Workshop on Transients

by

C.M. Greenfield

for Raffi Nazikian, Mark Foster,

and a cast of many

Presented at the Theory and Simulation of Disruptions Workshop

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

The Transients Workshop is Charged with Identifying Research Opportunities for "Solving" the Disruption and ELM Challenges

- **About the workshop**
  - Objectives, background, schedule, organization
  - Present status
- **Projected impact of recommended research**
- **What will our report say about disruption research?**
  - Findings and recommendations

- **The goal is to produce predictable solutions to the ELM and disruptions problems that can be implemented in ITER, FNSF, DEMO…**

We feel the ONLY way to approach this is through a coupled (experiment/theory/modeling) approach with the ultimate product including validated models that can be used to project to these future devices with confidence.

Transients Workshop: Background

- **Focus on disruptions and ELMs**
  - Can have deleterious effects on tokamak plasmas and have potential to cause damage
  - Generally tolerated in present devices
  - More severe impacts on ITER
  - Even more severe impacts on post-ITER devices (?)
  - "It is critical to develop the means to minimize these events and their consequences when they do occur."
- **Build on previous studies, including**
  - ReNeW (2009) – Thrust 2
    - Same scope, but the present workshop will:
      - Consider six more years of progress
      - Have more depth (this was 1/18 of the output of ReNeW)
  - FESAC Strategic Planning Panel report (2014) – identifies this as high priority initiative
  - USBPO Disruption Task Group

Transients Workshop: Objective

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

1. **Review recent progress**
2. **Identify the remaining science and technology challenges that must be addressed to demonstrate that magnetically confined tokamak plasmas with the characteristics desired for a fusion power plant can be robustly produced, sustained, and controlled without deleterious effects on the device's materials and structure**
3. **Based on thorough understanding of the remaining science and technology challenges, the workshop will identify specific research opportunities that can address these challenges in the next decade**
   - These may include both domestic research and international partnerships, and will be informed by the requirements of ITER and future burning plasma devices

