3D Magnetic Fields in Fusion Device Design:
Toward Improved Reliability and Maintainability*
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Issue: Designing for High Reliability and Availability

The RAMI panel, in notes distributed to the ReNeW community, has made the point that high reliability and availability in a fusion device can only be attained through purposeful design. They said, moreover, that:

1. We need to understand the underlying reasons for good and poor past performance and build on past experience; and
2. Design choices that promote reliability and maintainability have to be made which may be out of the mainstream and have far reaching consequences.

Stellarators and the Application of 3D Fields as a Design Choice

The benefits, risks, and research needs for stellarators have been extensively examined and reviewed, most recently by the FESAC Toroidal Alternates Panel (TAP) [1] and by the EU Fusion Facilities Review Panel [2]. Both saw stellarator research as important for developing the knowledge base for steady-state magnetic fusion reactors.

The key distinguishing feature of stellarators is their use of 3D magnetic fields from external coils to confine and shape the plasma. To the extent that disruptions and ELMs are mitigated or eliminated, current drive is reduced or eliminated, and steady-state operation is simplified, the use of 3D fields can be a design choice that promotes overall reliability. For example, elimination of disruption loads would greatly relax the structural requirements for in-vessel components and their attachments, with potentially significant reduction in maintenance times. A reduction in current drive requirements would relax the number and complexity of plasma heating systems. A reduction in active feedback control requirements could simplify the design of superconducting magnet conductor and structure due to the corresponding reduction in eddy current losses.

Three-dimensional fields can be applied in varying degrees to toroidal device design. [3] Modest perturbations of tokamaks can be used to eliminate VDEs or ELMs [4]; stronger perturbations

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can be used to eliminate the need for externally driven current or to nearly eliminate parallel currents altogether. In terms of the RAMI panel's perspective, none of these choices is far from the mainstream, but their consequences could indeed be far-reaching.

Research Requirements

In order to make the application of 3D fields available as a viable option for DEMO designers and to understand its overall ramifications for availability, stellarator research aimed at answering the scientific and technical questions identified by the TAP is needed in the ITER era. The TAP's highest priority for stellarators is to understand the risks associated with the complexities of stellarator coils and to seek ways to simplify them. The U.S. must have a stellarator program at a level sufficient to maintain at least its current leadership roles and to address gaps in the existing international program. It should include international collaborations to keep the U.S. well integrated with the world stellarator program and involved in the world's leading stellarator facilities.

Current U.S. Efforts

Though the scale of the U.S. stellarator program has been reduced with the cancellation of NCSX, we have re-structured it [5] with a new set of near-term goals: 1) Streamline stellarator design and construction; 2) Increase understanding of quasi-symmetric stellarators; 3) Contribute to tokamaks using stellarator tools. These goals are aligned with TAP priorities. To highlight some of the current activities:

1. Engineering studies of completed NCSX work packages to identify fundamental cost drivers (e.g., tolerances, geometries), and CAD modeling studies to identify ways to improve the NCSX and ARIES-CS designs to make them simpler and easier to assemble or disassemble.
2. A study of an advanced stellarator concept using passive magnetic materials instead of coils to shape the fields. Assembly and maintenance characteristics may be better than for coil-based designs.
3. Physics studies to improve understanding of optimization targets and constraints that drive design:
   - Beta limits: involving U.S. researchers and experiments on LHD.
   - Transport: involving theory and code development, experiments on HSX at the University of Wisconsin, and international collaborations.
   - Field errors: involving U.S. researchers and experiments on CTH at Auburn University. If it were possible to relax tolerances through better targeting of field errors, the benefits to stellarator engineering would be substantial.

4. Surveys of the quasi-symmetric stellarator design space to test complexity metrics and to identify promising directions for simplification.
5. Application of stellarator knowledge and tools to the investigations of ELM control coils for ITER and several existing tokamaks. For example, we are investigating the possible use of localized nonaxisymmetric fields in tokamaks to stabilize the vertical mode and eliminate VDEs.
6. Exploration of a possible long-term U.S collaboration on Wendelstein 7-X. In the near-term there may be opportunities for targeted contributions to W7-X construction, taking advantage of specialized U.S. engineering capabilities and deepening our understanding of stellarator design and construction. For the long-term, a collaboration on the linked issues of divertors, steady state operation, and control is being discussed.

Research Thrusts for the ITER Era

The application of 3D fields can be a design choice that promotes reliability in a fusion system. To become a viable design choice, however, stellarator research is needed to understand its benefits and risks. The U.S. should have a program that at least maintains its current leadership roles. Guided by the TAP report, the U.S. should develop an enhanced stellarator program, including significant international collaboration.

With respect to ReNeW, we assume that the Optimizing the Magnetic Configuration (Theme 5) group will take the lead in laying out research thrusts that address the TAP issues for stellarators. We hope that the ReNeW Fusion Power (Theme 4) chapter will:

1. Recognize the potential of 3D fields as a design choice that can promote reliability and maintainability in a fusion system.
2. Support the need for a U.S. stellarator research program that a) emphasizes understanding, including physics and engineering knowledge that bear on RAMI issues; and b) builds on past experience through understanding of the underlying reasons for both good and bad performance in order to guide future improvements.

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[1] FESAC Toroidal Alternates Panel Report, http://www.science.doe.gov/ofes/Toroidal%20Alternates%20Panel%20Report.pdf

[2] EU Facilities Panel Report, http://fire.pppl.gov/EU_fusion_facilities_rev_08.pdf

[3] Boozer, 2008 APS or EPS

[4] A.H. Reiman, Phys. Rev. Lett. **99**, 135007, Sept. 28, 2007

[5] U.S. Stellarator Community Plan for FY-09, http://nsdr.pppl.gov/stellaratorindex.html.