27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** (2000) 1040 -1043

Transport and Stability of Compact Drift Optimized Stellarators*

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The design of compact stellarators at aspect ratios $A = R/\langle a \rangle$ in the range $2 < A < 4$ is motivated by the desire to realize a more economically-sized, higher-power-density fusion reactor with little or no recirculating power and freedom from disruptions. For aspect ratios in this range, which are smaller than for any existing stellarators, the strong geometric toroidal and helical couplings necessarily require detailed numerical calculations to obtain credible stellarator designs. This strong coupling is unique to compact stellarators and results in challenging numerical problems arising from the broad spectra (in Fourier *m-n* space) of |B| and the metric elements g_{ij} when expressed in straight magnetic field line (flux) coordinates. While lower values of *A* lead to higher β limits for ballooning modes (provided strong locally unfavorable curvature regions – bends - are avoided), magnetic drifts are enhanced, leading to deterioration in the confinement of particles. Here, $\beta = \langle p \rangle / \langle B^2/2\mu_0 \rangle$ is the ratio of volume-averaged pressure to magnetic pressure.

Drift optimization [1], a technique based on aligning bounce-averaged particle drift surfaces with magnetic surfaces has been successfully applied to enhance energy and particle confinement in compact devices [2]. This approach is complementary to those based on strong quasi-symmetry (as in *NCSX* [3] for example). Previously [2], we have dealt with the lower-beta properties of one type of drift-optimized compact stellarator (DOCS): a low bootstrap current quasi-omnigeneous stellarator (QOS) with some helical symmetry features and a low-shear, stellarator-like transform ($\iota = 1/q$) profile that is relatively invariant to changes in β. This paper deals with the higher-β properties of another type of DOCS: a higher bootstrap current, tokamak-stellarator hybrid whose |B| spectrum exhibits approximate poloidal symmetry. These new configurations have a high shear, tokamak-like transform profile and exhibit transport properties that improve with β.

Unlike classical stellarators, or even some of the quasi-omnigeneous devices (QOS) previously considered, the new DOCS are distinguished by a small external rotational transform arising from coils (typically, $\iota_{coils} \sim 0.05 – 0.10$). Thus, the rotational transform profile is related to the internal plasma current profile much like in a tokamak and varies monotonically between $\iota(0) \sim 0.4$ and $\iota(1) \sim 0.1$, with approximately half of the small edge transform arising from currents in external coils. Note that this profile completely avoids the $\iota=1/2$ resonance (internal disruptions are suppressed) and most other low-order resonances. Except at the $\iota=1/5$ ($m=10$) resonance, which occurs well inside the plasma, these configurations are Mercier stable with a magnetic well over the entire cross section producing the dominant stabilization effect. Ballooning stable plasmas with $\beta > 15\%$ have been found that are consistent with the bootstrap current profile. The presence of finite bootstrap currents distinguishes these configurations from the previous (very low bootstrap current) QOS devices [2] and results in reductions of both the helical curvature and the connection length in DOCS. This gives rise to the higher ballooning stability β-limits observed.

The main effect of the external coils in DOCS is to substantially reduce (but not completely suppress) the self-consistent bootstrap current arising at finite β. The bootstrap current for DOCS is typically 1/3-1/5 that in the equivalent tokamak (a torus with the same axisymmetric, $n = 0$, boundary shape and rotational transform). Such a tokamak would have much too large a bootstrap current and requires either driven currents to cancel the bootstrap current, or a higher ι, for equilibrium. This reduction in bootstrap current in DOCS is due to the approximate quasi-poloidal symmetry of the |B| spectrum (similar to toroidally-linked mirrors). Exact quasi-symmetry would lead to a reduction by a factor $\sim\iota/N$ of the bootstrap current, which flows in the same direction as the equivalent tokamak current. Here, N is the number of field periods. This differs from the cancellation of toroidal and helical components of current in W7-X [1] and the low bootstrap current QOS [2]. In spite of this plasma current, DOCS are computed to be stable to low-*n* ideal MHD kink modes for values of $\beta \sim 7\text{–}8\%$. This is a significantly larger value of β (for kink-stability) than in the equivalent tokamak with no wall stabilization. Self-consistent bootstrap current profiles have been obtained in the range $2\% < \beta < 10\%$ which require little seed current (except in a *very* small volume near the magnetic axis) to achieve the optimized rotational transform profile. The present configurations are vertically unstable. However, stabilization of these low-*n* macroscopic modes should be possible either through plasma shaping (reduced elongation), current profile tailoring (reducing the pressure gradient, and hence the bootstrap current, near the plasma edge), a small increase in the edge external transform (something which seems to strongly stabilize the *NCSX* [3] plasma) or, dynamic feedback provided by suitable external coils as is done for shaped tokamaks.

