Advancing Stellarator Knowledge Through International Collaboration

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International collaboration offers good opportunities, sometimes the best opportunities, to pursue U.S. fusion science goals. Stellarator research in the U.S. has benefitted from international collaboration in many ways, including tangible contributions of design tools and hardware by other countries, and access to their unique experimental facilities. The U.S. has been a strong contributor as well, having developed codes that are used all over the world and having made key contributions to experiments on international facilities. Through international collaboration the U.S. has gained a world reputation in, for example, equilibrium analysis (including optimization and reconstruction) and Alfvén stability. Here we highlight as examples two important collaborations- stellarator physics with LHD, and an emerging opportunity for a partnership with Wendelstein 7-X.

LHD: Improving physics models, code development and validation

A multi-year collaboration with LHD is under way, with the aim of improving our understanding of equilibrium, stability and confinement physics. The task involves code development, improvements to theoretical models, and experiments on LHD. We are studying the loss of equilibrium flux surfaces and its possible connection with beta-limits. Experiments will test the significance of the magnetic well and MHD stability in forming high beta plasmas with peaked pressure profiles, and will explore the use of NB driven currents to modify the rotational transform in high beta plasmas. We will benchmark 3D equilibrium codes, including PIES and HINT, on high-beta LHD plasmas.

We have a substantial activity on LHD in Alfvén modes and flows and confinement, which has produced a series of publications and a 3D configuration stability code. High density modes have been obtained in LHD's super-dense core (SDC) regime with densities up to 1×10^{21} m^{-3}. If these regimes can be extrapolated to stellarator reactors, they can significantly reduce the potential for fast ion instabilities and the associated localized wall heating from fast ion losses.

Another task is to advance the understanding of the possible connection between optimization of neo-classical transport and improvement of turbulent transport, an issue being studied in LHD and HSX experiments. We will advance the understanding of the dependence on the configuration of zonal flows, turbulence, and turbulent transport, aided by analysis and interpretation of results from gyrokinetic simulations, using the GENE code from IPP Germany. We will benchmark U.S. and international turbulence simulations for stellarator equilibria.

Through this collaboration, we are making progress on stellarator issues identified by the Toroidal Alternates Panel (TAP), including Tier 1 issues:

1. Simpler Coil Systems: Since stellarator coil designs are driven by physics targets and constraints used in optimization codes, better physical models for beta limits and transport will improve targeting accuracy.
2. Confinement Predictability: Advances in physics understanding and code validation through this collaboration will advance the development of a validated predictive capability for stellarators. This collaboration provides access to a large, well-equipped stellarator facility.

Wendelstein 7-X: Divertors, Steady-State Operation, Plasma Control, and Engineering

The Wendelstein 7-X (W7-X) stellarator at Germany's Max Planck Institute for Plasma Physics (IPP), currently under construction, is scheduled to begin operation in 2014. As a large optimized stellarator with superconducting coils, a divertor, and excellent heating and diagnostic access, it will be one of the world's premier fusion research facilities. The U.S. has an opportunity to greatly expand its collaborations with IPP by becoming a partner in W7-X with a significant and coherent research role. Discussions among IPP, ORNL, and PPPL stellarator researchers have led to a vision of an exciting long-term U.S. collaborative program on W7-X. The current status of the discussions is summarized in a communiqué, appended to this document, that was drafted jointly by U.S. and IPP personnel at the close of a meeting at IPP in early February.

