IAEA-FEC 2025

A novel method to optimize omnigenity like quasisymmetry for stellarators

Caoxiang Zhu

Piecewise omnigenous fields: a radically new family of optimized magnetic fields for stellarator reactors

José Luis Velasco

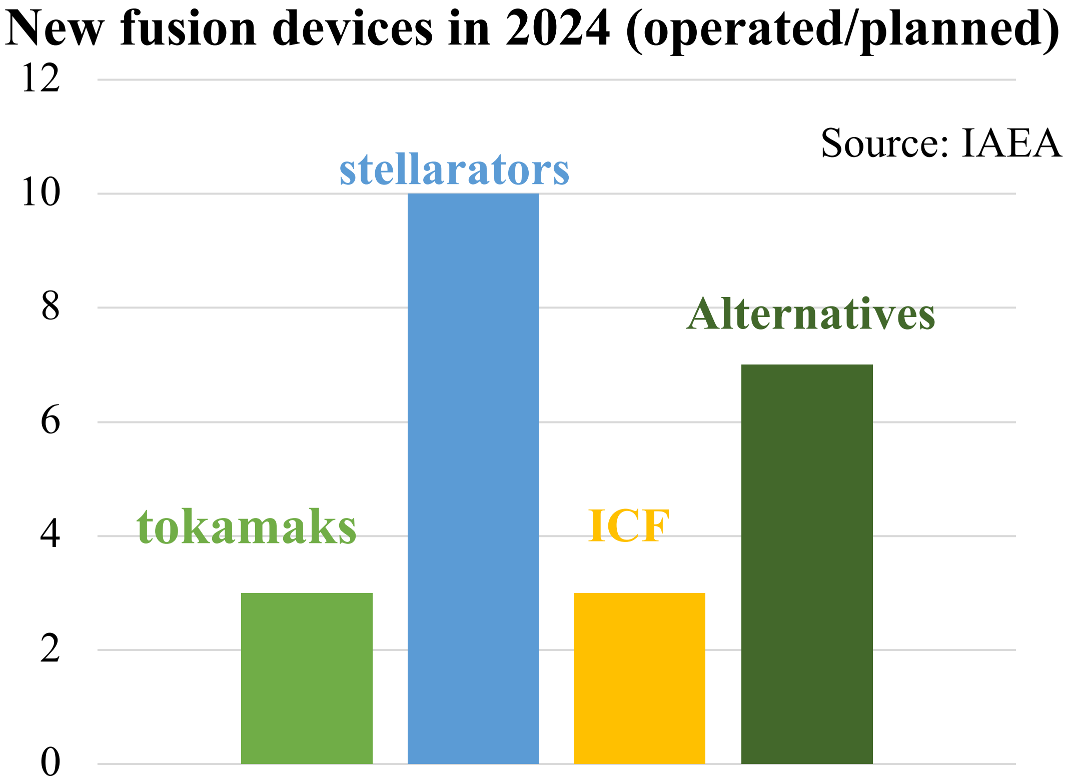
Introduction

Stellarators have become the rapidest growing fusion concept

❖ A stellarator is a toroidal plasma confinement configuration that uses external coils to produce a non-axisymmetric magnetic field.

❖ Stellarators have many advantages.

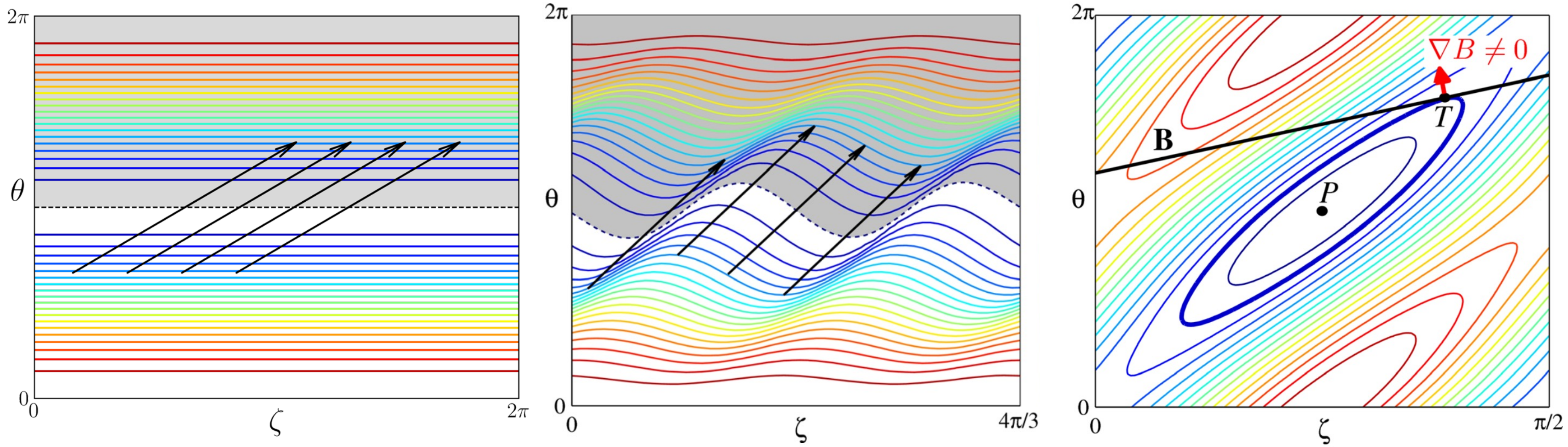
- ❑ **Steady state operation**
- ❑ **Low recirculating power**
- ❑ **Stable to plasma currents inducing MHD instabilities**
- ❑ **Free of disruptions**
- ❑ **High density operation**



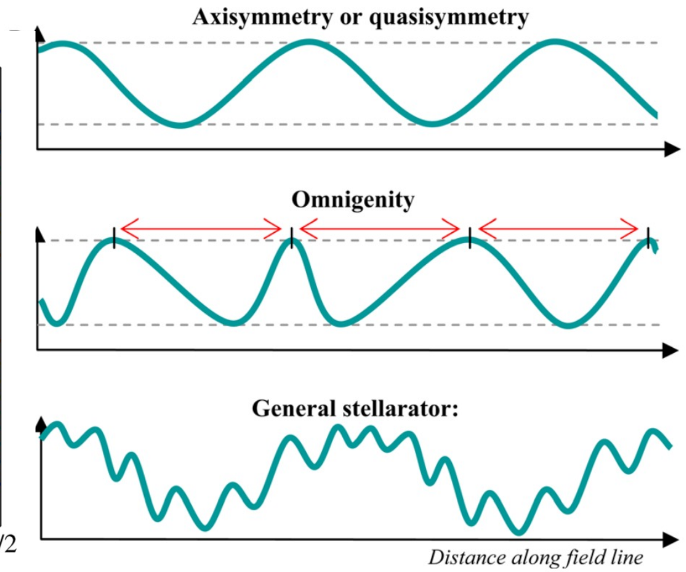
❖ Conventional stellarators suffered bad neoclassical transport and it can be overcome by carefully **optimized** magnetic field [Beidler Nature 2021].

Omnigenity is a primary way to improve confinement

Axisymmetry or quasisymmetry **Omnigenity** **General stellarator**



Magnetic field strength B on the flux surface



B along the field-line
[Landreman & Catto PoP 2012]

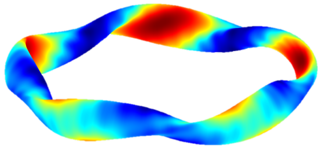
Omnigenity: time-averaged radial drift along each field line vanishes.

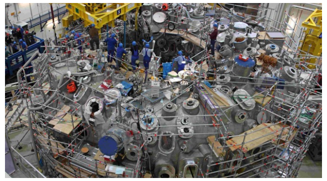
$$\langle \vec{v}_d \cdot \nabla\psi \rangle = 0 \Longleftrightarrow \frac{\partial \mathcal{J}}{\partial \alpha} = 0 \qquad \mathcal{J} = m\int v_{\parallel} dl = \sqrt{2m(u - q\phi)} \oint \sqrt{1 - \frac{B}{B^*}}\, dl$$

