Searching for SQuIDs: Stable Quasi-Isodynamic Designs for Stellarators

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ABSTRACT

Quasi-isodynamic (QI) stellarators are attractive fusion reactor candidates due to their low neoclassical transport and fusion-borne alpha particle losses, and vanishingly small toroidal currents [1]. Due to their geometric complexity, QI stellarators must generally be designed through numerical optimization, which requires an objective metric that quantifies the degree to which a given design is QI.

In this work, we present three novel optimization target functions that result in QI, maximum-$\mathcal{J}$ stellarators with significantly reduced ITG turbulence and enhanced MHD stability, without sacrificing neoclassical transport or fast ion confinement in the resulting configurations, which we call "SQuIDs". When the ITG target function is not included, we find configurations with particularly good QI quality, but extremely large flux surface elongations and large ITG-driven heat fluxes. We call these configurations "nautiluses": cephalopods to be sure, but not as evolved as their SQuID-cousins.

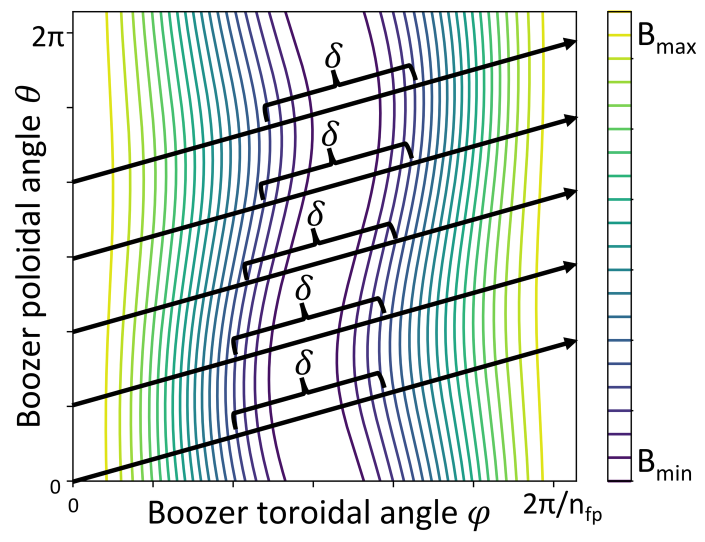
QI MAGNETIC FIELDS

Conditions for a flux-surface to be QI [2,4]:

(1) |B| contours close poloidally, not toroidally.

(2) $|B_{max}|$ contours are straight lines at $\varphi = 0$.

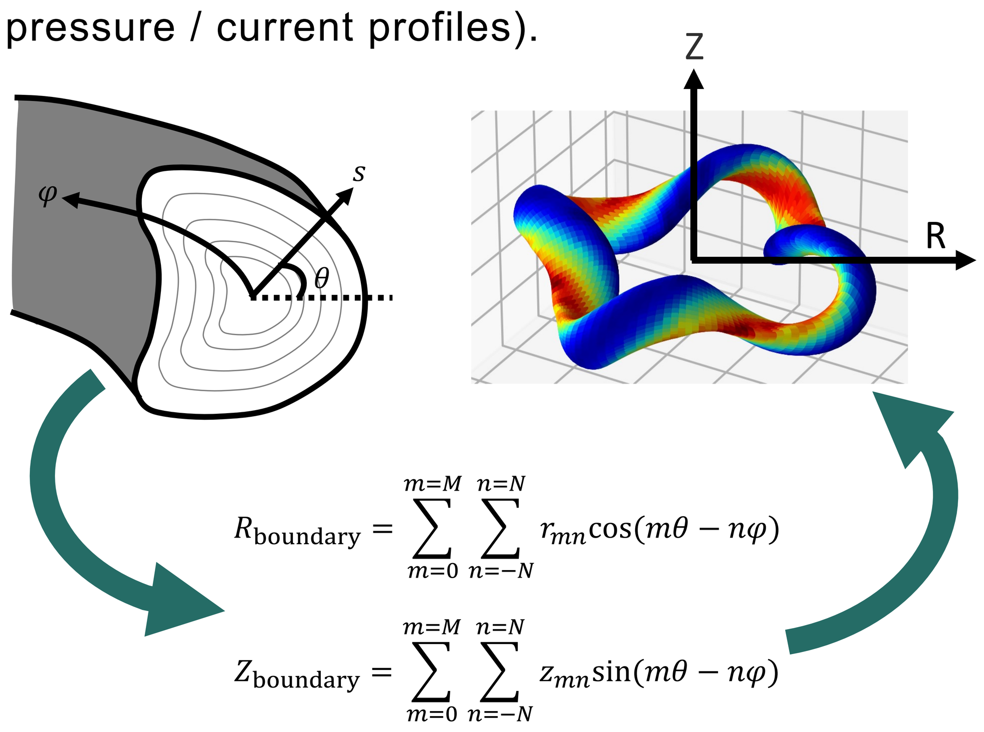
(3) Constant "bounce distance" $\delta(B_*, \alpha)$.