This collaboration would provide a way to make progress on many of the TAP stellarator issues. Examples from just the Tier 1 issues:

1. Simpler Coil Systems: By becoming involved in solving high-level engineering problems on W7-X, a real high-tech construction project, we will deepen our understanding of stellarator engineering and the possibilities for future improvement.
2. Confinement Predictability: Wendelstein 7-X will provide data at high beta in a configuration that has been optimized for good orbit confinement and has both similarities and differences with quasi-symmetric stellarators and tokamaks. Advances in physics understanding and code validation on W7-X will further the development of a validated predictive capability for magnetic confinement systems.
3. Divertors: Wendelstein 7-X will have an island divertor, over 10 MW of heating power, and pulse lengths up to 30 minutes. Control of the divertor plasma will be very important and the U.S., with its experience in diagnostics, equilibrium analysis, and plasma control, could make valuable contributions in this area. The IPP edge physics group has developed the EMC3/EIRINI code to model 3D divertors. A U.S.-IPP collaboration on the linked issues of divertors, steady-state operation, and plasma control could make outstanding contributions to international fusion science.

Research on Wendelstein 7-X does not fully address the issues of quasi-symmetric stellarators, the focus of the U.S. program, and clearly does not fill the need for an integrated high-performance quasi-symmetric stellarator experiment. A coherent national program including theory, large and small domestic experiments, design and engineering activities, and international collaboration is the model we should continue to follow in stellarator program planning. However, W7-X does provide valuable capabilities such as long pulse, an optimized plasma configuration, divertors, and large size, that can advance our goals and are likely out of reach for U.S. stellarator facilities in the near future. Even when we were planning for NCSX, it was envisioned that we would partly rely on collaboration with W7-X for research on steady-state and divertor issues. A substantial collaboration on W7-X should be an important component of the U.S. Fusion Energy Sciences program in the ITER era.

Research Thrusts

International collaboration provides very significant opportunities to pursue our ITER-era stellarator goals. Collaborations with LHD can and should be expanded.

With regard to W7-X, we should seriously consider the opportunity that is before us to become a partner, including the attendant benefits and privileges, as well as costs, responsibilities and risks. The discussions with IPP mentioned here are relatively recent, and have reached the point where they now need broader consideration by the U.S. fusion community, especially stellarator researchers. The OFES has been supportive of these discussions and we have kept them informed of progress. As a first step, we are supporting a PPPL engineer with NCSX experience to work with the W7-X assembly support team this fiscal year. Beyond that, no commitments have been made. We assume that DOE will be very interested in the community's assessment of the scientific benefits and risks of this collaboration, as input to future decisions on strategic planning and funding.

The contributions being discussed would address real and central needs of the W7-X program. They will require commitments on our part, including contributions to making W7-X a reality between now and 2014. The benefits, including the opportunity for influence and a strong role in the W7-X research program are described above and in the appended communiqué. The breadth and scope of our involvement are topics for future discussion and negotiation, but the two of us believe that a meaningful partnership in a program on the scale of W7-X would require U.S. participation of at least $2M per year.

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

1. Recognize that international collaboration offers opportunities to make progress on TAP issues by taking advantage of U.S. strengths, for example in:
   - Equilibrium analysis and reconstruction
   - Fast particle modes
   - Connection of configuration optimization to improved performance
   - Stochastic edge layers in stellarators and tokamaks
   - Engineering of 3D systems
2. Support the need for international collaboration in stellarators, especially with LHD and W7-X, as a strong component of a coherent stellarator research thrust within the U.S. fusion energy sciences program.
3. Consider the W7-X partnership opportunity described here, comment on its strengths and weaknesses, and offer suggestions for improvement as appropriate.

We will be glad to respond to comments and questions and we look forward to discussing these ideas at the Theme 5 Workshop.

