Disruptions in ITER:
Major Catastrophe or Minor Annoyance?

Sarah Angelini – April 21, 2011

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Disruptions

- Types of Disruptions
- Time Scales from the IDDB
  - Thermal Quench
  - Current Quench
- DINA Simulation Results
  - Thermal Loads
  - EM Loads
- Runaway Electrons
- Mitigation Efforts
  - Neural Networks
  - Massive Noble Gas Injection

Disruptions

- Two categories of disruptions:
  - Major Disruptions
  - Vertical Displacement Events
- Three "stages" of a disruption
  - Thermal quench
  - Current quench
  - Loss of vertical position
- The order of these "stages" determines the type of disruption

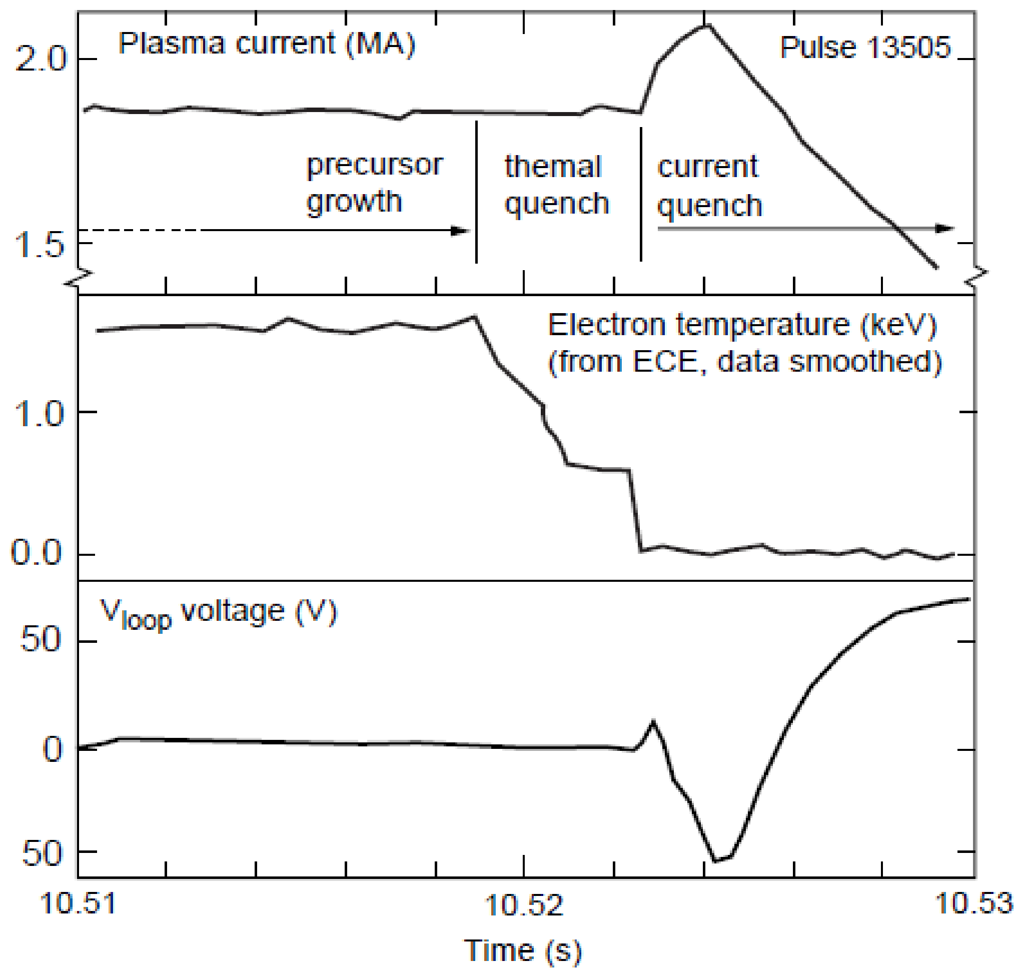
Major Disruptions

- Disruption starts because a stability limit is reached – Beta limit or density limit
- Loss of confinement leads to thermal quench – less than 1ms to reach sub KeV
- Impurities enter from the walls
- The plasma's resistance increases dramatically
- The current quenches at 1000 MA per second

