Innovative High β Stellarators

Don Spong (spongda@ornl.gov, July 27, 2012)

Oak Ridge National Laboratory

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I. Introduction

Optimized stellarators necessarily involve complex coil geometries; there are now multiple examples demonstrating that they can be costly and time-consuming to construct. Prior to restarting any research in this direction, a goal should be targeted that can result in fundamental changes in the landscape of fusion energy research. It will be argued below that future efforts should be focused on high β/high density stellarators that can lead to reactors with significantly higher fusion power densities than tokamaks, and that result in significantly more attractive fusion power economics.

II. The Problem

Fusion power density, $P_{DT} = n_D n_T \langle\sigma v\rangle_{DT} Q_{DT}$, scales as $\beta^2 B^4$. Since $\langle\sigma v\rangle_{DT}$ has a broad maximum in the 20-100 keV range, the most direct pathway to higher P_{DT} is through increased density and thus β. Tokamaks have density limits that keep their operational regime in the low 10^{20} m^{-3} range. This limits their power density to the $1 MW/m^3$ range; this fact and the energy confinement time scaling with size lead to reactors with large plasma volumes. Even if tokamaks were to overcome such density limitations, the increasing inefficiency of current drive at high densities and increasing disruptivity at high beta (high density) would present further barriers. Due to the large stored energies in the plasma current, disruptions cannot be tolerated and tokamak reactors are likely to be limited to $\langle\beta\rangle \sim 5\%$ with high bootstrap current versions limited to $\langle\beta\rangle \sim 2$ - 3%; ITER scenarios focus on the range around $\langle\beta\rangle \sim 2.5\%$. The problem with low fusion power density is that the large required plasma volumes lead to large capital costs in order to obtain DEMO-like power outputs. While ITER was never intended to be a demonstration of fusion power economics, the simple fact that its central core requires 23,000 tons of highly manufactured components to produce 500 Mw of fusion power sets an uncomfortable precedent; much of this mass is in magnets and doesn't yet include the full nuclear blankets, as are necessary in a reactor. In contrast, the ARIES-RS design, which was based on a device of 15,000 tons delivering 2170 MW of fusion power (1000 Mwe, 67 kWe/ton mass power density), was rated at 76 mill/kWh cost of electricity[1], which has been evaluated as being 2.5 to 8 times the cost of conventional power sources.[2] While one can argue that ITER is the first of its kind and that economies of scale will drive down costs in a fusion power economy, the increasing amount of mass required for a tokamak reactor is going to place significant limits on how far the cost of fusion produced electricity can be lowered. This issue could become especially acute in justifying U.S. fusion energy research due to the large resources of natural gas that are now being discovered; combined cycle gas turbines can produce electricity with 50% of the CO_2 output of coal; they also offer flexible power output levels, and better economics than either nuclear power or renewables.[3]

III. Solutions

As the above fusion power density scaling indicates, there are really only two pathways to higher levels of P_{DT}: increased magnetic field strength (B) or increased β. Tokamak reactor designs already have peak magnetic fields on the TF coil conductors operating close to critical superconducting limits so there is not much flexibility here. It may well be that materials research will eventually lead to new high-temperature superconductors with higher critical fields, but this is outside the realm of fusion research and the timescale is unpredictable. Also, higher magnetic field strengths require even more massive magnet support structures. High β and plasma density, on the other hand, are parameters that are legitimate goals for fusion plasma research and can lead to lighter weight, less costly magnets. Stellarators have experimentally demonstrated[4,5] access to significantly higher plasma density regimes (up to $n = 1.2 \times 10^{21}$ m^{-3} in the case of LHD) than tokamaks and stable $<\beta>$'s of 5.1%. Optimized stellarator designs have been analyzed up to ballooning (second) stable $<\beta>$'s of 23%.[6] This particular class of high β stellarators will be described in the next section. In addition to high β, they offer the usually touted advantages of stellarators, such as steady state operation with no need for current drive (low reactor recirculating power), low risk for disruptions and the associated runaway electrons, and stability to current-driven tearing and neoclassical tearing instabilities.

