TSVV-12: stellarator optimization

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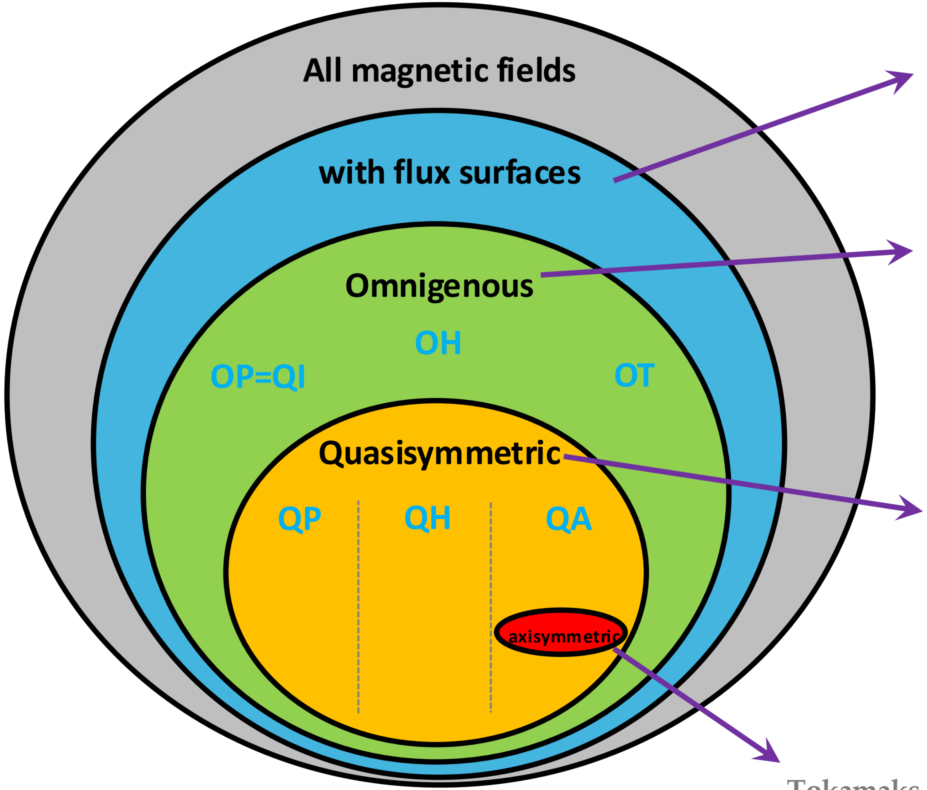
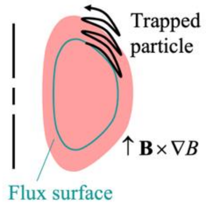
Where to optimize in the space of all magnetic fields?



does not guarantee confinement of trapped particles

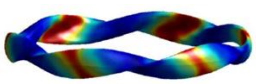


net radial drift = 0

→ |**B**| contours need to close OP/OH/OT

→ no easy recipe

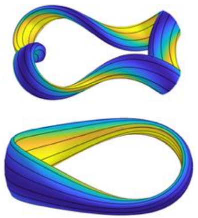
→ W7-X is approximately OP=QI



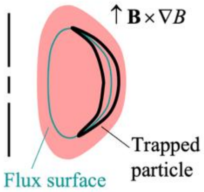
$|B| = |B|(\psi, M\theta - N\varphi)$ **in Boozer coordinates**