Our deliverable is a report to FES due June 30

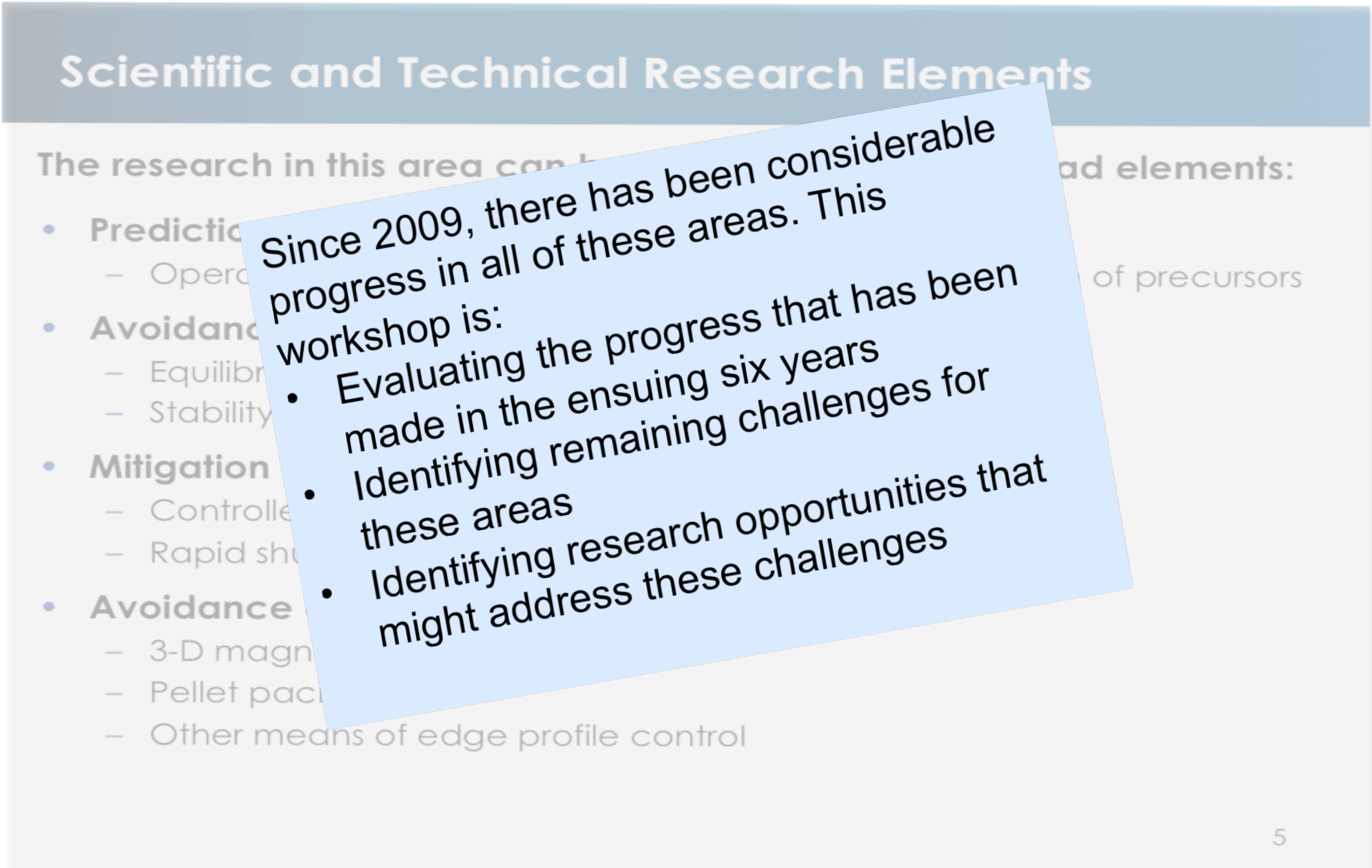
ReNeW Thrust 2 in 2009

Scientific and Technical Research Elements

The research in this area can be organized into four broad elements:

- **Prediction of disruptions**
  - Operating limits, real-time stability assessment, detection of precursors
- **Avoidance of disruptions**
  - Equilibrium control: detect and avoid stability limits
  - Stability control: active suppression of instabilities
- **Mitigation of disruptions**
  - Controlled shutdown
  - Rapid shutdown (e.g. impurity injection)
- **Avoidance or suppression of ELMs**
  - 3-D magnetic fields
  - Pellet pacing
  - Other means of edge profile control

