Stellarator divertor optimisation for a Stable Quasi-Isodynamic Design (SQuID): magnetic topology, divertor plates and baffle design

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Introduction

In this work we study stellarator divertor optimisation for a "Stable Quasi-Isodynamic Design" (SQuID). SQuIDs are a promising new class of optimised stellarator, receiving significant attention from the public and private sector [1,2,3]. "Quasi-Isodynamic" refers to the method of minimising neoclassical transport and "stable" refers to the fact that these stellarators are linearly MHD stable up to a sufficient plasma β and have relatively low electrostatic turbulent transport compared with existing stellarators. SQuIDs have also been shown to be compatible with buildable magnetic coils [2,3].

Stellarator divertors must address several challenges, for example: heat loads on plasma-facing components (PFCs) and plasma temperatures at the PFCs must be within material limits, and Helium ash and impurities must be efficiently removed to avoid core pollution. To date, the most well-explored stellarator divertor concept, and a natural candidate for SQuIDs, is the island divertor, successfully used by Wendelstein 7-X (W7-X) [4], in which an island chain diverts heat and particles away from the confined region onto divertor plates. Here we examine the edge magnetic topology of and create a first iteration of PFC design for a particular SQuID [2], a four field period device with 40 modular coils (5 distinct shapes, repeated and rotated eight times), a major radius of 20m, an average on-axis magnetic field strength of 7.5T, a core plasma β of β_{core}=8% and 3GW modeled fusion power. A top-down view of the coils and plasma is shown in Figure 1 (left), and the magnetic structure at several toroidal locations at a single plasma β_{core}=8% is shown in Figure 1 (right).

2. Magnetic structure

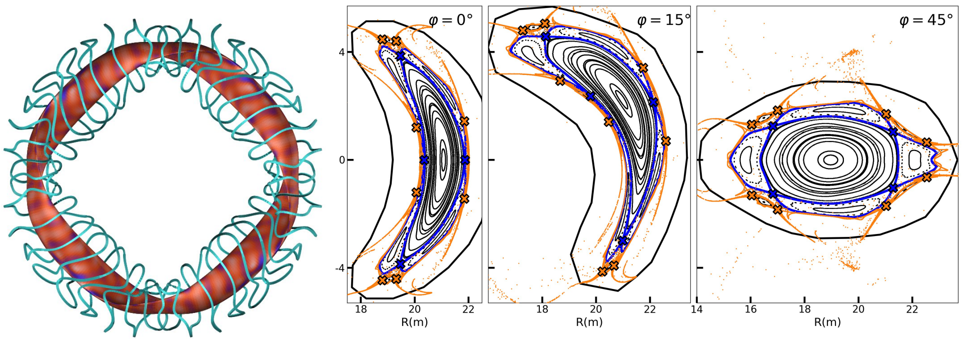

Figure 1. Top-down view of SQuID and magnetic structure (Poincaré and edge structures) at several toroidal locations at β_{core}=8%.

Two edge structures are visible in Figure 1: a conventional 4/4 island chain (blue), and a second set of X-points and O-points (orange). These differ from a normal island chain because there are eight X-points but only four O-points (verified using the scheme presented in [5]). Figure 2 shows these structures at toroidal location φ=45° at several β values, calculated using the HINT code [6]. The conventional island chain changes as β_{core} increases from 0% to 8%: from 4/4 to 8/8, and then back to 4/4 with reversed island phase (X-point → O-point). The second (orange) structures (more precisely, the manifolds of the X-points, see [5] for explanation) appear resilient to β, which could be attractive for divertor design. We refer to these as "tentacles" and examine in section 3 whether they are divertor-relevant.

