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Coil Design and Equilibrium Studies for a Quasi-Axially Symmetric Tokamak

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Abstract

A system of modular stellarator coils is proposed for a quasi-axially symmetric tokamak. This coil system is used for investigations of the free-boundary MHD equilibrium of the plasma configuration. It is demonstrated that the deformation and outward shift of the equilibrium and the deterioration of the quasi-axial symmetry due to finite $\langle\beta\rangle$ are compensated with good precision by application of a vertical magnetic field. Finally, a design of auxiliary coils for adjusting ι is presented.

Keywords:

quasi-axial symmetry, tokamak, modular coils, MHD equilibrium, tokamak-stellarator hybrid, equilibrium adjustment

1. Introduction

Quasi-axially symmetric tokamaks (QA-tokamaks) are an extension of the conventional tokamak concept [1]. They are based on the fact that for collisionless confinement of the guiding center orbits of the α-particles it is sufficient that the value of the magnetic induction $|\boldsymbol{B}|$ exhibits a symmetry in the magnetic coordinates [2]. In the case of a QA-tokamak configuration the magnetic induction is independent of the toroidal magnetic coordinate. For 3-dimensional QA configurations, part of the rotational transform in the plasma can be generated by the external magnetic field. The associated lower plasma current results in several advantages over the conventional tokamak. In particular, difficulties associated with current drive will be eased and may even be eliminated. The contribution to ι by the plasma currents may be supported by bootstrap current and ECR driven currents solely. On the other hand, creating a magnetic field with finite rotational transform, the coil system for a QA-tokamak will have the same complexity as that of a stellarator.

An optimized plasma equilibrium belonging to the class of QA-tokamaks, with an aspect ratio $A=4$ and a number of field periods $N_p=2$, was proposed by Nührenberg et al. The plasma boundary of this configuration is depicted in Fig. 1.

A set of modular (stellarator) coils was devised to confine a plasma in the outlined configuration. The design procedure used to obtain these coils and the resulting coil set are described in Section 2 of this paper. These coils were used in free-boundary NEMEC calculations to determine the effect of finite $\langle\beta\rangle$ on the plasma configuration and on the Fourier spectrum of the magnetic field. The results of these considerations are presented in Section 3. Finally, a set of auxiliary coils was designed in order to exert control on ι. These coils and their properties are outlined in Section 4.

2. Design of the Modular Coils

A set of modular coils was designed using the extended version of the NESCOIL code [3]. This code seeks the shapes of a current carrying surface (CCS) and of the filaments (the center lines of the coils) on that surface as to optimize the coil configuration with respect to properties of the magnetic field (field error,

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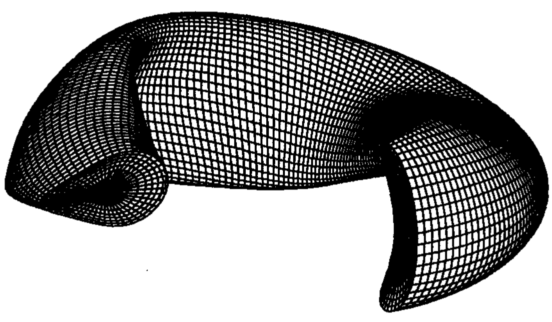

Fig. 1 One and a half of two periods of the plasma boundary of an optimized QA-tokamak.

magnetic well, profile of ι, axis position, magnitudes of islands) and geometrical properties of the filaments (curvature, filament distances, weighted curvature) [5, 6]. The (CCS) was confined to a volume delimited by an inner and an outer constraining surface. These surfaces have a uniform distance of 35 cm and 60 cm resp. from the plasma boundary. The discrete coils result in a ripple of the magnetic field in the confinement region. Keeping this ripple small requires that the distance between adjacent coils be sufficiently small compared with their distance to the plasma boundary. Therefore an approach using 10 coils per machine period was pursued. A view of the coils obtained with these prescriptions is shown in Fig. 2. They reproduce the desired plasma boundary with good precision. The magnetic well (vacuum) exceeds 5.5%. A total poloidal coil current (20 coils) of $I_{pol}=20$ MA is required to achieve a magnetic induction of $B_{axis}=2$ T on the axis. With a cross-section of the winding packs of 16×16 cm^2 this implies a current density of 40 MA/m^2. The minimum curvature radius of the filaments is 37 cm.

