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PIECEWISE OMNIGENOUS FIELDS: A RADICALLY NEW FAMILY OF OPTIMIZED MAGNETIC FIELDS FOR STELLARATOR REACTORS

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Abstract

An overview is presented of the concept of piecewise omnigenity, which has broadened the family of neoclassically-optimized stellarator fields. Stellarators with magnetic fields close to being piecewise omnigeous are argued to be promising candidates to be the basis of a stellarator reactor with a good balance between physics performance and technical feasibility.

1. INTRODUCTION

In stellarators, fusion plasmas are confined by means of a magnetic field organized into three-dimensional nested magnetic surfaces that is created by external coils. This makes stellarators qualitatively different from tokamaks, in which an inductive current is partially responsible for the magnetic field (which makes them prone to magnetohydrodynamic instabilities). However, the magnetic field of a stellarator has to be designed very carefully in order to have confinement properties similar to those of a tokamak. This is called optimizing the stellarator. In particular, in any candidate for a stellarator fusion reactor, the magnetic configuration is optimized to be close to omnigenity. In omnigenous stellarator magnetic fields [1], charged particles are perfectly confined in the absence of collisions and turbulence, as in an axisymmetric tokamak. When omnigenity is exactly achieved, the neoclassical transport (i.e., the transport associated to the magnetic geometry and particle collisions) of the device is comparable to that of a tokamak.

Recently, thanks to theoretical and computational breakthroughs, stellarator configurations with unprecedented level of omnigenity have been achieved [2]. A non-exhaustive list of examples of nearly omnigenous fields can be found in [3-12]. However, omnigenity imposes stringent constraints on the spatial variation of the magnetic field strength B [1]. In particular, the contours of constant B on the flux-surface must close either toroidally, poloidally or helically. In a stellarator, these constraints sometimes lead to complicated plasma coils [13].

In this work, a new notion of optimized magnetic fields, named *piecewise omnigenous stellarators* [14-17], will be reviewed. We will revisit the physical picture behind standard omnigenity, and then we will prove that piecewise omnigenous fields can also give exceedingly small collisional transport without satisfying the aforementioned topological constraints. In particular, the fact that the contours of constant B on the flux-surface do not close toroidally, poloidally or helically leads to the existence of several types of trapped-particle orbits, which in turn gives rise to specific transport properties that are potentially relevant for a reactor.

Piecewise omnigenous fields radically broaden the space of accessible reactor-relevant magnetic configurations [15]. Besides small collisional transport of the bulk plasma [14], some of these configurations exhibit favourable properties regarding bootstrap current [16], alpha-particle confinement, turbulent transport or coil simplicity [17].

The rest of the manuscript is organized as follows. Section 2 provides examples of ideal omnigenous and piecewise omnigenous fields. The former are included in subsection 2.1, and the latter in subsection 2.2. Section 3 illustrates how the notion of piecewise omnigenity enlarges the configuration space of optimized stellarator fields. Section 4 shows an example of nearly piecewise omnigenous configuration. The results are summarized in Section 5.

2. EXAMPLES OF OMNIGENOUS AND PIECEWISE OMNIGENOUS FIELDS

In this section, examples are provided of omnigenous and piecewise omnigenous field. All of the figures represent the variation of the magnetic field strength B on the flux-surface of a stellarator configuration. This variation is labelled by the so-called Boozer poloidal and toroidal angles, θ and ζ. In all the figures, a brighter/darker colour corresponds to a stronger/weaker magnetic field strength.

2.1 Examples of omnigenous fields

As discussed in the introduction, omnigenity imposes constraints on the spatial variation of the magnetic field strength B. Firstly, the contours of constant B on the flux-surface must close either toroidally, poloidally or helically. Additionally, in Boozer coordinates, the distance along the field lines between contours of the same value of B must be constant on the flux-surface. Figure 1 shows examples of such fields.

