EUROfusion

TSVV-12: Stellarator Optimization

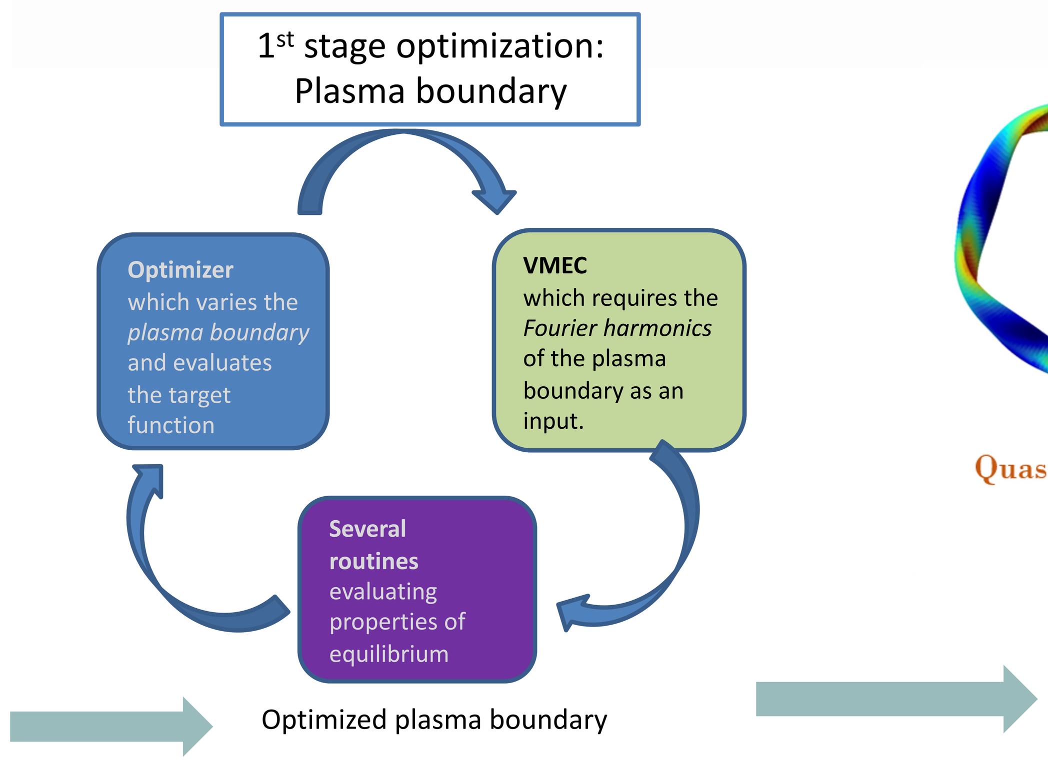
SA Henneberg*[1a], S Äkäslompolo[2], CG Albert[3], E Balkovic[4], M Drevlak[1a], Y Feng[1a], P Helander[1a], FJ Hindenlang[1b], S Kasilov[2], W Kernbichler[2], J Loizu[4], O Maj[1b], C Nührenberg[1a], FI Parra[5], GG Plunk[1a], E Sánchez[6], BW Shanahan[1a], JL Velasco[6], et al. *Acknowledgement:* CD Beidler[1a], I Calvo[6], R Davies[1a], FJ Escoto[6], JM Garcarcía-Regaña[6], AG Goodman[1a], T Ribeiro[1a], GT Roberg-Clark[1a], CB Smiet[4]