Vertical Displacement Events

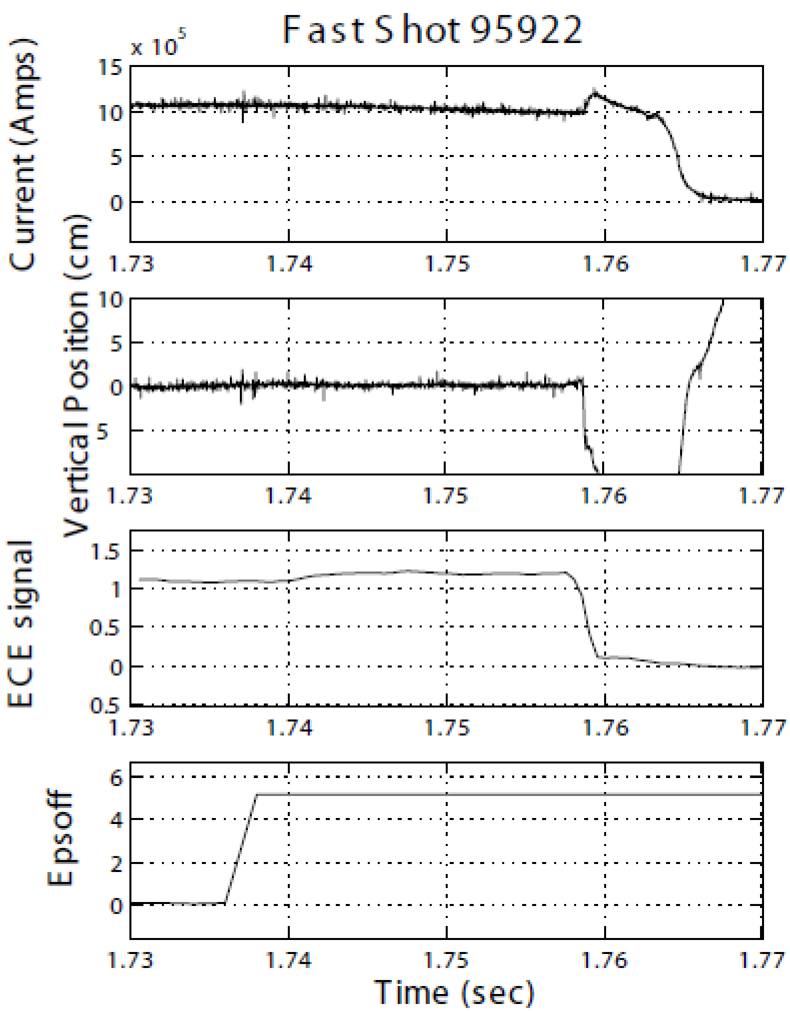
- Unlike a Major Disruption, VDEs start with a loss of vertical stability
- The current and thermal energy is not released until the plasma becomes limited
- VDEs have larger halo currents and thermal energy deposited into the wall
- VDEs can cause more damage, but are easier to predict

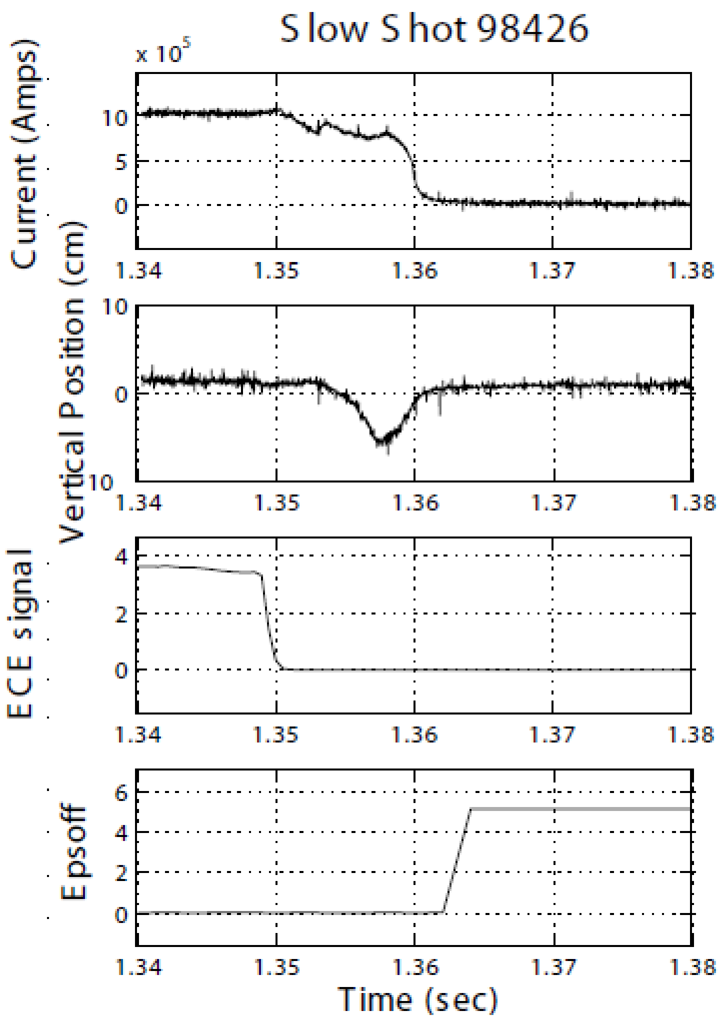
Typical Disruption (JET)