→ more easy recipe

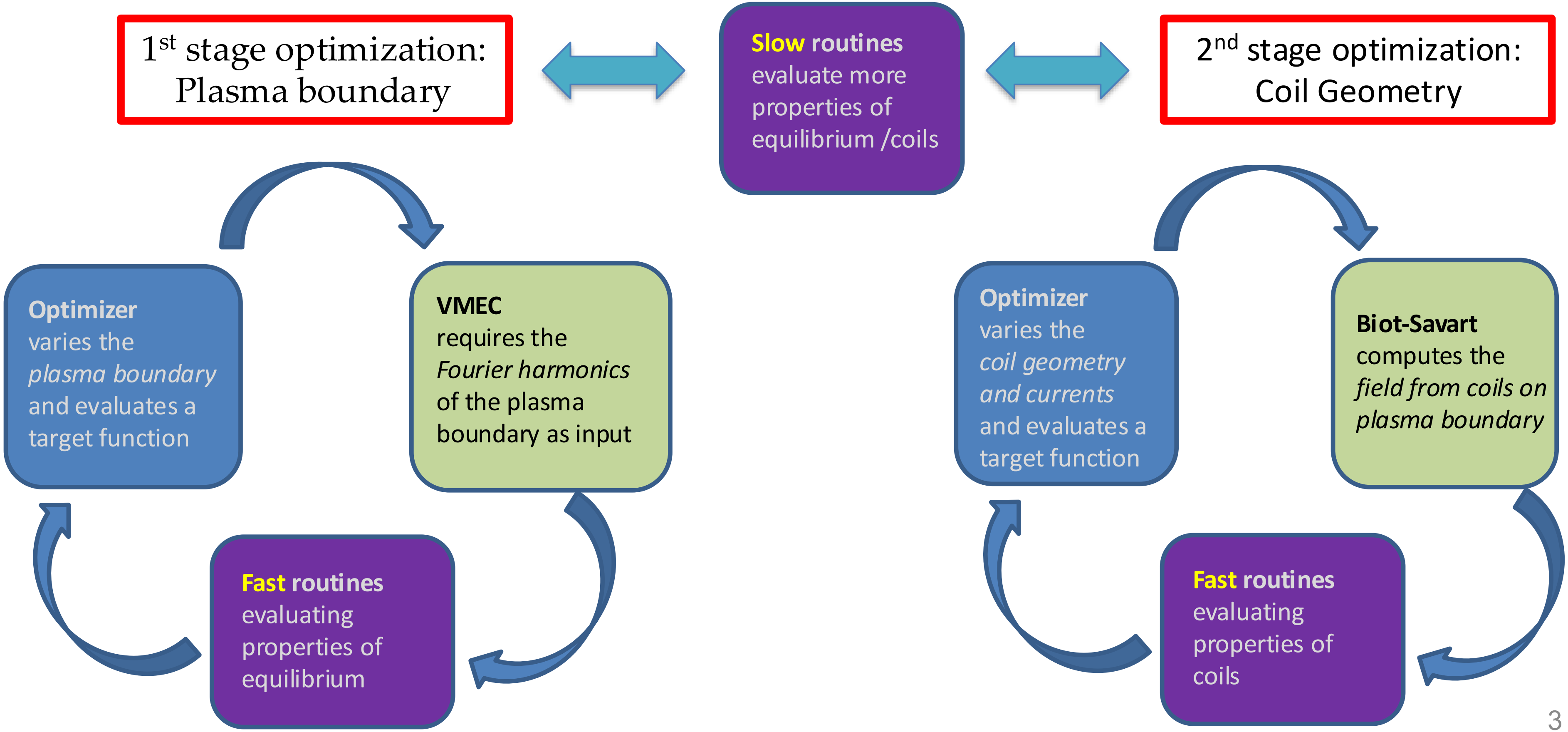
→ QA neoclassical physics = tokamak



Tokamaks



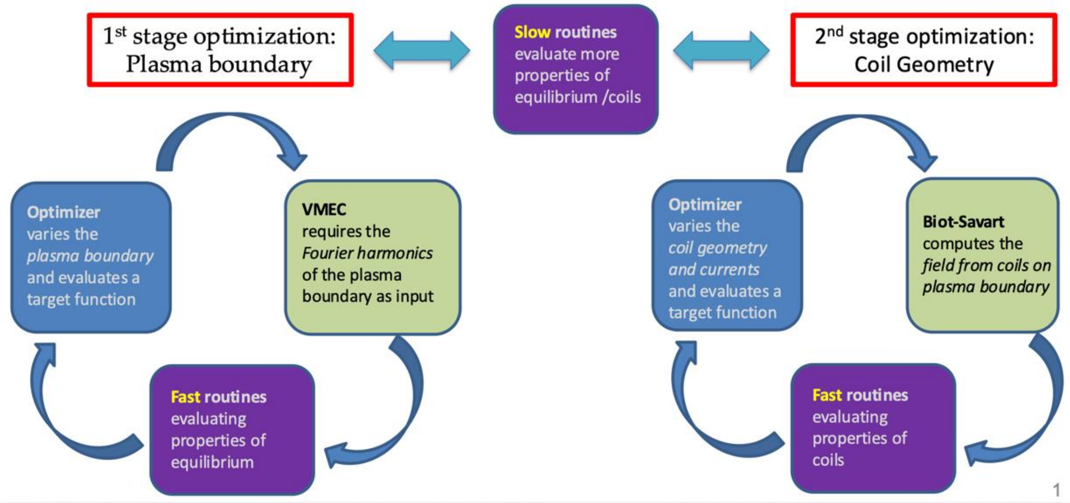
Traditional stellarator optimization



What is different today that allows much better designs?

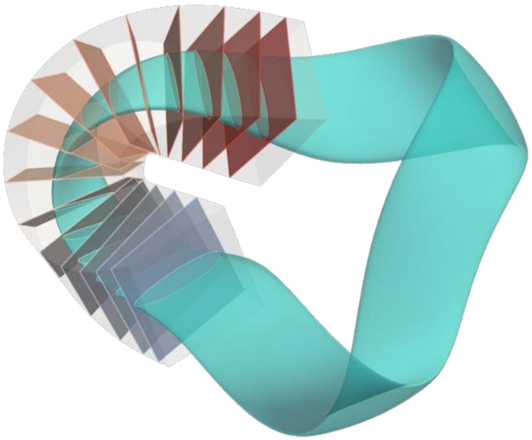
- Much faster computing (can explore more space)
- Devised efficient recipes for finding QI and QS (better target functions)
- Developed faster codes (can include more evaluations inside optimization loop)
- Derived new reduced models (more physics in optimization loop)
- Combined plasma-coil optimization or “single-stage“ (potentially accessing much better optimum)

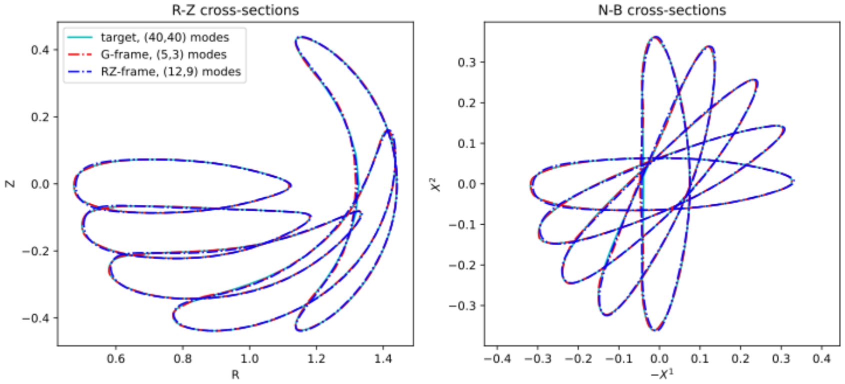
[Henneberg et al, JPP 2021]



Developed robust ideal MHD equilibrium code (GVEC)

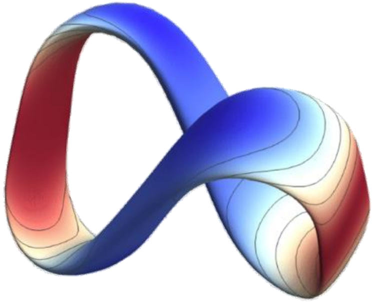
- **GVEC** improves upon VMEC on many aspects (numerics).
- General coordinate frame "**G-frame**" implemented in GVEC.
- G-frame aligns planar cross-sections (not R-Z) with plasma shape.
- Reduces degree-of-freedom to represent equilibrium.
- **Enables exploration** of strongly shaped configurations!



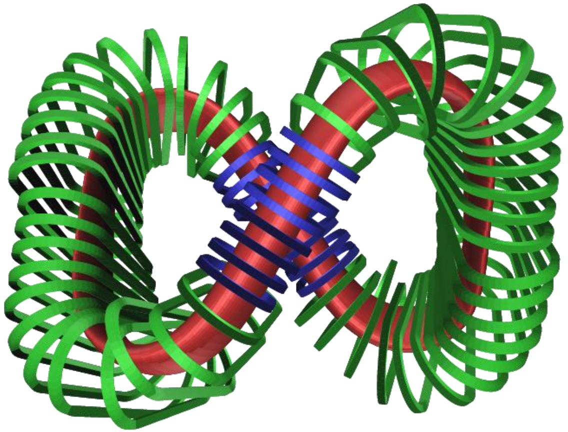


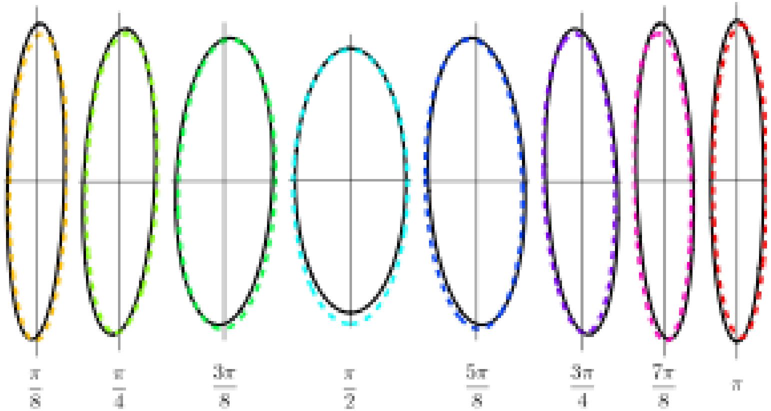
[Hindenlang et al, PPCF 2025]

First ever QI stellarator design with planar coils



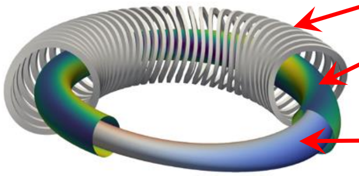
- GVEC integrated into optimization code SIMSOPT.
- **QI**-optimized stellarator with **planar coils**!
- It's a **figure-8** with nearly-elliptical cross-sections and stable magnetic well.