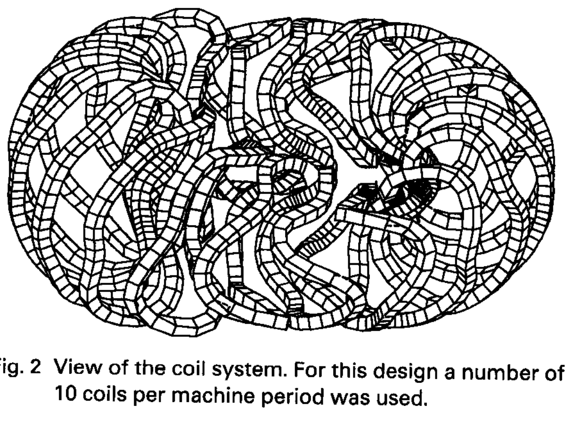

Fig. 2 View of the coil system. For this design a number of 10 coils per machine period was used.

3. Equilibrium Studies

Using the coil system presented, free-boundary calculations of the plasma equilibrium were carried out (NEMEC, [4]). It is observed that effects of finite $\langle\beta\rangle$ and net toroidal plasma current distort the shape of the plasma boundary to some extent. Figure 3 shows the shapes of the flux surfaces and the spectrum of Fourier coefficients of the absolute value of the magnetic field for three different cases. Case (1) is the fixed-boundary computation with vanishing net toroidal current, for which the optimization was carried out. In case (2) a free boundary was assumed and the presence of toroidal currents was simulated by fixing ι to a profile ranging from $\iota=0.75$ on the axis to $\iota=0.55$ at the plasma boundary. Under these conditions the plasma current assumes a value $I_{tor}/I_{pol}=0.85\%$. Case (3) uses the same assumptions, but with an external vertical magnetic field ($B_{z0}/B_{axis}=6.3\%$) applied to correct the effects encountered in (2). It is observed that this correction results in flux surfaces which are closer to those of case (1). Moreover, the spectrum of the magnetic field becomes very similar again to case (1), with the exception of component B_{01} which can be removed by individually adjusting the currents of the modular coils. The net toroidal plasma current increases to $I_{tor}/I_{pol}=1.3\%$.

4. Auxiliary Coils

A set of auxiliary coils as shown in Fig. 4 is proposed to exert control on ι. Using fully 3-dimensional auxiliary coils, such modifications of ι are achieved with little additional error of the magnetic field and good energy efficiency. With a total auxiliary current (8 coils) of $I_{aux}/I_{pol}=5.2\%$ ι on the axis is lifted from $\iota=0.36$ to $\iota=0.407$. The cross-section of the coils is 6×6 cm^2.

5. Summary and Outlook

The method of automated coil optimization was used successfully for designing a coil set for the QA-tokamak proposed. The resulting coils produce the desired field with good accuracy while exhibiting small curvatures and ample spacing between adjacent coils.

Free-boundary equilibrium calculations carried out with these coils reveal a certain sensitivity of the plasma shape and of the Fourier spectrum of the magnetic field to effects from finite $\langle\beta\rangle$ and net toroidal current. It is demonstrated, however, that these effects can be corrected with good precision merely by application of a vertical magnetic field and adjusting the coil currents.

There remain several issues which still must be addressed in the scope of a complete machine design. First, more detailed analysis of stability issues must be

