Workshop on Transients in Tokamak Plasmas

Preventing Device Damage from Disruptions

Final Report

by

Charles Greenfield

for Raffi Nazikian, Mark Foster, and a cast of many

Presented to the Theory and Simulation of Disruptions Workshop
Princeton, New Jersey

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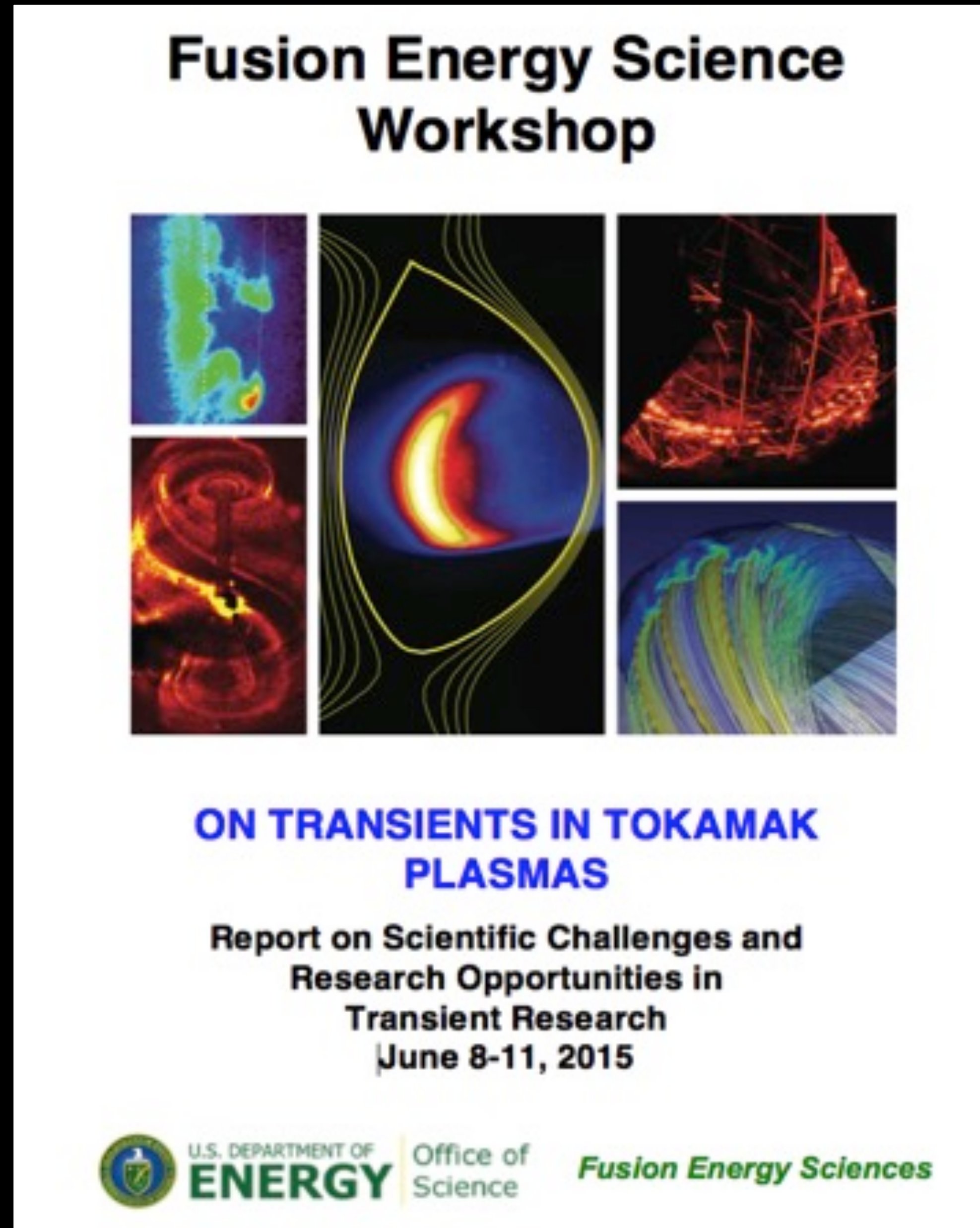

http://science.energy.gov/fes/community-resources/workshop-reports/

What and why?

