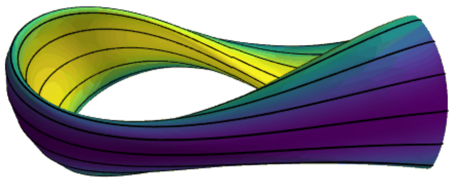
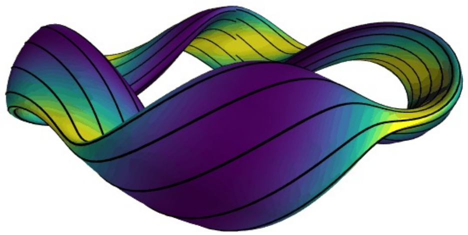
The Direct Optimization Framework in Stellarator Design: Transport and Turbulence Optimization

What quantities can we now directly optimize for?

How to combine several of these quantities together?



Rogerio Jorge[1]



EUROfusion Enabling Research Team, Lisbon[1], A. Goodman[2], M. Landreman[3] , S. Buller[3], A. Giuliani[4] , F. Wechsung[4] , P. Kim[3], W. Sengupta[5], N. R. Mandell[5], T. Qian[5], W. Dorland[3,5], M. Padidar[6], the SIMSOPT team

[1] IST, University of Lisbon, [2] Max Planck Institute for Plasma Physics ,[3] University of Maryland, [4] New York University, [5] Princeton Plasma Physics Laboratory, [6] Cornell University

June 11, 2023, IAEA Fifth Technical Meeting on Fusion Data Processing, Validation and Analysis

PART 1

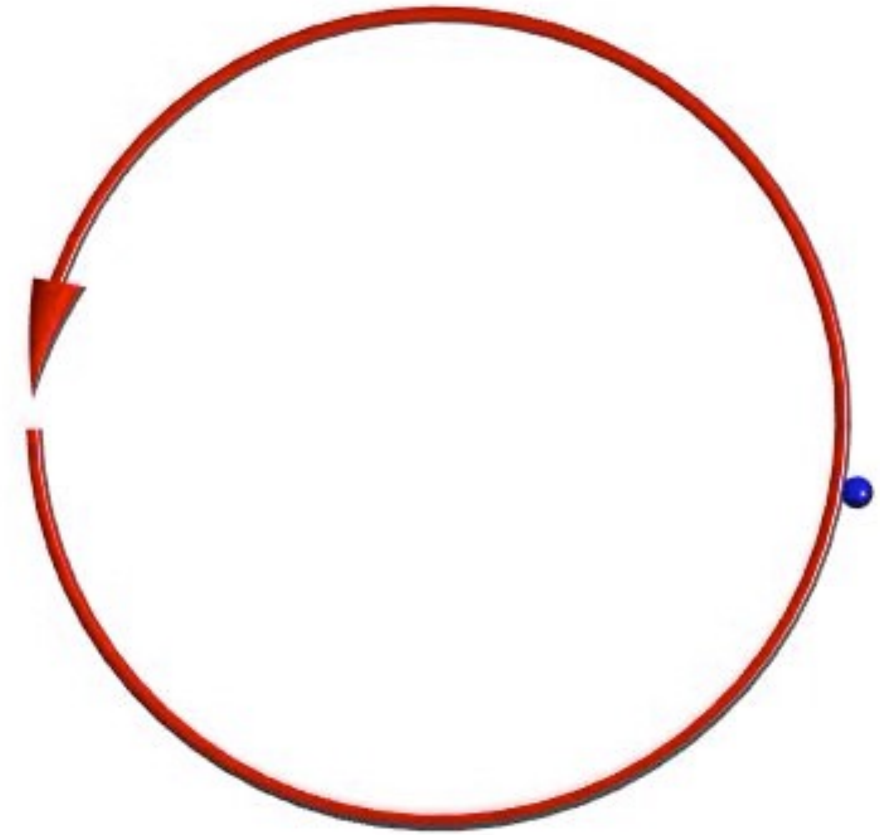
Introducing stellarators

How to use magnetic fields to confine plasmas?

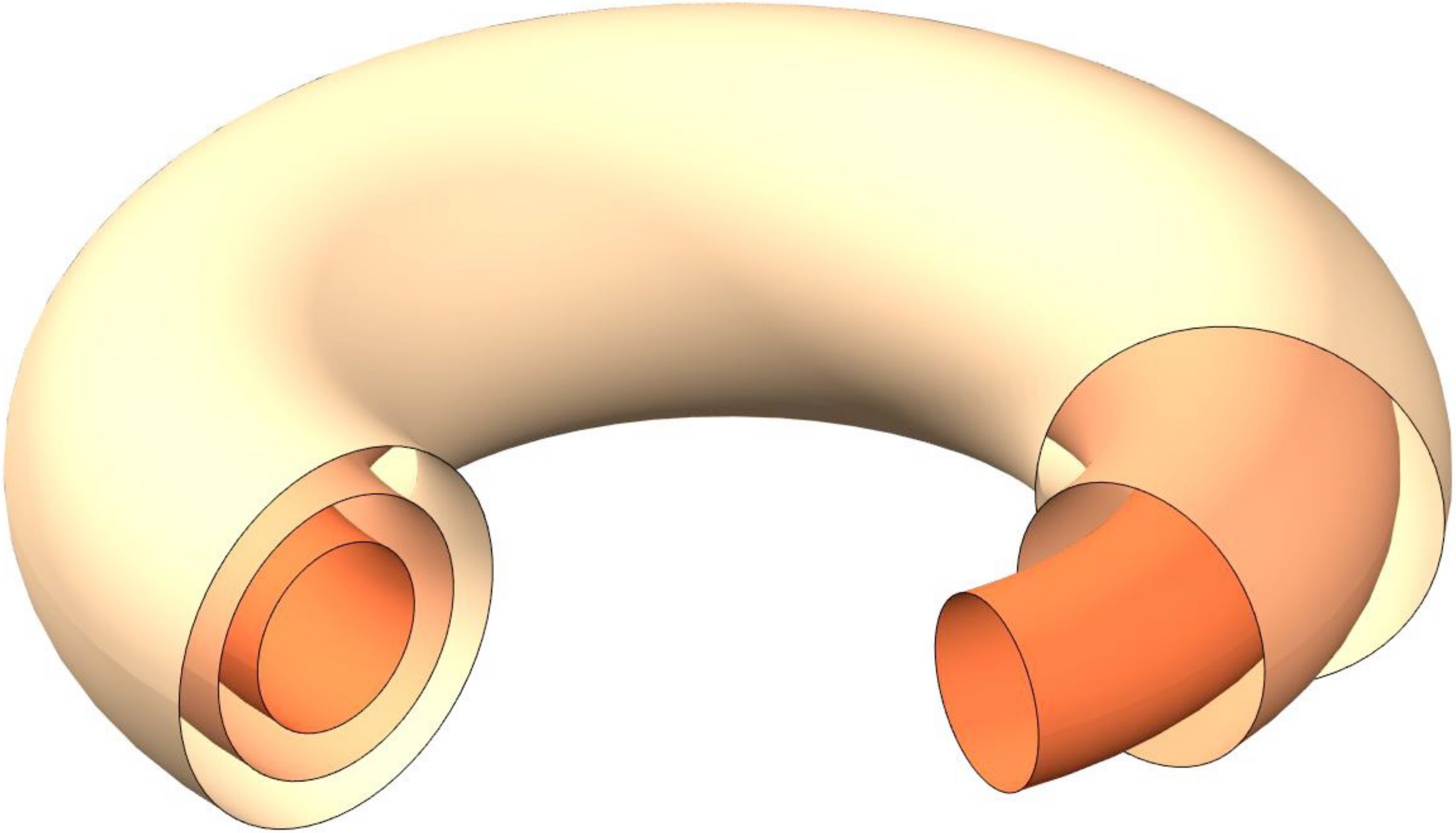
Losses at the ends

Vertical losses

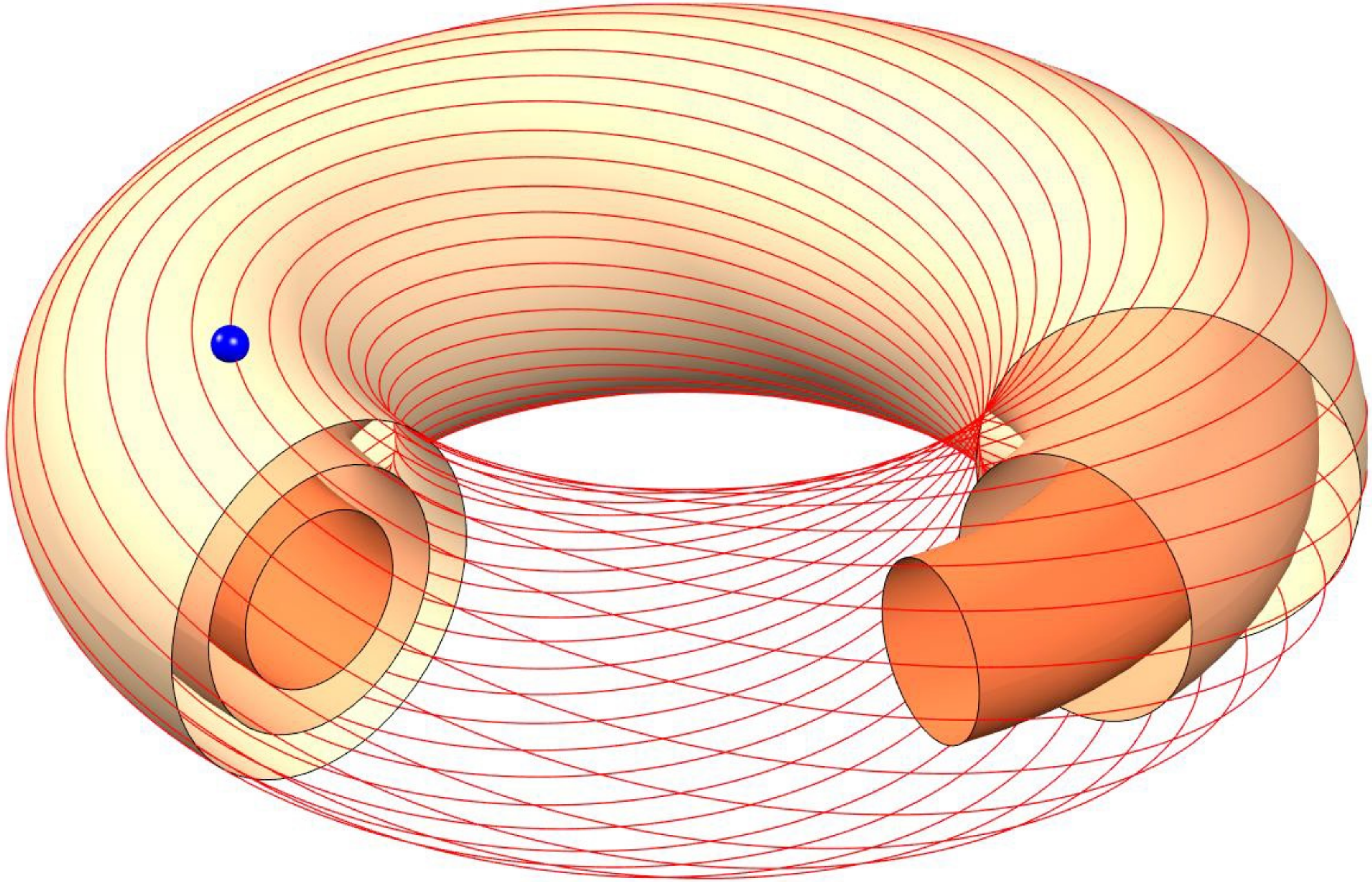
(the so-called drifts)



Solution: wrap field lines around a toroidal surface

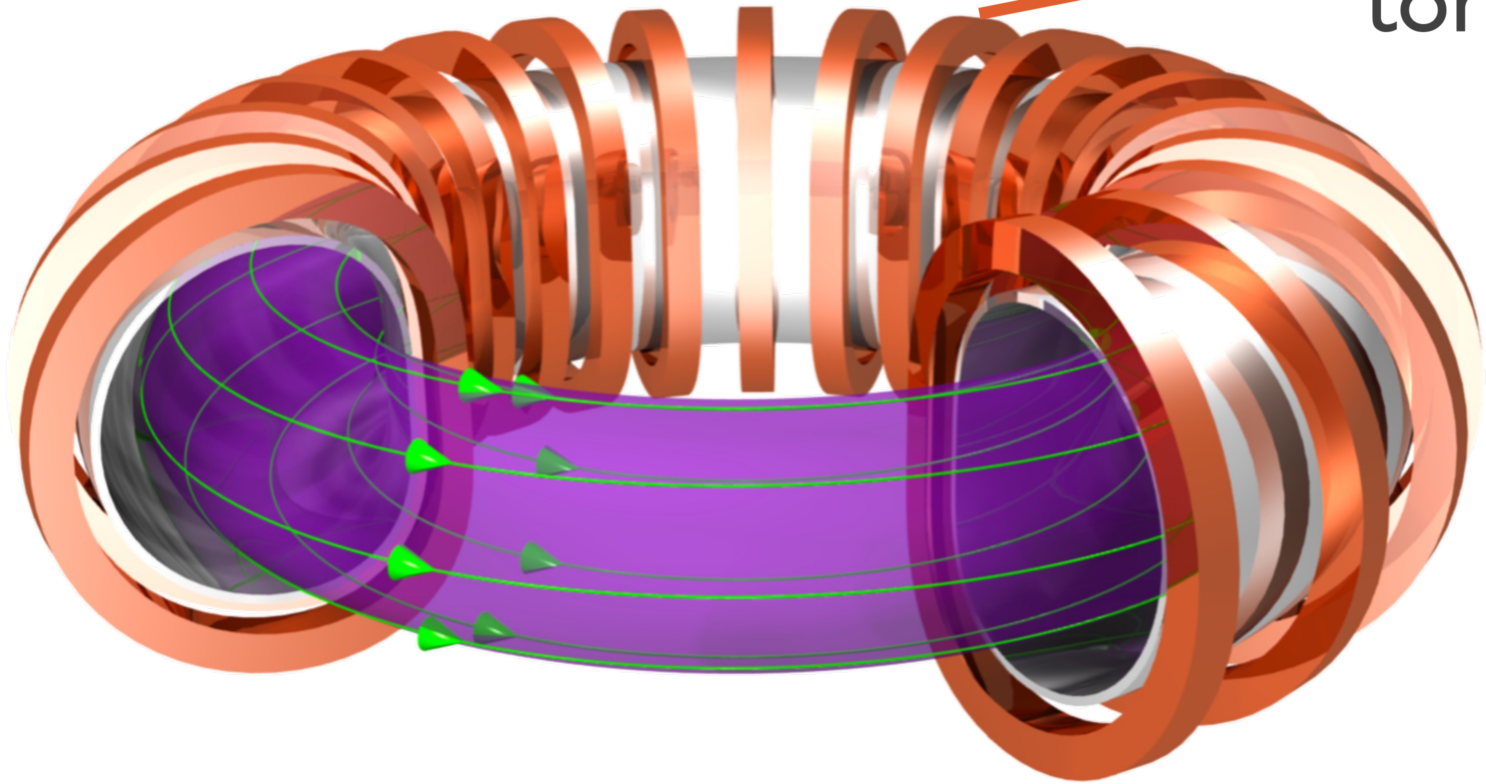


Particles are now confined



Two ways of creating nested magnetic surfaces

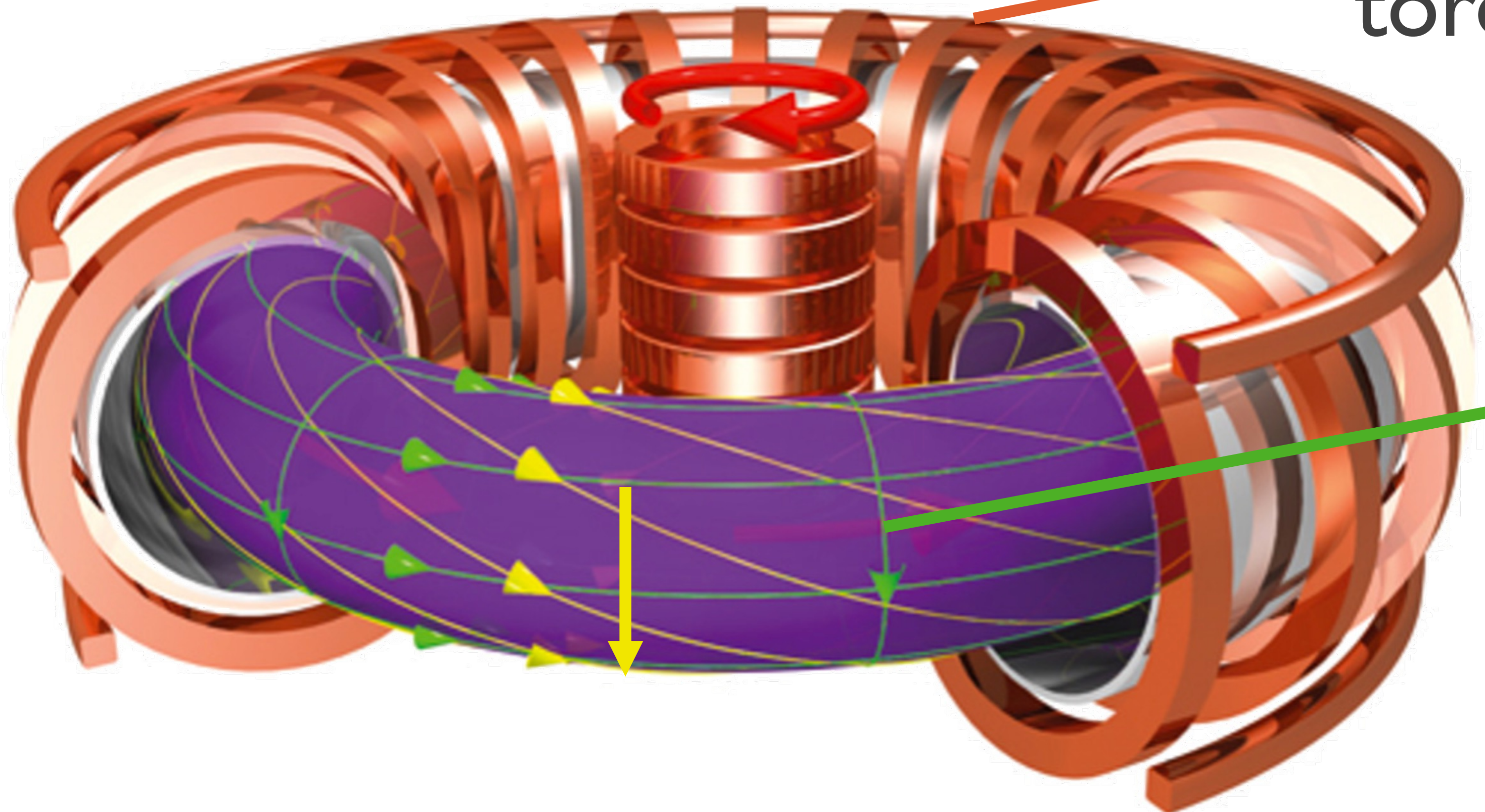
1. Tokamaks



Use coils to create a toroidal magnetic field

Two ways of creating nested magnetic surfaces

1. Tokamaks



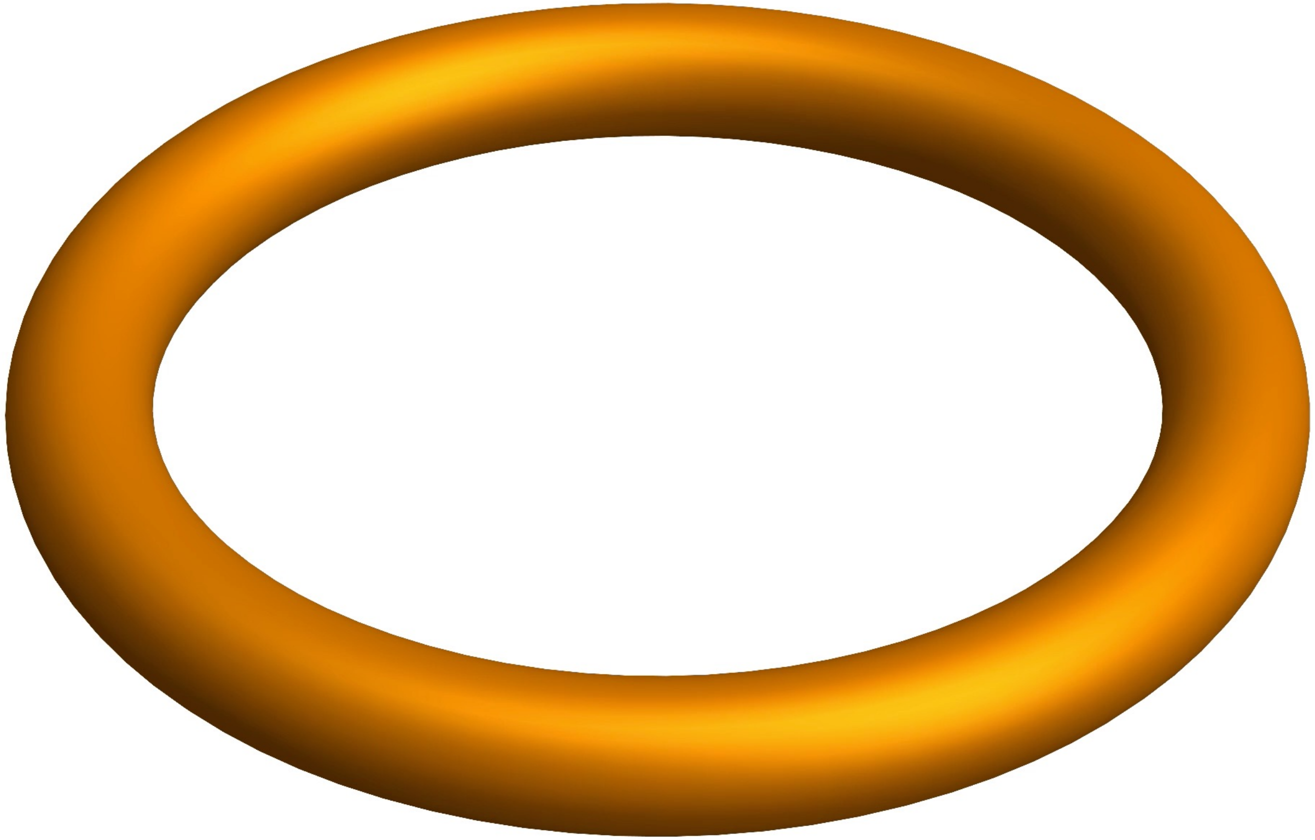
Use coils to create a toroidal magnetic field

Create extra poloidal field using a plasma current

To have nested surfaces, tokamaks need an internal current that can provide free energy for large scale instabilities

