EUROfusion

Energetic particle optimization of stellarator devices using near-axis magnetic fields

Rogerio Jorge

P. Rodrigues, J. Ferreira, A. Figueiredo, R. Coelho, D. Borba, P. Figueiredo

ipfn
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E FUSÃO NUCLEAR

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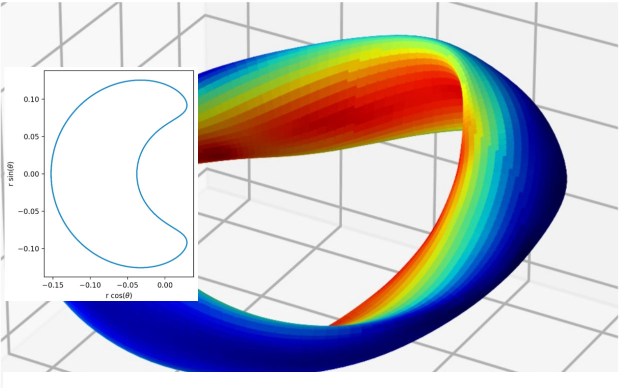
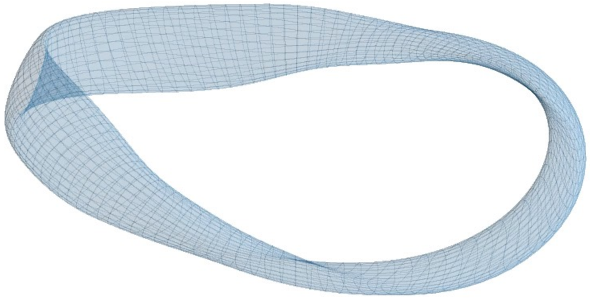
Motivation – Stellarator optimization

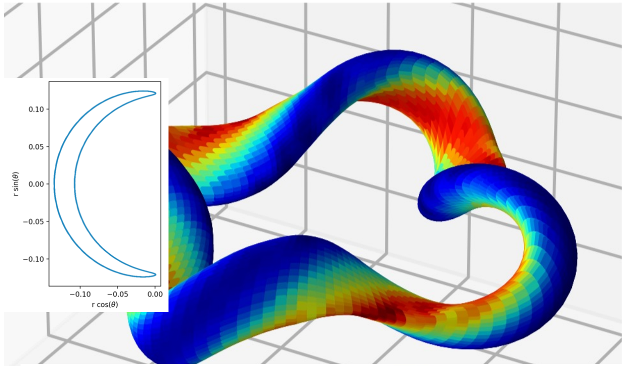
Seek **omnigenity** - $\Delta\psi = \int \boldsymbol{v}_d \cdot \boldsymbol{n}\, dt = 0$ - geometrically