- ➢ **No closed B contours**
- ➢ **Equal bounce distance**

Quasisymmetry is a subset of omnigenity

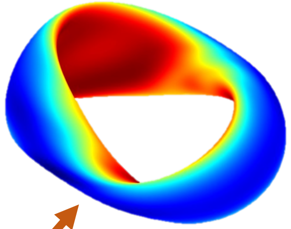
Quasi-Isodynamicity/PO

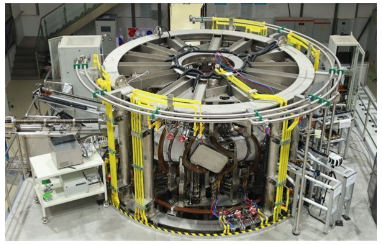




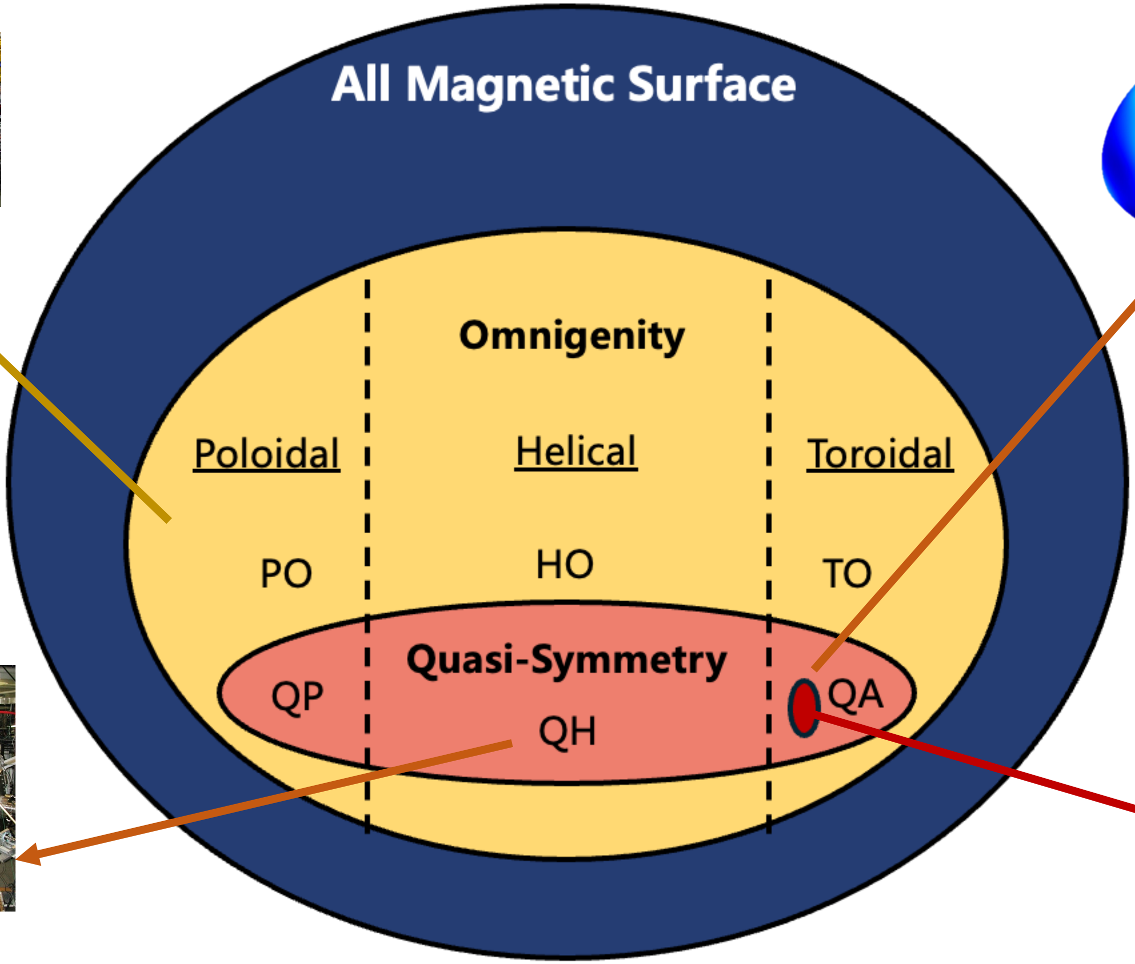
W7-X

Quasi-Axisymmetry

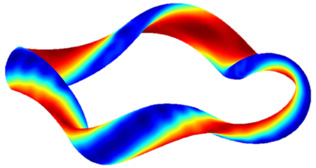


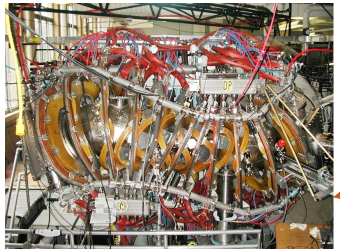


CFQS



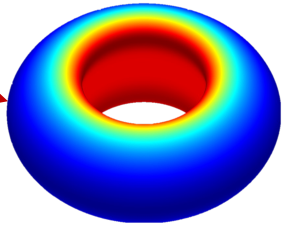
Quasi-Helical symmetry

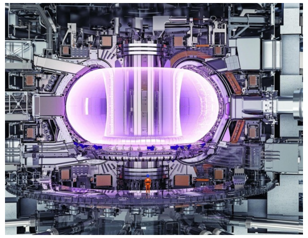




HSX

Axisymmetry





ITER

中国科学技术大学
University of Science and Technology of China

arXiv:2502.09350

A novel method to optimize omnigenity like quasisymmetry for stellarators

Caoxiang Zhu, Hengqian Liu, Guodong Yu, Ge Zhuang

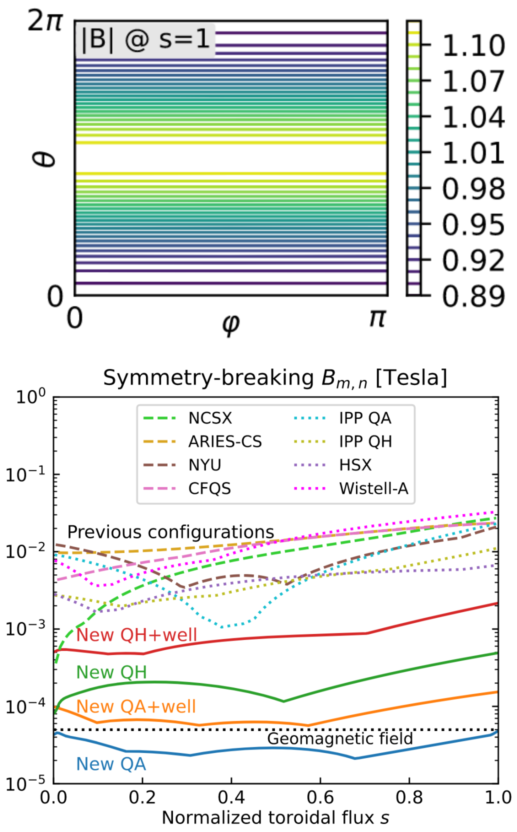
University of Science and Technology of China (USTC)

Email: caoxiangzhu@ustc.edu.cn

* *This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences under Grant No. XDB0790302 and the Anhui Provincial Key Research and Development Project under Grant No. 2023a05020008.*

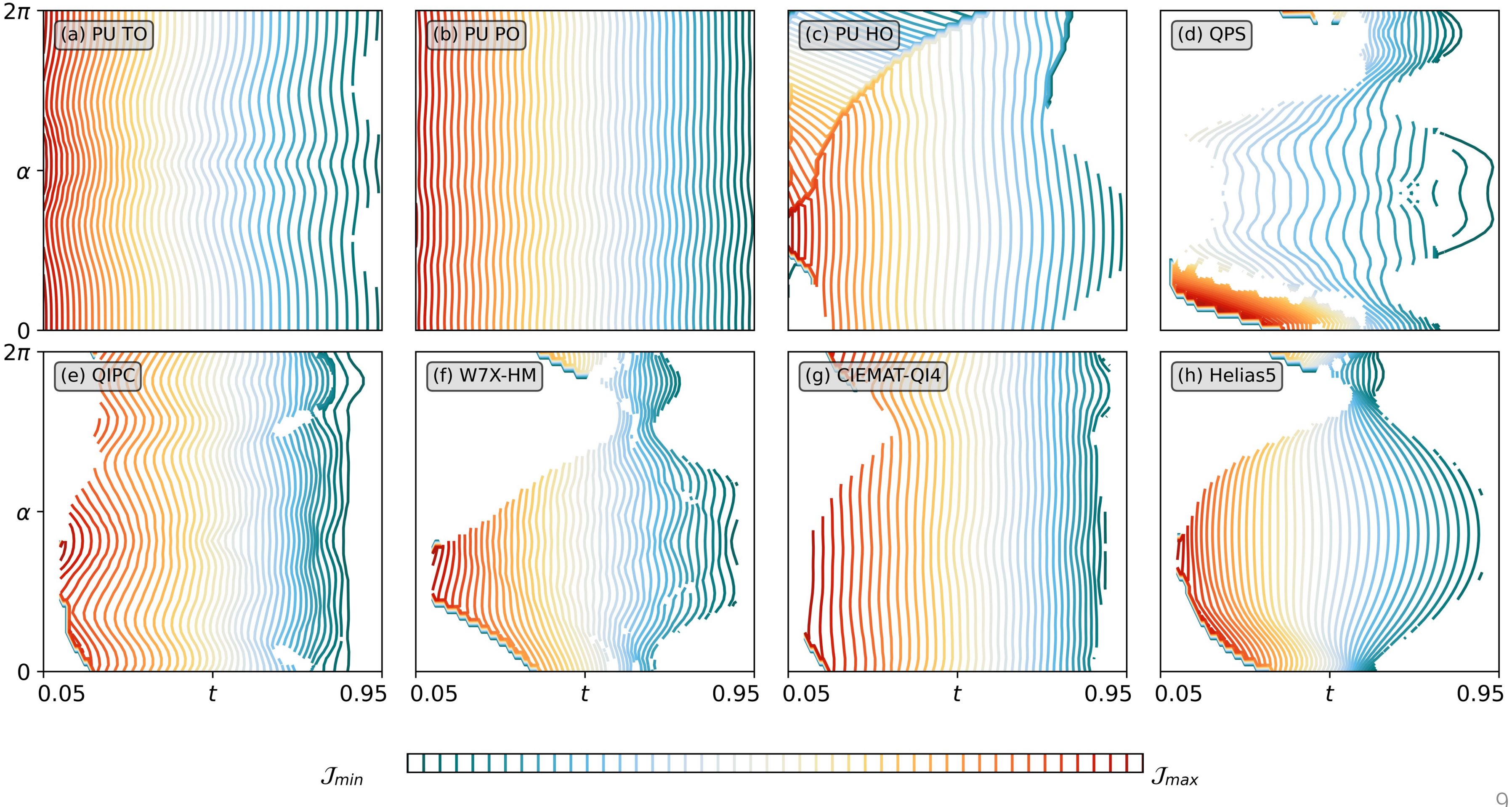
Optimizing non-QS omnigenity is not easy

- Quasisymmetry (QS) can be achieved at high accuracy by minimizing asymmetric modes.
- Non-QS omnigenity optimization is generally more difficult due to the lack of symmetry.



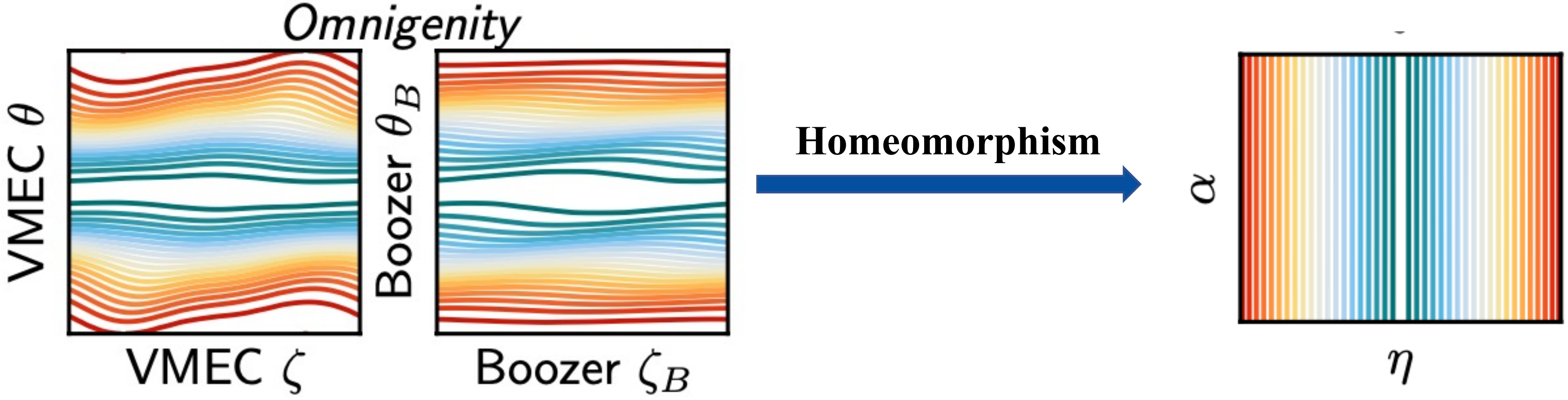
Precise QS configurations

[Landreman & Paul PRL 2021]



Homeomorphic coordinate mapping for omnigenity

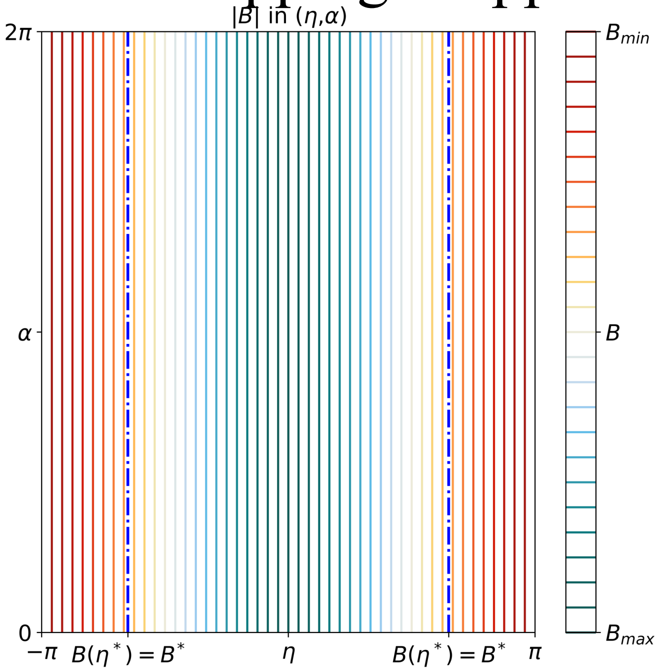
- Omnigenous fields have no locally closed contours.
- There exists homeomorphic coordinates where B contours are straight.