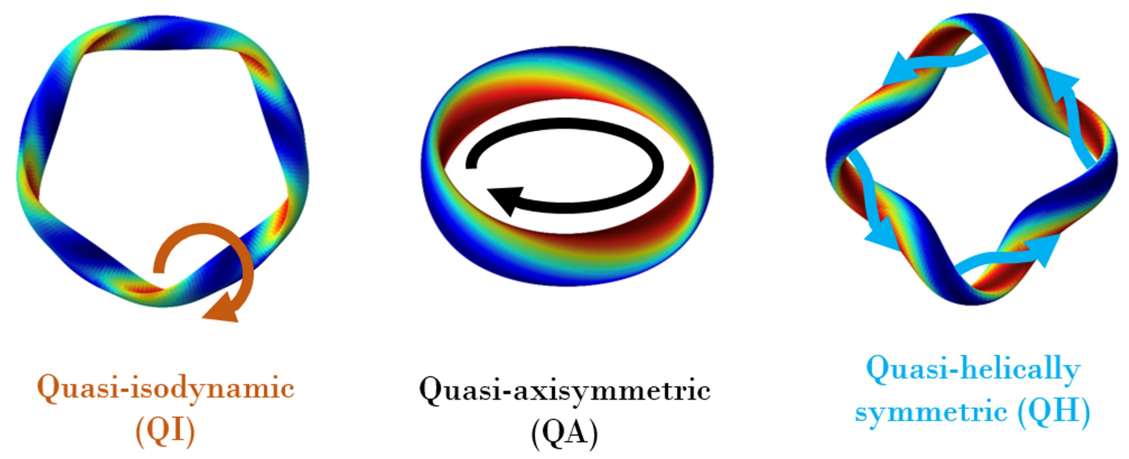
[1]Max-Planck-Institut für Plasmaphysik , [a]Greifswald, [b]Garching, Germany, [2]Aalto University, Aalto, Finland, [3]TU Graz, Graz, Austria, [4]EPFL, Lausanne, Switzerland, ([5]PPPL), [6]CIEMAT, Madrid, Spain

KEY DELIVERABLES

- ✓ Turbulent & Neoclassical Transport: *Integration of fast reduced models of turbulent transport into stellarator optimization codes (synergy with TSVV Task 13) Generalization of tools for the evaluation of radial neoclassical transport, so that it can be minimized in collisionality regimes beyond the 1/ν regime.*
- ✓ Bootstrap Current & Energetic Particle Confinement: *Accurate numerical tools for the evaluation of energetic particle confinement and for the calculation of the bootstrap current that are sufficiently fast to be integrated into stellarator optimization code.*
- ✓ MHD equilibrium and stability: *Efficient tools capable of assessing, for any stellarator equilibrium, ideal and resistive MHD stability (and the importance thereof), and robustness of the magnetic topology to current perturbations.*
- ✓ Improved optimization approaches: *Improved algorithms to be employed in stellarator optimization for reduced sensitivity to local optima in parameter space, and development of approaches for coil simplification and robustness against errors.*
- ✓ Stellarator Optimization: *Application to produce a set of highly optimized stellarator configurations.*
- ✓ Power Exhaust: *Investigation on the integration of power options for next-generation stellarators.*

BACKGROUND





OVERVIEW

- 95 EUROfusion pinboard entries:
  - **42 Journal publications**
  - **53 conference contributions**
- All but one of 16 promised milestones have been successfully achieved to date. New key objectives have now been identified.

New, improved or extended tools:

- Unique boundary representation
- Generalized Frenet frame in GVEC
- Combined plasma-coil optimization algorithms
- Efficient single-stage optimization of islands
- New codes to evaluate neoclassical transport quickly
- Ideal MHD GVEC code development progress
- New and fast metric for alpha-particle losses
- 3D BOUT++ simulations for edge turbulence and transport
- Global ideal MHD (CAS3D) in optimization
- Divertor target automated

- **Better understanding of stellarator physics:**
  - Solving the bootstrap riddle
  - Island healing
  - Piecewise omnigenous stellarators
  - Comparison magnetic well – gyrokinetic simulations
- **New predictions of equilibrium β-limits in stellarators**
  - Retrieved ideal stability in a stellarator with SPEC.
  - Reproduced Glasser-Greene-Johnson tearing stability in a tokamak with SPEC.
  - Reproduced nonlinear saturation of tearing modes with SPEC in a cylindrical tokamak