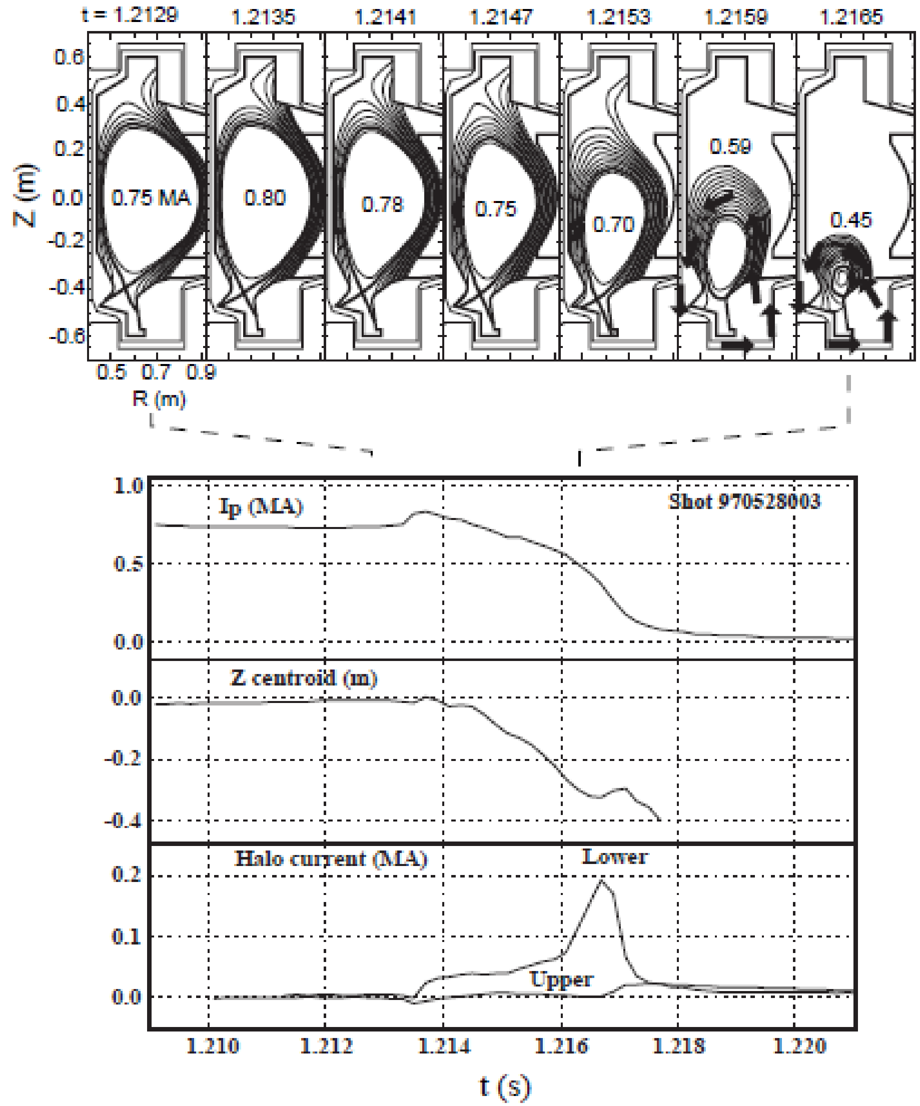
ITER Physics Basis, 1999

Disruptions (DIII-D)