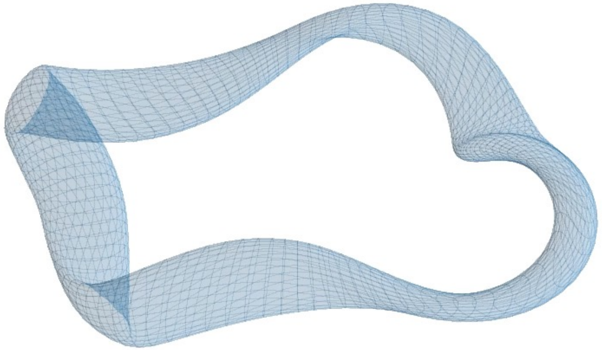
Quasi-axisymmetry



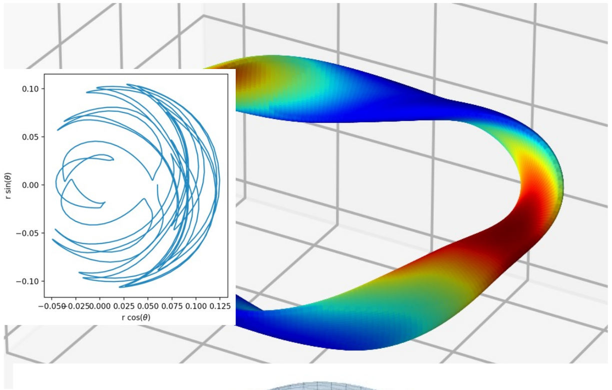


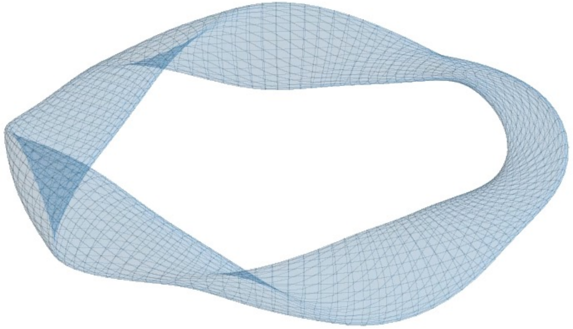
Quasi-helical symmetry





Quasi-isodynamic



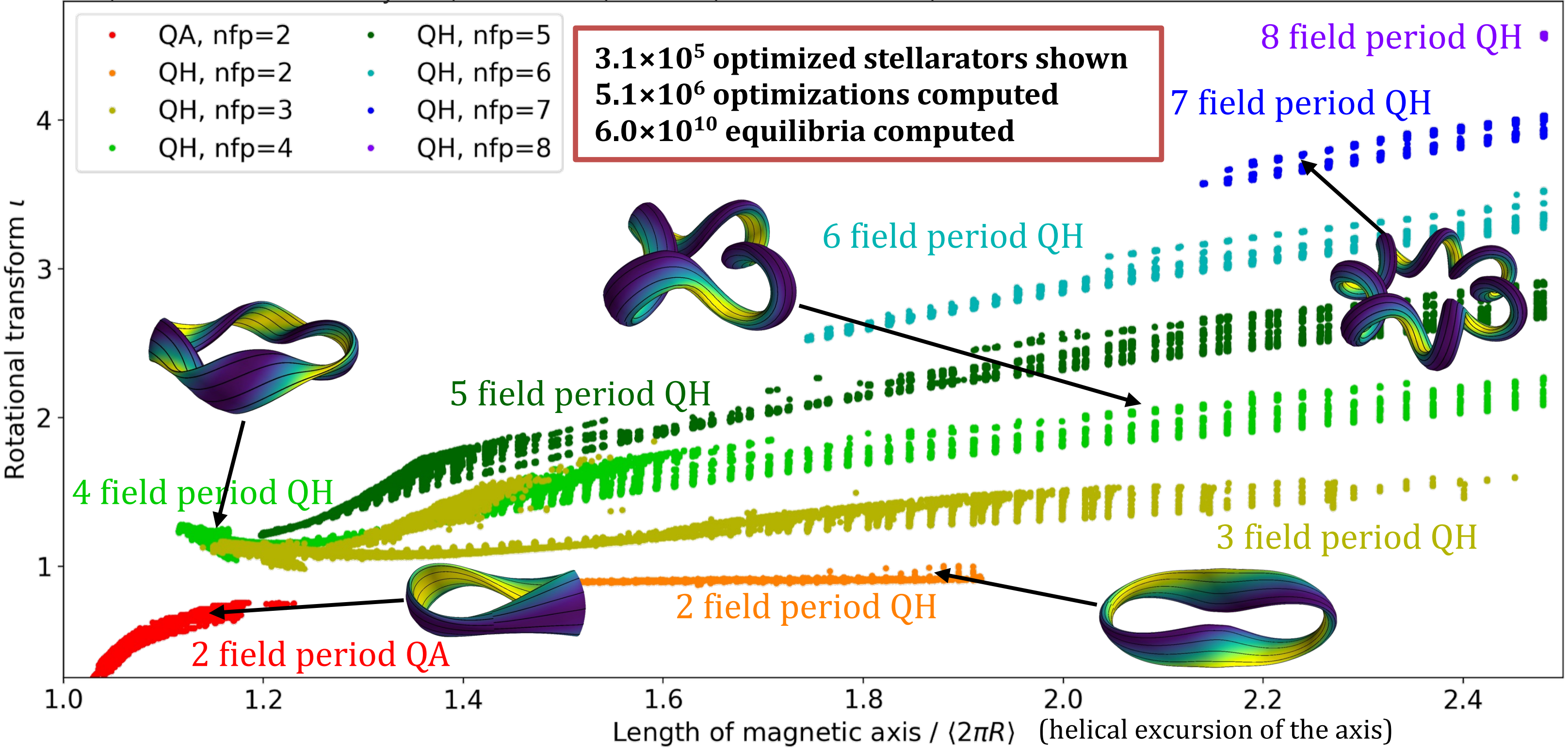


Motivation – Near-Axis Expansion

Large aspect ratio limit of the MHD equations $\left(\epsilon = \frac{r}{R} \ll 1\right)$

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

- Less input parameters
- Fast solutions



EnR Task Specification

The project is divided into 5 different tasks (WP)

- WP1 – Particle tracer code development (near-axis & full MHD)
- WP2 – Combine particle tracer and stellarator optimization codes
- WP3 – Optimized stellarator equilibria (QS, QI and General)
- WP4 – Physics study of Nemov's criterion
- WP5 – Fast particle orbits in realistic magnetic fields

2022 (WP1, WP2)

2023 (WP3, WP4, WP5)

People month per task per year is unchanged

With the following goals

- Create an open-source, user friendly, fully tested particle tracer (WP1, WP2)
- Perform the first direct fast particle optimization of a stellarator (WP3)
- Compare fast particle optimization with commonly used proxies (WP4)
- Extend the optimization to stochastic magnetic fields (WP5)

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2022 (WP1–WP2)

2023 (WP3–WP5)

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Model and Code validation

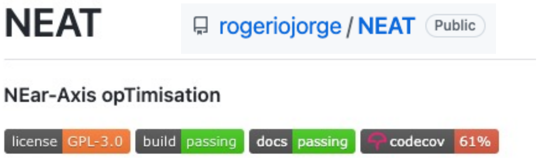
(shifted from 06.2022 to early 2023)