Two ways of creating nested magnetic surfaces

2. Stellarators

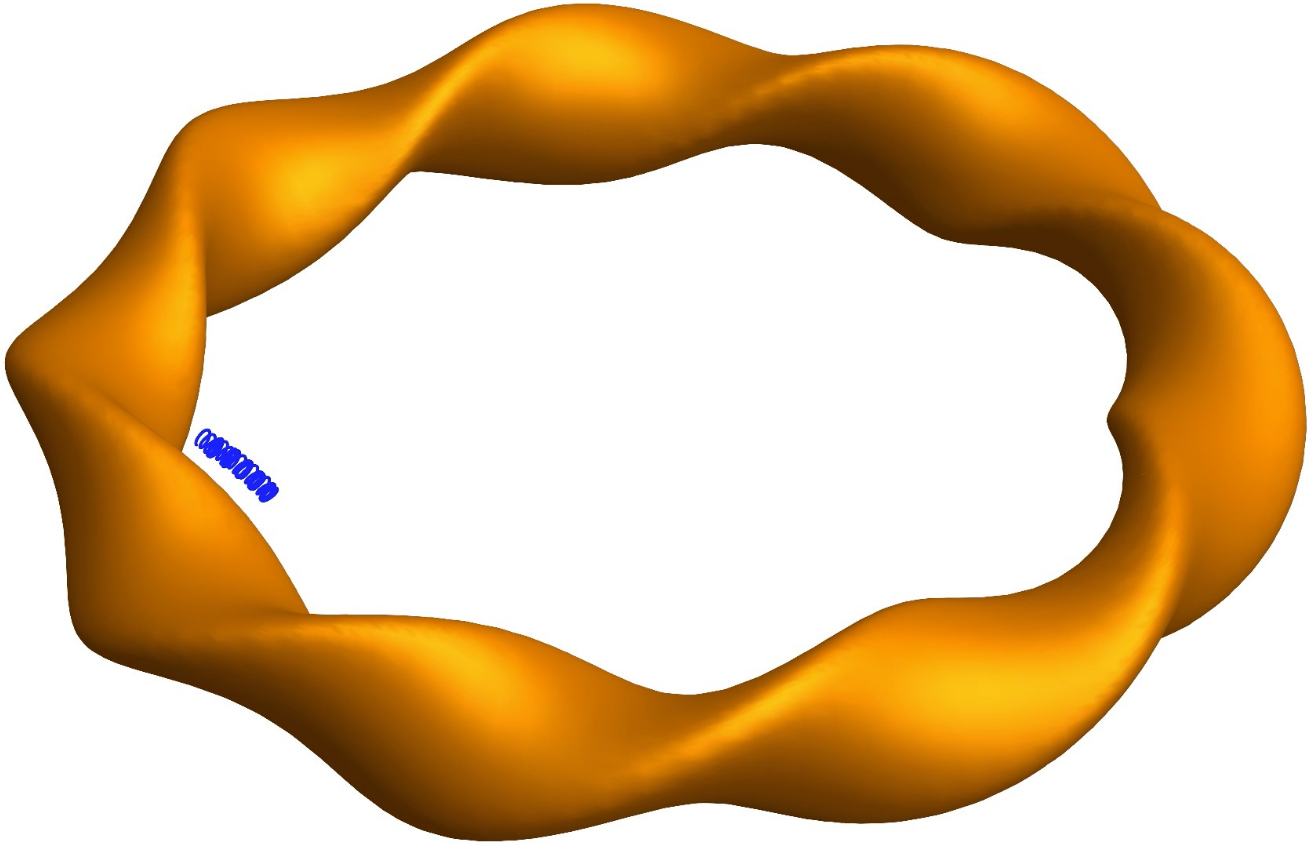


Break toroidal

symmetry

Two ways of creating nested magnetic surfaces

2. Stellarators

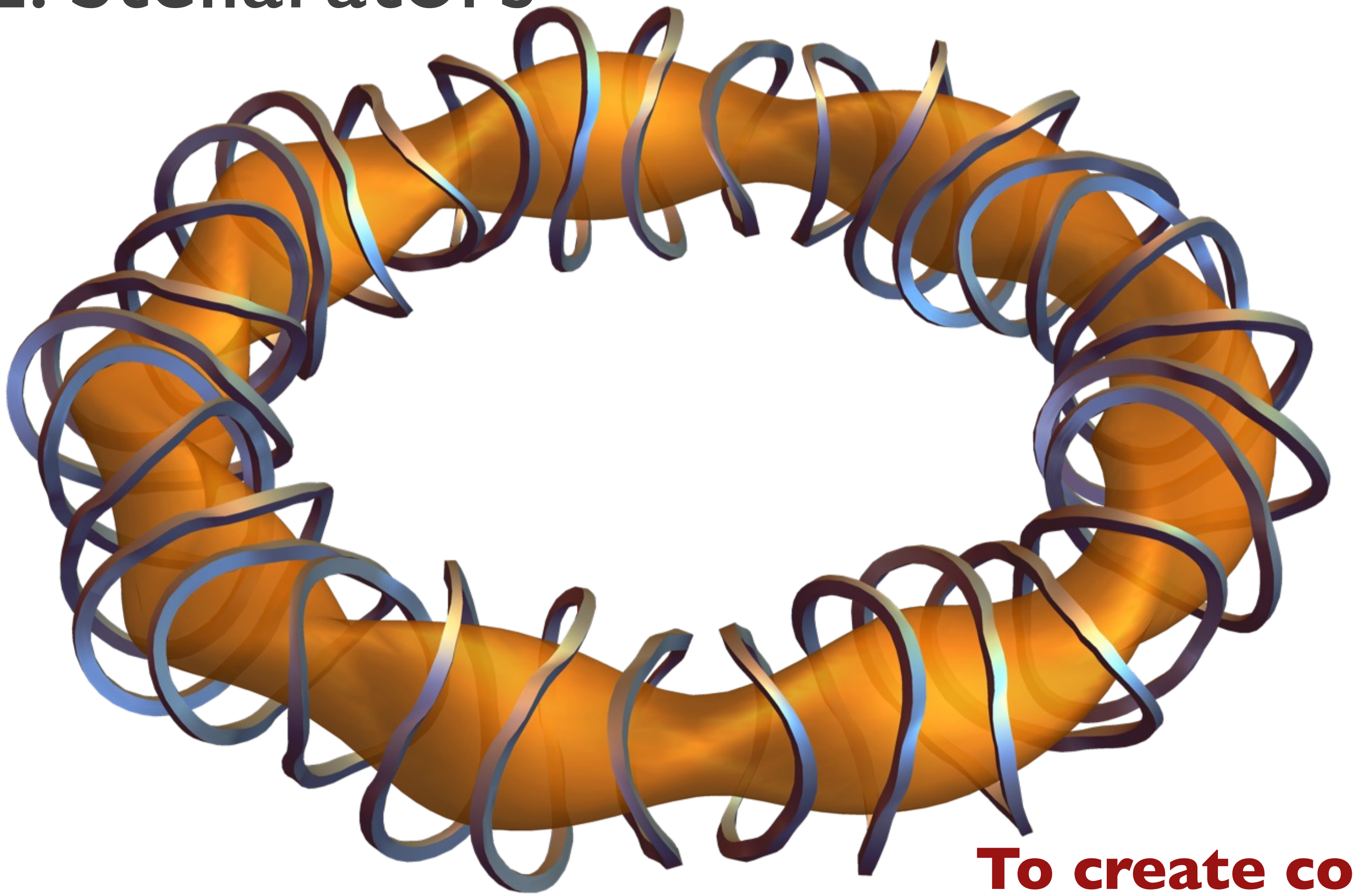


Break toroidal symmetry

Use extra freedom to confine particles

Two ways of creating nested magnetic surfaces

2. Stellarators



Break toroidal

symmetry

Use extra freedom to

confine particles

To create complex shapes

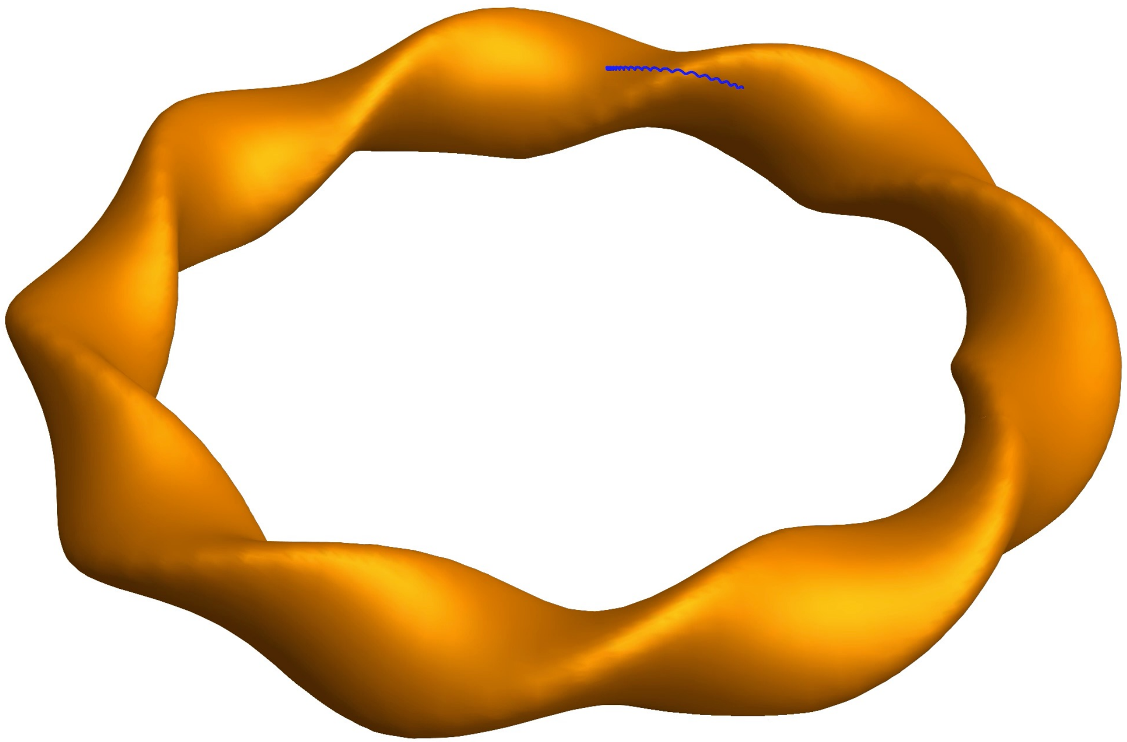
stellarators require complex

Stellarator optimization

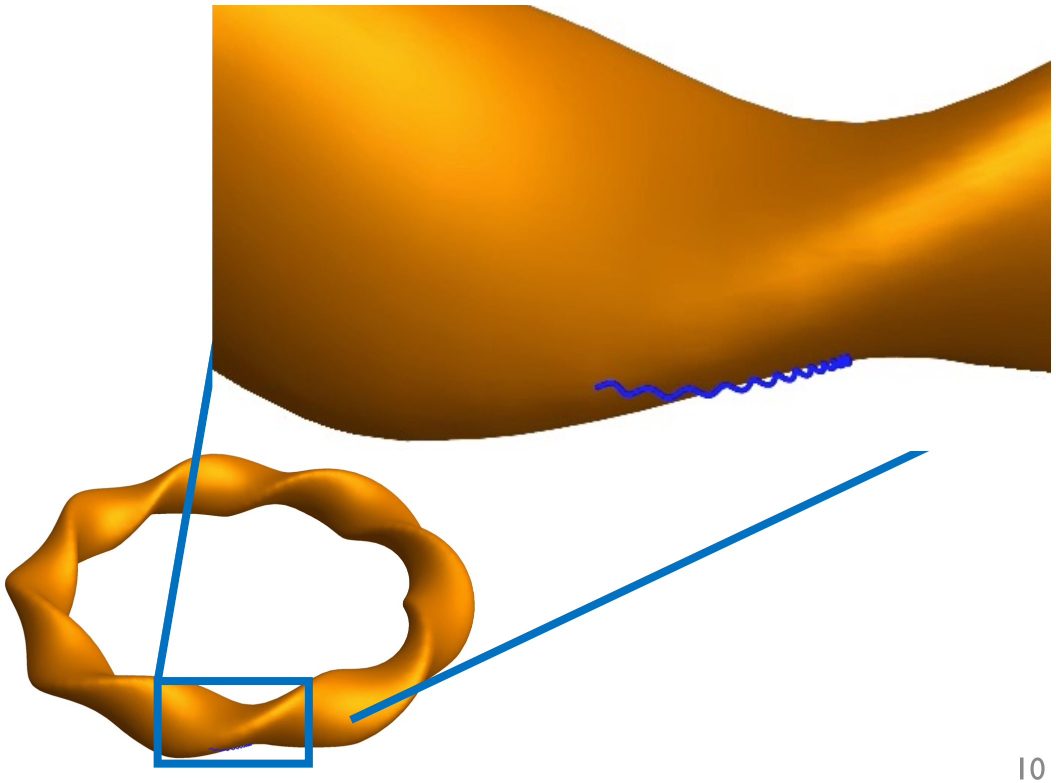
Radial Displacement

$$\Delta\psi = \oint dt\; \underbrace{\mathbf{v}_d}_{\text{Guiding center drift}} \cdot \overbrace{\nabla\psi}^{\text{Radial direction}} = 0$$ (averages to zero)

Turn this



Into this



How does the tokamak confine all particles?

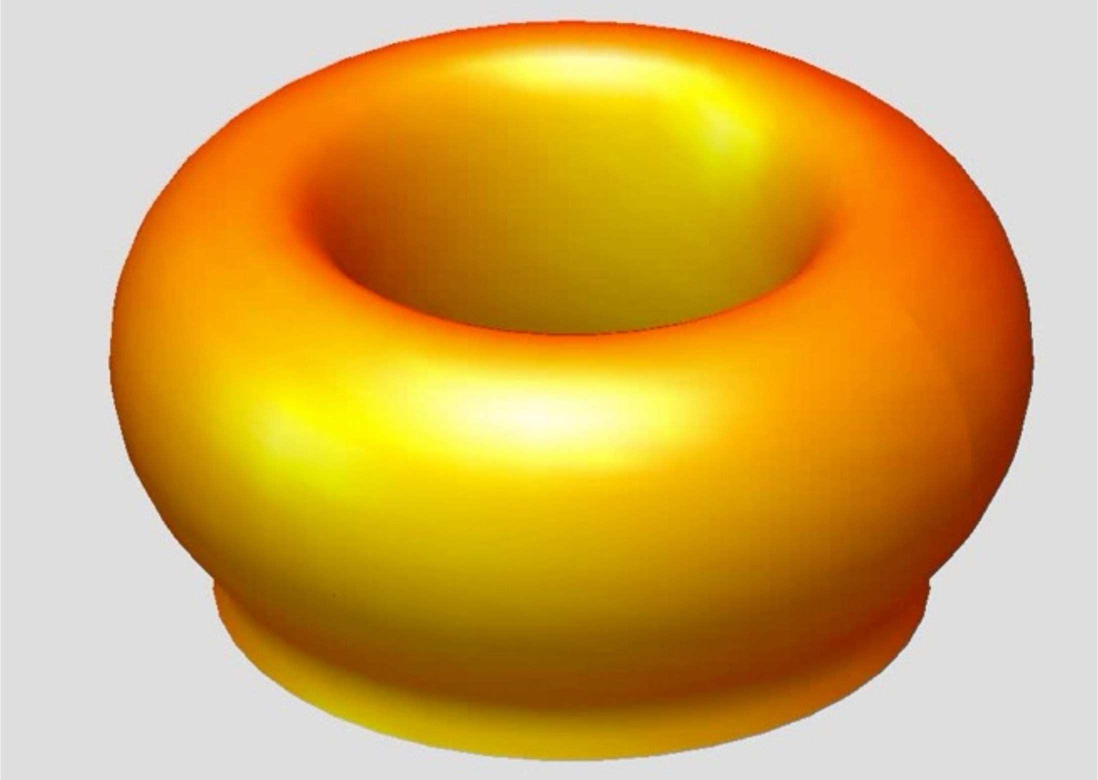
Tokamak $\boldsymbol{B}$ field is axisymmetric

↓

Conserved canonical angular momentum

↓

Confined trajectories



Can stellarators do the same?

Find a hidden symmetry in the Lagrangian

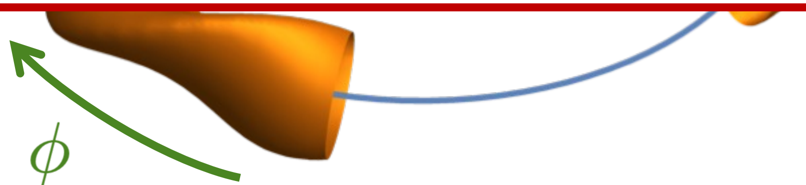
Lagrangian for a charged particle

$$L = \frac{m|\dot{\mathbf{x}}|^2}{2} + q\mathbf{A}\cdot\dot{\mathbf{x}}$$

Simplify L by removing fast gyromotion

L depends only on the angles θ and ϕ via $\mathrm{B} = |\boldsymbol{B}|$

If $\partial B/\partial\phi = 0$, the canonical angular momentum $p_\phi = \partial L/\partial\dot{\phi}$ is conserved!



This symmetry idea was the basis of the Simons collaboration

SIMONS FOUNDATION

Drs. Jim and Marilyn Simons

Hidden Symmetries and Fusion Energy Collaboration

Founding PIs - USA, Australia, Germany, Switzerland, England

University of Maryland, Princeton Plasma Physics Laboratory, Cornell University, Columbia University, New York University, University of Texas-Austin, University of Wisconsin-Madison, University of Colorado-Boulder, EPFL, Max-Planck Institute, The Australian National University

new stellarator optimization tool with unit testing, code coverage, docker containers, parallelization, documentation, etc…

JOSS
The Journal of Open Source Software

Editor: Dan Foreman-Mackey

Reviewers:

- @ZedThree
- @StanczakDominik

Submitted: 21 June 2021
Published: 10 September 2021

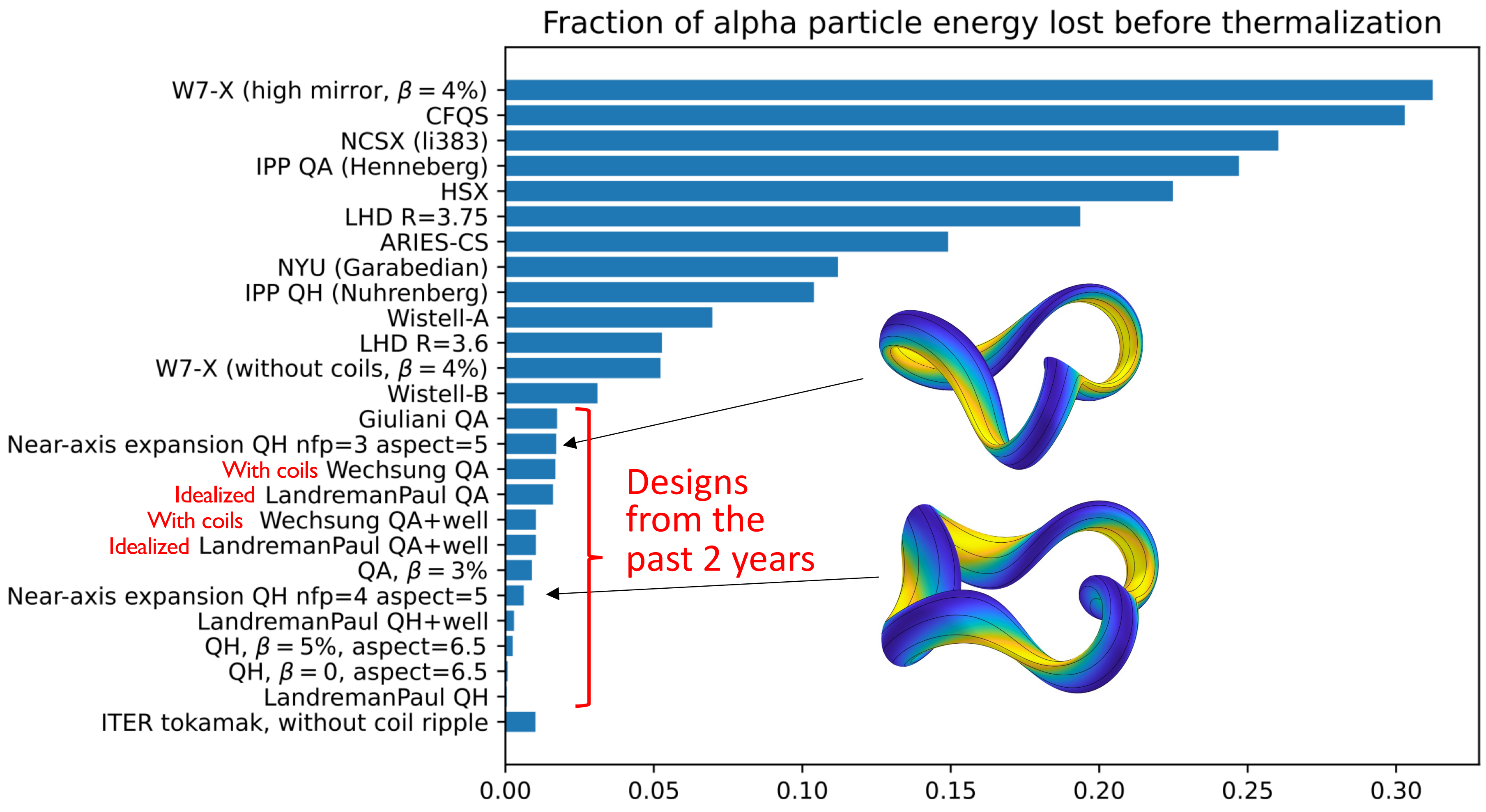
hiddenSymmetries / **simsopt** Public

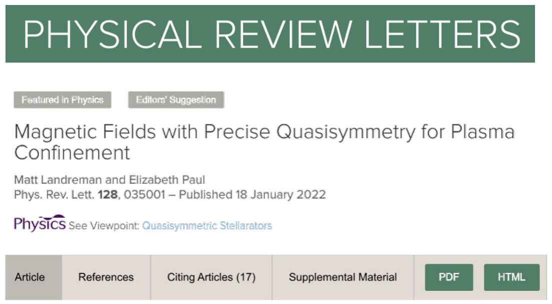
SIMSOPT: A flexible framework for stellarator optimization

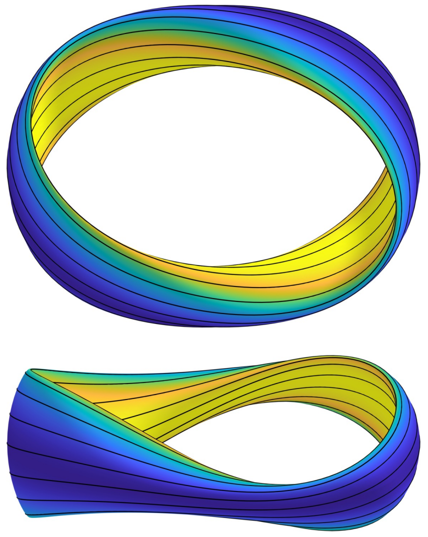
Matt Landreman[1], Bharat Medasani[2], Florian Wechsung[3], Andrew Giuliani[3], Rogerio Jorge[1], and Caoxiang Zhu[2]

1 Institute for Research in Electronics and Applied Physics, University of Maryland, College Park **2** Princeton Plasma Physics Laboratory **3** Courant Institute of Mathematical Sciences, New York University

Which led to tremendous progress in the stellarator world







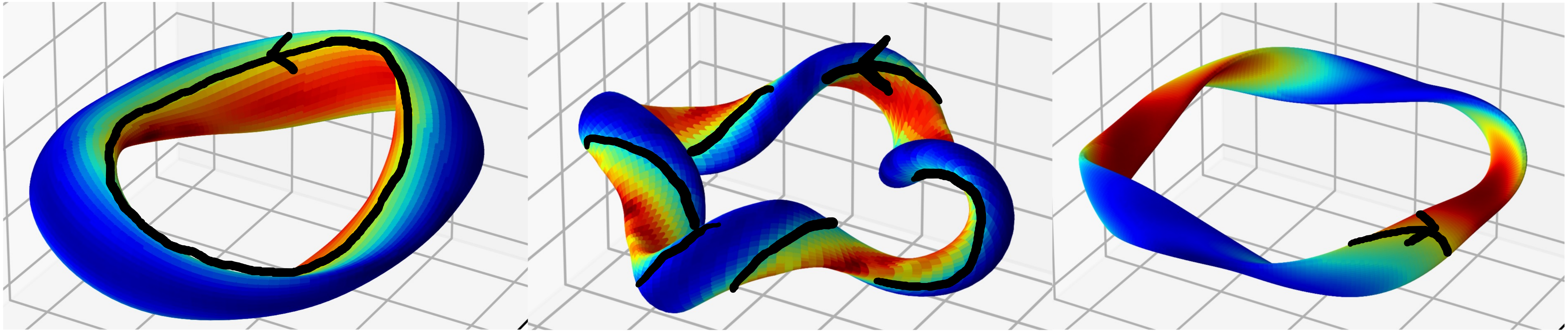
Courtesy of M. Landreman

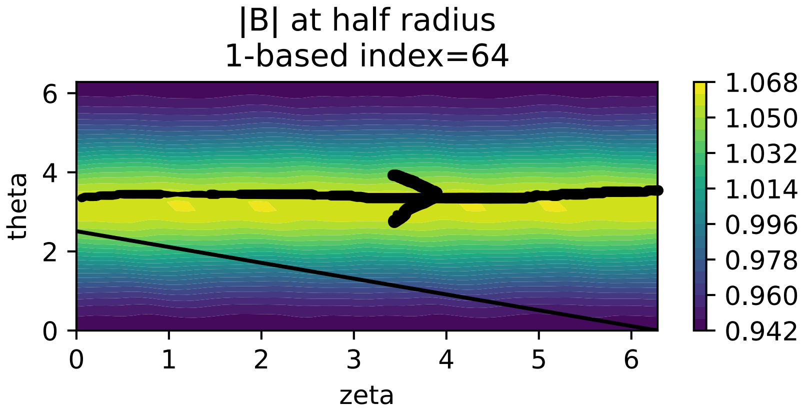
Stellarator optimization – optimize $|\boldsymbol{B}|$

