Proxima Fusion

ConStellaration: A dataset of QI-like stellarator plasma boundaries and optimization benchmarks

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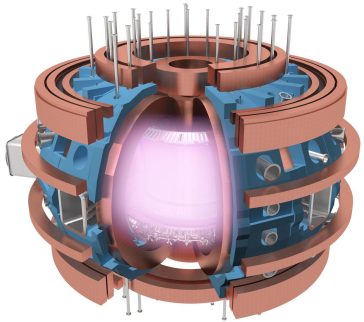
39th Conference on Neural Information Processing Systems | Datasets & Benchmarks Track (NeurIPS 2025).

Design, not *control*, holds the key to fusion

Stellarators are now an **engineering** challenge, not a **scientific** one

Tokamaks

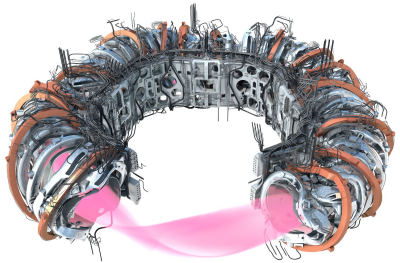
Tokamaks create helical magnetic fields via external coils and a large plasma current, which leads to instabilities.



Simple to design, but **hard** to operate.

Stellarators

Stellarators create a helical magnetic field via only external coils, with potential for intrinsic stability.



Harder to design, but **simple** to operate.

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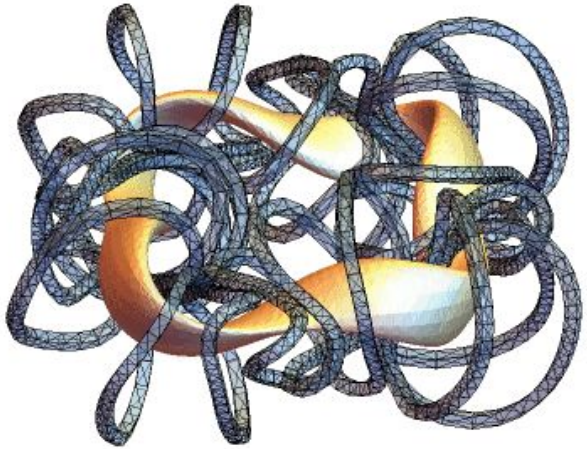
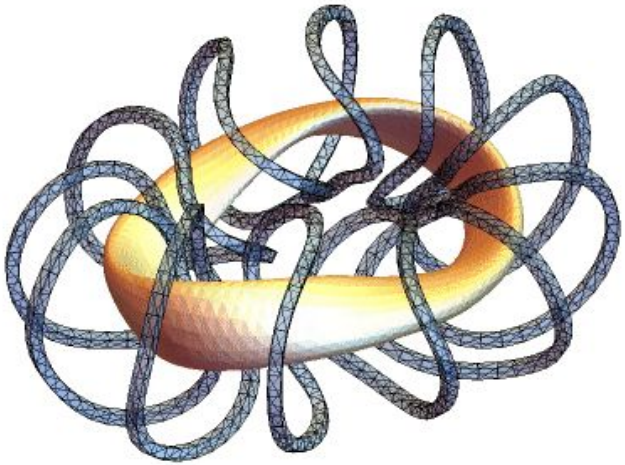
Stellarator optimization

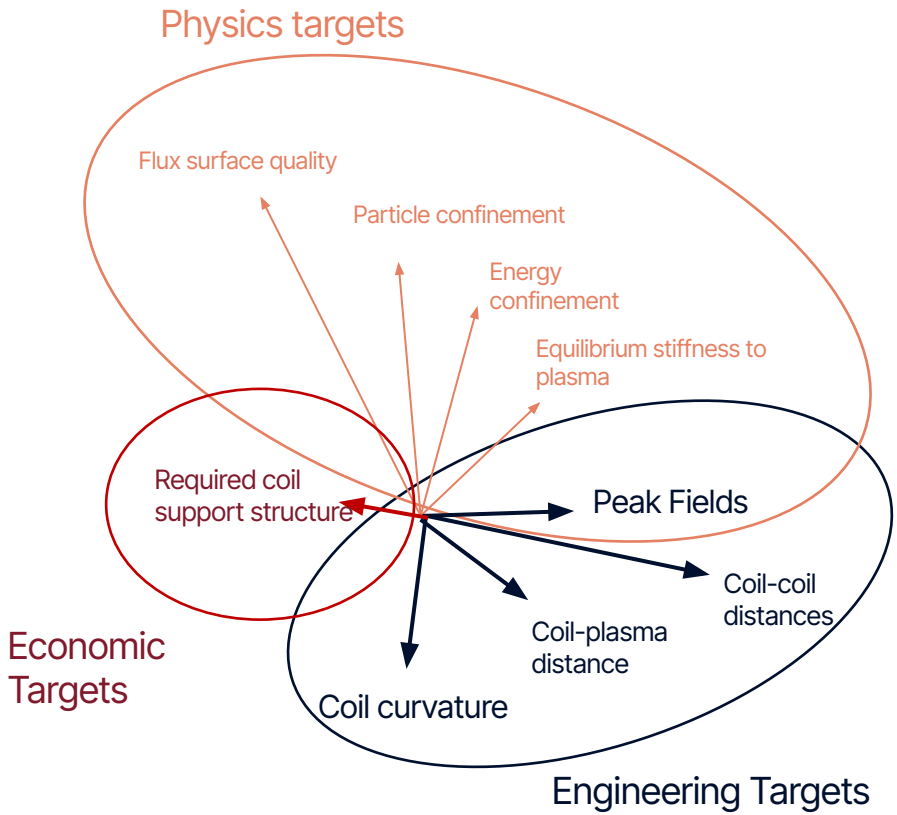
What are we looking for?