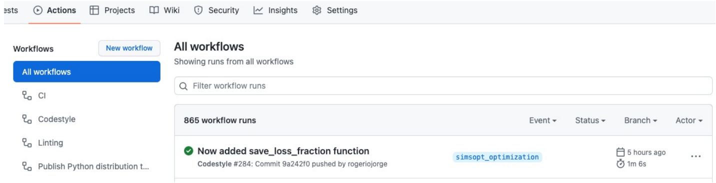
Summary of 2022

1. Development of the NEAT code (WP1)

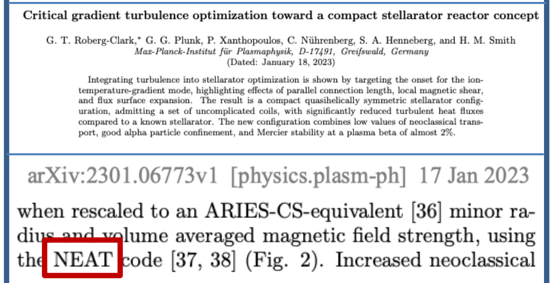
- Near-Axis Geometry
- Full MHD Geometry

GitHub Open-source and automatic testing with GitHub actions





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%.

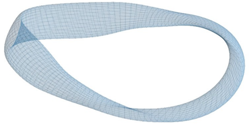
arXiv:2301.06773v1 [physics.plasm-ph] 17 Jan 2023

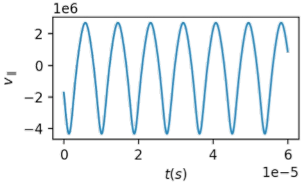
when rescaled to an ARIES-CS-equivalent [36] minor radius and volume averaged magnetic field strength, using the NEAT code [37, 38] (Fig. 2). Increased neoclassical

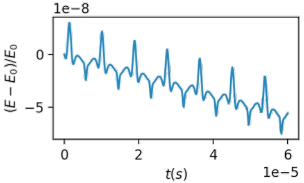
User-friendly example in near-axis geometry

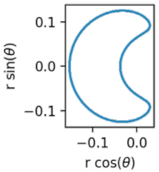
```python
from neat.fields import StellnaQS
from neat.tracing import ChargedParticle, ParticleOrbit
g_field = StellnaQS.from_paper(1)
g_particle = ChargedParticle()
g_orbit = ParticleOrbit(g_particle, g_field tfinal=1e-4)
g_orbit.plot_orbit()
```

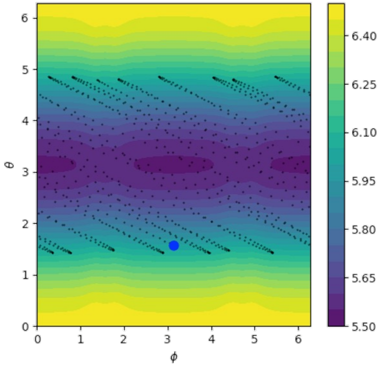
```python
print("Creating B contour plot")
g_orbit.plot_orbit_contourB()
```









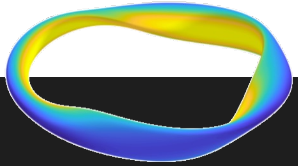


Summary of 2022

2. Integration with stellarator optimization frameworks (WP2)

- scipy.optimize.minimize or SIMSOPT – near-axis
- SIMSOPT - full MHD

User-friendly example in near-axis geometry



```
from simsopt.objectives import LeastSquaresProblem
from simsopt.solve import least_squares_mpi_solve
from simsopt.util.mpi import MpiPartition
from neat.fields import StellnaQS
from neat.objectives import EffectiveVelocityResidual
from neat.tracing import ChargedParticleEnsemble
mpi = MpiPartition()
nsamples = 500
tfinal = 4e-5
g_particle = ChargedParticleEnsemble(r_initial=0.03,r_max=0.1,ntheta=5,nphi=5,nlambda_trapped=10,nlambda_passing=2)
g_field = StellnaQS.from_paper('r1 section 5.1', nphi=51, B0=5)
g_field.fix_all()
g_field.unfix("etabar")
g_field.unfix("rc(1)")
g_field.unfix("zs(1)")
residual = EffectiveVelocityResidual(g_field,g_particle,nsamples,tfinal,2,0.1)
prob = LeastSquaresProblem.from_tuples(
    [(residual.J, 0, 40),
     (g_field.get_elongation, 0.0, 0.5),
     (g_field.get_inv_L_grad_B, 0, 0.1)])
least_squares_mpi_solve(prob,mpi,grad=True,max_nfev=20,ftol=1e-5)
```

