Dealing with the Risk and Consequences of Disruptions in Large Tokamaks

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MFE Roadmapping in the ITER Era

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ABSTRACT:

G. A. WURDEN, Los Alamos National Laboratory - ITER (and someday DEMO) will operate subject to multiple physics and engineering constraints, and to be successful they must satisfy many constraints simultaneously. One of the most serious issues a large tokamak will face is controlling 100’s of MJ of plasma energy that can be quickly released in the event of a disruption, whether due to burning plasma issues, or more everyday tokamak physics. The number of full energy disruptions that an armor system in a large tokamak can survive is very small, due to the opposing engineering constraints of rapid heat removal in steady-state, versus designing survivability to transient events. Multi-megaampere beams of runaway electrons (created by the avalanche effect after a disruption) hitting thin armor tiles will prevent achieving the desired science or energy missions, if not eliminated. A coordinated global effort to avoid, control, and mitigate tokamak disruptions must be developed with the highest priority. The timing for this effort must be now, before ITER begins operation, as a key element of prudent risk management in a global MFE program. Supported by DOE Contract DE-AC52-06-NA25396

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Outline

- Parameters of tokamaks
- Energy matters
- Disruption statistics
- Disruption runaways: Dreicer and Avalanche
- Examples of runaway damage: Tore Supra, JET, Alcator C-Mod, TFTR
- High speed video of tile disintegrating due to runaways
- Types of disruptions, causes
- Avoid, suppress, mitigate
- How might one mitigate? MGI, magnetic perturbations, …?
- What must be done in the next 5-10 years, before ITER comes online

What is THE problem with magnetic fusion energy?

There are many issues: But making the plasma is not one of them

- Controlled fusion isn’t here yet. (Corollary: Nuclear Fission was easy)

- 1). We don’t have materials to survive the plasma/neutron bombardment.

- 2). Not enough tritium fuel (and not yet made by a fusion blanket).

- 3). The machines to do it (nuclear fusion) are complex and hard to maintain.

- 4). We can’t yet simulate it even on the world’s biggest, fastest computers.

THE biggest problem is that the plasma is very hard to control

The loss of control can be very damaging

Total Energy at any one time matters! (Damage)

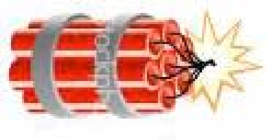
- **Tokamaks have explored up to ~10 Megajoules plasma kinetic energy**
- **Long pulse tokamaks have not dealt with instantaneous energy above a Megajoule level, although removal of ~1 Gigajoule of energy over long timescales has been demonstrated.**

Machine	Stored Energy	Pulse Length	Current	Cooling	Aux Heating	Plasma Volume
DIII-D	3.5 MJ	6 sec	2-3 MA	inertial	25 MW	21 m^3
TFTR	7 MJ	5 sec	3 MA	inertial	40 MW	30 m^3
JT-60U	10.9 MJ	20-60 sec	3-5 MA	inertial	50 MW	90 m^3
JET	10 MJ	10-30 sec	3-7 MA	inertial	20-40 MW	95 m^3
Tore Supra	0.3-1 MJ	400 sec	1.7 MA	water	3-9 MW	20 m^3
ITER	200-450 MJ	300-3000 sec	15-17 MA	water	70-100 MW	837 m^3
DEMO	600 MJ	steady	10-20 MA	helium	100 MW	500-1500 m^3

How much energy are we talking about?

60 MJ of runaways, 400 MJ of thermal quench, 600 MJ of poloidal magnetic field energy

600 MJ will melt ~ one ton of copper



15 MJ is released by 7 sticks of TNT

10 GJoule ≅ A380 flying at 700 km/h

100 MJ: F-14 Tomcat launched by steam catapult

Melting point of copper: 1356 K
Specific heat capacity of copper: 385 $\text{Jkg}^{-1}\text{K}^{-1}$
Specific latent heat of fusion (energy required to convert a solid at its melting point into a liquid at the same temperature): 205000 Jkg-1
So to melt 1 kg of copper we need (1056*385 + 205000) J = 611,560 J.

What are the "Four Horsemen" of major disruptions?

A large tokamak must always defend against each threat

- **Large Transient Electromagnetic Loads on vessel components**
- **Large Transient surface tile heating due to plasma radiation**
- **Large Transient surface tile heating due to plasma convection**
- **Large Transient volumetric tile heating in localized places due to runaway electron beam impact.**

What are the consequences of unmitigated disruptions in a large tokamak? (A lot of energy ends in in all the wrong places)

In hydrogen or deuterium operation:

- Prevention of subsequent operation by mechanical disturbances of armor integrity (ie, hot spots due to mis-shapen or warped tiles).
- Reduction of armor lifetime, up to and including total armor failure (ie, leak of coolant into the vessel). Possible over-pressure situation due to coolant spill onto hot tiles, causing subsequent protection systems (burst disks, Safety Drain Tanks, 460 m^3) to kick-in.
  Long (2-month minimum) downtime to repair.

For tritium operation:

- Chaos of tritiated water, due to water mixing with tritium held-up in the machine from previous shots. Added to the issues listed above.
- Ultimately, regulatory issues could prevent the introduction of tritium into the experiment, based on the likelihood of water leaks.

The lesser of two evils?

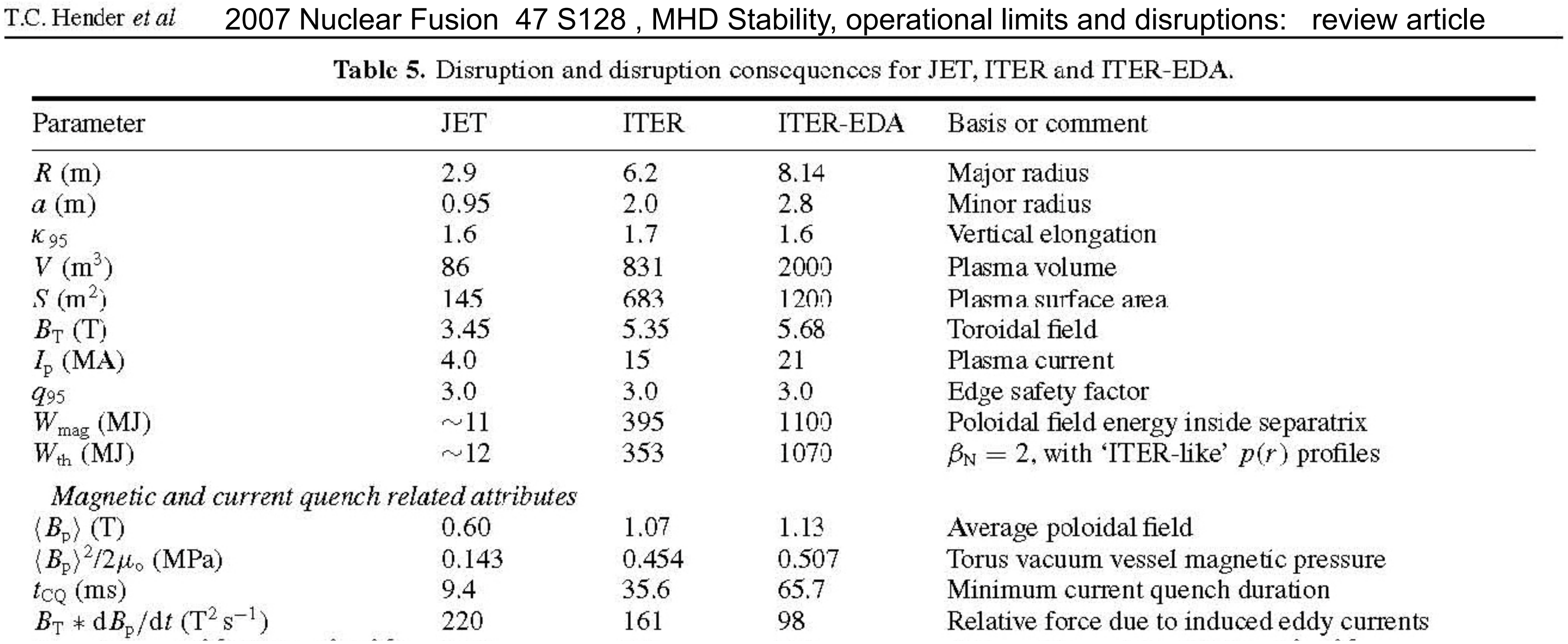
Assuming that you can in fact mitigate the dump of plasma energy during the thermal quench phase of a major disruption, through “uniform” radiation of that energy, so as to avoid significant surface melting…..you are left with insuring against:

- **Electromagnetic forces that rip apart structural components, due to too fast of a current quench?**

OR

- **Runaway electron beams, with nearly full plasma current magnitude, that e-beam weld wherever/whatever they** hit**?**

