On the implications of disruptions for the US MFE program

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The disruption is presently a showstopper for the long-term development of the tokamak/ST concept (FNSF or DEMO). This whitepaper attempts to look longer term at how disruptions should impact our program, given that the tokamak/ST is and will likely continue to be the confinement scheme of choice. *It is deliberately myopic, in order to emphasize this point*.

The approach here is that disruptions must be avoided, not "mitigated". We must support ITER, and so research in MGI, halo currents, RE control, and similar is important in the near term. However, it is not clear that our solutions envisioned for ITER will work in that device; many of them will almost certainly fail for a DEMO or FNSF. Hence, our long view must be to essentially avoid these events entirely.

It is likely that this paper best addresses charge #3, or possibly charge #2. It is almost certainly too expensive for charge #1. Furthermore, it is not clear to this author that an FNSF could realistically be built under the charge #3 guidance, even if all other research were terminated. Hence, a more modest program is suggested.

1. Implications for next step tokamak/ST options

It appears that most of the issues related to disruption avoidance could be examined in a tokamak/ST device with the following characteristics: i) hot walls and the ability to test various PFCs options, ii) full current drive with q-profiles at least similar to those expected in the next devices such as FNSF or DEMO, iii) excellent profile, divertor, and 3D field diagnostics, which may or may not be used in realtime control, iv) a variety of MHD control actuators, v) operation points both above and below the no-wall stability limit, vi) pulse durations many times longer than the longest recycling and wall evolution time-scales, vii) power densities to test PFCs in DEMO/FNSF relevant conditions. See ReNeW report (thrust 12 in particular) and other whitepapers about these combinations of parameters.

Note that this device will certainly produce neutrons, but is not intended for the nuclear component qualification mission; rather is it a bridge to a full-scale FNSF or DEMO (which I do believe are appropriate goals, potentially as international collaboration).

A key mission of such a device would be to operate at high core performance with acceptable heat flux solutions, for pulses longer than all relevant time scales, with all available disruption avoidance techniques, and demonstrate disruption avoidance and discharge stationarity at levels approaching that required for an FNSF or DEMO. It would then dial back the measurements and actuators towards what would be possible in an FNSF or DEMO, and determine if disruptions can still be avoided. This may be equivalent to bringing a knife to a gunfight, and the sooner the question is resolved, the better.

Finally, a device like that described above would have many other research missions for steady state operations, basic PMI studies relevant to all MFE geometries, transport physics with the relevant plasma boundary, model validation, and so on. This contribution deliberately emphasizes the disruption aspects of the mission.

2. Implications for FNSF

The diagnostics and actuator access in an FNSF or DEMO will be much more restricted than in present devices or the above described facility. If it is found that an unrealistically advanced level of realtime measurement and control is required for “complete” disruption avoidance, or that the required level of avoidance is not achievable even with best control techniques, then the logical choices are to i) abandon the tokamak/ST-based FNSF strategy, or ii) design a less ambitious FNSF that may have TBR<1 and lower levels of NWL, but can accomplish some fraction of the nuclear mission while tolerating disruptions.

These sorts of FNSF studies should be accomplished as part of a multi-institution engineering and physics study; this is critical since impressions of what an FNSF actually is vary widely across the community. This study should use data from NSTX-U, C-MOD, DIII-D, and international facilities, as well as realistic engineering considerations, to develop optimal FNSF designs; full utilization of those facilities will clearly increase the pace of developing these designs. An assessment of measurement and actuator capability would be a key component of the study. These would then provide a baseline for the design and operation of the facility noted in section 1. Indeed, the FNSF or DEMO goals should be integral with all aspects of that device.

There is a chance that sufficient new funding will be available to consider the construction of an FNSF without resolving these PMI/integration/disruption issues. In that case, the path taken depends on the level of risk the community and funding agencies are willing to take. The PMI/integration/disruption mission could be the first stage of an FNSF if sufficient H&CD power were available. However, this means that the expense of a nuclear-upgradable facility may be wasted if the disruption issues cannot be resolved. For this author, the risk seems too large at present.

3. Implications for non-tokamak configurations

There is only a single magnetic surface configuration that has demonstrated robust disruption avoidance: the stellarator. Other low-B systems may not have events with the phenomenology of tokamak disruptions, but rapid current terminations do occur in many of them. After the cancellation of the NCSX project, the US has a shell of a stellarator experimental research program: a couple of important but underfunded university devices, some diagnostics on LHD, and a meaningful but limited collaboration on W-7X.

We may not like some aspects of coil, divertor, and FW geometric complexity, but these may be more manageable in the long run than multiple MHD feedback systems and the imminent threat of violent discharge termination. Furthermore, the density can be much higher in a stellarator for the same poloidal field, potentially solving many of the PFC problems. In general, the decoupling of the internal profiles from the magnetic geometry makes the stellarator more robust; this robustness should be developed and exploited.

4. Implications for transformational research

Finally, there may be some possible breakthrough technologies that can reduce the scope of the disruption problem. Liquid PFCs may be better able to handle the thermal loads (though REs would likely still be unacceptable). Improved magnet technology may allow added safety factor, in both the technical and figurative sense. Dramatically improved confinement may allow the plasma current to be lowered, making disruption consequences manageable again; low-recycling PFCs may be a route to these regimes. These sorts of innovations should be pursued.

5. Suggestions for the US fusion program

Based on the above considerations, a 10-15 year program for the US fusion program could entail three aspects (and likely others as well):

- A multi-institutional effort should be initiated to design the next large US MFE facility, including one meeting the FNSF mission needs. This would have as a core element an evaluation of the impact and avoidance of disruptions. These studies would also include the design and operational program for the device described in Section 1. Full utilization of the existing facilities (not 8-10 run weeks a year) will provide the physics basis for these studies.
- A tokamak or ST facility meeting the specifications of section #1 should be designed, guided by long-term MFE goals, with construction beginning in the mid-to-later phases of the period.
- There should be a significant increase in stellarator research in the United States, including a PoP class facility.

6. US leadership and breakout potential

In defining any future program, it is critical to maintain US leadership in key areas, and to preserve breakout potential. The above program does so in the following sense:

- It would provide US leadership in the area of PMI in confinement devices.
- It would provide US leadership in disruption avoidance with all the relevant boundary conditions.
- It would position the US as a key player in stellarator physics, and one of only two nations with a truly “advanced” stellarator.
- By operating both advanced stellarator and tokamak/ST devices, it positions the US to rapidly develop either device configuration should the physics and funding situations become more favorable.

7. Summary

Disruption avoidance in high performance, DEMO/FNSF relevant conditions should be a core mission element, not a design assumption, of the next major tokamak/ST build in the United States, and alternative confinement schemes that do not suffer from disruptions should be pursued.