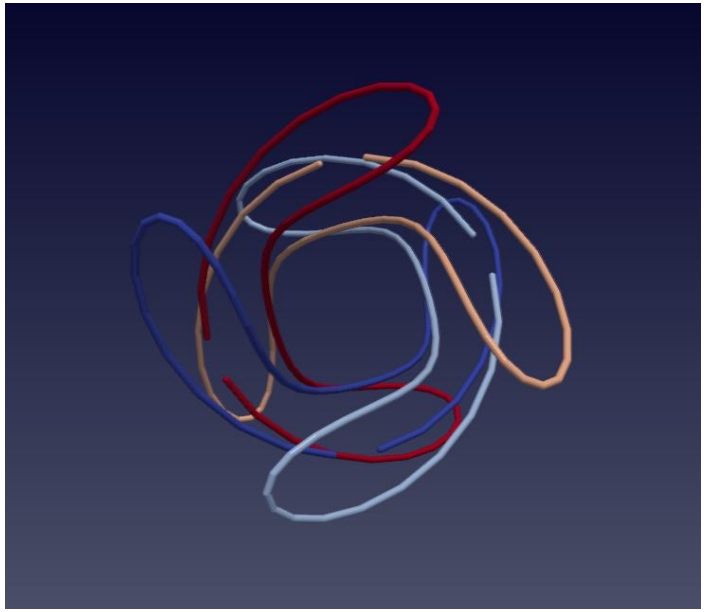
A=4.4





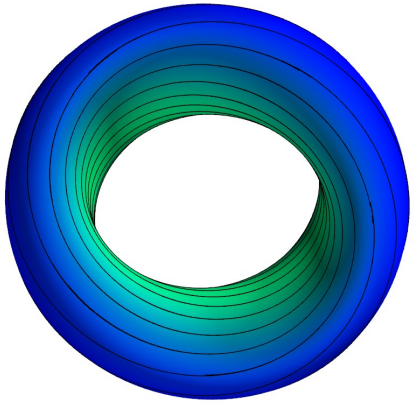
Including curvature target

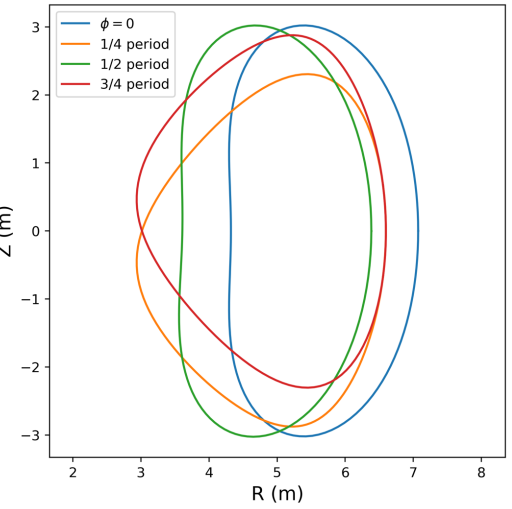




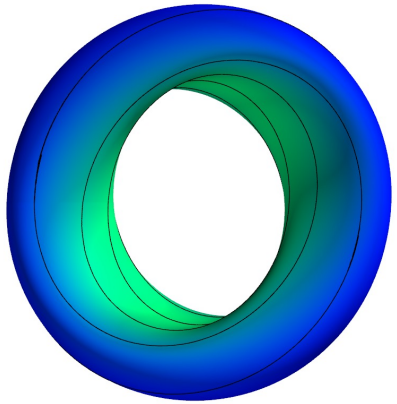
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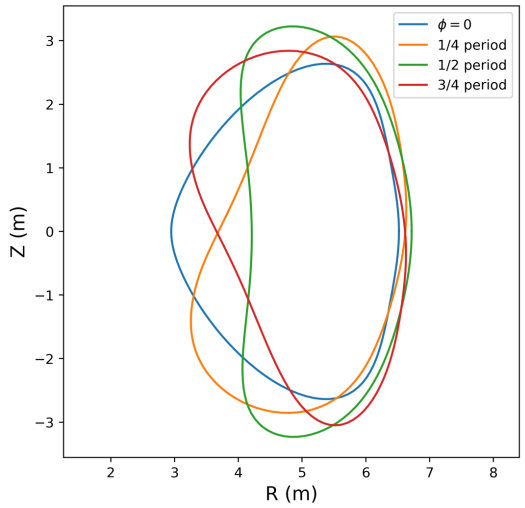
NFP=1