- The "FESAC 2014" report identified high priority research areas for the US Fusion Energy Science program – the first item on the list was "Control of deleterious transient events"
- In 2015, DOE-FES convened a set of four community workshops to identify research foci for the US program, on Transients, Plasma Material Interactions, Integrated Simulations, and Plasma Science Frontiers
- The Transients Workshop addressed disruptions (today's topic) and ELMs (not discussed here), with the goal of identifying research to eliminate these as show-stoppers for ITER and subsequent tokamaks

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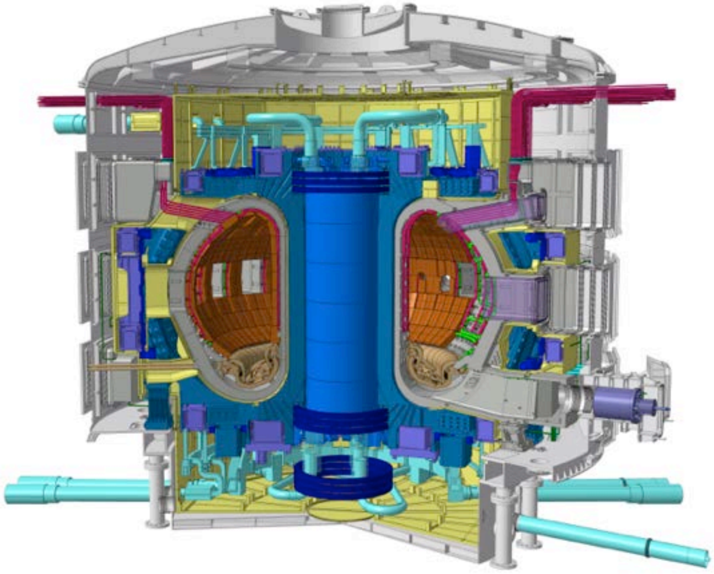
The workshop report is clearly and by design US-centric, but recognizes and explicitly recommends collaboration to combine our strengths with those of our international partners

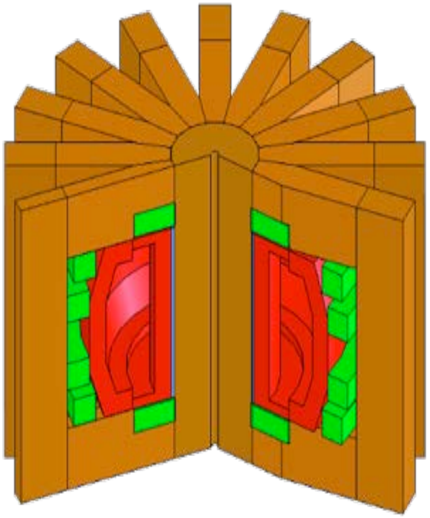
Transients Workshop: Objective

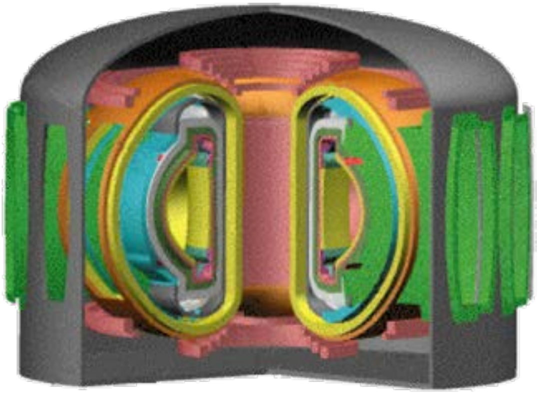
Building on the ReNeW effort, other workshop results, and the ongoing USBPO disruptions task force plans, this workshop:

- **Reviewed recent progress**
- **Identified remaining science and technology challenges**
- **Identified specific research opportunities**