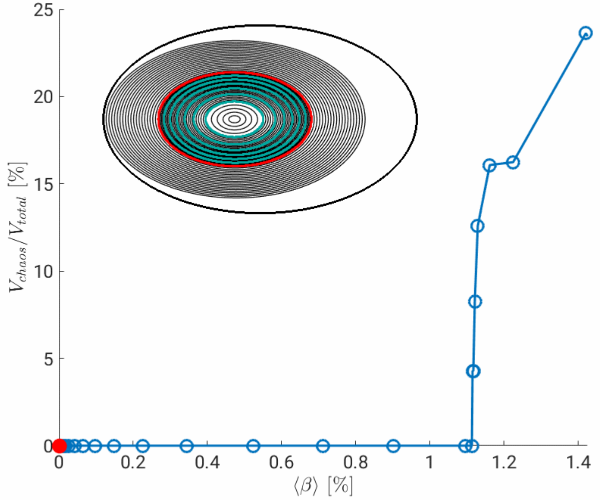


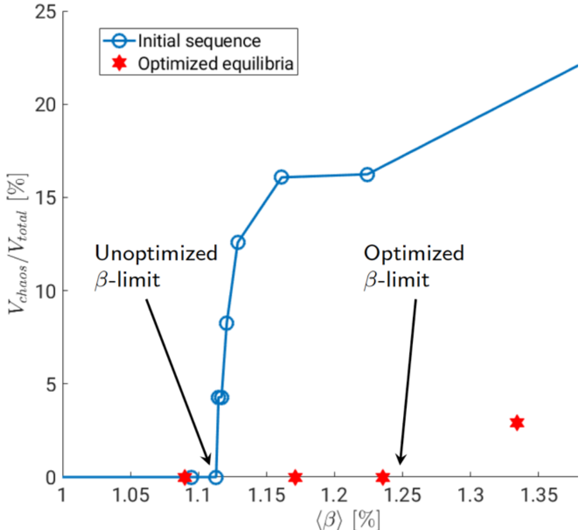
[Plunk et al, PPCF 2025]

SPEC used to quantify & optimize equilibrium β-limits



- **SPEC** allows fast calculation of free-boundary equilibria with islands & chaos, including effect of bootstrap current. [Baillod et al, JPP 2021]
- Quantified β above which volume of chaos $V_{chaos} > 0$. [Baillod et al, JPP 2023]
- SPEC integrated with SIMSOPT, allowing topology optimization. [Baillod et al, PoP 2022]

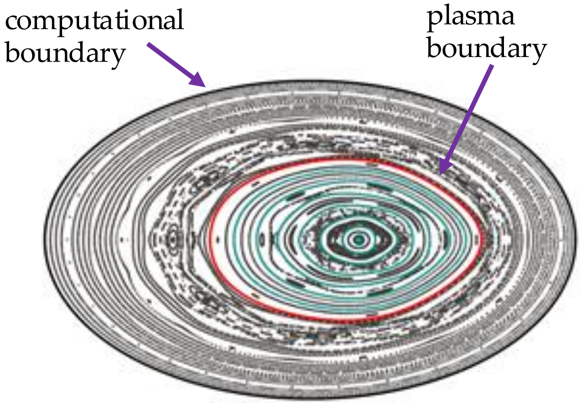




Efficient single-stage optimization of islands at finite-β

Objective: minimize R^2_{Greene} for selected resonances

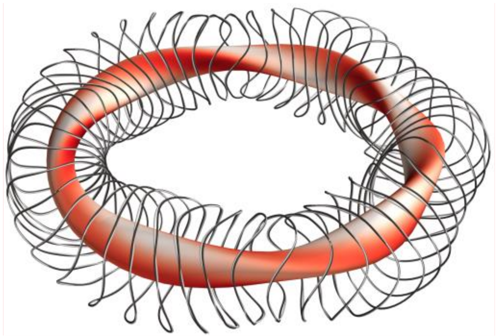
Degrees of freedom: coils geometry $\mathbf{x}_{mn}$ in Fourier

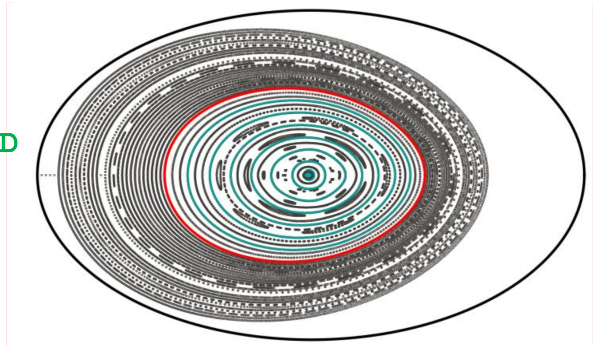


initial
(β ~1.5%)

coupling SIMSOPT + SPEC

80-dim optimization space with SVD



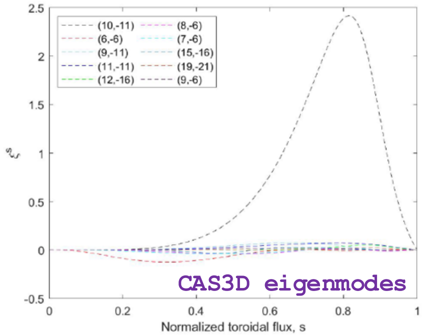


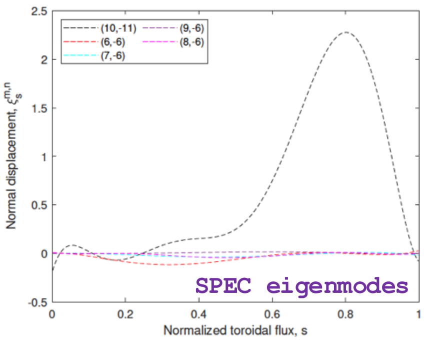
optimized
(β ~1.5%)

