Quasi-Isodynamic Configuration with Improved Confinement

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Abstract

The greatest difficulty in stellarator optimisation is to find magnetic configurations capable of confining fast particles well enough to avoid unacceptably large alpha-particle losses in a reactor. At the same time, the neoclassical transport of thermal particles must be kept low and the field should be compatible with a divertor. In the Wendelstein (HELIAS) line of stellarators, the latter relies on the existence of a chain of magnetic islands at the plasma edge, which requires the rotational transform to assume a specific, low-order rational value. This, in turn, calls for the bootstrap current to be minimised.

Here, a highly quasi-isodynamic ([1], [2]) HELIAS-type MHD([3], [4]) equilibrium is presented which exhibits very low neoclassical transport in combination with a stong mirror component of the field, resulting in good confinement of fast particles. In addition, the bootstrap current is kept small. The properties of various coil sets desiged for this configuration are compared and the dependence of the confinement of fusion α particles on the number of coils is investgated.

Configuration Optimisation

Optimisation of the MHD configuration is performed using the ROSE (**R**OSE **O**ptimises **S**tellarator **E**quilibria) code. ROSE uses VMEC[5] to compute an MHD equilibrium and VM2MAG[6] to evaluate the spectrum of the magnetic field in Boozer coordinates [7]. The code is written in C++ and makes use of software created for the ONSET suite of codes ([8] - [10]).

The parameter space subject to optimisation comprises the entire set of Fourier coefficients of the plasma boundary, represented in VMEC as

$$r = \sum_{m,n} r_{mn} \cos\left(2\pi\left(mu - nv\right)\right), \qquad z = \sum_{m,n} z_{mn} \sin\left(2\pi\left(mu - nv\right)\right) \tag{1}$$

where $r_{0,0}$ is always held constant.

The evaluation of the configuration properties generates a penalty function optimised by one of several possible optimisation algorithms. The most important ones include Brent's algorithm [11] and a massively parallel algorithm performing line minimisations in N principal axis directions and superpositions of these axes.

Some of the most important quantities entering into the penalty function minimised by the optimiser include

- ι-profile
- magnetic well
- curvatures of the plasma boundary
- magnetic mirror $R = \frac{B_{max}-B_{min}}{B_{max}+B_{min}}$
- Mercier stability
- quasi-symmetry
- B_{mn}-values and ratii between these
- effective ripple [12]

MHD Configuration

This work presents an approximately quasi-isodynamic configuration. It was obtained by optimising for a small effective ripple on flux surfaces located at $s = 0.4/0.5/0.6/0.75$ while the magnetic mirror was allowed to move freely in the interval $0.1 < R < 0.15$. Moreover, the use of an island divertor requires a small bootstrap current, resulting in a small perturbation of the boundary islands.

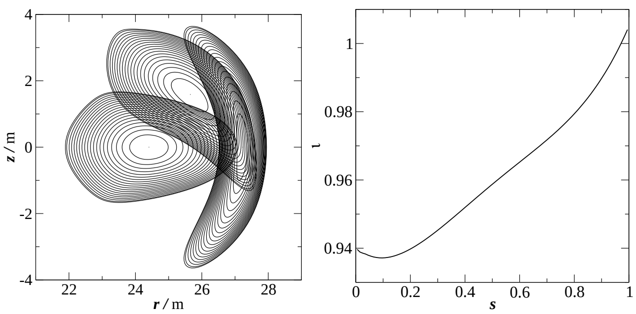

Figure 1: *Toroidal cuts of the flux surfaces of the configuration (left) and radial profile of the rotational transform (right)*

For this purpose, the ι-profile was optimised to lie inside an interval $\iota = 0.92...1.0$. In addition, the ratio of the magnetic field components (Boozer coordinates) $B_{1,0}/B_{1,1}$ was optimised for a prescribed radial profile. The aspect ratio was fixed at $A \sim 12$.

A set of toroidal cuts of the optimised boundary and a plot of the ι-profile are shown in Fig.1. The complete set of Fourier coefficients of the boundary is shown in Table 1.