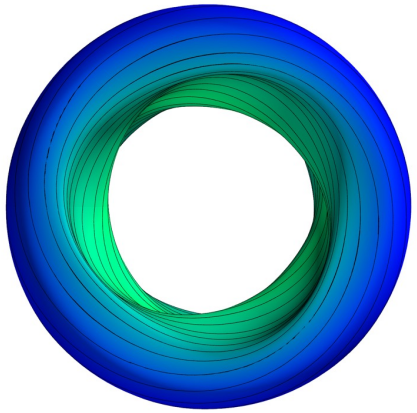


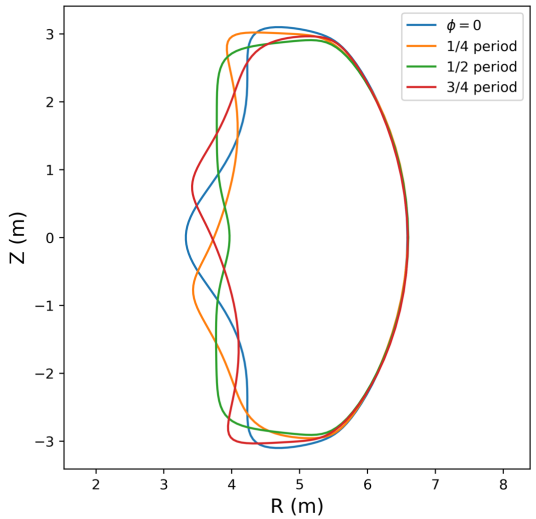
NFP=2



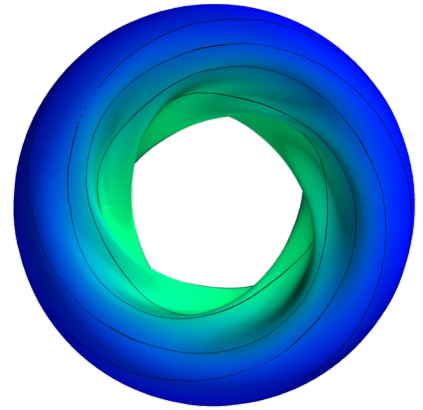


