Improvement of energetic particle confinement through stellarator optimisation

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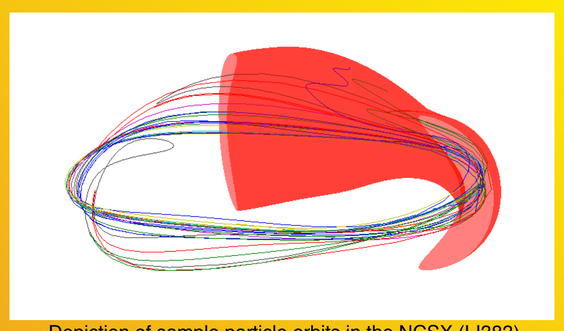
Introduction

A magnetic confinement nuclear fusion reactor based on the stellarator concept must be able to show that the majority of energetic particles (EP) stay confined long enough to deposit their energy in the bulk plasma. The large dimensionality of the stellarator optimization problem, coupled with the demonstrated capability to reduce neoclassical transport through optimization [1], motivates an optimization where improved energetic particle confinement is targeted. To this end, the BEAMS3D code [2] has been interfaced to the STELLOPT optimizer to evaluate the guiding center trajectories of an ensemble of particles.



Depiction of sample particle orbits in the NCSX (LI383) equilibrium. Trapped, passing, and lost orbits are depicted along with the equilibrium boundary over a single field period.

In this work, the first attempts to optimise a stellarator equilibrium for improved energetic particle confinement are documented. Results suggest machines with greater than 10,000 processors would be of great value to this work.

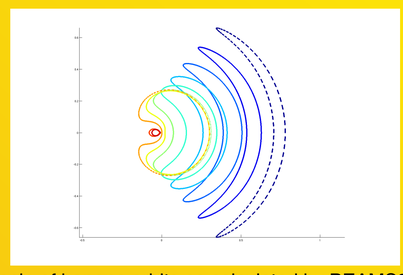
Method

The BEAMS3D code provides a means to track particle orbits given a magnetic field

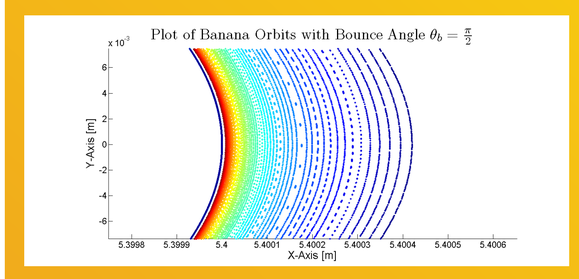
- Collisionless particle orbits
- Gyro-center motion
- Developed for stellarator neutral beam injection modelling
- All equilibrium quantities specified on cylindrical grid (R,PHI,Z)
- MPI based parallelisation over field construction and particle orbits

$$\frac{d\vec{R}}{dr} = \frac{\hat{b}}{qB} \times \left(\mu \nabla B + \frac{m v_{\|}^2}{B} \left(\hat{b} \cdot \nabla \right) \vec{B} \right) + v_{\|} \hat{b}$$

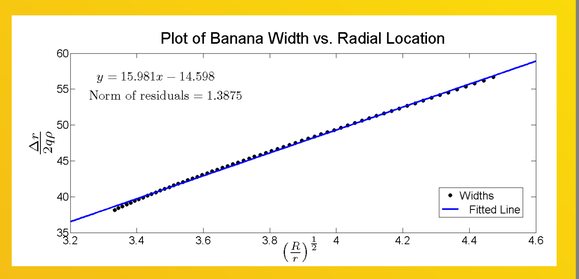
$$\frac{dv_{\|}}{dt} = -\frac{\mu}{m} \hat{b} \cdot \left(\nabla B \right)$$



Example of banana orbits as calculated by BEAMS3D code.