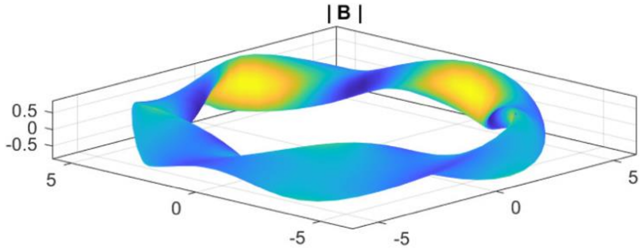
[Smiet et al, PoP 2025]

MHD linear/nonlinear stability with an equilibrium code

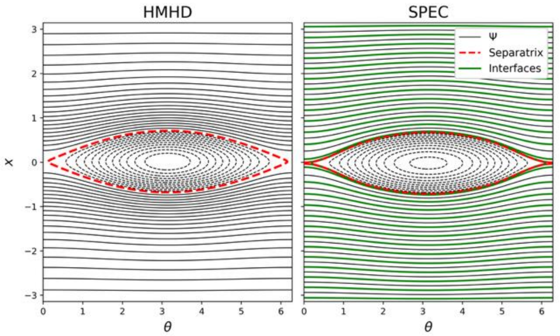
- Retrieved ideal MHD stability in a stellarator with SPEC. [Kumar et al PPCF 2022]

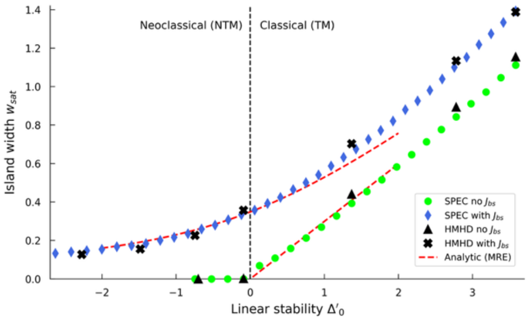






- Reproduced nonlinear saturation of tearing modes with SPEC. [Loizu et al JPP 2023; Balkovic PPCF 2024]



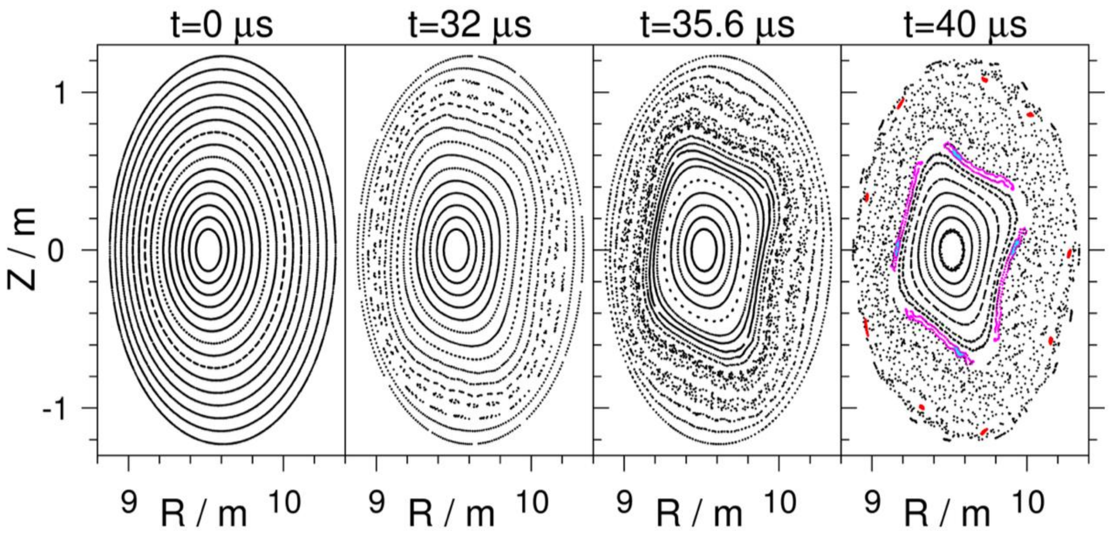


Resistive MHD simulation:
400 cpu-hours

Direct solve with SPEC:
0.1 cpu-hours

MHD linear/nonlinear stability with a gyrokinetic code

- Global GK simulations of MHD-unstable low-shear stellarators with **EUTERPE**.

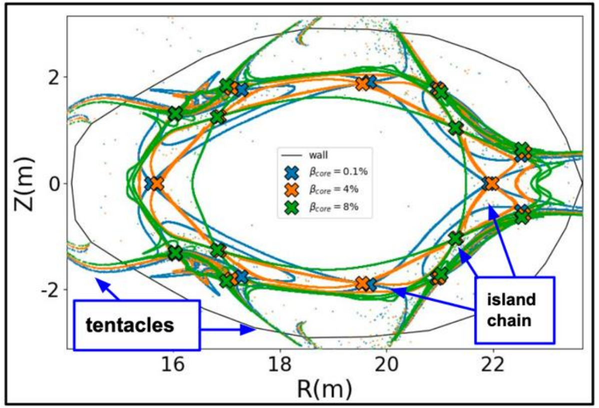


[Nührenberg et al JPP 2025]

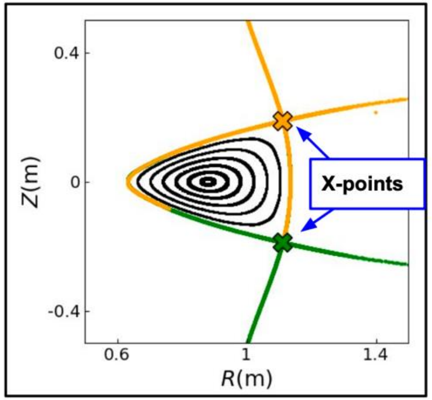
- Linear phase agrees with ideal MHD stability predictions (CAS3D)
- Nonlinearly, low-m modes can drive islands and ergodization, potentially affecting confinement

Topological methods used to monitor & control the edge

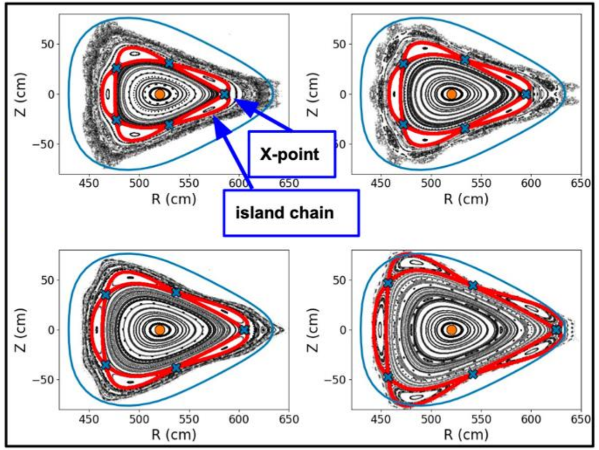
- Diversion in stellarators largely governed the existence & properties of fixed points (X-points/O-points).
- Topological methods used to understand and optimize fixed points to improve stellarator divertors.