- For quasi-symmetry (QS), Boozer coordinates satisfy such conditions.
- For non-QS omnigenity, one have to find a new coordinate system that meets the requirements and **preserves omnigenity**.

Constructing omnigenous fields in Boozer coordinates is easier

- Several mappings (Cary & Shasharina PoP 1997, Landreman & Catto PoP 2012, Dudt JPP 2024) have been proposed to construct omnigeneous fields.
  - **Omnigenity is preserved**
  - **Constant η is constant B**
- A similar mapping is applied here.



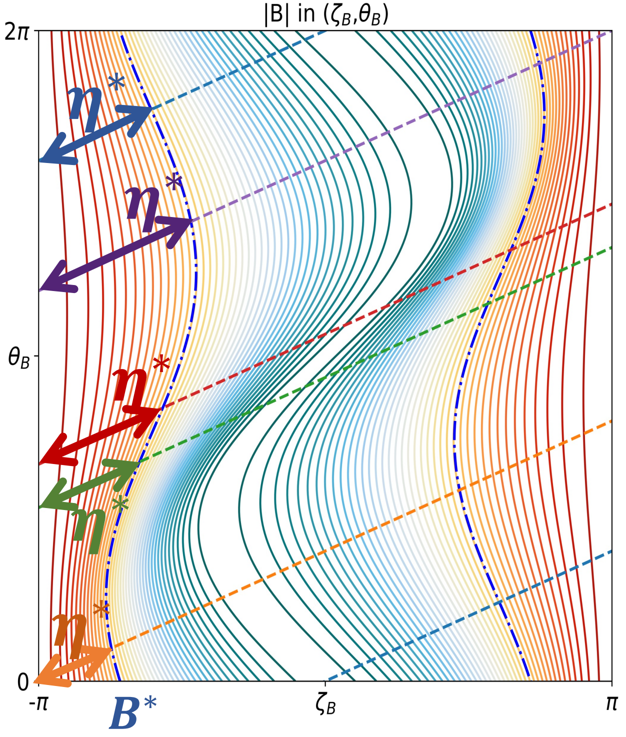
Preserve $\dfrac{\partial \tilde{J}(B^*,\alpha)}{\partial \alpha} = 0$

$$\tilde{\zeta}(\alpha,\eta) = \eta - D(\eta)\cdot S(\alpha,\eta)$$

$$\tilde{\theta} = \alpha$$

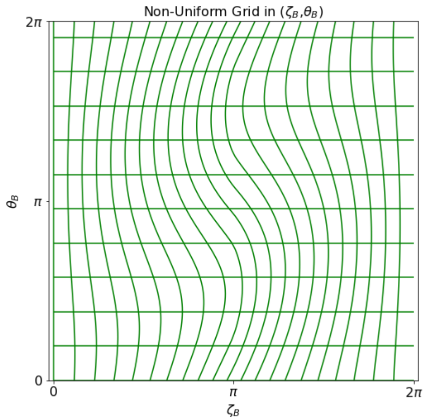
S controls the contour shape

D determines the bounce distance



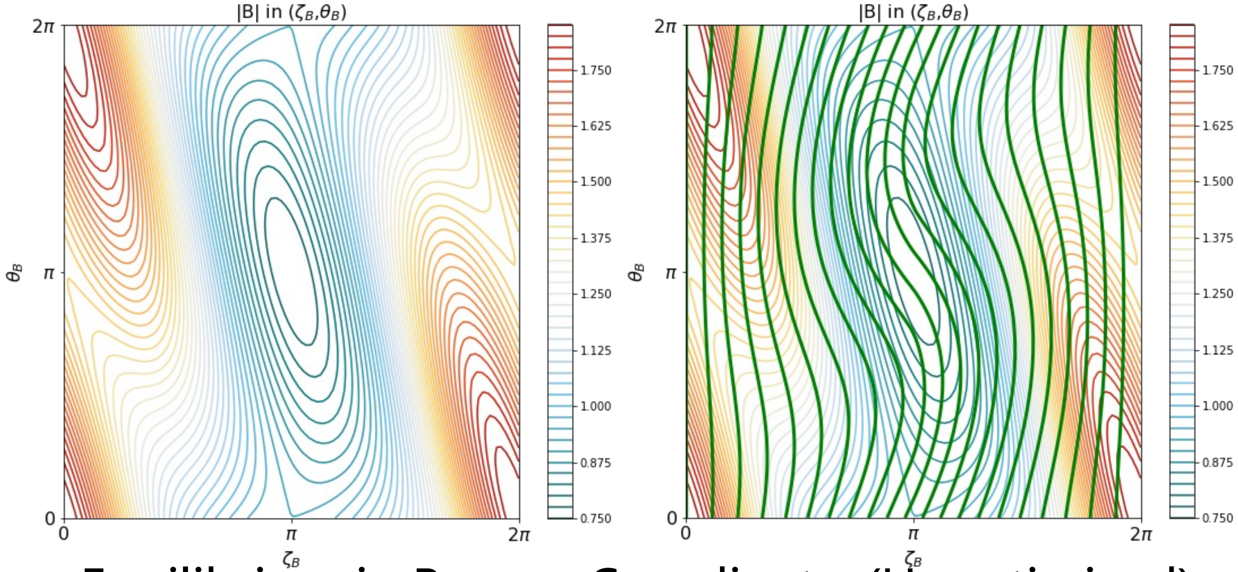
Omnigenity OPtimization like quasiSymmetry (OOPS)

Pick up an **arbitrary** omnigenity mapping

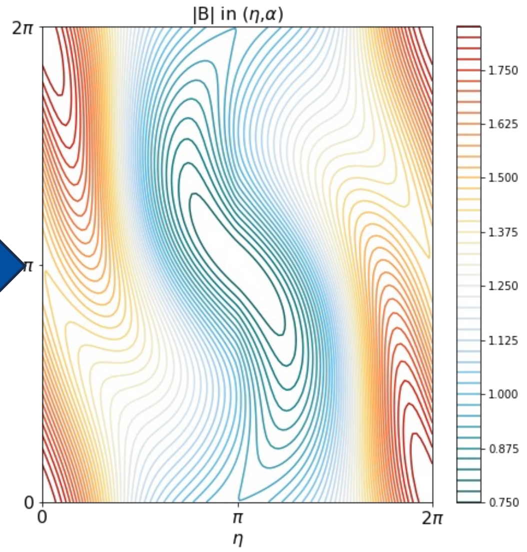


For quasisymmetry, we can use $\eta = \zeta_B, \alpha = \theta_B$

The omnigenity mapping can be varied during the iteration of optimization.
(For simplicity, we keep it fixed.)

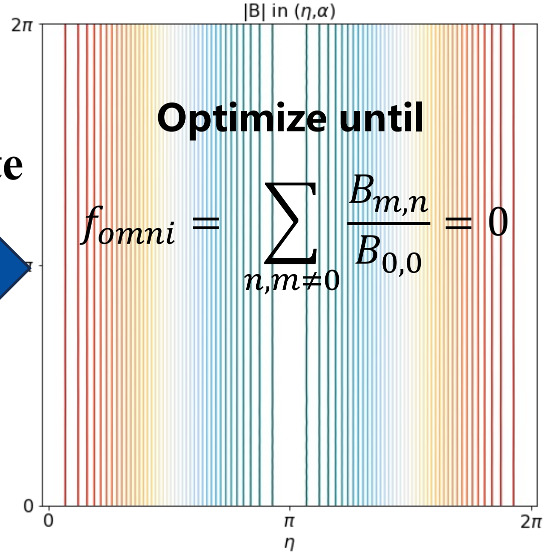


Equilibrium in Boozer Coordinates(Unoptimized)