ReNeW Thrust 2 in 2009

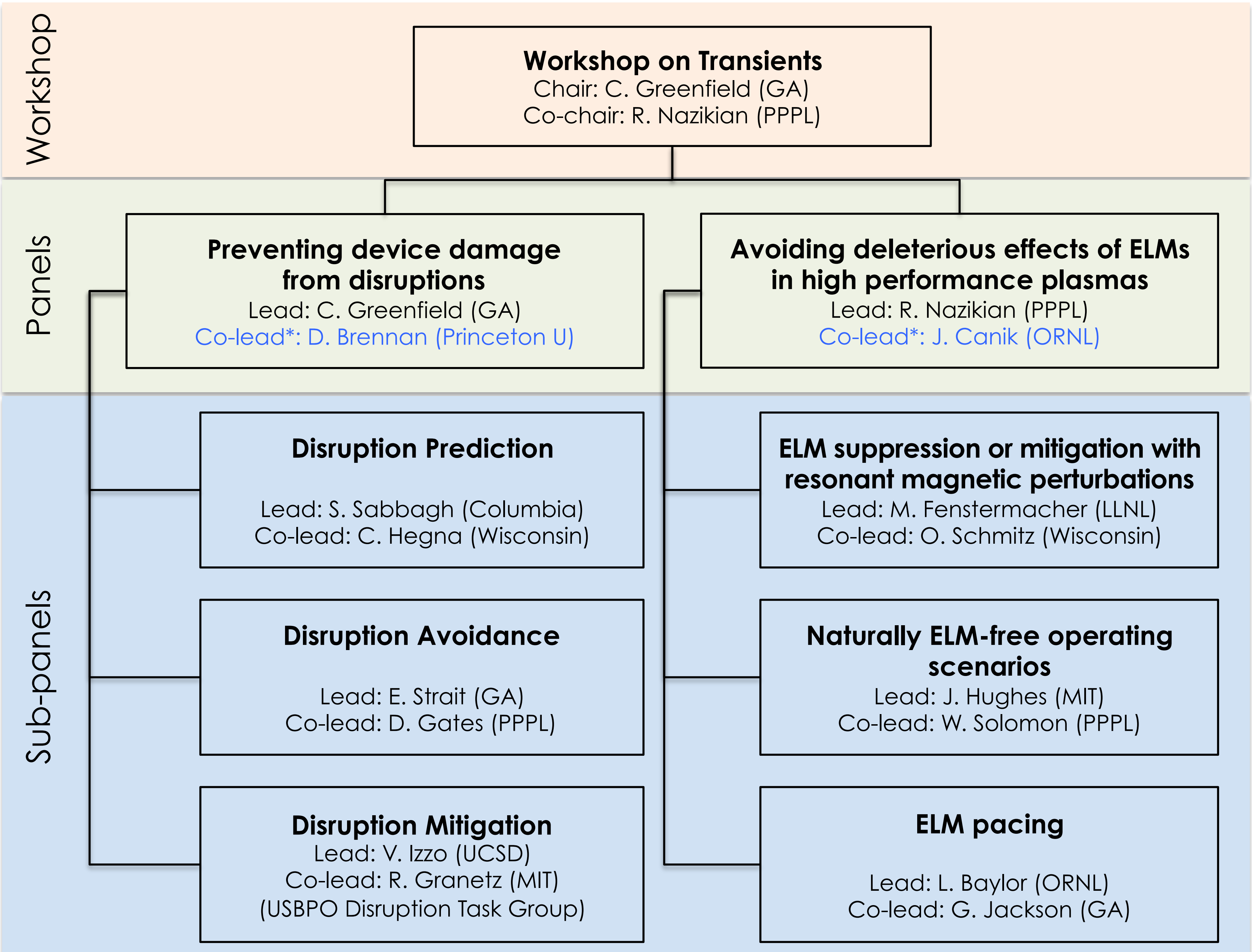


How is this Process Working?

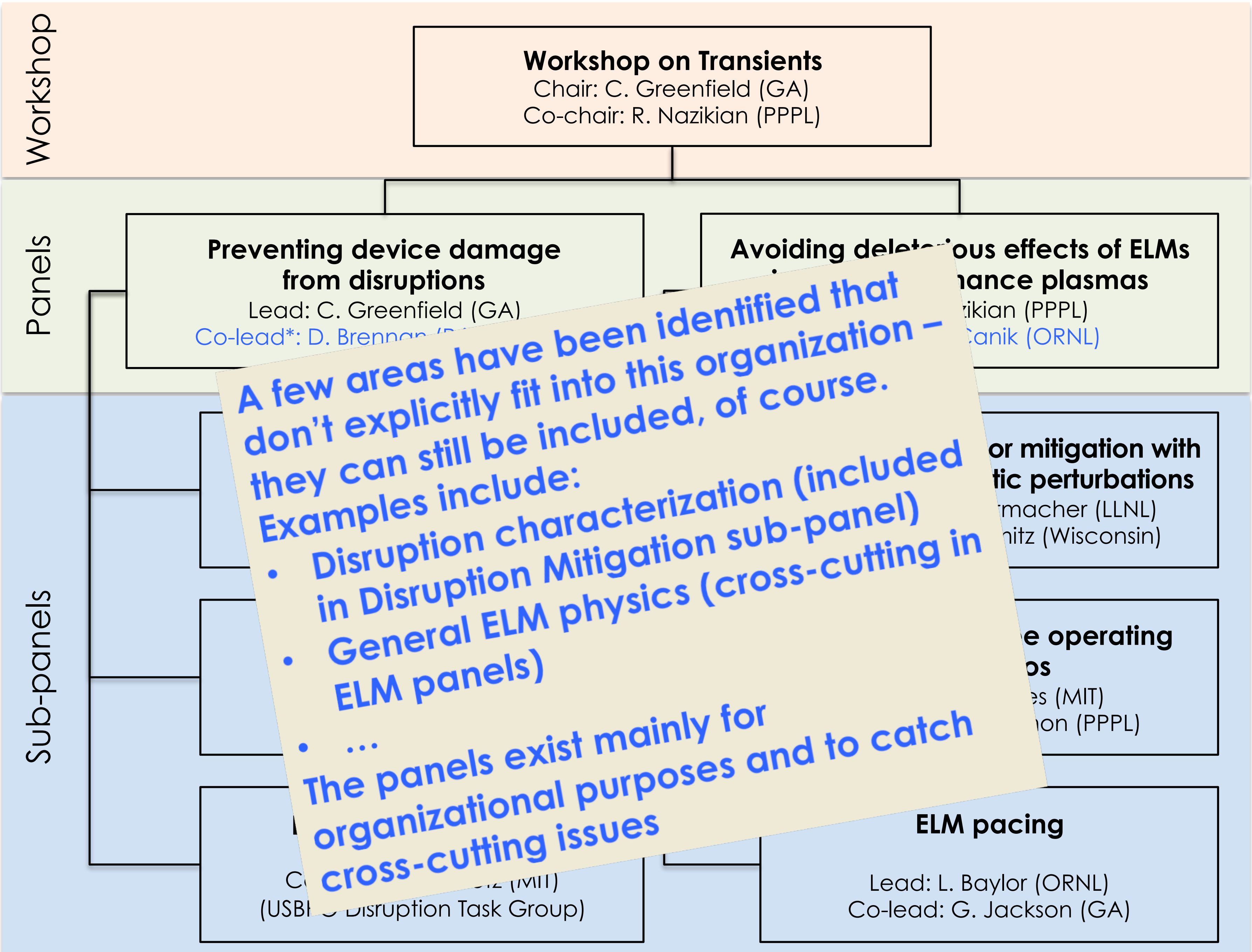
- **We have formed six sub-panels to create our report, based on**
  - Community input
  - Expertise of the panelists
- **The report is <u>not</u> required to include all proposals**
  - We have to strike a balance between inclusion and providing a focused report that will be useful to DOE
- **We have provided as much opportunity for community input as we could**
  1. Community input workshop – 36 contributions (plus input from the ITER Organization)
  2. 68 white papers (39 relevant to disruptions)
  3. Participation in the "main" workshop, June 8-10 at General Atomics (~65 participants)