The Transients Workshop addressed targets with two different timescales



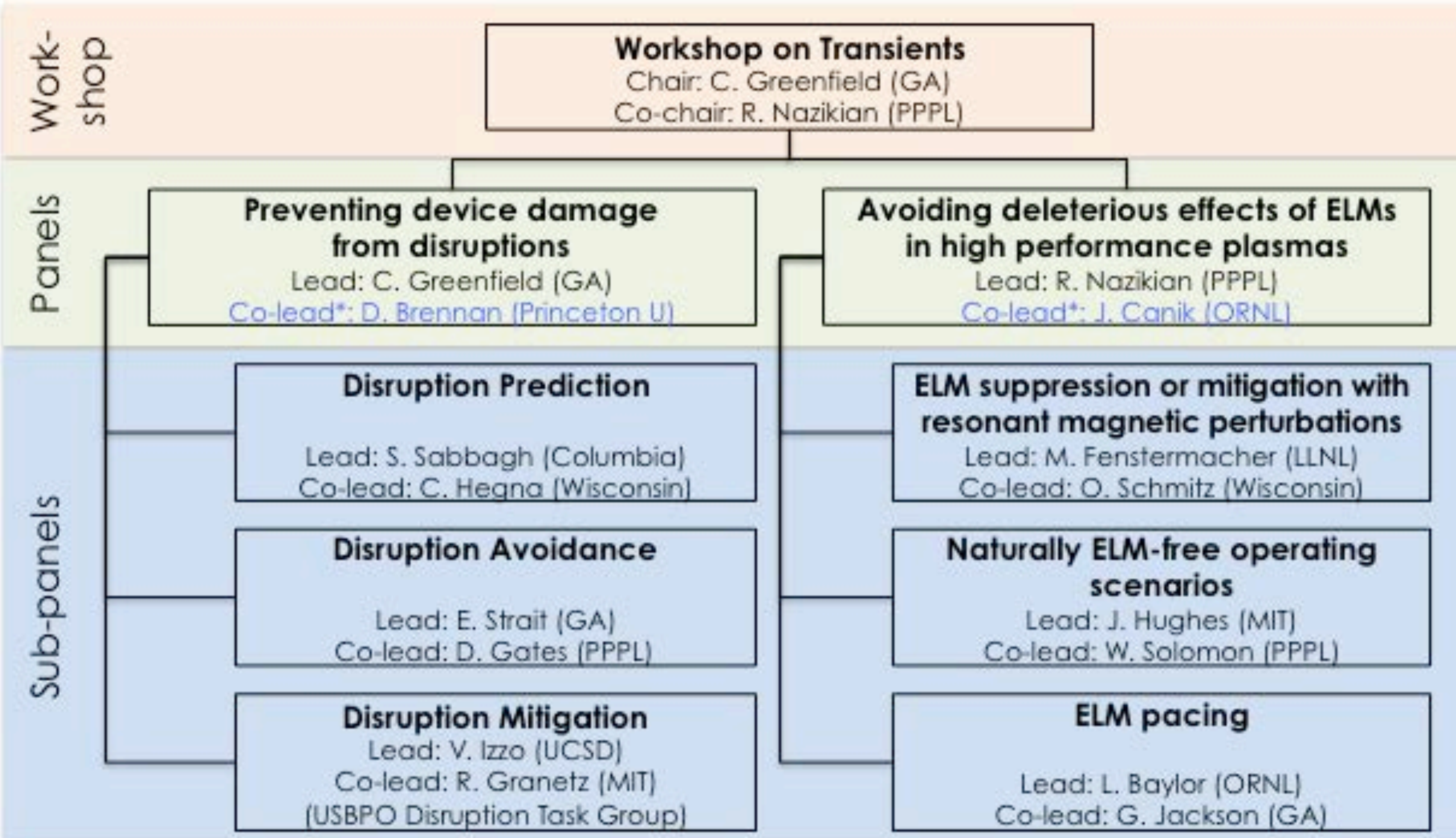




1. Ensure that ITER can successfully carry out its mission. *ITER is largely designed, with a rapidly closing window for design changes. Emphasis is needed on validating and optimizing use of the already specified transient control tools within a fairly short time span.*