Edge topology of SQuID reactor concept
Island chain present which flips phase as β increases
Additional X-points divert plasma in apparently resilient "tentacles"



Discovery of stellarator with "tokamak-like" X-points
Starting point for design of STAR_Lite at Hampton University, Virginia!



Topological optimisation in W7-X
Using optimisation schemes to "automatically" move the island chain by targeting X-point location

[Goodman et al, JPP 2025, accepted]

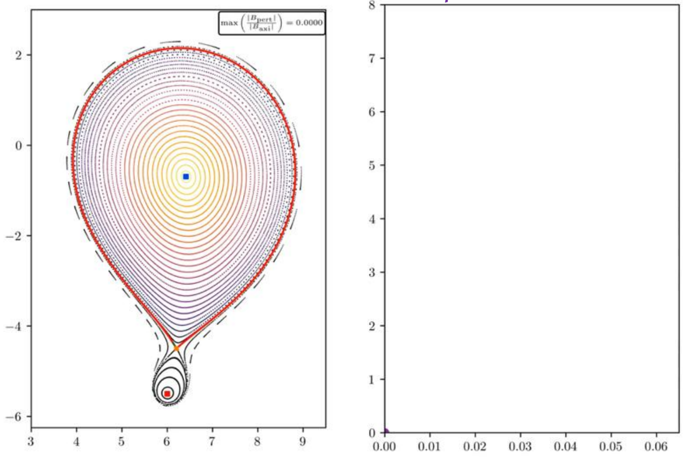
[Davies et al, NF 2025]

[Davies et al, in preparation]

We can now compute manifolds & turnstile lobe areas

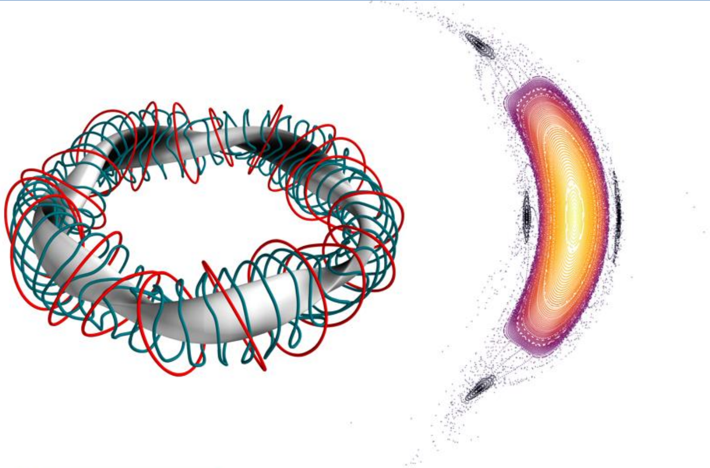
manifolds in a perturbed tokamak

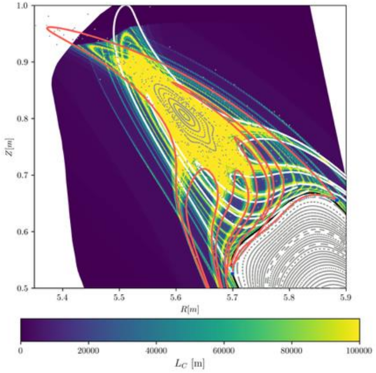
turnstile area versus *perturbation*



As the perturbation strength increases, islands appear and merge, and Poincaré trajectories jump, but the manifolds and turnstile areas vary smoothly.

All tools are being integrated in simsopt!





In W7-X configurations where the divertor island region is chaotic, intersecting turnstile lobes coincide with low connection length regions.

[Smiet et al, Chaos 2025]

Developed EMC3-Lite code for fast heat load evaluation

Heat transport equation solve by **EMC3-Lite**:

$$\nabla \cdot \left(-\kappa_e \nabla_{\parallel} T - \chi n \nabla_{\perp} T\right) = 0$$

Bohm condition at target:

$$q_{\mathrm{P}} = -\kappa_e \nabla_{\parallel} T = n C_s \gamma T_t$$

Numerics:

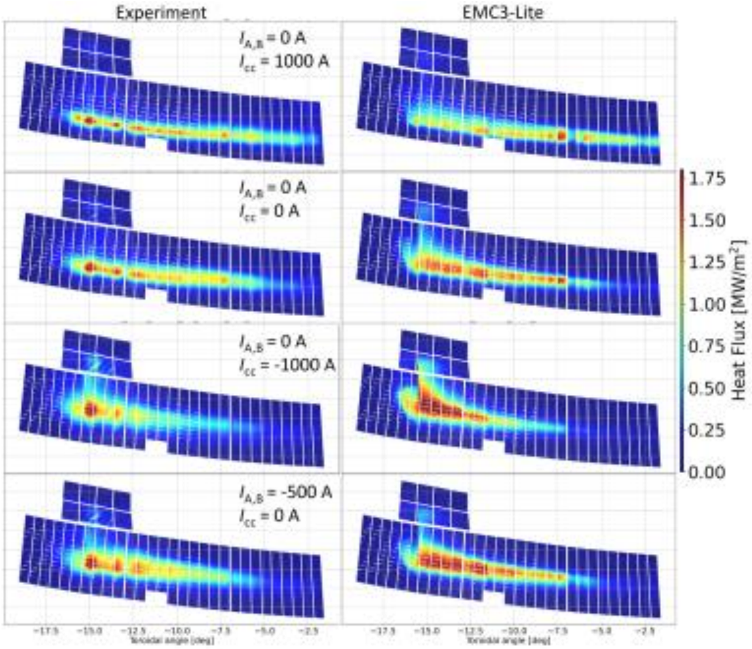
Monte-Carlo integrated with
Reversible Field-Line Mapping (RFLM)

Major features:

- 10^3 *times faster than conventional diffusive-field-line-tracing*
- *heat load distribution including the target shadow region*

[Feng et al PPCF 2022]