Transients Workshop: Schedule

Date	Activity	Participants
Early February	Organize panels	Workshop and sub-panel leads
February 20	Sub-panel kickoff videoconference	Workshop and sub-panel leads and co-leads
February, March	Sub-panel organization and conference calls as needed	Sub-panel leaders and members
March 30-April 2	Virtual workshop to gather community input	Community (submits 2-page white papers and give short presentations)
April 15	Deadline for submitting white papers	
April, May	Sub-panel conference calls as needed	Sub-panel leaders and members
June 8-10	Workshop on Transients *at General Atomics*	Leaders and sub-panel members invited. Others may attend on a first-come, first-serve basis (limits due to room size and lab attendee administrative limit)
June 11	Report writing *at General Atomics*	Leaders and writing committee
June 30	Submit completed report to FES	Leaders



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



A few areas have been identified that don't explicitly fit into this organization – they can still be included, of course. Examples include:

- Disruption characterization (included in Disruption Mitigation sub-panel)
- General ELM physics (cross-cutting in ELM panels)
- …

The panels exist mainly for organizational purposes and to catch cross-cutting issues

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

Present Status

- **Workshop was held as scheduled**
- **We set an ambitious schedule at the end of the workshop, with the report to be completed by the end of June**
- ***We are late***
- **A first full draft of our report was posted in a restricted area over the weekend**
  - Available only to workshop participants
- **The second draft will be made available to the broader community for comment**
  - Hoping for the end of next week, but there is a lot to do
- **Biggest issues**
  - Consolidating a large number of recommendations from different subpanels into a manageable list (first attempt coming later in this talk…)
  - Conflicting formatting of individual sections (hope to have help from publications staff to be named later)

Projected Impacts of Recommended Research

1. **Ensure ITER can operate reliably to accomplish its mission**
   - Requirements in DT phase: Acceptable disruption rate <5% with >95% mitigated
   - Hardware already in advanced state of definition
     - Heating, current drive, mitigation system, internal coils,…
   - Research will focus on how to use the hardware
   - Still no solution for runaway electron suppression/dissipation, but must be done with available tools (midplane SPI, RMP fields,…)
2. **Provide transient control solutions for subsequent devices (e.g. FNSF, DEMO,…)**
   - Some of ITER's solutions may not translate
     - No internal coils allowed in a DEMO?
     - Alpha dominated heating → External profile control more difficult
   - Requirements may be more stringent
     - DEMO likely to require <1 mitigated disruption/year

Connections With Other Workshops

- **We need to bring this out more clearly in our top level summaries, but cross-cutting issues are included in our recommendations**
- **Integrated Simulations**
  - Broad focus of Transients Workshop – research must integrate experiment, theory, modeling
  - All are needed to produce ultimate goal of a validated predictive capability that can be used to design solutions for future tokamaks
- **PMI**
  - Disruption causes: Wall materials entering plasma (dust, flakes, UFOs,…)
  - Disruption impacts: Erosion, melting or worse
  - Edge-core integration an issue for ELMs