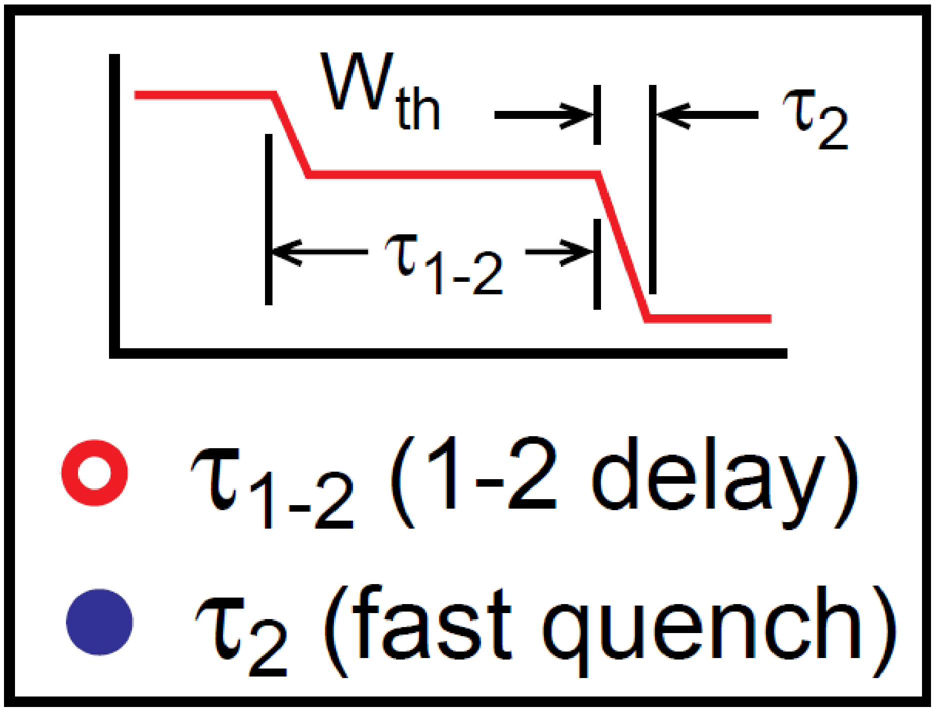


Halo Currents



ITER Physics Basis, 1999

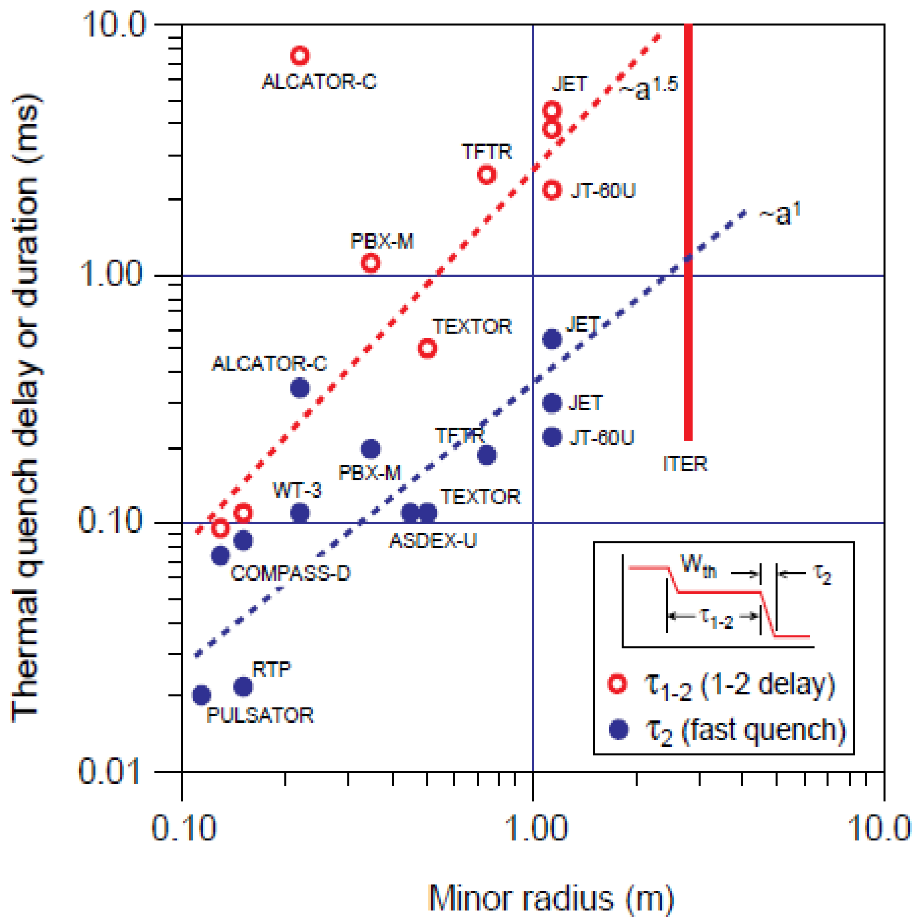
Thermal Quench Time Scale



- Typically, most of the energy (~90%) is dissipated during the thermal quench during the $\tau_{1\text{-}2}$ phase
- The remainder of the energy is lost when the plasma makes contact with the PFC during the τ_2 phase
- Thermal Quench in ITER extrapolated by minor radius: $\tau_{1\text{-}2} \sim 20$ ms and $\tau_2 \sim 0.7$ ms