2007 Nuclear Fusion 47 S128 , MHD Stability, operational limits and disruptions: review article

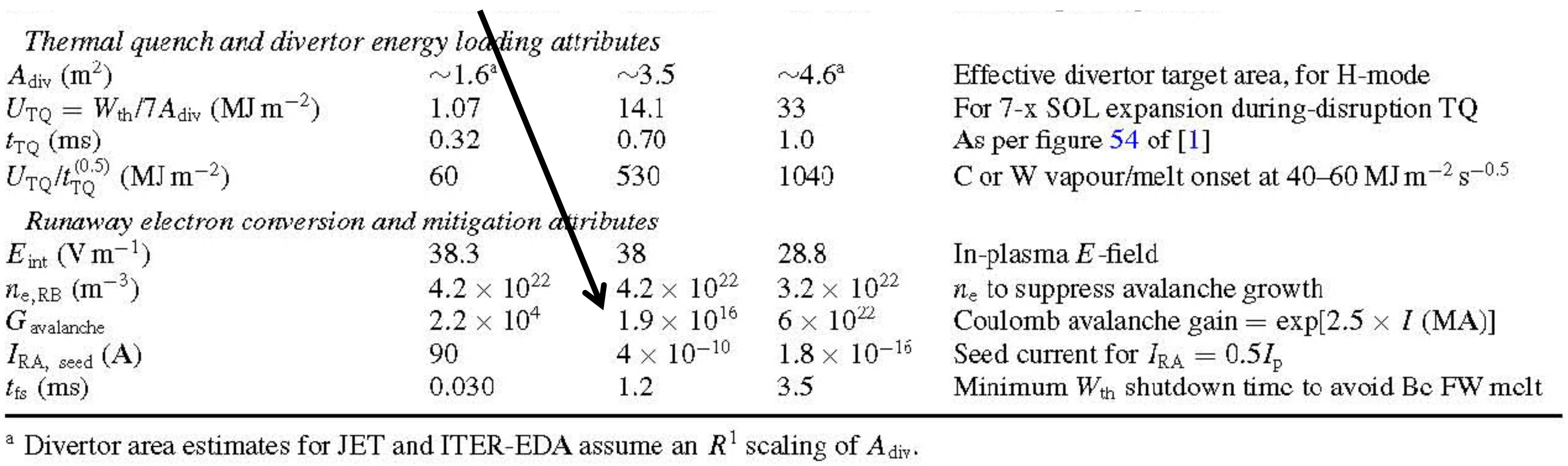


T.C. Hender *et al*

Table 5. Disruption and disruption consequences for JET, ITER and ITER-EDA.

Parameter	JET	ITER	ITER-EDA	Basis or comment
R (m)	2.9	6.2	8.14	Major radius
a (m)	0.95	2.0	2.8	Minor radius
κ_{95}	1.6	1.7	1.6	Vertical elongation
V (m^3)	86	831	2000	Plasma volume
S (m^2)	145	683	1200	Plasma surface area
B_T (T)	3.45	5.35	5.68	Toroidal field
I_p (MA)	4.0	15	21	Plasma current
q_{95}	3.0	3.0	3.0	Edge safety factor
W_{mag} (MJ)	~11	395	1100	Poloidal field energy inside separatrix
W_{th} (MJ)	~12	353	1070	$\beta_N = 2$, with 'ITER-like' $p(r)$ profiles
Magnetic and current quench related attributes				
$\langle B_p \rangle$ (T)	0.60	1.07	1.13	Average poloidal field
$\langle B_p \rangle^2/2\mu_o$ (MPa)	0.143	0.454	0.507	Torus vacuum vessel magnetic pressure
t_{CQ} (ms)	9.4	35.6	65.7	Minimum current quench duration
$B_T * dB_p/dt$ ($T^2 s^{-1}$)	220	161	98	Relative force due to induced eddy currents

Secondary Avalanche coefficient for runaways really stands out



Parameter	JET	ITER	ITER-EDA	Basis or comment
Thermal quench and divertor energy loading attributes				
A_{div} (m^2)	~1.6[a]	~3.5	~4.6[a]	Effective divertor target area, for H-mode
$U_{TQ} = W_{th}/7A_{div}$ ($MJ\,m^{-2}$)	1.07	14.1	33	For 7-x SOL expansion during-disruption TQ
t_{TQ} (ms)	0.32	0.70	1.0	As per figure 54 of [1]
$U_{TQ}/t_{TQ}^{(0.5)}$ ($MJ\,m^{-2}$)	60	530	1040	C or W vapour/melt onset at 40–60 $MJ\,m^{-2}\,s^{-0.5}$
Runaway electron conversion and mitigation attributes				
E_{int} ($V\,m^{-1}$)	38.3	38	28.8	In-plasma E-field
$n_{e,RB}$ (m^{-3})	4.2×10^{22}	4.2×10^{22}	3.2×10^{22}	n_e to suppress avalanche growth
$G_{avalanche}$	2.2×10^4	1.9×10^{16}	6×10^{22}	Coulomb avalanche gain = exp[2.5 × I (MA)]
$I_{RA,\ seed}$ (A)	90	4×10^{-10}	1.8×10^{-16}	Seed current for $I_{RA} = 0.5 I_p$
t_{fs} (ms)	0.030	1.2	3.5	Minimum W_{th} shutdown time to avoid Be FW melt

[a] Divertor area estimates for JET and ITER-EDA assume an R^1 scaling of A_{div}.

Let's look at the most problematic threat: Runaway Electrons are bad news for large tokamaks

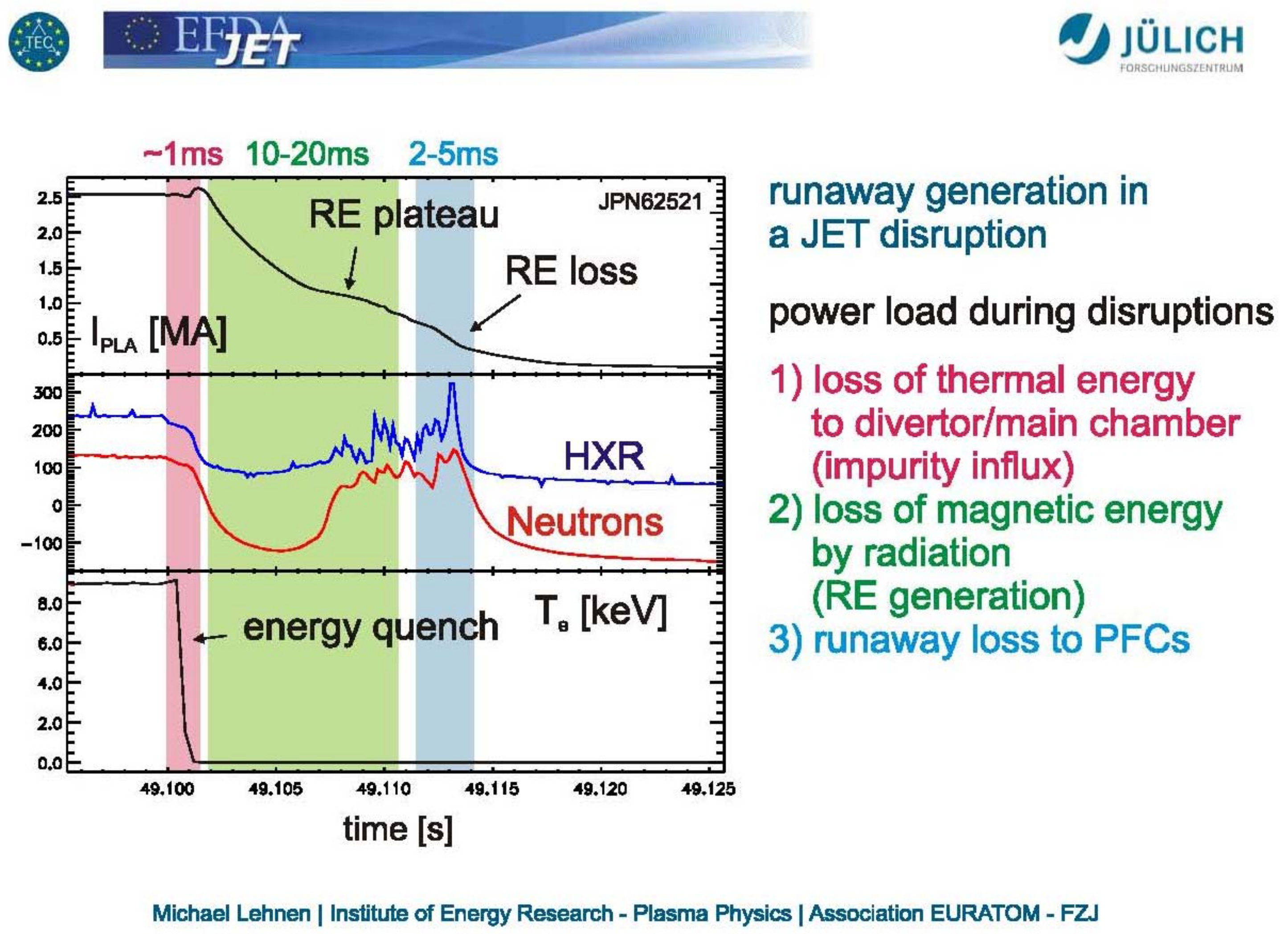
- **"The number of *e-foldings* supported by the avalanche mechanism is proportional to the plasma current and could be ~40 in ITER at 15 MA. This is sufficient to ensure that the plasma will transfer a significant fraction (up to 80%) of its current to a runaway population, in contrast to present experiments where the generation of runaway electrons is mild."**
- **"Disruption-free operation is a prerequisite for Demo and power plant and is important for ITER…..ITER must demonstrate a disruption mitigation method both for its own operation and for Demo."**

Progress in ITER Physics Basis, Nucl Fusion 2007, Chapter 9
Mukhovatov *et al. "ITER contributions for DEMO".*

- Multimegamp e-beams at energies of ~ 10 – 20 MeV loose inside of ITER simply cannot be tolerated, and will likely cause catastrophic failure of thin first wall components in exactly one occurrence.