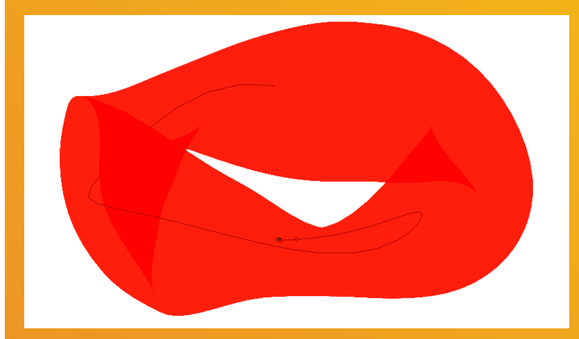
Banana orbits as calculated by BEAMS3D in an aspect ratio 10 circular cross section tokamak equilibrium.



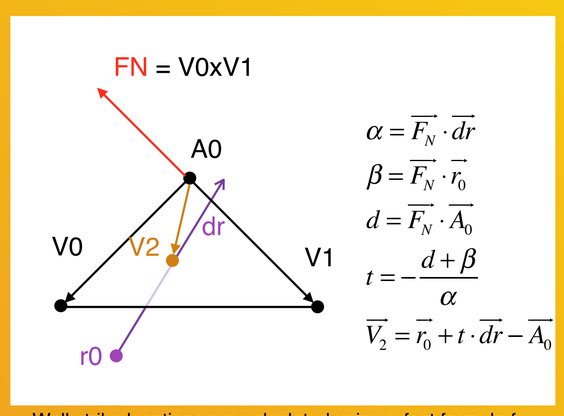
Linear scaling of banana orbit width is consistent with analytic results for trapped particles in this magnetic field

To optimise energetic particle confinement the BEAMS3D code was interfaced to STELLOPT

- Takes advantage of STELLOPT's new ability to run parallel codes inside it's parallel optimisers.
- Collision detection added to BEAMS3D using triangular tessellation of surfaces.
- Fixed boundary optimisation possible by treating VMEC boundary as tessellated surface.



Example particle orbit showing the path and subsequent loss of the particle through the VMEC boundary. Circles denote the last saved location before collision, the point of collision and the point just outside the VMEC boundary at which integration was terminated.



Wall strike locations are calculated using a fast formula for determination of the intersection of a line segment and a triangle.

The simulations presented here will focus on confinement of 9 [keV] protons in the NCSX baseline equilibrium.

- Proxy for 3.5 [MeV] alpha particles in ARIES-CS (rho/a preserved)
- 20x20 mesh used on the s=0.05 flux surface
- 30 distinct pitch angles examined (total of 12,000 particles per calculation)

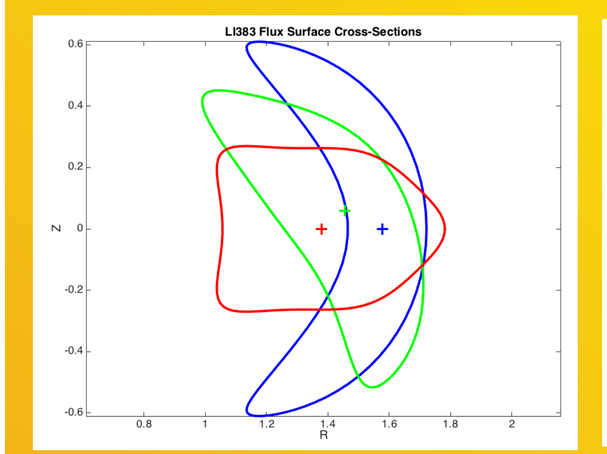
	NCSX	ARIES-CS
Particle	Proton	Alpha
Z	1	2
m [kg]	1.6026E-27	6.6442E-27
B-Field [T]	1.5	5.7
Minor Radius (a)	0.326	1.70
Energy [keV]	9	3500