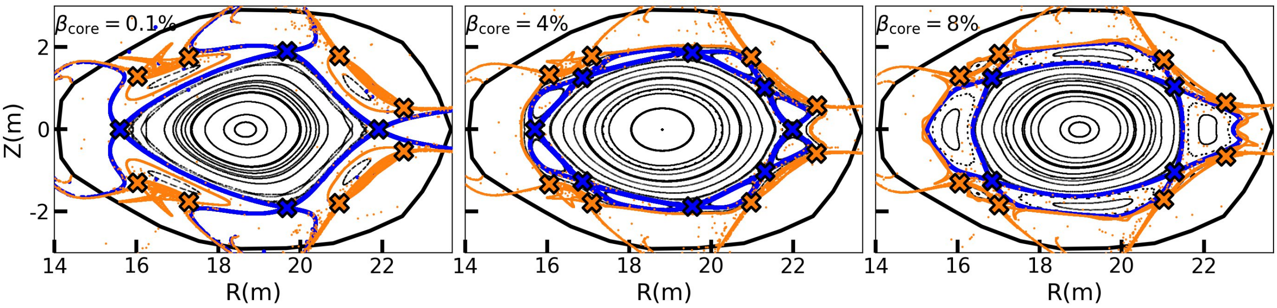

Figure 2. Magnetic structure at several values of plasma β.

Section 3 only considers PFC designs for β_{core}=8%. However, because island phase transition is likely to change the heat and particle strike location, we demonstrate that the phase at β_{core}=0 can be "corrected" to match that at β_{core}=8%, by changing the coil currents but *without* changing the coil geometry. We do this (a Poincaré section and edge structures are shown in Figure 3), by scanning the coil currents and detecting fixed points using a fast automated scheme, which will be described fully in [7]. Changing the coil currents, will affect the neoclassical transport, MHD stability and turbulent transport, although we do not investigate this here. Future work includes designing coils to ensure a β-resilient island phase.

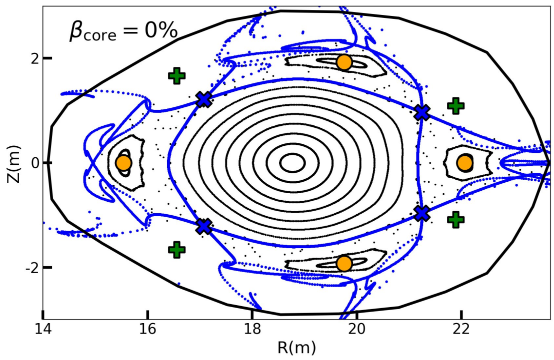

Figure 3. Corrected island phase at β=0.

3. PFC design

We design divertor plates using the scheme presented in [8], with simulated heat loads calculated using an anisotropic diffusion model implemented in EMC3-Lite [9]: $\nabla\cdot\left(-\kappa_e\nabla_{\parallel}T-\chi n\nabla_{\perp}T\right)=0$ (where n, T are the plasma density, temperature, $\kappa_e=\kappa_{e0}T_{LCFS}^{5/2}$ is the parallel thermal conductivity, κ_{e0} is a constant and T_{LCFS} is T at the last closed flux surface and χ is the perpendicular diffusivity).

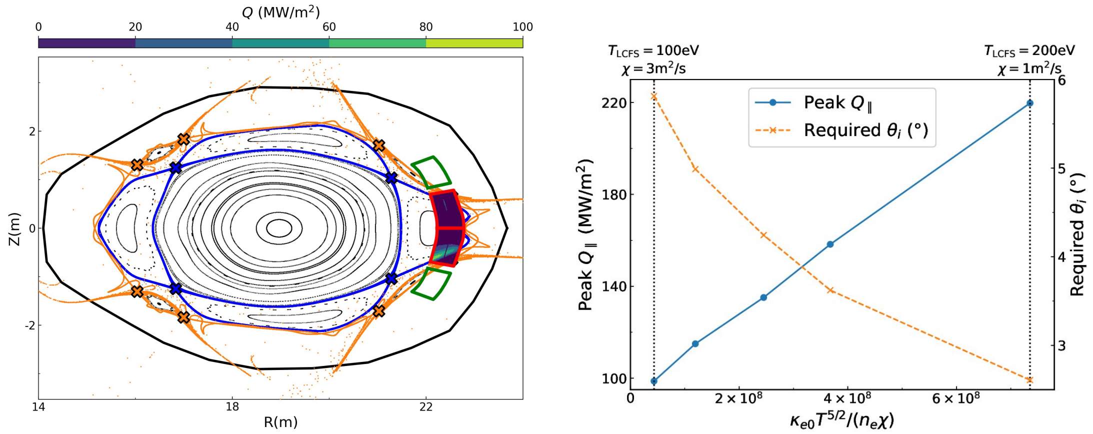

Fig. 4. PFCs for an island divertor. Left: Divertor plates (outlined red) and baffles (outlined green), before being "stretched" along the magnetic field to reduce heat loads. Heat loads shown for T_{LCFS}=100eV, n_{LCFS}=10^{19}m^{-3}, χ=3m^2/s. Right: Peak $Q_{//}$ as a function of parallel-to-perpendicular diffusivity and maximum θ_i which ensures $Q<10MW/m^2$.

