Improvement of energetic particle confinement through stellarator optimization

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Stellarator designs with good predicted energetic particle confinement are key to forwarding the stellarator concept as a reactor design. In a nuclear fusion reactor, alpha particles produced by the deuterium-tritium reaction must stay inside the plasma volume long enough to thermalize with the background plasma. Numerical optimisation of stellarator equilibria has already been used to demonstrate improvements in neoclassical confinement [1], the possibility of reduced turbulent transport [2], and inherent MHD stability [3] (no disruptions). In this paper, the capability to optimise stellarator designs for energetic particle confinement using the STELLOPT [5] and BEAMS3D [4] codes is documented.

Optimisation of stellarator equilibria has been carried out using the STELLOPT optimiser coupled to the BEAMS3D guiding center code. The STELLOPT code is designed to optimise the input parameters of an ideal MHD equilibrium (VMEC [6]) to various target physics parameters using Levenberg-Marquardt, Differential Evolution, and Particle Swarm optimisation techniques. In this work, the boundary harmonics (in Hirshman-Breslau form) of the NCSX fixed boundary baseline (LI383) are optimised with regards to Ballooning stability (provided by COBRA) and energetic particle targets. Sigmas are chosen so as to weight the chi-squared function toward energetic particle confinement. The BEAMS3D code provides a means to calculate the energetic particle orbits. Originally designed for neutral beam injection simulations, the code has been interfaced to STELLOPT allowing a user defined particle birth profile to be chosen. In this work, two energetic particle starting grids were used. The initial and 'optimised' equilibrium were evaluated using

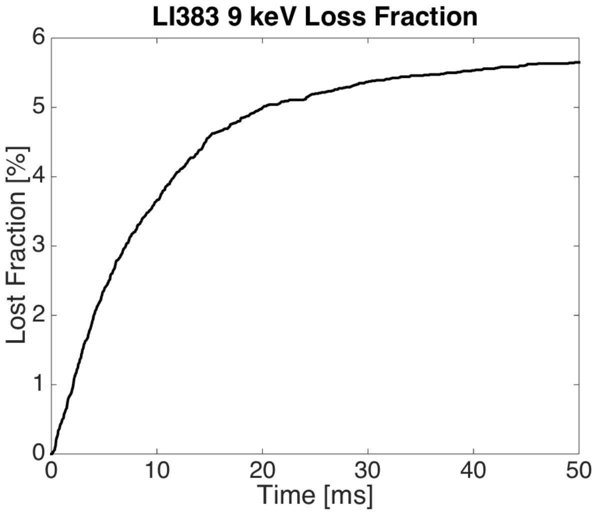

Figure 1: *9 keV proton loss rate in the LI383 configuration.*

12,000 particles, with particles born on a 20 by 20 grid in poloidal and toroidal space. In these runs, 30 pitch-angles were considered. In order to make the optimisation tractable on the Hydra cluster, a reduced set of particles was considered focusing on larger pitch angles particles (which were driving the majority of the losses). In all cases the particles were launched from the $s = 0.05$ (normalised toroidal flux) surface and had a total energy of 9 keV. Protons of this energy in NCSX have the same gyroradius to minor radius ratio as 3.5 MeV alpha particles in the ARIES-CS device. Particles were followed for 50 ms of simulated time as the loss fraction appears to asymptote by this point (Figure 1). The total time for conducting such a simulation is reduced through the parallel computation of the BEAMS3D code and that of STELLOPT.

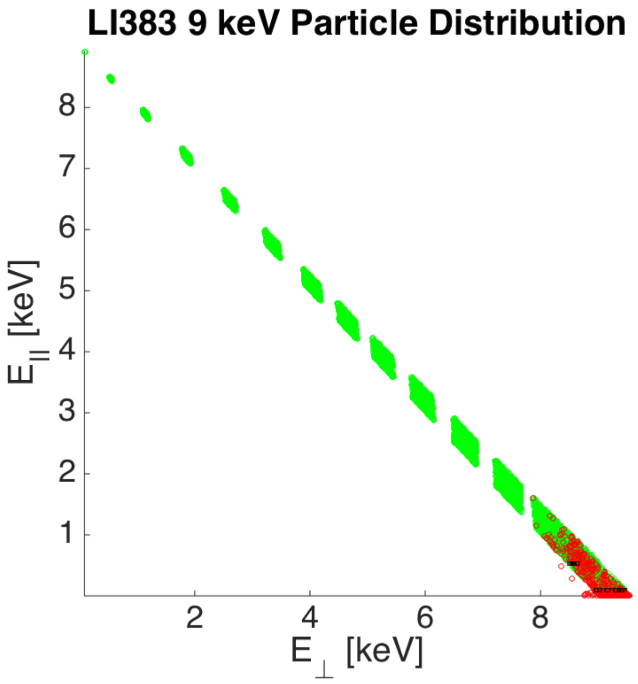

Figure 2: *Initial (sqaure) and final (circle) 9 keV particle velocity space distribution. Lost particles (red) are localised to large pitch angle, while confined particles (green) span make up a significant fraction of the population.*

