

Design of a Toroidally Symmetric Stellarator

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Abstract

A stellarator experiment with quasi-toroidal magnetic symmetry has been designed based directly on the recent concept of Garabedian. The experiment will test the reduced neoclassical ion transport and plasma viscosity expected of the nearly symmetric configuration. The chain of islands at the plasma edge will be exploited as a helical island divertor. The application of ohmic current to evaluate disruptions in hybrid operation is under consideration, and a test of the stability beta limit of this new configuration is also feasible in this device.

Keywords:

modular helias-like heliac, quasi-symmetry, axisymmetry, neoclassical transport, plasma rotation

1. Introduction

Stellarators with quasi-toroidal symmetry in the strength of the magnetic field offer the promise of improved neoclassical confinement over that of conventional stellarators. Furthermore, the lack of significant helical variation in the magnetic field magnitude allows the design of quasi-toroidal equilibria with relatively low aspect ratios, $A_p \leq 4$. A stellarator experiment based on Garabedian's modular helias-like heliac with two field periods (MH2) has been designed to explore the confinement and equilibrium of quasi-toroidal stellarator plasmas [1]. The main goal of this prototype experiment is to demonstrate reduced neoclassical transport and viscosity of this particular symmetric configuration. Reduced viscosity of stellarator plasmas may be crucial to reliably achieving similar transport barriers observed in tokamaks. This flexible device may also be used to test hybrid operation with plasma current to

understand disruption limits in stellarator plasmas in which a significant fraction of the rotational transform is provided by internal current, *e.g.*, bootstrap current, and is also capable of testing stability β limits with sufficient heating power.

2. Overview of the QUATOS Device

The parameters of the 2-field period prototype quasi-toroidal stellarator (QUATOS) under design are listed in Table 1. The device has a relatively large average minor radius of $\bar{a} = 0.27$ m because of the low aspect ratio of $A_p = 3.5$. Cross sections of the flux surfaces and mod-B contours at several toroidal locations are shown in Fig. 1. At zero pressure, the rotational transform ι is tokamak-like, decreasing monotonically from $\iota = 0.5$ on the magnetic axis to ι near 0.4 at the boundary. The plasma edge is defined by a chain of

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Table 1 Quatos device and expected plasma parameters

Major Radius R_0	0.95 m	Density \bar{n}_e	$\leq 1 \times 10^{19} \text{ m}^{-3}$
Average Plasma Minor Radius \bar{a}	0.27 m	Electron temperature T_e	200 eV
Plasma Aspect Ratio A_p	3.5	Ion temperature T_i	150 - 500 eV
Rotational Transform ι	0.5 - 0.4	Ion collisionality ν^*	≤ 1
Magnetic Field Strength B_0	0.2-0.7 T	$[\nu_{ii}/\epsilon_t^{3/2} \iota (v_{thi}/R_0)]$	
Number of Field Periods N	2	Heating Power	260 kW
Number of Coils/Field Period	8	(ICRF & IBW @ 6 - 30 MHz)	
Magnetic Well Depth (typ.)	1.2%	τ_{LHD}	2 ms

islands at the $\iota = 2/5$ surface. The islands can be accessed from either the high or low field side, and their efficacy as island divertors will be tested as a function of edge biasing and small changes in rotational transform.

Plasmas in QUATOS will be generated by ICRF launched with a Nagoya type-III antenna, as in CHS [2]. Ion heating for transport studies and localized flow drive for viscosity studies will be performed with ion Bernstein waves (IBW). IBW heating is attractive in this application for two reasons. It damps directly on the thermal ion population without the formation of an energetic ion tail which would suffer high direct orbit losses in the low field QUATOS plasma. Furthermore, IBW provides localized poloidal flow drive through the ponderomotive force [3] which is believed to give rise to transport barriers in tokamaks [4]. In QUATOS, the $7\omega_{cD}$ resonance, where ω_{cD} is the cyclotron frequency of deuterium, will be used for on-axis heating, and the $5\omega_{cD}$ resonance is planned for flow drive near the mid-radius of the plasma. The corresponding IBW frequencies are 26 MHz and 20 MHz, respectively, for operation at $B_0 = 0.5$ T. Alternate schemes are also under consideration for direct ion heating (as well as electron heating). These include high-field side launch ICRF slow wave heating, and ion-ion hybrid heating[5].