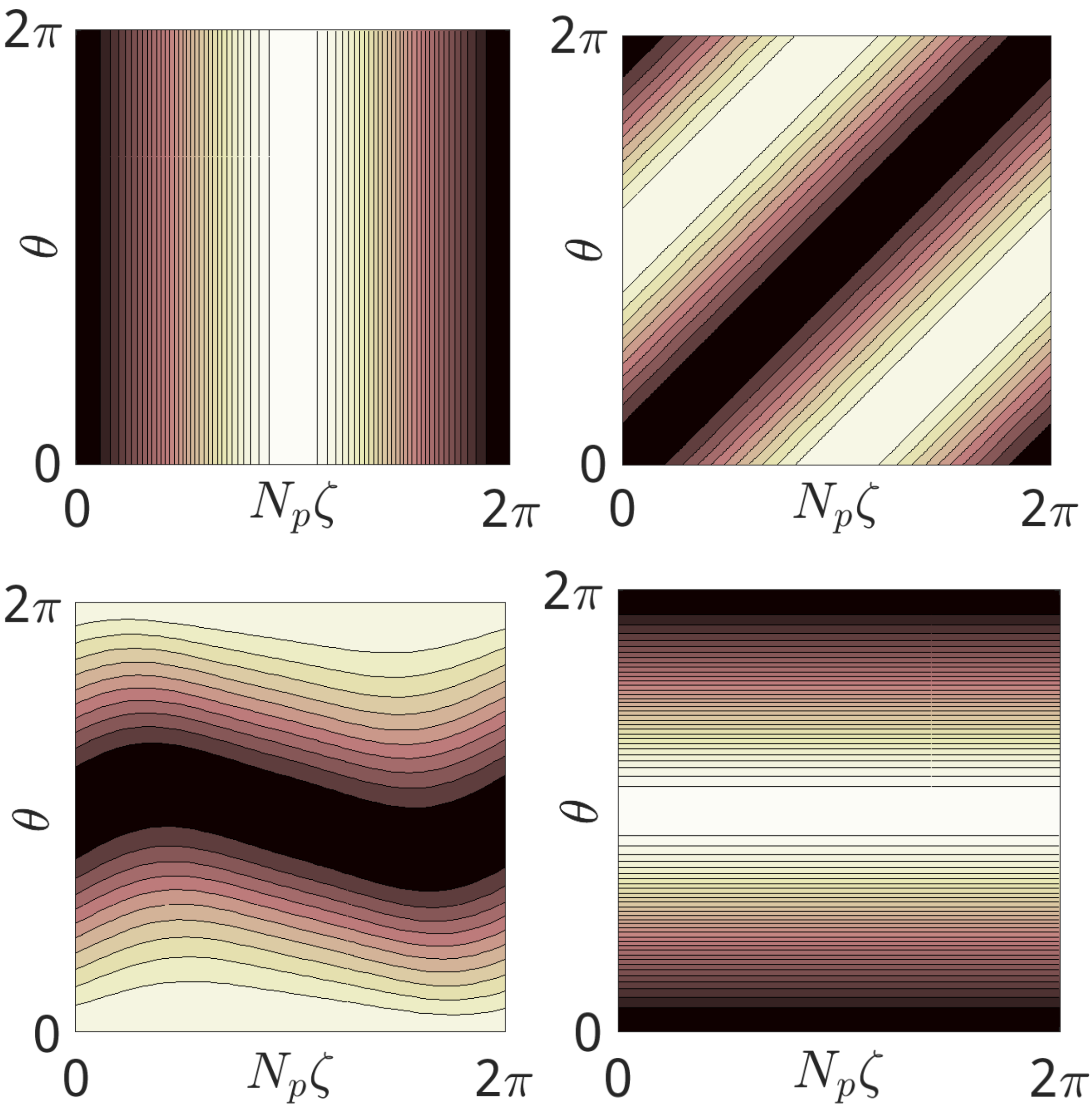

FIG. 1. Examples of omnigenous fields.

2.2 Examples of piecewise omnigenous fields

As discussed in the introduction, piecewise omnigenity removes some of the stringent constraints on the spatial variation of the magnetic field strength *B*. In particular, not all the contours of constant *B* on the flux-surface must close either toroidally, poloidally or helically. Figure 2 shows examples of such fields. In some examples, field lines corresponding to different types of orbits are depicted in purple, green or magenta.