Firstly, "vertical plates" are constructed at a single toroidal location, designed to catch a sufficiently high fraction of non-radiated heat. Secondly, the plates are "stretched" along the magnetic field, reducing the incidence angle θ_i and increasing the wetted area to reduce PFC heat loads Q. Two important parameters here are: (1) the assumed non-radiated power, which we take to be 60MW, consistent with 3GW fusion and 90% radiated fraction; (2) the ratio of parallel-to-perpendicular diffusion, $\kappa_e/(n_e\chi)$, which determines the required θ_i assuming the simple relationship $Q=Q_{//}\sin(\theta_i)$ where $Q_{//}$ is the parallel heat flux, and is θ_i-independent. $\kappa_e/(n_e\chi)$ is not known *a priori*; we therefore scan a range of values. Locations where baffles can be placed are also found, using the methodology presented in [10]; we seek locations with low total heat loads and low $Q_{//}$. These are intended to impede the neutral particles, promoting neutral and plasma density build-up at the PFCs.

Figure 4 shows an island divertor for the SQuID; the vertical plates (left subplot) intersect the 4/4 island chain, and are then stretched along the magnetic field to ensure Q<10MW/m^2 for all $\kappa_e/(n_e\chi)$. Baffle locations are also shown. The peak $Q_{//}$ and required θ_i as a function of $\kappa_e/(n_e\chi)$ is shown in Figure 4, right. We also find vertical plates which intersect the tentacles and catch over 90% of the non-radiated heat. To do so, it is necessary to place targets at 2 toroidal locations, φ=0° and φ=45° (shown in Figure 5).

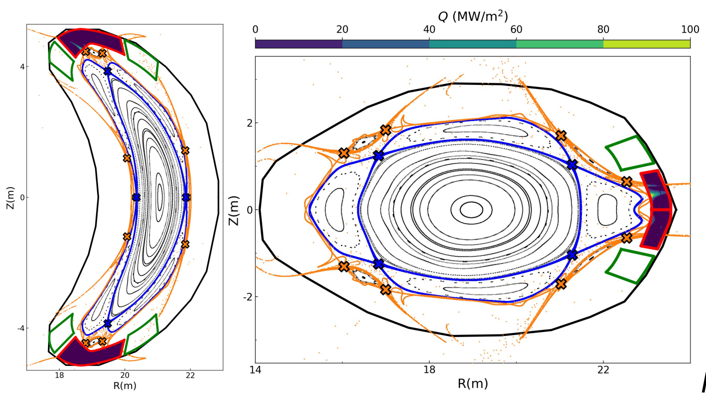

Fig. 5. Divertor plate (red) and baffles

(green) for "tentacle" divertor "vertical plates".

5. Conclusion and outlook

This work describes magnetic topology and PFC design for a SQuID. We show a geometrically "open" island divertor, with divertor plates intersecting a 4/4 island chain. The island chain is sensitive to plasma β; we present a crude phase correction by changing the coil currents. β-resilient island design is future work. We also find β-resilient "tentacles", which appear compatible with divertor plates. Our PFC design scheme, by itself, is insufficient to construct a provably reactor-relevant divertor solution, but serves as a starting point.

The simple transport model used allows fast iterations of PFC design but is the most serious drawback of our scheme. Plasma transport, radiation and neutral dynamics are likely to be complex in a stellarator reactor and require comprehensive high-fidelity simulations. A hierarchy of tools, from cheap but simple to comprehensive but expensive, is likely necessary for reactor-relevant divertor optimisation.

Acknowledgments

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

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