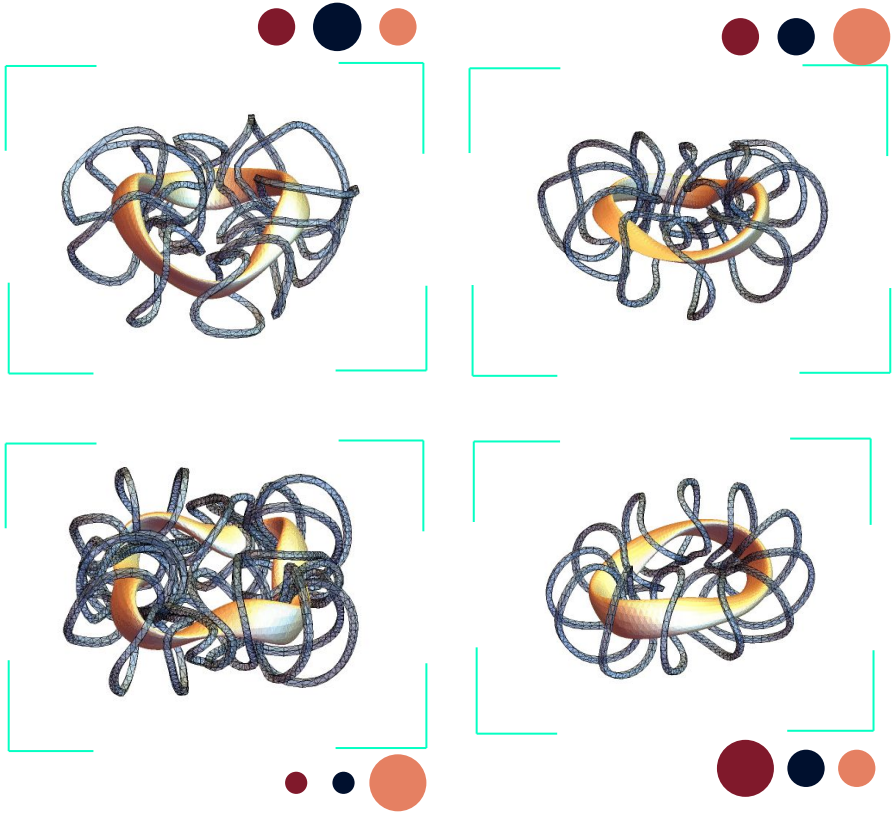
Stellarator optimization: identifying core plasma and magnet geometries that meet target criteria



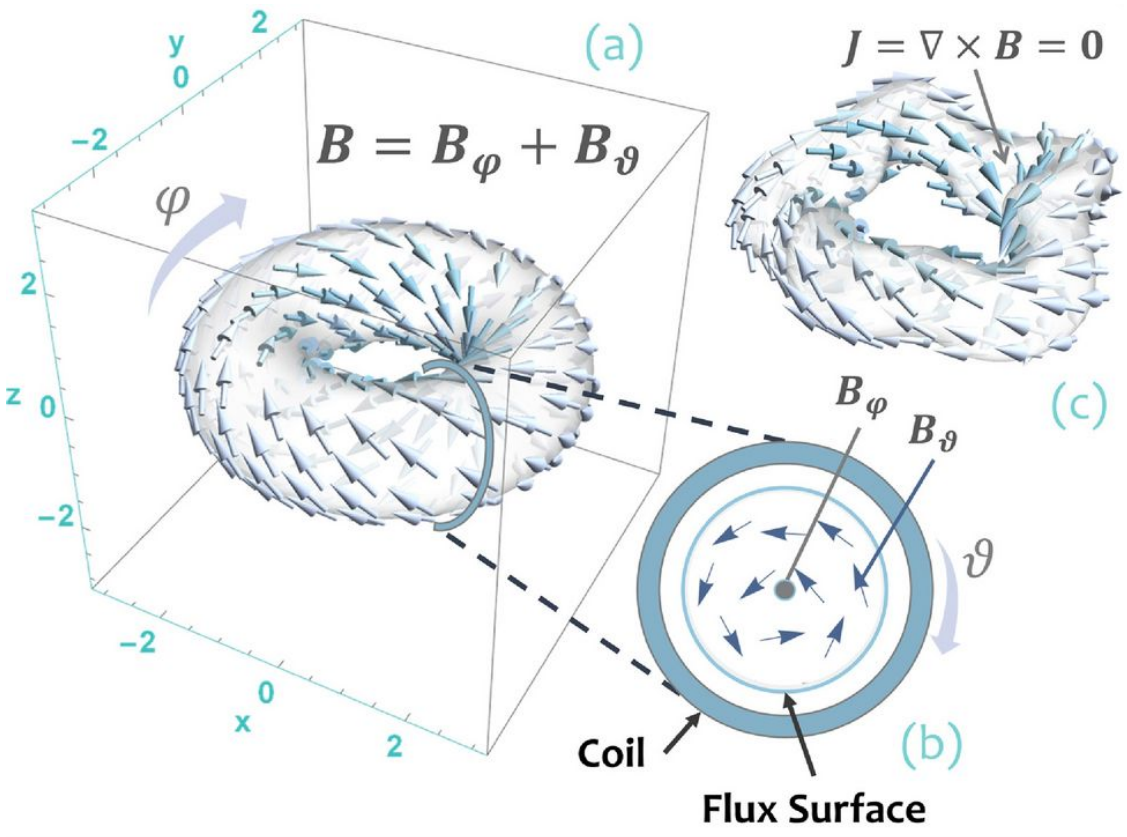


Trade-offs exist between objectives





What do plasma shapes (flux surfaces) represent?