OPTIMIZATION TARGETS & METHODS

Fast and accurate calculation of neoclassical transport: Needed for the evaluation of neoclassical transport within the optimization loop: Γ_α and Γ_δ (computed with KNOSOS): figures of merit for prompt losses of energetic ions. **KNOSOS-MC**: rigorous orbit-averaged calculation of fast-ion transport in stellarators. **MONKES:** a fast (< minute/point) and accurate code for radial and parallel neoclassical transport.
J. L. Velasco *et al.*, NF 61, 116059 (2021), F. J. Escoto *et al.*, NF (2024).

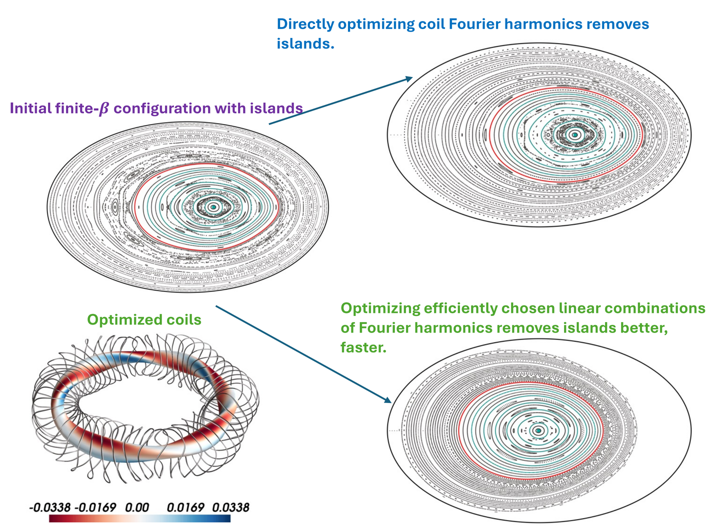
Efficient single-stage optimization of islands in finite-β stellarators

Free-boundary SPEC is coupled to `simsopt`.

Magnetic islands in the edge are controlled by **directly varying the coils** and simultaneous evaluation of the equilibrium.

Computational cost is reduced and better optima are achieved by reducing the dimensionality of the optimization problem.

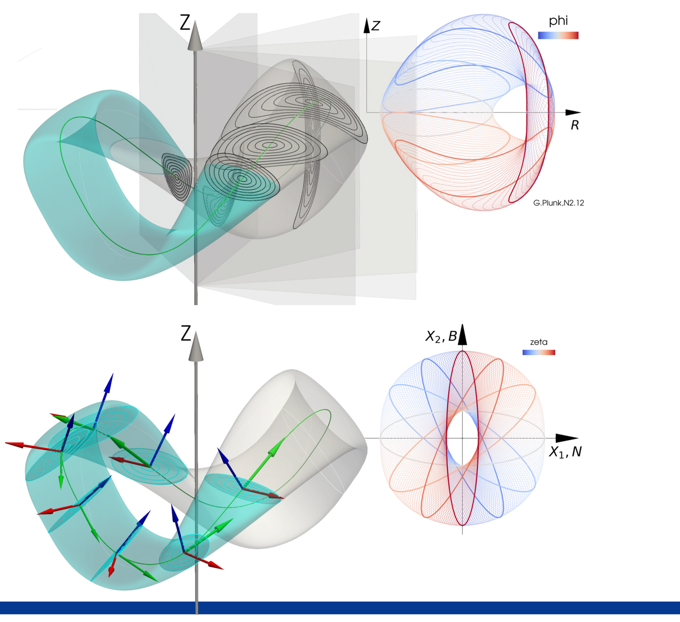
https://arxiv.org/pdf/2407.02097



Generalized Frenet frame for MHD equilibrium solver GVEC

New QI-configurations found by NAE: highly shaped magnetic axis, highly shaped cross-section in (R,Z) frame (top) but simple cross-sections in axis-following `G-frame` (bottom), implemented in GVEC. Much less resolution is needed, but G-frame is more accurate.