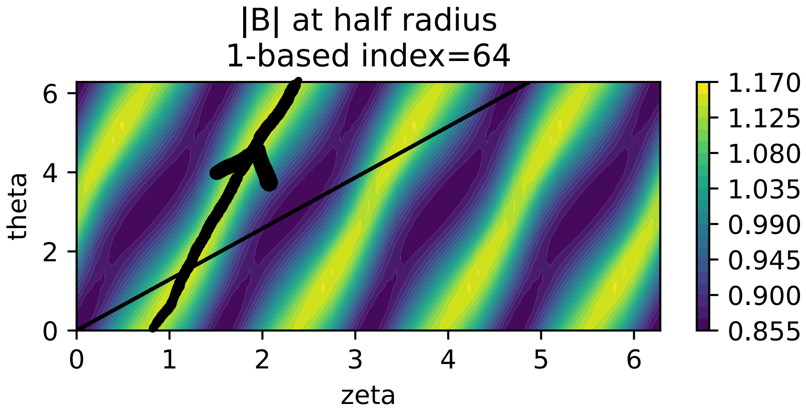
Quasi-axisymmetry

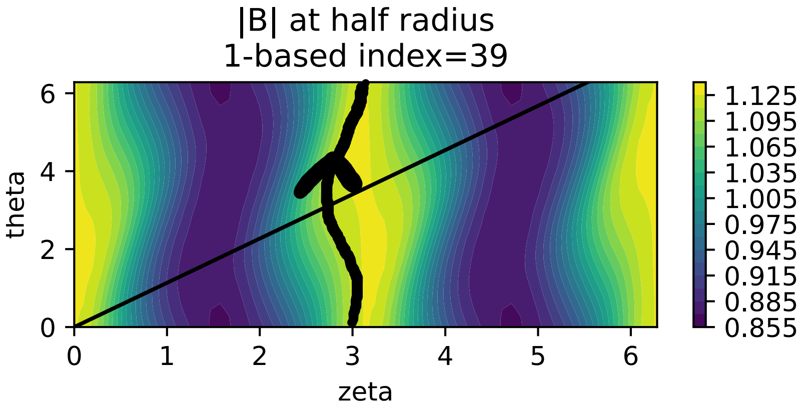
Quasi-helical symmetry

Quasi-isodynamic



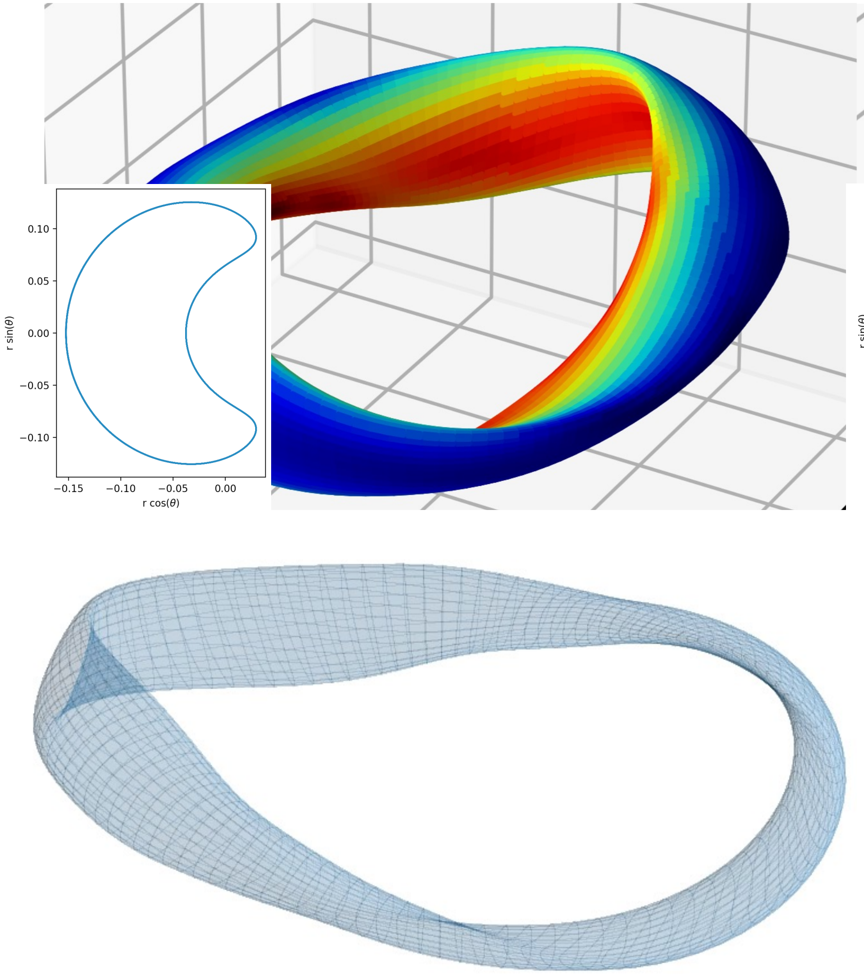




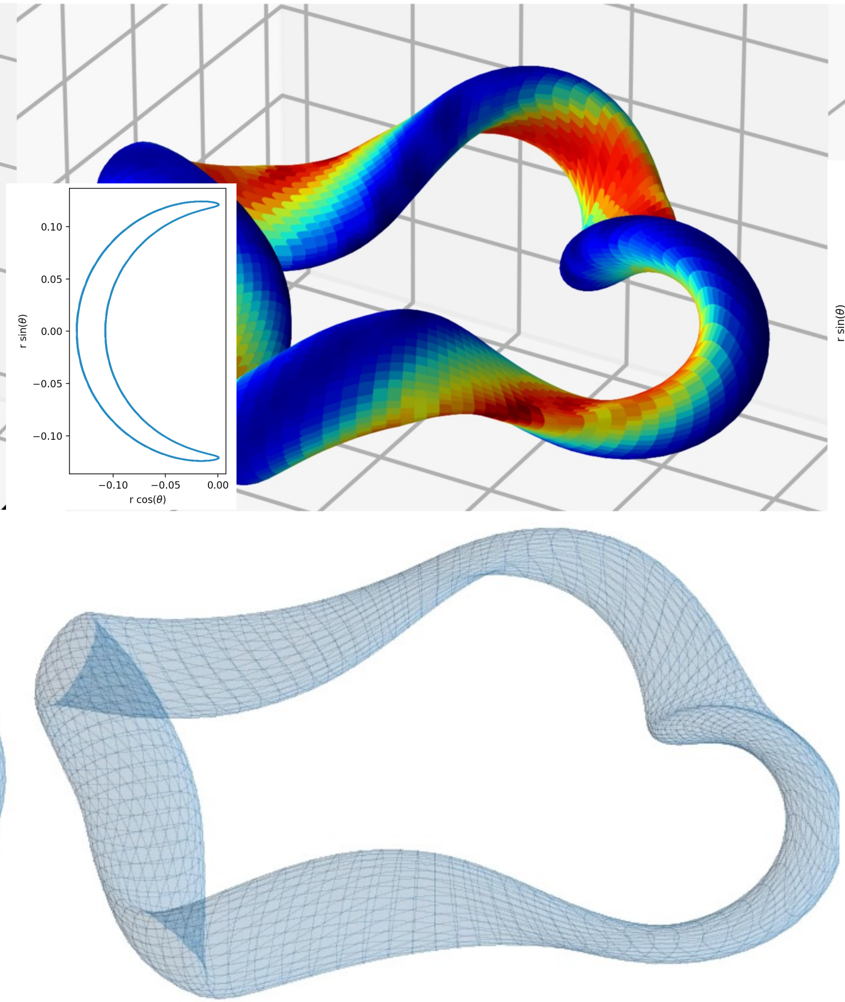


Stellarator optimization – optimize $|\boldsymbol{B}|$

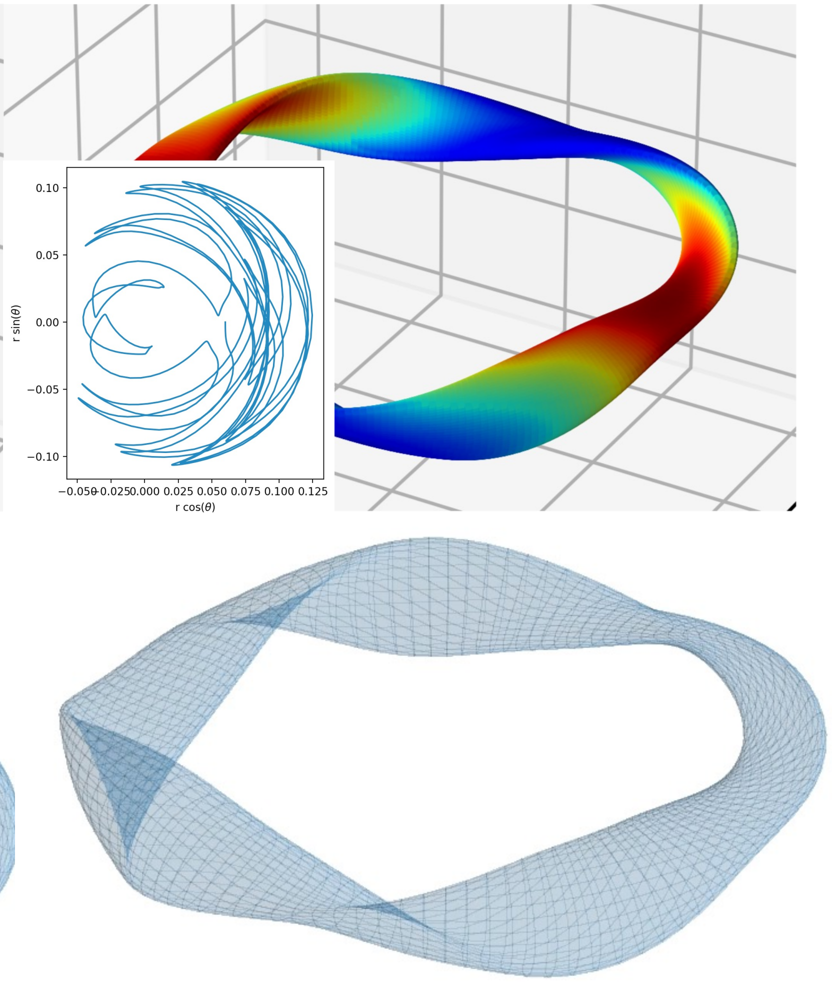
Quasi-axisymmetry



Quasi-helical symmetry



Quasi-isodynamic



PART 2

Recent breakthroughs in stellarators

A new idea…

Direct stellarator optimization

Directly minimize the quantity you want to minimize

It may or may not be a good idea… → Compare with proxies

What is the ultimate cost function? And initial conditions?

Direct quantities	Proxies
Fast particle confinement Low neoclassical transport	Quasisymmetry, Quasi-isodynamic…
Coil complexity	Shape complexity, $L_{\nabla B}$ …
Turbulent transport	Effective radius of curvature, quasilinear…
Plasma stability	Mercier criterion, shape complexity…
Best possible stellarator (robustness, global minimum)	Near-axis, good initial points…

VS

What shall we do? Direct or proxy optimization?

Direct approaches covered today

- Direct constructions using the near-axis expansion
- Direct fast particle optimization
- Direct turbulence optimization: quasi-linear and nonlinear approaches
- Direct coil optimization: single-stage approaches

Direct approaches covered today

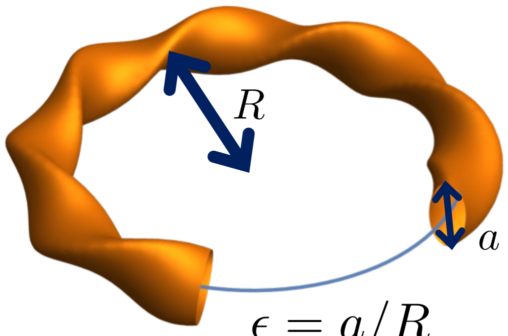
- Direct constructions using the near-axis expansion
- Direct fast particle optimization
- Direct turbulence optimization: quasi-linear and nonlinear approaches
- Direct coil optimization: single-stage approaches

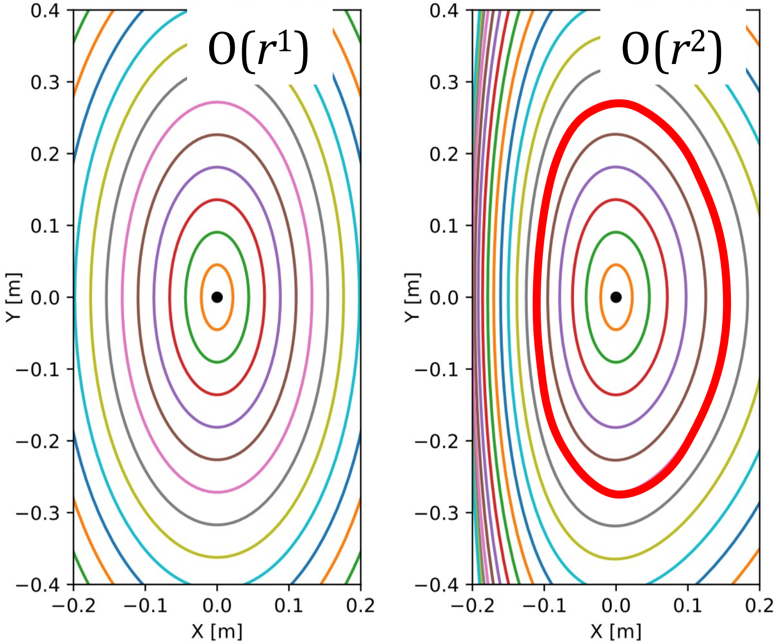
What is the near-axis expansion?

- Inputs:
  - Shape of the magnetic axis.
  - 3-5 other numbers (e.g., current on the axis).

$$\mathbf{r} = \mathbf{r}_0 + \sqrt{s}\left[\frac{\bar{\eta}}{\kappa}\cos\theta\,\mathbf{n} + \frac{\kappa}{\bar{\eta}}(\sin\theta + \boxed{\sigma}\cos\theta)\mathbf{b}\right]$$

- Outputs:
  - Shape of the surfaces around the axis.
  - Rotational transform on axis.
  - …

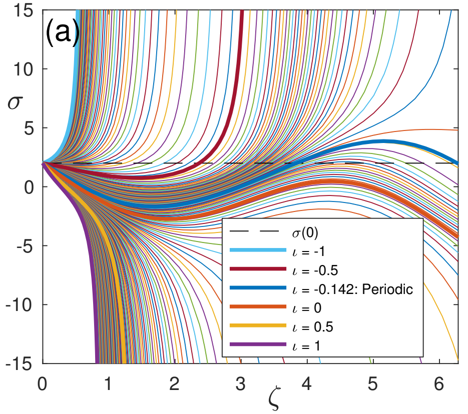




- Quasisymmetry guaranteed in a neighborhood of axis.
- Can pick any surface to pass to traditional MHD solver

The ideal MHD equation at O(ϵ) yields $\mathbf{J}\times\mathbf{B} = \nabla P$

$$\boxed{\frac{d\sigma}{d\varphi} + (\iota_0 - N)\left(\frac{\bar{\eta}^4}{\kappa^4} + 1 + \sigma^2\right) - \left(\frac{I_2}{B_0} - \tau\right)\frac{L\bar{\eta}^2}{\pi\kappa^2} = 0}$$



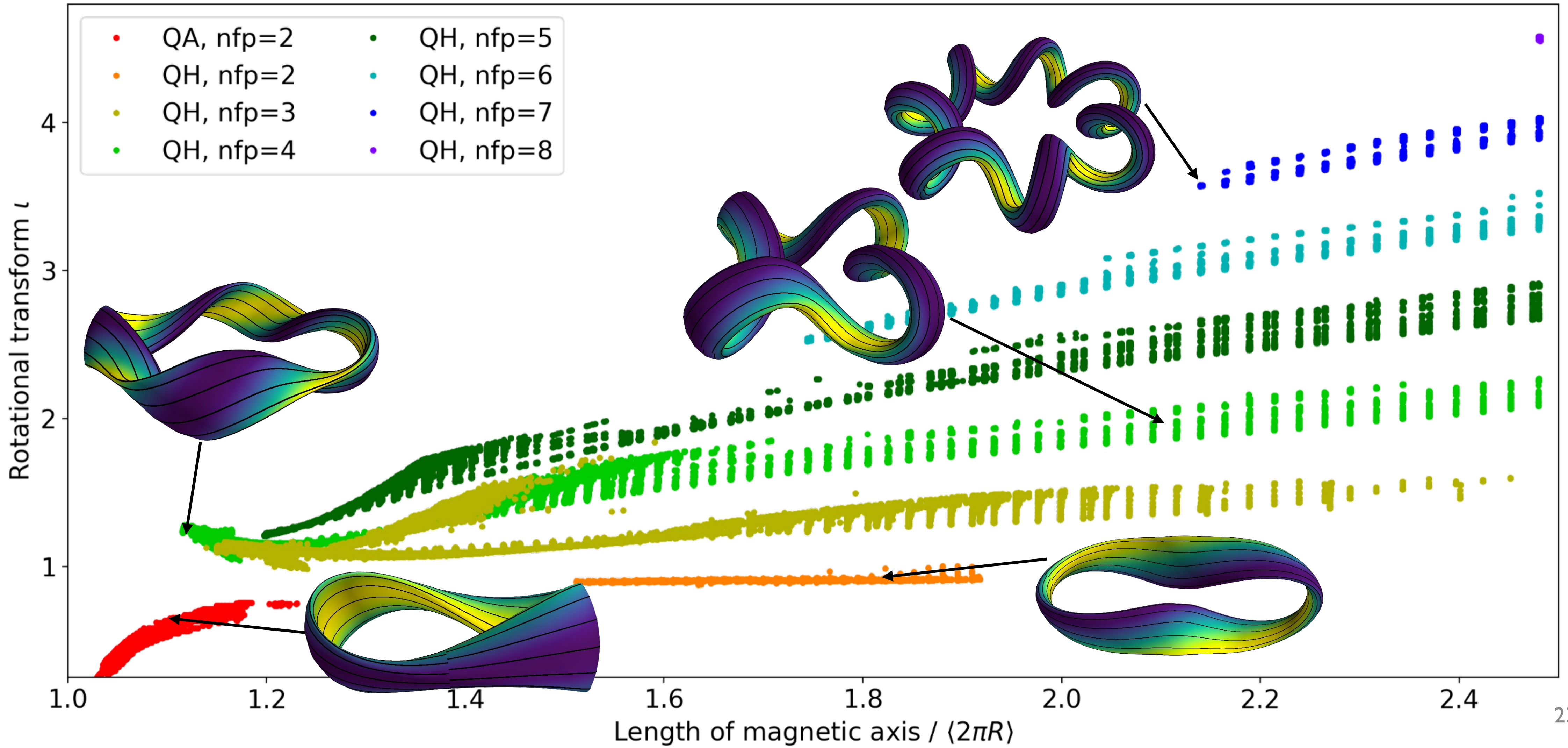
Now able to compute higher order solutions fast

M. Landreman, Journal of Plasma Physics , Volume 88 , Issue 6 , December 2022 , 905880616

landreman / qsc Public

3.1×10^{5} optimized stellarators shown
5.1×10^{6} optimizations computed
6.0×10^{10} equilibria computed

The "rainbow" plot



How does it compare with traditional optimization?

R. Jorge & M. Landreman, Plasma Phys. Control. Fusion 63, 1 (2020)

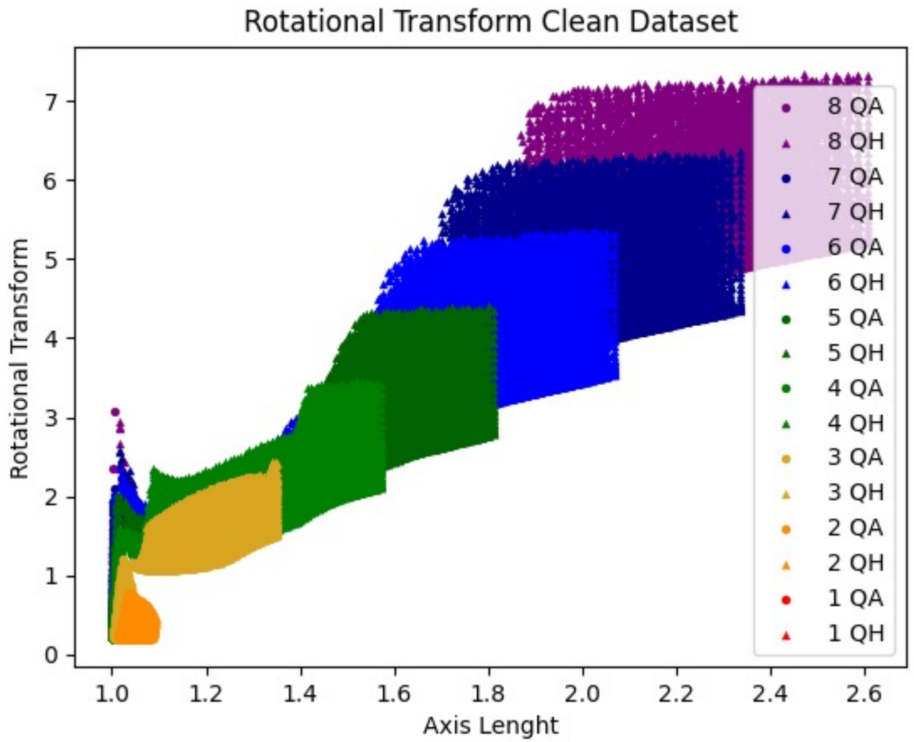
Take $|\boldsymbol{B}|$ from VMEC and fit to near-axis $|\boldsymbol{B}|$

Configuration	Aspect ratio A	Field periods n_{fp}	Plasma pressure β	ι from optimized configuration	ι from construction	Best-fit $\overline{\eta}$ $[\mathrm{m}^{-1}]$	B_0 [T]
NZ1988	12	6	0%	1.42	1.42	0.157	0.205
HSX	10	4	0%	1.05	1.06	1.28	1.00
KuQHS48	8.1	4	4%	1.29	1.27	0.147	1.20
WISTELL-A	6.7	4	3%	1.09	1.03	0.791	2.54
Drevlak	8.6	5	4%	1.50	1.50	0.0899	3.97
NCSX	4.4	3	4%	0.392	0.409	0.408	1.55
ARIES-CS	4.5	3	4%	0.412	0.498	0.0740	5.69
QAS2	2.6	2	3%	0.260	0.267	0.347	1.79
ESTELL	5.3	2	0%	0.202	0.202	0.570	1.00
CFQS	4.3	2	0%	0.382	0.515	0.586	0.933
Henneberg	3.4	2	3%	0.317	0.314	0.302	2.41

Table 1: Quasisymmetric configurations considered in this study.

Use the database to train a **neural network** (J. Candido, IST Lisbon)

Take a dataset with both moderate and low elongation stellarators



Train a NN on the scaled inverse problem

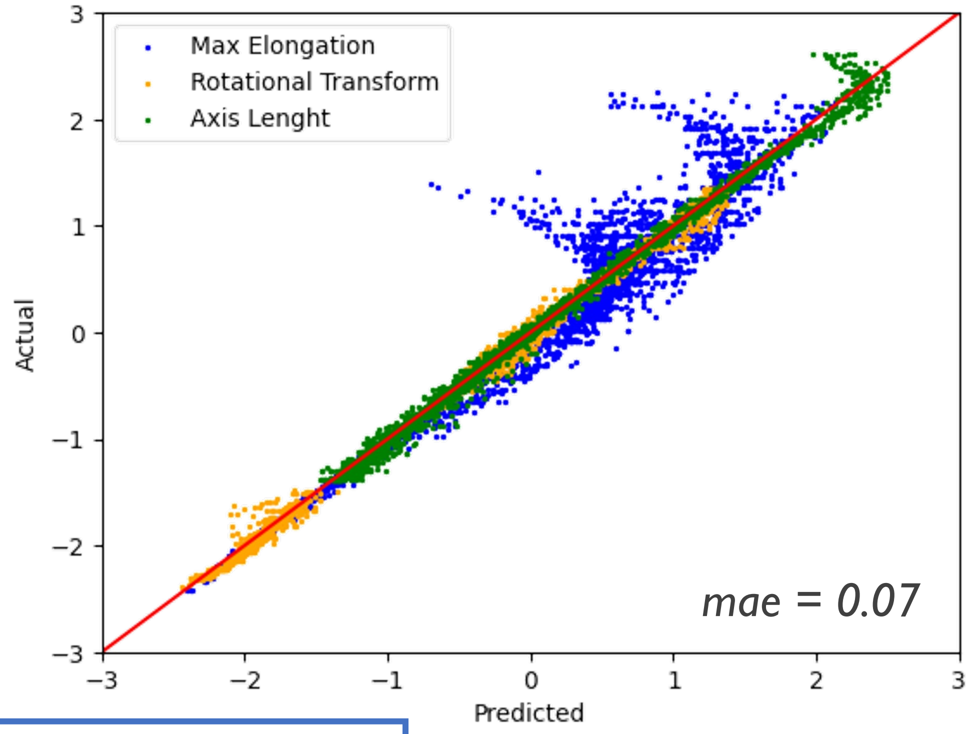
$$y = (\text{axis length}, \iota, \text{elongation})$$

$$x = (\text{axis shape}, \bar{\eta})$$

Tanh activation

Hidden layer sizes = *(35, 35, 35)*

Solver = *Adam*



This allows us to find stellarator shapes with a particular shape instead of finding them via optimization

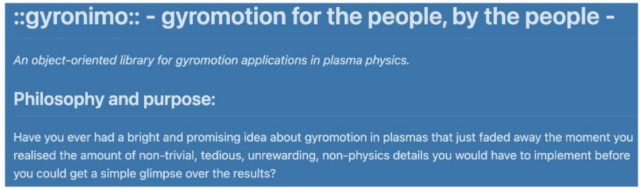
How do particles behave in near-axis fields? (P. Figueiredo, IST Lisbon)

- Ongoing work: Enabling Research grant EUROfusion (ENR.IST.MOD.01)
- Developed a new code: **NEAT** (python)

Integration with DESC underway

Based on a new open-source library **gyronimo**

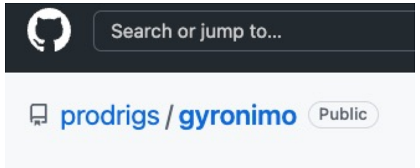
Solve guiding-center equations of motion in arbitrary coordinates


::gyronimo:: - gyromotion for the people, by the people -

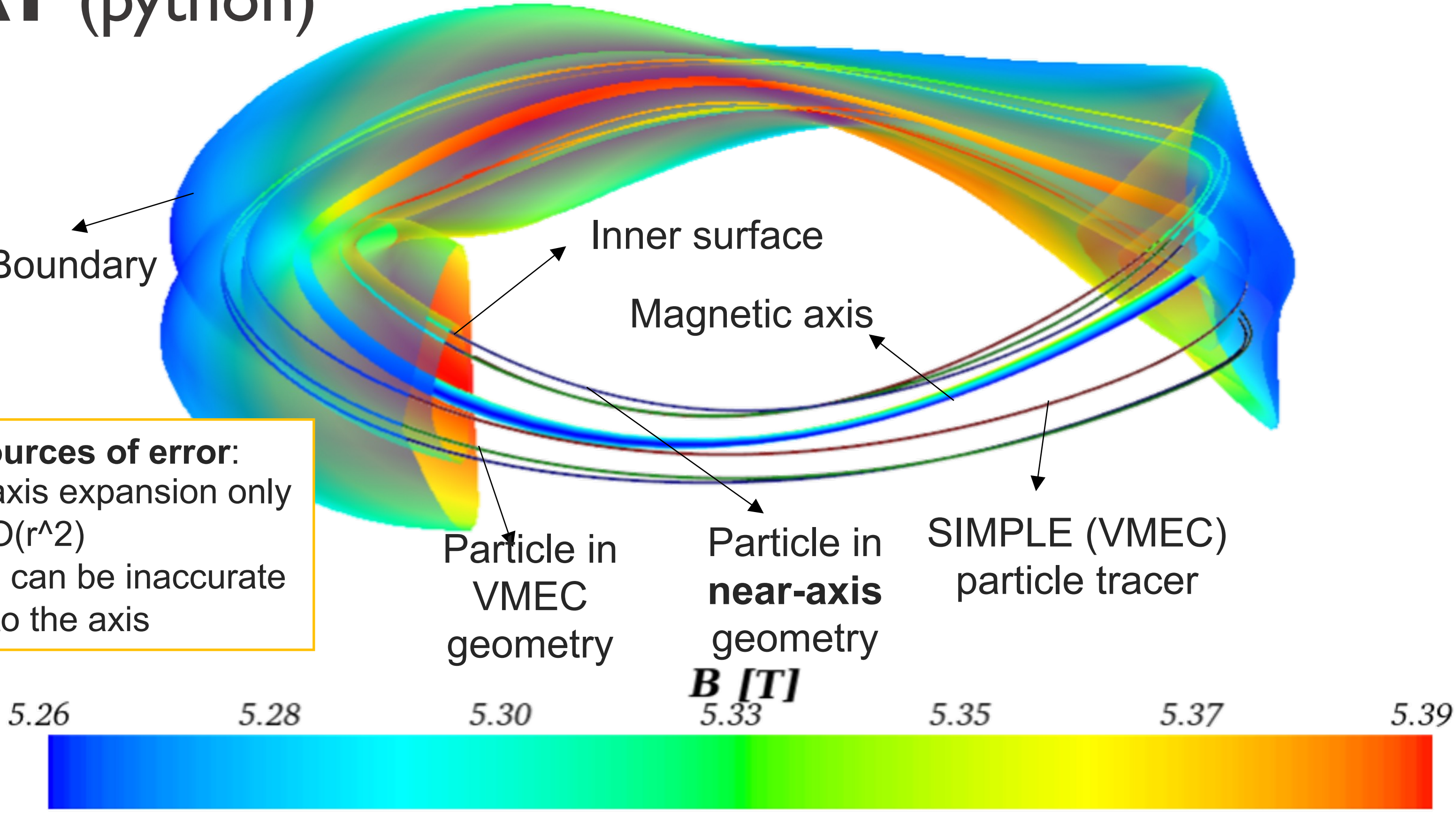
An object-oriented library for gyromotion applications in plasma physics.