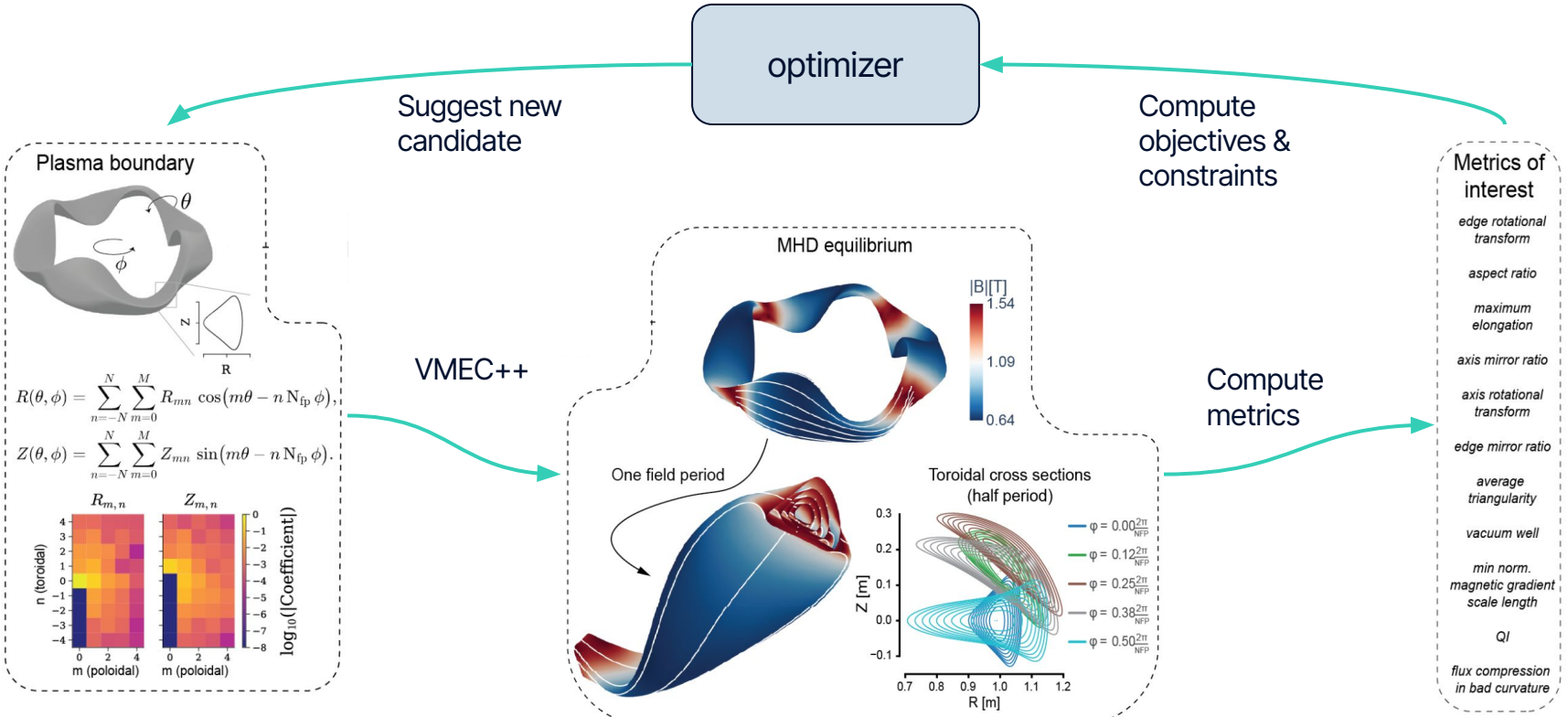


Imagine the magnetic field as water flowing through space. **Flux surfaces are like invisible pipes guiding the flow.** The magnetic field never pierces through these surfaces—it always glides along them (i.e., it lies tangential to them).

The surfaces shape can be derived via the knowledge of the magnetic field.

Sato, Naoki. "Existence of weakly quasisymmetric magnetic fields without rotational transform in asymmetric toroidal domains." Scientific Reports 12.1 (2022): 11322.

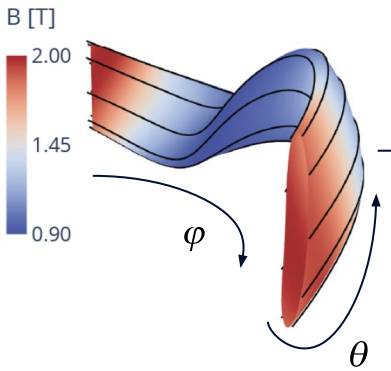
Plasma boundary optimization using VMEC++ in the loop.



Stellarators can be designed to possess symmetries that live in a space of transformed coordinates

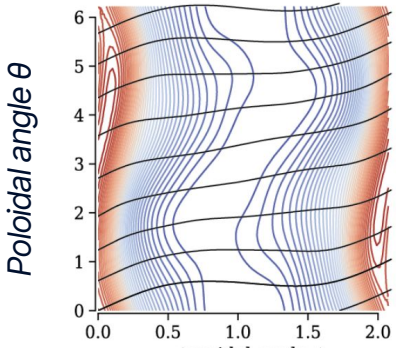
Introducing ***Boozer coordinates***
(aka the coordinate system that particles "see")