$$\frac{\rho}{a} \propto \frac{\sqrt{mE}}{ZBa}$$

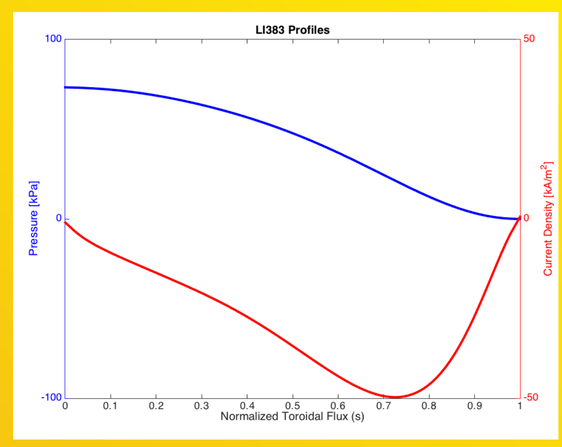
Results

The NCSX LI383 fixed boundary equilibrium was utilised as an initial condition for the optimiser

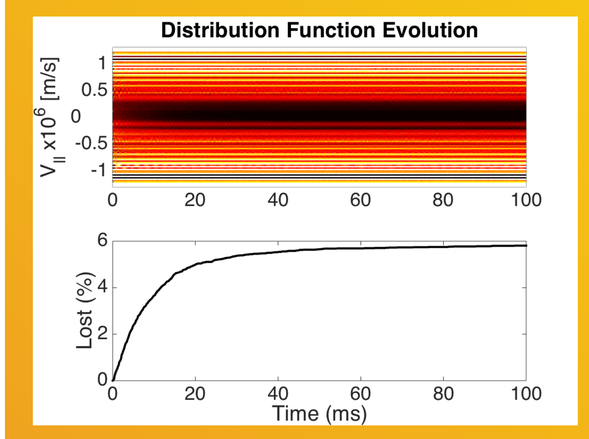
- Finite beta and current equilibrium
- Optimised using the Hirshman-Breslau boundary representation



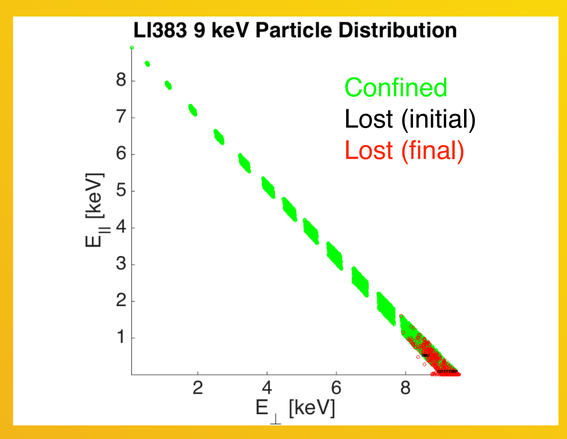
Three toroidal cuts of the LI383 equilibrium indicating its general shape.



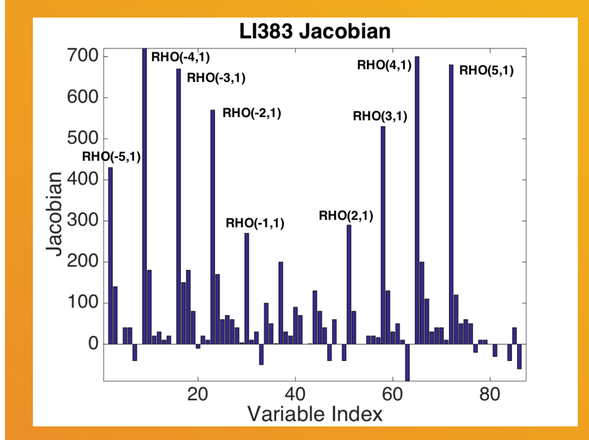
Pressure and current profile for this 4.2% beta and -174 [kA] equilibrium.



