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

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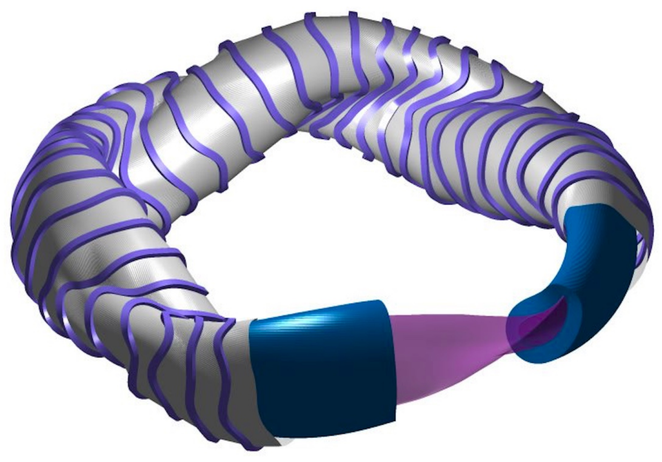
1. The stellarator concept as a reactor candidate

- Lack of inductive current is a solid advantage for a commercial reactor.
- Although coil complexity was a challenge, the success of **Wendelstein 7-X** shows that optimized stellarators with superconductive coils can be built.
- Since then, major theoretical advances and improved computing tools have allowed the optimization of some aspects (e.g. fast-ion confinement) that in W7-X were insufficiently optimized for reactor extrapolation.

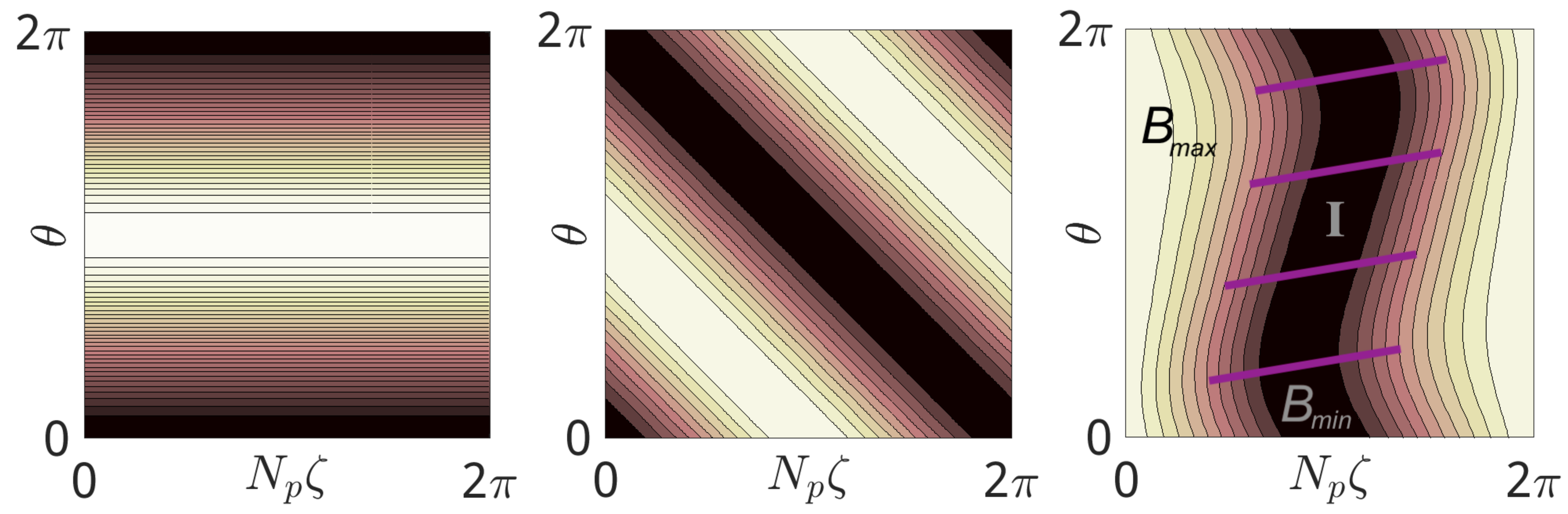
Example: **CIEMAT-QI4X**, see [Sanchez (2023) NF; (2024) ISHW; Palermo, this conference].