Half a period



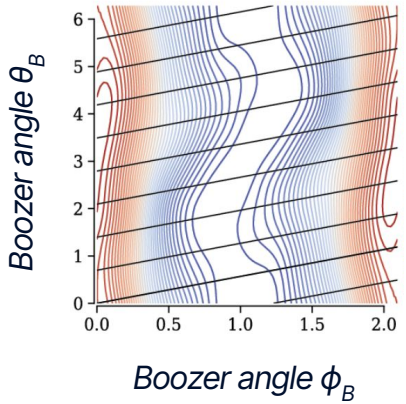
Unfold

Lab coordinates



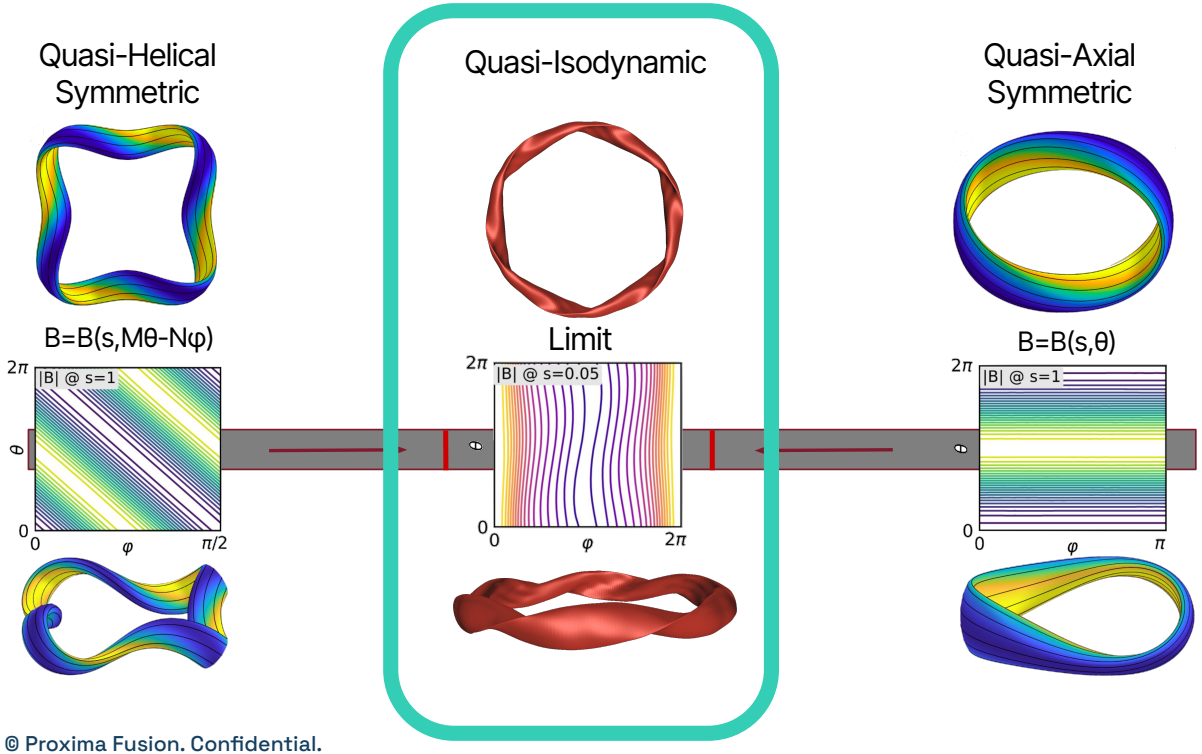
Boozer transform

Boozer coordinates



Cadena et al 2025 Constellaration

"Quasi-symmetry" (or the more general *Omnigenity*) improves confinement of trapped particles.



Quasi-symmetry: when |B| depends on linear combination of ϕ_B and θ_B

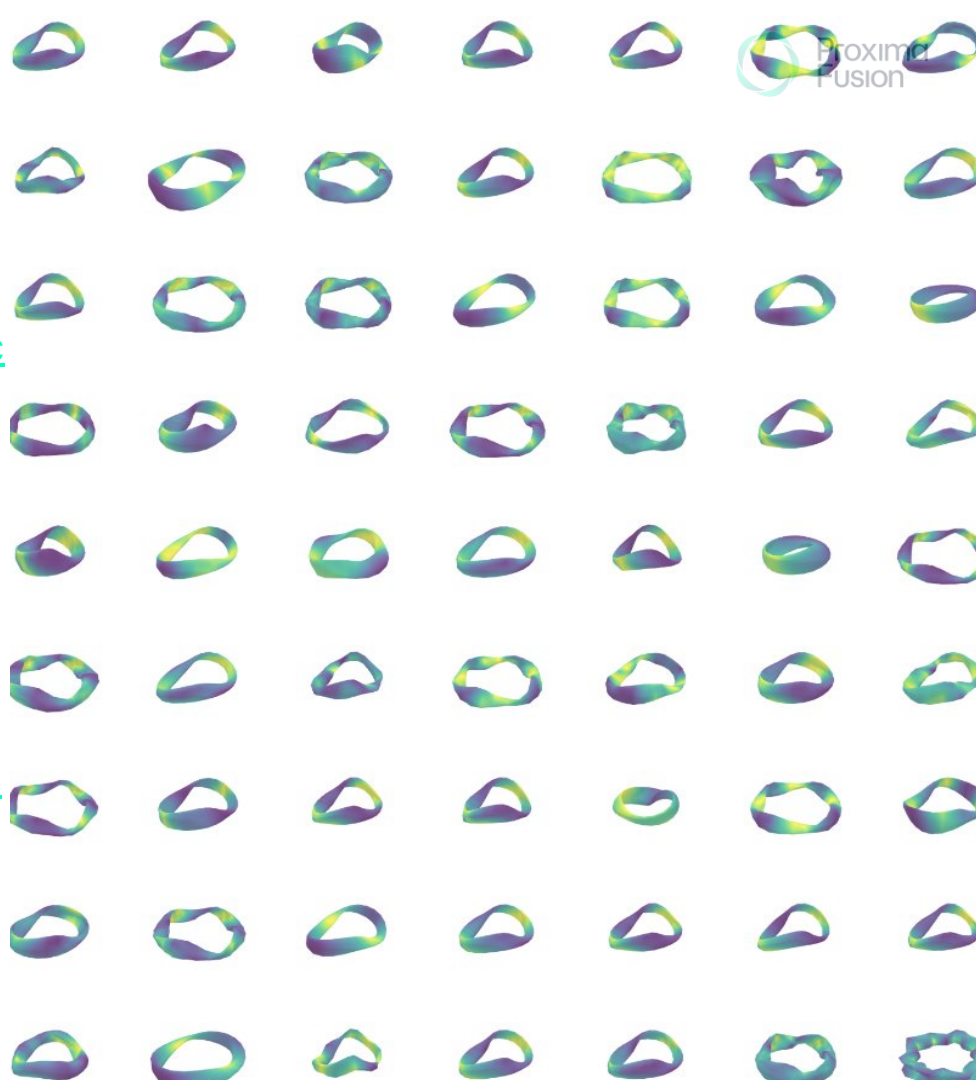
Omnigenity (a relaxation of Quasi-symmetry) improves confinement of trapped (bouncing) particles.