Some JET disruption data

JET runaway database
JPN50000-69626
8% disruptions
23% RE generation (divertor)



runaway generation in a JET disruption

power load during disruptions

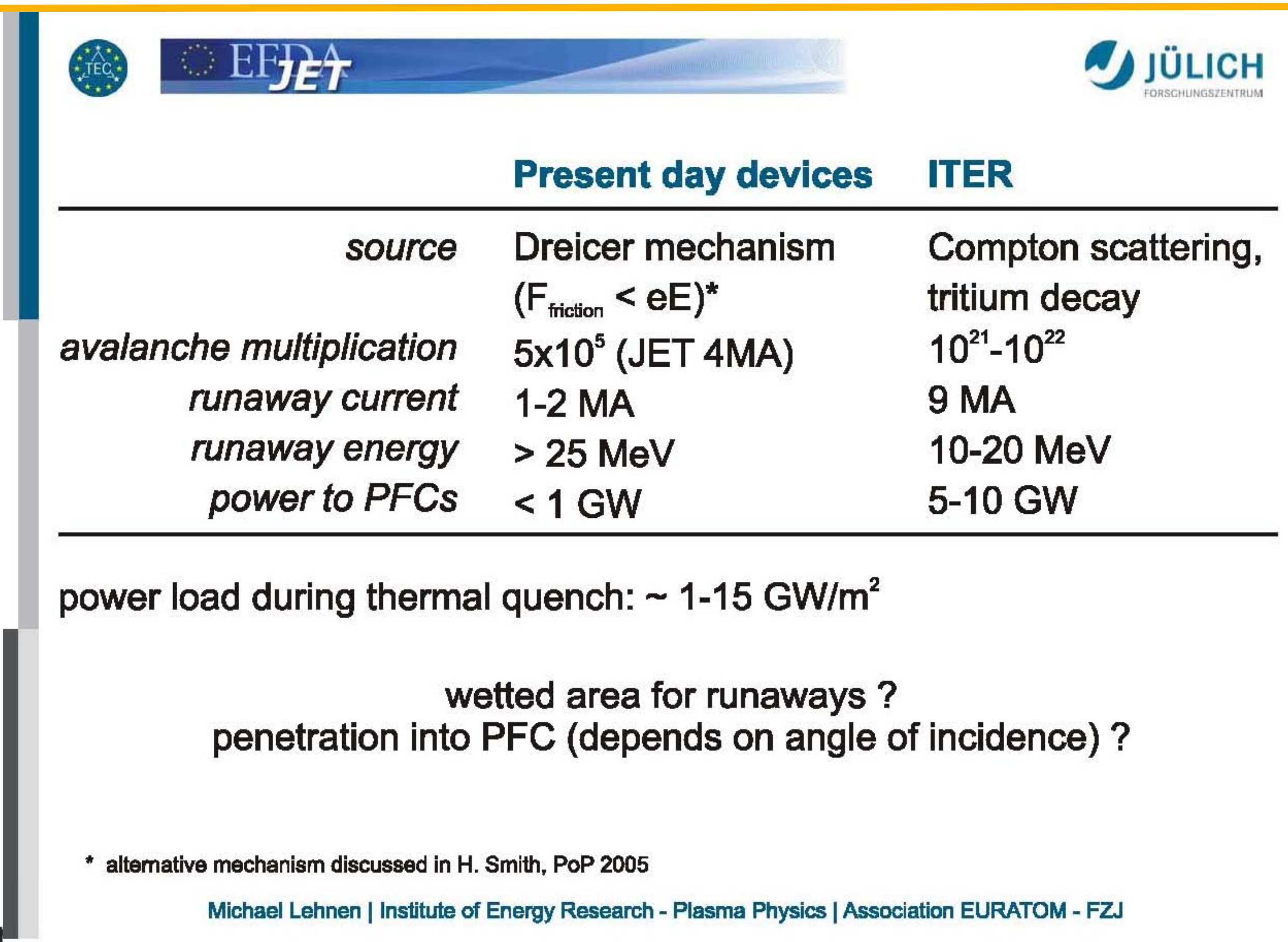
1) loss of thermal energy to divertor/main chamber (impurity influx)
2) loss of magnetic energy by radiation (RE generation)
3) runaway loss to PFCs

Michael Lehnen | Institute of Energy Research - Plasma Physics | Association EURATOM - FZJ

Comparing runaways, now and for ITER

“Runaway electron generation is expected in every ITER disruption”*

M. Lehnen, et al, FZJ, 2008 PSI Conference paper & Friday talk ***(unmitigated)**



	Present day devices	**ITER**
source	Dreicer mechanism ($F_{friction} < eE$)*	Compton scattering, tritium decay
avalanche multiplication	5×10^{5} (JET 4MA)	10^{21}-10^{22}
runaway current	1-2 MA	9 MA
runaway energy	> 25 MeV	10-20 MeV
power to PFCs	< 1 GW	5-10 GW

power load during thermal quench: ~ 1-15 GW/m^2

wetted area for runaways ?
penetration into PFC (depends on angle of incidence) ?

* alternative mechanism discussed in H. Smith, PoP 2005

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A closer look at stopping power & Runaway Electrons

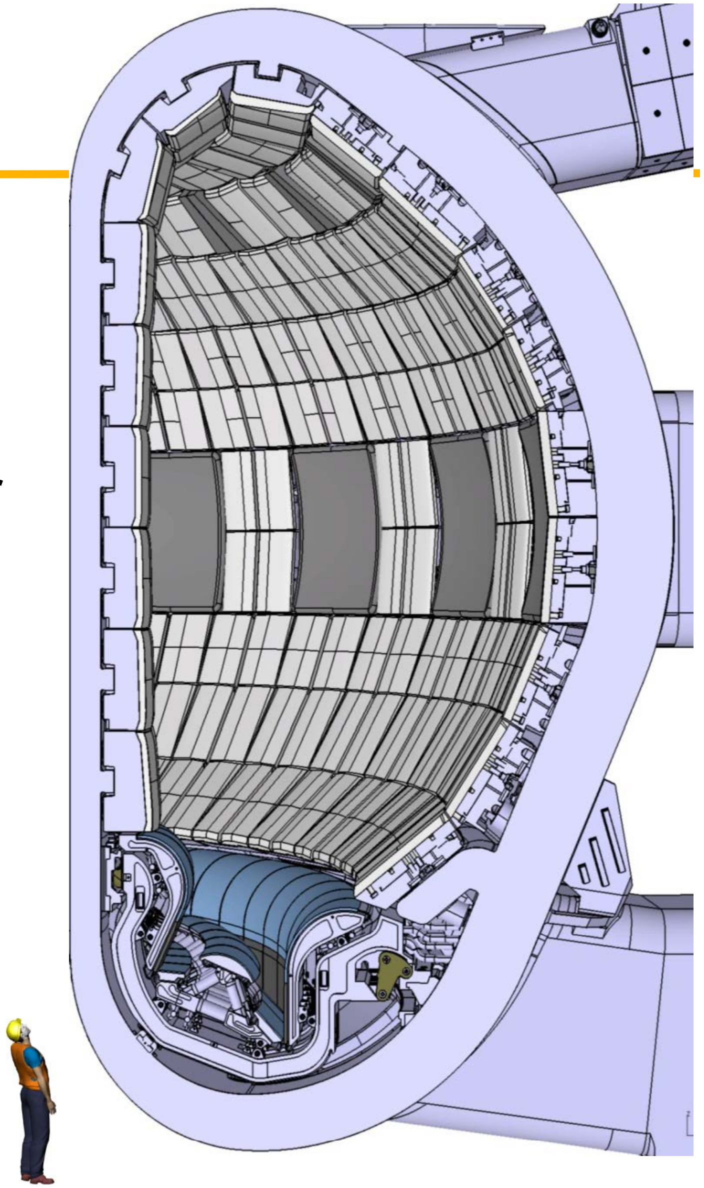
- **Fast electrons will penetrate into the armor to various depths, depending on their initial energy**
- **Presently the majority of the ITER first wall has 8 mm of Beryllium on top of 5 mm of CuCrZr, before coming to water cooling channels.**
- **Some data for 10 MeV electron slowing down**

Material	Density	CSDA Range	Depth of Penetration
Be	1.85 gm/cm^3	6.3 g/cm^2	3.4 cm
C	1.7 gm/cm^3	5.66 g/cm^2	3.3 cm
Cu	8.96 gm/cm^3	6.18 g/cm^2	0.7 cm
W	19.3 gm/cm^3	6.2 g/cm^2	0.3 cm

- **When Millions of Amperes of runaway electrons are produced as a result of a single disruption, orbiting in ITER, then you have created a huge e-beam welder when they finally impact on something physical.**

Will ITER be the last tokamak ever built?

