

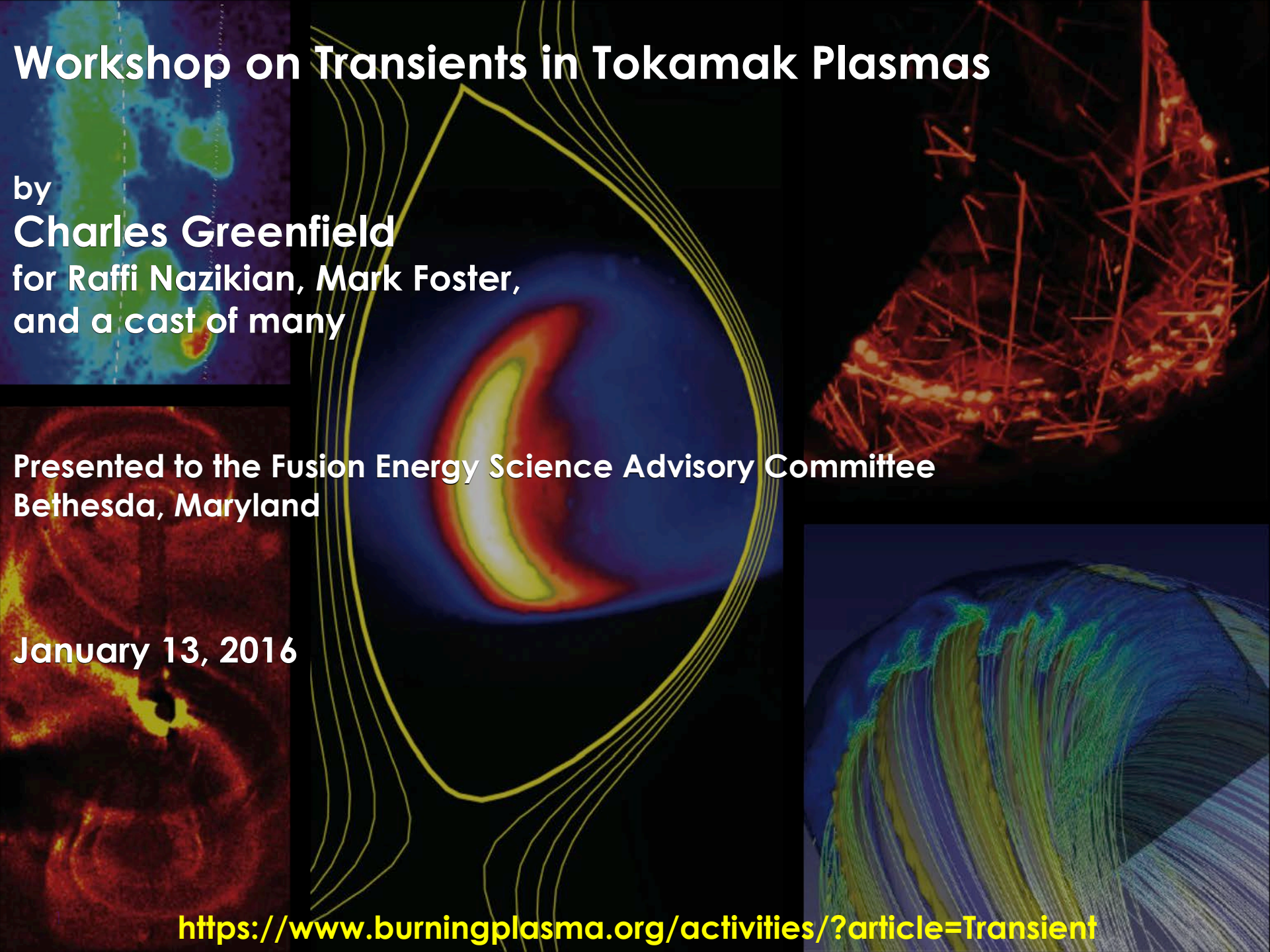
Workshop on Transients in Tokamak Plasmas