Philosophy and purpose:

Have you ever had a bright and promising idea about gyromotion in plasmas that just faded away the moment you realised the amount of non-trivial, tedious, unrewarding, non-physics details you would have to implement before you could get a simple glimpse over the results?

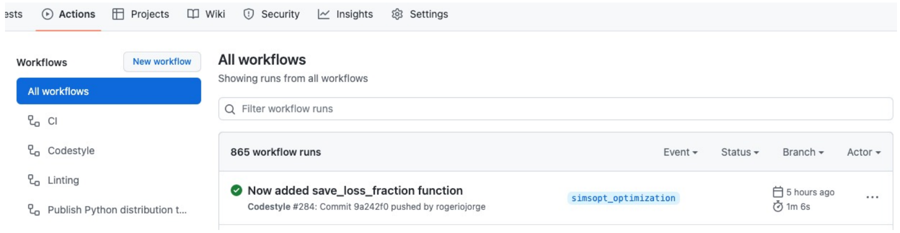


Main sources of error:
- Near-axis expansion only up to O(r^2)
- VMEC can be inaccurate close to the axis



New code: NEAT

Open-source and automatic testing with GitHub actions

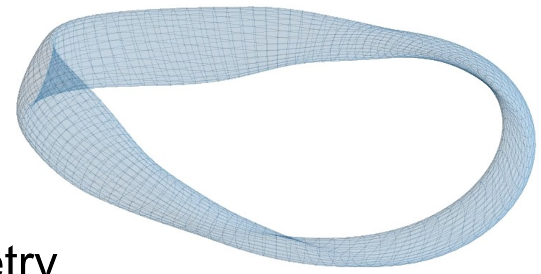


NEAT

rogeriojorge / NEAT Public

NEar-Axis opTimisation

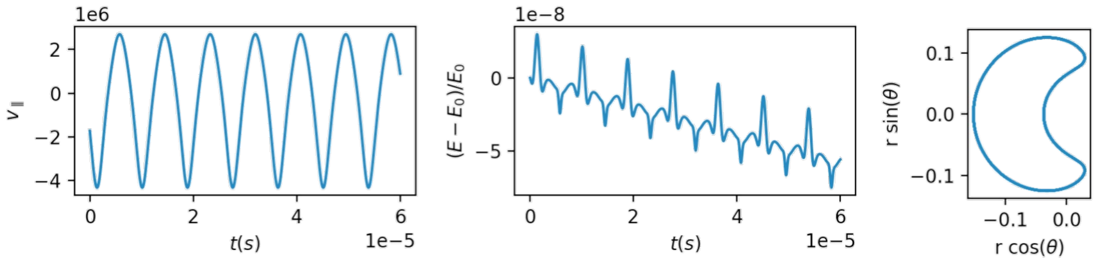
license GPL-3.0 | build passing | docs passing | codecov 61%



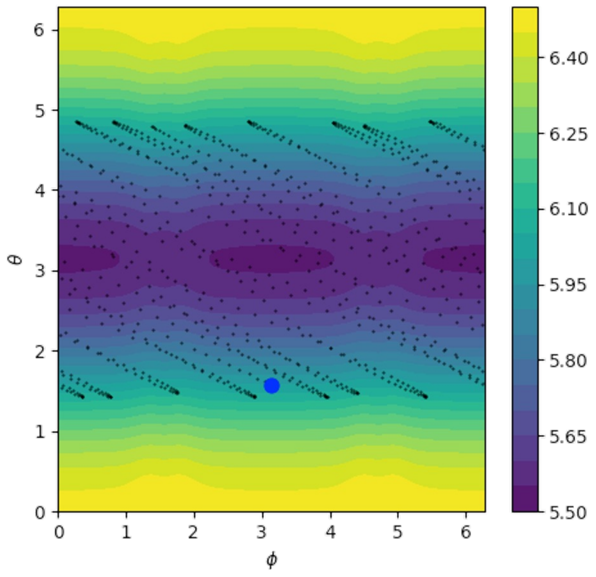
User-friendly example in near-axis geometry

```python
from neat.fields import StellnaQS
from neat.tracing import ChargedParticle, ParticleOrbit
g_field = StellnaQS.from_paper(1)
g_particle = ChargedParticle()
g_orbit = ParticleOrbit(g_particle, g_field tfinal=1e-4)
g_orbit.plot_orbit()
```

Similarly for VMEC




```python
print("Creating B contour plot")
g_orbit.plot_orbit_contourB()
```



Already being used by the stellarator optimization community

Critical gradient turbulence optimization toward a compact stellarator reactor concept

G. T. Roberg-Clark,* G. G. Plunk, P. Xanthopoulos, C. Nührenberg, S. A. Henneberg, and H. M. Smith
Max-Planck-Institut für Plasmaphysik, D-17491, Greifswald, Germany
(Dated: January 18, 2023)

Integrating turbulence into stellarator optimization is shown by targeting the onset for the ion-temperature-gradient mode, highlighting effects of parallel connection length, local magnetic shear, and flux surface expansion. The result is a compact quasihelically symmetric stellarator configuration, admitting a set of uncomplicated coils, with significantly reduced turbulent heat fluxes compared to a known stellarator. The new configuration combines low values of neoclassical transport, good alpha particle confinement, and Mercier stability at a plasma beta of almost 2%.

arXiv:2301.06773v1 [physics.plasm-ph] 17 Jan 2023

when rescaled to an ARIES-CS-equivalent [36] minor radius and volume averaged magnetic field strength, using the NEAT code [37, 38] (Fig. 2). Increased neoclassical

Direct approaches covered today

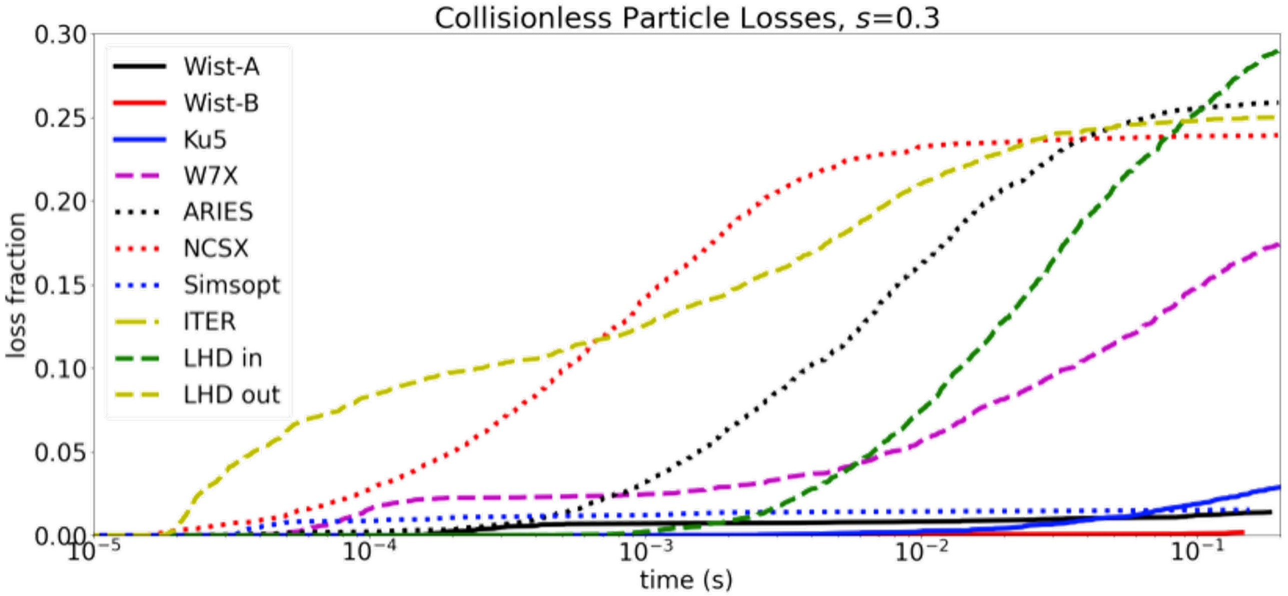
- Direct constructions using the near-axis expansion
- Direct fast particle optimization
- Direct turbulence optimization: quasi-linear and nonlinear approaches
- Direct coil optimization: single-stage approaches

Fast particle optimization

Typical proxies

- Quasisymmetry
- Quasi-isodynamic
- Nemov's Γ_c
- Γ_α

J. L. Velasco et al., Nuclear Fusion, Volume 61, Number 11, October 2021, 116059



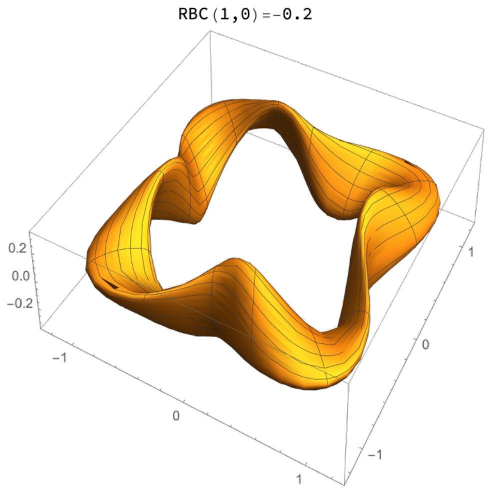
A. Bader et al., Nuclear Fusion, Volume 61 , Number 11, October 2021, 116060

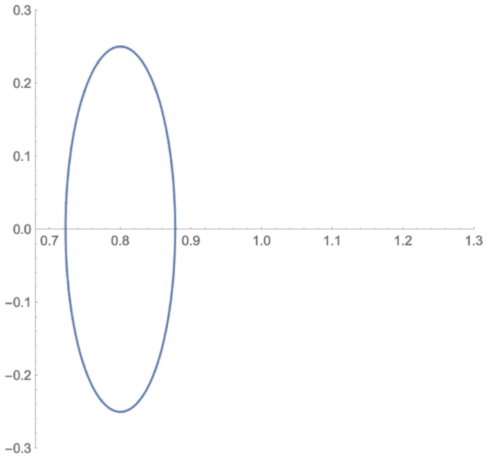
What if we directly minimize particle losses?

Direct fast particle optimization using NEAT

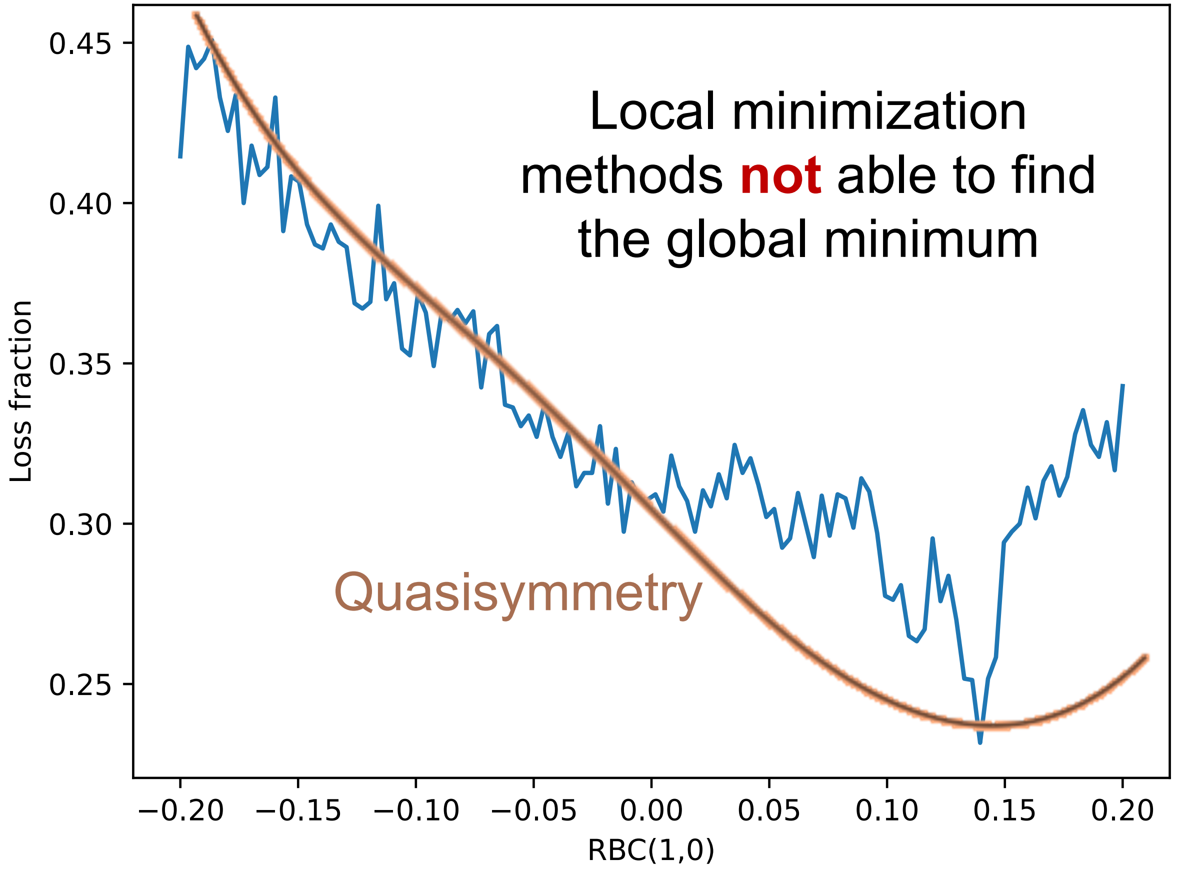
Minimal benchmark problem

- Trace 2400 particles for 5×10^{-4} s with the SIMPLE code
- Scale the minor radius and magnetic field to half of the ARIES-CS reactor
- Save the fraction of loss particles in an array for each RBC(-1,1)
- Each point takes ~1 second on a laptop





Minimize particle loss fraction to the wall



Direct fast particle optimization using NEAT

Stochastic optimization – generalized dual annealing

Initial condition:

- Circular torus without current
- 100% particle losses

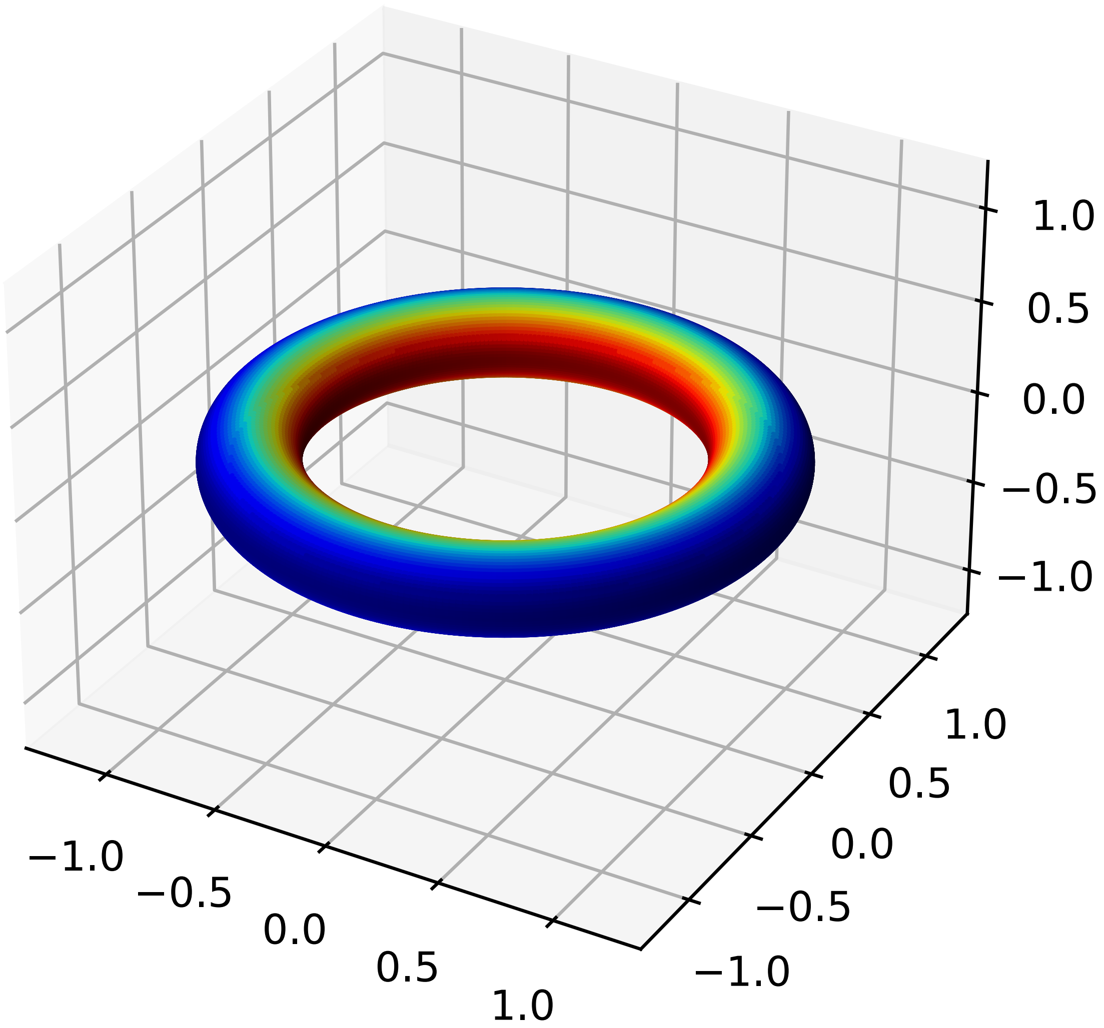
Parameter space – 9 parameters:

- RBC(1,0), RBC(1,1), RBC(0,1), RBC(-1,1)
- ZBS(1,0), ZBS(1,1), ZBS(0,1), ZBS(-1,1)

100% losses

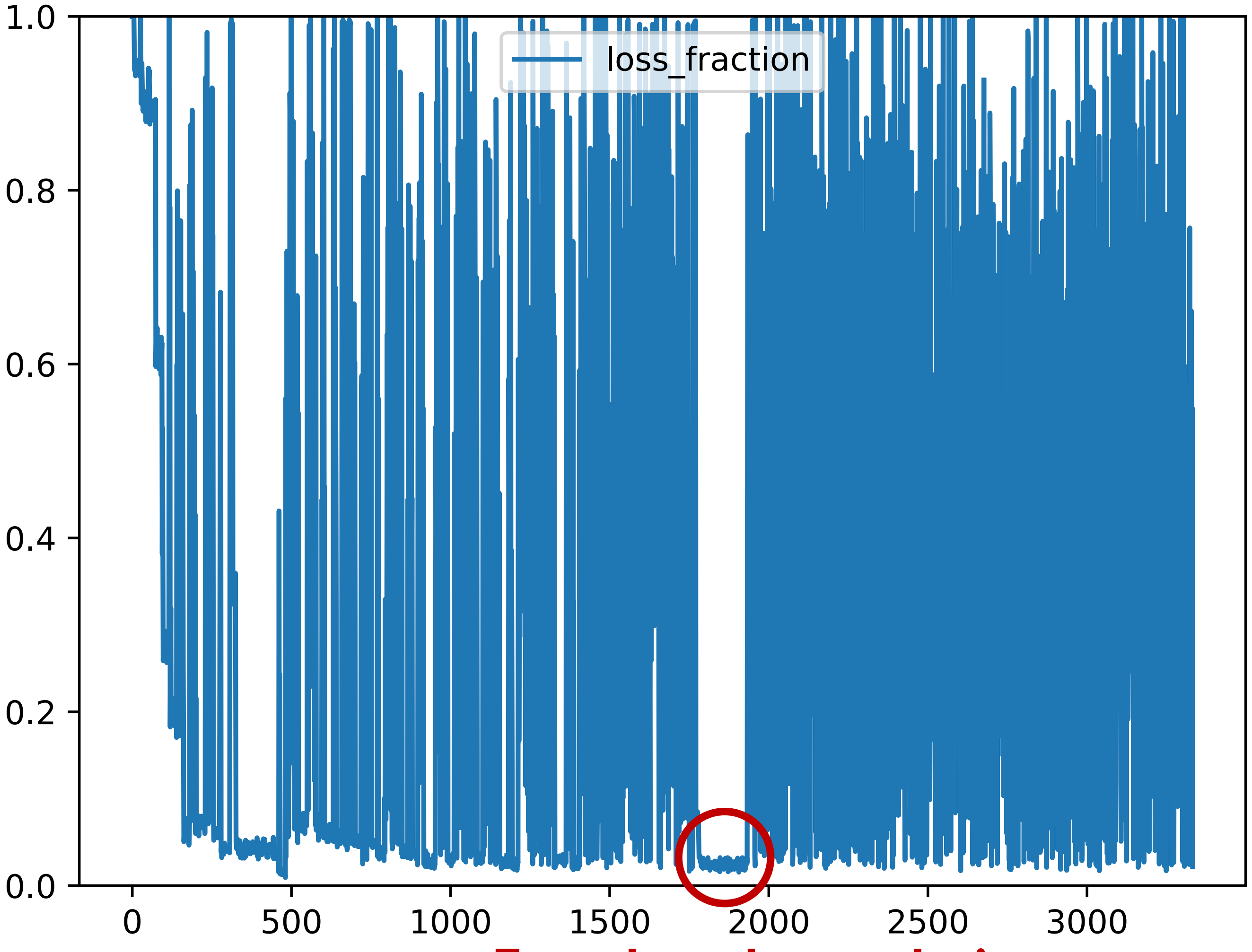
scipy.optimize.dual_annealing

```
scipy.optimize.dual_annealing(func, bounds, args=(), maxiter=1000, minimizer_kwargs=None, initial_temp=5230.0, restart_temp_ratio=2e-05, visit=2.62
```



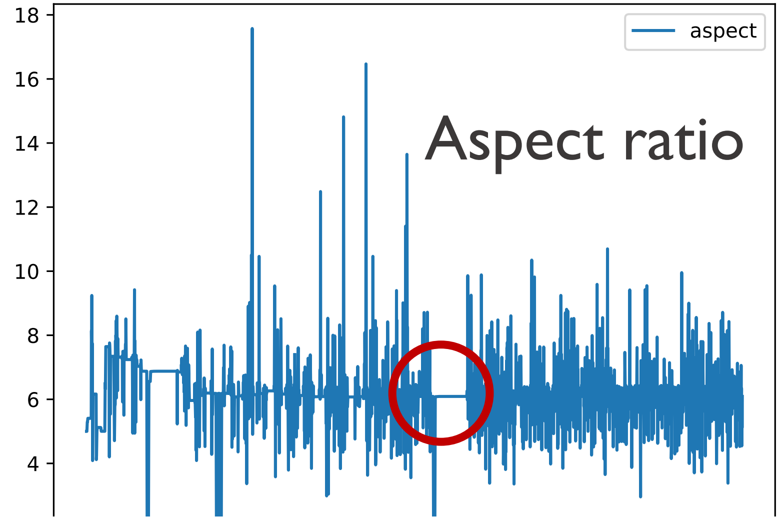
Direct fast particle optimization using NEAT