- Yes….if the real mission of ITER is not accomplished!
- The goal of ITER is routinely described as studying DT burning plasmas with a Q ~ 10.
- In reality, ITER has a much more important first order mission. In fact, if it fails at this mission, the consequences are that ITER will never get to the performance needed for studying a burning plasma.
- The real mission of ITER is to study (*and demonstrate successful)* plasma control, including consequent plasma/material wall interaction issues, with ~10-15 MA toroidal currents and ~100-400 MJ plasma stored energy levels in long-pulse scenarios.
- This mission must be accomplished in hydrogen or deuterium discharges, or else tritium will never be allowed (or needed) in ITER.



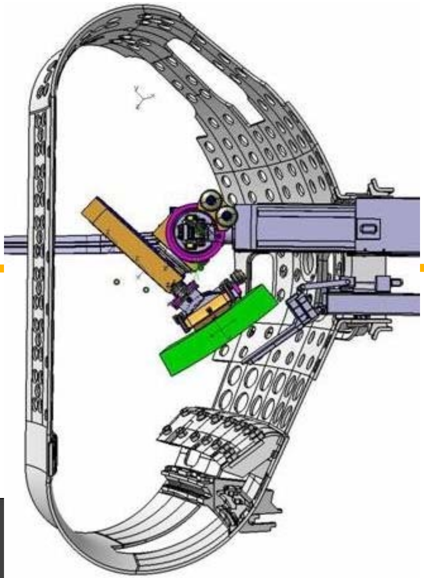
ITER cross-section with armor

Key differences between today’s tokamak and ITER:

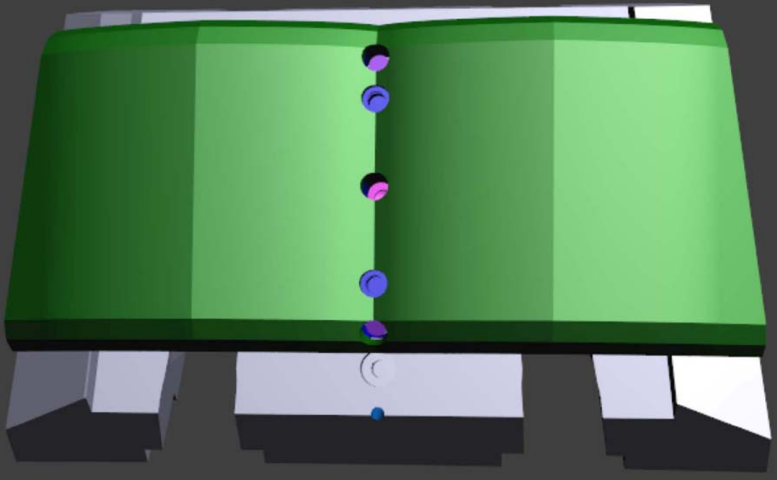
The requirement for surviving the large stored energy loss while also operating with long pulse lengths

- **Tiles have a contradictory mission: Being able to take out large amounts of energy over long timescales vs. being able to survive transient “off-normal” events.**
- **Doing the first requires large area, thin rapidly cooled surfaces… water-cooling in ITER is only a cm below the tile surface. The second requires thick ablative armor.**
- **The ITER 2004-2007 Design Description document (DDD 16) for the first wall armor analysis (section 2.4), considers that for 10 mm thick Be armor, 2 mm of said armor will melt from 50 MJ/m^2 runaway electron events, with 12.5 MeV exponential energy distribution, while the temperature max (526 °C) at the Cu/Cr/Zr bonding to the heat sink is still within limits.**
- **DDD 16 suggests that the armor will survivable for 5-15 such “rare” events, based on the expected “statistical distribution of the event location on the plasma chamber surface”.**
- **One problem is, there may be more total energy in the runaways than assumed, on shorter timescales, than this analysis considered, due to back EMF as large runaway currents decay.**

Most recent ITER Blanket & Armor*



- ITER's first wall (FW) is made of 440 two-part modules.
- The front piece is multiply-shaped, to reduce the visibility of its edges.
- The front piece weighs between 800-1000 lbs, and each one has two water connections.
- The robot arm will be used to swap out pieces.
- By removing a nut, and cutting an access cover, one can reach the water pipes, which have to be cut.
- There are 18 different main types of armor sections, with 42 variants, and then another 100 minor variations.
- Minimum estimated time to change out one front segment is 2 months, assuming spares are on the shelf, and the back plate is not damaged (ITER SRD-16-BS).
- This doesn't count the time to find the water leak.



The green part is the first wall module (~1.4m across). The larger silver grey part is the shield blanket (larger than the FW because of curvature of the wall). *Courtesy Mike Ulrickson, Sandia National Lab

What happens when you put too much energy into a material too quickly? Or into two different bonded materials?

- **Beyond the melting/boiling point, and faster than it can be radiatively/convectively cooled?**
- **Answer: “It blows up”.**
- **On TFTR a major disruption sounded like a small bomb going off**

….. for a reason.

- **Did TFTR carbon tiles ever “blow up”……actually yes.**

1 kg of HE, General Fusion shot

(video)

Remember TNT energy equivalent*

1 MJ (TFTR)	0.217 kg TNT
2 MJ (**Jelly Doughnut**)	0.434 kg TNT
1 GJ (ITER)	217 kg TNT

*In an HE explosion, energy is released in 100 usec. In ITER, fortunately the thermal energy release timescale is 10 to 30 times slower.

500 lb WWII bomb has

~ 150 kg of TNT equivalent

“Statistical analysis of disruptions in JET”

P.C. de Vries, M.F. Johnson, I. Segui and JET EFDA Contributors, Nuc. Fusion 49 (2009) 055011

“The question arises what factors determine the disruption rate and disruptivity of tokamak plasmas. Here the disruption rate is defined as the percentage of discharges that disrupt, while the disruptivity is the likelihood of a tokamak discharge in a specific state t disrupt.”

The most recent JET paper , “**Survey of disruption causes at JET” P.C. de Vries, M.F. Johnson, et al,** Nuclear Fusion **51** 53018 (2011), states: “The development of more robust operational scenarios ha reduced the JET disruption rate over the last decade from about 15% to below 4%. A fraction of all disruptions was caused by very fast, precursorless unpredictable events. The occurrence of these disruptions may set a lower limit of 0.4% to the disruption rate of JET. If one considers on top of that human error and all unforeseen failures of heating or control systems this lower limit may rise to 1.0% or 1.6%, respectively.”

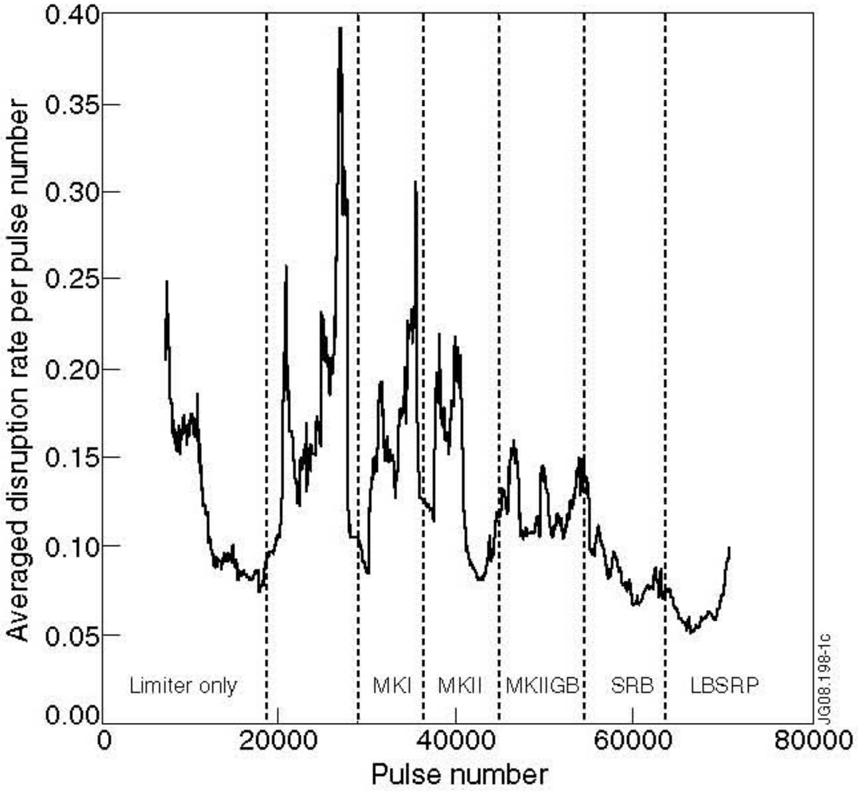


Figure 1. The moving average of the disruption rate over 2000 pulse numbers as a function of pulse number. The vertical dashed lines show the start of X-point operations and the various phases of the JET divertor, as given in table 1(a).