Choose particle ensemble

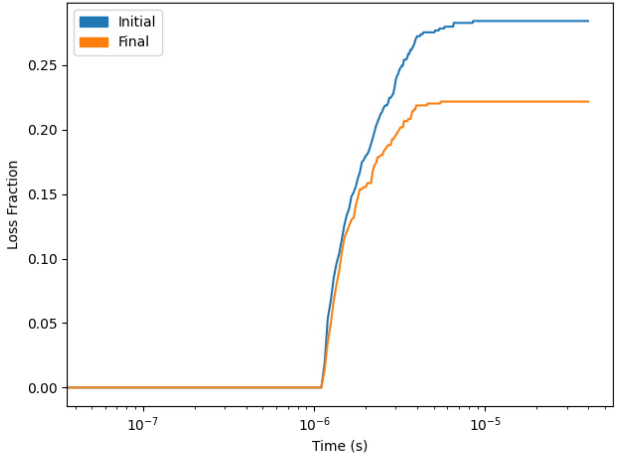
Choose geometry

Choose degrees of freedom

Choose objective function

Optimize

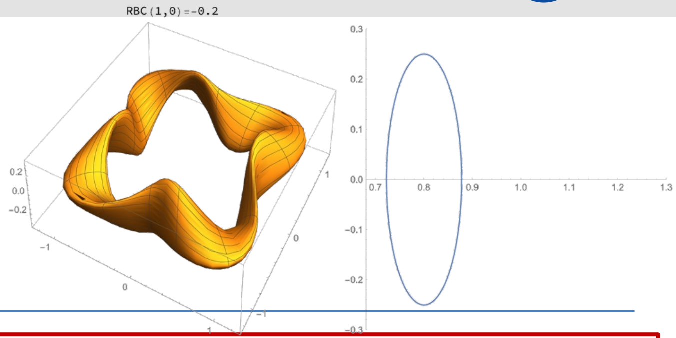
Reduction in loss of alpha particles



Summary of 2022

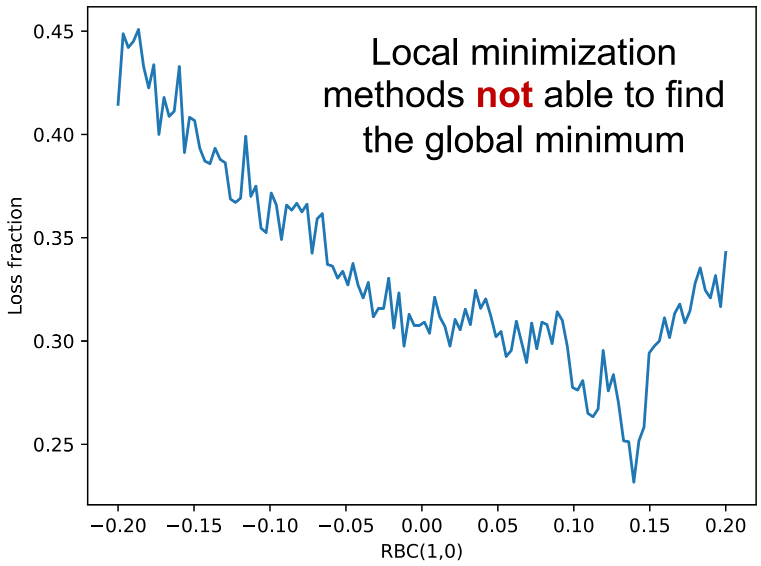
3. Optimized stellarator configurations (WP3)

- Obtained Near-Axis Optimizations (previous slide)
- Obtained full MHD Optimizations



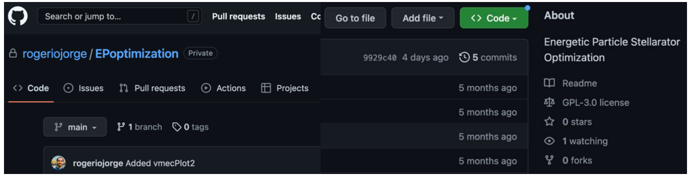
Minimal benchmark problem

- Trace 2400 particles for $5{\times}10^{-4}$ 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