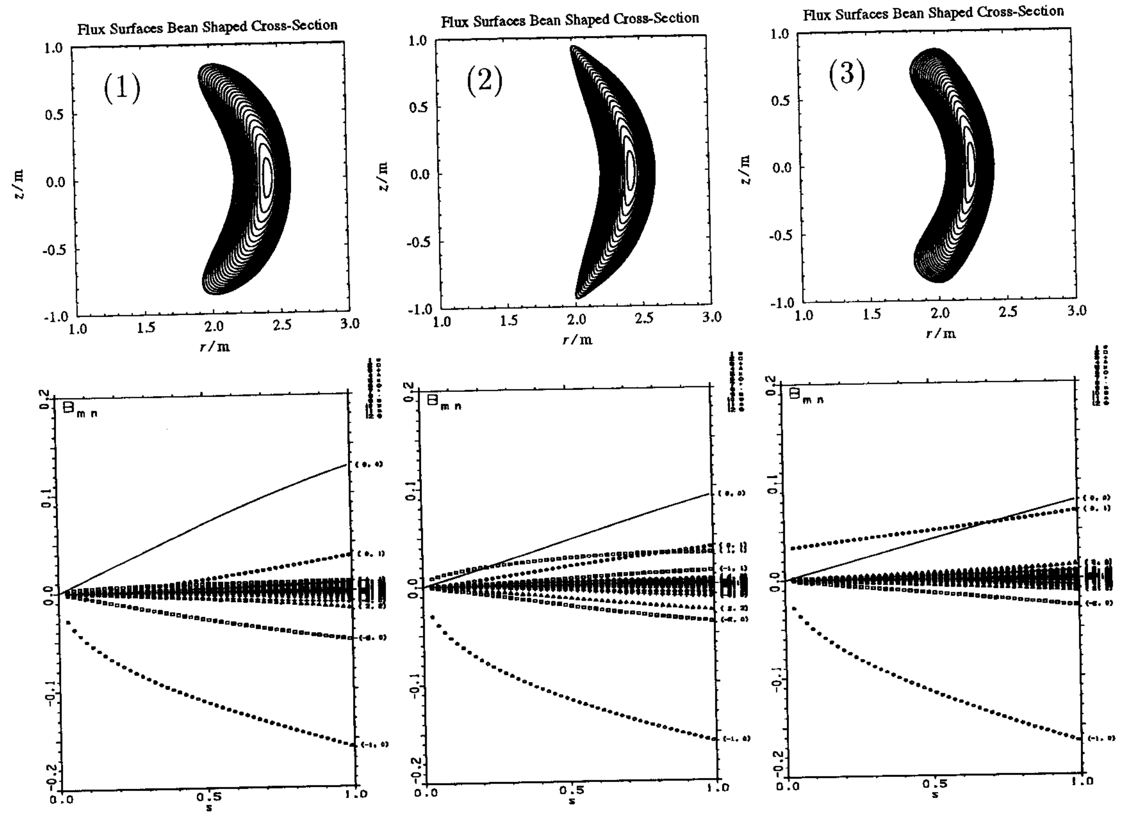

Fig. 3 Flux surfaces (top) and Fourier spectra (bottom) of the magnetic field in magnetic coordinates at different conditions ($\langle\beta\rangle = 2\%$). This figure compares a fixed-boundary case (1) with a free-boundary case featuring a net toroidal plasma current (2) and a case with correction of the equilibrium properties by a vertical magnetic field ($B_{z0}/B_{axis} = 6.3\%$) (3).

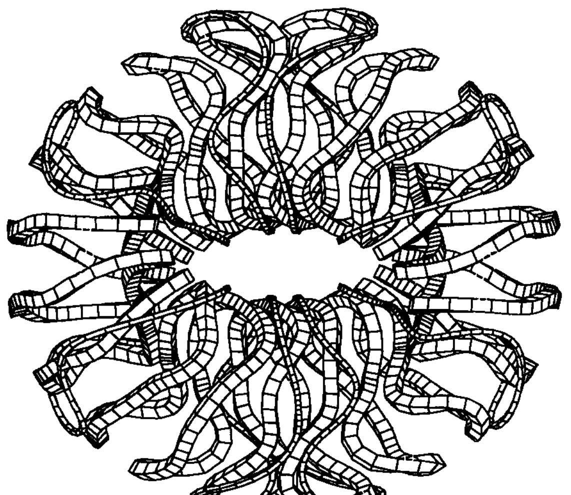

Fig. 4 View of the auxiliary coils mounted on the primary coils. They were designed to fit tighly so that only little space is consumed near the major axis of the machine.

carried out, in particular stability to ballooning modes. Second, free-boundary calculations of the equilibrium including islands should be done, for instance using the HINT code. Finally, neoclassical transport should be simulated and the potential of the configuration for even higher values of $\langle\beta\rangle$ should be explored.

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