by
Charles Greenfield
for Raffi Nazikian, Mark Foster,
and a cast of many

Presented to the Fusion Energy Science Advisory Committee
Bethesda, Maryland

January 13, 2016

<https://www.burningplasma.org/activities/?article=Transient>

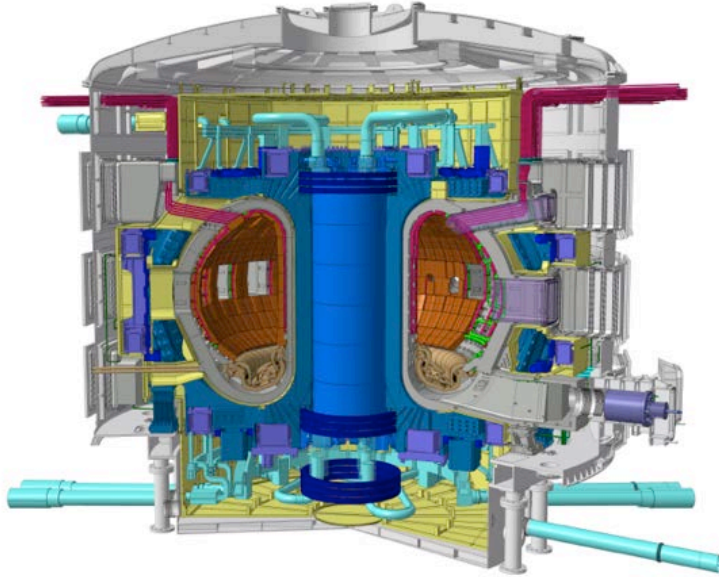


The tokamak is capable of attaining high performance in a stable state, and our objective should be to identify and maintain such states

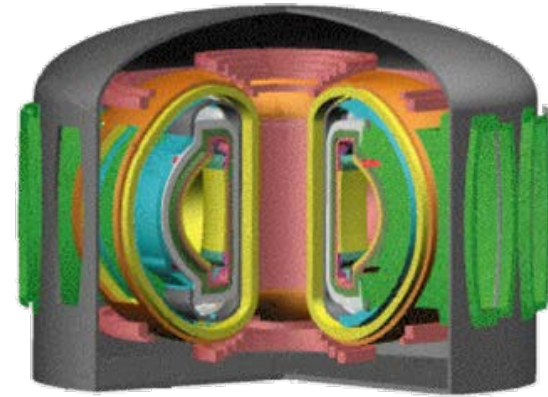
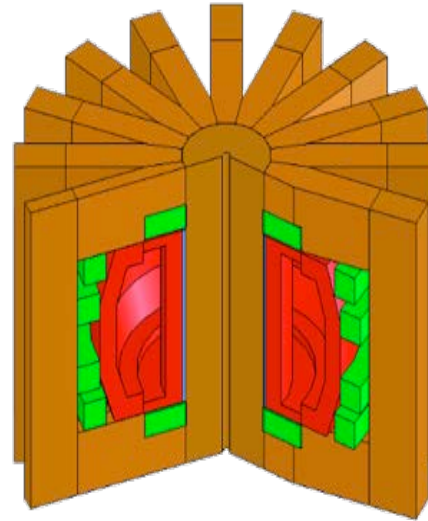
- **Requires progress in controlling transients (ELMs and Disruptions):**
 - Improve the physics basis
 - Develop and demonstrate control techniques...
 - That rely on ITER's capabilities
 - Post-ITER devices will pose new
 - Challenges: More restrictive environment
 - Opportunities: Not constrained by ITER's design
 - Identify and demonstrate high performance operational scenarios that are naturally ELM-free and passively stable to disruptive instabilities
- **The US Fusion Energy Science program is already a clear world leader in the transients areas – this should not change**

A coupled (experiment/theory/modeling) approach is needed to ensure accurate extrapolation of experimental results in present day devices to ITER and beyond

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.*

The Transients Workshop focused on research that is already being carried out with the highest priority

- **ITER is designed with capabilities, based largely on US research, to address ELMs and Disruptions**
 - Immediate needs to validate physics basis and fine-tune design requirements
- **The US is already world-leading in these areas**
 - If we don't resolve these issues for ITER, who will?
 - Need to maintain leadership for the health of our program
- **The other workshops are more forward-looking while we are dealing with now**
 - But... the Transients Workshop also addresses post-ITER challenges and opportunities
- **The Transients Workshop is in many ways a concatenation of two workshops, on ELMs and Disruptions**
 - Our report is very long (over 300 pages in Microsoft Word)