Summary of 2022

Scripts available on
https://github.com/rogeriojorge/EPoptimization



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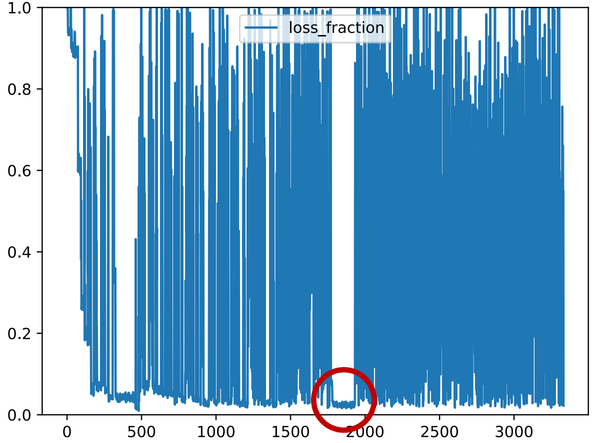
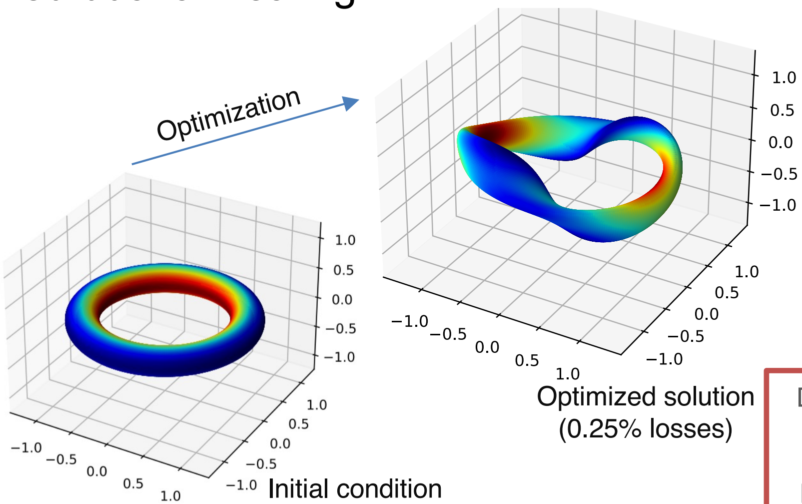
Stochastic optimization – generalized dual annealing



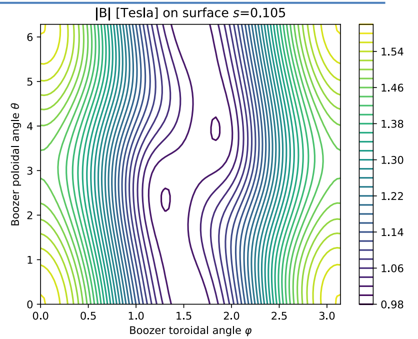
Number of iterations

Found a robust solution



Initial condition (100% losses)

Optimized solution (0.25% losses)

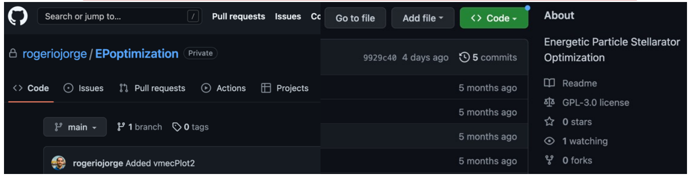


The optimizer found a quasi-isodynamic stellarator

Direct fast particle optimization of stellarator devices, R. Jorge, P. Rodrigues, J. Ferreira, A. Figueiredo, R. Coelho, D. Borba, P. Figueiredo, ***to be submitted***

Summary of 2022

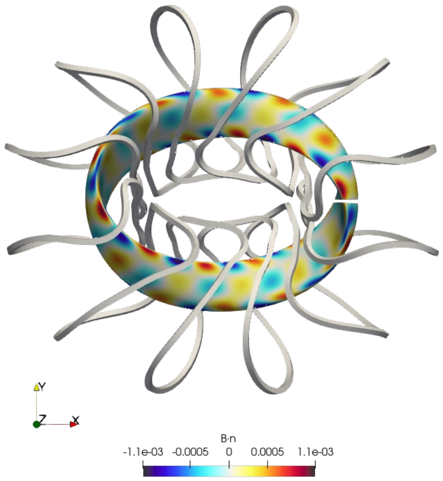
Scripts available on https://github.com/rogeriojorge/single_stage_optimization

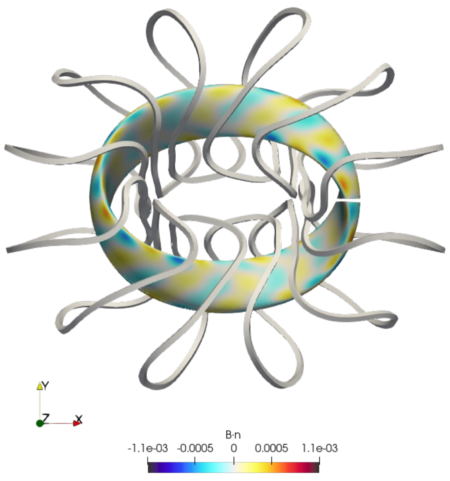


3. Optimized stellarator configurations (WP3)

- Obtained Near-Axis Optimizations (previous slide)
- Obtained full MHD Optimizations