Disruption statistics

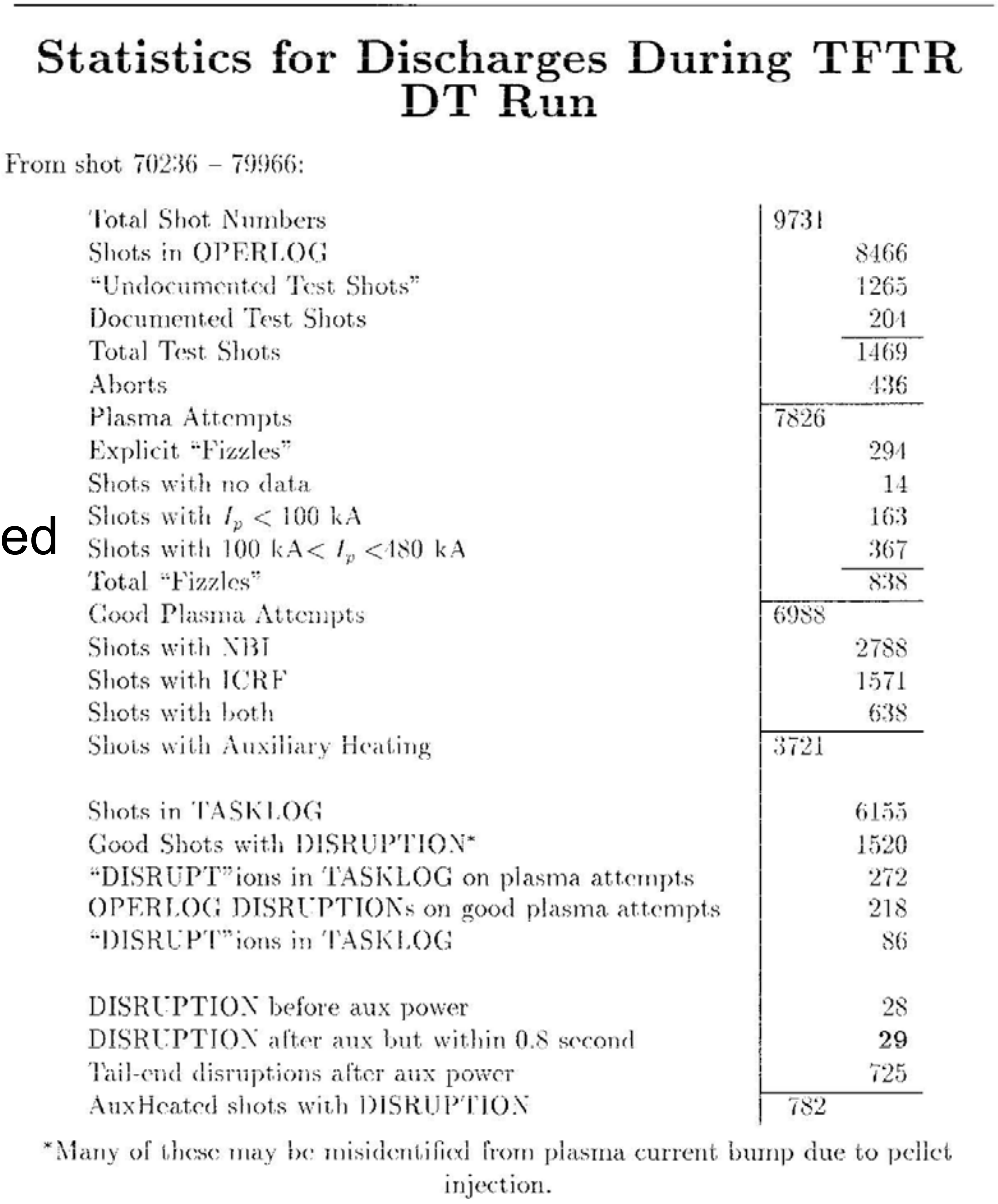
- Even after years of operation:

~10% of TFTR discharges disrupted

- Most occurred after aux heating

- Largest disruption in TFTR:

Plasma stored energy 7 MJ



Statistics for Discharges During TFTR DT Run

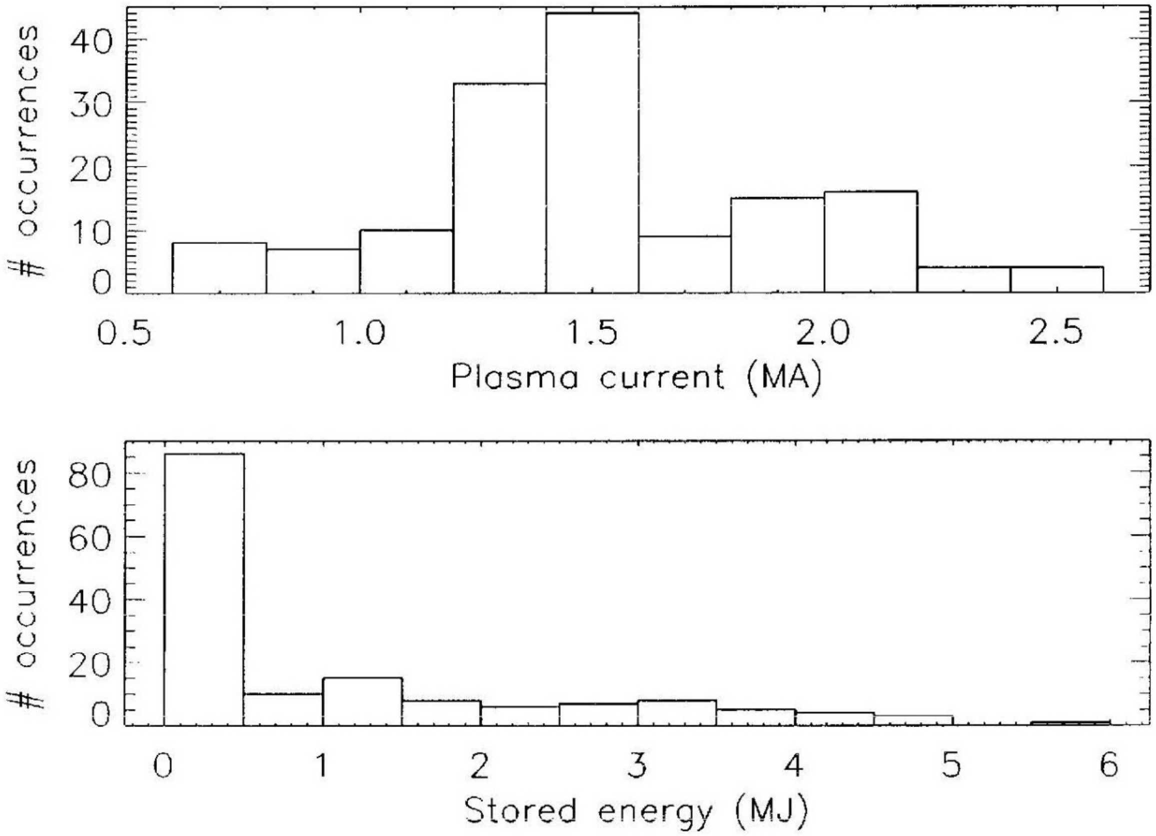
From shot 70236 – 79966:

Total Shot Numbers	9731	
Shots in OPERLOG		8466
"Undocumented Test Shots"		1265
Documented Test Shots		204
Total Test Shots		1469
Aborts		436
Plasma Attempts	7826	
Explicit "Fizzles"		294
Shots with no data		14
Shots with $I_p < 100$ kA		163
Shots with 100 kA< I_p <480 kA		367
Total "Fizzles"		838
Good Plasma Attempts	6988	
Shots with NBI		2788
Shots with ICRF		1571
Shots with both		638
Shots with Auxiliary Heating	3721	
Shots in TASKLOG		6155
Good Shots with DISRUPTION*		1520
"DISRUPT"ions in TASKLOG on plasma attempts		272
OPERLOG DISRUPTIONs on good plasma attempts		218
"DISRUPT"ions in TASKLOG		86
DISRUPTION before aux power		28
DISRUPTION after aux but within 0.8 second		**29**
Tail-end disruptions after aux power		725
AuxHeated shots with DISRUPTION	782	