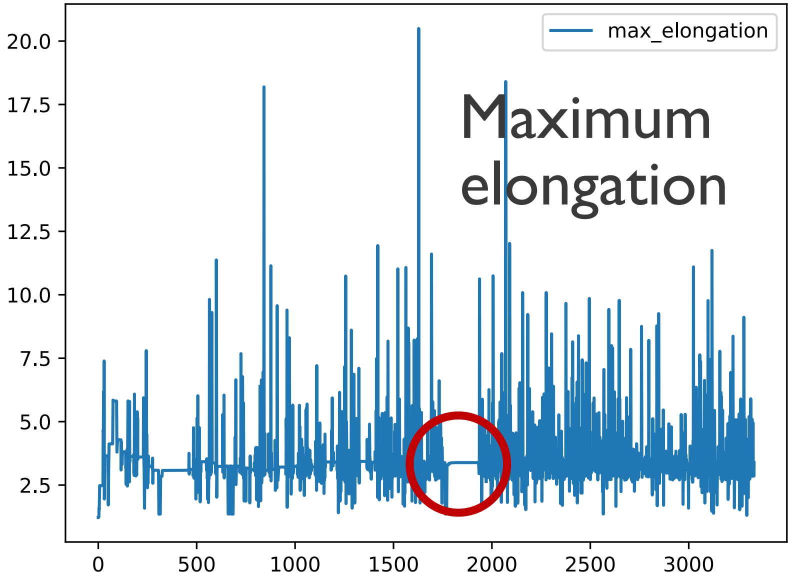
Optimization process



Found a robust solution

Number of function evaluations

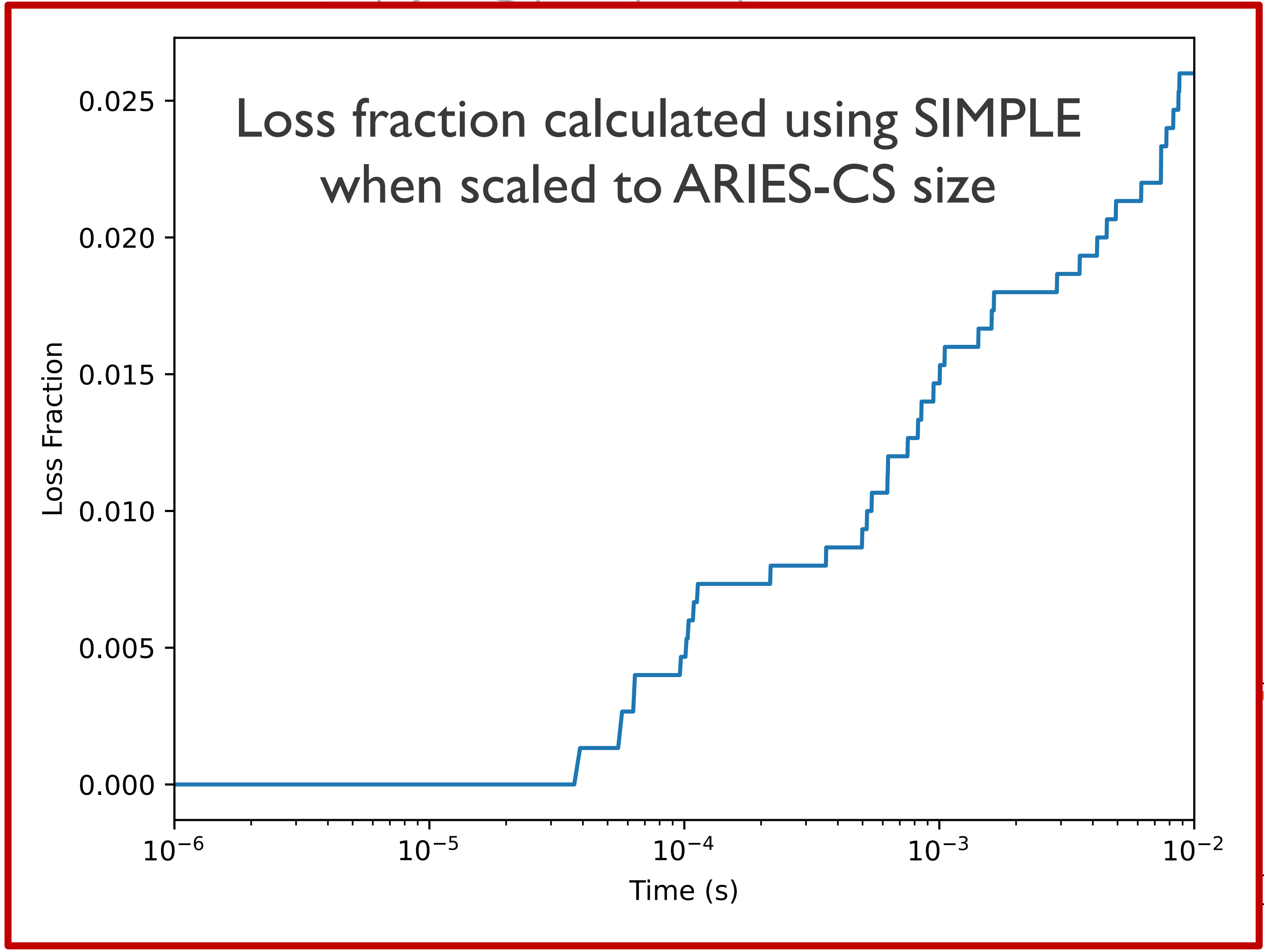


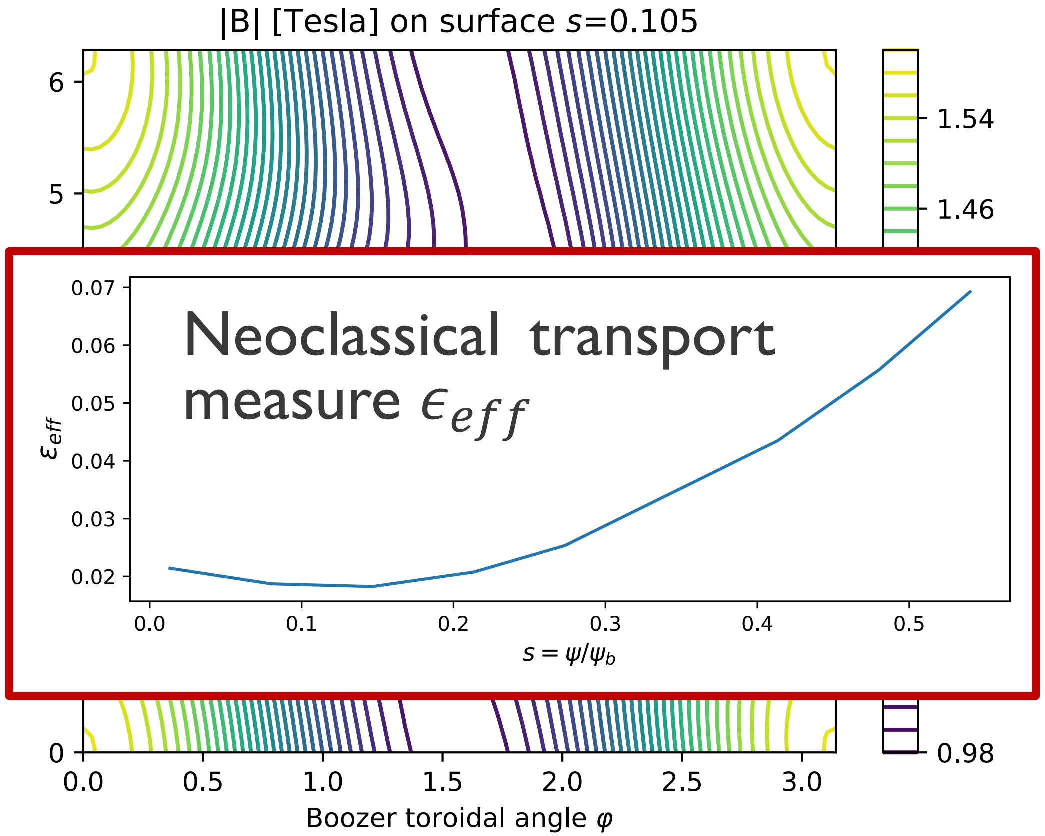


Direct fast particle optimization using NEAT

Solution found

rogeriojorge / EPoptimization





The optimizer found a quasi-isodynamic stellarator

Include collisions and realistic birth profiles – *Bindel, Landreman, Padidar (2023)*

arXiv > physics > arXiv:2302.11369

Physics > Plasma Physics

[Submitted on 22 Feb 2023]

Direct Optimization of Fast-Ion Confinement in Stellarators

David Bindel, Matt Landreman, Misha Padidar

Optimize for small lost energy

$$\underset{\mathbf{w}\in\mathbb{R}^{n_\mathbf{w}}}{\text{minimize}} \quad \mathcal{J}(\mathbf{w}) := \mathbb{E}_{\mathbf{x},v_\parallel}[\mathcal{J}_{\text{energy}}(\mathbf{x}, v_\parallel, \mathbf{w})]$$

$$B_-^* \le B(\mathbf{x}, \mathbf{w}) \le B_+^* \quad \forall \mathbf{x} \in \mathcal{P}$$

Restrict mirror ratio

Radial birth distribution of particles

$$f_s(s) \propto (1 - s^5)^2(1 - s)^{-2/3}\exp(-19.94(12(1 - s))^{-1/3}).$$

Particles uniformly distributed over flux surfaces

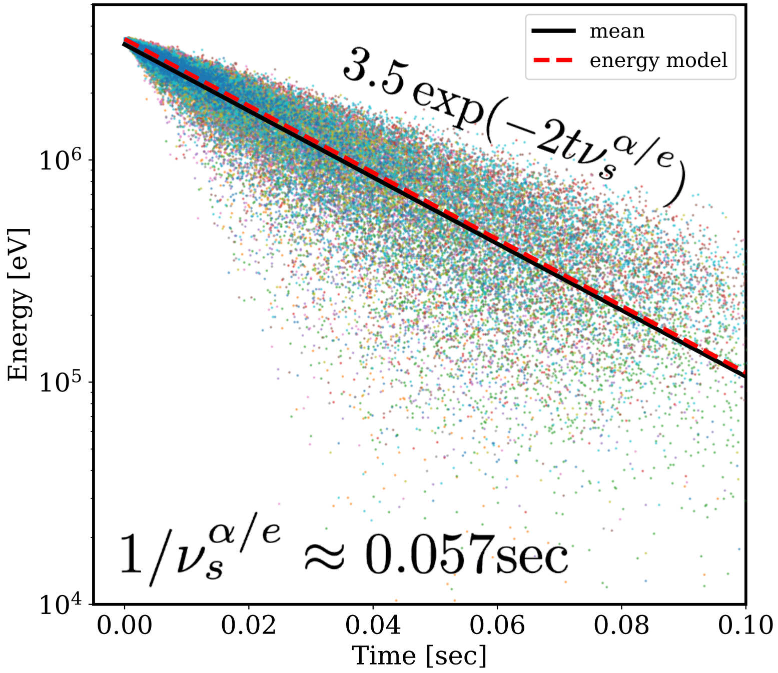
$$f_{\theta,\zeta}(\theta, \zeta \,|\, s) \propto |\sqrt{g}|.$$

Energy loss model

$$\mathcal{J}_{\text{energy}}(\mathbf{x}, v_\parallel, \mathbf{w}) = 3.5e^{-2\mathcal{T}(\mathbf{x},v_\parallel,\mathbf{w})/t_{\max}}$$

$$\mathcal{T} = \min\{t, t_{\max}\}$$

Obtained using a fit to 200 000 tracings



Particle tracing simulations with collisions using the ANTS code

Include collisions and realistic birth profiles – *Bindel, Landreman, Padidar (2023)*

arXiv > physics > arXiv:2302.11369

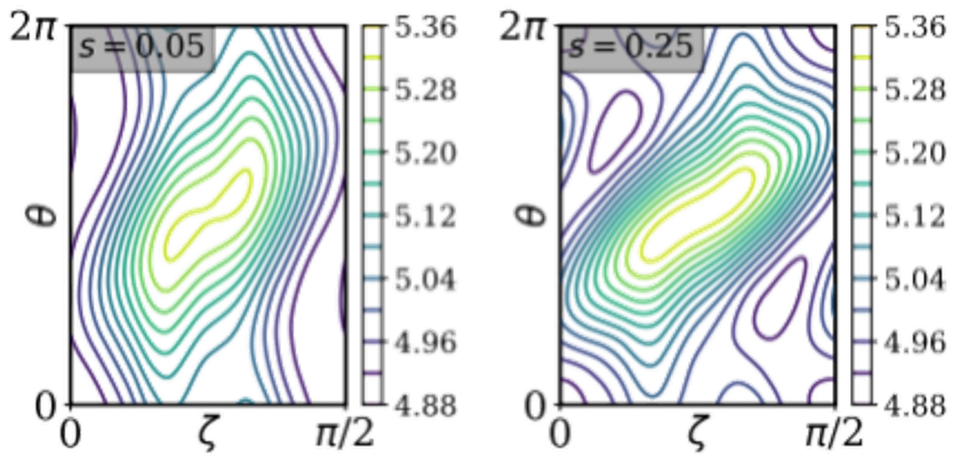
Physics > Plasma Physics

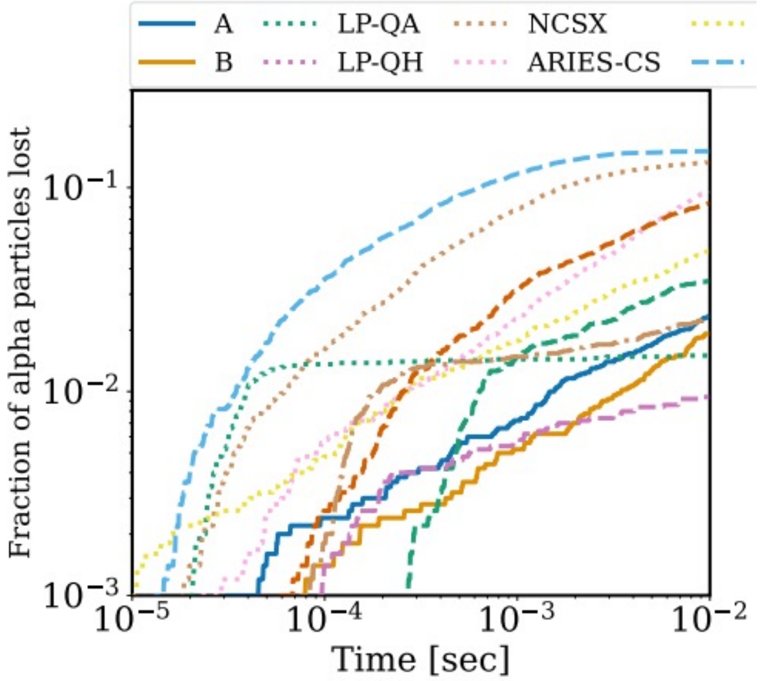
[Submitted on 22 Feb 2023]

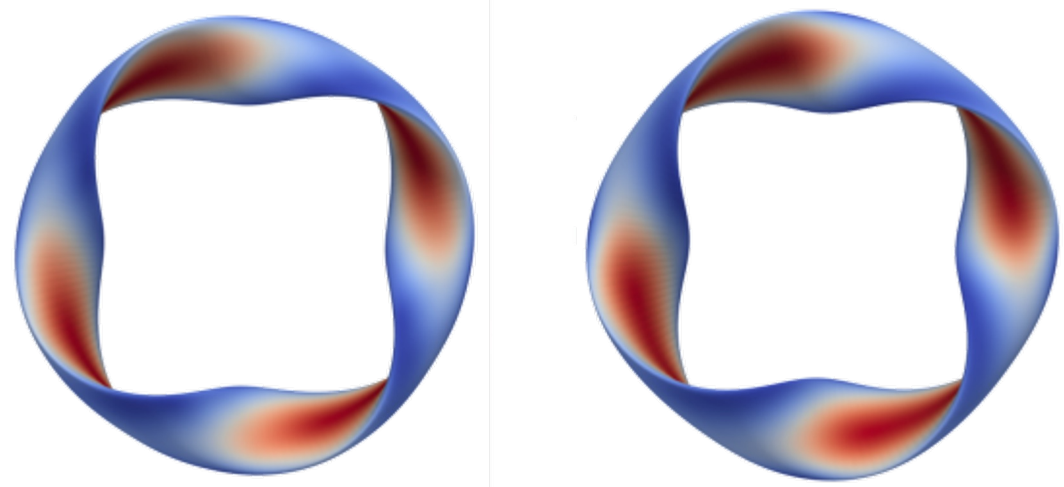
Direct Optimization of Fast-Ion Confinement in Stellarators

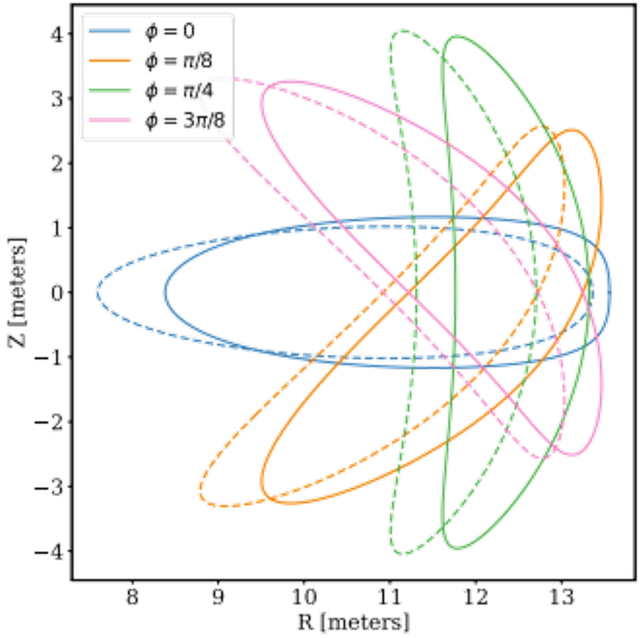
David Bindel, Matt Landreman, Misha Padidar

Resulting stellarators **far** from omnigenity









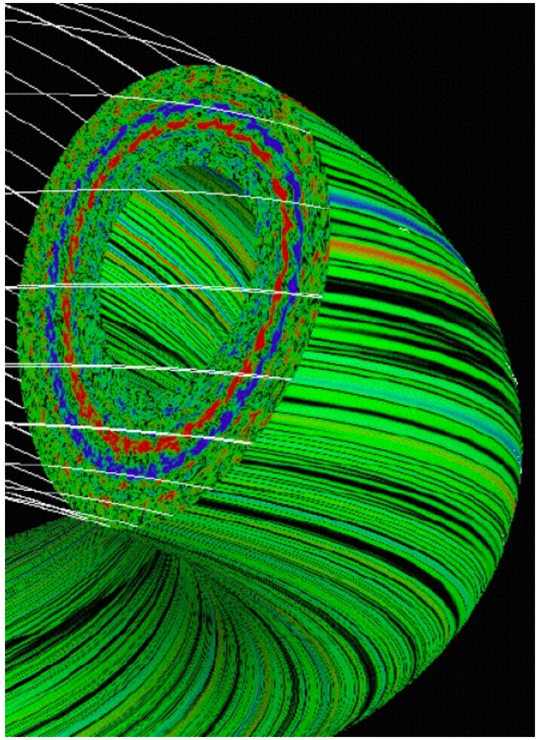
Direct approaches covered today

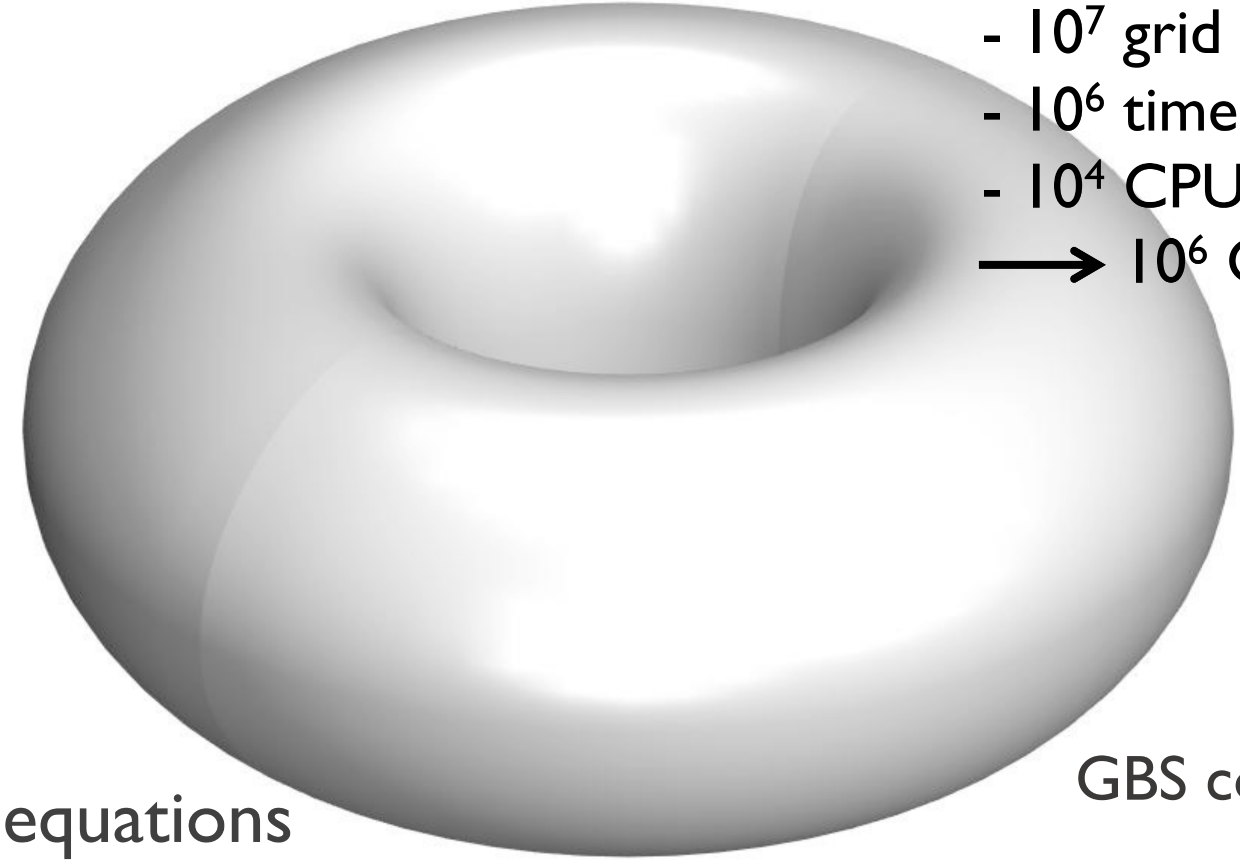
- Direct constructions using the near-axis expansion
- Direct fast particle optimization
- Direct turbulence optimization: quasi-linear and nonlinear approaches
- Direct coil optimization: single-stage approaches

Direct stability optimization

The gyrokinetic equation

$$\frac{\partial F}{\partial t} + \dot{\mathbf{R}} \cdot \nabla F + \dot{v}_{\|} \frac{\partial F}{\partial v_{\|}} = \langle C(F) \rangle$$





- 10^7 grid points
- 10^6 time steps
- 10^4 CPUs

$\longrightarrow$ 10^6 CPU hours

GBS code (EPFL)

Fluid equations

$$\frac{\partial n}{\partial t} = -\frac{[\phi, n]}{B} + \frac{2}{eB}\left[nC(T_e) + T_e C(n) - enC(\phi)\right] - n(\mathbf{b} \cdot \nabla z)\frac{\partial V_{\|e}}{\partial z} - V_{\|e}(\mathbf{b} \cdot \nabla z)\frac{\partial n}{\partial z} + S_n,$$

$$m_i n \frac{\partial V_{\|i}}{\partial t} = -\frac{m_i n}{B}[\phi, V_{\|i}] - m_i n V_{\|i}(\mathbf{b}\cdot\nabla z)\frac{\partial V_{\|i}}{\partial z} - \frac{2}{3}(\mathbf{b}\cdot\nabla z)\frac{\partial G_i}{\partial z} - (\mathbf{b}\cdot\nabla z)\frac{\partial[n(T_e + T_i)]}{\partial z}$$

Direct stability optimization

arXiv > physics > arXiv:2008.09057

Search...

Help | Advanc

Physics > Plasma Physics

[Submitted on 20 Aug 2020]

The Use of Near-Axis Magnetic Fields for Stellarator Turbulence Simulations

R. Jorge, M. Landreman

The gyrokinetic equation

$$\boxed{\frac{\partial F}{\partial t} + \dot{\mathbf{R}} \cdot \nabla F + \dot{v}_{\parallel} \frac{\partial F}{\partial v_{\parallel}} = \langle C(F) \rangle}$$

Fluid equations

$$\frac{\partial n}{\partial t} = -\frac{[\phi, n]}{B} + \frac{2}{eB}\left[nC(T_e) + T_e C(n) - enC(\phi)\right] - n(\mathbf{b}\cdot\nabla z)\frac{\partial V_{\parallel e}}{\partial z} - V_{\parallel e}(\mathbf{b}\cdot\nabla z)\frac{\partial n}{\partial z} + S_n,$$

$$m_i n \frac{\partial V_{\parallel i}}{\partial t} = -\frac{m_i n}{B}[\phi, V_{\parallel i}] - m_i n V_{\parallel i}(\mathbf{b}\cdot\nabla z)\frac{\partial V_{\parallel i}}{\partial z} - \frac{2}{3}(\mathbf{b}\cdot\nabla z)\frac{\partial G_i}{\partial z} - (\mathbf{b}\cdot\nabla z)\frac{\partial [n(T_e + T_i)]}{\partial z}$$

List of all coefficients needed to solve the gyrokinetic and fluid equations

$$\mathbf{Q} = \{B, \mathbf{b}\cdot\nabla z, |\nabla\psi|^2, |\nabla\alpha|^2, \nabla\psi\cdot\nabla\alpha, (\mathbf{b}\times\nabla B)\cdot\nabla\alpha, (\mathbf{b}\times\nabla B)\cdot\nabla\psi, (\mathbf{b}\times\boldsymbol{\kappa})\cdot\nabla\alpha\}.$$

How to directly optimize?