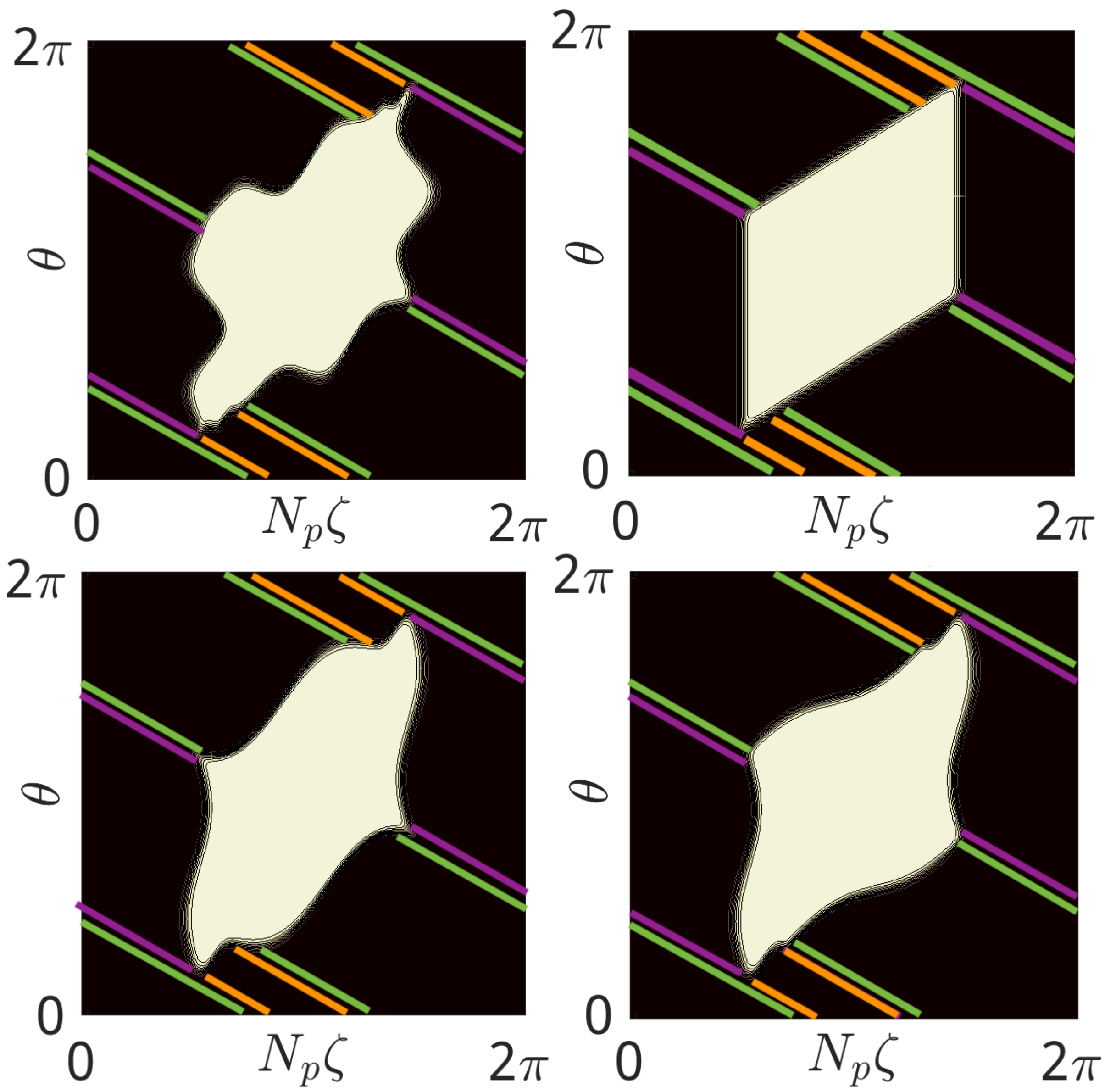

FIG.2. Examples of piecewise omnigenous fields.

We note that, for some of the examples, some of the B contours (those closer to the minimum value of B) do close toroidally, poloidally or helically. Strictly speaking, they could be considered [15] somewhere in between omnigenous and purely piecewise omnigenous fields.