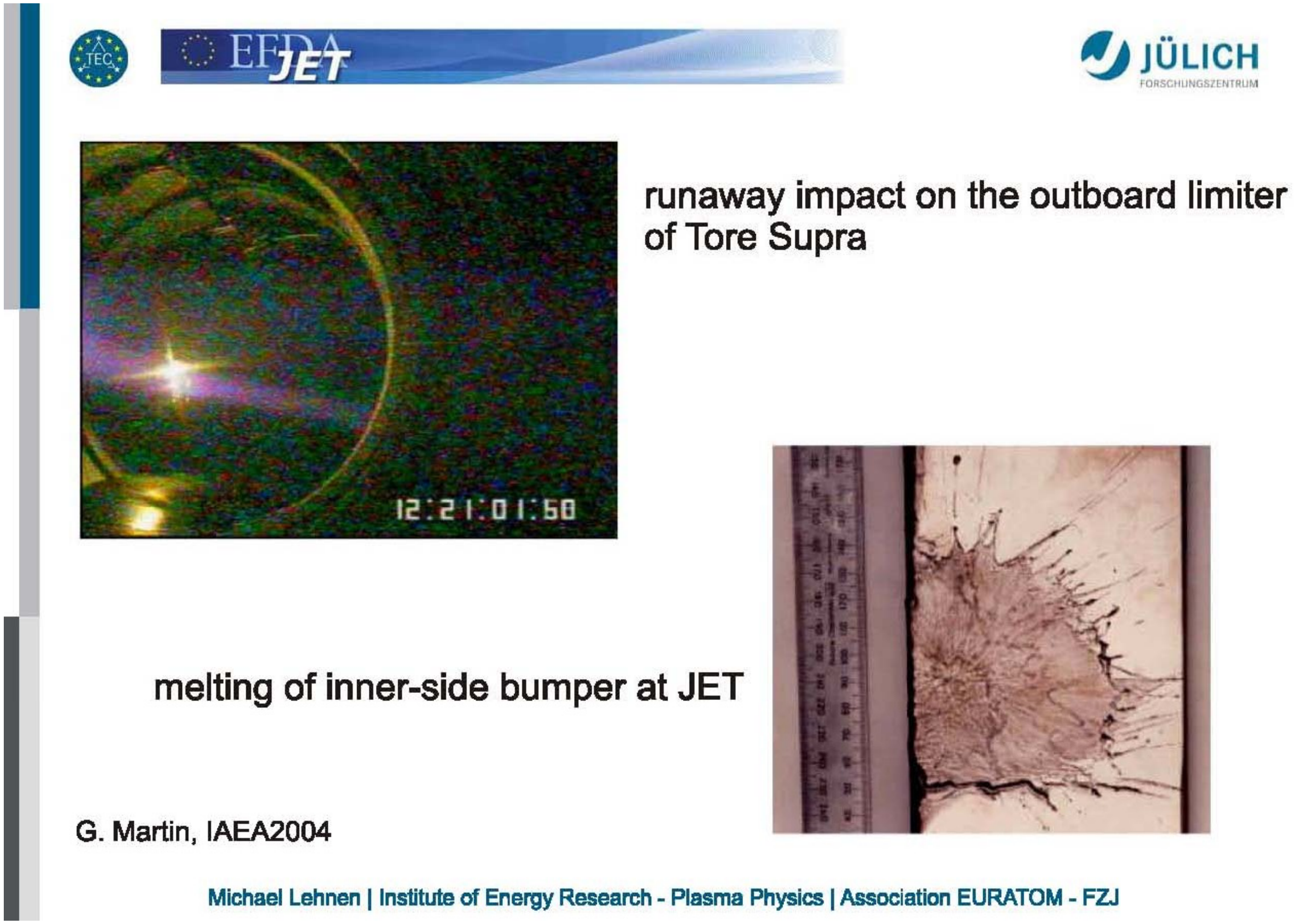
*Many of these may be misidentified from plasma current bump due to pellet injection.

One Year of TFTR Disruptions (1996)

- **153 Disruptions**
- **Total of 166 MJ stored kinetic energy dumped**
- **Low energy ones were either during current ramp-up, or at tail end**
- **Less energy than 1 shot in ITER**



Runaway damage in present machines



runaway impact on the outboard limiter of Tore Supra

melting of inner-side bumper at JET

G. Martin, IAEA2004

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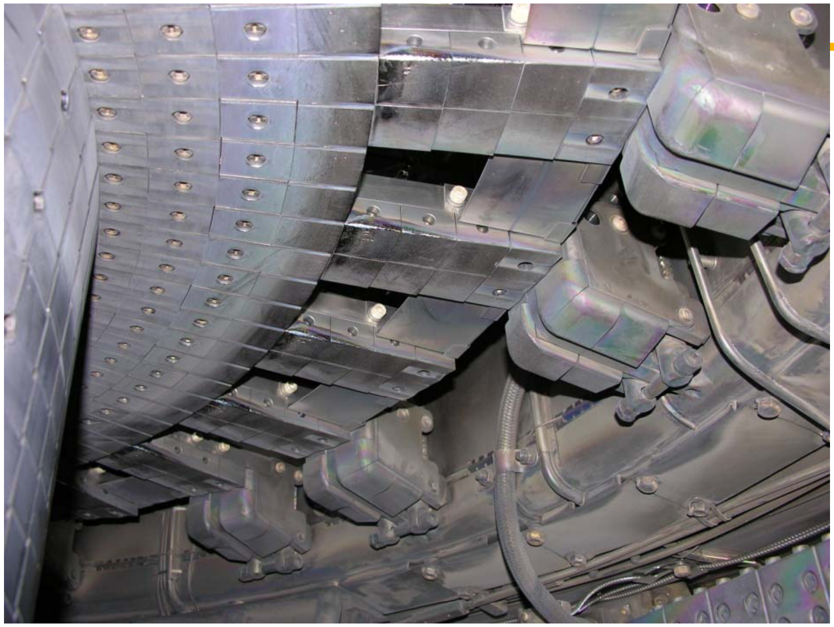
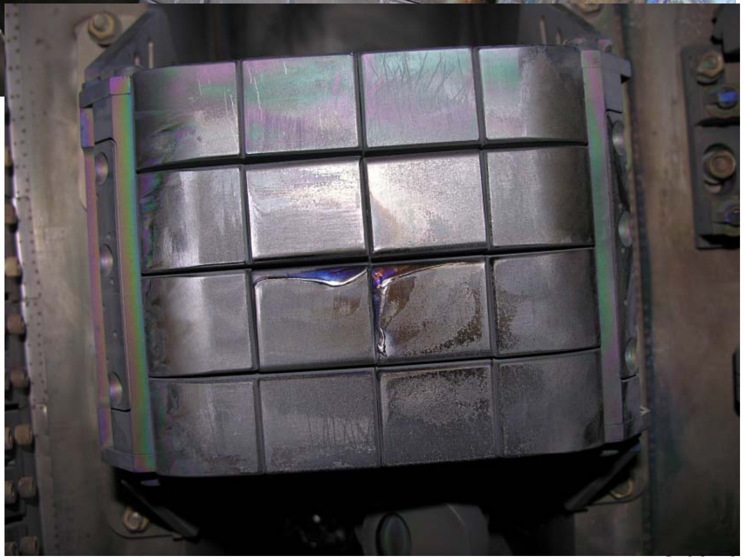
June 2008 Alcator C-Mod, in-vessel inspection