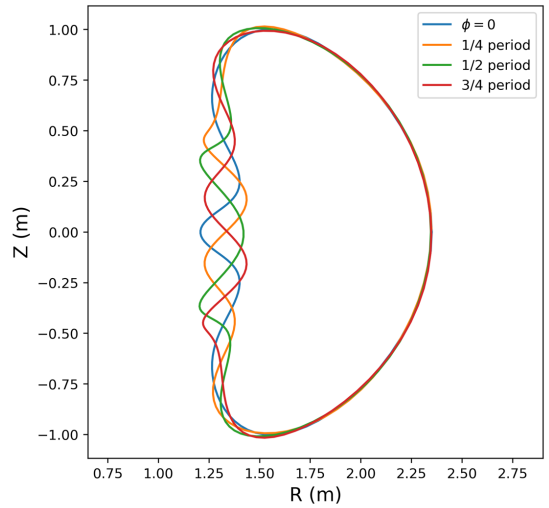
NFP=3



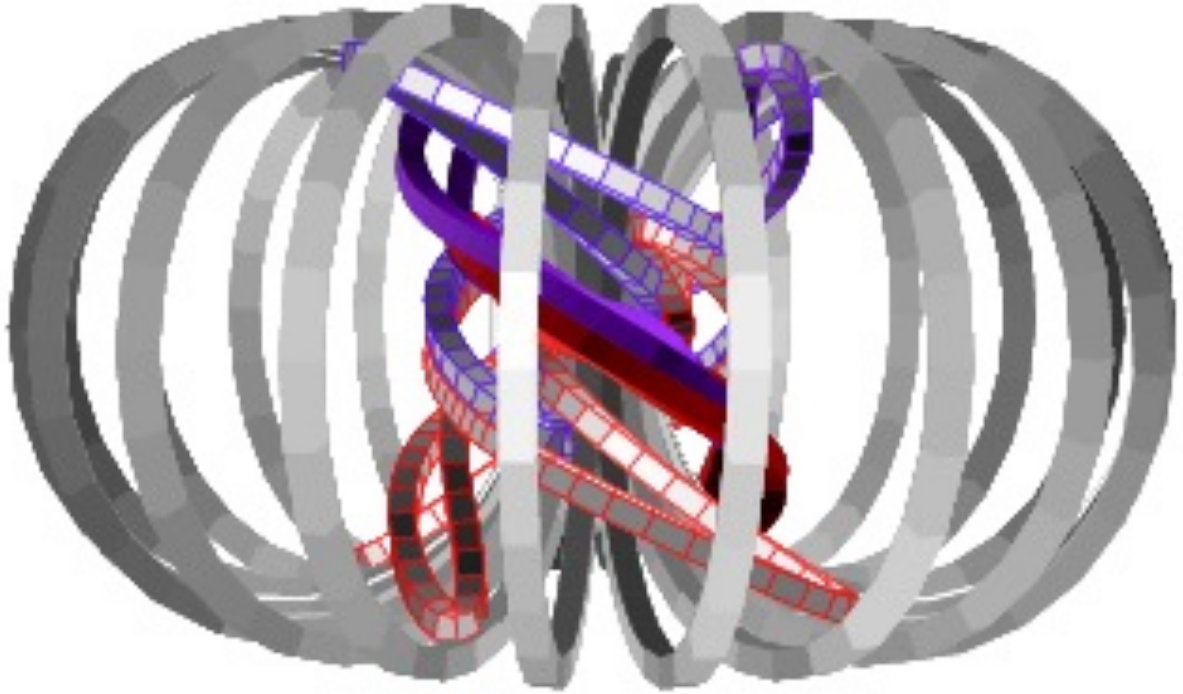


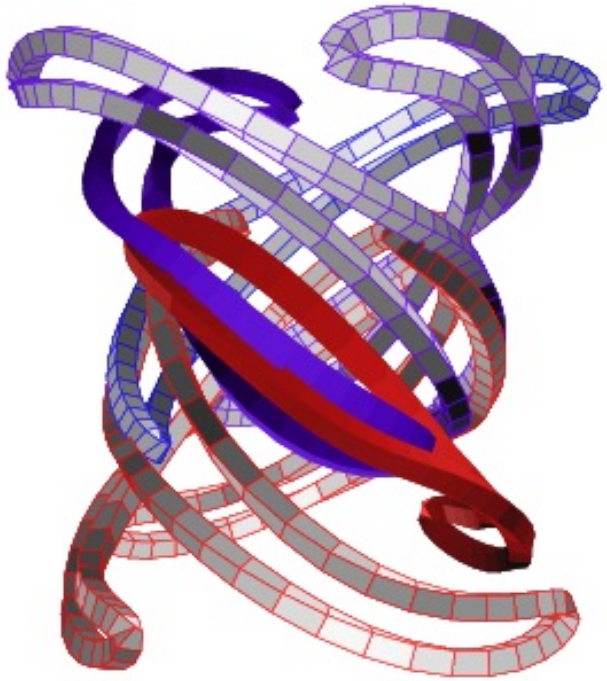
NFP=5