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**

Transients Workshop: Schedule

Date	Activity
Early February	Organize panels
February 20	Sub-panel kickoff videoconference
February, March	Sub-panel organization and conference calls as needed
March 30-April 2	Community Input Workshop to gather community input
April 15	Deadline for submitting white papers
April, May	Sub-panel conference calls as needed
June 8-10	Workshop on Transients (<i>at General Atomics</i>)
June 11	Report writing (<i>at General Atomics</i>)
November 10	Draft report submitted to FES

Transients Workshop: Schedule

Date	Activity
Early February	Organize panels
February 20	Sub-panel 38 presentations
February, March	Sub-panel organization and conference calls as needed
March 30-April 2	Community Input Workshop to gather community input
April 15	Deadline for submitting white papers
April, May	Sub-panel conference calls as needed
June 8-10	Workshop on Transients / 68 white papers
June 11	Report writing (at General Atomics)
November 10	Drafting the FES

65 attendees

Opportunities for community input

Transients Workshop: Present status

- **The written report is complete and is now with the technical editor (John Greenwald, PPPL)**
- **It does require rather extensive cleanup (fonts, consistency in section numbering, consistency in references)**
- **It is longer than I had hoped (over 300 pages in Microsoft Word)**
 - More like two reports concatenated: One on ELMs and one on Disruptions
 - Each section has a shorter introductory section summarizing the important points including findings and recommendations
 - Longer, more detailed sections were written by each sub-panel

Transients Workshop: Present status

- The written report is complete and is now with the technical editor (John Greenwald, PPPL)
- It does require rather extensive cleanup (fonts, consistency in section numbering, consistency in references)
- It is longer than I had hoped (over 300 pages in Microsoft Word)
 - More like two reports concatenated: One on ELMs and one on Disruptions
 - Each section has a shorter introductory section summarizing the important points including findings and recommendations
 - Longer, more detailed sections were written by each sub-panel

**These should be sufficient
for the casual reader**

Transients Workshop Organization

Workshop

Workshop on Transients

Chair: C. Greenfield (GA)
Co-chair: R. Nazikian (PPPL)

Panels

Preventing device damage from disruptions

Lead: C. Greenfield (GA)
Co-lead*: D. Brennan (Princeton U)

Avoiding deleterious effects of ELMs in high performance plasmas

Lead: R. Nazikian (PPPL)
Co-lead*: J. Canik (ORNL)

Sub-panels

Disruption Prediction

Lead: S. Sabbagh (Columbia)
Co-lead: C. Hegna (Wisconsin)

Disruption Avoidance

Lead: E. Strait (GA)
Co-lead: D. Gates (PPPL)

Disruption Mitigation

Lead: V. Izzo (UCSD)
Co-lead: R. Granetz (MIT)
(USBPO Disruption Task Group)

ELM suppression or mitigation with resonant magnetic perturbations

Lead: M. Fenstermacher (LLNL)
Co-lead: O. Schmitz (Wisconsin)

Naturally ELM-free operating scenarios

Lead: J. Hughes (MIT)
Co-lead: W. Solomon (PPPL)

ELM pacing

Lead: L. Baylor (ORNL)
Co-lead: G. Jackson (GA)

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

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)

PANEL 2: Avoiding deleterious effects of ELMs in high performance plasmas (30 members)

Lead: Raffi Nazikian (PPPL)

Co-lead: John Canik (ORNL) joint with the PMI workshop

Sub-panel 4. ELM SUPPRESSION OR MITIGATION WITH RESONANT MAGNETIC PERTURBATIONS

- Leads: Max Fenstermacher (LLNL) and Oliver Schmitz (Wisconsin)
- Members: J.-W. Ahn (ORNL), C.S. Chang (PPPL), T. Evans (GA), N. Ferraro (GA), A. Loarte (ITER), R. Moyer (UCSD), J.-K. Park (PPPL), R. Nazikian (PPPL), C. Paz-Soldan (GA), F. Waelbroeck (Texas)