Validation at W7-X

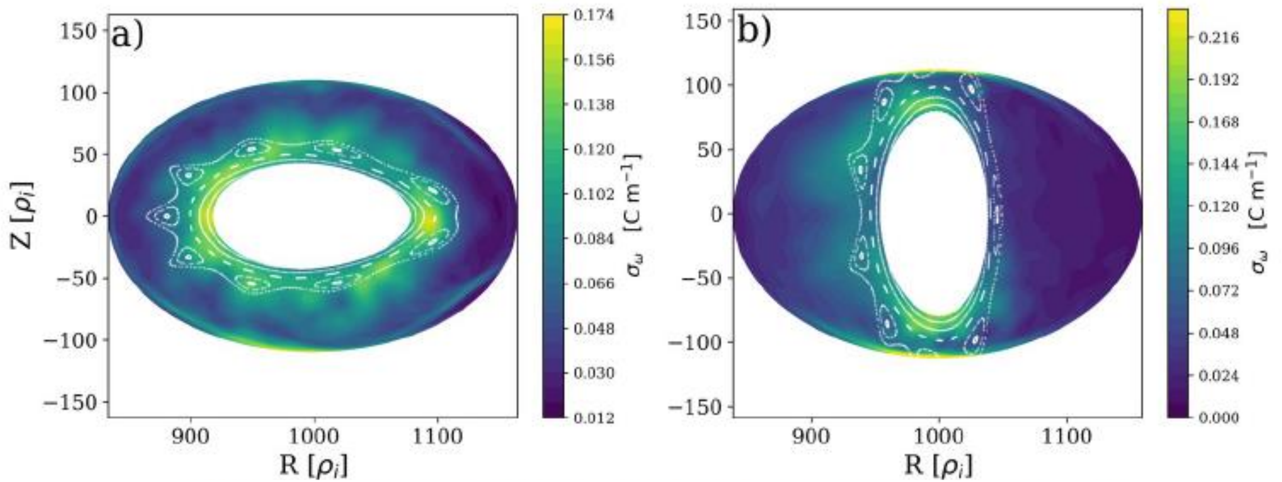


[Gao et al NF 2023]

Extended BOUT++ for stellarator edge turbulence

- Fluid turbulence simulations have been performed with **BOUT++** in the edge of an analytic stellarator configuration with an island divertor. [Shanahan et al JPP 2024]

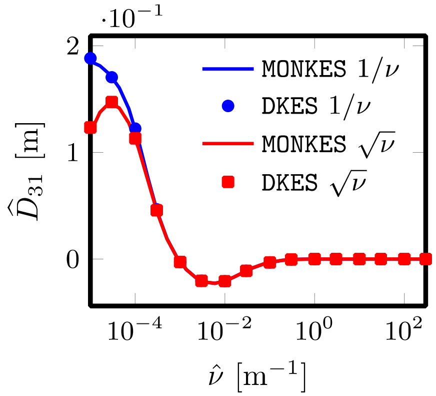
- Synergy with TSVV-3 work, with GBS simulations of the same configuration. [Coelho et al NF 2022]



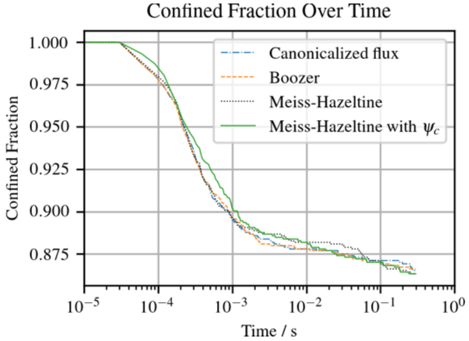
- Opens the way to V&V studies for stellarator edge turbulence simulations. [Coelho et al NF 2023]

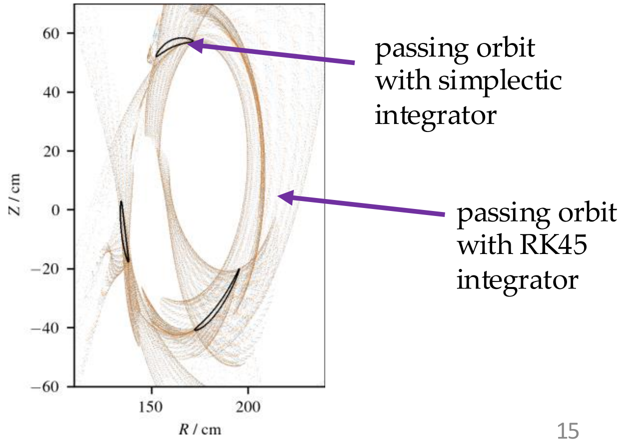
Fast & accurate neoclassical and orbit-following codes

- **MONKES**: accurate neoclassical code [Escoto et al NF 2024]
  - very fast (< minute / point, using 1 core)
  - evaluation of monoenergetic transport coefficients
  - bootstrap current calculation can be put into optimization loop



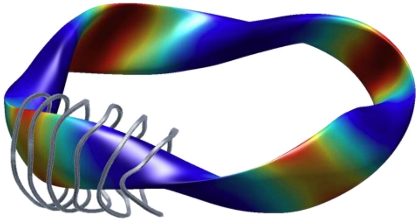
- **SIMPLE**: fast α -particle orbit follower with simplectic integrators
  - long-term stability at large time steps [Albert et al PPCF 2025]
  - applied to calculate confined fraction of α's in a SQuID
  - applied to study alpha particle heat loads on a reactor wall



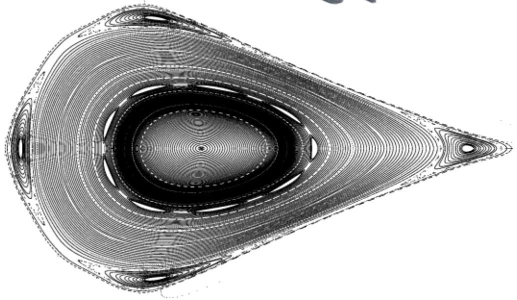


CIEMAT-QI family of reactor-relevant configurations

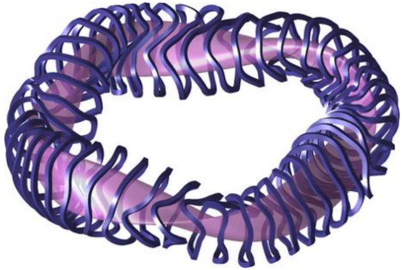
CIEMAT-QI4, first **QI configuration** with: [Sanchez et al NF 2023]



- ι profile avoides low order rationals, compatible with island divertor,
- Ideal MHD stability up to β = 5%,
- Low neoclassical transport and bootstrap current,
- Very good fast ion confinement for $1.5\% < \beta < 4\%$,
- Reduced turbulent transport,
- Set of filamentary coils preserving properties.