localized melt damage most likely due to runaways



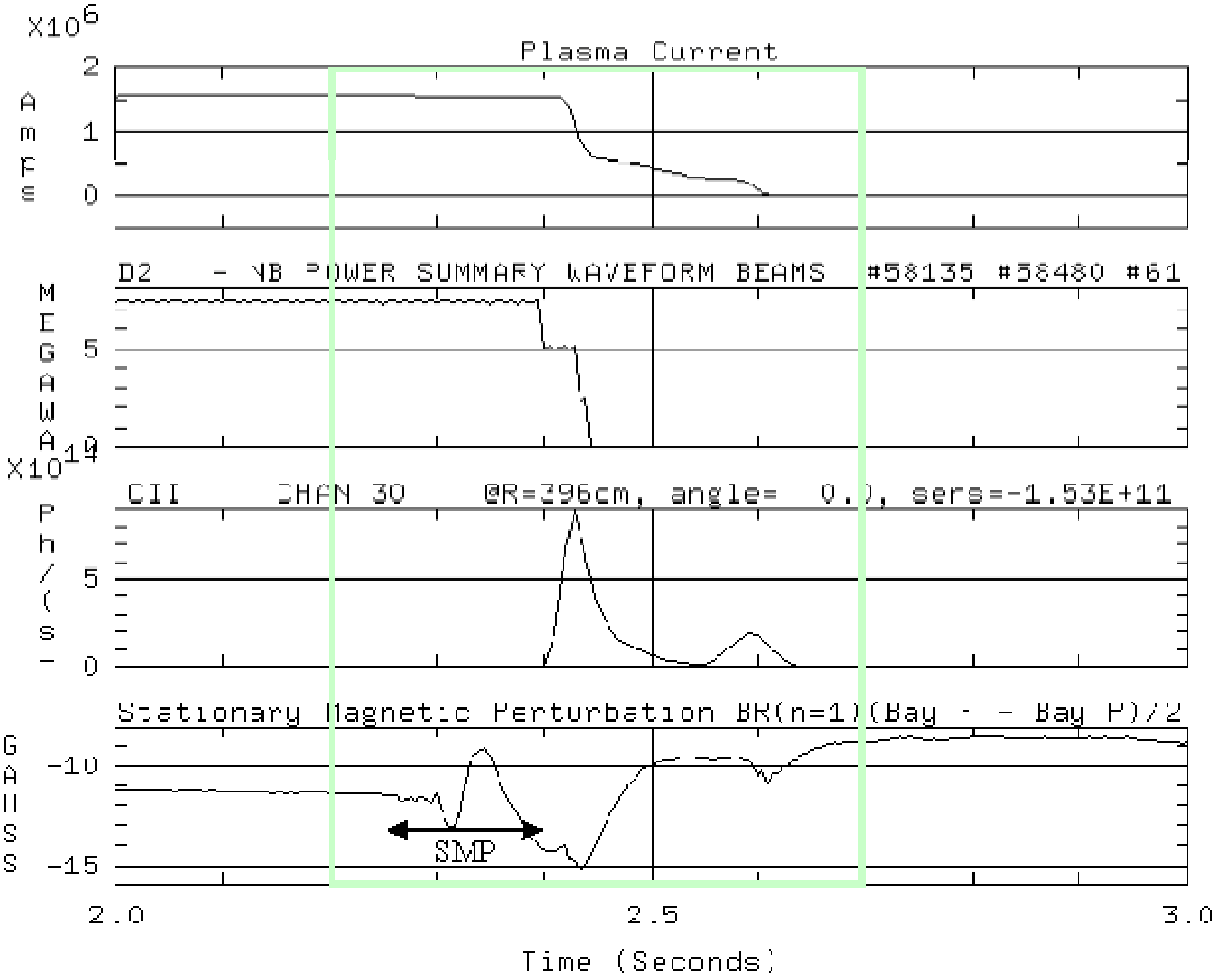
Melt damage at upper edges

“Far away” diagnostic harness burned/melted by runaways



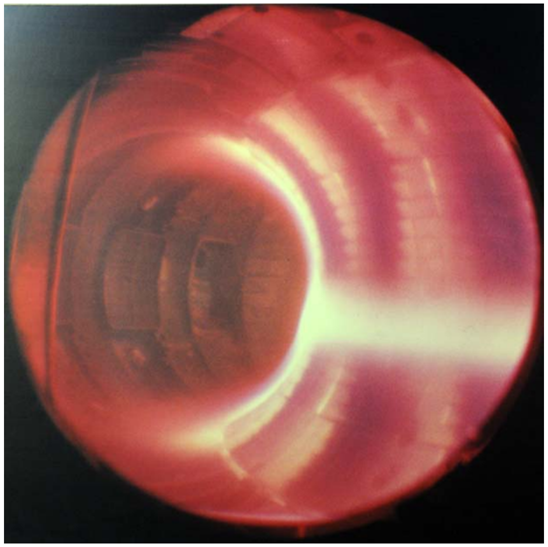
TFTR Shot 103681 Waveforms

Locked Mode Disruption with 300 kA of runaways



TFTR experienced 300kA-700kA of runaway generation from 1.6 MA discharge disruptions

- **TFTR had inertially cooled carbon armor tiles. When they were hit by runaways formed during MJ disruptions, they simply disintegrated.**
- **The consequence to operations was typically minimal….a day of glow discharge cleaning and shot conditioning to recover.**
- **Unlike ITER, TFTR did not have water cooling buried in its tiles**



- Video, shot 103681
- Disruption at 2.42 seconds due to locked mode. 1.6 MA discharge, with 7.5 MW NBI. 300 kA of runaways developed.
- 2000 fps/30usec exposure
- Outboard midplane ICRH RF antenna protection limiters destroyed.

Disruption Control

- **There are some generally agreed groupings of the “types” of disruptions**
  - Density limit
  - Low-q
  - Mode locking
  - Impurity bloom
  - Technical failures
  - Beta limit (especially high β-poloidal)
  - Mystery (~20% of JET disruptions in 1991 or 1.4% in 2011)
- **Some disruptions (high β_p and mystery) have little in the way of precursors**
- **Three “solutions”: Passive disruption avoidance and protection (by design), precursor detection and active prevention, and finally …mitigation during.**

“Disruptions in Tokamaks”, F. C. Schueller, Plasma Phys. Control. Fusion 37 A135 (1995). Proceedings of ITER Workshop on Disruptions and VDE’s, Garching, March 13-17, 1995.

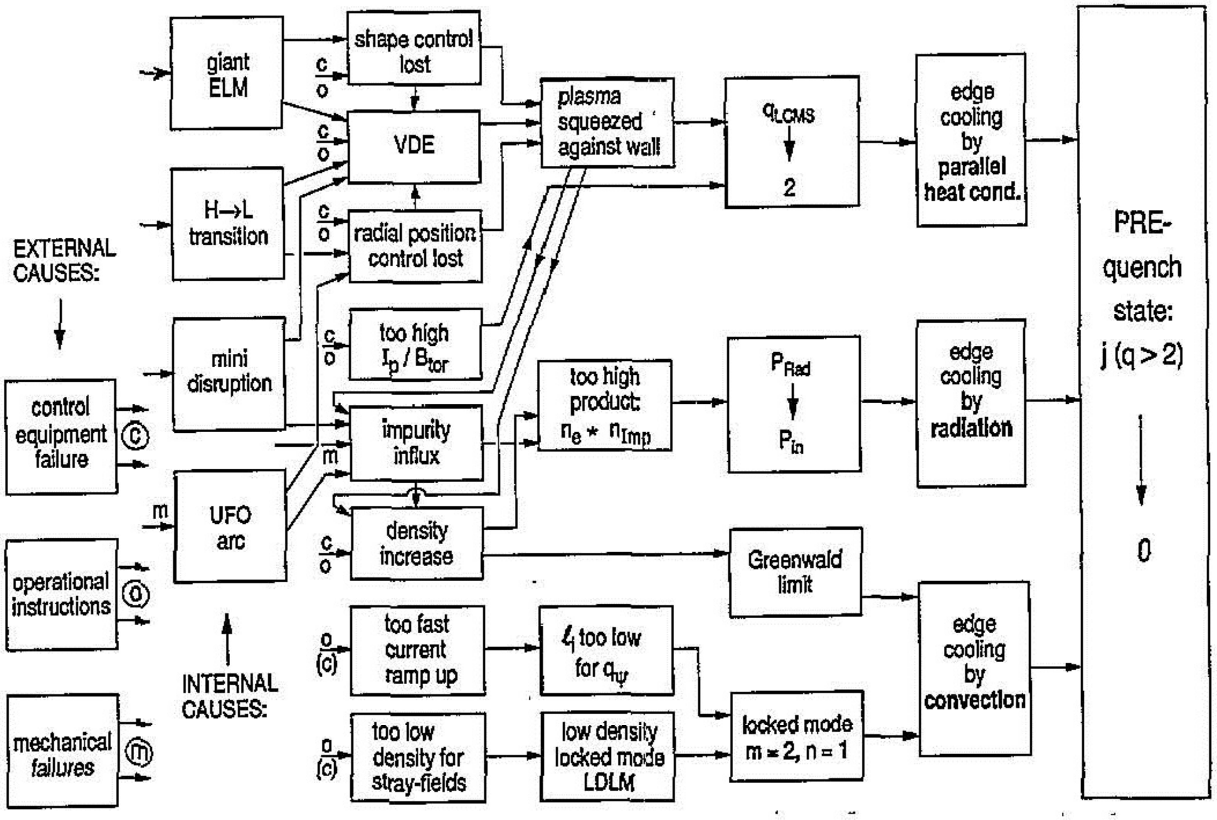


Figure 12. A scheme of possible initiating events and precursor scenarios leading to a prequench state with deficient edge.

Solving the Disruption Issue is Essential for Tokamaks

- **Let us insist on a priority examination of the issue of disruptions:**

  In the last 15 years of research, how much have we reduced the likelihood of disruptions in Tokamaks? Factor of 3x?

  In the next 15 years are we going to essentially eliminate disruptions through the development of avoidance techniques? What is the probability of 99.9% success? Is that good enough?

- **We tend to look at a parts of the problem in isolation…for example, fixing VDE disruptions by detection (pretty easy, they are usually slow) followed by massive gas injection to reduce halo currents or thermal quench radiation. Ok, but this then generates runaways(?), and puts a large load on the cryopanels. Can the same procedure work for high beta-poloidal disruptions…probably not….no or very fast precursors. How about flakes falling in (unexpected density limit disruptions)? How exactly will the neural network control system learning phase be accounted for in ITER? Not clear.**
- **We must demonstrate reliable control of high energy tokamak plasmas before ITER**
- **An integrated, multi-machine disruption control program, focused on the scientific understanding and engineering for both prevention (active avoidance and controls) and mitigation of the consequences of disruptions, must be initiated.**
- **We can use existing devices, for database mining and developing control techniques, and new machines for long-pulse demonstrations.**

How can runaways be prevented/mitigated?

