Improved Fast Particle Confinement from Optimised Coil Currents

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Abstract

One of the principal goals of the W7-X stellarator is to demonstrate good confinement of energetic ions at finite β. This confinement is however sensitive to details of the magnetic field configuration and is thus vulnerable to small design modifications of the coil geometry. Here, the collisionless drift orbit losses for 60keV protons in W7-X are studied using the ANTS code.

Several approaches to adjust the coil currents (5 main field coil currents + 2 auxiliary coil currents) for improved confinement were applied. These strategies include human experience as well as nonlinear optimisation of various properties of the magnetic field.

It is shown that significant improvement of fast particle confinement can be achieved. As a consequence, the experimental goal of demonstrating confinement improvement with rising plasma pressure is recovered.

1 Introduction

Stellarator reactors, like any viable fusion device, need to confine fast α-particles long enough so that heating of the majority plasma by these particles can maintain sustained plasma burn. One of the primary goals of the W7-X experiment is to demonstrate that optimised stellarators can achieve good confinement of energetic ions at finite β. This confinement is however sensitive to details of the magnetic field configuration and is thus vulnerable to small design modifications of the coil geometry.

Fig. 1 shows a comparison of the confinement behaviour for fast particles of an early design configuration [1] (fixed boundary VMEC [2] solution) and the actual machine (free boundary VMEC w. external coils). Shown are loss fractions of 60 keV protons injected at a normalised flux of $s = 0.06$, corresponding to a quarter normalised radius. The magnetic field on the axis was set to 2.5T. The results are obtained from a collisionless integration of the drift orbits in a magnetic field obtained from VMEC calculations (finite $\langle\beta\rangle$) or directly from the external coils (vacuum). Particle loss was detected when the particles leave the VMEC domain. It can be seen that, while the behaviour at $\langle\beta\rangle$=0 is similar, the losses at finite $\langle\beta\rangle$ are enhanced in the case of the actual machine. Note that for $\langle\beta\rangle = 4\%$, the losses have accumulated to $> 13\%$ at $t = 0.1$s. The extent of the deterioration is such that a primary goal of W7-X, the demonstration of fast particle confinement in optimised stellarators, would be lost.

2 The ANTS Code

The collisionless drift orbit losses for 60keV protons in W7-X are studied using the ANTS (plasm**A** simulatio**N** with drif**T** and collision**S**) code. This code is a full-f Monte Carlo code created using existing code originally written for the ONSET [3] and EXTENDER [4] packages. In particluar, the code is able to use the entire range of coil types available from the ONSET package in order to describe the external magnetic field. Moreover, the same range of classes for the representation of mesh fields is used.

For integrating the drift orbits, ANTS keeps a mesh field covering the entire domain of computation, and the integration of the particle orbits is carried out in cartesian coordinates. This approach provides the greatest flexibility and also facilitates a faithful treatment of magnetic fields with islands or stochastic regions.