3. Magnetic Spectrum and Transport

The radial variation of the five largest terms in the spectrum of the magnetic field strength,

$$B(\psi, \theta, \phi) = B_0 \sum_{m,n} b_{mn}(\psi) \cos(m\theta - n\phi)$$

are shown in Fig. 2 as a function of the flux surface label. Here ψ is the normalized flux ranging from 0 on axis to 1 at the boundary, and θ and ϕ are the poloidal and toroidal angles, respectively, in Boozer coordinates [6]. The amplitudes b_{mn} are normalized to the value of b_{00} on axis, and the plotted value of $b_{00}(\psi)$ is actually $b_{00}(\psi) - b_{00}(0)$. The spectrum is dominated by the single toroidal curvature term $b_{10} \leq 0.15$. All

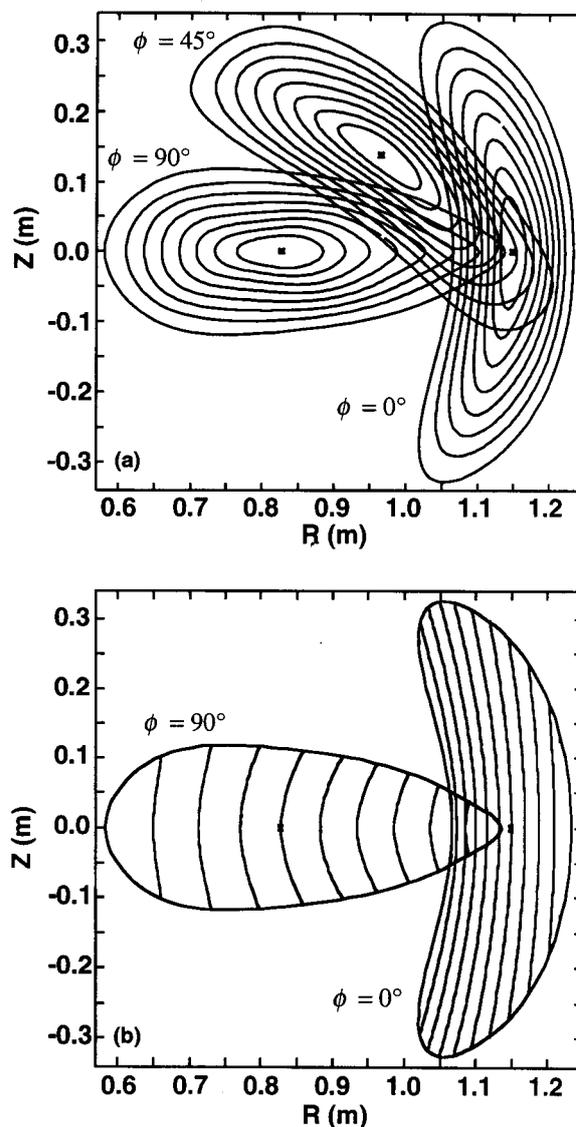


Fig. 1 (a) Poloidal cross sections of the QUATOS flux surfaces at the toroidal angles $\phi = 0^\circ, 45^\circ,$ and 90° encompassing one-half of a field period. (b) Contours of the magnetic field magnitude at the toroidal angles $\phi = 0^\circ$ and 90° showing the $1/R$ variation of the quasi-toroidal magnetic field configuration.

helical and mirror terms ($n \neq 0$) have considerably smaller amplitudes, resulting in reduced neoclassical transport and viscosity compared to that of a conventional stellarator.