Approach to Disruptions

- **Issue: If severe, plasma disruptions and related phenomena can damage the device**
  - Major disruptions (full current quench)
  - Minor disruptions (large thermal collapse)
    - Do we all agree that these are included in our scope?
- **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…

Prediction

Avoidance

Mitigation

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 shut down the tokamak safely while avoiding damage from the release of the plasma's thermal and magnetic energy. This would be applied as a last re-sort 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 Disruptions Panel

1. **Disruption prevention is fundamentally an issue of Integrated Plasma Control**
   It requires
   - *Theory-based and experimentally validated models of plasma stability to map out regimes of stable operation*
   - *The development of a control system (including sensors, actuators, and physics-based control logic) 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 termination of the discharge*
2. **A significant amount of research is still required to determine the optimal use of the currently planned ITER disruption mitigation system**
3. **Additional resources are required in order to build on recent advances to resolve outstanding challenges in Integrated Plasma Control in time for ITER's initial operation**
   - *Existing US tokamaks are well suited to the recommended research, with possible upgrades of heating and current drive systems and other control actuators*

Recommendations of the Disruptions Panel

1. **Develop integrated predictive plasma control for reliable high performance tokamak operation**
2. **Determine the optimal use of the currently planned ITER disruption mitigation system**
3. **Advance disruption research with new capabilities for existing facilities**
4. **Integrated demonstration of high-performance disruption-free operation**

Disclaimer: This represents a consolidation of the 12 recommendations made by the three Disruptions sub-panels that has not yet been discussed extensively within our group. I believe the details represent a consensus, but the high level description does not (yet).*

*but it should

Recommendation 1: Develop Integrated Predictive Plasma Control for Reliable High Performance Tokamak Operation

Objective	Predicting Boundaries of Tokamak Stability	Sustaining Stable Tokamak Operation
Identify and demonstrate passively stable high performance operating scenarios	Develop and validate theoretical maps of stable operation including reduced models	Develop controls to sustain passively stable tokamak fusion plasmas based on validated predictions
Develop capabilities to extend the tokamak's operating range	Establish thresholds for avoidance and mitigation with accurate real time disruption forecasting models	Extend the operating range of existing devices through active control or avoidance of instabilities
Develop techniques to recover from non-plasma-physics events		Provide robust responses to off-normal events (hardware failure, human error,…)

Transform existing experiments into an integrated predictive research environment. Real-time stability prediction including active probing of plasma stability, is needed as a first step toward integrated control.

Recommendation 2: Determine the Optimal Use of the Currently Planned ITER Disruption Mitigation System

Establish a firm physics basis for mitigation of the thermal quench heat loads in ITER and future reactors
Develop predictive understanding of current quench forces, in order to define limits on ITER's operating space and aid in the mechanical design of future large tokamaks
Develop methods to protect ITER and future reactors from runaway electron damage, including the physics basis for understanding runaway electron amplification and suppression

- **Includes testing of prototypes for ITER DMS**

Recommendation 3: Advance Disruption Research with New Capabilities for Existing Facilities

Predicting the Boundaries of Tokamak Stability	Develop the diagnostic requirements needed for advanced disruption prediction. Research is needed to develop models of "synthetic diagnostics" and to identify the minimum diagnostic for robust, real-time stability analysis
Sustaining Stable Tokamak Operation	Possible upgrades of heating and current drive systems and other control actuators
Disruption mitigation for ITER and beyond	Pursue advanced disruption mitigation concepts for devices beyond ITER. Other untested possibilities beyond the current ITER design may exhibit better performance

Recommendation 4: Integrated demonstration of high-performance disruption-free operation

Prove the effectiveness in present facilities of an integrated control system for stability prediction, sustainment of stable operation, and disruption mitigation

The US Program Can be Expected to 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,…

The Transients Workshop Report Represents a Great Deal of Hard Work on the Part of Many People

- **There is a lot more detail in our (currently) 287 page report than I am able to cover in this talk**
- **We have been working with the Integrated Simulations and PMI Workshops to avoid inconsistencies (ongoing)**
  - Modeling and simulation needs for disruptions
  - Disruption damage to plasma facing components and impact of PFCs on the plasma
  - I don't believe there are any big problems here, but we are evaluating…
- **We believe that following the Transients Workshop recommendations will contribute strongly to the goal of reliable, high-performance operation of a tokamak in a stable state, and that this goal is realizable**
- **Watch for a public draft in the coming weeks…**