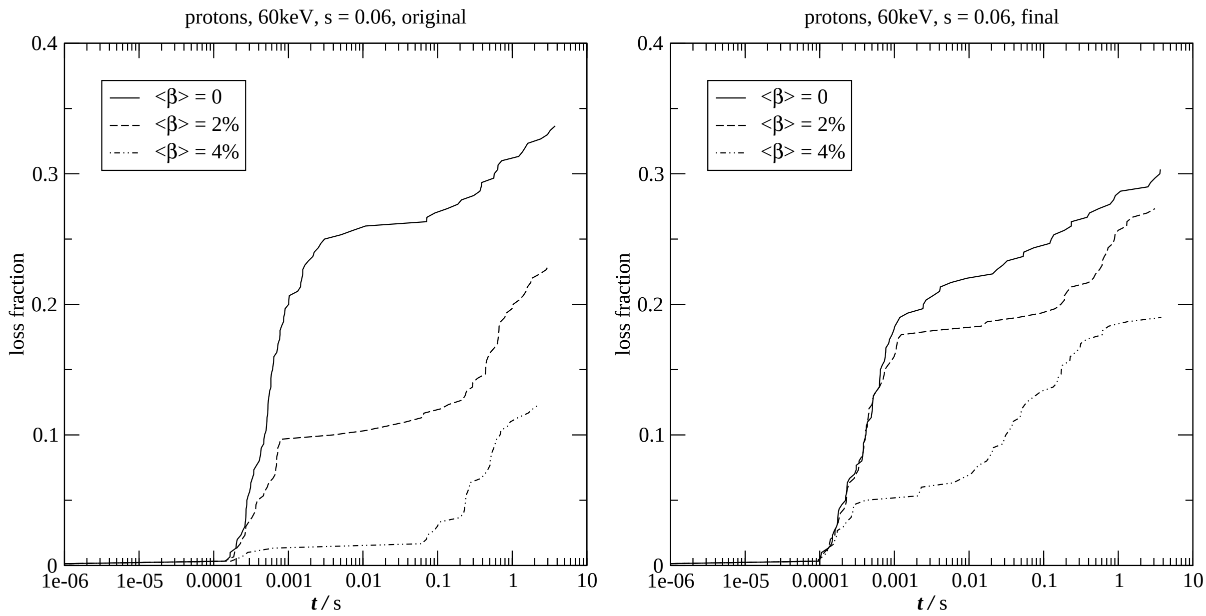

Figure 1: simulated loss fraction of 60keV protons in the design configuration (left) and the actual machine (right). The simulations were carried out with 300 particles.

3 Optimisation Approaches

Once the geometry of the coils creating the magnetic field in a stellarator is fixed, there remain several factors which have the potential to influence the confinement behaviour of the device. Firstly, the currents in the coils can be adjusted so as to influence the magnetic field. Secondly, the shape of the pressure profile can be modified. In particular, a more peaked pressure profile can lead to a redistribution of the plasma currents that results in an improved confinement of particles deep inside the plasma.

In the work presented here, the pressure profile was kept fixed at $p \sim 1-s$ as this was considered a safe and conservatice choice. Any improvements of the presssure profile to a steeper shape would then hold the potential to improve confinement beyond what will predicted in this paper. This is in contrast to [5], where an optimisation of the pressure profile was included in an effort to improve the confinement behaviour.

Several approaches to adjust the coil currents (5 main field coil currents + 2 auxiliary coil currents) for optimised confinement were applied.

1. **Experience**
   The idea is to keep the velocity of the trapped particles parallel to $\vec{B}$ constant as long as possible. At the same time, the reflection of the particles is effected in toroidal regions as narrow as possible so as to minimise the radial drifts occurring as a by-product. On a flux surface this may be achieved by keeping $|B|$ flat around the field minimum and extending this region toroidally as far as possible. As a consequence, the gradients of $|B|$ are concentrated around the toroidal location of the field maxima which are located at the tips of the bean shaped cross sections. The resulting configurations approximate an ideal linked-mirror field with almost the same mirror length for all trapped particles.

2. **Min-Max**
   was obtained by minimising the variance of B at the B_{min}-contour (pentagonal

cross section) and B_{max}-contour (bean shaped cross section). The optimisation was performed for a flux surface 6cm off the magnetic axis.

3. **Hybrid**
   was obtained by minimising the variance of $|B|$ on the B_{min}-contour (pentagonal cross section) and variance of the second adiabatic invariant J for barely trapped particles. Again, a surface 6cm off axis was used.

4. **J Variance**
   was obtained by minimising the variance of J for differently deeply trapped particles. A surface 6cm off axis was used for the optimisation.