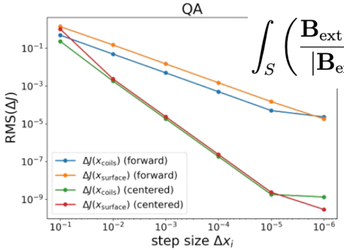
Single-Stage Optimization





Minimize simultaneously

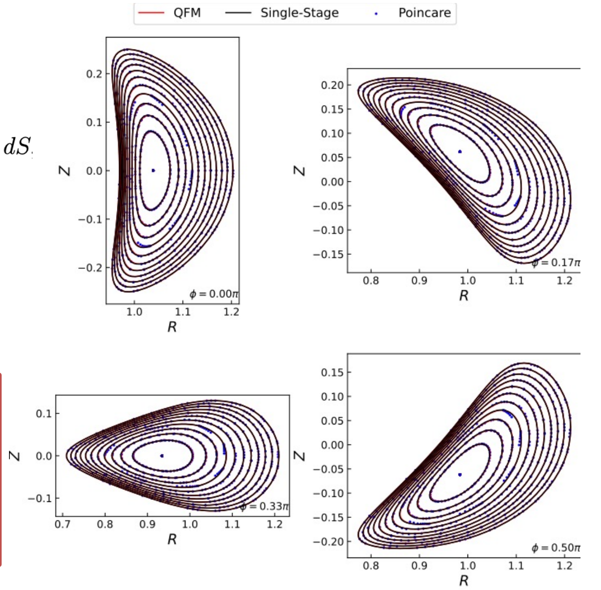
$$J = J_{MHD} + J_{coils} + J_{particles}$$



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

Single-Stage Stellarator Optimization Of Fixed Boundary Equilibria, R. Jorge et al, ***to be submitted*** (PPCF, Varenna 2022)

Validation of resulting Biot-Savart field

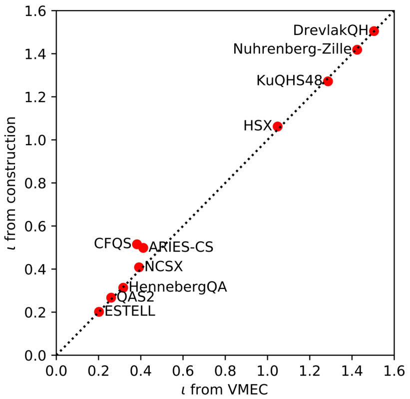


Early 2023

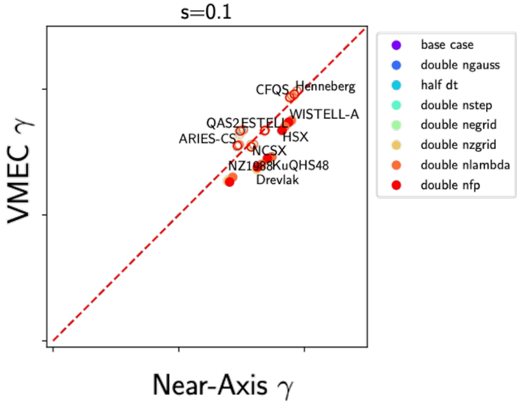
4. Validation and Verification of Model and Codes

- 4.1: Accuracy of the near-axis expansion
- 4.2: Multi-code validation

4.1: Continue the work carried out in recent years testing the limits of the near-axis expansion



Matt Landreman 2019 Plasma Phys. Control. Fusion ***61*** *075001*



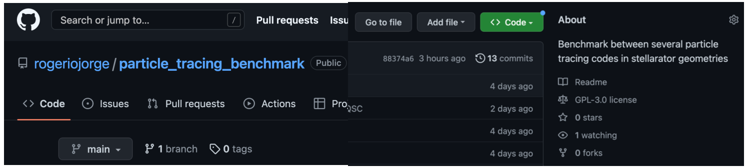
R Jorge and M Landreman 2021 Plasma Phys. Control. Fusion ***63*** *074002*

How do guiding center orbits compare in the contrasting worlds of near-axis and VMEC models?

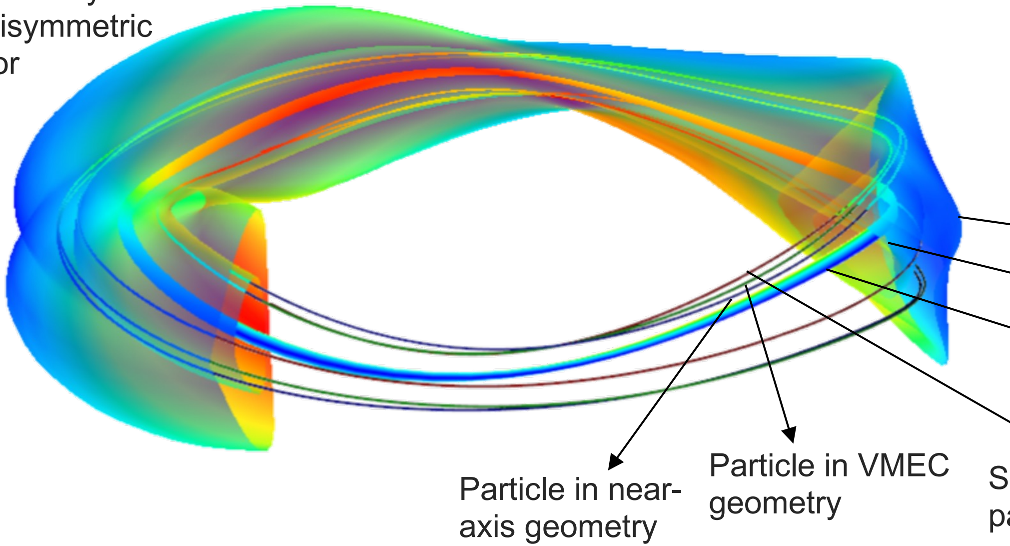
Early 2023

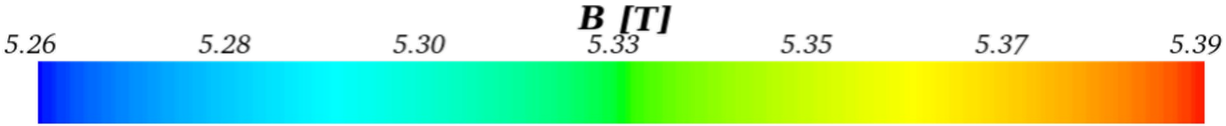
- 4.1: Accuracy of the near-axis expansion