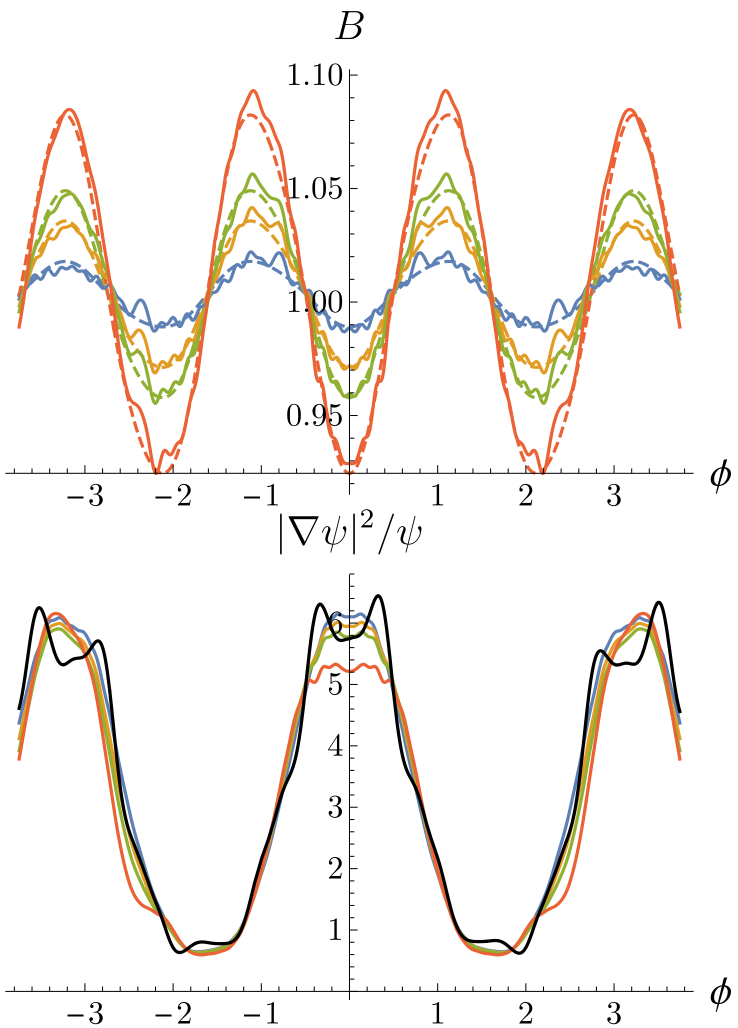
- Use VMEC/DESC/SPEC/GVEC or use the near-axis expansion
- Calculate coefficients at each step of the optimization

Direct stability optimization using the near-axis expansion

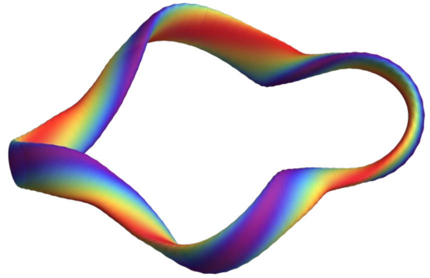
R Jorge and M Landreman 2021 Plasma Phys. Control. Fusion 63 014001

rogeriojorge / NearAxisGyrokinetics Public

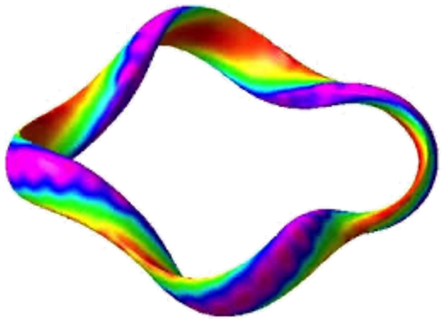
Comparison of coefficients between HSX and near-axis equivalent



HSX Near-axis



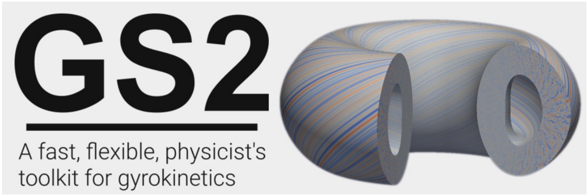
HSX VMEC

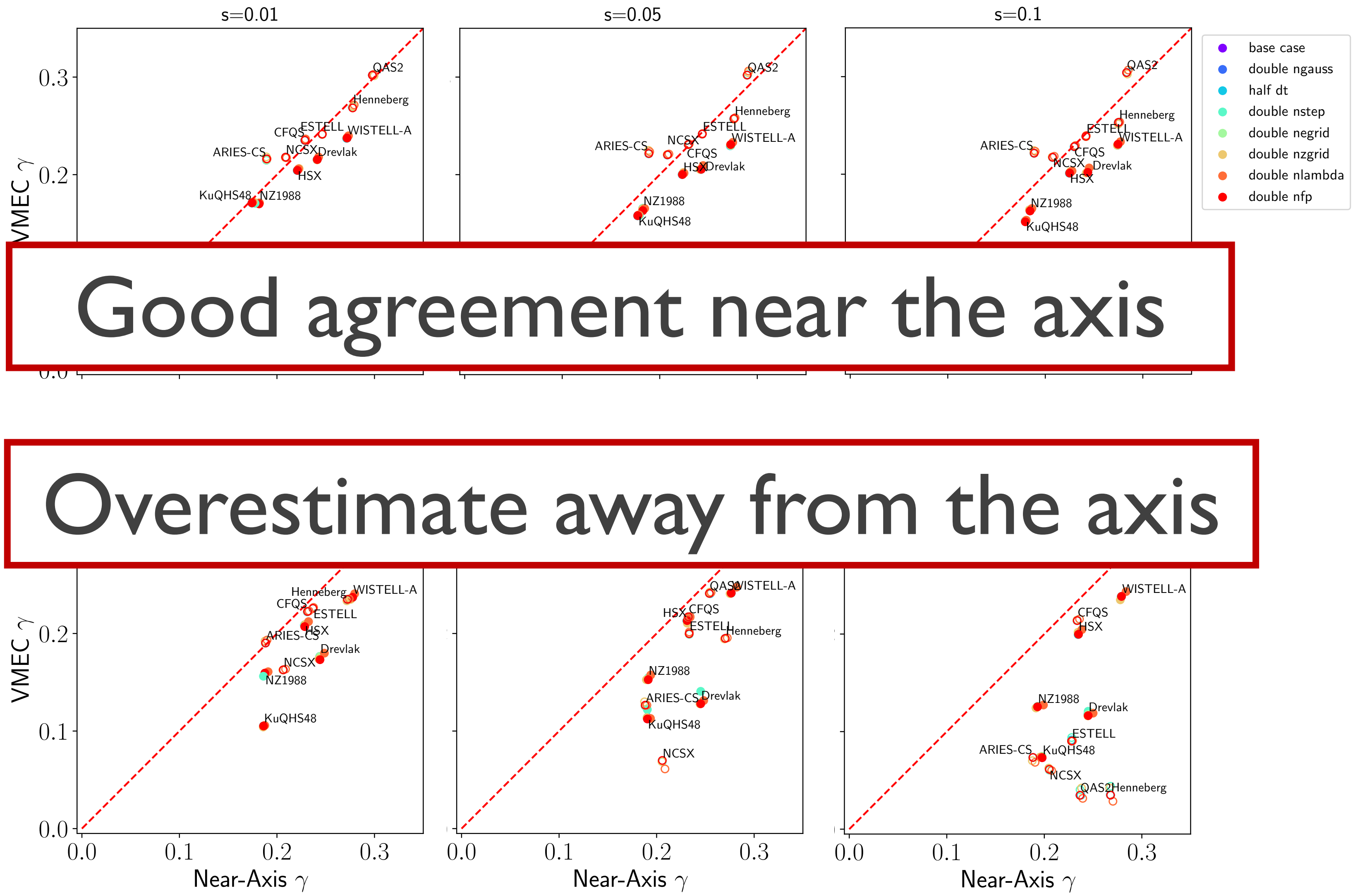


Direct stability optimization using the near-axis expansion

R Jorge and M Landreman 2021 Plasma Phys. Control. Fusion 63 074002

$k_y\rho$=1 a/L_T=5 a/L_n=2



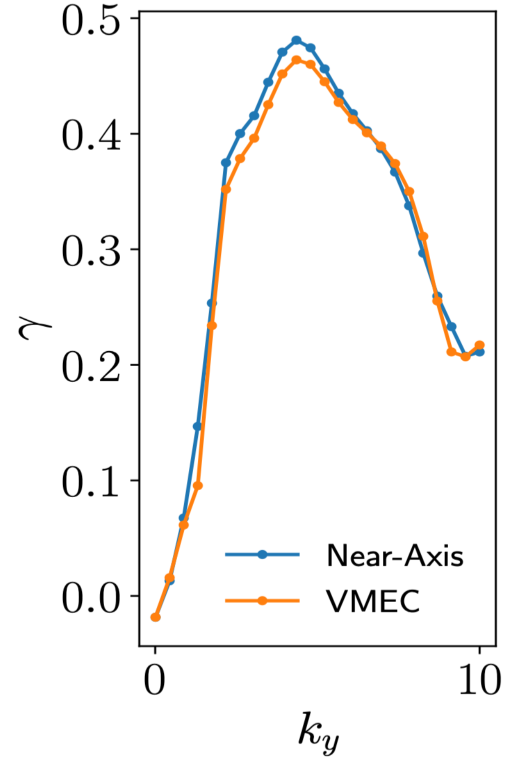


Good agreement near the axis

Overestimate away from the axis

ITG stability at HSX

$s = 0.01, a/L_T = 6, a/L_n = 4$



Direct microstability optimization – *R. Jorge et al.*

arXiv > physics > arXiv:2301.09356

Physics > Plasma Physics

[Submitted on 23 Jan 2023]

Direct Microstability Optimization of Stellarator Devices

R. Jorge, W. Dorland, P. Kim, M. Landreman, N. R. Mandell, G. Merlo, T. Qian

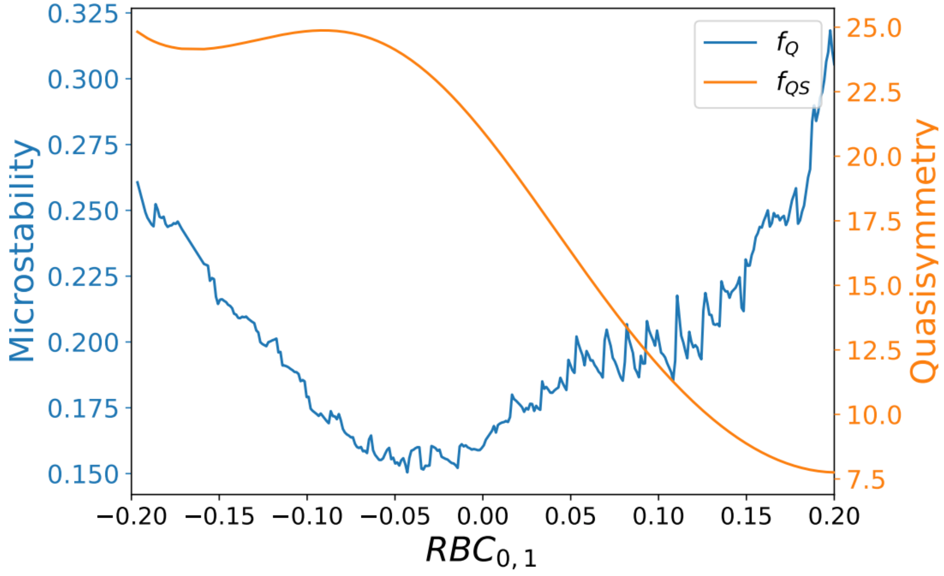
rogeriojorge / single_stage_optimization Public

$$J = \omega_{f_Q} f_Q + f_{QS}$$

Quasilinear estimate for the heat flux

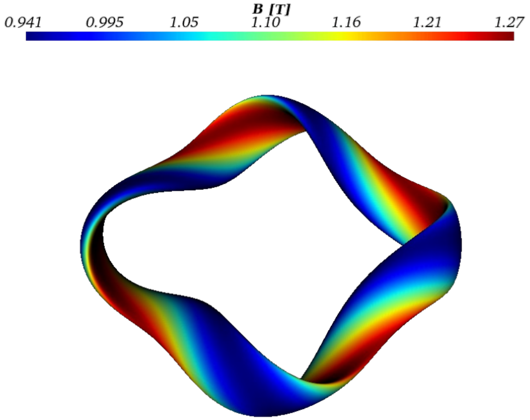
Quasisymmetry cost function

$$f_Q = \sum_{k_y} \frac{\gamma(k_y)}{\langle k_\perp^2 \rangle (k_y)}$$

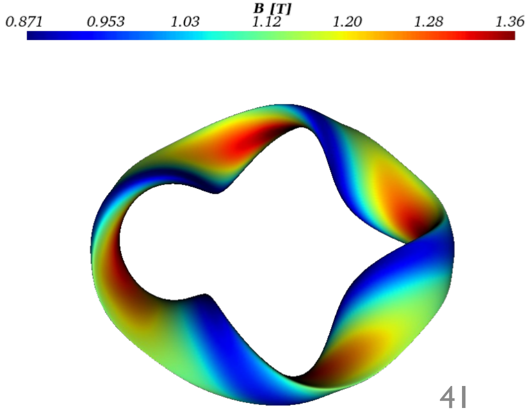


Optimization for

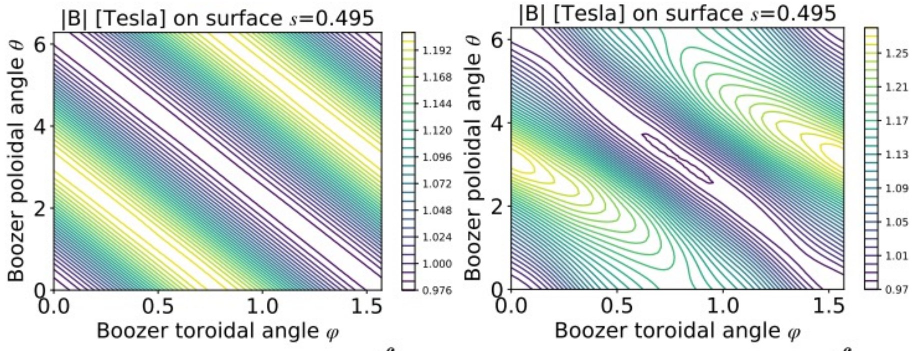
Quasisymmetry

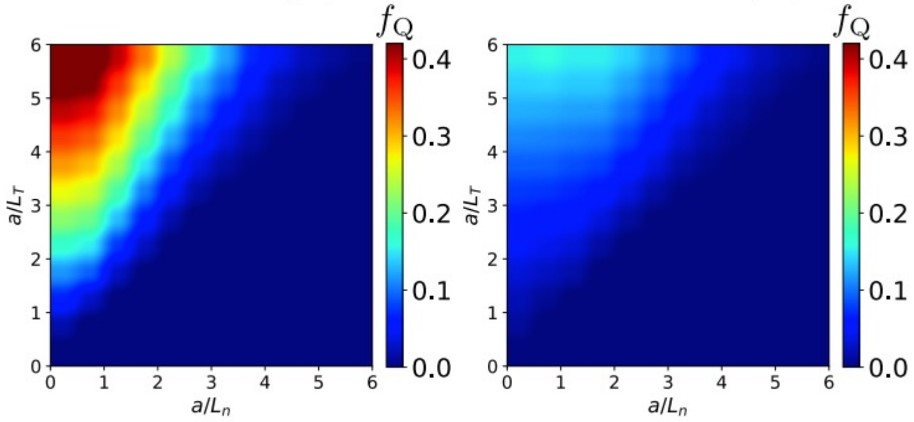


Quasisymmetry + Turbulence



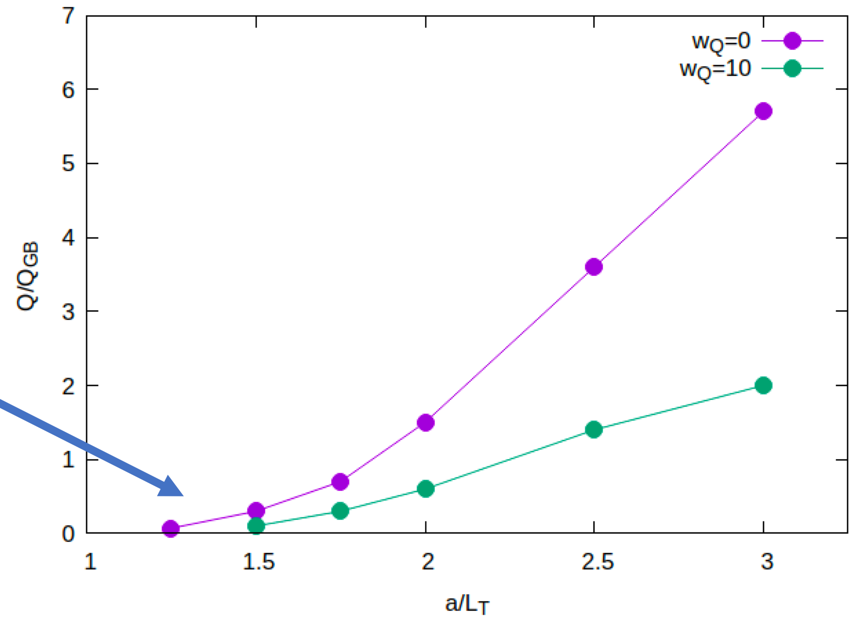
Direct microstability optimization – *R. Jorge et al.*



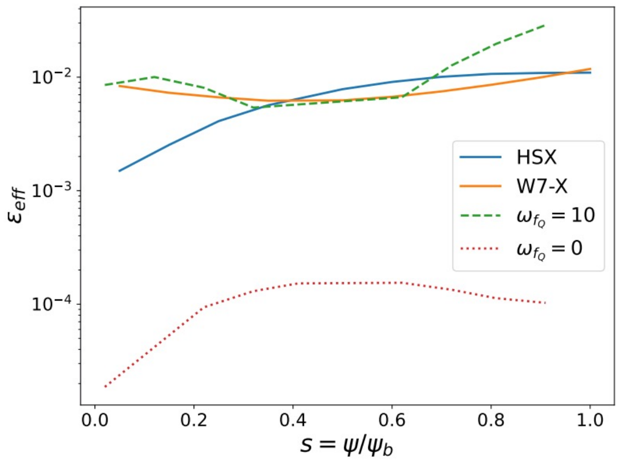


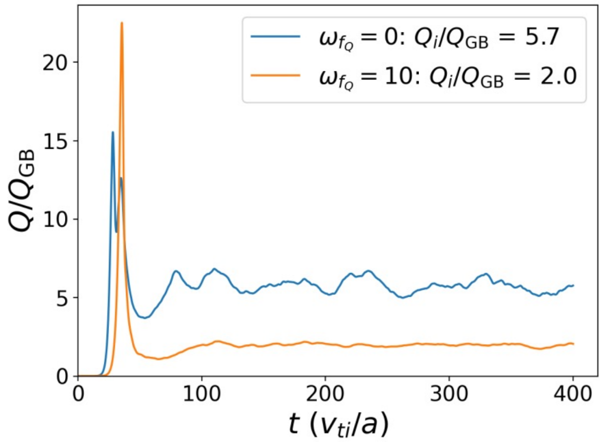
Major improvements

- Critical gradient
- Heat flux

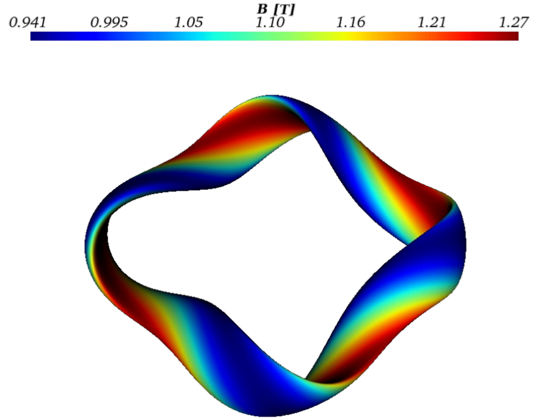


Optimization for

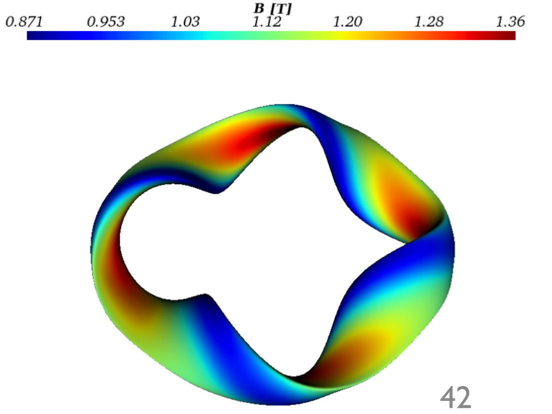




Quasisymmetry



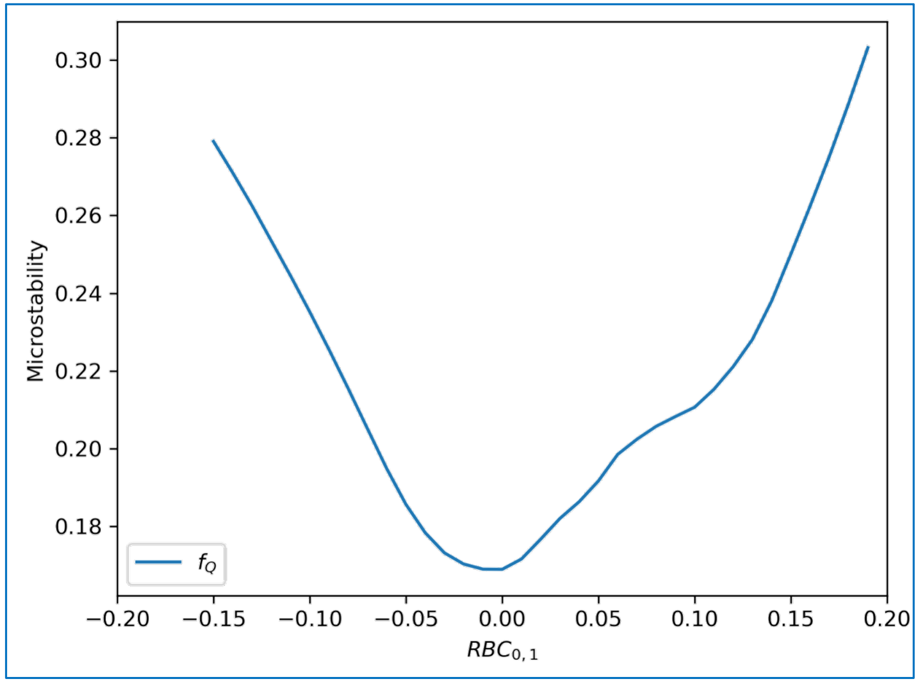
Quasisymmetry + Turbulence



How good is a quasilinear estimate? – *S. Buller (Sherwood 2023)*

Similar exercise but using:

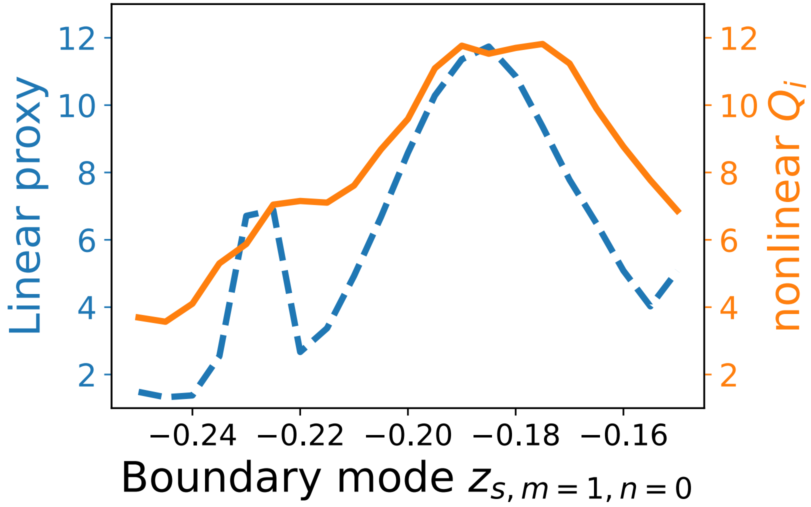
Gyrokinetic *stella* code stellaGK / **stella** Public



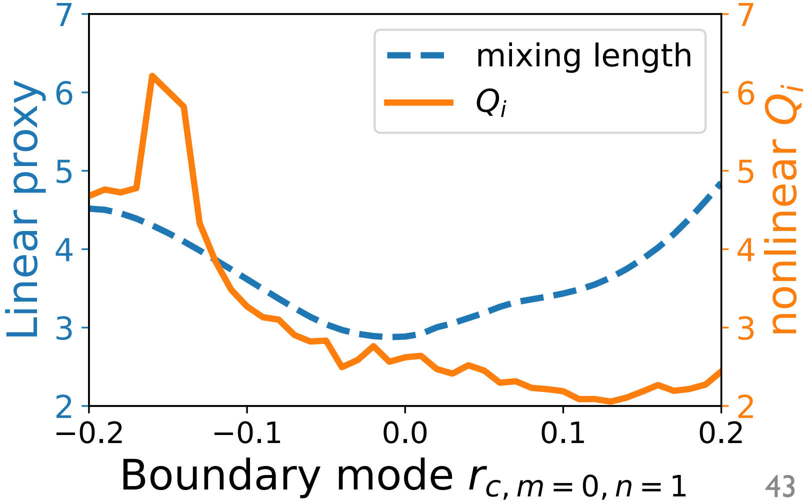
Noise-free objective function!