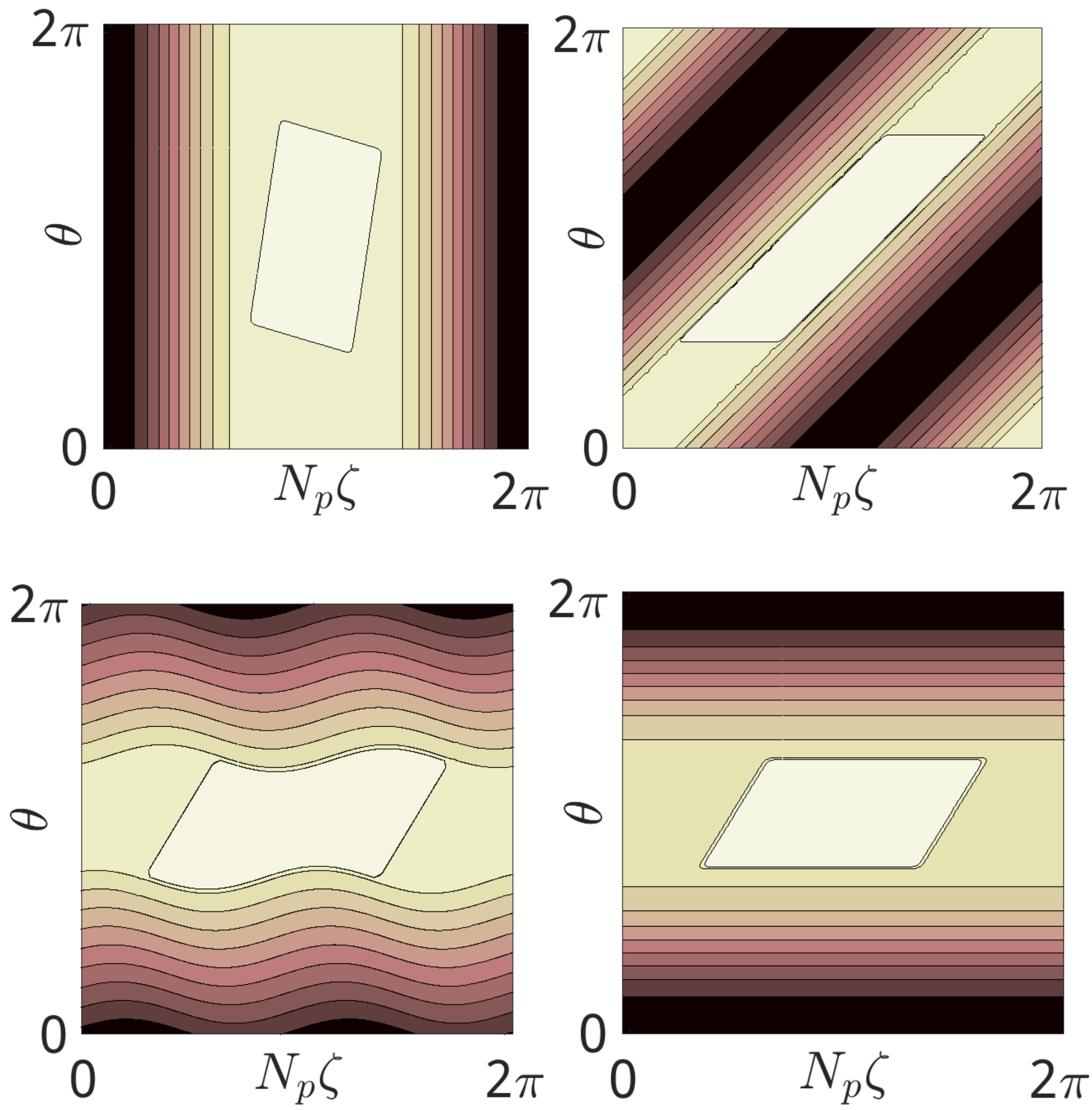

FIG.2 (continued). Examples of piecewise omnigenous fields.

3. THE NEW CONFIGURATION SPACE OF STELLARATOR MAGNETIC FIELDS

Figure 3 shows a diagram that illustrates the configuration space of stellarator fields as a result of the introduction of the notion of piecewise omnigenity.

—The thick black line separates fields in which collisionless orbits are confined from those in which the particles in these orbits drift away from the original magnetic surfaces and quickly leave the device. Piecewise omnigenous fields, omnigenous fields and quasisymmetric field lie within this line and can be candidates for a stellarator fusion reactor.

—The thick dashed line separates fields in which all the contours of constant *B* close in the toroidal, poloidal or helical direction from fields in which this is not the case. Because of this property, these fields can be subsequently separated by dotted lines according to their symmetry direction.

—The thin black lines separates fields in which all the B contours are straight in Boozer coordinates from those in which they can be non-straight.