QI is a one type of Omnigenous stellarator kinds

The ConStellaration challenge

What is ConStellaration?

- A ~160k dataset of QI-like stellarator plasma boundaries + equilibria + metrics: https://huggingface.co/datasets/proxima-fusion/constellaration
- Three optimization benchmarks with tools and baselines: https://github.com/proximafusion/constellaration
- A public leaderboard of the challenge with 🤗: https://huggingface.co/spaces/proxima-fusion/constellaration-bench
- Paper: https://arxiv.org/abs/2506.19583 , accepted at NeurIPS

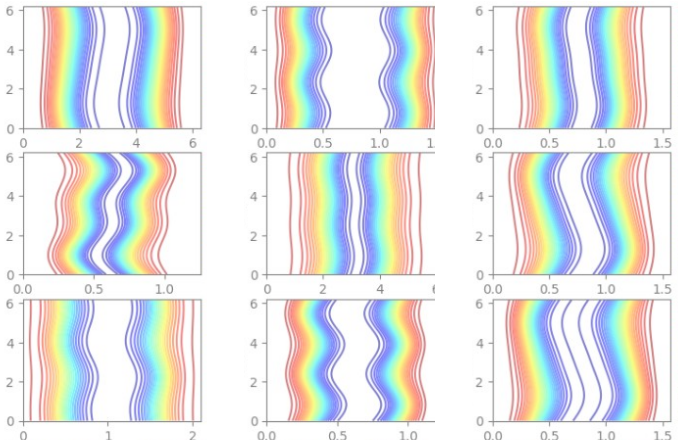


How do we sample diverse boundaries that are physics relevant (QI)?

Proxima Fusion

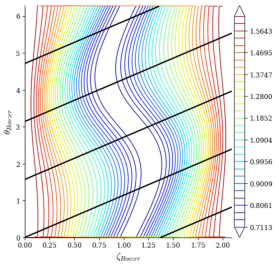
1. We sample *ideal* target QI fields

- Using a direct parameterization of these
- We also sample number of field periods, aspect ratio, rotational transform



A sample

Target



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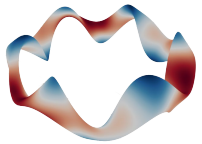
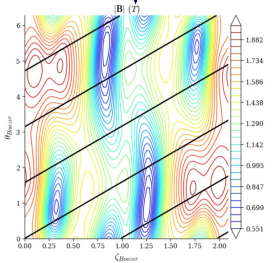
Initial guess



Boozer transform



To minimize

2. We run an optimization to match the target boozer field

How do we sample diverse boundaries that are physics relevant (QI)?

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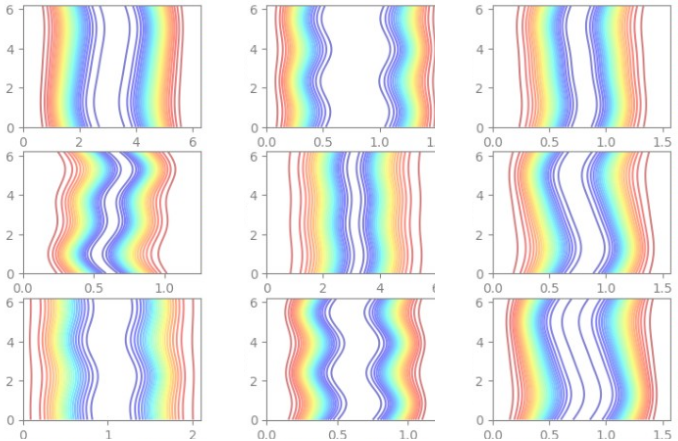
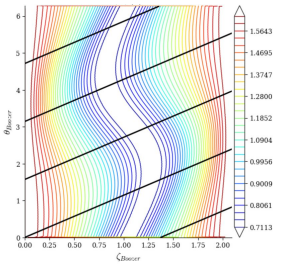


A sample

Target



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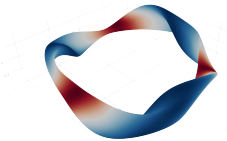
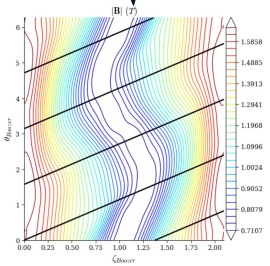
2. We run an optimization to match the target boozer field