Microstability reduced configurations can be found much more efficiently

Quasi-axisymmetric case



Quasi-isodynamic case



Direct turbulence optimization – *Kim, Mandell, Qian, et al.*

arXiv > physics > arXiv:2209.06731

Physics > Plasma Physics

[Submitted on 14 Sep 2022 (v1), last revised 19 Oct 2022 (this version, v3)]

GX: a GPU-native gyrokinetic turbulence code for tokamak and stellarator design

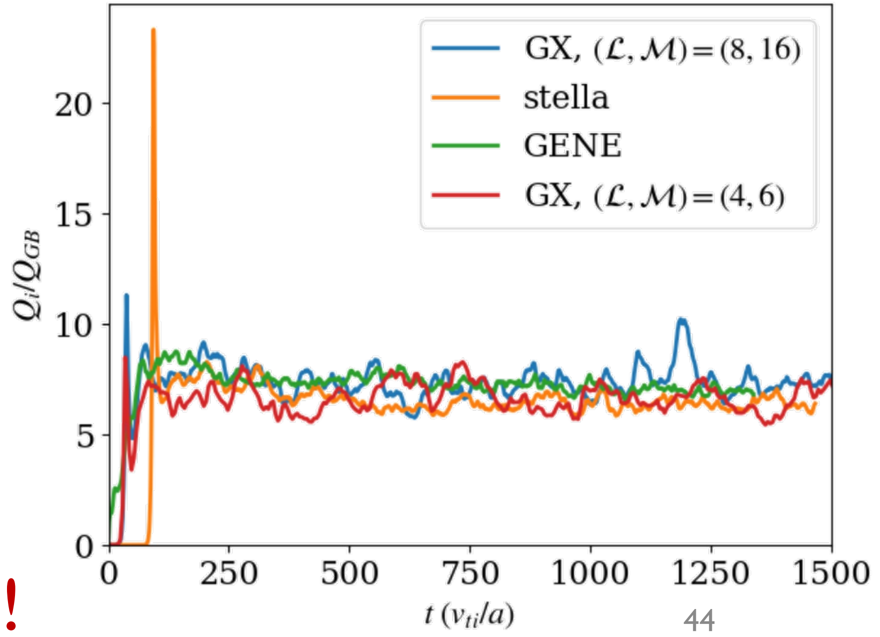
N. R. Mandell, W. Dorland, I. Abel, R. Gaur, P. Kim, M. Martin, T. Qian

	$\mathcal{L}$	$\mathcal{M}$	Q_i/Q_{GB}	wallclock (min)	time/step (s)	Δt
	16	32	7.4 ± 0.9	467	0.14	0.01
$\star$	8	16	7.3 ± 0.9	61	0.037	0.02
	6	12	7.5 ± 0.7	31	0.023	0.025
	4	8	7.4 ± 0.9	9	0.011	0.04
$\star$	4	6	7.3 ± 0.8	6	0.0092	0.05

GX code (gyrokinetics in GPUs)

Hermite-Laguerre decomposition

DESC+GX optimization currently underway

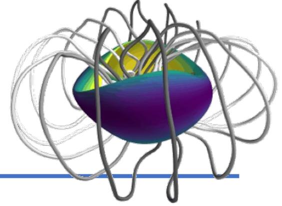


We can obtain an accurate heat flux in just 6 minutes!

Direct approaches covered today

- Direct constructions using the near-axis expansion
- Direct fast particle optimization
- Direct turbulence optimization: quasi-linear and nonlinear approaches
- Direct coil optimization: single-stage approaches

Coil optimization



Coil performance

Aim for $\boldsymbol{B}.\boldsymbol{n} = 0$ to achieve:

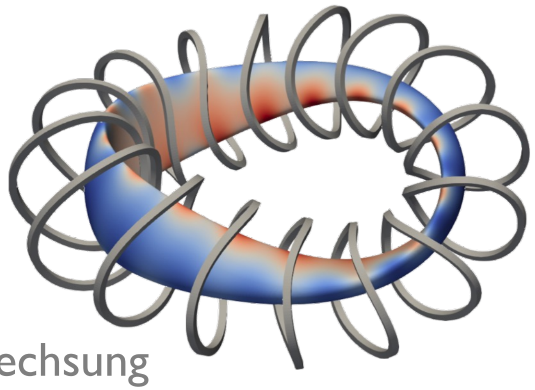
- Quasi-symmetry
- Rotational transform
- Particle confinement

Coil complexity

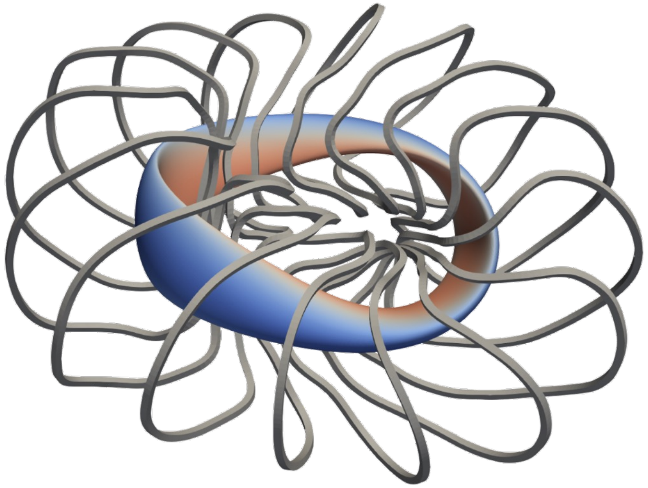
Include regularization terms to control:

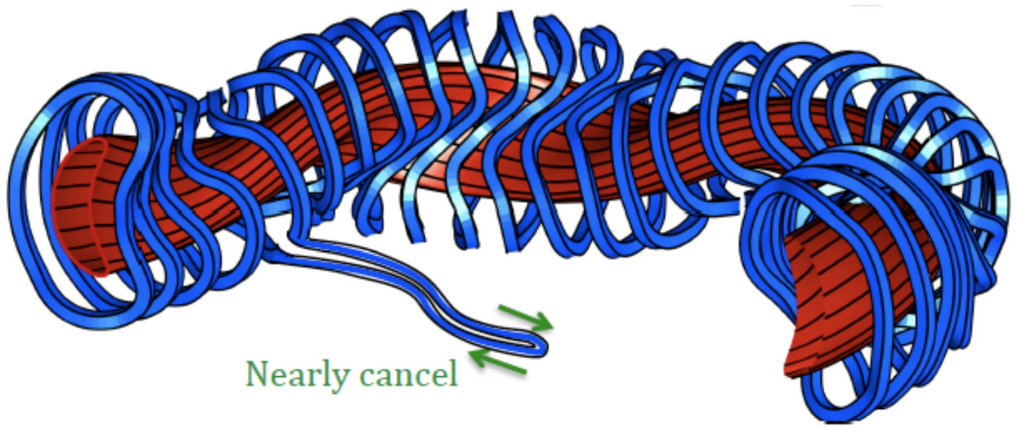
- Coil curvature
- Coil-to-coil separation
- Coil length

Finding coils that reproduce a given field is an ill-posed problem



F.Wechsung
Simons 2022

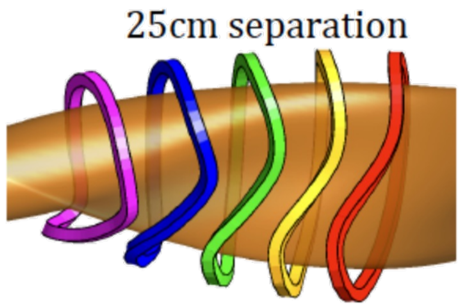


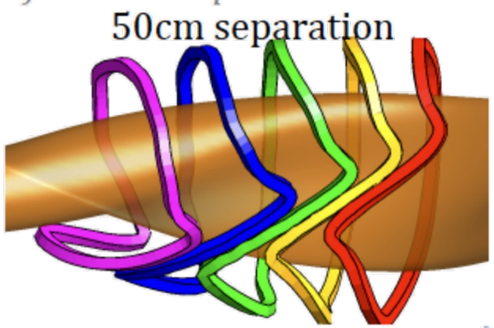


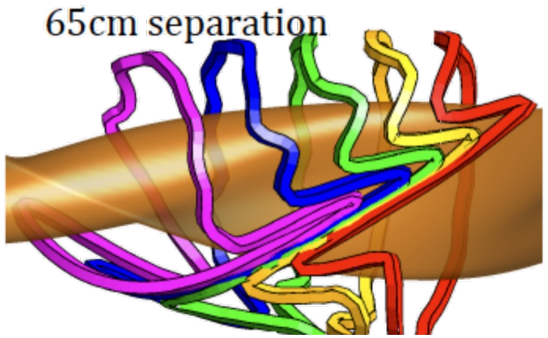
M. Landreman
Simons 2019

Simple coils far away from the plasma are difficult to find

Coils offset a uniform distance from W7-X plasma:







Direct coil + near-axis optimization – *A. Giuliani et al. 2021*

arXiv > physics > arXiv:2010.02033

Search...

Help | Adva

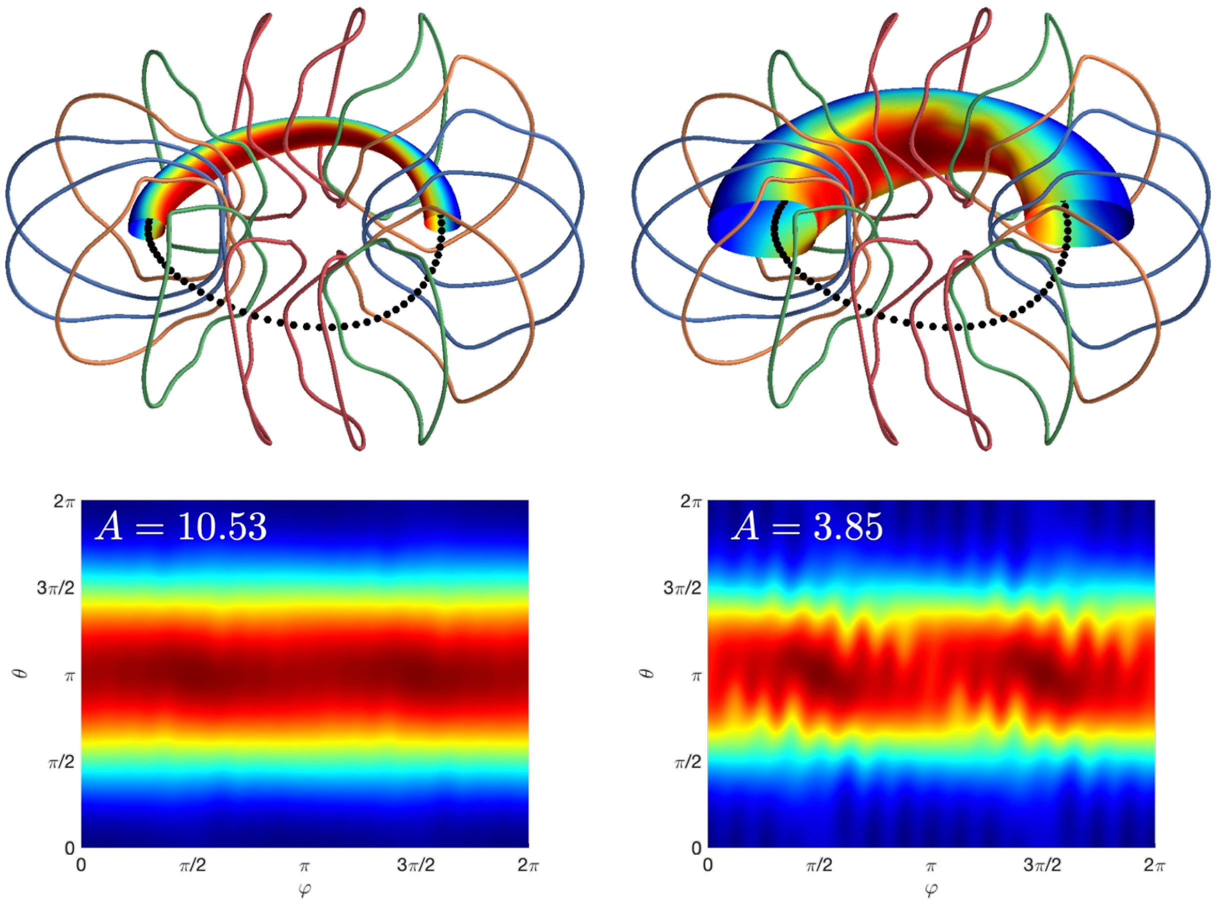
Physics > Plasma Physics

[Submitted on 1 Oct 2020 (v1), last revised 15 Mar 2022 (this version, v2)]

Single-stage gradient-based stellarator coil design: Optimization for near-axis quasi-symmetry

Andrew Giuliani, Florian Wechsung, Antoine Cerfon, Georg Stadler, Matt Landreman

Resulting solution



From the near-axis expansion, combining

$$\mathbf{r} = \mathbf{r}_0 + \sqrt{s}\left[\frac{\bar{\eta}}{\kappa}\cos\theta\mathbf{n} + \frac{\kappa}{\bar{\eta}}(\sin\theta + \boxed{\sigma}\cos\theta)\mathbf{b}\right]$$

with the definition of Boozer coordinates

$$\mathbf{B} = \nabla\Psi \times \nabla\theta + \iota\nabla\varphi \times \nabla\Psi$$

$$\mathbf{B} = G\nabla\varphi$$

we can find coils that minimize

$$\hat{J}(\mathbf{c}, \mathbf{a}, \sigma, \iota) = \frac{1}{2}\int_{\Gamma_\mathbf{a}} \|\mathbf{B}_{\text{coils}}(\mathbf{c}) - \mathbf{B}_{\text{QS}}(\mathbf{a})\|^2\, dl + \frac{1}{2}\int_{\Gamma_\mathbf{a}} \|\nabla\mathbf{B}_{\text{coils}}(\mathbf{c}) - \nabla\mathbf{B}_{\text{QS}}(\mathbf{a}, \sigma, \iota)\|^2\, dl$$

Direct surface and coil optimization – *A. Giuliani et al. 2023*

arXiv > physics > arXiv:2210.03248

Search...

Help | Advance

Physics > Plasma Physics

[Submitted on 6 Oct 2022 (v1), last revised 13 Mar 2023 (this version, v3)]

Direct stellarator coil optimization for nested magnetic surfaces with precise quasi-symmetry

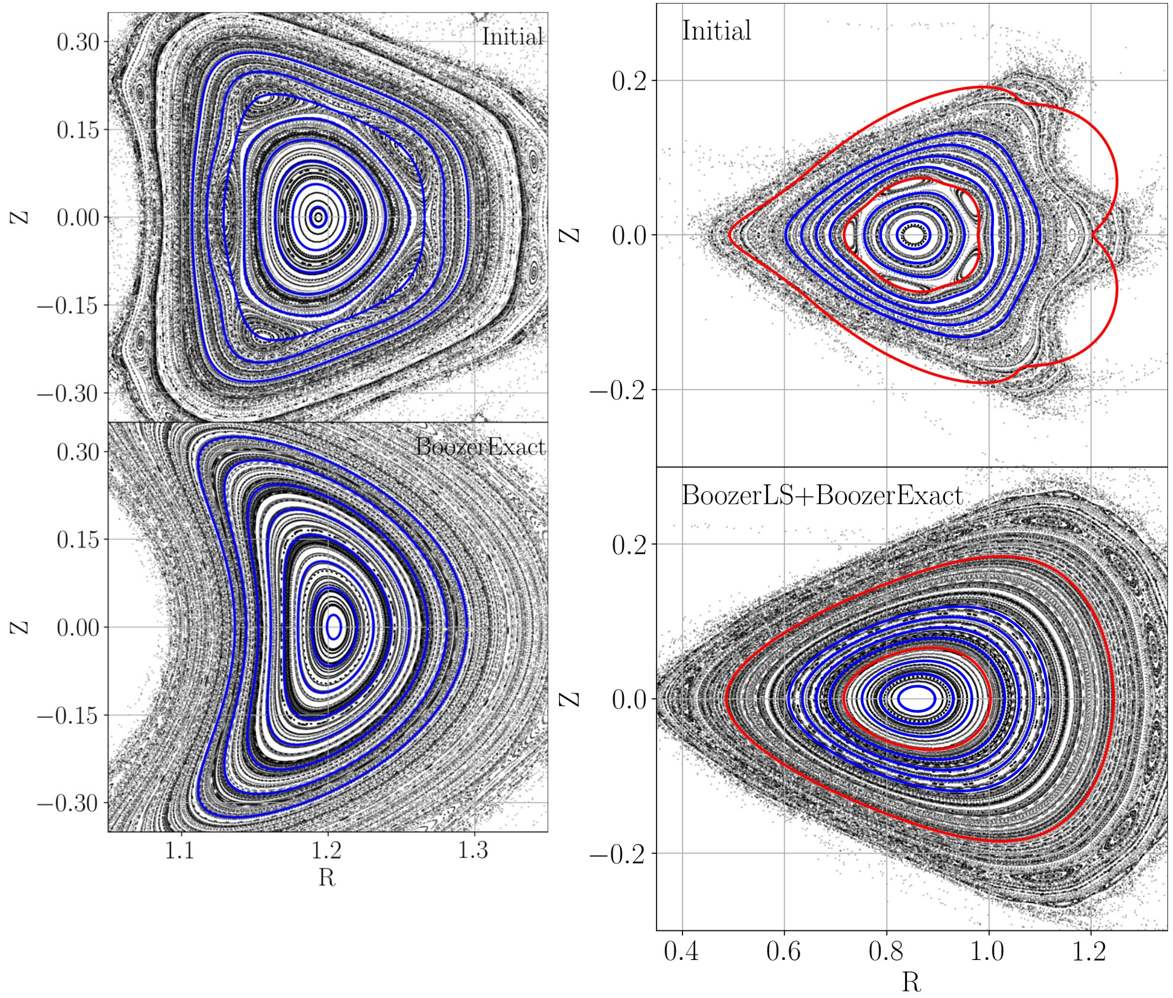
Andrew Giuliani, Florian Wechsung, Antoine Cerfon, Matt Landreman, Georg Stadler

We can now heal magnetic islands

By finding surfaces in the Biot-Savart magnetic field directly ("Boozer" surfaces)

$$G\mathbf{B} - \|\mathbf{B}\|^2 \left(\frac{\partial \boldsymbol{\Sigma}}{\partial \varphi} + \iota \frac{\partial \boldsymbol{\Sigma}}{\partial \theta} \right) = 0,$$

$$V(\boldsymbol{\Sigma}) - V_{\text{target}} = 0.$$



No need for MHD solvers!

Direct coil optimization (fixed boundary) – *R. Jorge et al. 2023*

arXiv > physics > arXiv:2302.10622

Physics > Plasma Physics

[Submitted on 21 Feb 2023]

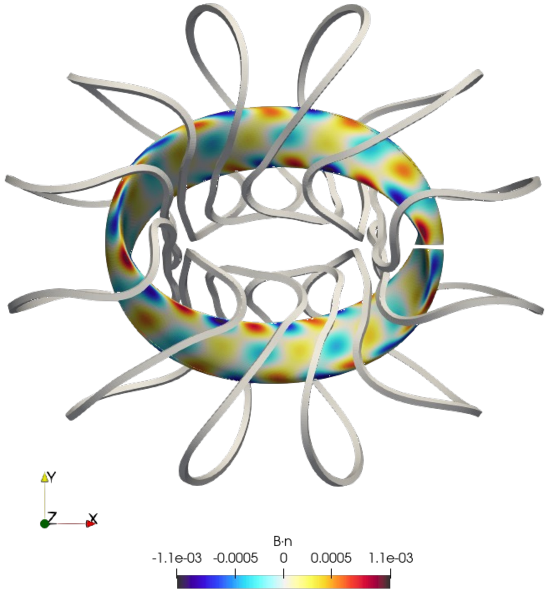
Single-Stage Stellarator Optimization: Combining Coils with Fixed Boundary Equilibria

R. Jorge, A. Goodman, M. Landreman, J. Rodrigues, F. Wechsung

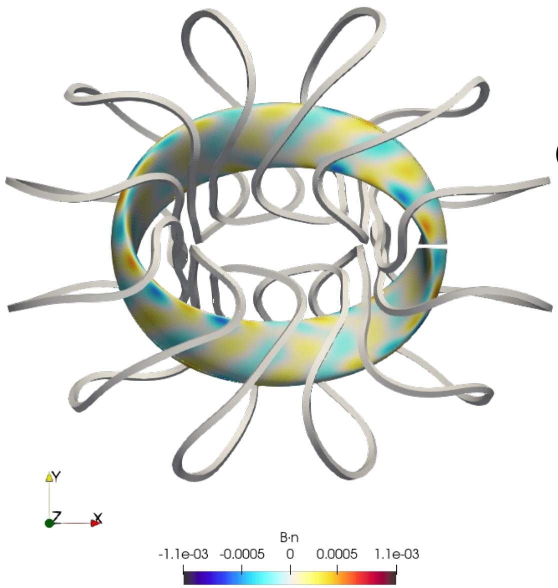
Minimize simultaneously

$J = J_{QS} + J_{coils}$ using an expanded array of degrees of freedom

Stage 1 + Stage 2



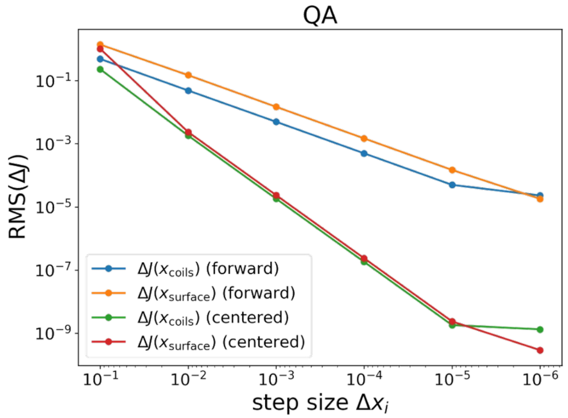
Single Stage



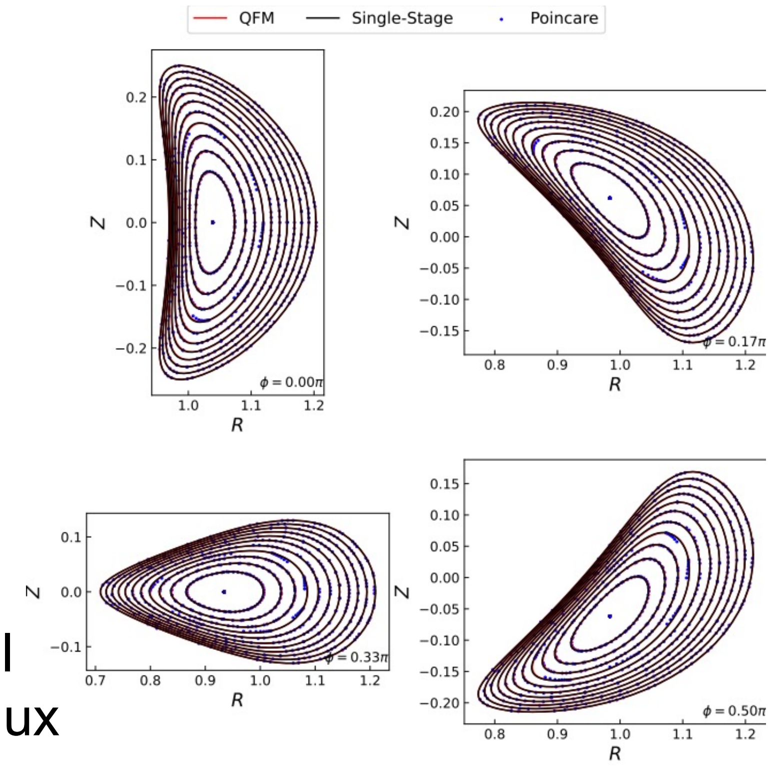
Coil cost function Jcoils: the squared flux

$$\int_S \left(\frac{\mathbf{B}_{\text{ext}} \cdot \mathbf{n}}{|\mathbf{B}_{\text{ext}}|} \right)^2 dS$$

Validation of the analytical derivatives of the squared flux



Validation of resulting Biot-Savart field



Single-Stage Stellarator Optimization Of Fixed Boundary Equilibria
R Jorge et al 2023 Plasma Phys. Control. Fusion 65 074003