Equilibrium in $(\boldsymbol{\eta}, \boldsymbol{\alpha})$

iterate



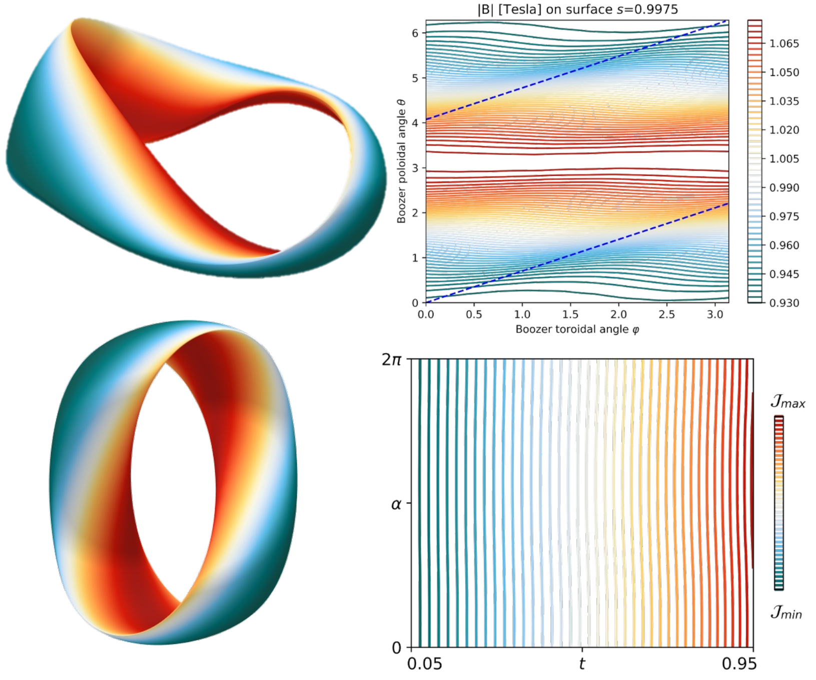
Optimize until

$$f_{omni} = \sum_{n,m\neq 0} \frac{B_{m,n}}{B_{0,0}} = 0$$

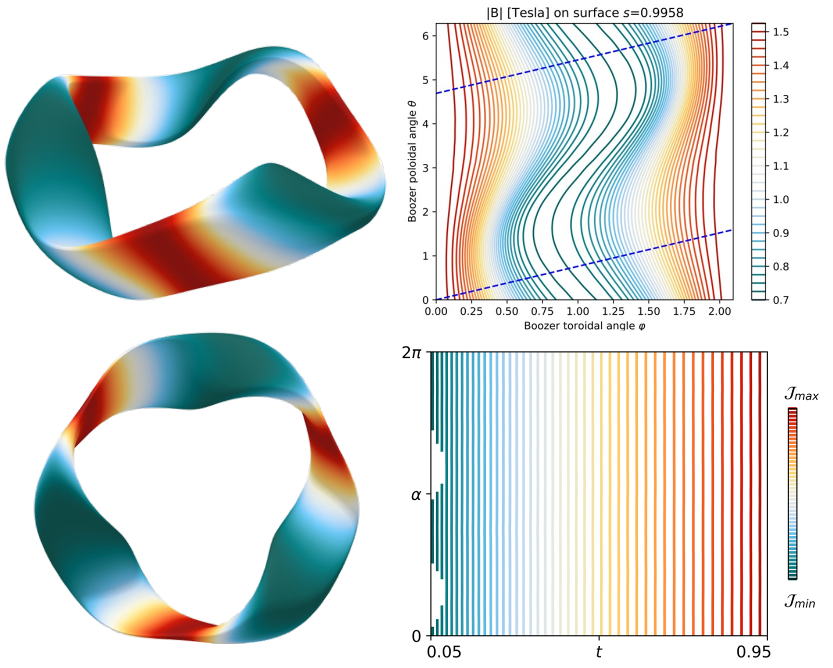
Target

Precise, compact omnigenous configurations have been obtained

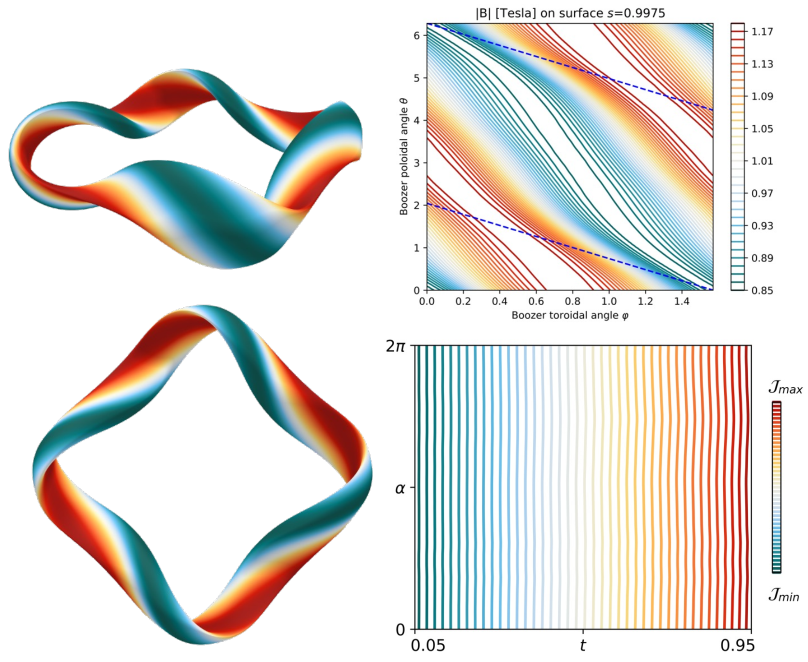
Toroidal Omnigenity (TO)
Nfp=2 Ap=6 $\iota_{edge} = 0.711$



Poloidal Omnigenity (PO)
Nfp=3 Ap=6.5 $\iota_{edge} = 0.765$



Helical Omnigenity (HO)
Nfp=4 Ap=8 $\iota_{edge} = 1.326$

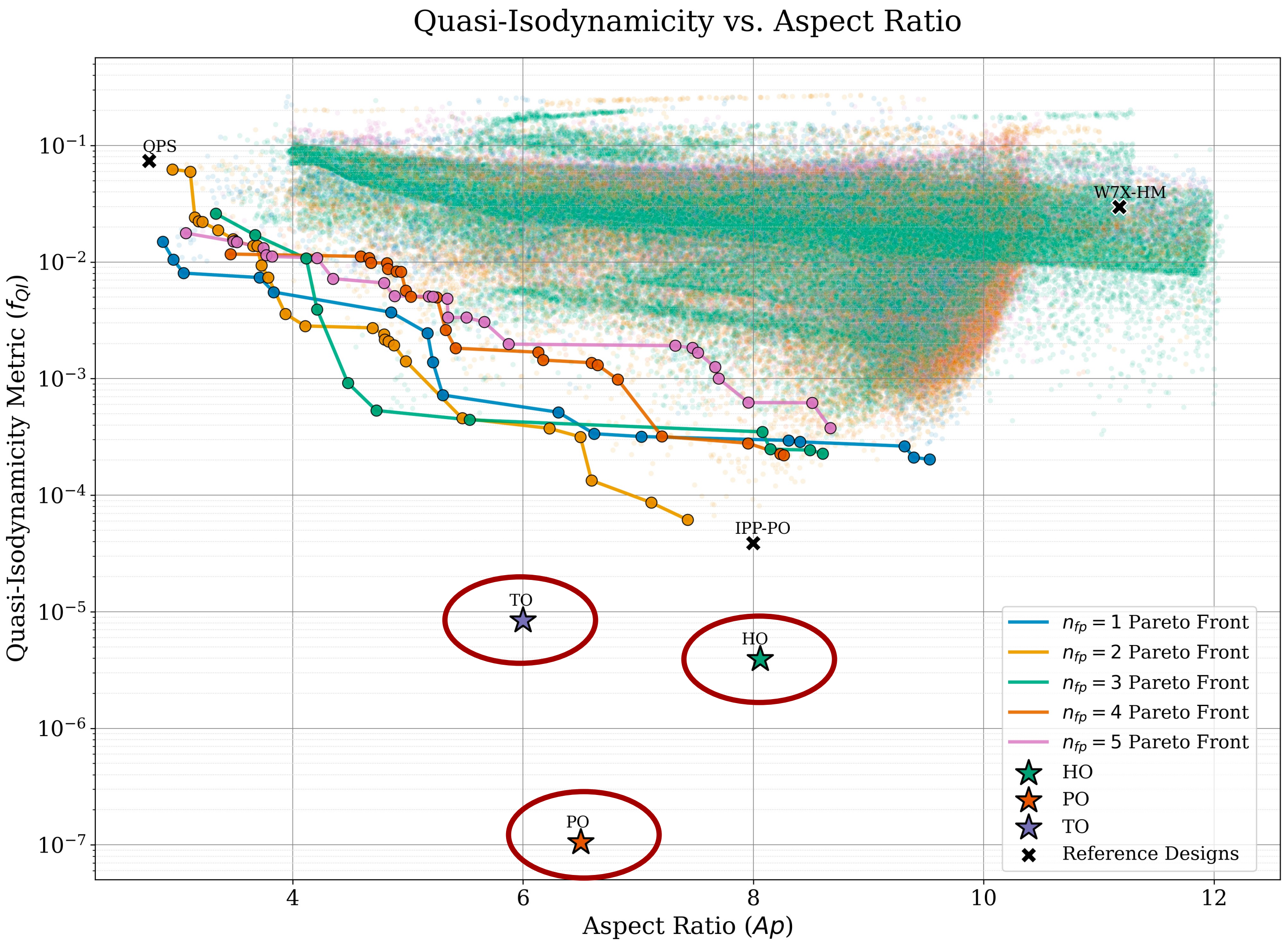


- ➢ **No warm starts needed. Initial guesses are circular torus.**
- ➢ **Simplest mapping is used. (One single Fourier coefficient)**
- ➢ **Alpha-particle losses at reactor size < 1%.**

Beyond the Pareto fronts of the "Constellaration" database

- Proxima Fusion recently released the "Constellaration" database [Cadena arXiv 2025].
- 158, 000 QI configurations were optimized using existing approaches.
- Pareto fronts of the QI-quality (f_{QI}) and aspect ratio (Ap) for each period are identified.

$$f_{QI} = \frac{1}{4\pi^2} \iint (B(\theta,\phi) - B^{QI}(\theta,\phi))^2 d\theta d\phi$$



Piecewise omnigenous fields: a radically new family of optimized magnetic fields for stellarator reactors

J.L. Velasco[1],
I. Calvo[1], V. Fernández-Pacheco[2], E. Sánchez[1], A. Alonso[1], F.J. Escoto[1], J.M. García-Regaña[1], R. Gaur[3], P. Helander[4], F.I. Parra[5], H. Thienpondt[1]

Laboratorio Nacional de Fusión Ciemat EUROfusion

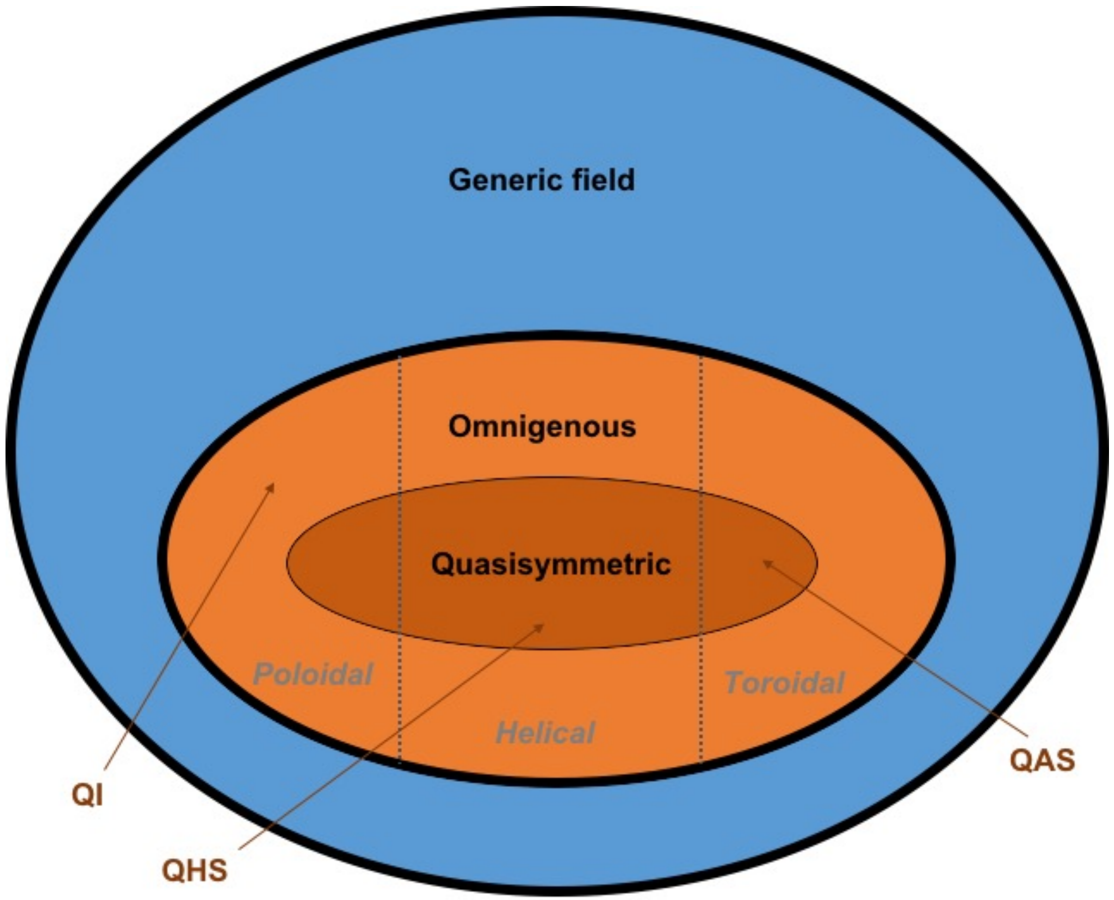
[1] Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain; [2] Universidad Carlos III, Madrid, Spain; [3] Princeton University, USA; [4] Max Plank IPP, Greifswald, Germany; [5] Princeton Plasma Physics Laboratory, Princeton, USA

IAEA-FEC 2025

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Are there any other $B(\theta, \zeta)$ that confine orbits perfectly?