Properties of QI stellarators include:
(1) Perfect fast-particle confinement.
(2) Zero $1/\nu$ neoclassical transport.
(3) Zero toroidal bootstrap current [1].
(4) Low Shafranov shift and PS currents [2].

STELLARATOR OPTIMISATION

In ideal MHD, a magnetic field is determined by the **shape of the plasma's boundary** (and its pressure / current profiles).

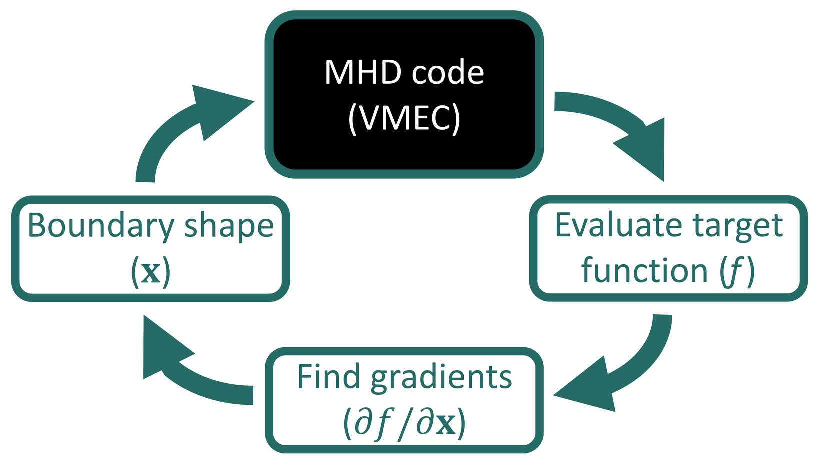


$$R_{\mathrm{boundary}} = \sum_{m=0}^{m=M} \sum_{n=-N}^{n=N} r_{mn} \cos(m\theta - n\varphi)$$

$$Z_{\mathrm{boundary}} = \sum_{m=0}^{m=M} \sum_{n=-N}^{n=N} z_{mn} \sin(m\theta - n\varphi)$$

Optimisation input space: $\mathbf{x} = (r_{mn}, z_{mn})$.
Physics determined by $\boldsymbol{B}(\mathbf{x})$.

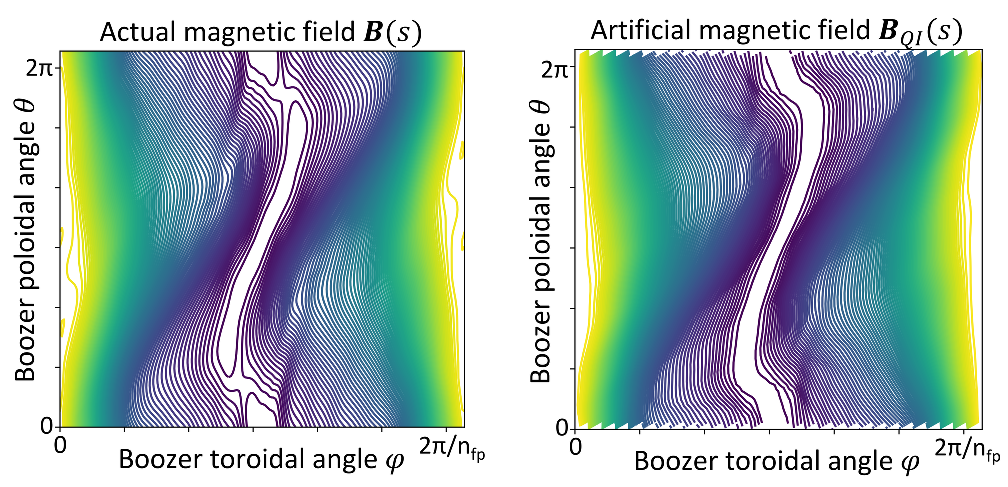
The "optimisation loop" is thus:



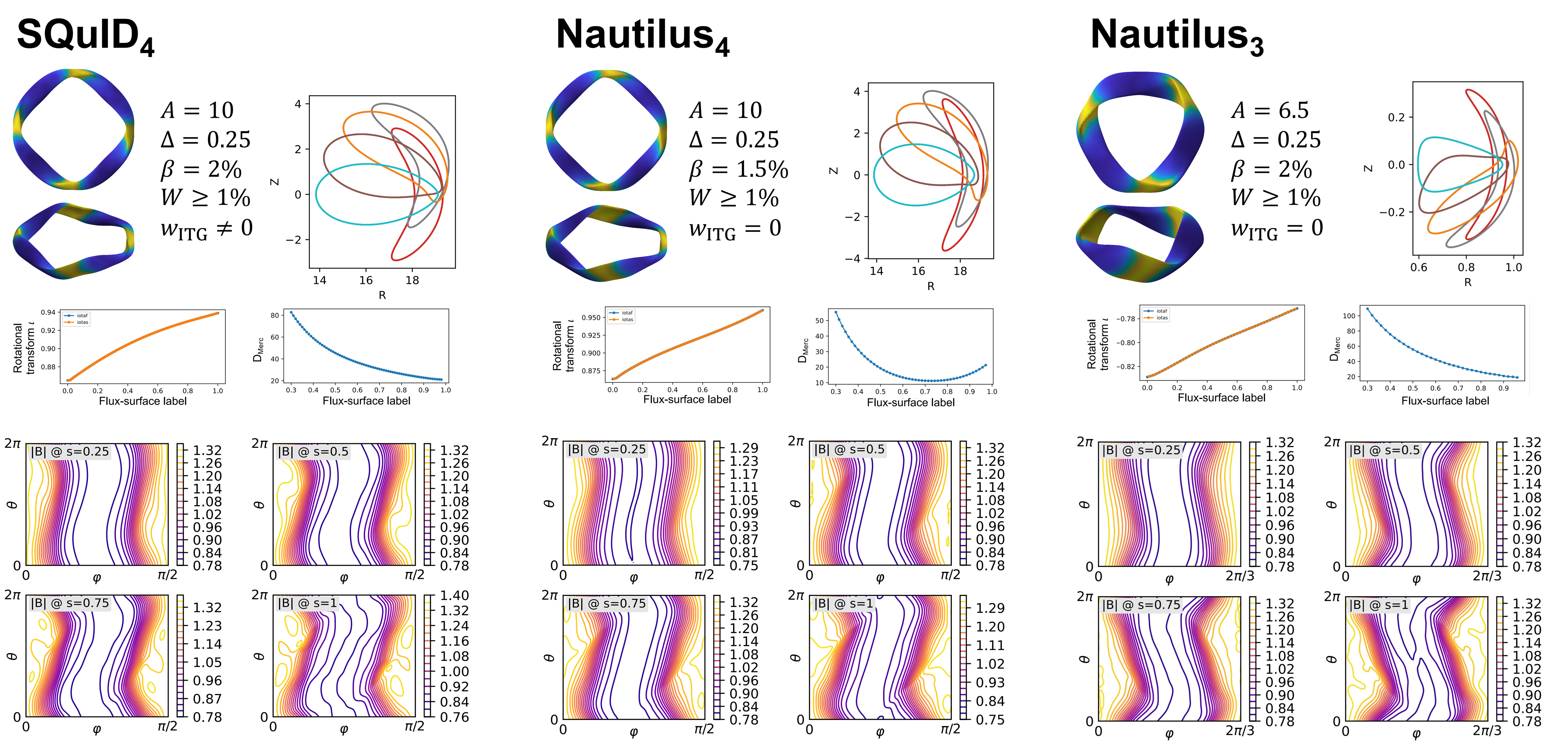
SQUID TARGET FUNCTION

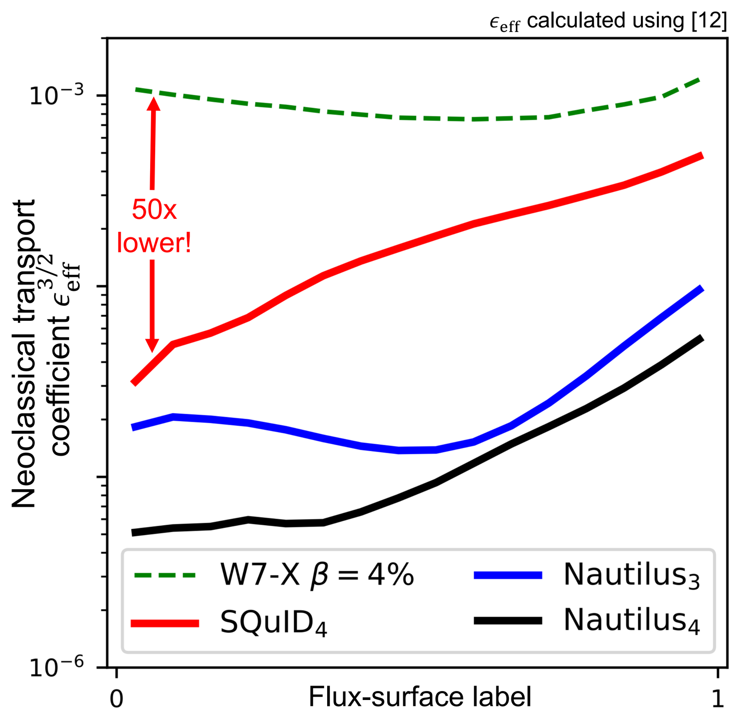
QI fields are targeted in a similar way to [2], which calculates the magnetic field $B(s)$ on a flux-surface and constructs