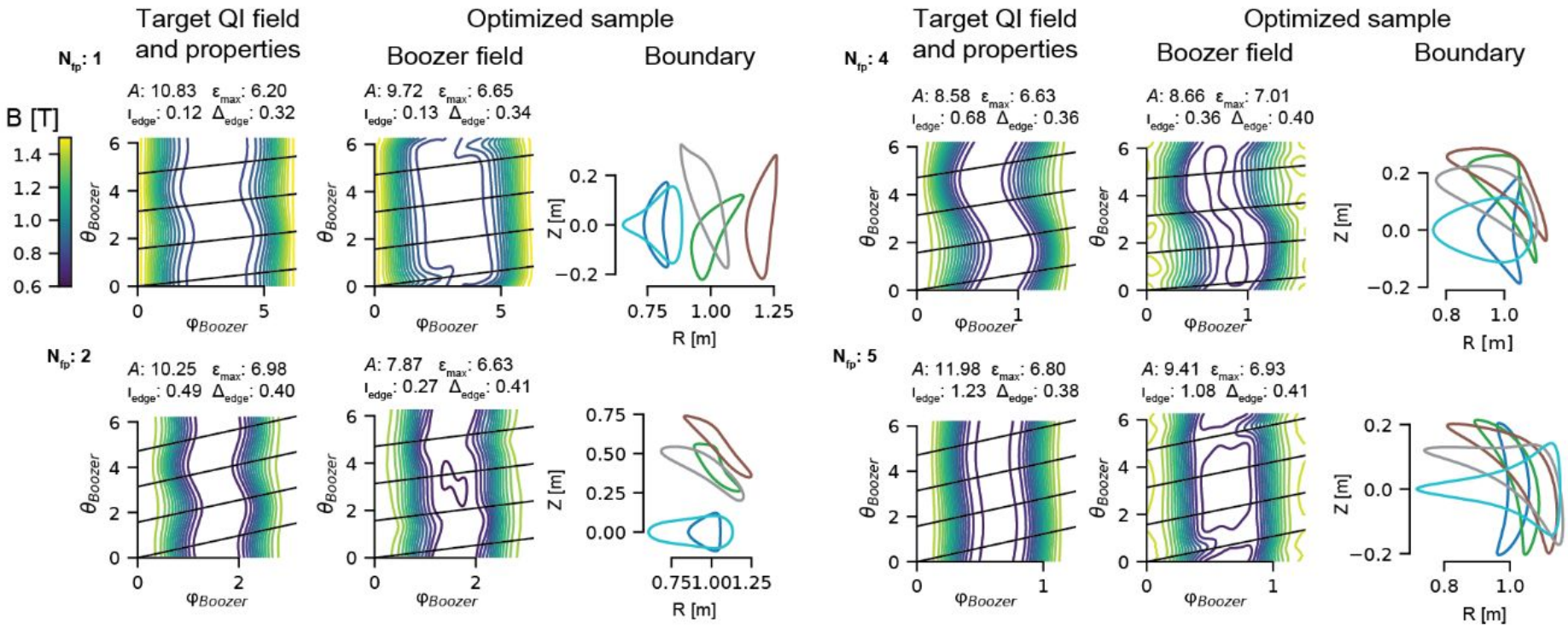
Optimized boundary



Boozer transform



We obtained diverse QI-like samples



Optimization benchmarks

Optimization benchmarks

Geometric Problem

$$\min_{\Theta} \epsilon_{\max}$$
$$\text{s.t.} \quad A \leq A^*, \quad \bar{\delta} \leq \bar{\delta}^*, \quad \tilde{\iota} \geq \tilde{\iota}^*.$$

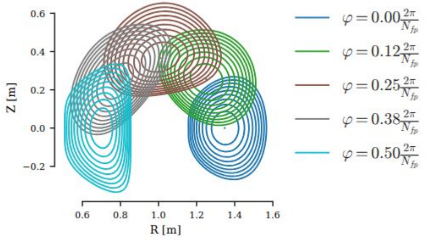
Simple-to-build QI

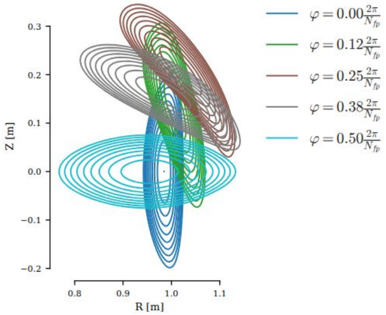
$$\min_{\Theta} -\widetilde{L}_{\nabla B}$$
$$\text{s.t.} \quad \tilde{\iota} \geq \tilde{\iota}^*, \quad QI \leq QI^*$$
$$\Delta \leq \Delta^*, \quad A \leq A^*$$
$$\epsilon_{\max} \leq \epsilon_{\max}^*$$

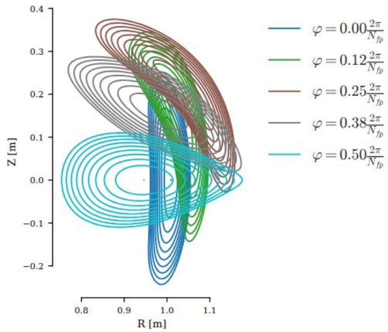
MHD-stable QI (multi-objective)

$$\min_{\Theta} \left(-\widetilde{L}_{\nabla B}, \ A\right)$$
$$\text{s.t.} \quad \tilde{\iota} \geq \tilde{\iota}^*, \quad QI \leq QI^*$$
$$\Delta \leq \Delta^*, \quad W_{\mathrm{MHD}} \geq 0$$
$$\langle \chi_{\nabla r} \rangle \leq \langle \chi_{\nabla r} \rangle^*$$