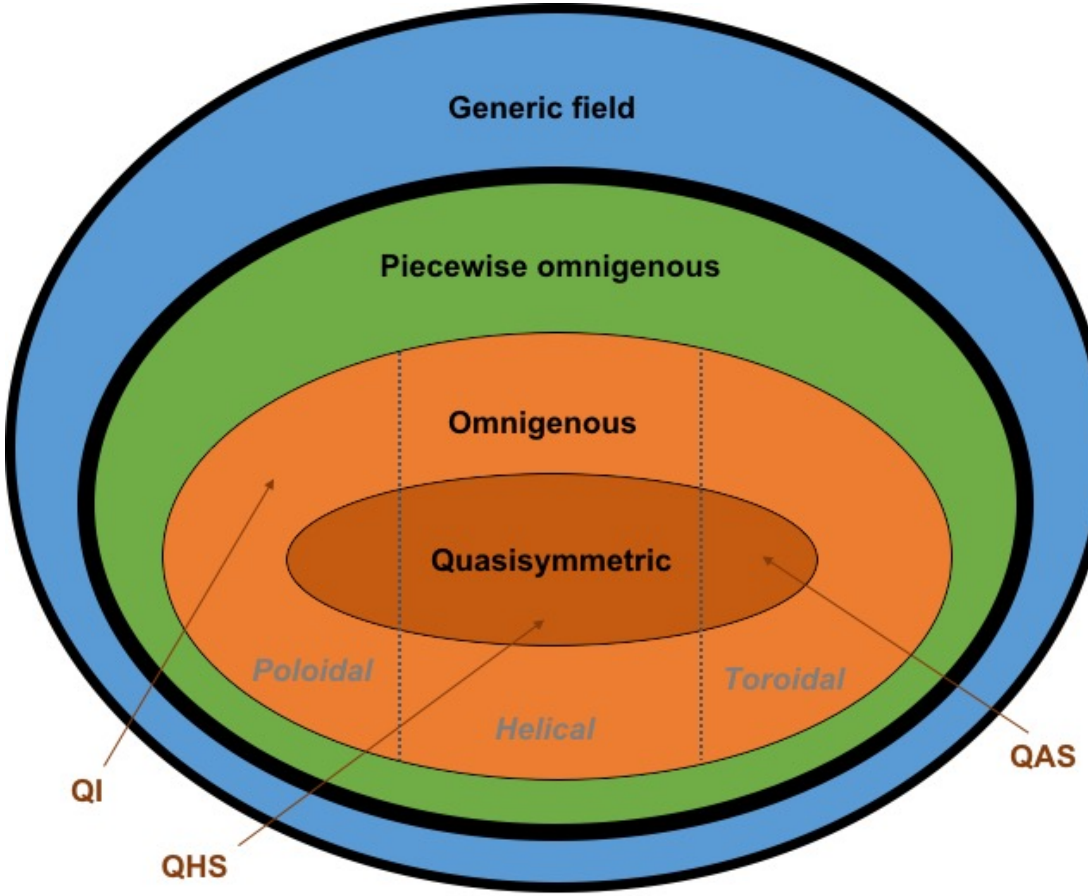


Piecewise omnigenity generalizes omnigenity:

- Motivation: fulfilling constraints of omnigenity may lead to complicated plasma shapes and coils, and to fields sensitive to design errors.
- Goal: **remove constraint** that all contours of constant B close in the toroidal, poloidal or helical direction while **keeping collisionless confinement of orbits.**

If no global direction of symmetry, **broader region of configuration space.**

Are there any other $B(\theta, \zeta)$ that confine orbits perfectly?



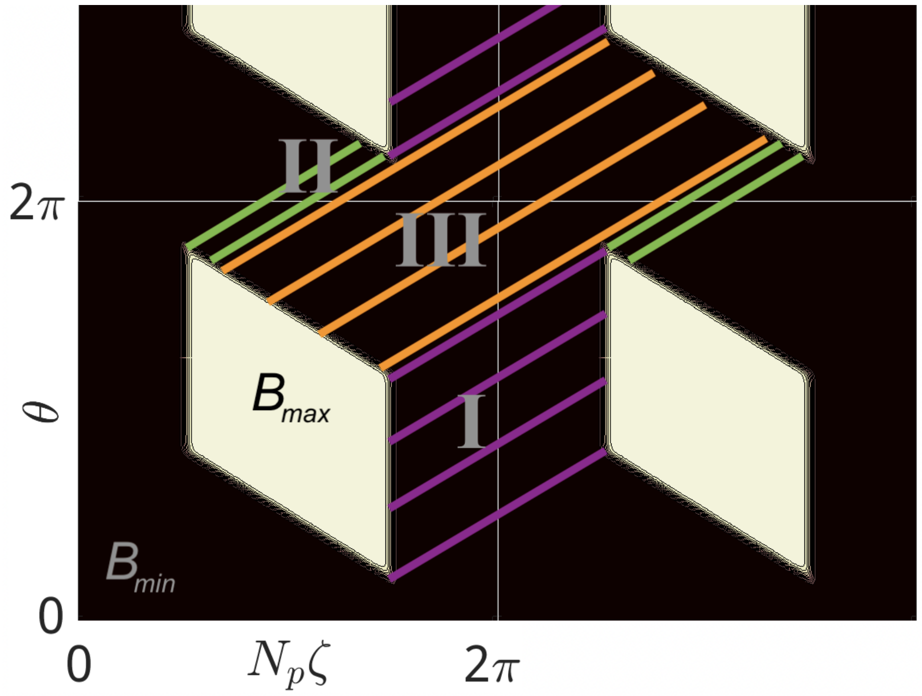
Piecewise omnigenity generalizes omnigenity:

- Motivation: fulfilling constraints of omnigenity may lead to complicated plasma shapes and coils, and to fields sensitive to design errors.
- Goal: **remove constraint** that all contours of constant B close in the toroidal, poloidal or helical direction while **keeping collisionless confinement of orbits.**

If no global direction of symmetry, **broader region of configuration space.**

Piecewise omnigenity: example of model field [Velasco (2024) PRL]

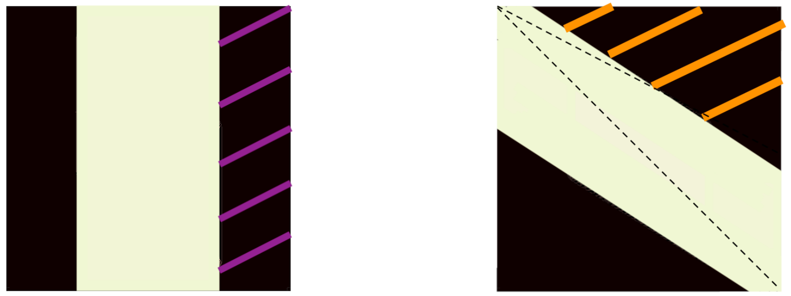
Example of piecewise omnigenous (pwO) field:



- $B(\theta,\zeta) = B_{\max}$ inside a parallelogram.
- $B(\theta,\zeta) = B_{\min}$ outside.
- ι such that corners are connected by field lines.

- **Several regions / classes of orbits:**
  - Purple orbits *locally see* an omnigenous field.
  - Orange (and green) see a *different* omnigenous field.

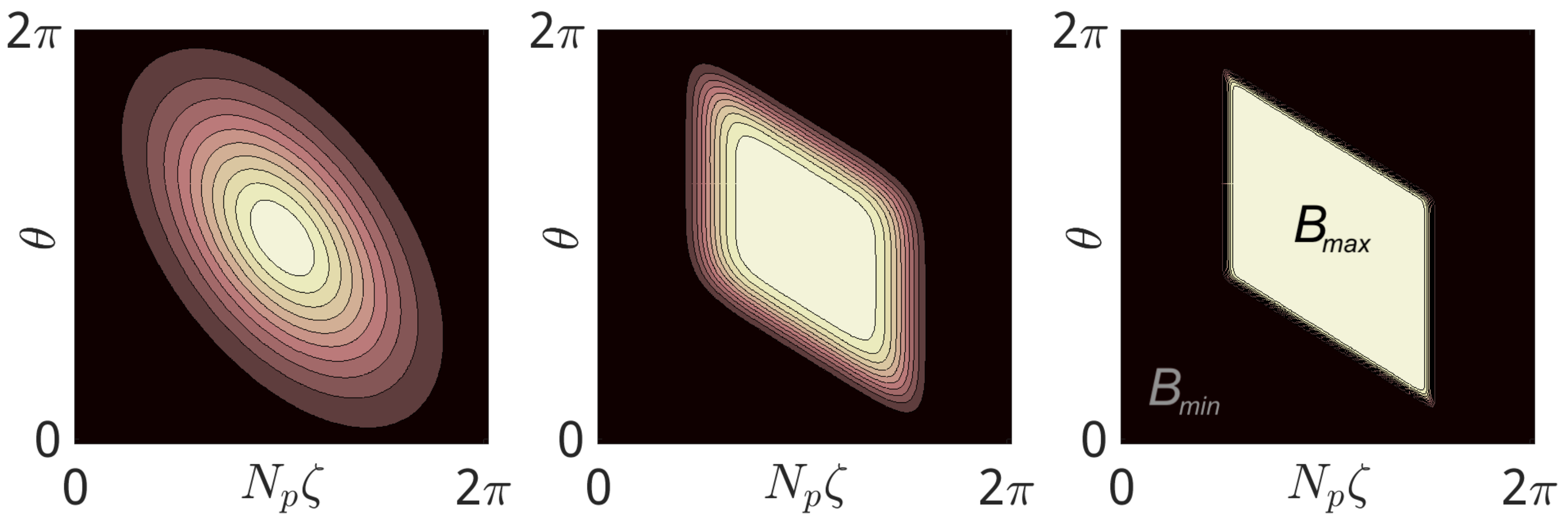
  B-contours not necessarily aligned with $M\theta - N_pN\zeta$.