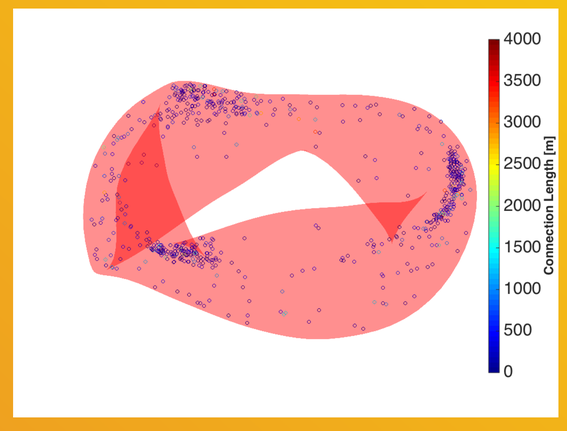
Evolution of parallel velocities (top) and loss fraction (bottom) for an ensemble of 9 [keV] protons launched from the s=0.05 flux surface. 12,000 particles were used for this simulation and 10,000 processors.



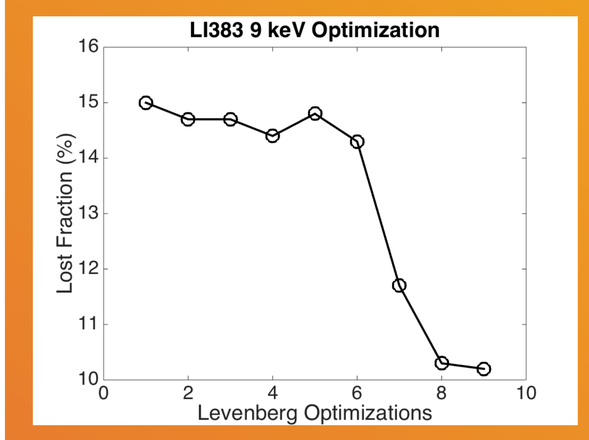
Losses of particles appear to be from particles with fairly large pitch angles. Initial location of the particle along the flux surface played little role in confinement. A subset of particles was used to speed up the optimisation.



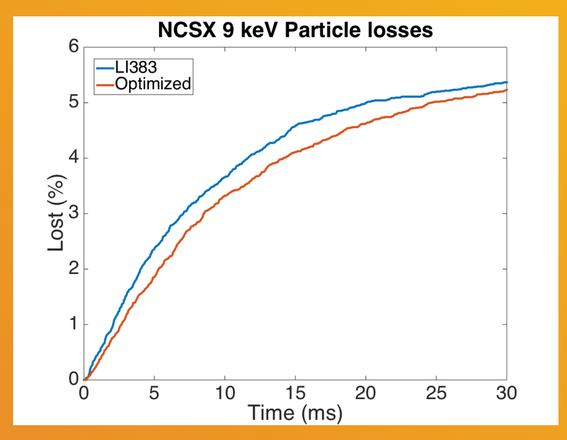
The STELLOPT jacobian for energetic particle confinement allows identification of relevant modes to particle confinement. The m=1 modes displayed the largest effect on confinement of



Strike points for lost particles with color coded connection lengths. Note the large number of particle promptly loss near the 'bullet' cross-section.



The Levenberg-Marquardt optimiser was used to reduce the number of lost particles. For the optimisation a set of 1000 large pitch angle particles were used to speed up the code.



Lost particle fraction for initial and optimised case. Changes in lost particle fraction were small suggesting an insufficient number of particles were used in the optimisation steps.

Discussion

A first exercise in energetic particle optimisation using STELLOPT with the newly coupled BEAM3D energetic particle code has been conducted. This exercise has demonstrated a few key points for future work:

- Simulations with many particles take significant computational resources (4hrs to run 12,000 particles with 4000 processors).
- Optimisation dominated by n=1 modes.
- Losses dominated by particles with predominately perpendicularly directed energy.

References

[1] Canik J M, Anderson D, Anderson F, Likin K, Talmadge J and Zhai K, Phys. Rev. Lett. 98, 085002 (2007)

[2] McMillan M and Lazerson S Plasma Physics and Controlled Fusion 56, 095019 (2014)