a closely-related, perfectly QI field $B_{\mathrm{QI}}(s)$, and penalizing

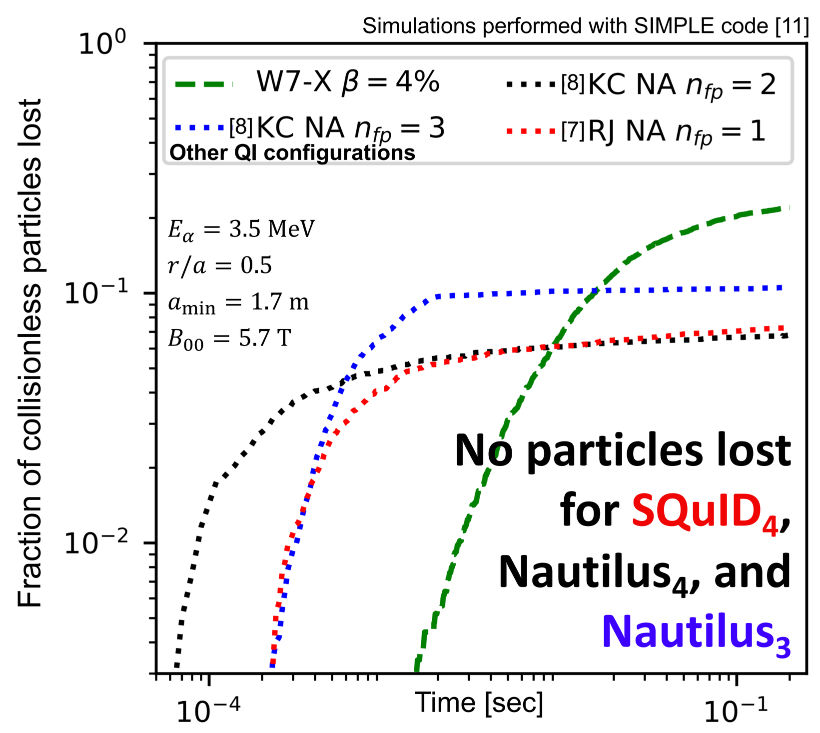
$$f_{QI} \propto \sum_{\theta\varphi} \left(B(\theta,\varphi) - B_{\mathrm{QI}}(\theta,\varphi)\right)^2$$