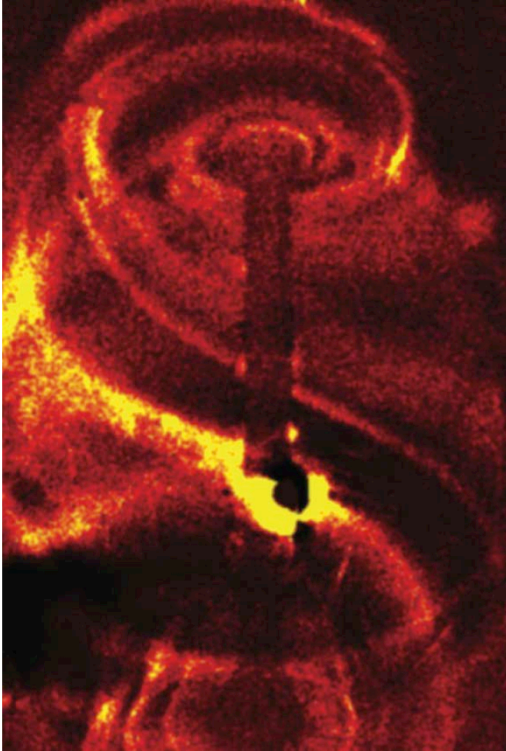
Sub-panel 5. NATURALLY ELM-FREE OPERATING SCENARIOS

- Leads: Jerry Hughes (MIT) and Wayne Solomon (PPPL)
- Members: K. Burrell (GA), A. Garofalo (GA), G. Huijsmans (ITER), D. Mansfield (PPPL, ret), J. Rice (MIT)

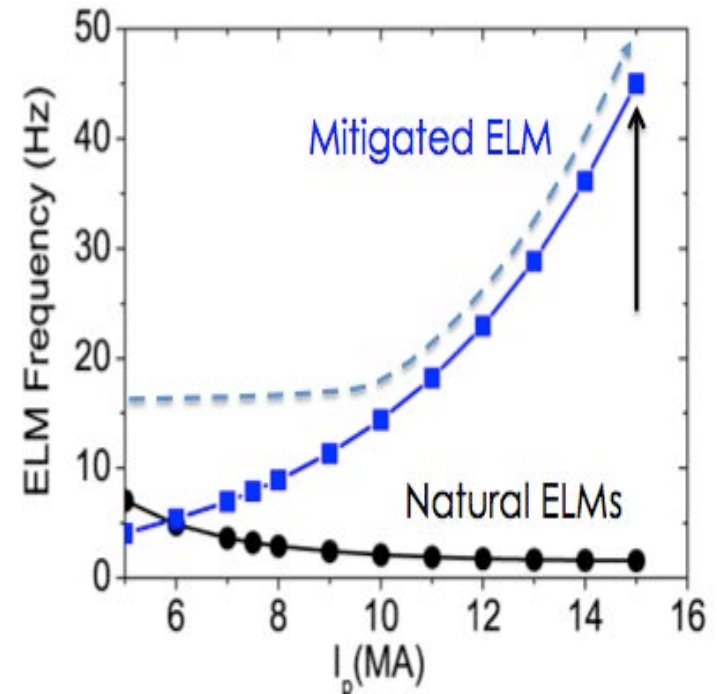
Sub-panel 6. ELM PACING

- Leads: Larry Baylor (ORNL) and Gary Jackson (General Atomics)
- Members: A. Bortolon (PPPL), N. Commaux (ORNL), S. Diem (ORNL), G. Huijsmans (ITER), T. Jernigan (ORNL, ret), A. Loarte (ITER), D. Mansfield (PPPL, ret), T. Osborne (GA), D. Shiraki (Columbia)

The ELM challenge for ITER and next step Reactors



PEGASUS



About three orders of magnitude separates present tokamaks from ITER in boundary heat flux

- **Up to 10% of stored energy can be released by single unmitigated ELM**
 - Largest ELM on DIII-D is ≈ 100 kJ
 - A 1 MJ “Giant ELM” in JET can be a discharge terminating event.
- **One single unmitigated ~ 30 MJ ELM on ITER could trigger a disruption**
 - Impurity influx, H-L back transition, loss of position control
 - 500 unmitigated ELMs expected in one high power ITER plasma
- **30-50x mitigation required to prevent surface melting, but long term consequences unclear**
 - These mitigated ELMs will burn through the detachment front
 - Source of erosion and redeposition
- **Next step reactors beyond ITER will likely require**
 - Complete ELM suppression/avoidance, or
 - Development of divertor/boundary solution that can eliminate the negative consequences of natural or mitigated ELMs

