Integrated whole device modeling as a target for optimization

(Primary panel C; Secondary panel D)

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The combination of integrated whole device modeling with an optimization strategy can potentially lead to a powerful new approach for performance improvement and avoidance of serious transient phenomena. Within the U.S. fusion program, the primary example of optimization in high dimensional parameter spaces has been in the design of stellarators, e.g., the STELLOPT optimization model. The STELLOPT approach[1,2,3,4] is based on identifying a large number of target (or cost) functions coupled with a selection of independent control variables. This system can then be advanced towards an optimum state through a variety of algorithms, such as Levenberg-Marquardt, differential evolution, or genetic approaches. While the stellarator design application remains of interest, this approach has more general applicability to the operation and design of fusion systems, as described below. High dimensional optimizations also are readily adapted to new leadership computing platforms. The original version of STELLOPT was based on an MPI parallelization over the evaluation of the target functions in the different directions of the control space. It should be possible to extend this to a more hierarchical parallelization (MPI/OpenMP/GPU) for target functions that have been internally parallelized. A newer optimization framework, the DAKOTA[5] SciDAC project, is also available, includes both gradient-based and derivative-free methods, and should be applicable to the problems described here. In the following, three areas are described where such an optimization approach coupled with whole device modeling could lead to new and transformative directions in fusion energy research.

I. Tokamak discharge trajectory optimization

Sustaining plasmas in the ignited plasma regime will involve complex balances between self-heating, stability, external fields, and control of particle and energy sources. The conventional control approach is to rely on a collection of sensors/controls/actuators that are programmed to respond in real time to a variety of events and keep the discharge on track towards some predetermined goal. However, such a model is limited to responses that are localized in time and many of the dynamic phenomena to be controlled are characterized by time non-locality, memory effects, hysteresis, etc. For example, the off-axis minimum q-profiles required for advanced tokamak operation have to be "baked-in" during the current ramp-up phase by appropriately mixing/phasing of Ohmic and neutral beam current drive; the conditions leading to disruptions may build over a sequence of slowly growing neoclassical tearing modes leading up to mode locking; runaway electron avalanches at the current quench phase may be influenced by fast electron seed populations that were created during the initial breakdown phase of the discharge; neutral populations may evolve over long equilibration times coupled with wall pumping effects. These examples and others motivate a more holistic approach to control that takes into account the full discharge evolution from breakdown to flat-top to termination.

As integrated whole device modeling improves in fidelity and becomes validated/predictive, an optimization approach for the whole discharge becomes feasible. Alternately, optimal control theory methods could be used, which should provide similar capabilities.[6] The optimization approach would be to consider the full discharge waveform as an optimization object, with time just another dimension and identify a set of optimization goals. This could consist of a Dakota optimization wrapped around a sequence of IPS (plasma state) time slices. The optimization objective function could be related to performance, steady-state (bootstrap driven) operation, machine protection, avoidance of disruptions, etc. The available control variables included the external vertical plus 3D magnetic fields, and the particle/energy sources and sinks. The output result would be an operating script in time for levels of the various control variables through the discharge. This approach is expected to lead to different strategies than current scenario planning methods. The ease, short pulse length, and relatively low cost of operating existing experiments have not motivated such an approach. However, the much greater expense, limited machine time, and safety issues of ITER operation are expected to make discharge planning and optimization a much more formal process. In the meantime, such an approach could be tested on existing devices and could possibly lead to discovery of new enhanced confinement regimes, or improved ways to sustain those that have been found. Even if predictive models were not available for all phenomena of interest, such optimizations could be supplemented with empirical information derived from discharge data-mining. Based on our experience with the computational optimization of stellarators, it quite possible that a whole discharge trajectory optimization process could find new scenarios that have been missed by human intuition.

II. 3D tokamak configuration optimization

Future tokamaks are likely to use 3D control coils for a variety of reasons: ELM/RWM suppression, error field correction, and divertor exhaust strike-point optimization. Current 3D control coils are largely based intuitive designs using simple window-pane geometries; these may succeed in making the outer flux regions stochastic, but they also often project 3D effects more deeply into the plasma[7] than desirable. Ideally a more surgical/focused approach is needed that only delivers 3D fields where needed and structures their variation in a more optimal way for the physics being controlled. 3D coil design will also become more demanding for DEMO and FNSF devices, which will likely move the 3D coils outside the vacuum vessel, further from the plasma. This motivates the use of a more comprehensive coil geometry optimization approach, as was used in the STELLOPT/COILOPT suite of codes.

