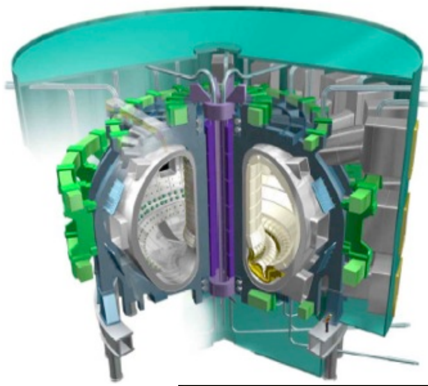
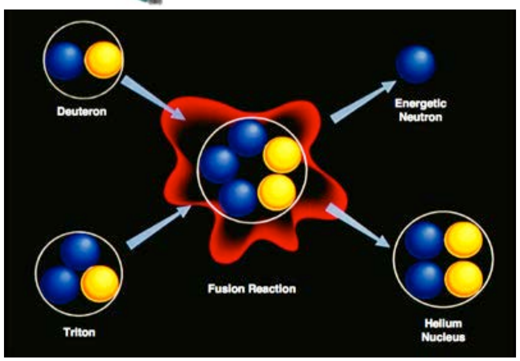
United States
Burning Plasma Organization

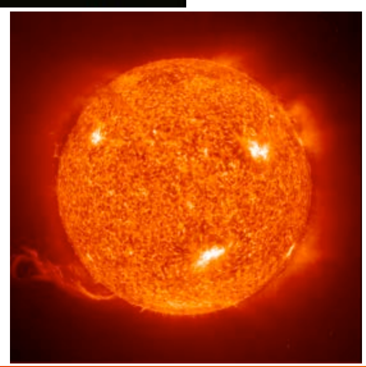


Experimental Campaign Coordination



Charles M. Greenfield

(with thanks to Nick Eidietis, John Wesley, Stefan Gerhardt, and all of you)



Theory and Simulation of Disruptions

July 19, 2013

GENERAL ATOMICS

Disclaimer

I do not claim to be a disruption expert, but I do recognize the extreme importance of the topic

- **The success of ITER and the entire tokamak line depends on our success in preventing, predicting, and mitigating disruptions**
- **We are here because we believe the problem is tractable**

What do we need to solve and when?

- **Disruption occurrence rates probably overstated**
  - Most disruptions in present day tokamaks happen because we don't care
- **Disruptions pose a serious risk to ITER**
  - In ITER we will have to care about each disruption!
- **Multi-level solution is needed**
  - Reliable disruption prediction – both false positives and negatives are bad
    - Disruption avoidance
    - Provide trigger for disruption mitigation system
  - Disruption mitigation system (DMS) – FDR January, 2017
    - Limit thermal energy to divertor and first wall (FW) surfaces
    - Prevent "hot plasma" VDEs and FW energy deposit
    - Minimize halo current forces in blanket/shield modules
    - Control eddy current forces in B/S modules
    - Control and dissipate runaway electron (RE) currents

Overall strategy for Disruption Mitigation/ Avoidance

Disruption mitigation in ITER involves a multi-facetted approach:

- **Disruption detection and avoidance to ensure identification of approaching disruption with high success rate:**
  - Plasma Control System can trigger “rapid shutdown|” if time permits
  - alternatively, PCS triggers interlock system to fire DMS

- **DMS subsystem for thermal quench mitigation:**
  - mitigates thermal loads and EM loads of disruptions/VDEs
  - injected from 3 Upper and 1 Equatorial Port
  - high pressure gas, shattered pellets, or solid pellets are candidates
  - Ne, Ar, or D_2/He at up to 2 kPa.m^3; 0.5 – 2.5 g of solid/ dust material

- **DMS subsystem for RE suppression/ mitigation**
  - may involve both control of RE beam and MMI to provoke either deconfinement or deceleration
  - multiple injectors from single Equatorial Port
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January 2017 FDR

Resources to address disruptions are limited

- The present landscape for disruption mitigation research
- Specific research areas where theory coordination is needed
- Suggestions for coordination

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- **The present landscape for disruption mitigation research**
  - DIII-D, JET, ASDEX-U all active
    - Some reluctance to disrupt "on purpose" in metal-walled machines
    - Limited run time availability for disruption experiments
  - Formerly major contributors, but no longer available: C-Mod, Tore Supra, NSTX
  - May become major contributors: NSTX-U, EAST, KSTAR
- **Limited coordination between experiments and with theory community**
- **Actuators and diagnostic sets are sufficiently different as to make joint experiments difficult**
- **Much of the data we have is empirical and anecdotal**
- **Best approach to ITER DMS is a coordinated program of experiments and theory/ modeling to tie them together and extrapolate to ITER**
  - But… to date, even interpolation between existing tokamaks doesn't always yield satisfying results