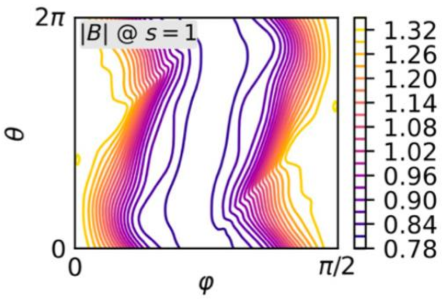
CIEMAT-QI4X: [Sanchez et al, submitted NF]

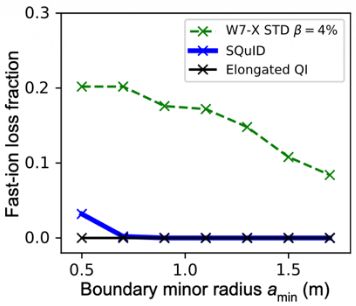


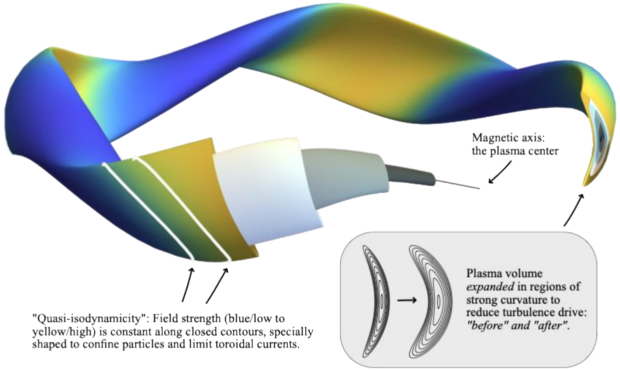
- Improved flux surface quality & robustness of divertor island,
- Simpler coils with larger separation,
- Ongoing study of breeding blanket feasibility.

SQuID family of QI designs with reduced ITG turbulence

➢ **SQuIDs**: *Stable Quasi-Isodynamic Designs* [Goodman et al PRX Energy 2024]





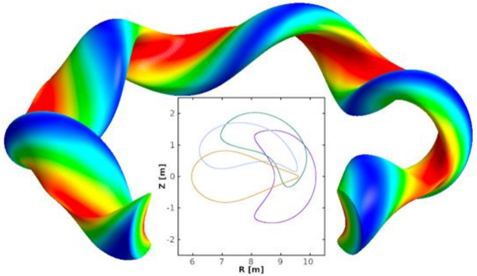


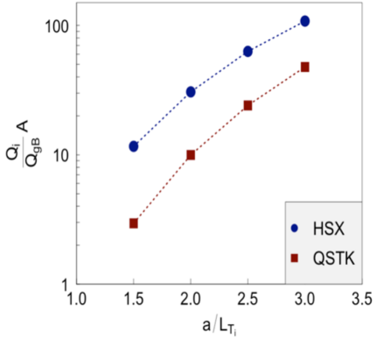
- Very close to perfect QI
- Ideal MHD stability up to β = 3%,
- Low bootstrap current (~ 15 kA)
- Very good fast ion confinement at target β
- Reduced turbulent transport
- Filamentary coils with complexity ~ W7-X

Turbulence optimization can improve core confinement

➢ **QSTK**: QH with **reduced ITG turbulence**

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

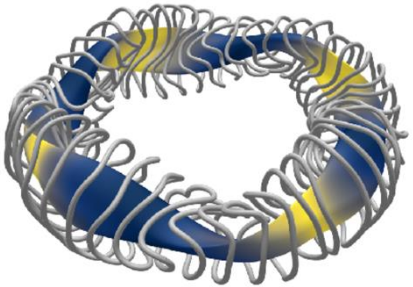


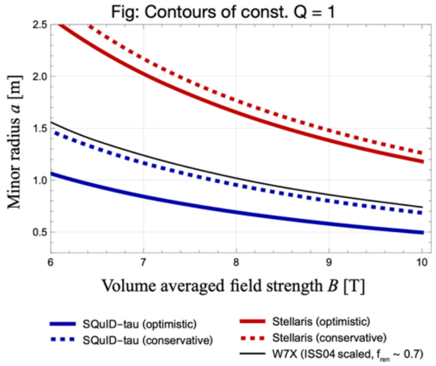


[Roberg-Clark et al PRR 2023]

➢ **SQUID-*τ***: stable QI with **enhanced turbulent particle pinch**

- Zero losses (collisionless) of fusion-born alphas.
- Mercier stability to $\langle\beta\rangle \sim 7\ \%$
- Coil compatibility
- KBM stability
- Negligible bootstrap current (~ 10 kA)





[Plunk et al, submitted 2025]

Can optimize for $E_r > 0$ in the core

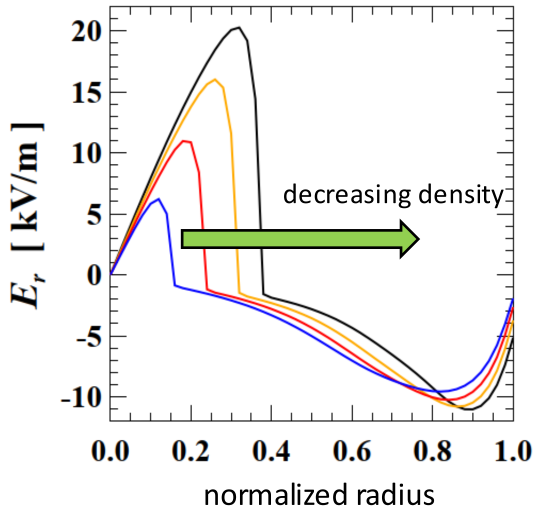
In most stellarators, radial electric field determined by requirement of ambipolar neoclassical transport:

Usually $E_r < 0$ in stellarators (ion root)

- Causes strong inward neoclassical transport for highly charged impurities.

$E_r > 0$ (electron root) observed in low-density plasmas with $T_e > T_i$, but has recently been found to be possible in the core if $T_e = T_i$.

- Beneficial for impurity expulsion
- Sharp transition may cause transport barrier.
- Can be achieved through targetted optimsation.



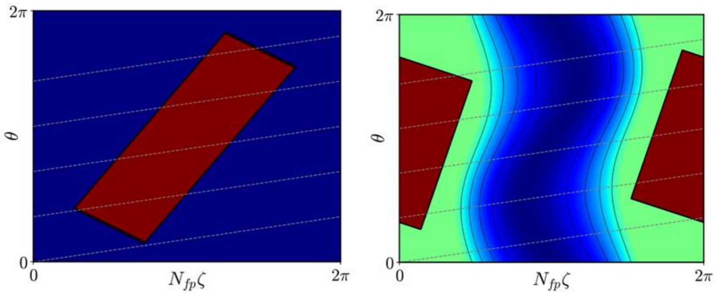
Onset of electron root approximately when

$$D_e^{1/\nu} > D_i^{\sqrt{\nu}} \quad \Rightarrow \quad \frac{T_e}{T_i} \geq \left(\frac{m_i}{m_e}\right)^{1/7} \left(\frac{\epsilon_i \nu_{*i}}{\epsilon_{\rm eff}\, \rho_{*i}}\right)^{3/7}$$