Direct coil optimization (fixed boundary) – *R. Jorge et al. 2023*

arXiv > physics > arXiv:2302.10622

Search | Help |

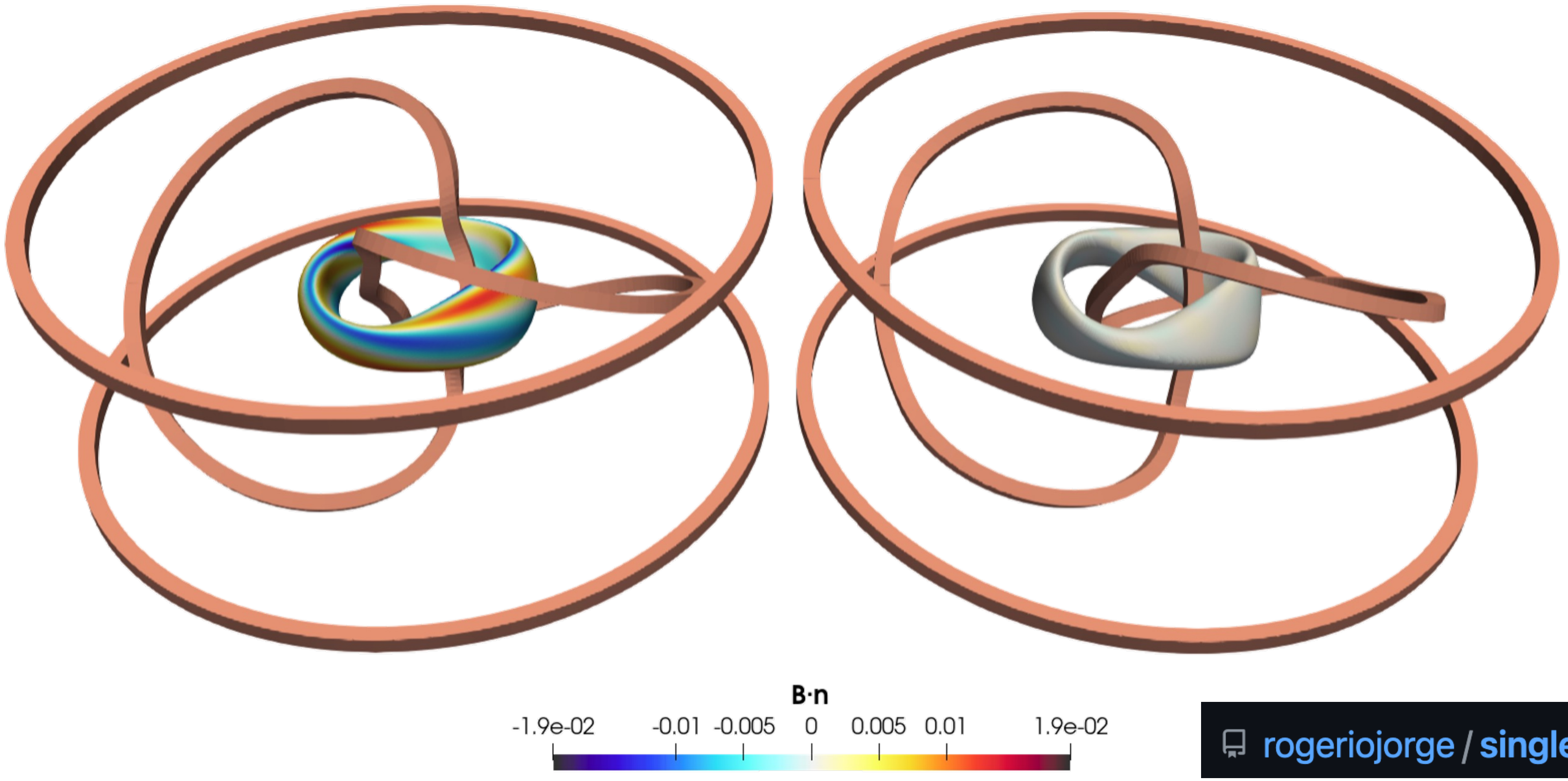
Physics > Plasma Physics

[Submitted on 21 Feb 2023]

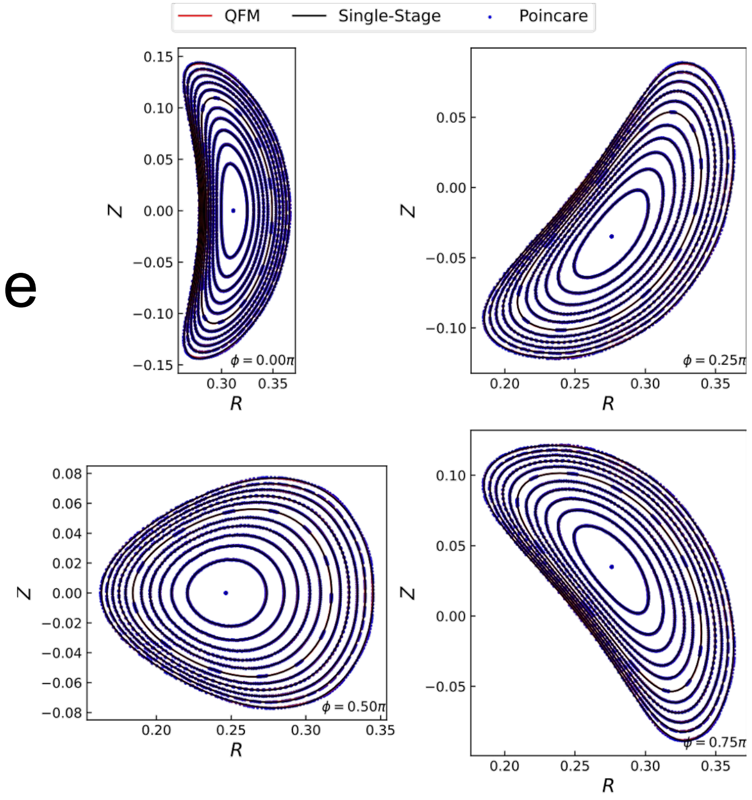
Single-Stage Stellarator Optimization: Combining Coils with Fixed Boundary Equilibria

R. Jorge, A. Goodman, M. Landreman, J. Rodrigues, F. Wechsung

4-coil quasisymmetric stellarator designed using single-stage



Validation of resulting Biot-Savart field



Single-Stage Stellarator Optimization Of Fixed Boundary Equilibria, R. Jorge et al, ***Submitted to PPCF***
https://arxiv.org/abs/2302.10622

rogeriojorge / **single_stage_optimization** Public

Direct coil optimization with finite β – *R. Jorge et al. 2023*

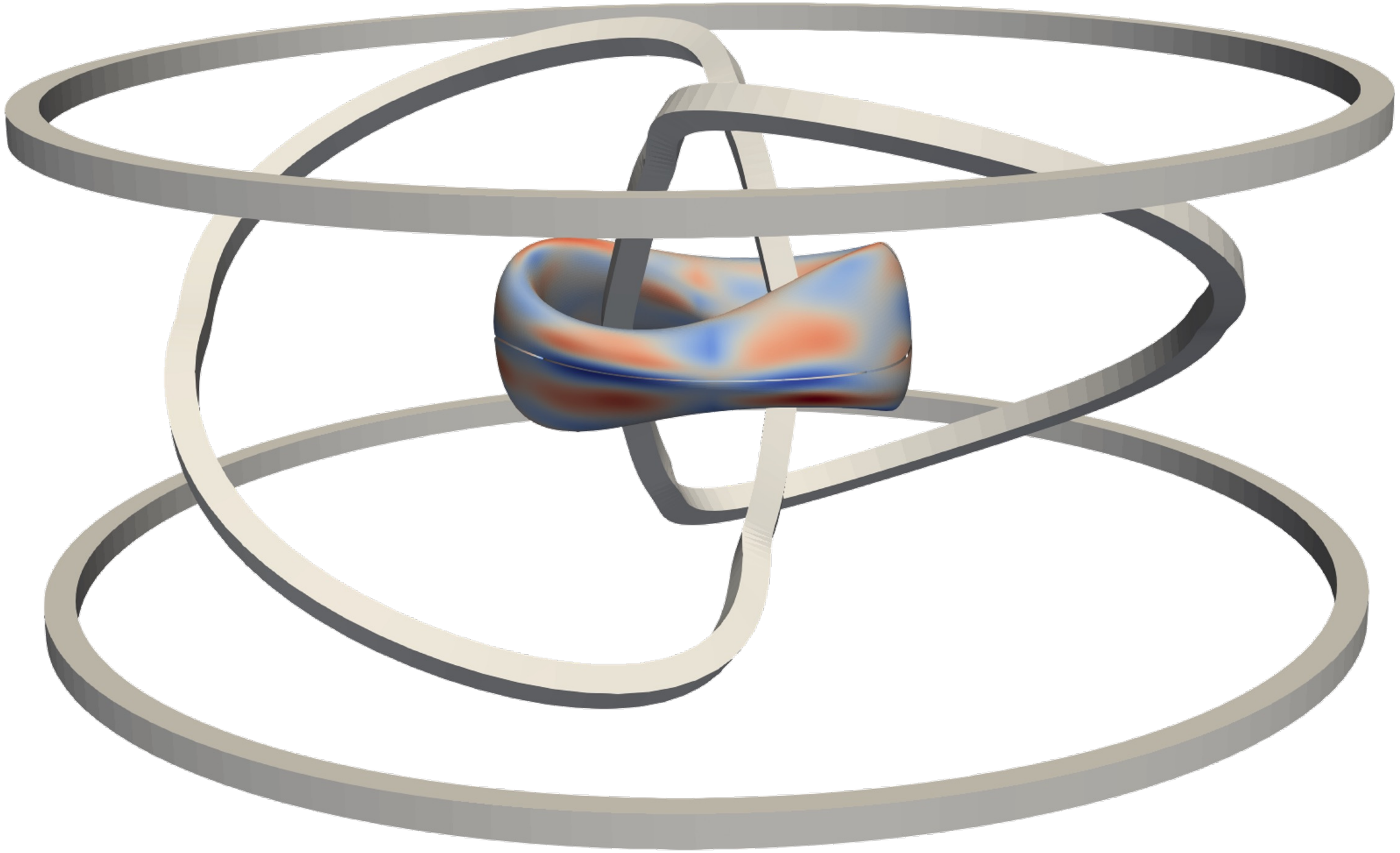
New coil cost function Jcoils taking into account plasma pressure

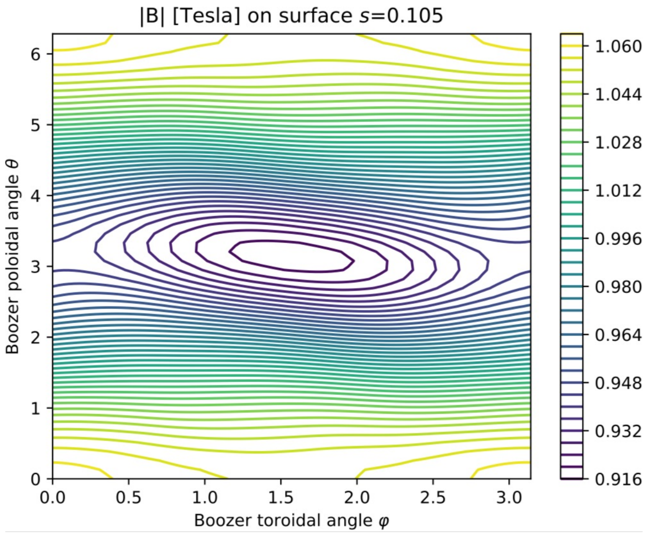
$$\int_S \left[\frac{(\mathbf{B}_{\rm ext} - \mathbf{B}_{\rm target}) \cdot \mathbf{n}}{|\mathbf{B}_{\rm ext}|}\right]^2 dS$$

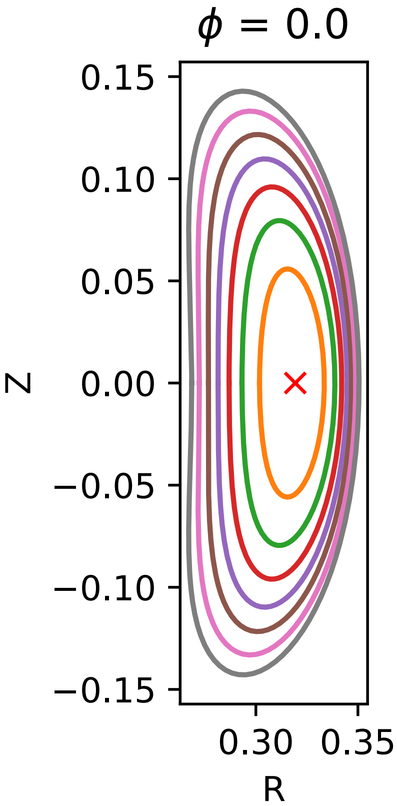
VMEC $\boldsymbol{B}$

$$\mathbf{B} = \mathbf{B}_{\rm plasma} + \mathbf{B}_{\rm target}$$

Coils targeted to reproduce vacuum field







2% β on-axis

$\boldsymbol{B}_{plasma}$ calculated using the Virtual Casing principle (BIEST code)

hiddenSymmetries / **virtual-casing** Public

dmalhotra / **BIEST** Public

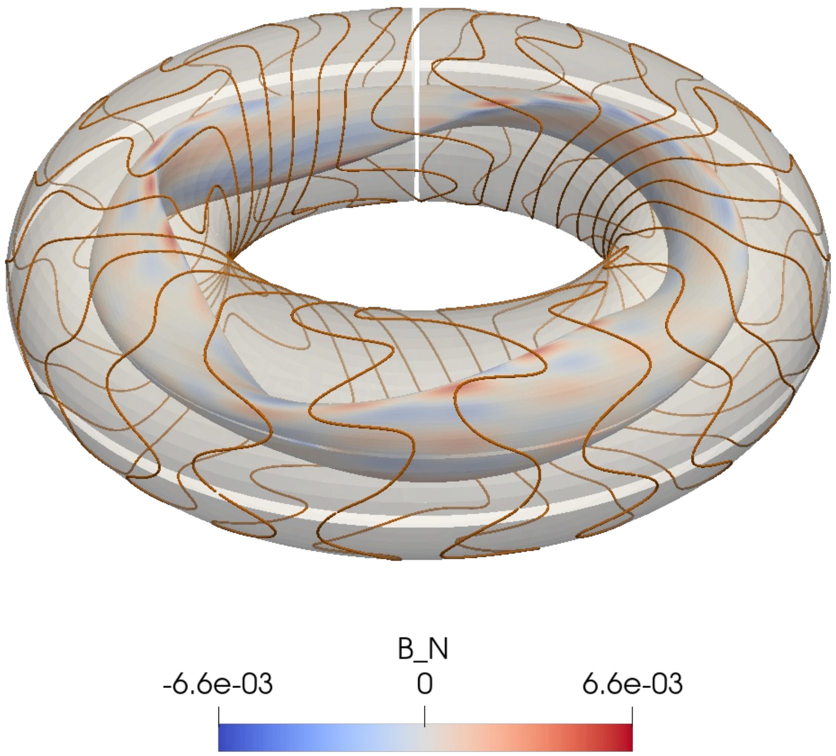
D. Malhotra *et al. 2020* PPCF **62**

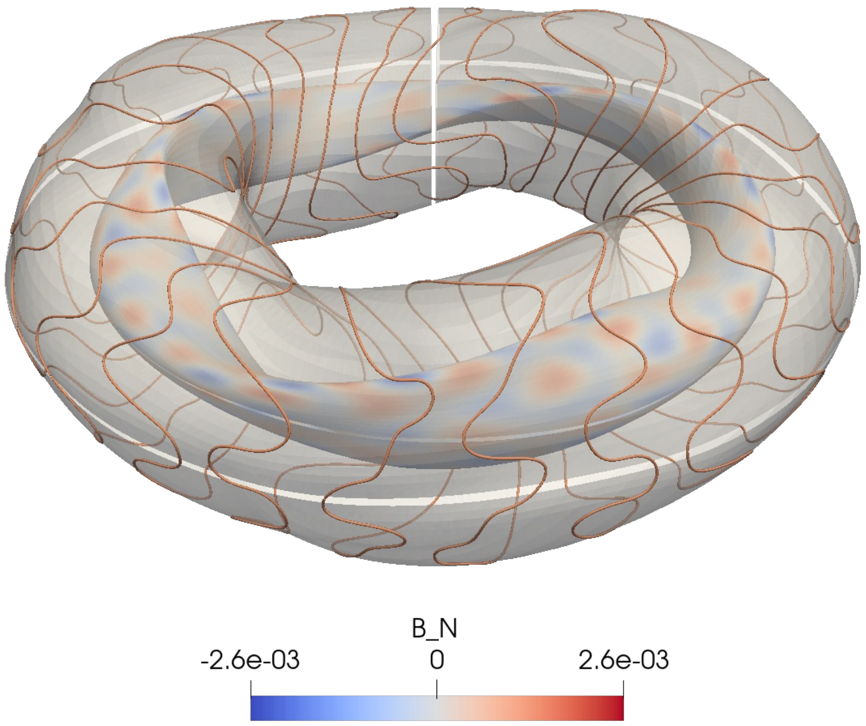
Coil Winding Surface optimization – *J. Biu (IST Lisbon)*

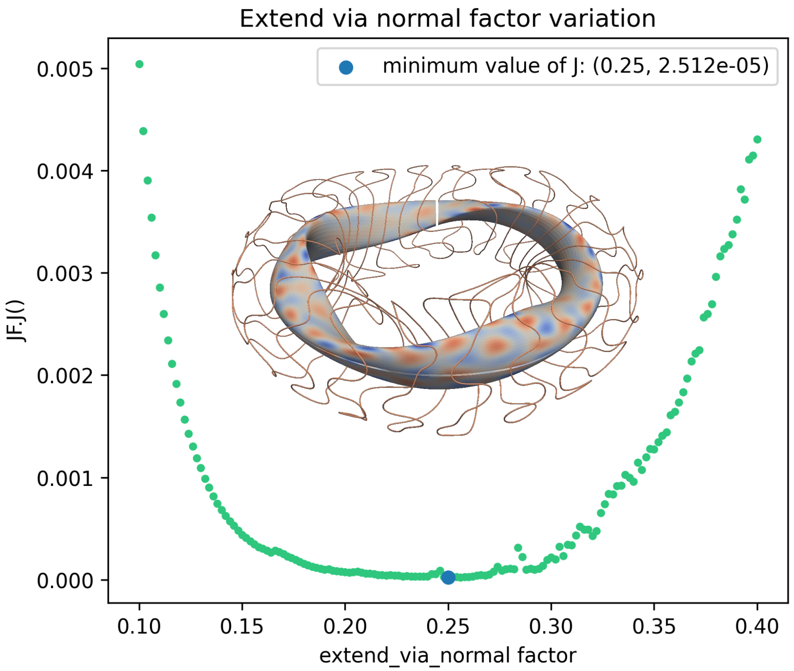
Single-stage optimized plasma for an axisymmetric coil surface

Coil surface that follows the plasma boundary improves ripple

Optimal plasma to surface distance: 0.25/Major radius

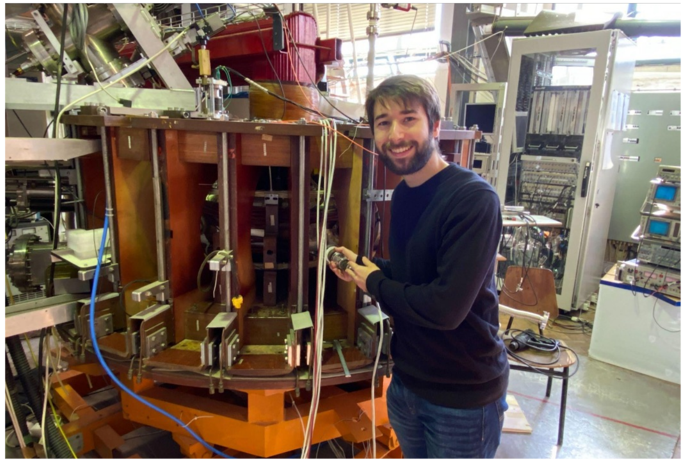




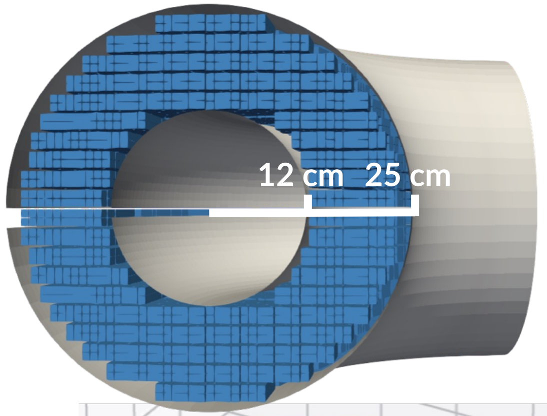


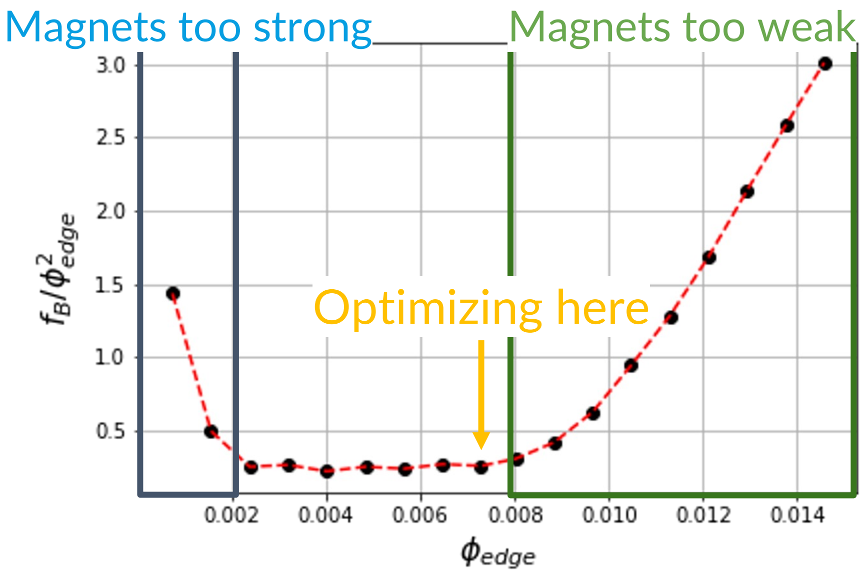
Single-stage & Permanent Magnets – *M. Madeira (IST Lisbon)*

This is **ISTTOK** + Miguel Madeira

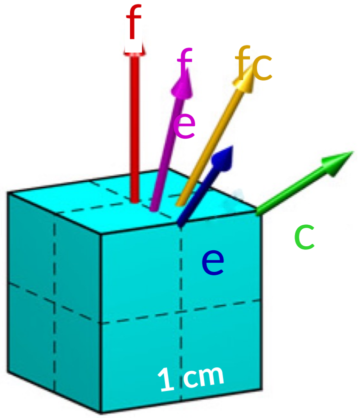


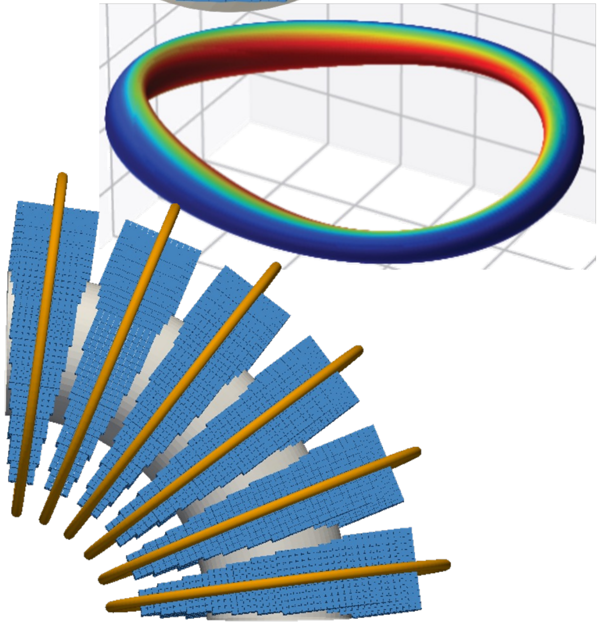
This is **ISTTELL** – a QA stellarator to fit into ISTTOK



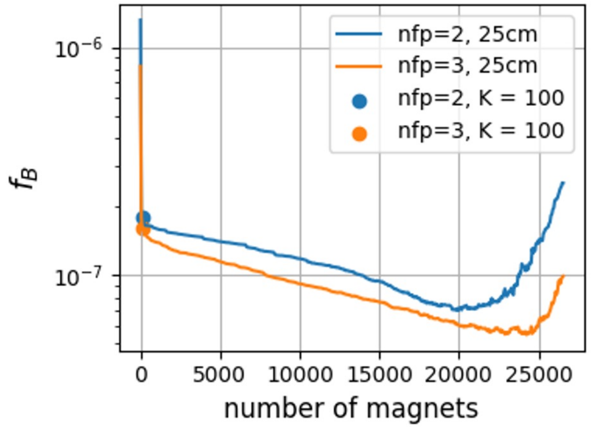


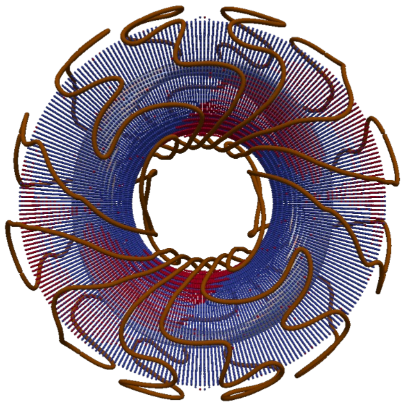
Use **permanent magnets** to convert a tokamak into a stellarator without new coils





Permanent magnets can also be used to fix coil ripple in stellarators





Conclusions

- Proxies start to be replaced by accurate figures of merit
- Near-axis expansion is the Swiss Army Knife of stellarator optimization

- Direct fast particle may require global optimization methods
- Direct turbulence optimization enabled by new turbulence codes
- Direct coil optimization performed using single stage methods
- Next steps: *direct plasma stability, particle flux, maximum-J,* ***help from AI***