W7-X and CIEMAT-QI4X: (to different degree) nearly omnigenous magnetic fields.



2. Omnigenous fields

Omnigenous magnetic fields achieve collisionless confinement of particles thanks to a very **specific on-surface variation of magnetic field strength**, $B(\theta,\zeta)$ [Cary & Shasharina (1997) PRL].



Properties of sufficiently omnigenous fields:

- Alpha-particle confinement comparable to tokamaks.
- For bulk species, banana regime instead of deleterious $1/\nu$.

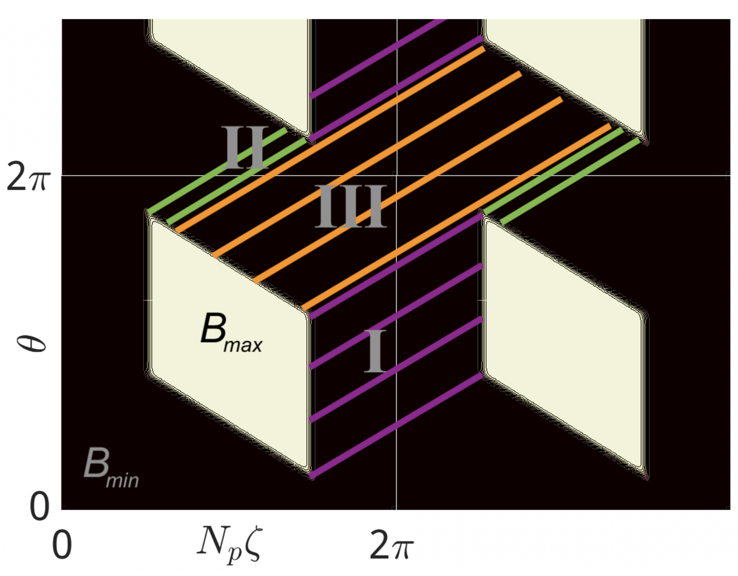
Nevertheless:

- Achieving omnigenous $B(\theta,\zeta)$ may **complicate coils** [Strykowsky (2009)].
- Choice of omnigenous *family* **constrained** by the strategy to deal with other reactor design criteria (e.g. island divertor).
- Some key aspects of stellarator physics (e.g. turbulence at reactor β), **insufficiently studied**.

3. Piecewise omnigenous fields [Velasco (2024) PRL].

Example of pwO field:

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



- Differently to omnigenous fields, **several regions / classes of orbits, but all of them collisionless confined:**
  - Purple orbits *locally see* an omnigenous field.
  - Orange (and green) see a *different* omnigenous field.

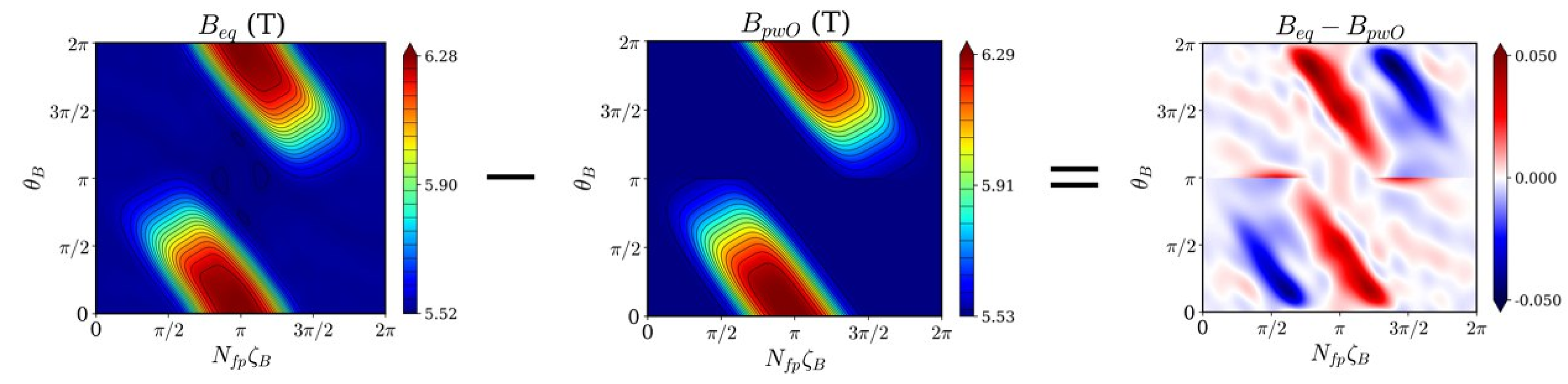
Properties:

- **Tokamak-like neoclassical transport**.
- If, additionally, the $B(\theta,\zeta) = B_{\rm max}$ region has a particular shape, **zero bootstrap current** at low collisionality [Calvo (2025) PRE].

There exist many more examples of pwO fields [Velasco (2025) NF] to draw reactor candidates from.

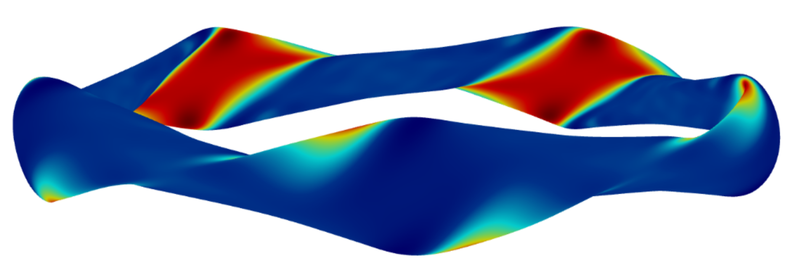
4. CIEMAT-pw1: a nearly pwO stellarator configuration

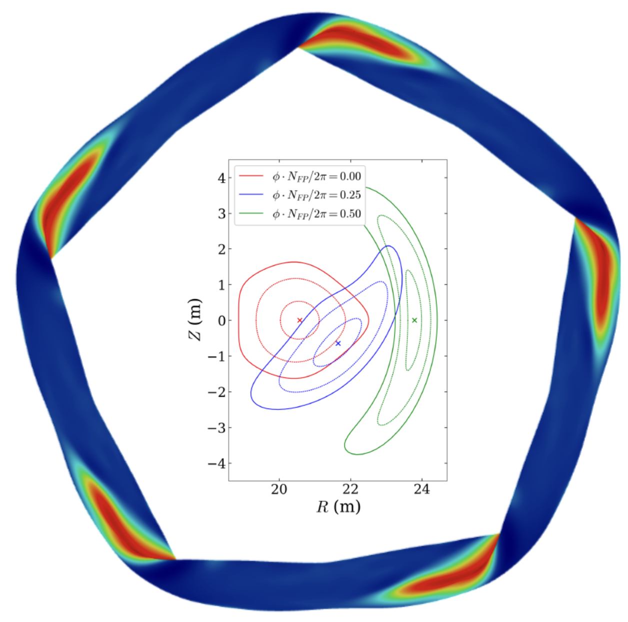
- pwO fields implemented in DESC [Fernández-Pacheco, Master Thesis].
- Goal of the work: **push the boundaries of the concept** of pwO.
  1. Select family of B_{pwO} as far as possible from omnigenity.
  2. Make B_{eq} approach B_{pwO} on a flux-surface as much as possible.