In order for a magnetic confinement device to offer higher fusion power density capability and improved reactor economics, at least three characteristics are necessary: high β limits ($<\beta> \sim 10$ to 20%), high density operation ($n \sim 0.4$ to 1×10^{21} m^{-3}), and good configurational flexibility. The latter characteristic refers to the ability of the concept to preserve its properties over a range of aspect ratios since higher fusion power density will likely require greater surface to volume ratios.

IV. High β Stellarators

One of the unexpected discoveries made during the QPS (Quasi-Poloidal Stellarator) design effort was that stellarators based on this optimization strategy had first and second ballooning stable regions that were separated by a relatively narrow unstable window. This was a unique feature of QP-symmetry; when similar analysis[7] was applied to quasi-toroidal systems (e.g., NCSX) while the first stability boundary was less limiting than QPS, the first-to-second unstable window was broader (implying more difficult access), and for quasi-helical systems (e.g., HSX) no second stable regime was found. At high β's, quasi-toroidal configurations also may be limited by current driven instabilities from the increasing levels of bootstrap current, and quasi-helical configurations generally have bootstrap currents in the direction that unwinds rotational transform. However, it should be noted that stellarator optimization efforts for all of these systems have generally not tried to target β's above the 5% range that characterize tokamak reactors. It may well be that both quasi-toroidal and quasi-helical systems can also go beyond this regime with further optimization. The LHD stellarator experiment operates up to $<\beta> = 5.1\%$, which exceeds that demonstrated in many tokamaks. In addition to high β access, QPS configurations had a number of other attractive features such as suppressed levels of bootstrap current, access for direct ion magnetic beach heating, high poloidal flow shearing, low levels of ripple/neoclassical transport, and regimes of stability to trapped particle mode micro-instabilities. Unfortunately, these potential advantages were not tested experimentally since DOE cancelled the QPS project around the same time as NCSX, as it became clear the costs for NCSX were spiraling out of control.

A variety of QP-optimized stellarators were examined for second stable access and this was found to be a generic feature of these configurations. This was studied in most detail for a particular hybrid configuration.[6] In this case ballooning stable $<\beta>$'s of up to 23% were verified; current driven modes were stable up to $<\beta> = 11 - 15\%$ (for a Tryon factor, $\beta_N = 19$). In this regime another favorable characteristic of the magnetic configuration, alignment of flux surfaces with |B| surfaces or isodynamic optimization, was present. Monte Carlo simulations verified improved alpha particle confinement from this effect.

As mentioned above, higher fusion power densities require reactor configurations with greater ratios of wall surface area to volume. Initial verification of this configurational flexibility of QP-symmetry optimized devices has been demonstrated[8] at higher aspect ratios. Such devices not only maintain access to second stability, but also show improved quasi-poloidal symmetry and increased suppression of bootstrap current levels. Other forms of stellarator optimization also show such flexibility.

V. Conclusions

The fusion power economics of large tokamaks is becoming increasingly predictable and headed in a direction that seems unlikely to be competitive with other energy sources for quite some time into the future. The most direct way to break out of this dilemma is to begin shifting focus to magnetic confinement systems that can access higher density and higher β regimes. Current stellarator experiments have already demonstrated access to higher density/higher β regimes than most tokamaks. QP-symmetrical stellarators have been theoretically shown to have even higher β limits. This approach should be revisited and developed experimentally. Due to the fact that stellarator construction is now well known to be high risk with respect to coil engineering, a natural evolution from smaller devices to larger seems prudent. Also, realistic expectations of the timescale of the ITER project imply that crash programs are not necessary. Testing the stability of high β, high density regimes in stellarators is likely to require unconventional heating approaches to keep the costs within reason. For example, smaller, short time-scale shock/compressive heated systems could perhaps be useful specifically for testing MHD stability limits followed by larger, longer time-scale experiments for transport studies. Coupled with high β stellarators, improved 3D theory and modeling will be required since many existing models either are not valid or are not routinely tested above the $<\beta> = 5\%$ regime.

Unlike the past, the U.S. fusion program needs to make a more firm/stable long-term commitment to stellarator research, as has been done for many years in Europe and

Japan. Innovative high β stellarators would provide challenging physics and a research focus area that is not pursued anywhere else in the world; if successful, this could have very significant positive impacts on fusion power economics.

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