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Implications of Recent Tokamak Research for Stellarator Design

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Abstract

Recent advances in tokamak physics can be used in the quest to optimize the stellarator concept. In particular the experimental confirmation of strong bootstrap currents suggests the possibility of taking advantage of non-zero current in steady-state stellarators. In addition the observation of neoclassical islands suggests important issues for design optimization, in order to operate in a regime in which neoclassical effects heal stellarator islands.

Keywords:
stellarator, tokamak, bootstrap current, neoclassical island

The last ten years have seen dramatic advances in experimental and theoretical tokamak research including:

- Experiments and theory demonstrating flow-shear stabilization.
- Confirmation of current-drive power requirement scalings.
- Confirmation of the predicted neoclassical bootstrap current.
- Improved theoretical models for turbulent transport, including both "standard" regimes and internal transport barriers.
- Scaling of beta limits with shaping, R/a, and current profile (including the effect of "shear reversal").
- Neoclassical effects on resistive island growth & suppression.

While it has often been discussed that the impressive range of research on "alternate concept" devices sheds light on the physics of tokamaks, the thesis presented here is that the insights gleaned from the last decade of tokamak research can help illuminate physics issues for other approaches to toroidal confinement.

There have, of course, also been tremendous advances recently in stellarator design. The W7-X concept minimizes bootstrap and Pfirsh-Schlüter currents, reduces shear, and provides orbit optimization by minimizing the excursion of trapped particles from flux surfaces. The quasi-helical stellarator minimizes transport by moving to a very nearly helically symmetric |B| spectrum, in Boozer coordinates. These optimization procedures lead, however, to rather high aspect ratio. Working from the tokamak-based intuition that low aspect ratio can provide high beta, the small-aspect-ratio toroidal hybrid, SMARTH, concept [1] of Hirshman *et al.*, moves to $R/a \sim 3$, and still provides orbit optimization via very large ripple, giving rise to quasi-omnigeneity in the sense of Cary and Shasharina [2]. The rotational transform is provided by a large $l=1$ helical component, peaked on axis, combined with externally driven current, so that a conventional tokamak q profile obtains over most of the radius, and a substantial equilibrium beta can be supported. The result is a device with ~25x confinement improvement over the unoptimized configuration, stable to ballooning modes over the inner 80 % of the radius, with volume average beta of 6 %.

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Another approach, studied by Kovrizhnykh [3], Nührenberg [4] and Garabedian [5], and more recently by Reiman and Zarnstorff [6], takes advantage of the fact that magnetic fields with magnitude |B| which is nearly toroidally symmetric in Boozer coordinates can provide significant rotational transform at low aspect ratio. This provides good orbit confinement in a symmetric system, which is then free to rotate toroidally, possibly providing shear flow for turbulence suppression. Furthermore, as beta increases these devices develop substantial positive bootstrap current which then permits less distorted modular coils, further from the plasma – key issues in stellarator reactor optimization.

Theoretical calculations indicate that these devices share the properties of reversed-shear advanced tokamaks, including a core region which appears to be second-stable to ballooning modes. In tokamak experiments reversed shear regions, at high bootstrap current, are stable against resistive island growth. Theoretically this same property should be very valuable in a stellarator, in that islands which might otherwise grow in the equilibrium as beta increases should be suppressed by about an order of magnitude, for a radially increasing iota, and positive bootstrap current. Specifically

$$W = (W_{\mathrm{ext}}^2 + W_{\mathrm{b}}^2)^{1/2} - W_{\mathrm{b}}$$

where

$$W_{\mathrm{b}} \equiv \frac{2\mu_0 R j_{\mathrm{b}}}{mB\iota'}$$

and W_{ext} is the island size which would have been present in the absence of the bootstrap suppression effect. In the limit of $W_{\mathrm{ext}}=0$, this result reduces to that developed by Hegna and Callen [7], for the case of unfavorable neoclassical island drive in a helically-symmetric stellarator, due to negative bootstrap current.

The presence of externally provided toroidally quasi-symmetric transform should allow the shear reversal point to be moved outwards towards the edge of the plasma, avoiding instabilities associated with $q'=0$ generally observed in high-performance reversed-shear tokamaks. The elimination of the edge current drive needed in the advanced tokamak should reduce the low-n kink drive, reduce the recirculating power requirement, and allow high edge density for optimal divertor performance. Seed transform could be provided by the stellarator fields as well. External transform may eliminate or ameliorate disruptions; in W7-A rather modest amounts of external transform (~ 0.13) allowed non-disruptive operation even at $q(a) < 2$. The marriage of stellarator and advanced tokamak concepts in the quasi-axisymmetric, high-bootstrap stellarator may therefore offer compactness, good confinement, high beta, low recirculating power, stability, and relative simplicity – an attractive package if it is realizable.

In sum, the tokamak has been a very productive vehicle for learning high-temperature plasma physics. As embodied in the steady-state advanced tokamak, it may itself provide the physics concept for an attractive fusion reactor. However it also has provided a valuable resource of physics knowledge for optimizing the stellarator approach to toroidal confinement, which may ultimately prove to be the more attractive.

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