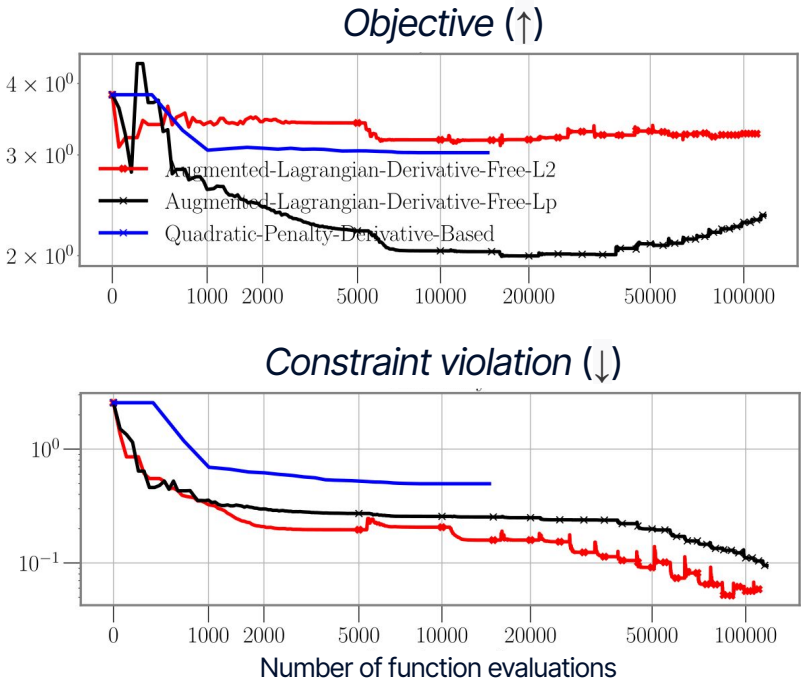
Baselines

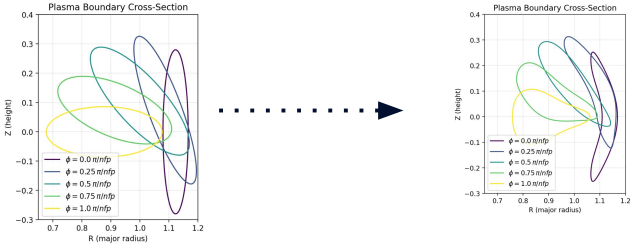


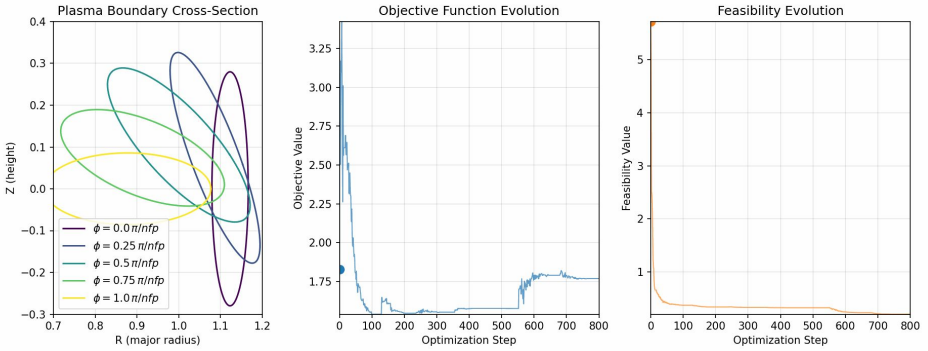




We generated baselines with the Augmented Lagrangian Method using gradient-free evolutionary strategies







https://github.com/proximafusion/constellaration/tree/main/optimization_examples

Our baselines have already been beaten 🎉!

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Simple-to-build QI design

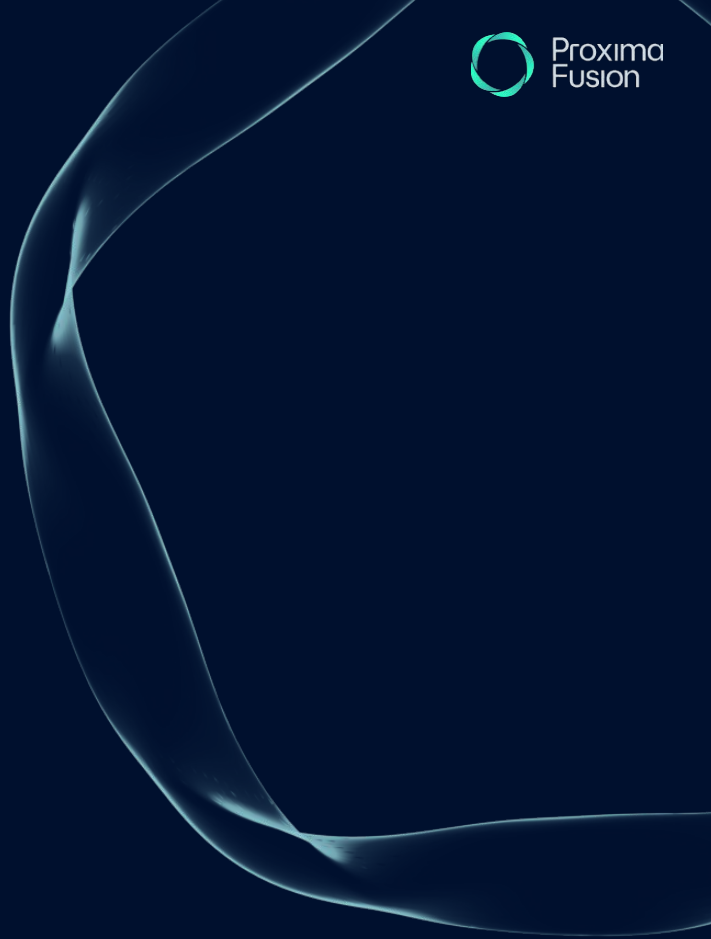
submission time	problem type	user	score	full results
2025-09-02T10:31:19.976883	simple_to_build	DMCXE	0.49853602632198885	link
2025-08-14T09:57:47.488429	simple_to_build	NianRan1	0.4367098218770565	link
2025-08-14T09:59:30.532373	simple_to_build	NianRan1	0.4367098218770565	link
2025-07-01T19:59:48.038381	simple_to_build	scadena-pf	0.4307230550411947	link