Additionally, there is a clear need for a more comprehensive approach to overall tokamak design optimization, taking into account not only plasma physics, but also engineering and cost components. The ITER experience has certainly demonstrated that numerous on-the-fly design changes (e.g., adding in-vessel coils to insure vertical stability and 3D coils for ELM control) can negatively impact costs and schedules. The designs of FNSF and DEMO will have to be done in a more methodical and integrated way using well-tested optimization tools if costs are to be controlled.

III. 3D Stellarator design

The U.S. fusion program seems to take a serious interest in stellarators sporadically, i.e., on a cycle time of around ~20 years (i.e., early Spitzer stellarators => C-stellarator => ATF => NCSX/QPS => ?). However, many have expressed the belief that tokamaks cannot ultimately be attractive fusion reactors or neutron sources due to issues with disruptions, ELMs, and a lack of efficient current drive solutions for steady state operation. A more balanced program that developed tokamaks and stellarators on an equal footing (such as pursued in Europe and Japan) would provide us with a good insurance policy against the risks of a single-minded pursuit of the tokamak. Also, the higher density limits achieved in stellarators can potentially lead to attractive options not possible in density-limited tokamaks, for example: D-T systems with low temperature ignition[8] (less stress on walls and divertors), more compact (higher power density) reactors,[9] and a potential pathway to advanced fuel cycles, such as catalyzed D-D,[10] with significantly lower neutron damage on walls. But unresolved issues/opportunities with stellarator design remain: fast ion confinement, divertor design, coil simplification and cost, and core turbulence suppression. An ongoing program of optimization target function improvement, informed by improved integrated whole device modeling, should be maintained; newer optimization tools, such as Dakota, should also be implemented. This should be coupled with continuing configuration optimization activity, looking at several different options, in preparation for a future shift in direction to the stellarator as a fusion reactor.

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References

[1] Hirshman, S.P. ; Spong, D.A.; Whitson, J.C.; Lynch, V.E.; Batchelor, D.B.; Carreras, B.A.; Rome, J.A., "Transport optimization and MHD stability of a small aspect ratio toroidal hybrid stellarator," Physical Review Letters, **80**, 528 (Jan. 1998).

[2] Spong, D.A.; Hirshman, S.P.; Whitson, J.C.; Batchelor, D.B.; Carreras, B.A.; Lynch, V.E.; Rome, J.A., "J* optimization of small aspect ratio stellarator/tokamak hybrid devices," Physics of Plasmas, **5**, 1752, (May 1998).

[3] Reiman, A.; Fu, G.; Hirshman, S.; Ku, L.; Monticello, D.; Mynick, et al., "Physics design of a high-β quasi-axisymmetric stellarator," Plasma Physics and Controlled Fusion, **41**, suppl.12B, B273, (Dec. 1999).

[4] Extensive information on running STELLOPT and its components has been assembled by Sam Lazerson at http://vmecwiki.pppl.wikispaces.net/STELLOPT.

[5] http:dakota.sandia.gov, and http:dakota.sandia.gov/content/journal-papers for publications.

[6] Ross, I. M., *A Primer on Pontryagin's Principle in Optimal Control*, Collegiate Publishers, 2009. ISBN 978-0-9843571-0-9.

[7] T. E. Evans, "Status and future needs for ELM control using resonant magnetic perturbations," Workshop on Transients: Community Input Workshop, April 1, 2015.

[8] N. Ohyabu, T. Morisaki, S. Masuzaki, R. Sakamoto, M. Kobayashi, J. Miyazawa, M. Shoji, A. Komori, O. Motojima, and LHD Experimental Group, "Observation of Stable Superdense Core Plasmas in the Large Helical Device," Phys. Rev. Lett. **97**, 055002 (2006).

[9] F. Najmabadi, A. R. Raffray, ARIES-CS team, “The ARIES-CS compact stellarator fusion power plant," Fusion Science and Technology, **54**, 655 (2008).

[10] J. Sheffield, D. A. Spong, "Generic stellarator-like magnetic fusion reactor," in preparation, 2015.