Key findings of the Panel on ELM Mitigation and Avoidance

- **The US fusion program is a world leader in developing ELM control solutions for ITER and next Step reactors. US innovations are central to the ITER plans for ELM control.**
- **The US is uniquely positioned to provide continued leadership in ELM mitigation and avoidance through world leading and complimentary facilities, advanced simulation and theory capability, and fusion technology.**
- **A significant amount of research is still required to determine the most effective use of the currently planned ITER ELM control tools and to determine effective ELM control and avoidance solutions for next step reactors.**
- **The risk posed by ELMs to the ITER mission and next step reactors is substantial and additional resources and coordination is required to address the ELM challenge in time for ITER's initial operation.**
- **The US is ideally suited to to the recommended research with the necessary addition of resources and with a nationally coordinated activity aimed at accelerating progress towards ELM control and avoidance.**

Recommendation #1: Increase emphasis on ELM control and avoidance at national fusion facilities (1-3 years)

- **Form a national task force** and a funded national initiative focused on developing the physics basis for ELM control and avoidance solutions for ITER and next step reactors.
 - Additional runtime and resources on current US facilities
 - Improved coordination and planning
- **Leverage collaboration on international tokamaks with capabilities that are complimentary to US facilities**
 - Metal wall (AUG/JET), long pulse (EAST/KSTAR), large scale (JET)

The overall goal is to integrate and leverage the strengths of the US laboratories and coordinate effort to more effectively address the ELM challenge for ITER and next step reactors.

Recommendation #2: National theory and simulation initiative on ELM control and avoidance (1 - 5 years)

- **Multiscale edge-plasma simulations** are required for predicting access and control requirements for ELM stable and ELM mitigated reactor regimes. This requires:
 - **Multiscale physics models** of long wavelength MHD and 3D magnetic field interactions with microturbulence and transport in the plasma edge. (Scientific grand challenge)
 - **Models of natural and mitigated ELMs**, including reduced models and advanced simulations, to predict the mode structure, 3D heat and particle pulses
 - **Whole device modeling**, with reduced models of the pedestal, actuators, and core transport, required to predict and optimize plasma performance consistent with ELM control solutions

Recommendation #3: Targeted upgrades to existing US facilities for optimization and model validation (1-5 years)