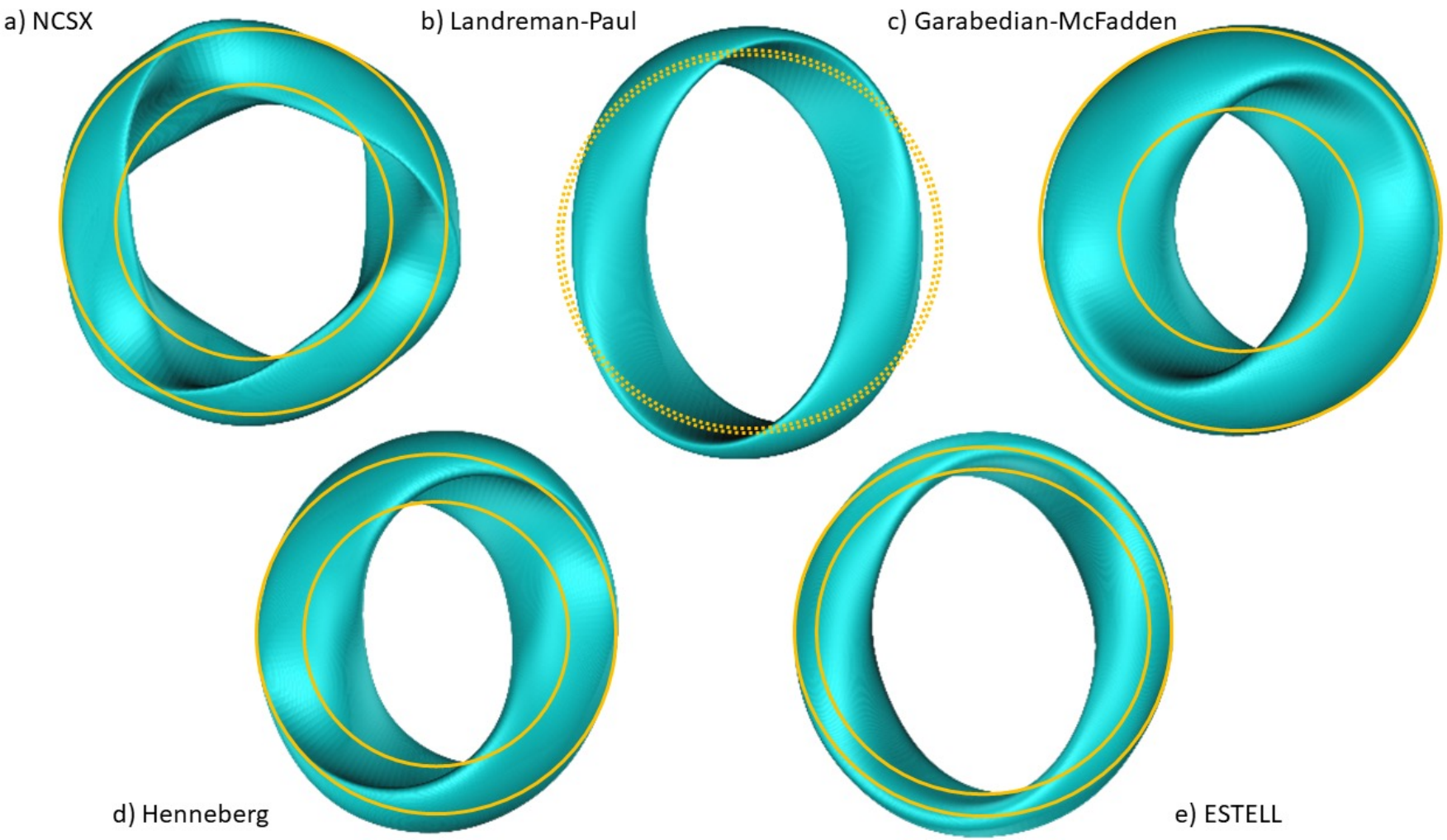


Other coil sets



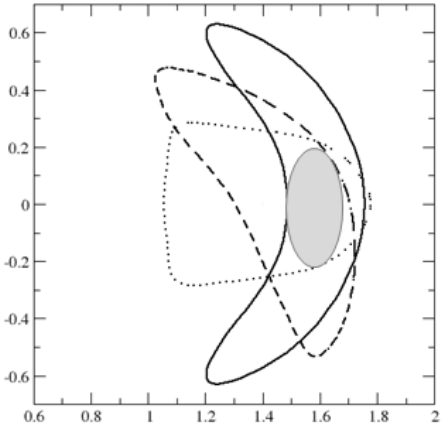


Let’s have a look at previous QA-stellarator designs