2. **Prepare for post-ITER devices** *that are still largely undefined. They will undoubtedly pose new and greater technical challenges than ITER, but also present unconstrained opportunities to develop new tools. Research will continue through the next decade or more.*

Transients Workshop Organization



** Disruption and ELM panel co-leads are joint appointments with Modeling and PMI workshops respectively*

The traditional approach to disruptions

- **Issue: If severe, disruptions and related phenomena can damage the device**
  - Major disruptions (full current quench)
  - Minor disruptions (large thermal collapse)
- **Objective: (overall) Define a research plan to solve the disruption issue in tokamaks, including future high performance plasmas operating in steady-state conditions**
- **Approach: Prediction, Avoidance, Mitigation (PAM)**
  - This is how we organized ourselves for the workshop, but we realized this isn't a good description…

Premise: The tokamak is capable of attaining high performance in a stable state, and our objective should be to identify and maintain such states

- **Disruption Prediction → Predicting the Boundaries of Tokamak Stability**
  Identify research to facilitate predicting limits of stable operation and forecasting when a disruption might be imminent
- **Disruption Avoidance → Sustaining Stable Tokamak Operation**
  Identify research to devise methods to sustain stable tokamak operation through both passive and active means. In addition to "plasma-physics causes" (primarily MHD instability), this includes responses to off-normal events that might be caused by hardware failure or human error
- **Disruption Mitigation → Mitigating the Effects of Disruptions**
  Identify research to safely shut down the tokamak while avoiding damage from the release of the plasma's thermal and magnetic energy. This is a last resort when a disruption becomes otherwise unavoidable. A major focus of this research in the next few years will be preparation for the ITER Disruption Mitigation System, due for a final design review in 2017

The Workshop produced four broad findings for disruption research

1. While the US has been a pioneer in important elements of research on disruption in tokamaks, a more focused and coordinated effort is needed to maintain leadership and to resolve this critical issue in time for ITER's operation.
2. Disruption prevention is fundamentally an issue of integrated disruption prediction and plasma control. Such a system needs to be developed.
3. A significant amount of research is still required to determine the most effective use of the currently planned ITER disruption mitigation system. We note that the United States will supply this system to ITER and will be largely viewed as responsible for its success.
4. Substantial additional resources are required to resolve outstanding challenges in Integrated Disruption Prediction, Control, and Mitigation in time for ITER's initial operation and for next-step reactors. The United States is a world leader in plasma stability and control research and is ideally suited to the recommended research with the necessary addition of resources.

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Each finding has a set of associated recommendations…

Finding #1. A more focused and coordinated effort is needed…

Recommendation #1: **The United States should address the disruption challenge for ITER and future tokamak fusion reactors by**

a) **Developing a National Initiative for Elimination of Disruptions in Tokamaks to best leverage and evolve the combined strengths of the present U.S. facilities for this purpose. A product of this effort would be an Integrated Disruption Prediction and Plasma Control System that sustains stable high-performance plasma operation while forecasting and avoiding stability limits that could lead to disruption.**

b) **Evolving U.S. experimental programs to have greater focus on means of controlling plasma stability and predicting the limits of stability in real-time, as well as mitigation of disruption when the limits are exceeded, specifically integrating and utilizing past research to produce quantifiable progress in these areas.**

c) **Leveraging international collaboration on existing tokamaks focusing on unique physics and control aspects such as size (JET), long pulse length, and constraints in devices with superconducting magnets (EAST and KSTAR). This approach also allows rapid access to a larger tokamak database that will be essential for developing and testing algorithms for prediction of stability limits, and control and mitigation capability.**

Finding #2: Disruption prevention is fundamentally an issue of integrated disruption prediction and plasma control…