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…a sampling of questions raised at this meeting:

Disruption prediction

1. **Approaches that require a training set (neural net) of data not applicable to ITER**
   - Quantitative understanding is needed
2. **Test physics-based disruption predictor (Gerhardt) on multiple devices**
3. **Assess disruption causes & disruption predictor on ITER demonstration discharges from multiple devices**
4. **Develop methods for disruption proximity detection, not just binary detection**
   - Can we recover the shot?
   - Is there enough advance notice for a soft shutdown?
   - When do I need to trigger the DMS?
5. **Include first-principle, physics-based loss-of-control warning in all equilibrium and stability control loops, as inputs to a disruption predictor**

Disruption properties

1. **VDE**
   - Rotation: What drives it, what is expected in ITER, what determines the current distribution?
   - Under what conditions can the edge-q become low enough that strong 1/1 kinking and sideways forces are observed?
2. **Can we predict and measure vessel forces?**
3. **What are the properties of the thermal quench in an unmitigated disruption (time scales, heat flux distribution,…)?**
4. **Halo and Hiro currents**
   - Need modeling of fiducial Asdex-U VDE used for DINA/TSC benchmarking by Zakharov's codes, including Hiro current effects
   - Can experiments and simulations resolve the relative role of Evans and Hiro currents in determining forces on the vessel and in-vessel structures?
   - Does it recreate temporal evolution?
   - Can I_P asymmetries be measured in parallel with the Halo/Hiro current entrance and exit points, in order to unify the understanding from different devices with different measurement types?

Research needed for ITER DMS

1. **What is the real critical density for preventing formation of a runaway electron channel?**
2. **What is the most effective way to introduce particles to the plasma (massive gas injection, shattered pellets,…)**
3. **Radiation asymmetries and MHD**
   – Injection from how many locations?

Runaway electrons

1. **What are the mechanisms for anomalous runaway electron (RE) dissipation?**
   - What are their relative importance?
   - Need numerical predictions (to match to present data)
   - How do they scale to ITER?
   - Does this lower n_{crit} enough to consider collisional suppression?
2. **What is the scaling for the RE "wetted area?"**
   - Need experimental scaling (DIII-D, JET,…) and physical basis to match
3. **How well will SPI/MGI penetrate into nascent RE beam forming during cold CQ?**
4. **What sets the radius of the hot RE core? How does that scale to ITER?**
5. **What role do the impurity injection details/plasma target play in runaway production in DIII-D? Do any of these sensitivities affect ITER or is it just too big?**

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- **Suggestions for coordination**

What tools do we need?

1. **Run time on tokamaks**
   - Disruption research is messy but important
2. **Diagnostics – everybody measured different things**
   - Example: Vessel forces measured or inferred (or not) in different ways in different tokamaks
3. **Need to be able to compare mitigators on an even footing**
   - Massive gas injection widespread
   - Shattered pellet injection only on DIII-D
   - Shell pellets being prepared for DIII-D, but Be won't be a possibility – JET?
4. **A little bit of irony: ITER's biggest risk may be runaway electrons, but they are difficult to generate on present-day devices**
   - DIII-D uses argon pellets
   - JET will attempt using argon gas puffing
5. **Theory and modeling**
   - Goal – and challenge - should be validated models
   - Needed to tie above together and extrapolate to ITER
   - In many cases, current models do not successfully *interpolate*

A coordinated program is needed

- **US Domestic Agency has responsibility for providing ITER DMS hardware, but responsibility for specifying the system remains with the ITER Organization and all seven partners**
- **Within the US: US Burning Plasma Organization Task Group led by Bob Granetz and John Wesley has been formed to coordinate research**
  - Intention was to provide an opening for entire US fusion community to participate in this extremely important research
  - US experimental program has shrunk to one device – DIII-D – so that the USBPO Task Group is now almost indistinguishable from the DIII-D Disruption Task Force
    - This is a temporary situation until NSTX-U begins operation
  - USBPO Task Group can provide "added value" by providing a forum for participation by the theory community
    - There is a need for more manpower to analyze, simulate, and interpret experimental results
- **USBPO also functions as interface between ITPA and US community**
  - ITPA has become very active in this area internationally

DIII-D is organizing a National Fusion Science Campaign

- US fusion science community has been invited to participate in a national campaign on DIII-D
- Mainly (but not exclusively) targeted at major facilities (MIT, PPPL)
- Science topics TBD, but disruption research is certainly fair game