Multi-objective MHD stable designs

submission time	problem type	user	score	full results
2025-08-12T09:00:48.480632	mhd_stable	NianRan1	103.02479639835846	link
2025-07-02T07:38:21.817193	mhd_stable	scadena-pf	129.796069251409	link
2025-08-12T07:53:37.758128	mhd_stable	NianRan1	133.50051029413004	link

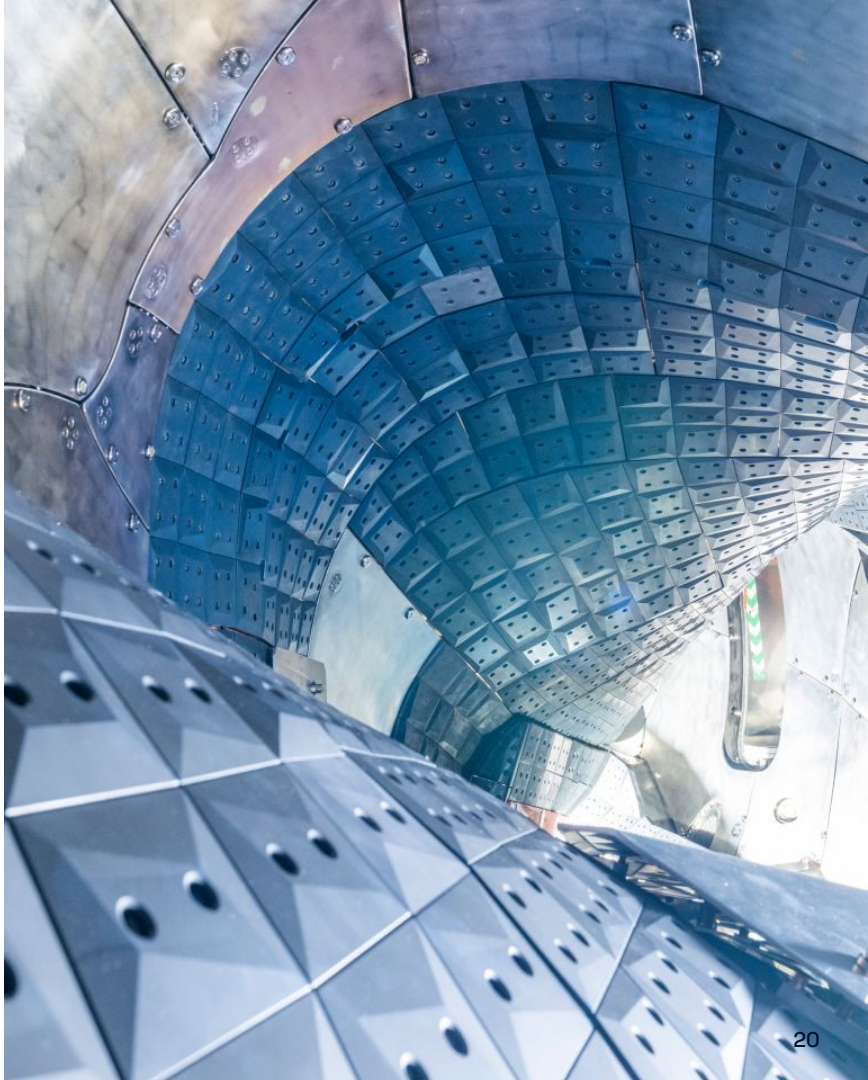
https://huggingface.co/spaces/proxima-fusion/constellaration-bench

Conclusions



Conclusions

- Effective stellarator optimization involves scientific and engineering targets and trade-offs.
- We believe that a larger community can contribute to the problem of stellarator optimization.
- We open sourced tools, data, and benchmarks to enable people to contribute better approaches.
- We have an open leaderboard to track progress



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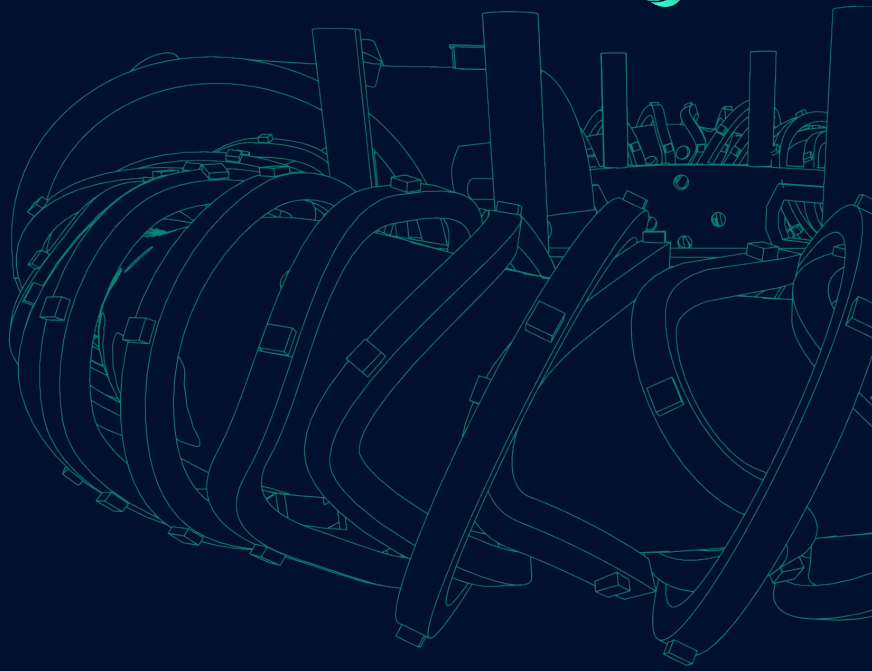

Thank you!

Clean energy, for good