In order to compare the transport and viscosity in QUATOS with that of a standard helical device, a set of eight auxiliary toroidal field coils operated in pairs with opposing polarity are used to modify the magnetic

spectrum. The value of the b_{02} term can be raised from 0.02 to 0.15 on axis with only a small reduction of the rotational transform. Series operation of the auxiliary coils with the same polarity allows the rotational transform to be varied.

Transport modeling of QUATOS is performed with a Monte Carlo calculation in Boozer coordinates [7]. An example is shown in Fig. 3 in which the

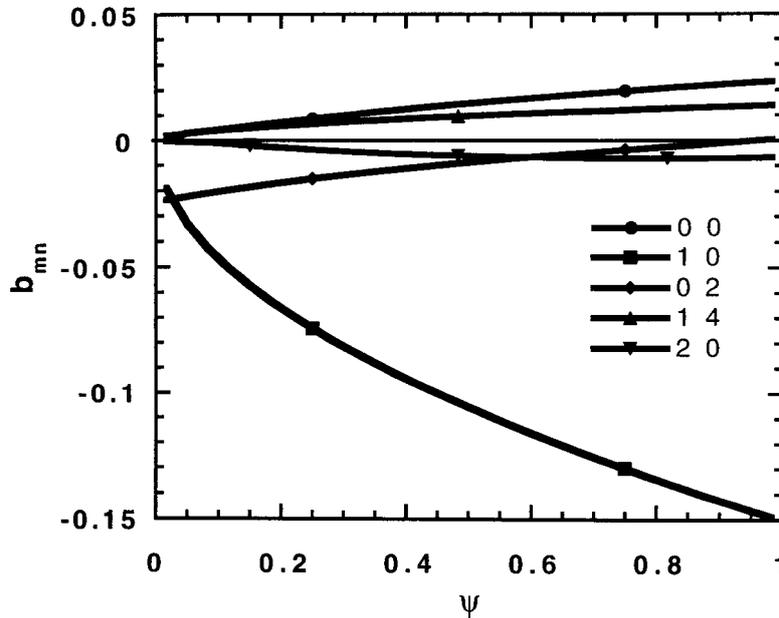


Fig. 2 Coefficients of the magnetic spectrum of the QUATOS configuration vs. normalized toroidal flux.

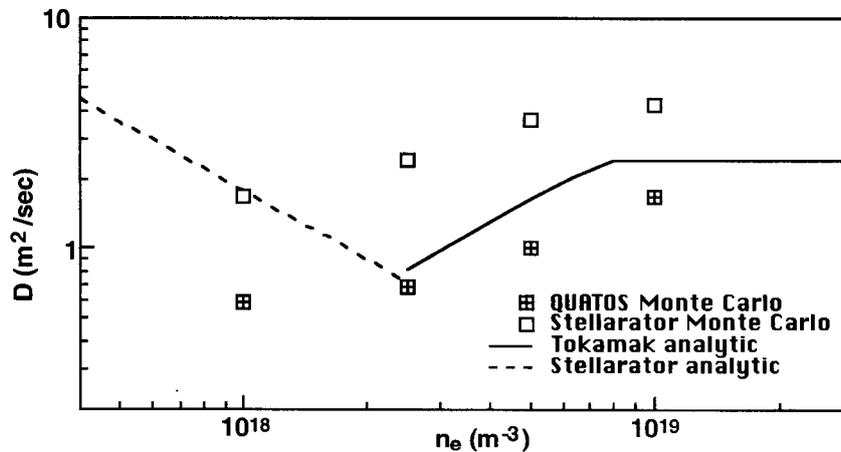


Fig. 3 Monoenergetic ion diffusion coefficient from Monte Carlo calculations vs. plasma density. The crossed squares are for the QUATOS standard configuration, and the open squares are for the simulated stellarator ($b_{02} = 0.15$); $E_i = 200$ eV, $r/\bar{a} = 0.5$. Also shown are the analytic representations of the banana and plateau diffusion coefficients in an equivalent circular tokamak ($A_p = 3.5$) and the appropriate $1/\nu$ diffusion coefficient for the degraded QUATOS configuration.