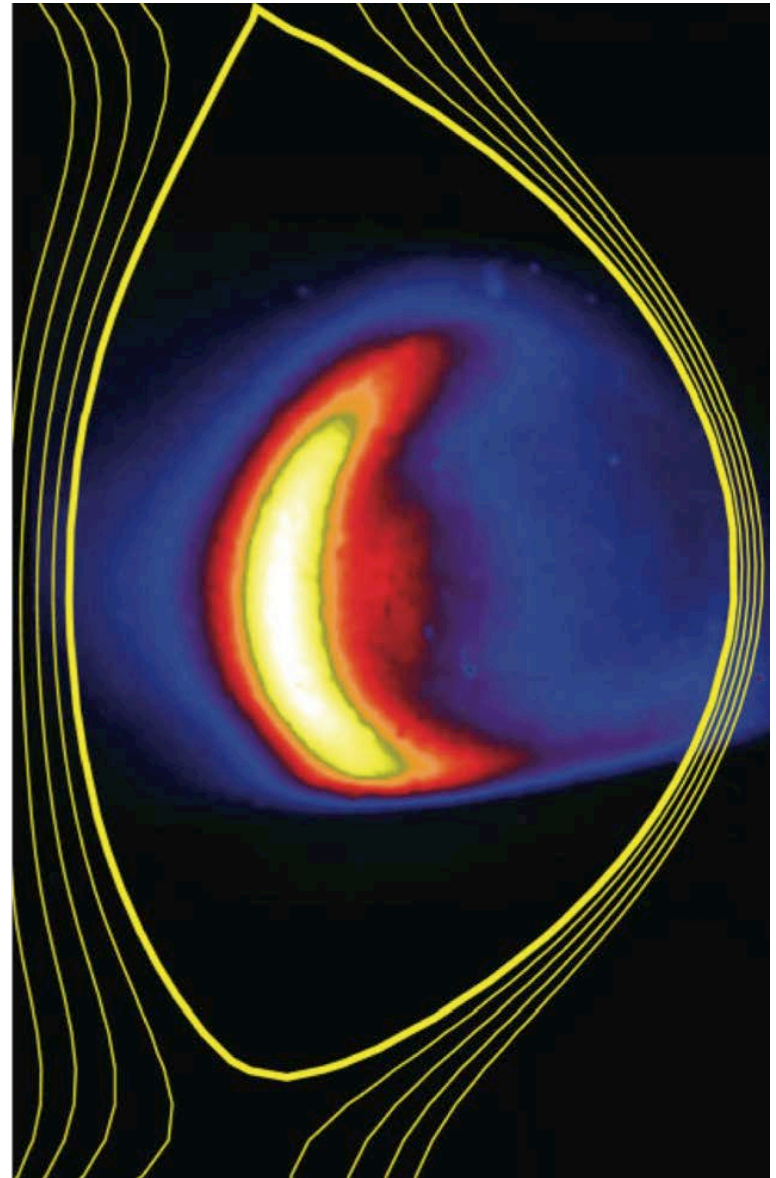
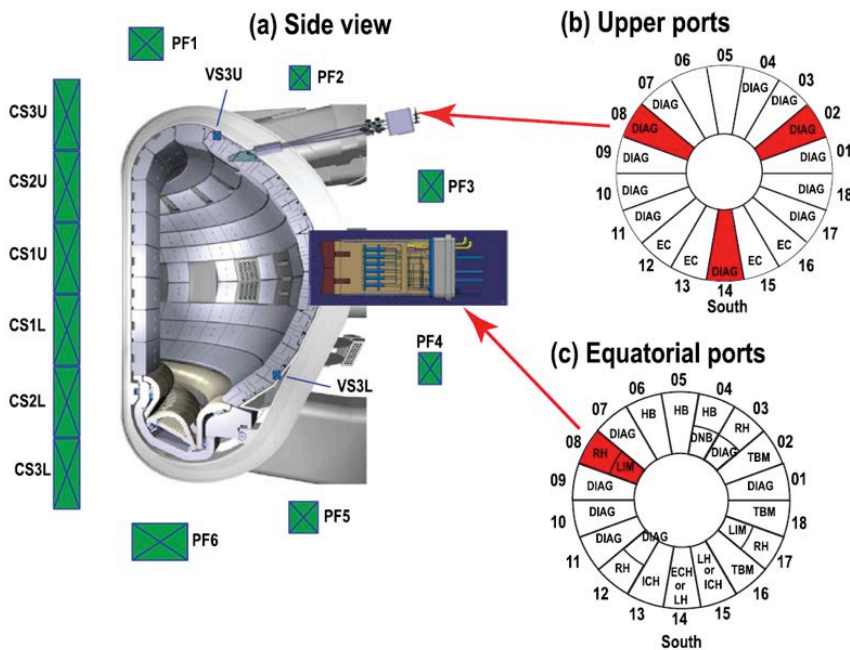
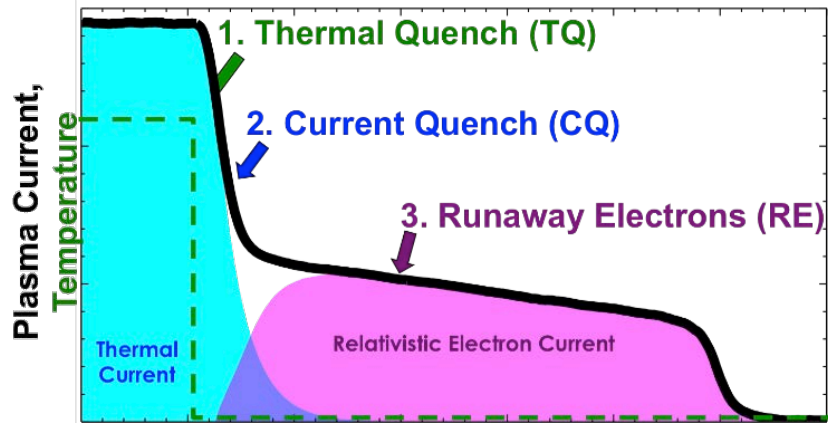
- **Accelerate ELM control and avoidance research through state-of-the-art diagnostics and actuators**
 - Comprehensive imaging of the particle/heat fluxes to the walls including fast ELM resolved imaging
 - Toroidally distributed profile and 3D magnetic measurements for accurate 3D equilibrium reconstruction
 - Fast time resolution profile and fluctuation measurements for capturing pedestal dynamics
 - Advanced edge transport actuators such as flexible high field 3D magnetic coils, and novel methods for edge electric field control (e.g. RF waves, ...)
 - Advanced pellet pacing techniques, both hydrogenic and high-Z pellets and for a range of injection geometries