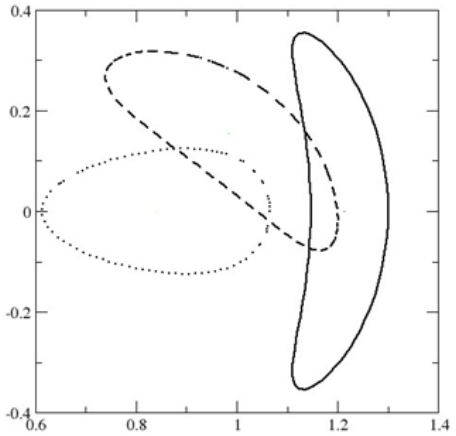


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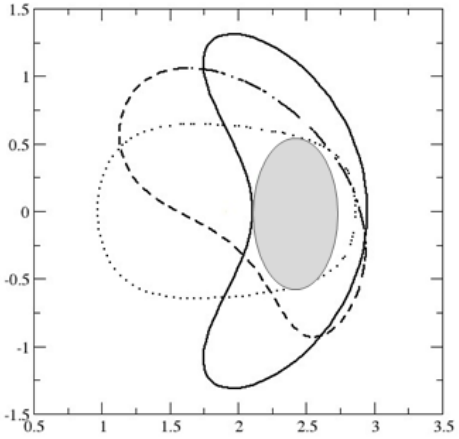
a) NCSX