Benchmark available on https://github.com/rogeriojorge/particle_tracing_benchmark



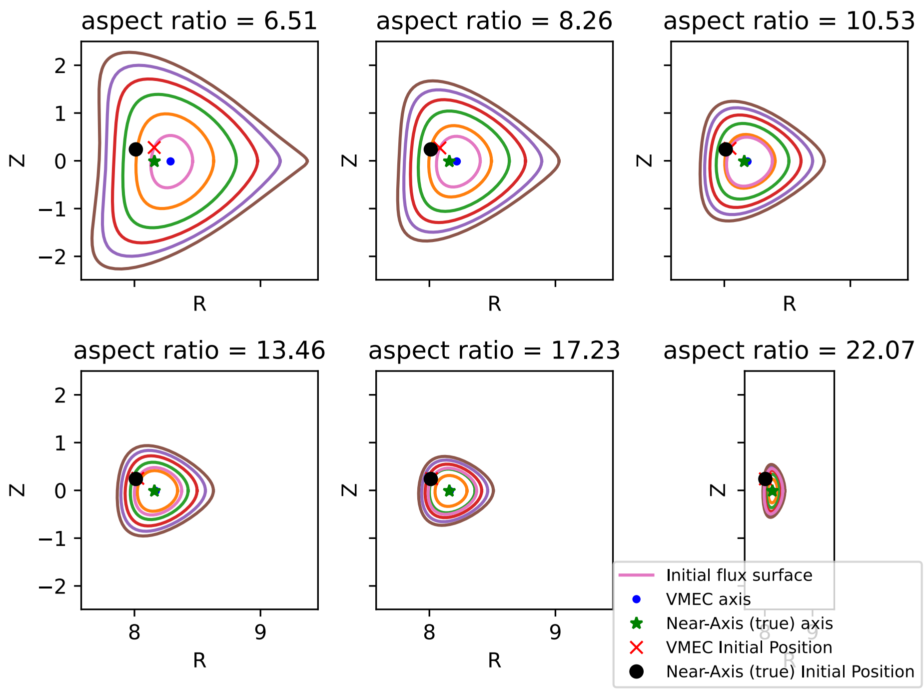
Validation study on a quasi-axisymmetric stellarator



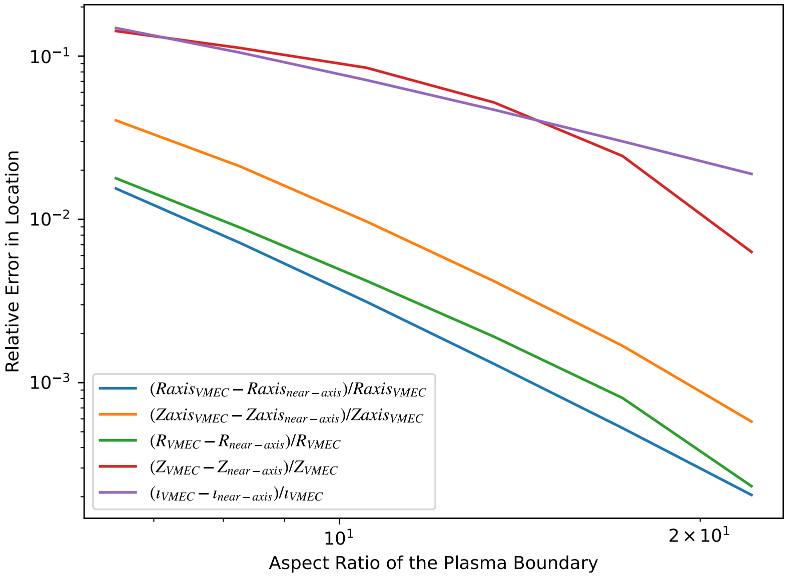


Early 2023

- 4.1: Accuracy of the near-axis expansion



Use the near-axis framework to create plasma boundaries at increasingly higher aspect ratio as VMEC inputs. Ask VMEC what the (R,Z) values are of a given point close to the axis