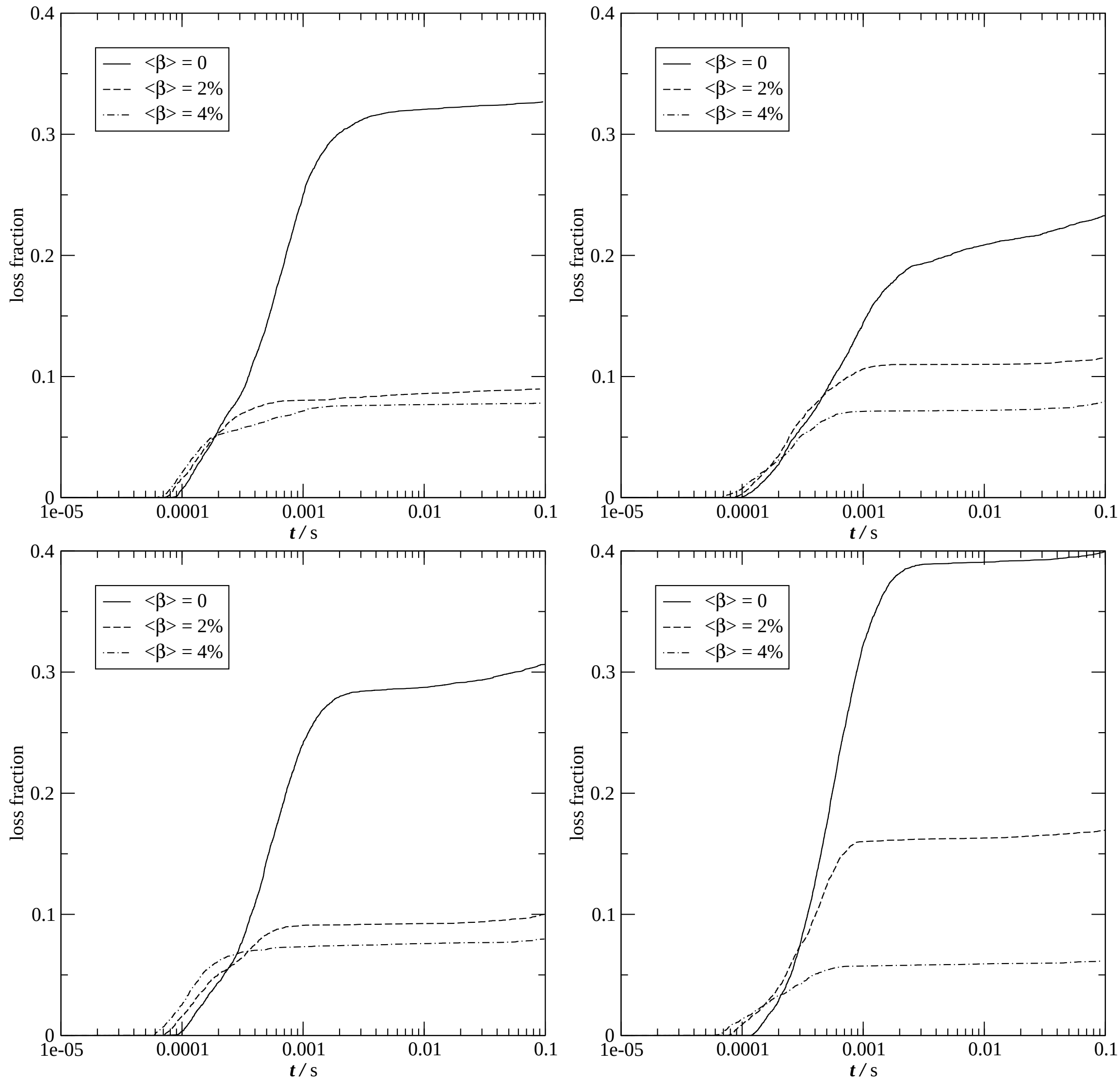

Figure 2: Loss fraction over time for the four optimised configurations. Shown are the configurations “Experience” (top left), “Min.-Max.” (top right), “Hybrid” (bottom left) and “var(J)” (bottom right).

The optimisations 2-4 were carried out with alternating runs of ONSET, VMEC and EXTENDER. In this procedure, ONSET was used to optimise the 5+2 coil currents according to the aforementioned criteria. During this optimisation, the magnetic field from the plasma currents, which was included in the total magnetic field, was held fixed. Once the optimisation had converged, VMEC was used to calculate a free boundary equilibrium for the new coil currents. Finally, the new magnetic field from the plasma currents was obtained using EXTENDER. This loop over consecutive current optimisations and VMEC calculations converges after a few iterations.

4 Results

The coil currents obtained with the optimisation approaches outlined in section 3 are summarised in Table 1.

Configuration	Coil Current / A.U.						
	1	2	3	4	5	A	B
Standard	1.0	1.0	1.0	1.0	1.0	0.0	0.0
Experience	1.366	1.161	0.888	1.093	1.038	-0.455	-0.0911
Min.-Max.	1.107	0.996	0.886	1.020	0.931	0.0115	0.0485
Hybrid	1.179	0.916	0.737	0.988	0.953	0.159	0.0666
var (J)	1.377	0.899	0.746	0.863	0.901	0.15	0.0648

Table 1: Relative magnitudes of the coil currents for the primary modular coils (1-5) and the auxiliary coils (A,B). Counting starts at the bean shaped cross section.

The confinement behaviour of the configurations obtained with the procedure described in Section 3 was simulated using the ANTS code. The evolution of the loss fraction with time for the optimised configurations is shown in Fig. 2. It can be seen that, while the results differ to some extent, the losses at finite $\langle\beta\rangle$ are reduced to about 10% .

5 Conclusions

It was shown that it is possible to improve the confinement behaviour for fast ions in W7-X by adjusting the currents in the main and auxiliary coils. The extent of the improvement is similar for all 4 cases investigated, albeit with a stronger dependence on β in the case of the pure J-optimisation. In each case, the improvement is large enough to enable W7-X to demonstrate its ability to achieve pressure - induced confinement of fast particles.

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