- $\overline{\mathbf{v_M} \cdot \nabla s} = 0$ **for all classes of orbits.**
- *Junctures* between regions I, II and III do not cause $1/\nu$ transport.

Tokamak-like neoclassical transport ($\varepsilon_{eff} = 0$).

Piecewise omnigenity as a target for a stellarator reactor design

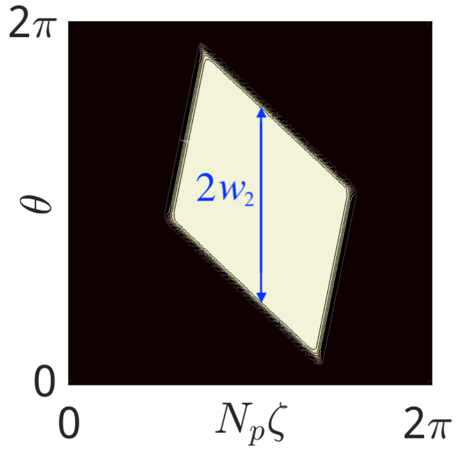


($B(\theta, \zeta)$ from left to right: from less to more piecewise omnigenous model fields).

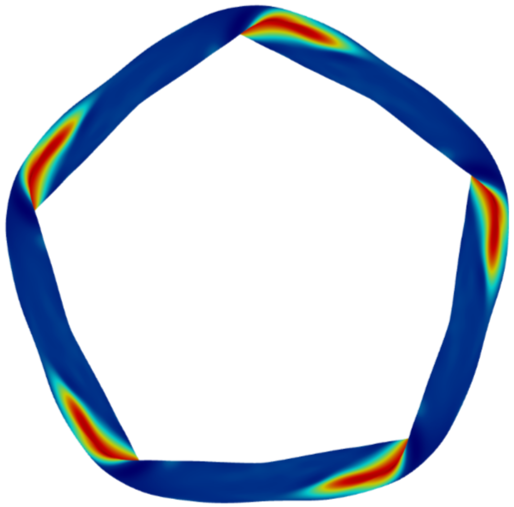
Neoclassical transport compatible with a reactor requires only *approximate* piecewise omnigenity.

A stellarator reactor requires a divertor:

- The most mature concept, the island divertor, was thought to be compatible only with QI fields.
- A subset of pwO fields ($w_2 = \pi$) have reduced bootstrap current, a requirement of an island divertor [Calvo (2025) PRE].

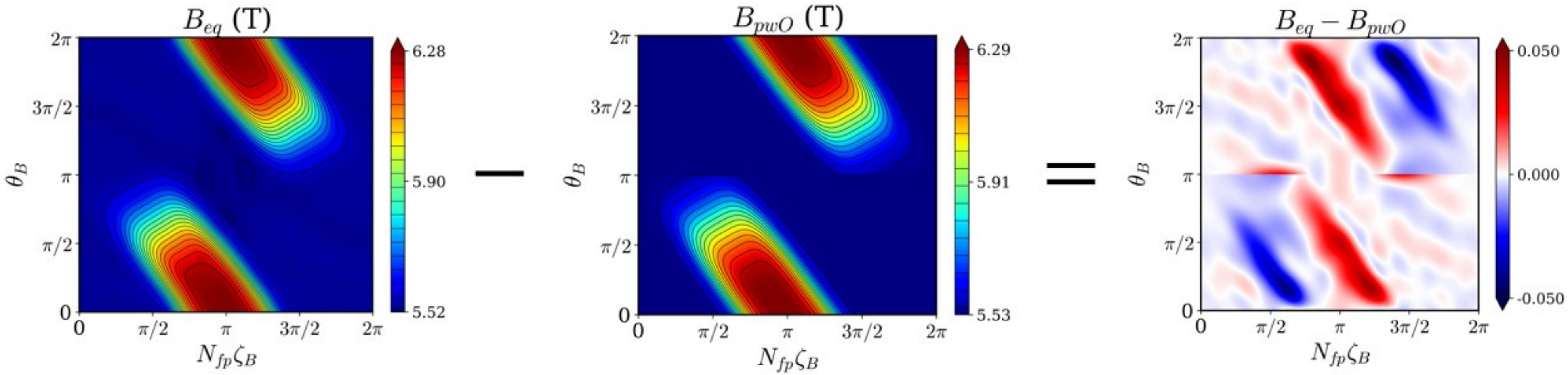


How close to piecewise omnigenity can a magnetic configuration be?



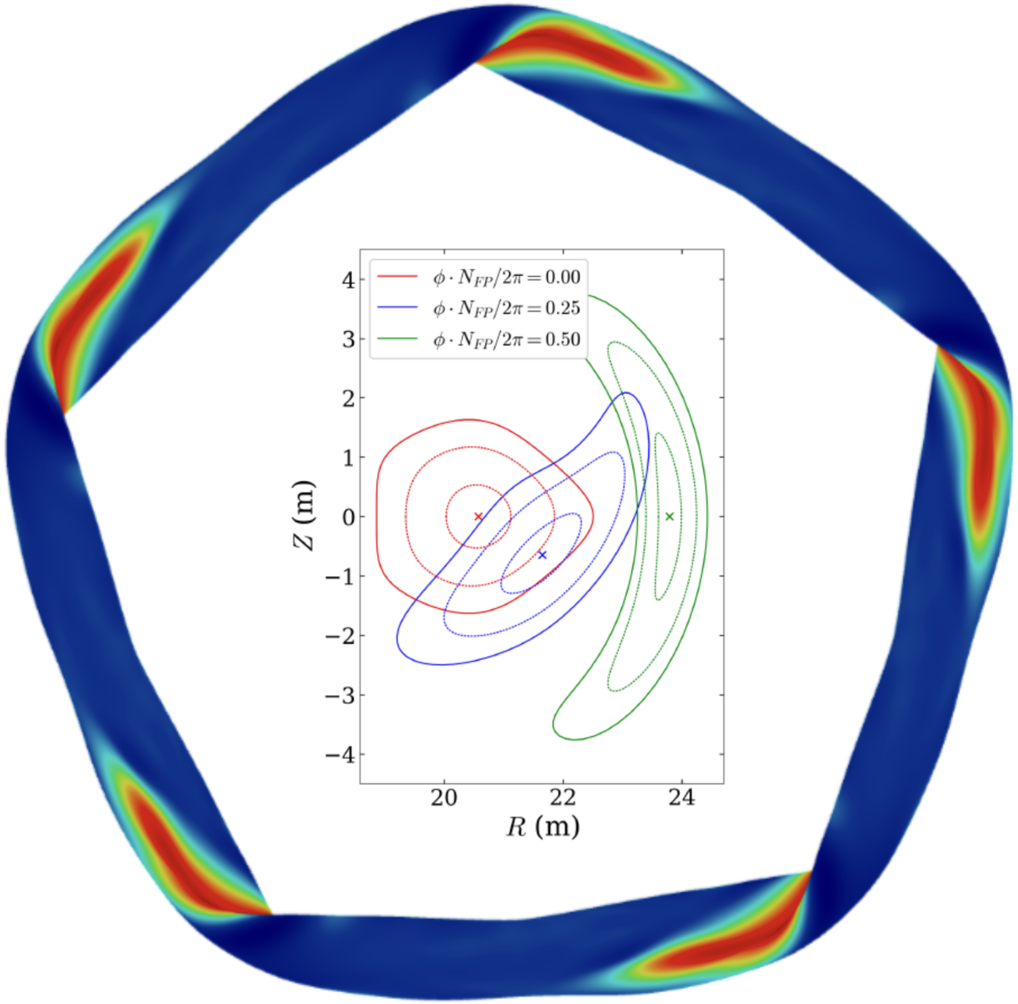
Master Thesis of Víctor Fernández-Pacheco, paper in preparation.

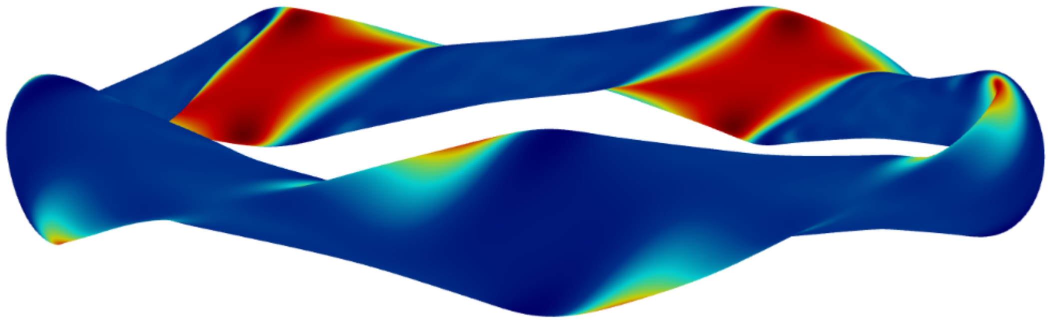
- Optimization w.r.t. piecewise omnigenity implemented in `DESC`.
- Goal of the work: **push the boundaries of the concept** of pwO.
  1. Select family of B_{pwO} as far as possible from omnigenity.
  2. Make B approach B_{pwO} on a flux-surface as much as possible.
     - In a reactor candidate, we can (and we will) relax 1 and 2.
  3. Check that MHD equilibria exist with reasonable shapes and basic properties.



Equilibria with $|B - B_{pwO}|/B_{pwO} < 1\,\%$ (and likely smaller) can be found.

CIEMAT-pw1: reactor-relevant physics properties [Fernández-Pacheco]





- $N_p = 5$, $A = 12.7$, $\kappa = 6.7$
- Mercier MHD stability.
- $4/5 < \iota < 5/5 \Rightarrow$ no low order rationals, compatible with island divertor.
- Reduced neoclassical transport ($\varepsilon_{eff} < 0.005$).
- Reduced bootstrap current ($\Delta\iota_{LCFS} < 1\,\%$).
- Good fast ion confinement at reactor β ($> 95\,\%$ alpha-heating efficiency, most losses for $t > 0.01\,$s).