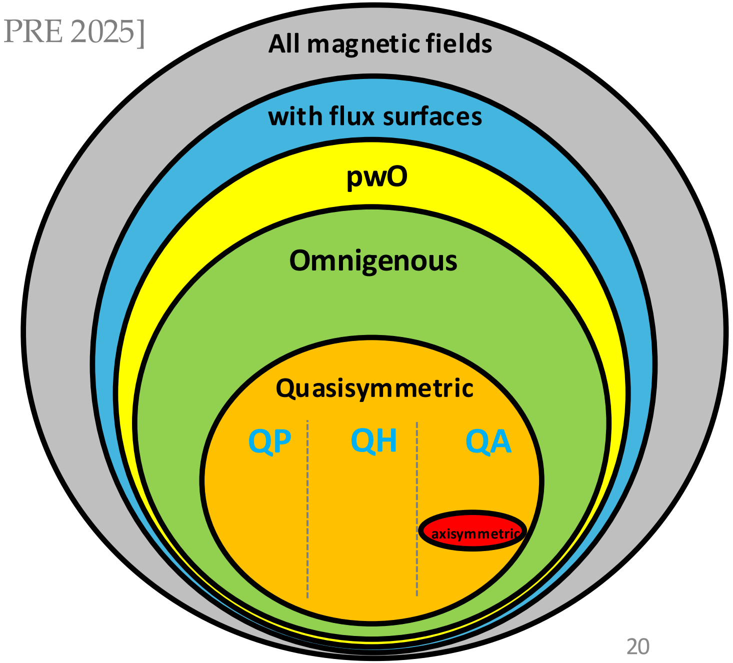
[Beidler et al., Nucl. Fusion 2024], [Helander et al., JPP 2024]

Discovery of pwO enlarges optimization space

- *Piecewise omnigeneous* **pwO** fields: a new class of fields with tokamak-like neoclassical transport
  - $B = B_{max}$ is parallelogram-shaped (different from omnigeneous)
  - can be optimized for zero bootstrap current [Calvo et al PRE 2025]
  - less constraining, potentially requires less shaping



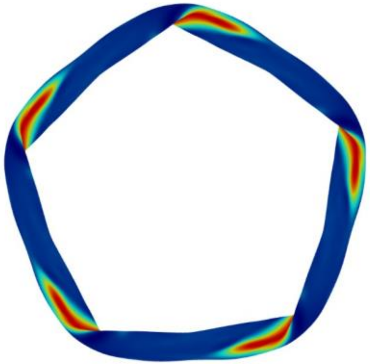
[Velasco et al PRL 2024]
[Velasco et al PPCF 2025]

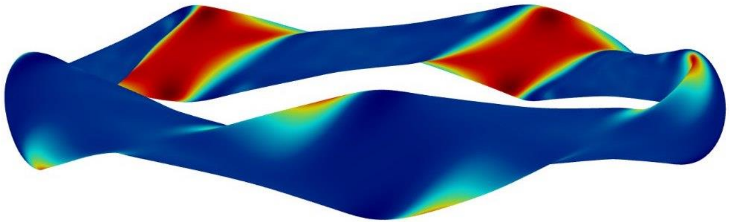


A nearly pwO configuration made reactor relevant

CIEMAT-pw1 fulfills a standard set of plasma physics criteria required for a stellarator reactor:

- Mercier MHD stability,
- $5/6 < \iota < 5/5 \Rightarrow$ no low order rationals, compatible with island divertor,
- Reduced neoclassical transport and bootstrap current ($\Delta \iota_{LCFS} < 1$ %),
- Good fast ion confinement at reactor β (> 95 % alpha-heating, most losses for $t > 0.01$ s),
- Reduced turbulence (maximum-J property)

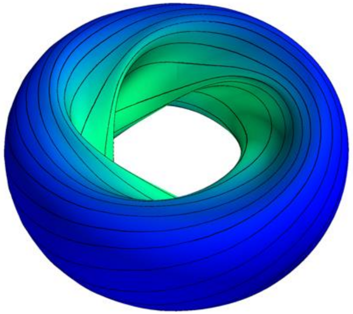


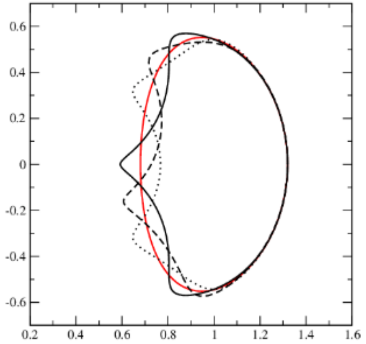


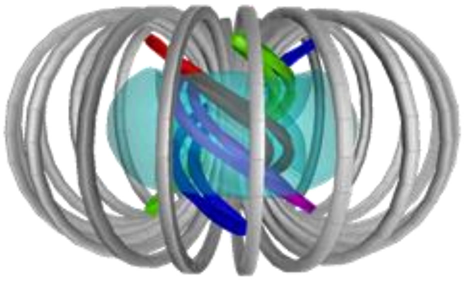
[Fernández-Pacheco, in preparation]

Revived concept of tokamak-stellarator hybrid

- Optimized compact tokamak to preserve **good QA**, flux surfaces, and **external rotational transform**.
- Optimization with self-consistent bootstrap current and magnetic well.
- 4 “**banana coils**“ coils of a **single type** (in addition to TF coils + PF coils).
- Also possible with modular coils.



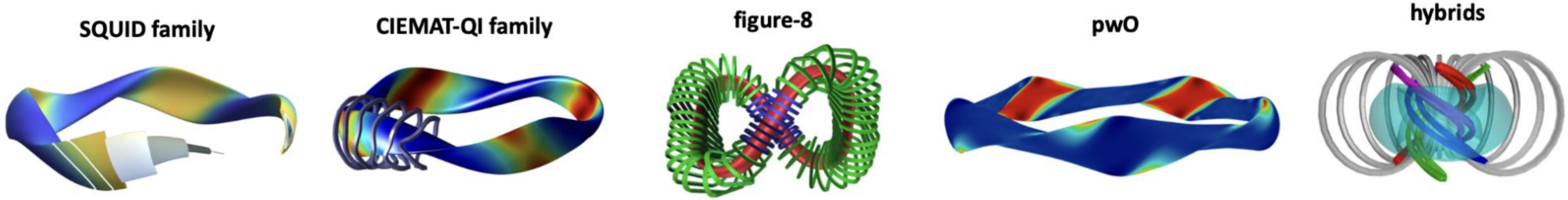




[Henneberg & Plunk PRR 2024]
[Schuett & Henneberg, PRR 2024]
[Henneberg & Plunk et al PPCF 2025]
[Schuett & Henneberg PPCF 2025]

Conclusion: a new ecosystem of tools & stellarator designs

- European collaboration TSVV-12 has pushed the frontier of stellarator optimization.
- Thanks to a excellent team with broad expertise, ~50 zoom meetings, strong links with other TSVVs and with the *Simons Collaboration* (5 in-person meetings in NY), and fantastic ACH support.
- The result is **66 journal publications** and a **new ecosystem** of modern **tools** and stellarator **designs**.



- **TSVV-i** will bring these (and other) designs to further maturity, incorporating latest tools & metrics.