U.S. – IPP Collaboration on 3D Plasmas and Stellarators

Introduction

- There is a long history of productive U.S.-IPP collaboration in the physics and engineering of stellarators.
  - Theory and codes, e.g. VMEC, PIES, CAS3D, NESCOIL, V3FIT, DKES
  - Experiments on W7-AS.
  - Design, construction, and program planning for NCSX.
- W7-X offers unique opportunities for new science of importance to MFES.
  - Validate theory and physics models (equilibrium, stability, and transport) for 3D plasmas. Such models are critical for predictive capability and design.
  - Understand the control of steady-state stellarator plasmas with divertors and superconducting magnets.
  - Found by the EU fusion facilities review panel to be of "very high" priority for DEMO-oriented R&D, particularly "with respect to steady-state operation in a reactor perspective." They said, "Wendelstein 7-X should investigate steady-state operation of relevance to ITER as well as demonstrate the reactor potential of the Stellarator concept."
  - Large new world-class device: current staff of about 500; about 20% collaborators.
  - Envisioned by IPP as an international fusion science research facility that incorporates collaborators (~50% collaborators foreseen), following the successful Asdex-Upgrade model. Collaborations with other EU countries have already started. Research will be guided by an international program advisory committee (~50% non-IPP).
  - Scientific staff during operations (envisioned): ~100 IPP + ~100 collaborators. Task force leaders will include collaborators (must be on site during operations). Collaborators have complete access to all data. Transparent file system accessible from anywhere.
  - With early integration during the build-up of a strong scientific team, there is maximum opportunity for significant influence on the course of the research program. Early contributions lead to strongest roles in the research.
- U.S. fusion community has experience and expertise in stellarator theory, experiment, and engineering, including specialized capabilities relevant to current and future W7-X needs.
- A long-term U.S.-IPP partnership focused on the linked issues of divertors, steady-state operation, and plasma control in W7-X, issues which are central to success of W7-X, would produce important contributions to international fusion science and would benefit the fusion programs of both parties.
  - Edge and divertor diagnostics and interpretation
  - 3D equilibrium reconstruction (integrated analysis of magnetics signals)
  - Control of plasma-divertor interface through a)divertor target alignment and operational limits (3D electromagnetic analysis of vessel and in-vessel components) and b) control of diverted magnetic field lines with trim coils.

– Fusion engineering science: solutions to targeted problems in the integration of a complex fusion research facility with important similarities to ITER (large size, superconducting magnet technology). Contributing to W7-X develops high-level engineering capabilities necessary for future research facilities. U.S. will make engineering contributions that either a) support the physics goals of the collaboration (diagnostics and trim coils) or b) take advantage of specialized U.S. stellarator engineering capabilities (critical assembly issues).

Specific Near-Term Tasks
(Possible tasks discussed at IPP, 4-6 February 2009. Need further evaluation and selection of a subset for U.S. contributions)

During initial operation W7-X will have an inertially cooled Test Divertor Unit (TDU); plasma heating up to 11 MW of ECRH plus NBI (~10 sec) or ~1 MW for ~1 minute; magnetic field up to 3 T.

Diagnostics needed by 2014 (end of assembly).

- Hα, Hγ, C II/III filterscopes for divertor imaging (8 systems for symmetry investigations during 1st operational phase / Test Divertor Unit (TDU) phase, ~10 sec)
- CXRS observation system (endoscope + high throughput spectrometers + cameras) – ideally with long pulse capability
- Divertor spectroscopy (Balmer series, Stark broadening, …)
- Opto-mechanical design and construction of Thomson scattering transmission line.

Diagnostics needed during the first operational phase (2014-2016).

- Impurity pellet injection
- Li-beam (midplane, density profiles and CXRS)
- Reflectometer
- Pellet injector (plasma fuelling)
- Fast ion loss detectors

U.S. Engineering contributions supporting the physics goals of the collaboration

- Magnetic code and eddy current force analysis for divertor components
- Trim coil fabrication
- Diagnostics (see above)
- Investigation of the applicability of microwave codes for stray radiation calculations in real geometry

Critical Assembly Problems Utilizing Specialized U.S. Capabilities

- Configuration space management (T. Dodson: 6-month assignment with W7-X back office)

- Port handling & installation (backup tooling scheme)
- Cryogenic superconducting current lead handling and installation.
- Superconducting bar joint insulation
- Selection of piezoelectric valves for gas injection
- Cryopump for NBI
- Parametric modeling for critical support elements and ports.