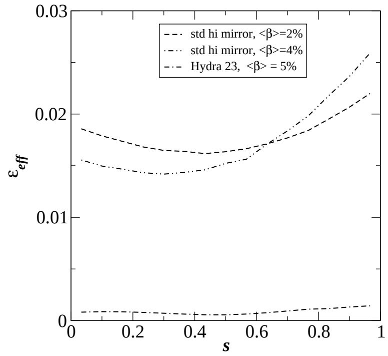

Figure 2: *Effective ripple of the optimised configuration compared with W7-X.*

Transport and Fast Particle Confinement

The neoclassical behaviour was investigated with the 1D transport code NTSS [13] using mono-energetic transport coefficients computed by DKES[14]. The bootstrap current density and the particle densities obtained with this procedure are shown in Fig. 3.

The ability of the configuration to confine fast particles is of paramount importance for the operation of a viable fusion device. Since it is expected that the density will have a rather flat radial profile, it is necessary to confine fusion αs launched at great distances from the magnetic axis. Fig.4 shows the evolution of the α particle loss fraction for different starting surfaces and the losses obtained for a realistic fusion α population correspont ing to the profiles obtained with NTSS.

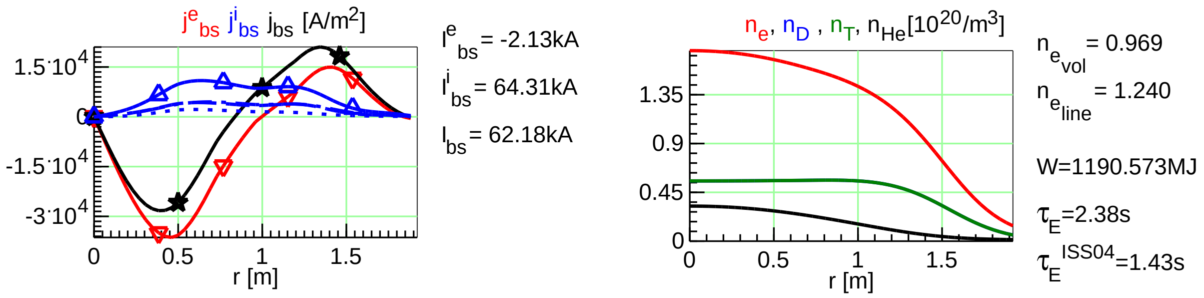

Figure 3: *bootstrap current density (left) and particle density profiles (right).*

Coils and Modular Ripple

Fast-particle losses in stellarators are to a significant degree determined by the magnitude of the modular ripple. This is especially the case for particles located at greater distances from the magnetic axis. Therefore, the dependence of particle losses on the number of modular coils was investigated. Fig.5 shows the losses as a function of time and s for unoptimised coil sets with 8-14 coils per period. It can be seen that the losses decrease noticeably as the number of coils is increased.

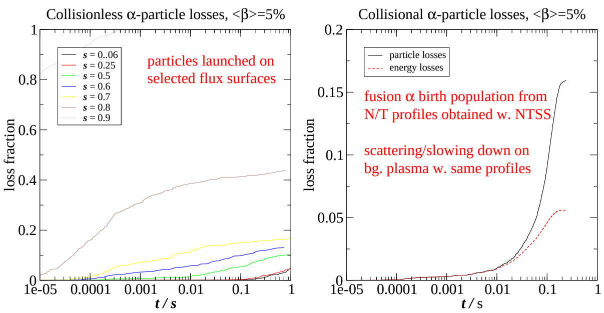

Figure 4: *Particle losses for α particles launched at prescribed radial coordinate (left) and for a realistic fusion population resulting from a 1D transport analysis (right).*