F.Hindenlang, G.Plunk, O.Maj preprint: http://arxiv.org/abs/2410.17595

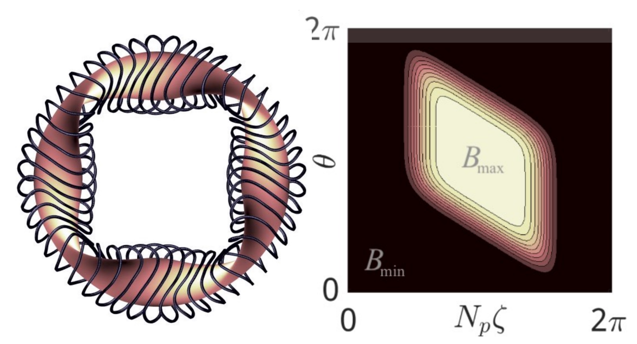


IMPROVED UNDERSTANDING

Piecewise omnigenous (pwO) stellarators:

Novel concept of neoclassically optimized stellarator fields: Qualitatively different from QI, QA or QH fields. Result could broaden enormously the space of accessible reactor-relevant stellarator configurations.

J. L. Velasco *et al.*, PRL, 133, 185101 (2024)



Fast alpha particle loss metrics in stellarators

Implemented two generations of orbit classifiers in the symplectic code SIMPLE. Speed-up of 1-2 orders of magnitude for loss metrics. Importance of orbital resonances linked to tokamak resonant transport regimes.

CG Albert, et al, JPP 89 (3), 955890301

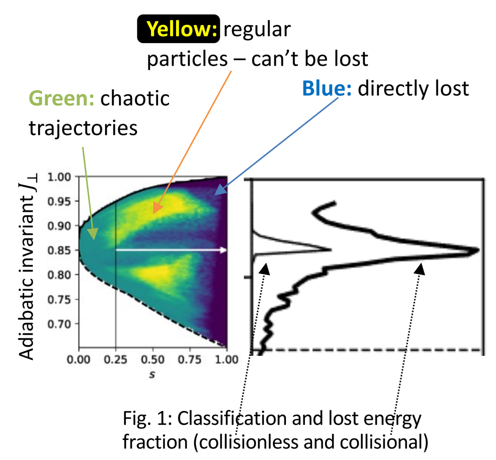
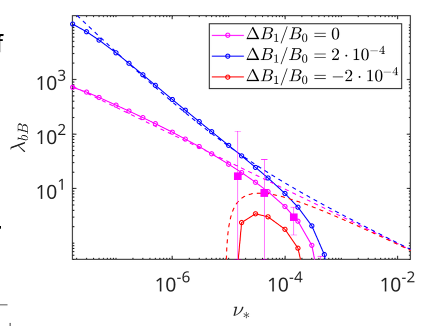
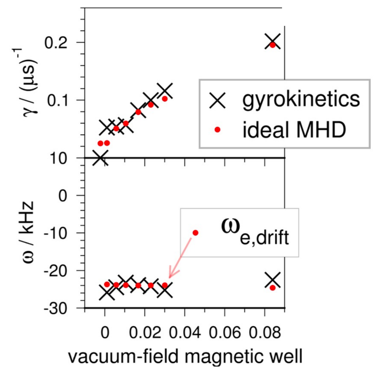


Fig: Convergence of the bootstrap coefficient to the new semi-analytical limit (dashed) compared to DKES (squares) and NEO-2 (circles)



Fast bootstrap current metrics in stellarators

Up to now, collisionless limit of bootstrap current in stellarators deviated from theoretical results. Theoretical results from this work accurately predict this offset for optimized stellarator configurations. Implementation of a generalized variant based on NEO-2 is ongoing Albert, et al. arXiv preprint arXiv:2407.21599