diffusion coefficient of 200 eV ions is calculated at $r/\bar{a} = 0.5$ ($T_{i0} \approx 400$ eV) for $b_{02} = 0.02$ and 0.14. Also shown in the figure for comparison are analytic formulas for axisymmetric tokamaks and the $1/\nu$ regime for stellarators for QUATOS parameters. Even for these low energies, the ion diffusion coefficient increases a factor of three or more. An accompanying analytic calculation of the transport including the effect of a predicted neutral population indicates that the central temperature drops by at least 30% when the spectrum is altered as described. More accurate calculations will be performed in the future with a stellarator transport code.

4. Plasma Rotation

The quasi-toroidal stellarator configuration naturally exhibits low neoclassical parallel viscosity. This may prove beneficial to the formation of transport barriers resulting from velocity shear that lead to improved confinement regimes in tokamaks. In QUATOS, the parallel viscosity will be varied by adjusting the b_{02} mirror term in the spectrum with the use of the auxiliary TF coils. Because this term is maximum on axis (see Fig. 2), changes in plasma rotation resulting from neoclassical damping can be isolated from the effect of neutral damping (which is expected to be strong in outer region of the plasma). In the plateau regime, the parallel viscous damping rate can be raised from $2.0 \times 10^{-4} \text{ s}^{-1}$ in the optimized quasi-symmetric case to $1.3 \times 10^{-3} \text{ s}^{-1}$ with the use of the coils to reduce the toroidal symmetry. The controlled plasma rotation in QUATOS will be driven by IBW, and the use of a neutral beam to directly drive toroidal rotation is also being explored.

5. Advanced Scenarios of Operation

The bootstrap current in the quasi-toroidal stellarator configuration is predicted to be relatively high compared to the helically symmetric and the Wendelstein stellarators, and high performance quasi-toroidal devices are consequently expected to operate with finite plasma current. To explore this mode of hybrid operation, tests of the disruption behavior of quasi-toroidal plasmas are planned in QUATOS plasmas with ohmic current. Because of the existing toroidal symmetry of QUATOS, the presence of plasma current does not significantly alter the magnetic spectrum, and therefore is not expected to degrade the neoclassical transport. The rotational transform will be controlled as needed with the auxiliary TF coils.

The equilibrium β limit of QUATOS is predicted to be $\langle \beta \rangle \approx 4\%$ [8]. However, with parameters comparable to those of the CHS high β study [9], the prototype QUATOS device should be capable of exploring stability β limits up to values $\langle \beta \rangle = 2\%$ with 2 MW or less of heating power.

6. Conclusion

An exploratory experiment has been designed to test the confinement and rotation properties of the quasi-toroidal stellarator concept. In particular, the formation of transport barriers with the application of IBW will be explored. Flexibility of the configuration is provided by auxiliary TF coils to alter the magnetic spectrum and rotational transform of the base configuration. Advanced scenarios of research on QUATOS include ohmic operation in anticipation of the presence of finite bootstrap currents in larger quasi-toroidal devices, and test of the ballooning mode β limit.

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References

- [1] P. Garabedian, *Phys. Plasmas* **4**, 1617 (1997).
- [2] K. Nishimura *et al.*, *Fusion Technol.* **17**, 86 (1990).
- [3] H. Biglari, M. Ono, P.H. Diamond and G.G. Craddock, *Radio Frequency Power in Plasmas*, Charleston, SC, 1991; *AIP Conference Proceedings* 244, AIP, New York, (1992) p.376.
- [4] B. LeBlanc *et al.* *Phys. Plasmas* **2**, 741 (1995).
- [5] S. Masuda *et al.*, *Nucl. Fusion* **37**, 53 (1997).
- [6] A.H. Boozer, *Phys. Fluids* **25**, 520 (1982).
- [7] Code provided by D. Spong, ORNL.
- [8] P. Garabedian, in these Proceedings, p.148 (1998).
- [9] S. Okamura *et al.*, *Nucl. Fusion* **35**, 283 (1995).