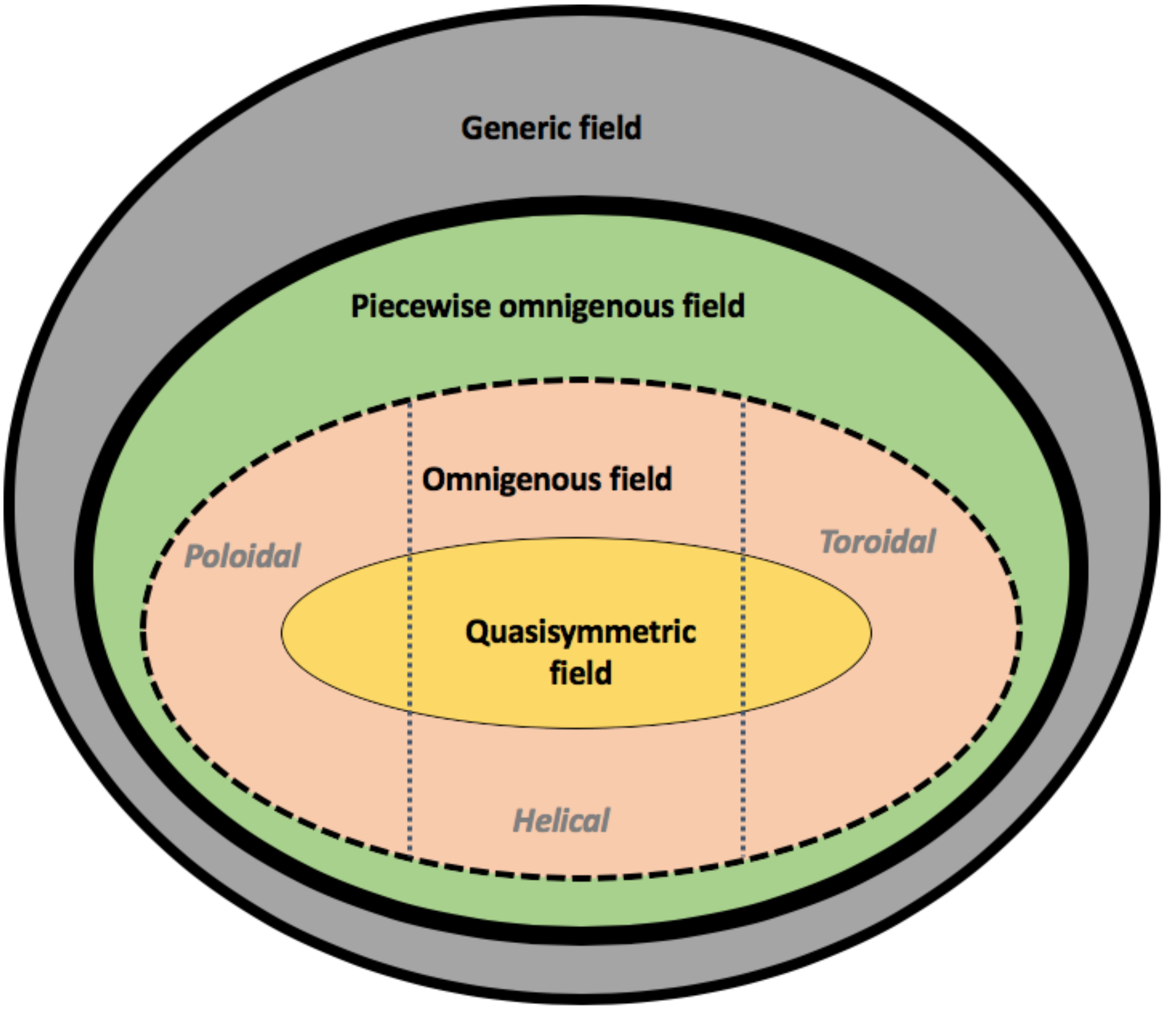

FIG. 3. Diagram illustrating the configuration space of stellarators.

Prior to [14], it was considered that only the fields within the dashed line were suitable for a stellarator reactor. Thanks to the concept of piecewise omnigenity, the family of reactor candidates has been demonstrated to be actually much broader.

4. AN EXAMPLE OF NEARLY PIECEWISE OMNIGENOUS FIELD

Piecewise omnigenous fields, similarly to generic omnigenous fields, are not analytical. For this reason, it could be in principle questionable that such fields can be approximated in magnetohydrodynamic equilibria. Although approximately piecewise omnigenous fields had been already identified [18], in [17] it has been shown that piecewise omnigenous fields can be realized with high level of accuracy. Furthermore, [17] demonstrates, employing the optimization suite DESC [11], that piecewise omnigenity is compatible with the physics design criteria of a stellarator reactor. In this section, in figure 4, we illustrate this with an intermediate magnetic configuration obtained during the optimization campaign with DESC.