In order to determine if particles are lost, a wall collision model has been integrated into the BEAMS3D code. The wall is modelled using triangular tessellation, allowing both simple and complex geometries. Calculation of collisions between a particle trajectory and the wall is done using ray tracing. Every time-step the code determines if the ray formed by the particle position at the previous time-step and the current time-step intersects one the the triangles defining the wall. If the trajectory strikes the wall, the strike location is saved and trajectory integration for that particle ends. For the fixed boundary equilibrium used in this work, the VMEC boundary for a given equilibrium is used to generate a tessellated wall composed of 120 points in the poloidal and toroidal direction.

The optimisation begins with an initial evaluation of particle confinement in the LI383 equilibrium. In this configuration, particles are uniformly lost from the flux surface. No one starting location for the particles appears to be more ill-conditioned to confine particles than another. Examining the velocity space distribution it becomes clear that losses are coming from particles with fairly large pitch angles (Figure 2). While in experimental devices this can be solved by tangential neutral beam injection, a reactor suffers from a more isotropic alpha particle distribution. It should also be noted that the total percentage of lost particles is in line for predictions made for the NCSX stellarator at 40 keV neutral beam injection [7]. Note that in these calculations no slowing down or scattering effects were included.

Figure 3 depicts the successive reduction in particle losses as the optimiser found new minima. In each case changes to the equilibria were small, highlighting the high sensitivity of the equilibrium to boundary changes. Examination of the parameter space Jacobian shows that the $n = 1$ modes tend to dominate the descent. These modes show the steepest gradients. The Levenberg trajectory, calculated by STELLOPT, found minima which were not of lower value than those found during the Jacobian evaluation. Thus the STEPOPT routine turns on which evaluates combinations of the finite difference calculation yielding the greatest reduction in Chi-squared ($\chi^2 = \sum \left(f_i^{target} - f_i^{equil.} \right)^2 / \sigma_i^2$). This contributed to the relatively small changes in the equilibrium.

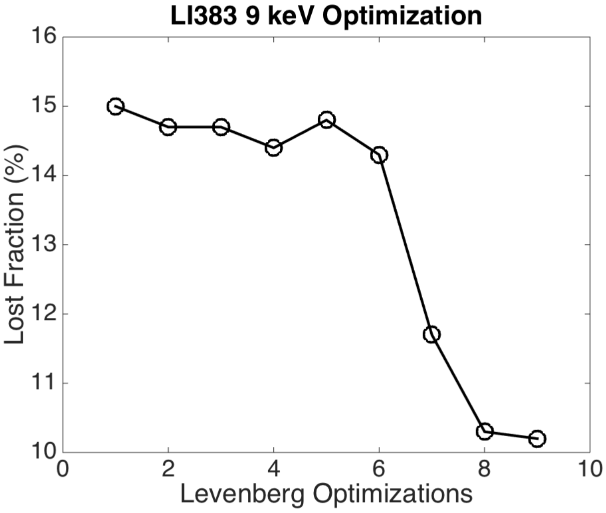

Figure 3: *Optimisation of particle losses using reduced particle set. The bump at iteration 5 is due to the equilibrium being restarted from iteration 3.*

The final optimised configuration shows a reduction in lost particle fraction from 5.4% to 5.2% overall. This comes after the sub-population, with pitch angles in the range of $v_{\|}/v_{\perp} = [0.1, 1.0]$, saw a reduction of lost particles from 15% down to just above 10%. Work is underway to develop runs with larger particle populations in order to drive down losses. The current runs are limited by the available processors and 24 hours simulation time.

The capability to optimise stellarator equilibrium for improved energetic particle confinement is being developed using the NCSX baseline configuration. In this work, 9 keV protons were utilised as a proxy for 3.5 MeV alpha particles in ARIES-CS. Given the current computational resources (10,000 processors for 24 hrs), runs with over 10,000 particles proved problematic for optimisations. This could be alleviated by longer runs and a larger number of processors. Given the scaling documented on the Hydra machine, a single Levenberg optimisation using 10,000 particles in 24 hours time would require around 90,000 processors. It may also be possible to improve the results using a reduced set of particles by increasing the number of particles modestly.

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