Early 2023

4. Validation and Verification of Model and Codes

- 4.1: Accuracy of the near-axis expansion
- 4.2: Multi-code validation

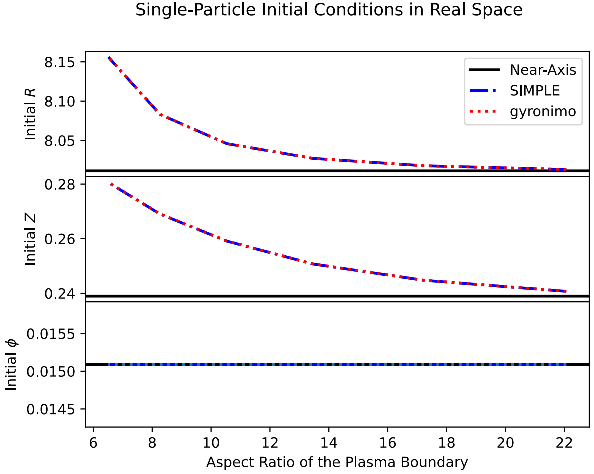
Fill a gap in the literature:

Stellarator particle tracer

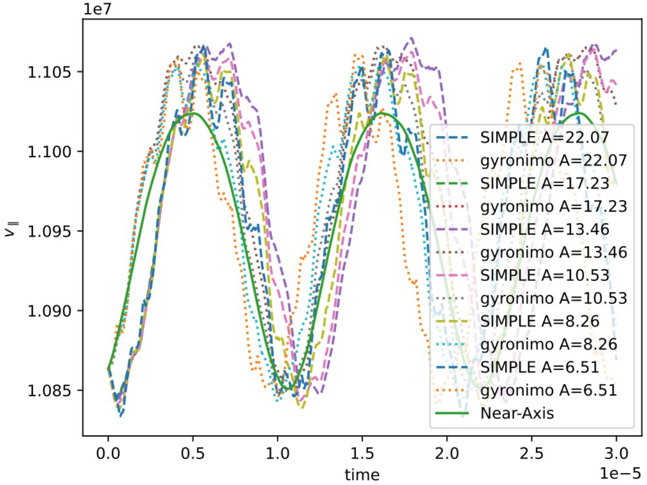
code validation

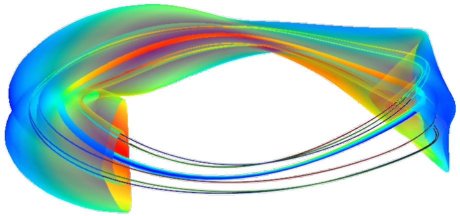
- 4.2: Multi-code validation (gyronimo + SIMPLE)

Test interpolation of tracers



Test trajectories (preliminary)





Workplan for 2023

- Perform code validation study and test near-axis accuracy
- Submit *both manuscripts* for WP1, WP2 and WP3 results

- Assess new optimization metrics (WP4)
- Orbits in Biot-Savart (coil) and stochastic magnetic fields (WP5)

Software development

- Extension to GPU parallelization
- Improve scalability of gyronimo particle tracer code with the number of cores (parallelization)

Collaborations

Main:

- TU Gratz: developers of the SIMPLE code (C. Albert *et al.*)
- IPP Greifswald: NEAT used as day-to-day particle tracer framework

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Starting conversations:

- IPP Greifswald: test new objective functions for quasi-isodynamic stellarators (A. Goodman *et al.*)
- EPFL: integration of SPEC equilibrium and benchmark with VENUS-LEVIS (J. Loizu *et al.*)

Beyond 2023:

1. arXiv:2301.09356 [pdf, other] physics.plasm-ph

Direct Microstability Optimization of Stellarator Devices

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

Submitted to PRL

- IST Lisbon + PPPL:
  - integration of fast-particle optimization with turbulence optimization (GX code)

Miscellaneous

IPFN Stellarator talks 2022

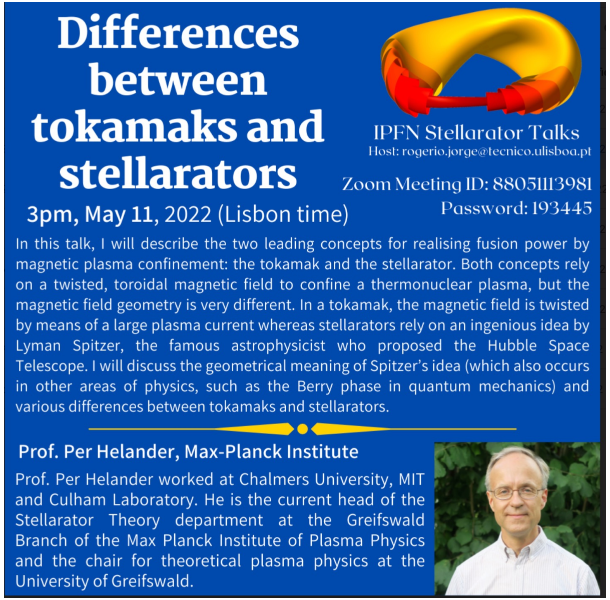
- Series of online seminars organized by members of this EnR
- Overall a successful project with ~40 participants per talk

May 11, 2022 – Per Helander

May 25, 2022 – Joaquim Loizu

April 27, 2022 – Matt Landreman

June 8, 2022 – José Luis Velasco



End