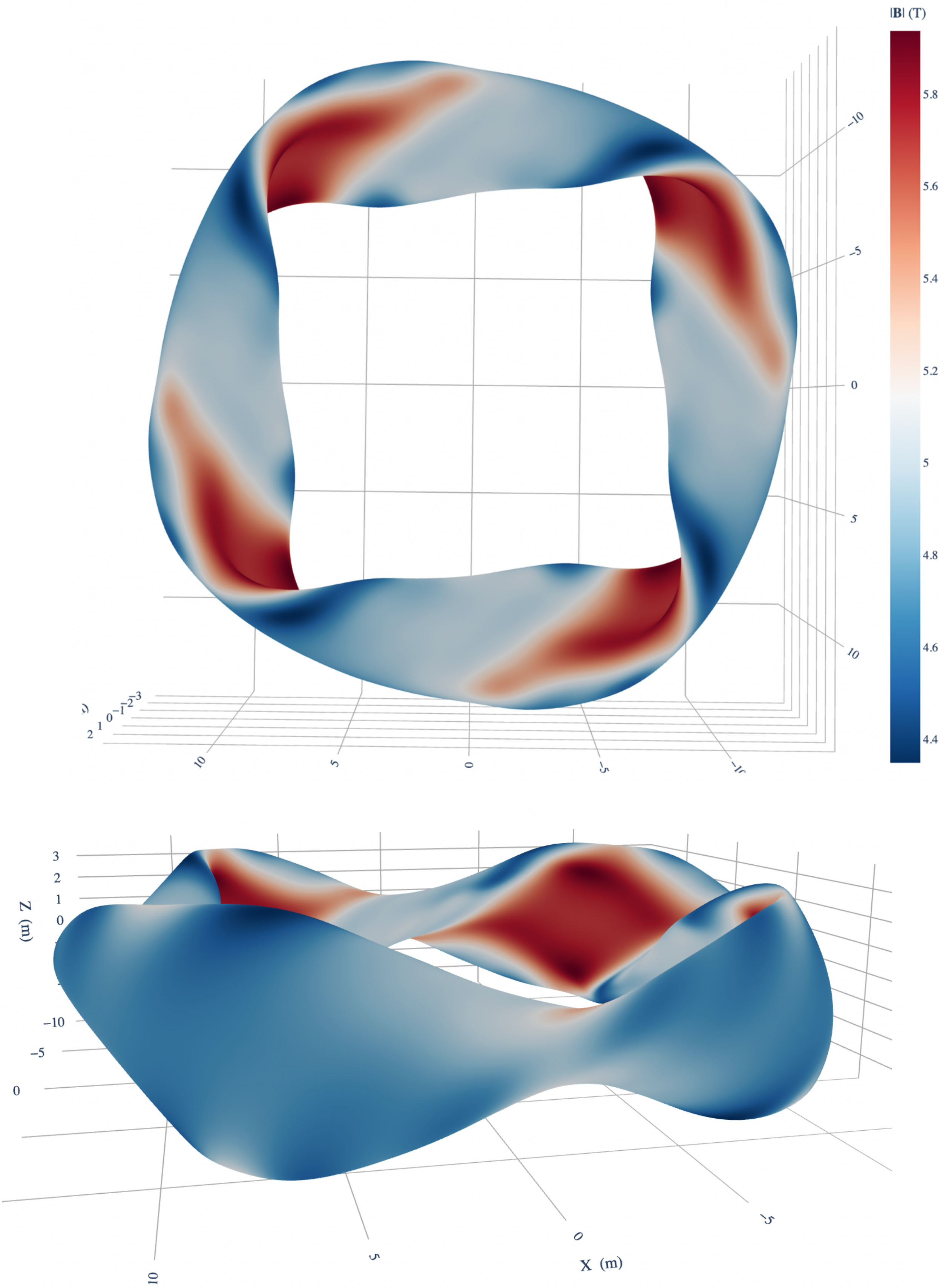

FIG. 4. Example of a magnetic configuration with a nearly piecewise omnigenous field.

5. SUMMARY

The family of reactor-relevant stellarator magnetic fields has been broadened in a series of recent publications [14-17]. Ongoing work aims at fully validating the concept of piecewise omnigenity as a promising candidate for future fusion reactors.

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