The small external transform and low number of field periods (N = 2-4) in DOCS result in relatively simpler modular coils compared with conventional, lower current, compact QOS stellarators. Modular coils for an N =2, A = 2.7 compact stellarator are shown in Fig. 1.

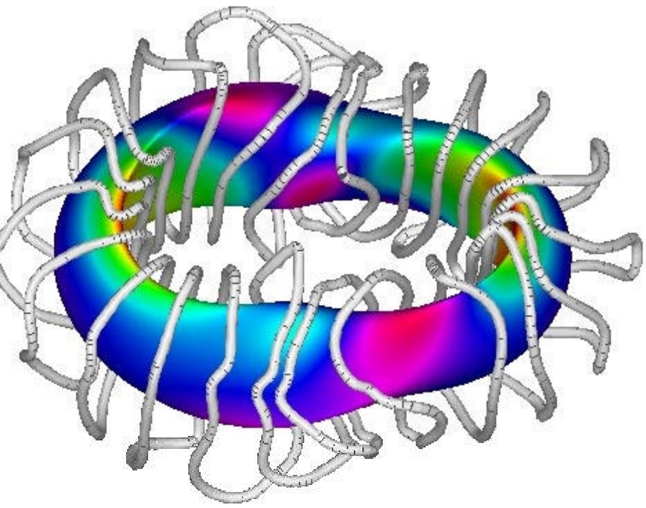

Figure 1 Plasma and coils for N=2, A=2.7 compact stellarator. Shading indicates |B| strength.

Adequate distances between the plasma and the coils, as well as between adjacent coils needed for plasma heating and diagnostic access, have been obtained. Values of the ratio of coil separation to minor radius are found which imply favorable scaling to compact-reactor sizes. Numerical free-boundary plasma reconstructions using these coils indicate that they approximately reproduce the desired plasma physics properties.

These potentially high-β, moderate bootstrap stellarators have been developed by incorporating fast calculations of the 3-D bootstrap current and ballooning stability (using the *COBRA* code [4]) into the Oak Ridge Stellarator Optimizer Code (*ORSOC*) [2]. Kink-mode stability was assessed after the completion of the other optimizations using the *TERPSICHORE* code [5]. Various cross-sections in one field period for a DOCS with $N = 2$, $A = 2.7$ and $\beta = 6\%$ are shown in Fig. 2. This configuration is marginally stable for this value of β across the entire cross section, as shown in Fig. 3. From the variation of the growth rate with β, it appears that the core plasma ($s \sim [r/a]^2 < 0.7$) is in the "second-stability" regime, whereas the edge region is first-regime stable. The calculated ion neoclassical energy confinement time τ_E^{neo} has a strong dependence on the electric field. Comparison of the ion

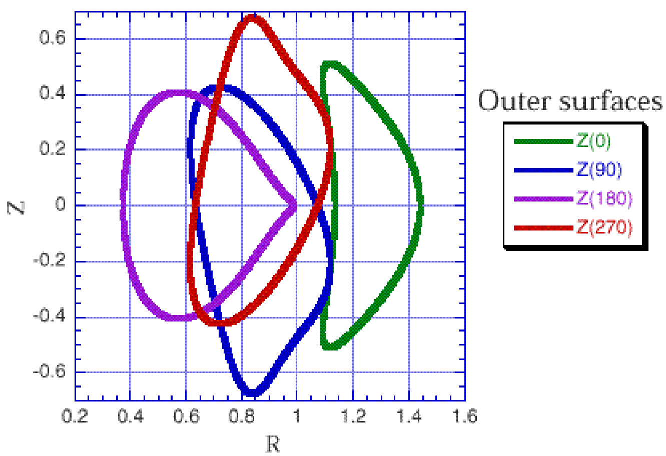

Figure 2 Magnetic surfaces for N=2, A=2.7, β=6% compact stellarator at various toroidal angles