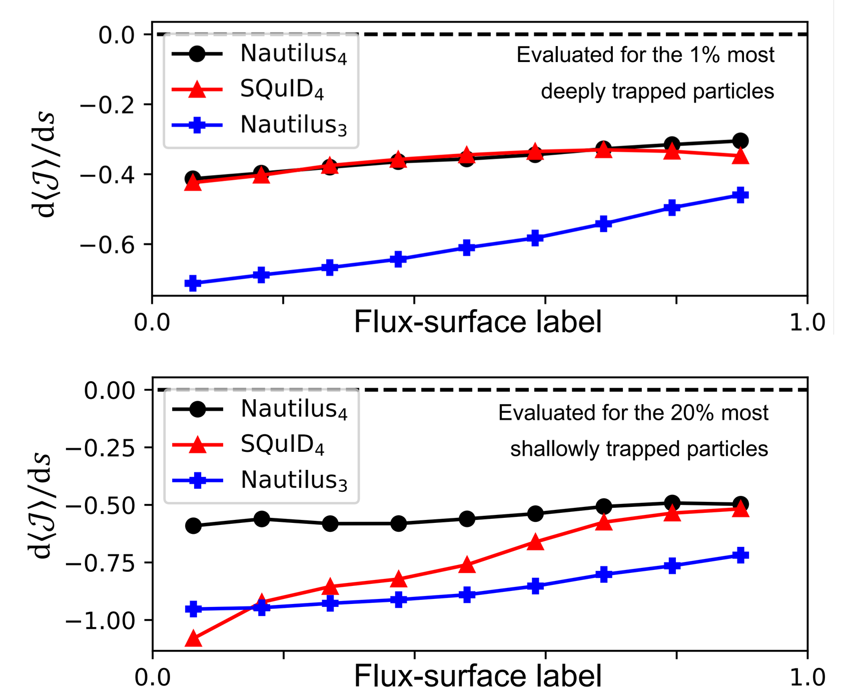


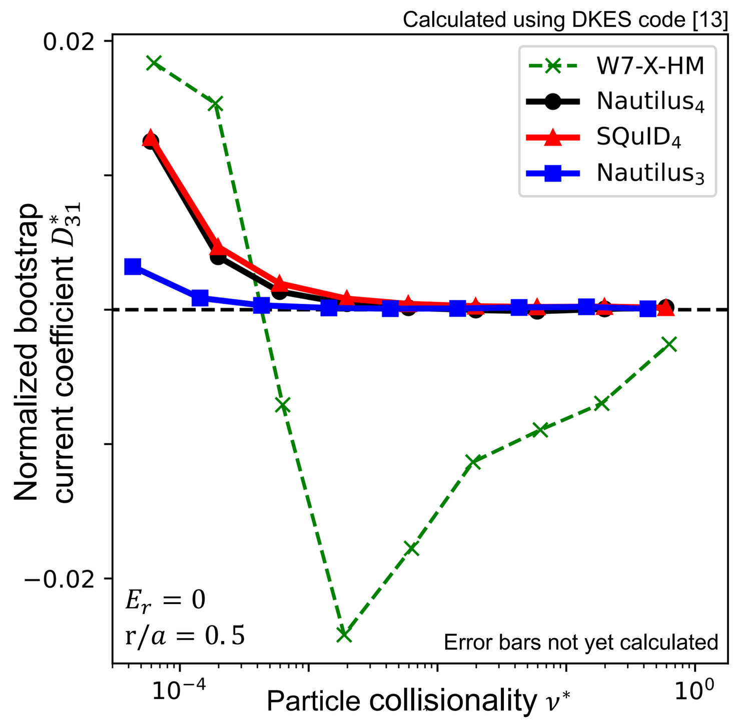
RESULTS

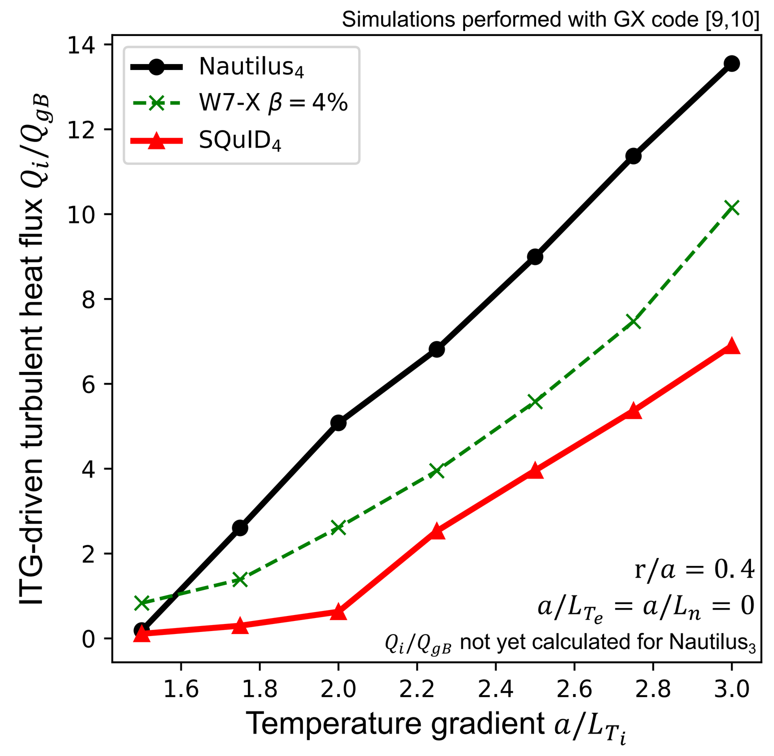












- ITG simulations performed with adiabatic electrons
  - Simulations with EM effects underway
- SQuID_4 heat flux less than W7-X std. at all gradients
  - ~8x less at threshold
  - ~2x less in strongly-driven regime
- The strong performance of SQuID_4 shows the effectiveness and importance of f_{ITG}
- Two important properties of SQuID_4:
  - Larger critical gradient than W7-X
  - Lower "stiffness" than $\mathrm{Nautilus}_4$

In addition to being QI, a viable stellarator reactor must satisfy other criteria:

- **MHD stability**: targeted using "magnetic well" ($W \propto \mathrm{d}^2V/\mathrm{d}s^2 < 0$) and rotational transform shear ($\mathrm{d}\iota/\mathrm{d}s$) proxy [5], the latter of which also allows for an island divertor.
- **Aspect ratio** ($A \leq A_*$): directly targeted.
- **Mirror ratio** ($\Delta \leq \Delta_*$): directly targeted.
- **Avg. pressure** ($\beta \leq \beta_*$): directly targeted.
- **Maximum−$\mathcal{J}$**: targeted $\mathrm{d}\mathcal{J}/\mathrm{d}s < 0$ [14,15], which reduces fast-ion losses [2,3] and numerous turbulence drives [3,14,15], and causes $\mathrm{d}^2V/\mathrm{d}s^2 < 0$.
- **Reduced ITG turbulence**: targeted by controlling local flux-surface compression.

$$f = \underbrace{f_{\mathrm{QI}} + w_{\mathrm{ITG}} f_{\mathrm{ITG}}}_{\text{Minimized}} + \underbrace{f_\Delta + f_A + f_\iota + f_\beta + f_{\max\mathcal{J}}}_{\text{Kept below "threshold"}}$$

CONCLUSIONS

Using a set of newly-designed target functions, we are able to find precisely QI configurations (to which we give the moniker "Nautilus") that are Mercier stable and maximum-$\mathcal{J}$, even at low plasma β.

Further, using a new target function based on flux-expansion effects [6], we significantly reduced ITG-driven turbulence over a wide range of gradients in configurations we call SQuIDs. we conserve low neoclassical transport, bootstrap current, and fast-ion losses, even when ITG heat flux is reduced significantly. We expect this turbulence to reduce further when maximum-$\mathcal{J}$ effects are included in these simulations [3,14,15].

Future SQuIDs will be given more in-depth analysis, and optimized with coils, with the goal of being candidate designs for successors to Wendelstein 7-X.

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