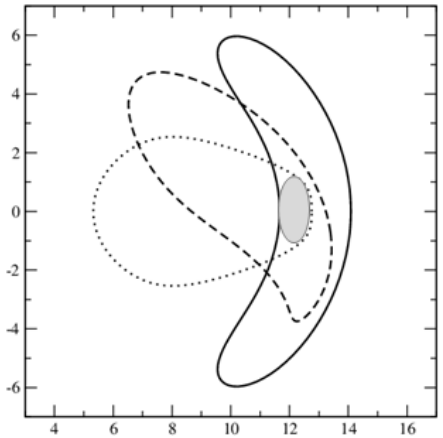
b) Landreman-Paul



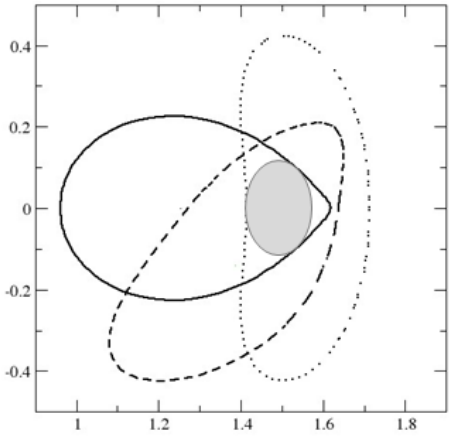
c) Garabedian-McFadden



d) Henneberg

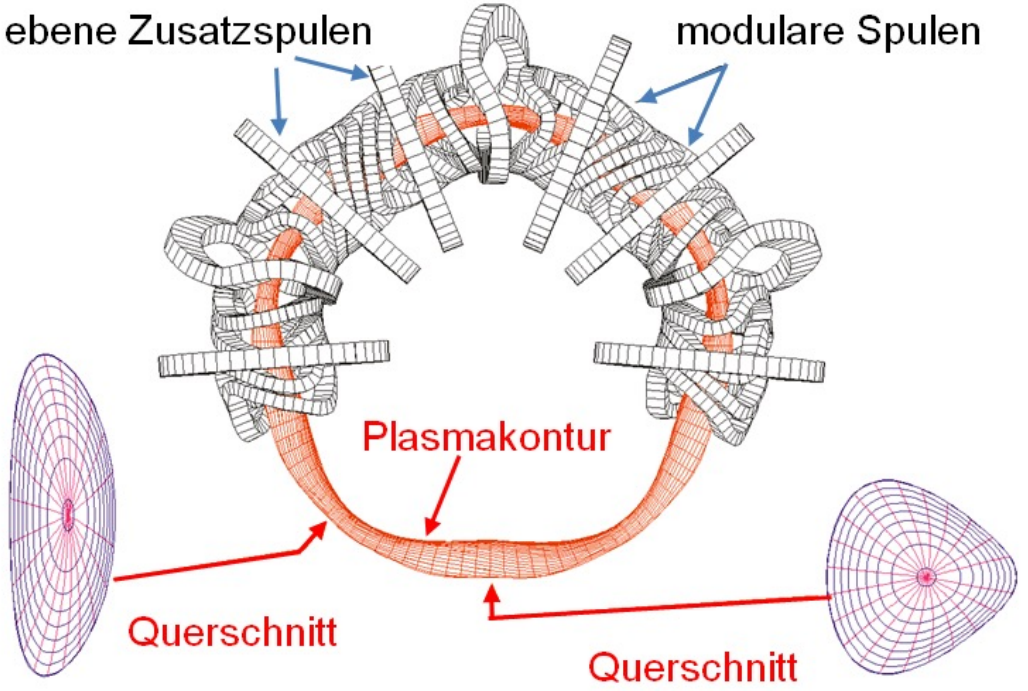


e) ESTELL



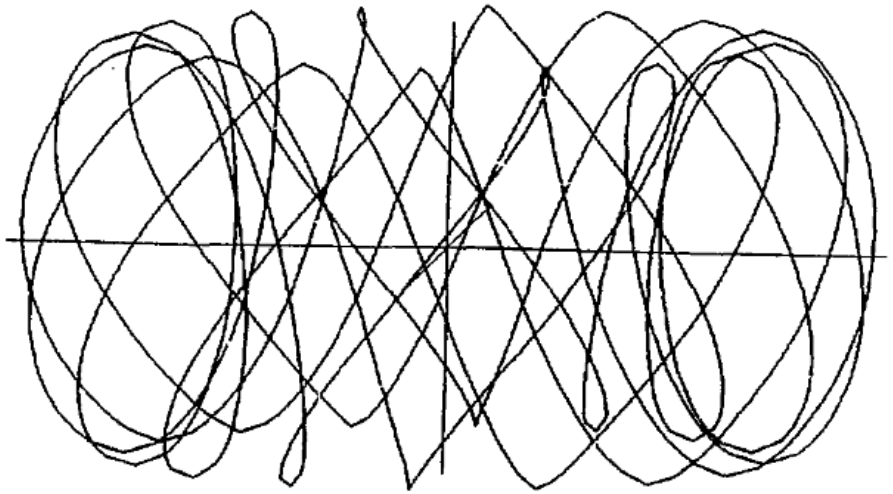
Let’s learn from the past: Previous hybrids

- Wendelstein 7-AS



Let’s learn from the past: Example hybrids

- Tokastar concept



K. Yamazaki and Y. Abe, PPFT, 1985