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

$N_p = 5$, $A = 12.7$, $\kappa = 6.7$



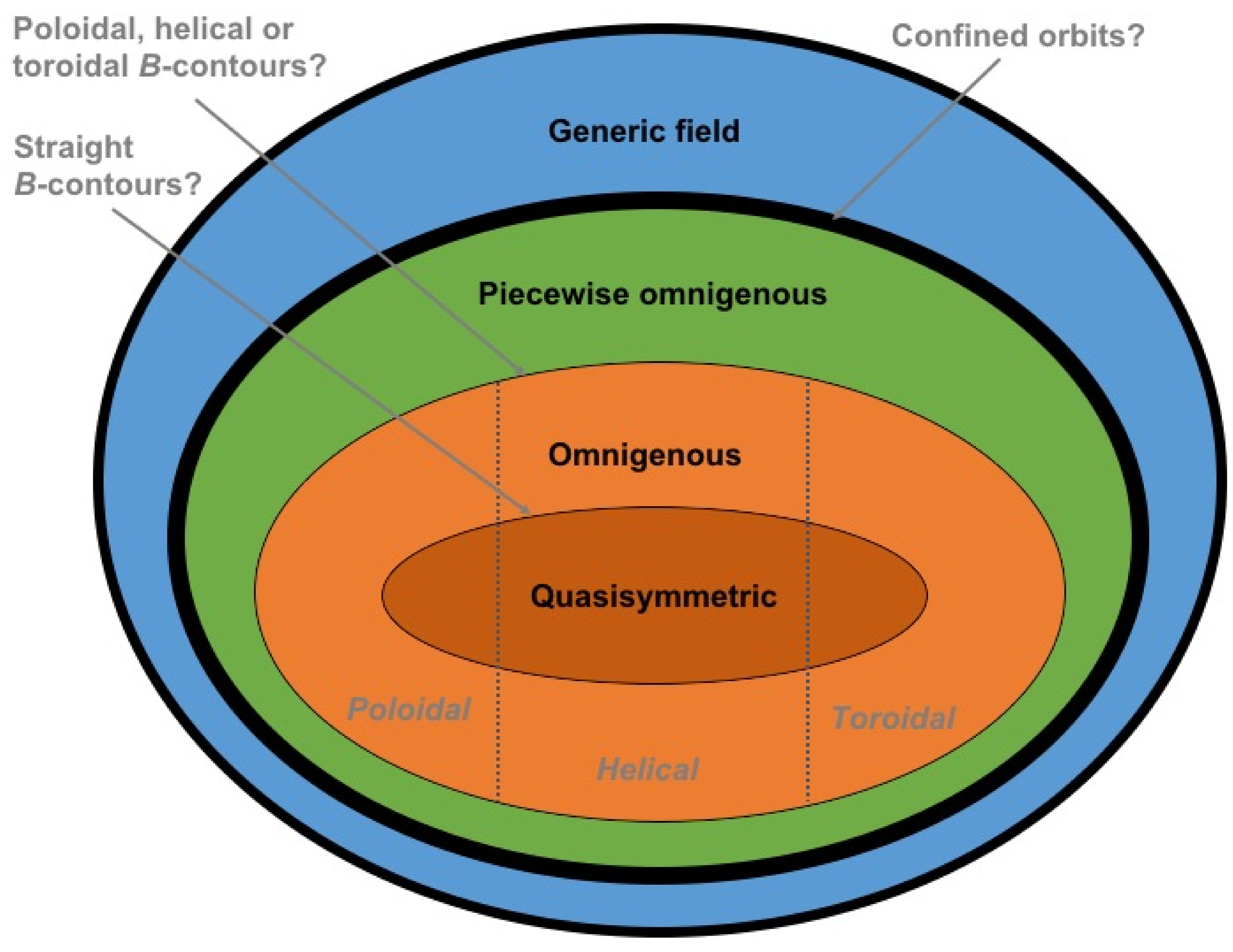


CIEMAT-pw1, with physics properties compatible with a reactor:

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

5. Summary: a new family of stellarators to be explored

- B-contours do not need to be closed in the $M\theta - N_pN\zeta$ direction $\Rightarrow$ no clear *helicity* $\Rightarrow$ **vast region of configuration space!**
- Another *direction* towards which one can optimize, fully **compatible with main physics criteria for a reactor.**



Outlook:

- Study in detail neoclassical (bulk and fast) transport, turbulence...
- Optimize with additional/alternative criteria, e.g.:
  - Maximum-J (turbulence stabilization as in W7-X).
  - Large magnetic shear (turb. stabilization, helical divertor...).
- Try a variety of sets of coils.
- Explore other families of pwO fields.