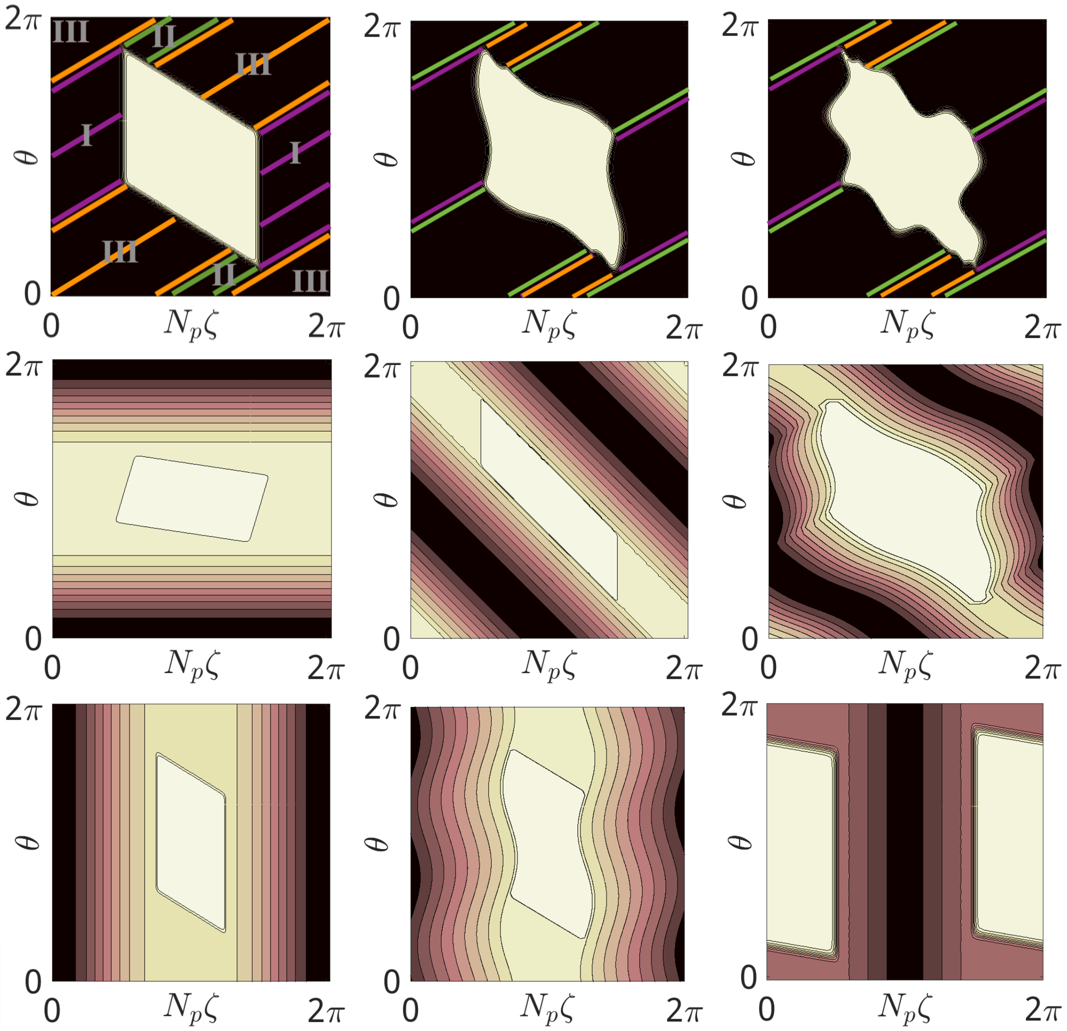
Physics properties compatible with a reactor.

Piecewise omnigenity: vast region of stellarator conf. space [Velasco (2025) NF]

Different types of model fields proposed:

- Fields **completely away from omnigenity** (as in [Velasco (2024) PRL]).
  - Reactor-relevant configurations exist.
- Fields that combine omnigenity with piecewise omnigenity.
  - Deeply and barely trapped particles would behave differently.
- Special relevance: fields with (small) **deviations from QI** that cause negligible neoclassical radial and parallel transport [Calvo (2025) PRE, Velasco, in preparation].
  - $B \approx B_{min}$-contours: closed poloidally
  - $B \approx B_{max}$-contours: parallelogram shape.

The best reactor candidate could lie somewhere in between.

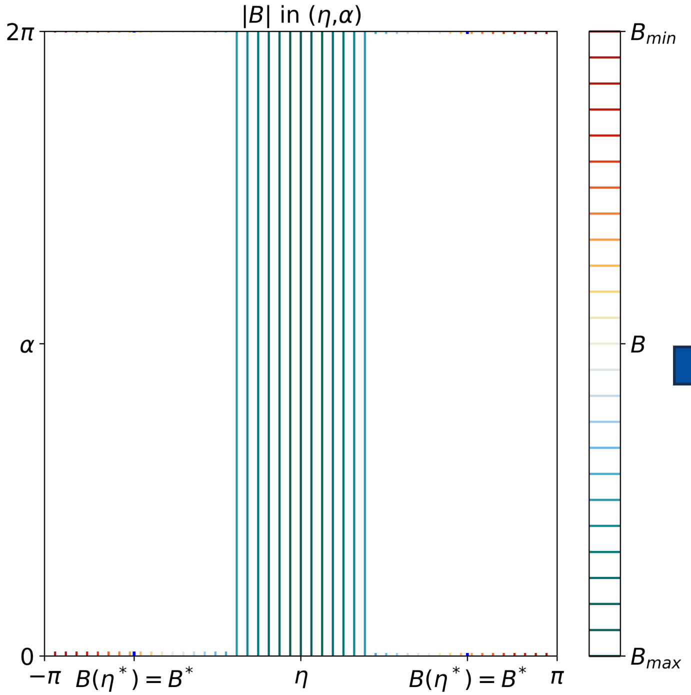


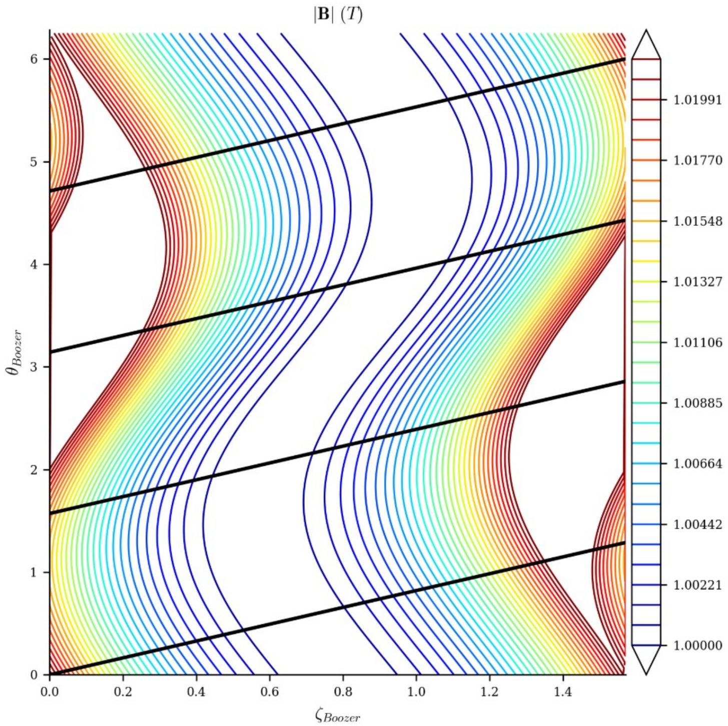
Configurations Combining Omnigenity and Piecewise Omnigenity

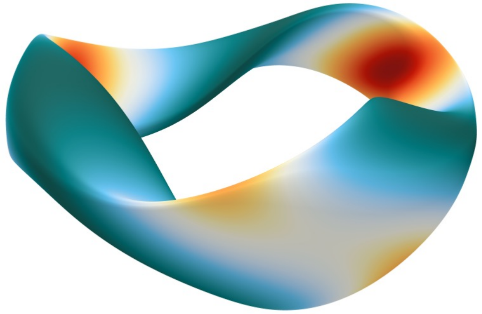
Optimizing pwO using OOPS

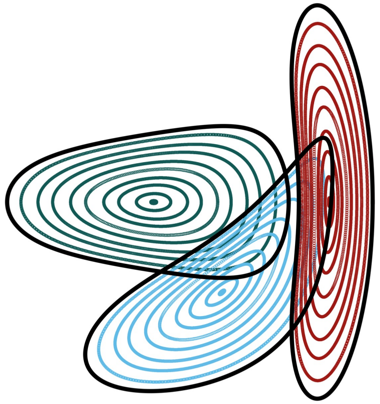
pwO configurations have locally closed contours, however:

- OOPS can still work if we **bound *η*** and focus out of the Bmax region.
- *B* contours have to be **strongly shaped** such that $B_{\max}$ regions can close and form "parallelograms".