Recommendation #2: **The United States should address the disruption challenge for ITER and future tokamak fusion reactors by developing the necessary elements of physics-based prediction and control of plasma stability for maintaining reliable, high performance plasma operation. These elements include:**

a) **Theory-based and experimentally validated models of plasma stability to map out regimes of stable operation, ultimately available in real-time.**
b) **Improved diagnostics and validated reduced physics models as synthetic diagnostics for accurate real-time forecasting of disruptions that can be used to take corrective action.**
c) **Robust control systems and active stability evaluation (including sensors, actuators, physics-based control logic, routine MHD spectroscopy) to access and maintain a stable operating point.**
d) **Validated predictions of the results of unplanned excursions away from the operating point and control algorithms to take appropriate actions, ranging from recovery of the original operating point to controlled termination of the discharge.**
e) **Improved diagnostics and controls to optimize the performance of passively stable tokamak regimes, and to predict, avoid and/or suppress instabilities**

Finding #3. Significant… research is still required to determine… effective use of the currently planned ITER DMS…

Recommendation #3: **Expand research on existing U.S. facilities, with additional run time and staffing, to determine the most effective use of the currently planned ITER disruption mitigation system by developing:**

a) **Validated predictive physics models for the thermal quench heat loads and their mitigation, and runaway electron amplification and suppression in ITER.**

b) **Mitigation methods to protect ITER (and future reactors) from runaway electron damage while maintaining the current decay rate in a safe range, including validation of models in existing experiments for extrapolation to reactor scale.**

Finding #4. Substantial additional resources are required to resolve outstanding challenges…

<u>**Recommendation #4:**</u> **The United States should deploy an Integrated Disruption Prediction, Control, and Mitigation System in one or more existing U.S. facilities to (a) maintain reliable disruption-free operation, and (b) effectively mitigate unavoidable disruptions, in time for ITER operation. This requires:**

a) **Significant facility upgrades including additional heating flexibility and current drive capability, additional sensors and actuators for disruption prediction and plasma control.**

b) **Additional run-time and staffing, and further focus on existing facilities to develop validated reduced physics models, and to refine the Integrated Disruption Prediction, Control, and Mitigation System at the very low levels of plasma disruptivity needed in future devices, with quantitative and robust demonstrations of these goals.**

The US program will make critical and unique contributions to the worldwide fusion program in coming years

- **Substantial resources are required to meet the challenge of controlling transients in time for operation of ITER and to develop design solutions for next step reactors**
  - Manpower, modeling, fusion technology, runtime
- **The US fusion program is positioned to provide these solutions by building on a strong foundation of outstanding facilities, world-leading theory and fusion technology**
  - Flexible and well diagnosed facilities in the US are ideally suited to validate emerging physics models and to produce scientific innovations
- **We will need to collaborate with our international partners with complementary capabilities**
  - Size, long-pulse, materials,…

This workshop provided community input for DOE-FES to use in their program planning

PANEL 1: Preventing device damage from disruptions (26 members)

Lead: Charles Greenfield (General Atomics)
Co-lead: Dylan Brennan (Princeton University) joint with Integrated Modeling Workshop

Sub-panel 1. DISRUPTION PREDICTION

- Leads: Steve Sabbagh (Columbia) and Chris Hegna (Wisconsin)
- Members: P. deVries (ITER), N. Ferraro (GA), J. Ferron (GA), R. Granetz (MIT), S. Kruger (TechX), R. La Haye (GA), D. Maurer (Auburn), B. Tobias (PPPL), K. Tritz (JHU)

Sub-panel 2. DISRUPTION AVOIDANCE

- Leads: Ted Strait (GA) and David Gates (PPPL)
- Members: J. Hanson (Columbia), S. Gerhardt (PPPL), D. Humphreys (GA), E. Kolemen (Princeton), R. La Haye (GA), M. Lanctot (GA), S. Sabbagh (Columbia), J. Snipes (ITER)

Sub-panel 3. DISRUPTION MITIGATION

- Leads: Val Izzo (UCSD) and Bob Granetz (MIT)
- Members: N. Eidietis (GA), M. Lehnen (ITER), R. Raman (Washington), D. Rasmussen (ORNL)