- **Presently, only two overall techniques**
  - **1). Prevent them from forming in the first place by boosting the post disruption thermal quench density by a factor of 100x**
  - **2). Increase their losses dramatically ….through magnetic field perturbations**
- **So far the required density limit has not been achieved in today's tokamaks. Massive gas injection, killer pellets, shattered pellets, dust injection, etc. Effect on ITER pumping systems and vessel conditioning remains to be seen. Also, if the resulting current quench is too fast, the electromagnetic forces will be too high.**
- **Magnetic perturbations (~ 10^{-3} $\Delta B/B$ stochastic fields from edge) may not have sufficient reach into the core, where they are most needed. Especially if the current channel moves away from the internal ELM coils.**

Sergei Putvinski (left) and fusion physicist François Saint-Laurent (IRFM) are not manning a Gatling machine gun. They stand next to the prototype Disruption Mitigation System gun cartridge that will run its first tests in Tore Supra*.

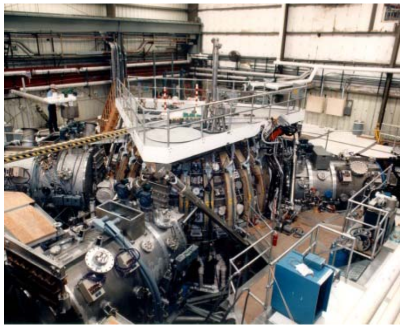
*ITER Newsline #176, May 2011

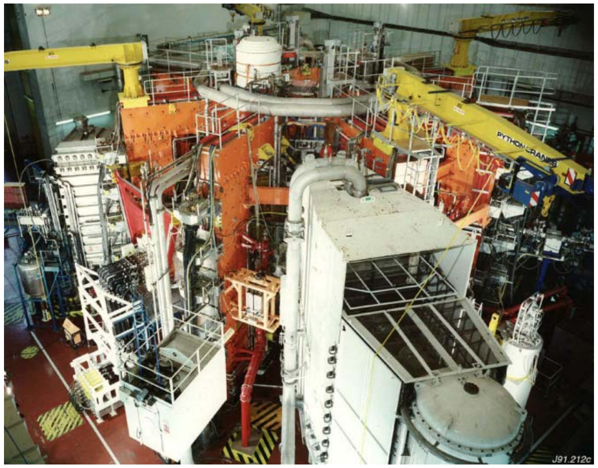
Mitigation also has serious impacts on operation

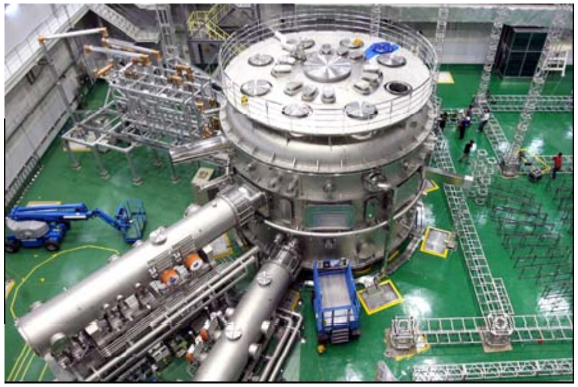
- **Keeping the accelerating electric field ratio $E_{||}$/Ecrit < 1, by massively (100x) increasing the electron density (either bound or free electrons) to prevent runaway electrons from forming.**
  - Impact on pumping systems
  - Impact on NBI conditioning (gate valves can't be closed fast enough)
  - Impact on gas recycyling (separations) systems
  - Impact on wall conditioning (if any)
  - Impact on dI/dt ….too rapid of a current quench, bigger EM force loads
- **Dissipate the thermal quench energy more uniformly, through radiation by introducing gas puffs at several (many?) toroidal locations.**
  - Does this cause even more runaways?
  - A giant 1-10 eV flash lamp can still cause ablation of the armor. How much?
- **Trying to "land a disruption" in specific locations that might be more robust…for example, on the center stack armor.**
  - Do you have control, every time? Is this plausible? Superconducting coils and thick vessel response time are problematic. Only in-vessel coils could be counted on.
- **Use massive gas injection (MGI) to enhance runaway electron scattering, and spread their impact over a larger region of the wall (Tore Supra experiments).**

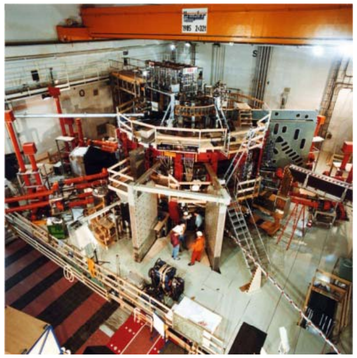
Let’s increase the runtime devoted to disruption issues in present machines….in a big way

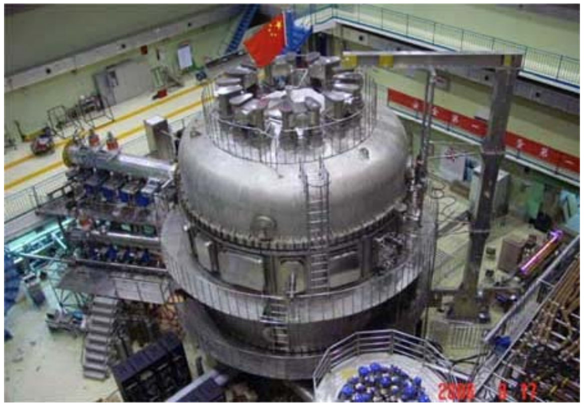
- Studying turbulence or transport is nice….but a 20% effect here in the next five years won’t make or break ITER.
- But finding a way to demonstrate control of disruptions & runaways will let us prevent ITER from breaking itself.











Where is it best to study tokamak disruptions...not ITER!

- JET, with its new “ITER-like” wall, will tread very carefully for the near term, to avoid unnecessary damage. Systematic disruption studies are unlikely.
- DIII-D is well armored, and can both make runaways, and bring a broad range of diagnostics to bear, as well as test potential control systems.
- ASDEX-U has to be careful of its internal passive plates, and doesn’t take well to hard disruptions
- EAST needs more diagnostic and control capabilities.
- Alcator C-Mod has moly metal armor, and is able to take 1 MA, 100kJ disruptions routinely, but doesn’t like to deal with runaways any more than necessary. Avalanche coefficient is low, and rarely has runaway plateaus.

U. S. Disruption Strategy Should Include Elements of Both Mitigation and Avoidance

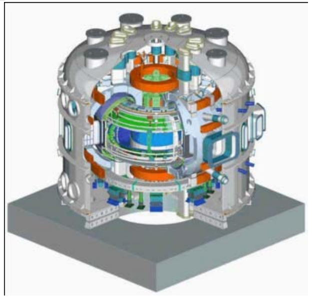
- **Mitigation needs to be tested in devices that can**:
  - Operate with elongated ‘ITER-like’ plasmas
  - Produce significant runaways
- Withstand effects of numerous disruption/runaway events

- **Avoidance needs to be tested on devices that have:**
  - A full set of control/actuators to actively modify the plasma state
- Sufficient pulse length to test avoidance in stationary/steady-state operation

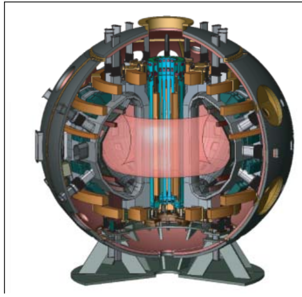
- **The strong capabilities we have in the US can leverage international collaborations**

DIII-D

EAST



KSTAR



JT-60SA

Diagnosing disruptions?

- What time resolution is necessary for any important diagnostic measurement (in a disruption). Which diagnostics function (and remain on-scale) throughout the disruption.
- What are the post thermal quench plasma conditions?
- Halo currents. Look for poloidal & toroidal asymmetries.
- Can we determine the plasma inductance and current profile as the disruption progresses?
- Measure the energy and spatial distributions, as a function of time, of the runaway electrons. What is the total energy in the runaway beam?
- Determine the location and duration of energy deposition on wall elements. Radiation versus convection? Bursts?
- Measure the forces on vessel components.
- Characterize the precursors (duration, signature) of every disruption.

Summary:
Reliable high energy tokamak plasma control is the key

- For the next 5-10 years, we have to use machines that exist, or are soon to be existing.
- For long pulse, this means extensive (big American teams) international collaboration on the Asian tokamaks:

  KSTAR, EAST and JT-60 Super Advanced

- Low risk disruption studies on lower energy short pulse machines such as DIII-D (good diagnostic set, RWM coils, real-time control systems, massive particle injection, etc.)
- Not only can disruptions cause serious damage to the tokamak, but our lack of control of disruptions causes damage to the credibility of our future tokamak fusion reactors…and to magnetic fusion energy in general.
- No one but us owns this problem….we need to take responsibility for it.
- Otherwise, and by the way….we should (must) build stellarators.