neoclassical confinement to the ISS95 time is shown in Fig. 4 for both low and high bootstrap configurations. For B=1T, R = 1 m, n=3X10^{13} cm^{-3}, T=1.8 keV (in the low collision frequency regime), we find $\tau_E^{neo}/\tau_E^{ISS95}$ = 3-5 for expected values of the radial electric field and with a confinement enhancement factor H=1. Electron neoclassical heat transport is only 2-5 times smaller, indicating the weak effect of the radial electric field on confining electrons. Under these conditions, anomalous processes should dominate the thermal transport. Drift optimization based on J* alignment with flux surfaces is only an approximate collisionless measure of transport quality at these finite values of ι/N. Thus, the *DKES* code, which includes effects of collisions, was used within *ORSOC* to further improve the neoclassical confinement time for these plasmas, after a promising neighborhood in phase space had been identified by J* optimization. Factors of 2 improvement in τ_E^{neo} were obtained by minimizing the local transport coefficient L_{11} at several surfaces without sacrificing ballooning and kink stability. Further confinement improvement must be achieved for energetic beam or alpha particles and may be possible by improving the degree of quasi-poloidal symmetry during the optimization process. The drift and flux surfaces approach omnigeneity with increasing <β> as in W7-X [1], improving alpha particle confinement..

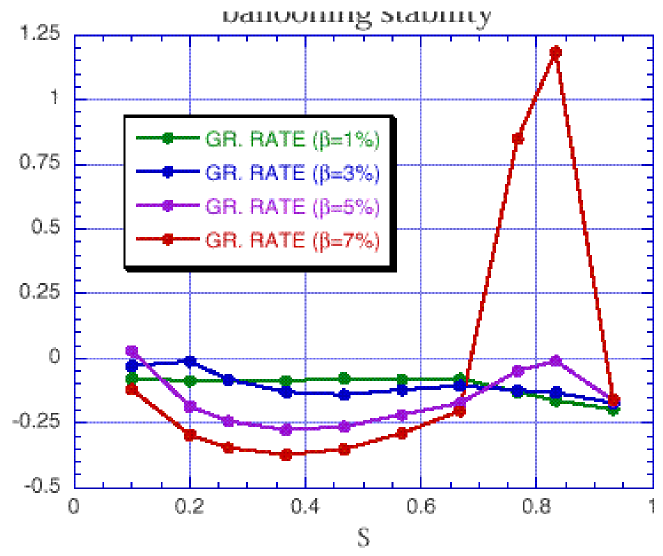

Figure 3 Ballooning growth rates for stellarator in Fig. 2 vs. s = $(r/a)^2$

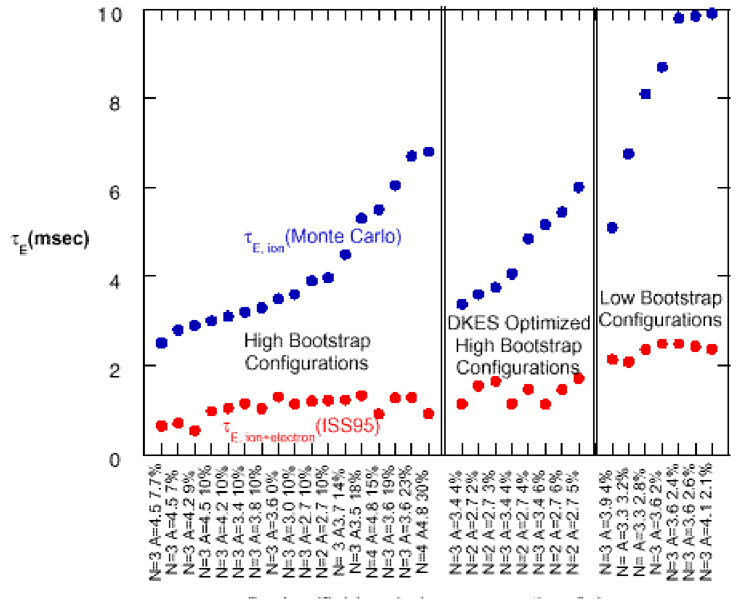

Figure 4 Ion neoclassical (solid) and ISS95 (open, H=1) energy confinement times for several *N*, *A*, and β values for low and high bootstrap configurations.

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*Research supported by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725 and under Grant No. DE-FG 03-97ER54423 at the University of Montana.