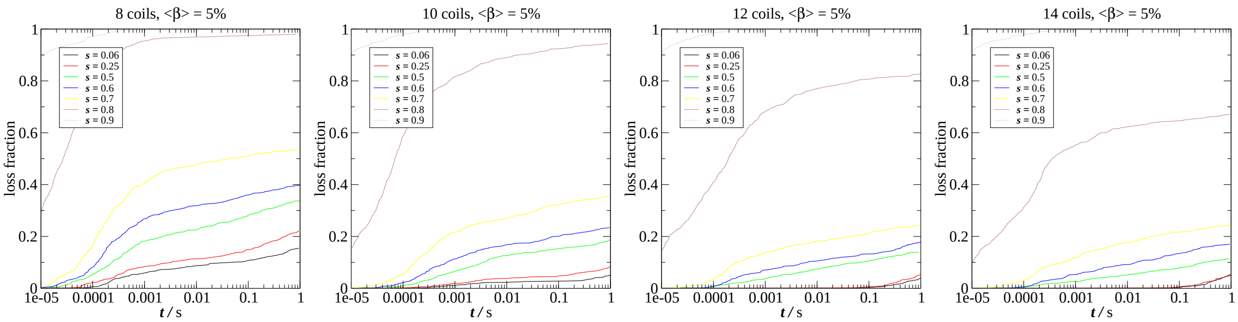

Figure 5: *Collisionless losses of α-particles launched at individual flux surfaces for different numbers of coils.*

Optimised Coils

A first coil design was undertaken using ONSET. Purely modular coil sets encountered difficulties from a series of slanted coil sections located at the inboard side of

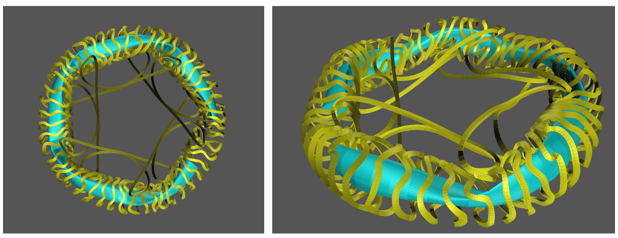

Figure 6: *Tentative coil design including a pair of modulated toroidal coils at the inboard side of the machine.*

the bean-shaped cross section. Fig. 6 shows a coil set where in addition to the modular coils a pair of modulated toroidal (MT) coils is used to mitigate this problem. These MT coils approach the inboard side if the bean shaped cross section so as to mimic a helical coil situated at this location while assuming a greater distance from the plasma at the complementary symmetry plane. In subsequent optimisations it will be attempted to seek plasma configurations that can be espablished with a simpler coil set.

n	m	r_{mn}	z_{mn}
0	0	25.4298	0
1	0	1.09593	-1.36459
2	0	-0.0399858	-0.115748
3	0	-0.00537742	-0.00305466
4	0	0.00174473	-0.00495772
5	0	0.00337058	-0.00034427
-5	1	0.000674323	-0.0023505
-3	1	-0.00514378	-0.0143292
-2	1	-0.0156841	-0.00353282
-1	1	0.151769	0.230968
0	1	1.84208	2.50824
1	1	-1.00169	0.792056
2	1	-0.125854	0.1714
3	1	0.0369412	-0.0179021

n	m	r_{mn}	z_{mn}
4	1	0.0217173	-0.0130012
5	1	0.0044125	0.00522588
-3	2	0.000761007	-0.00430612
-2	2	0.0195295	0.0188931
-1	2	0.0553224	0.109673
0	2	0.221458	0.0817899
1	2	0.11248	0.0287965
2	2	0.258959	-0.20012
3	2	0.0519387	-0.0964283
4	2	-0.00644124	-0.00929519
-3	3	0.0130093	-0.000837961
-2	3	-0.00273641	0.00175197
-1	3	-0.0196624	-0.0219563

n	m	r_{mn}	z_{mn}
0	3	0.00202364	0.0535335
1	3	-0.0146856	-0.0502491
2	3	-0.0768693	-0.0385529
3	3	-0.0921131	0.0784001
4	3	0.00394272	0.0147176
-2	4	-0.00547501	-0.00235218
0	4	-0.0311839	-0.031407
1	4	0.0511426	0.0335454
2	4	0.00529469	0.0423136
3	4	0.0156413	-0.0218105
-1	5	-0.00533847	-0.00642917
0	5	0.000311829	0.00602492
1	5	-0.00507777	0.00560832
3	5	0.00242683	0.00985353

Table 1: *Fourier coefficients of the optimised plasma boundary*

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