Assessment of vacuum-field magnetic well

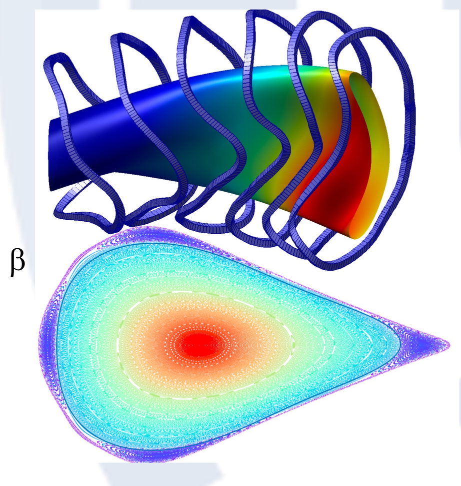
offset for Comparative study uses linear MHD stability (CAS3D) and non-linear PIC gyrokinetics (EUTERPE). Excellent agreement in spatio-temporal mode structures. Both models show that the vacuum-field magnetic well is indispensable for stability against low-order MHD modes.

EXAMPLE OF NEW DESIGNS

QI: CIEMAT-QI-family

- ι profile avoiding low order rationals.
- Ideal MHD stability up to reactor β.
- Low neoclassical transport and reduced bootstrap current.
- Very good fast ion confinement at low β (1.5%). Excellent at reactor β.
- Reduced turbulent transport.
- Preliminary set of filamentary **coils** preserving the above properties.

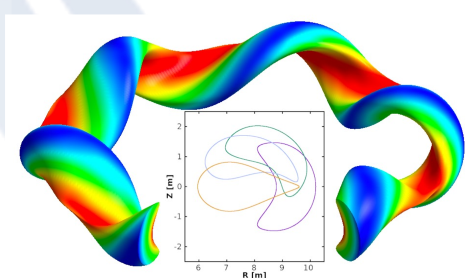
In addition: SQuIDs
Goodman, et al., JPP 89 (5), 905890504



E. Sánchez *et al.*, NF 63, 066037 (2023)
J. L. Velasco et al., NF 63,126038 (2023)

QH: QSTK

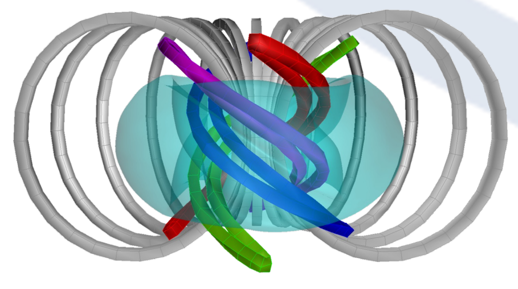
- Better fast-ion confinement than W7-X
- Lower thermal neoclassical transport than W7-X
- MHD stable
- ITG turbulence reduced



Roberg-Clark, et al., PRR (2023)

QA: Compact stellarator-tokamak hybrid

- Can be operated as a tokamak or a stellarator or anything in between.
- Compact: aspect ratio down to 2.3
- Good QA accuracy (Smaller neoclassical transport than in W7-X)
- 4 simple saddle coils of a single type (in addition to TF coils + PF coils)
- Flux surfaces in vacuum



Henneberg, Plunk, PRR 2024
Schuett, Henneberg, PRR 2024

FUTURE DEVELOPMENT

- Exhaustive study of novel designs (pwO, compact stellarators)
- Comparison of stellarators of different topological classes.
- Divertor optimisation.
- Develop a 'new-SPEC' code that is more robust and can easily handle strongly shaped geometries.
- Apply the 'direct nonlinear stability calculation' approach to tokamaks and stellarators.
- Develop useful metrics for controlling islands and chaos in the stellarator edge.
- Free-boundary version of GVEC.
- Using the newly development metrics and approaches in optimization, e.g. Generalized Frenet Frame

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