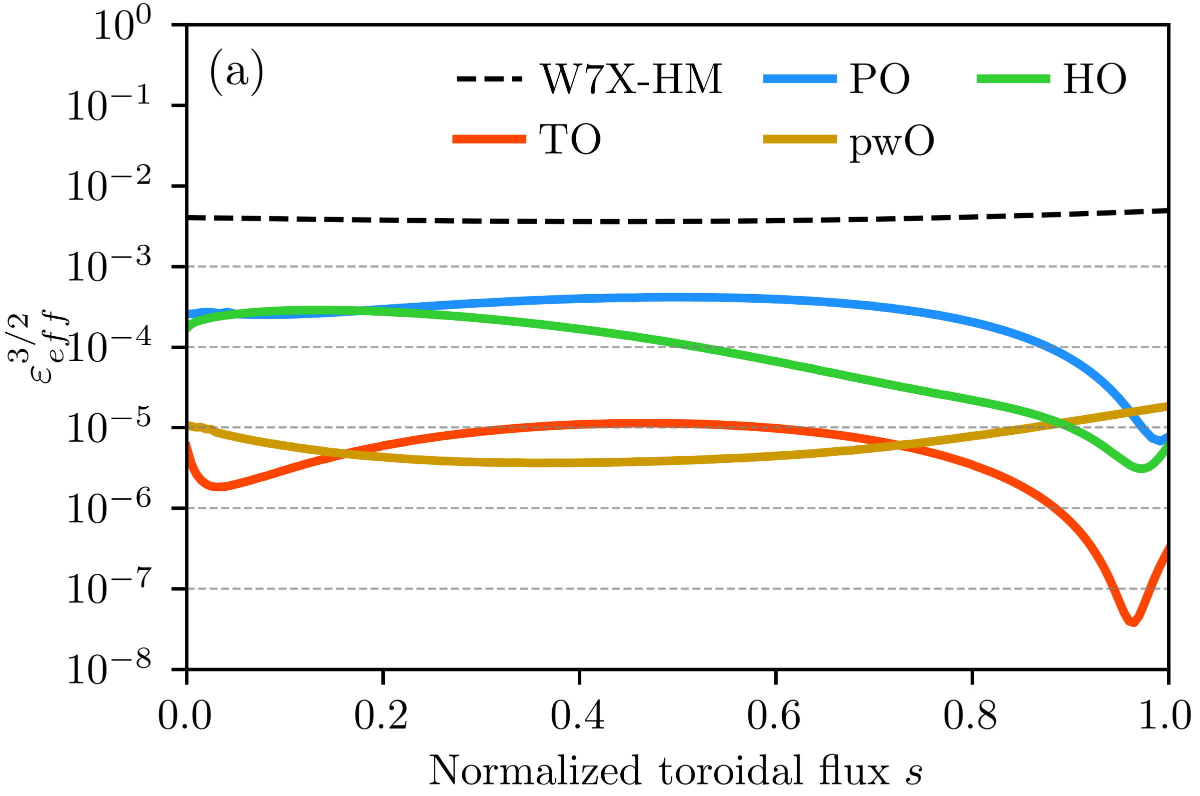




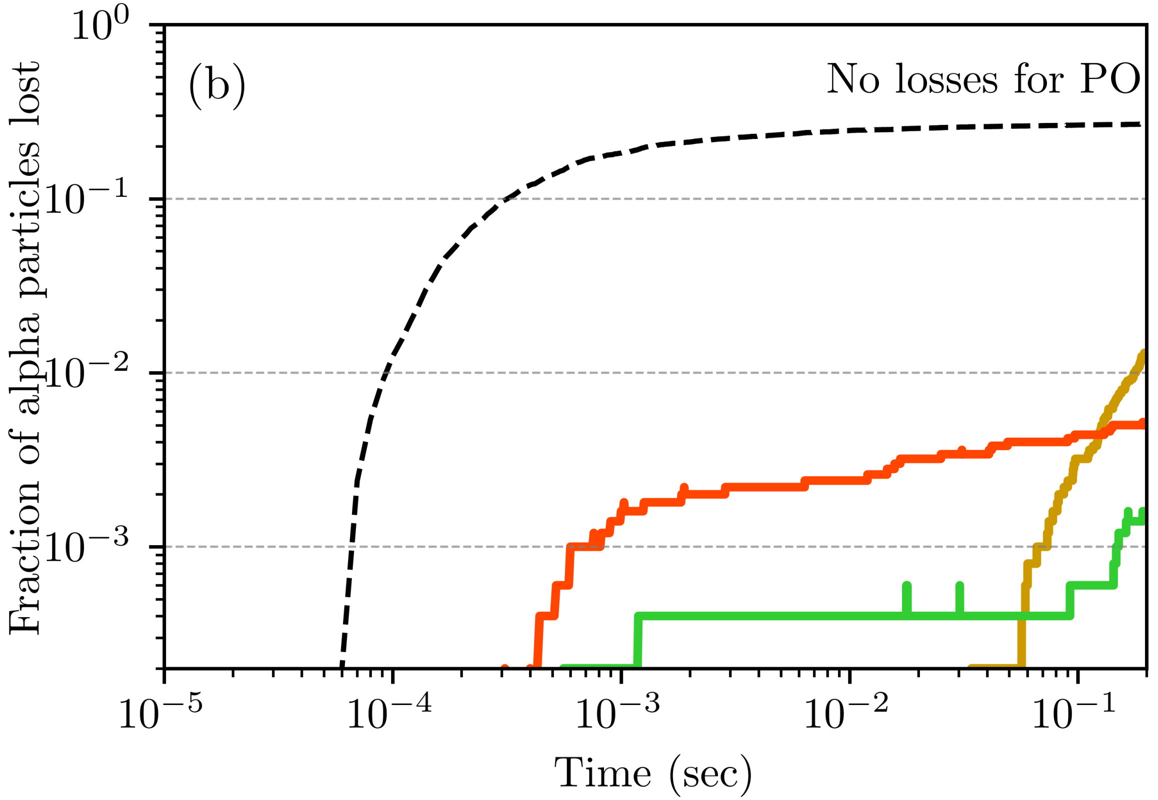


Good confinement properties have been achieved

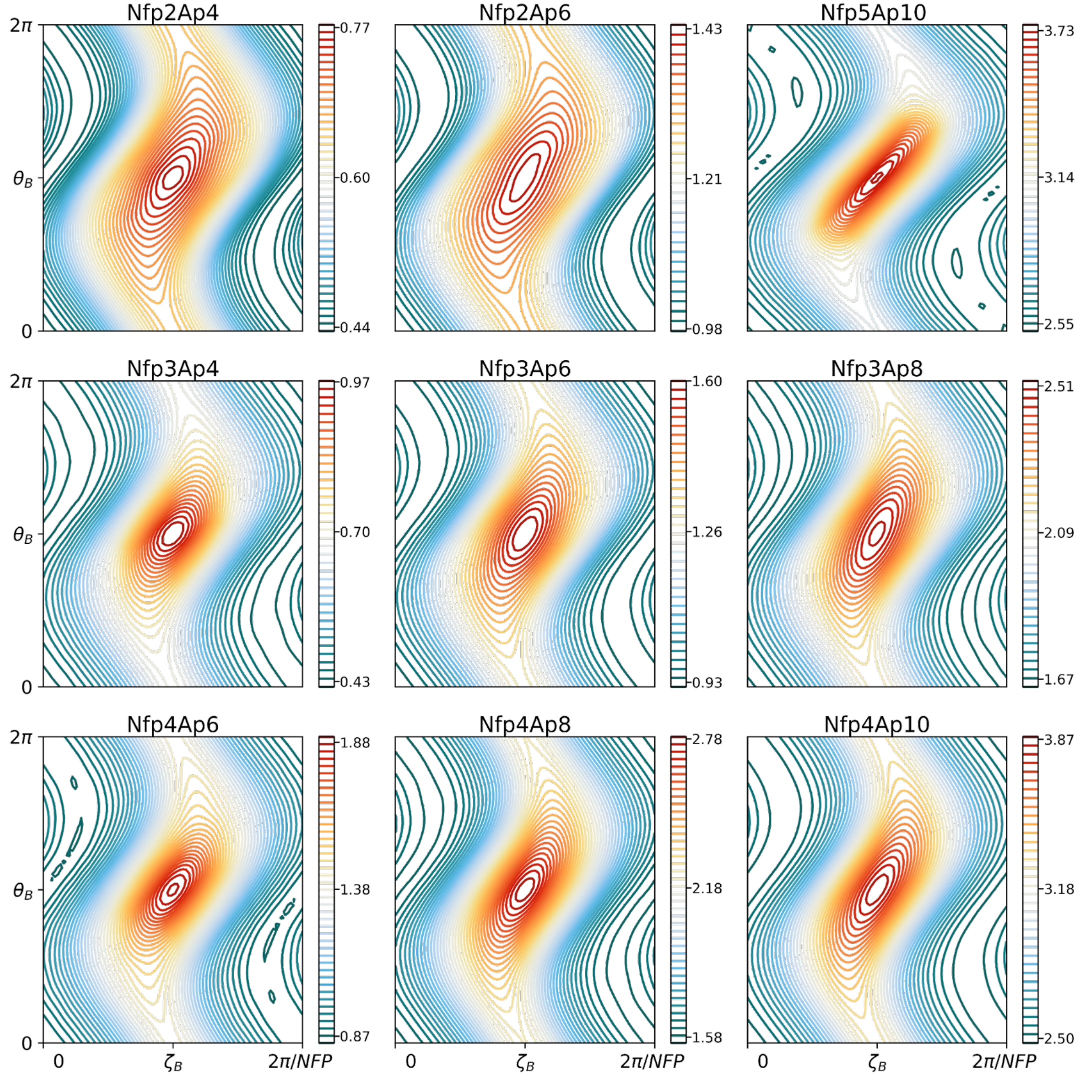
Effiective Ripple $\epsilon_{eff}^{3/2}$

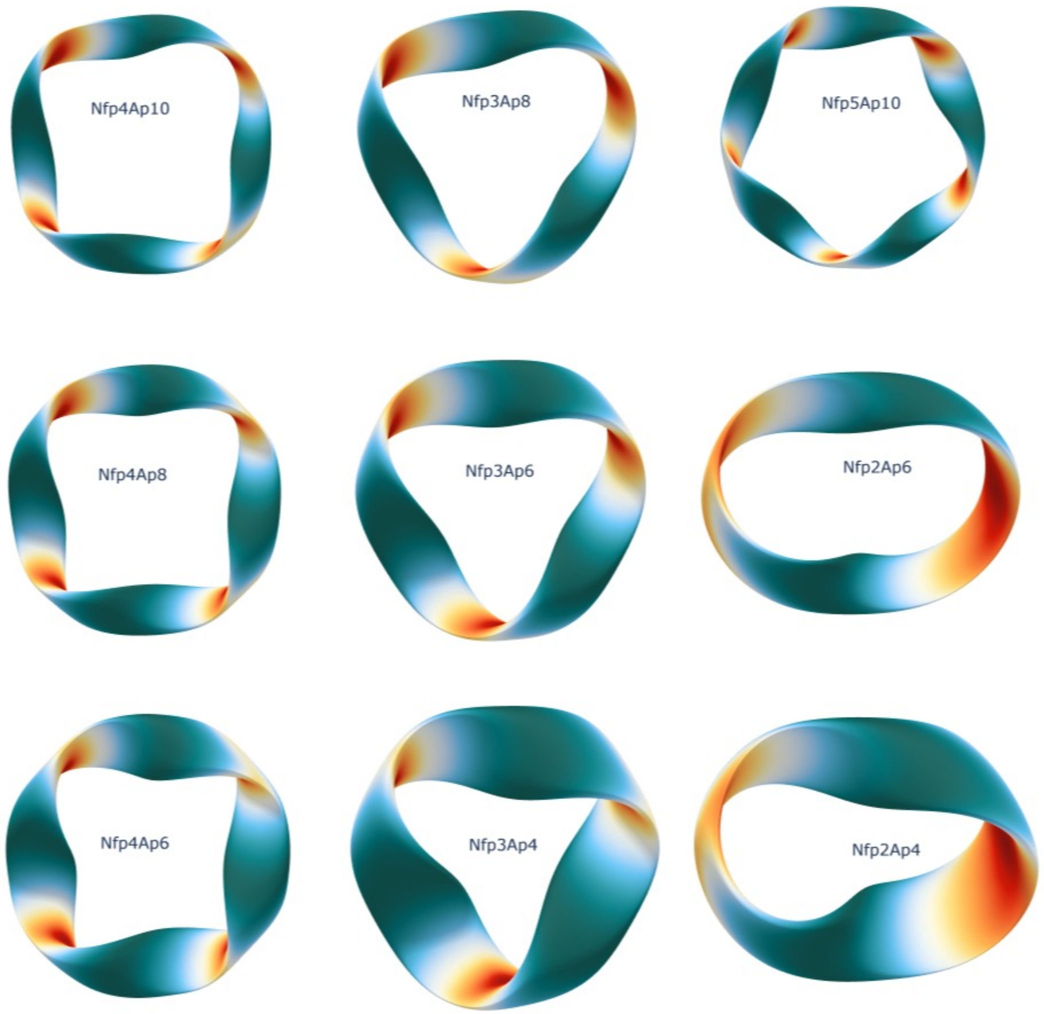


Loss Fraction of Collisionless 3.5 MeV α-Particles



More pwO + QI configurations are available





Summary

- A new method, OOPS, has been proposed to optimize omnigenity. Precise, compact omnigenous configurations have been obtained.
- Piecewise omnigenity radically broaden the parameter space of optimized stellarators.
- Various configurations that combine omnigenity and piecewise omnigenity have been obtained using OOPS, with the potential to achieve more compact configurations and/or to use simpler coils while keeping good confinement.

Thanks for your attention! **Both posters available on Saturday morning**