Recommendation #4: Opportunities for major facility upgrades and new facilities to advance ELM control

- **More flexible heating with reduced torque**
 - Access to ELM stable and ELM mitigated regimes with ITER relevant rotation
- **Advanced divertors**
 - Compatibility of ELM control methods at ITER collisionality* with radiating and detached boundary solutions
- **High-field advanced divertor experiment**
 - ELM controlled regimes at ITER relevant density, magnetic field, collisionality and normalized size

* **Note: Access to ITER relevant peeling stability regime for pedestal is and should continue to be a strength of the US fusion program.**

The Disruption Challenge



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

Key findings of the Panel on Preventing Device Damage from Disruptions

- **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.**
- **Disruption prevention is fundamentally an issue of integrated disruption prediction and plasma control. Such a system needs to be developed.**
- **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 we will be largely viewed as responsible for its success.
- **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.

Recommendations of the Panel on Preventing Device Damage from Disruptions

The following recommendations should guide the development of a research program aimed at ensuring safe and reliable research operation of ITER at the highest possible performance. Looking further into the future, this research aims to eliminate the disruption challenge as an obstacle to further development of the tokamak as a platform for FNSF and DEMO class devices.

Recommendation #1: Increase emphasis on disruptions across the US portfolio of experiments

- Develop a **National Initiative for Elimination of Disruptions in Tokamaks** to best leverage and evolve the combined strengths of the present US facilities
- **Evolve US 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 disruptions when the limits are exceeded, specifically integrating and utilizing past research to produce quantifiable progress in these areas.
- Leverage **international collaboration on existing tokamaks** focusing on unique physics and control aspects
 - Allows rapid access to a larger tokamak database – essential for producing and testing disruption prediction understanding and algorithms, and control and mitigation aspects

Recommendation #2: Develop the necessary elements of physics-based prediction and control of plasma stability

...for maintaining reliable, high performance plasma operation.

- **Theory-based and experimentally validated models of plasma stability** to map out regimes of stable operation, ultimately available in real-time
- **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
- **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
- **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
- **Improved diagnostics and controls** to optimize the performance of passively stable tokamak regimes, and to predict, avoid and/or suppress instabilities

Recommendation 3: Expand research on existing US facilities to determine the most effective use of the currently planned ITER DMS

Includes:

- **Validated predictive physics models** for the thermal quench heat loads and their mitigation, and runaway electron amplification and suppression in ITER
- **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
- **Explore alternative mitigation schemes** for application in post-ITER devices

ITER's DMS is largely designed, but challenges remain to (a) validate that the right choices are being made, and (b) optimize its use. The US is best suited of all the ITER parties to do this.

Recommendation 4: Deploy an Integrated Disruption Prediction, Control, and Mitigation System in one or more existing US facilities

This recommendation combines the output of recommendations 2 and 3 to provide an integrated demonstration of our premise that *The Tokamak is Capable of Attaining High Performance in a Stable State, and Our Objective Should be to Identify and Maintain Such States* and it requires:

- **Significant facility upgrades** including
 - Additional heating flexibility and current drive capability
 - Additional sensors and actuators for disruption prediction and plasma control
- **Additional run-time and staffing**, and **further focus on existing facilities** to
 - Develop validated reduced physics models
 - Refine the Integrated Disruption Prediction, Control, and Mitigation System at the very low levels of plasma disruptivity needed in future devices
 - Demonstrate quantitative and robust achievement 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,...