ITER Physics Basis, 1999

Thermal Quench Time Scale



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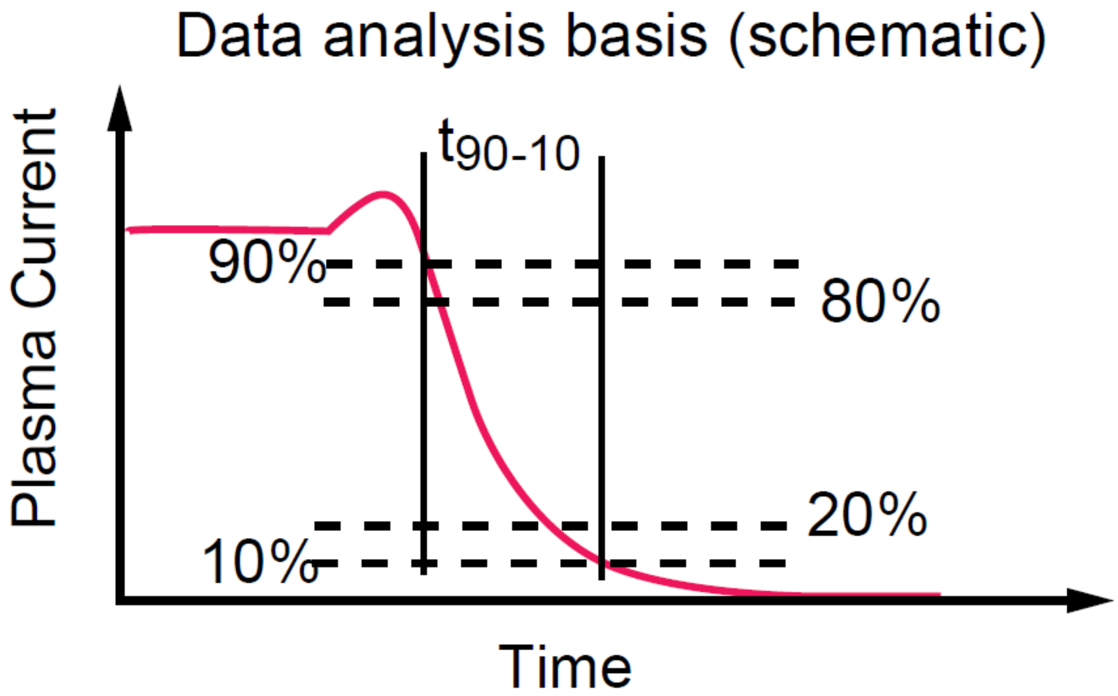
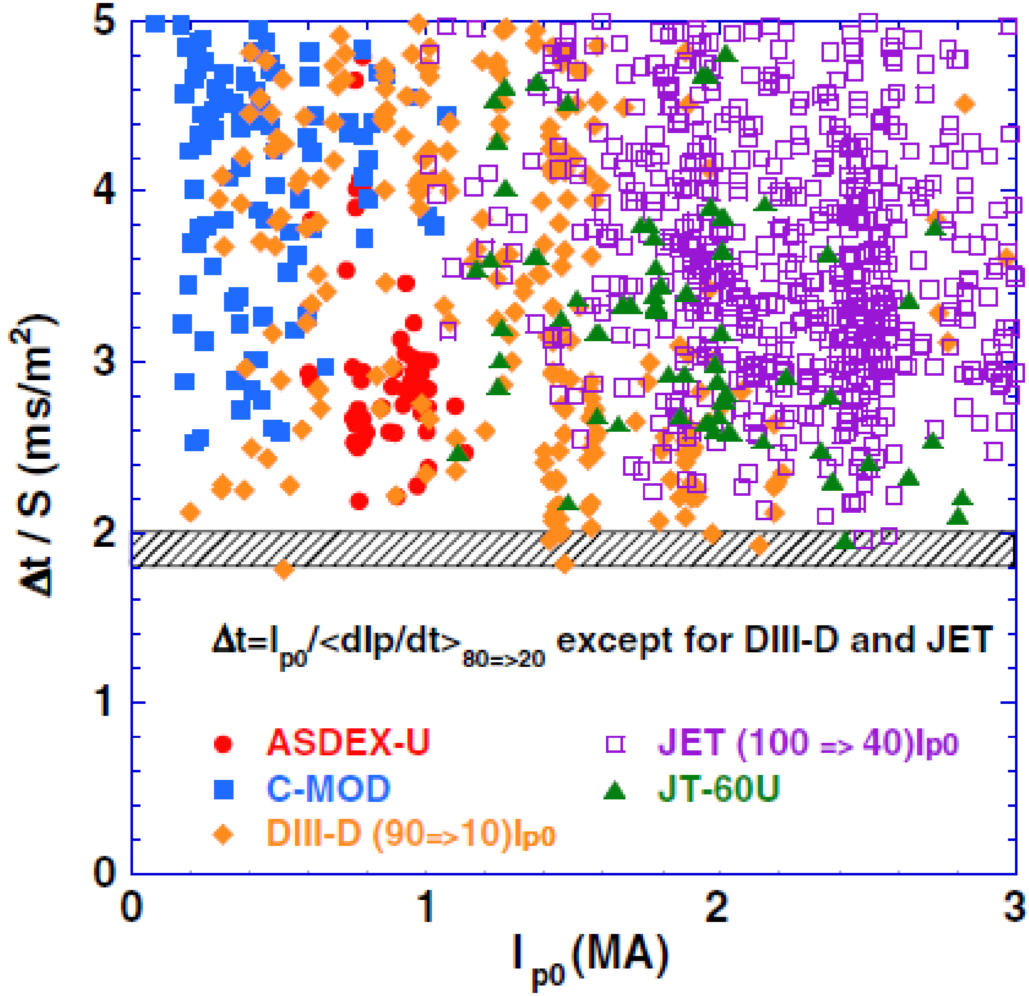
Current Quench Time Scale



- Data from seven different tokamaks was used to determine scaling
- τ_{60} was used as the standard, although the basis for determining the constant was not initially consistent among the machines

ITER Physics Basis, 1999

Current Quench Time Scale



- Current Quench extrapolated by cross sectional area $\pi\kappa a^2$: $\Delta t_{60}/S^* \sim 0.8$ ms/m^2
- 100% decay rate 1996 ~1.33 ms/m^2
- 100% decay rate 2007 ~1.8 ms/m^2
- Expected current quench time in ITER: t_{60} ~36 ms linear or an exponential time constant of 18 ms

T.C. Hender, et. al., 2007

DINA Simulations

- Uses the "inverse variable" technique to find the locations of the equilibrium magnetic surfaces
- Calculates a 2-dimensional equilibrium on closed and open magnetic surfaces with 1-D transport
- Circuit equations are solved for VV and passive and active coils
- Includes neutral beam heating, heating from a particles, bootstrap current, fueling by pellet injection
- Equilibrium configuration before disruptions is the reference inductive scenario:

$$\beta_p = 0.7,\ l_i = 0.85,\ I_p = 15\text{ MA},\ q_{95} = 3,\ \kappa_{95} = 1.7$$

R.R. Khayrutdinov and V.E. Lukash, 1993
M. Sugihara, et. al., 2007

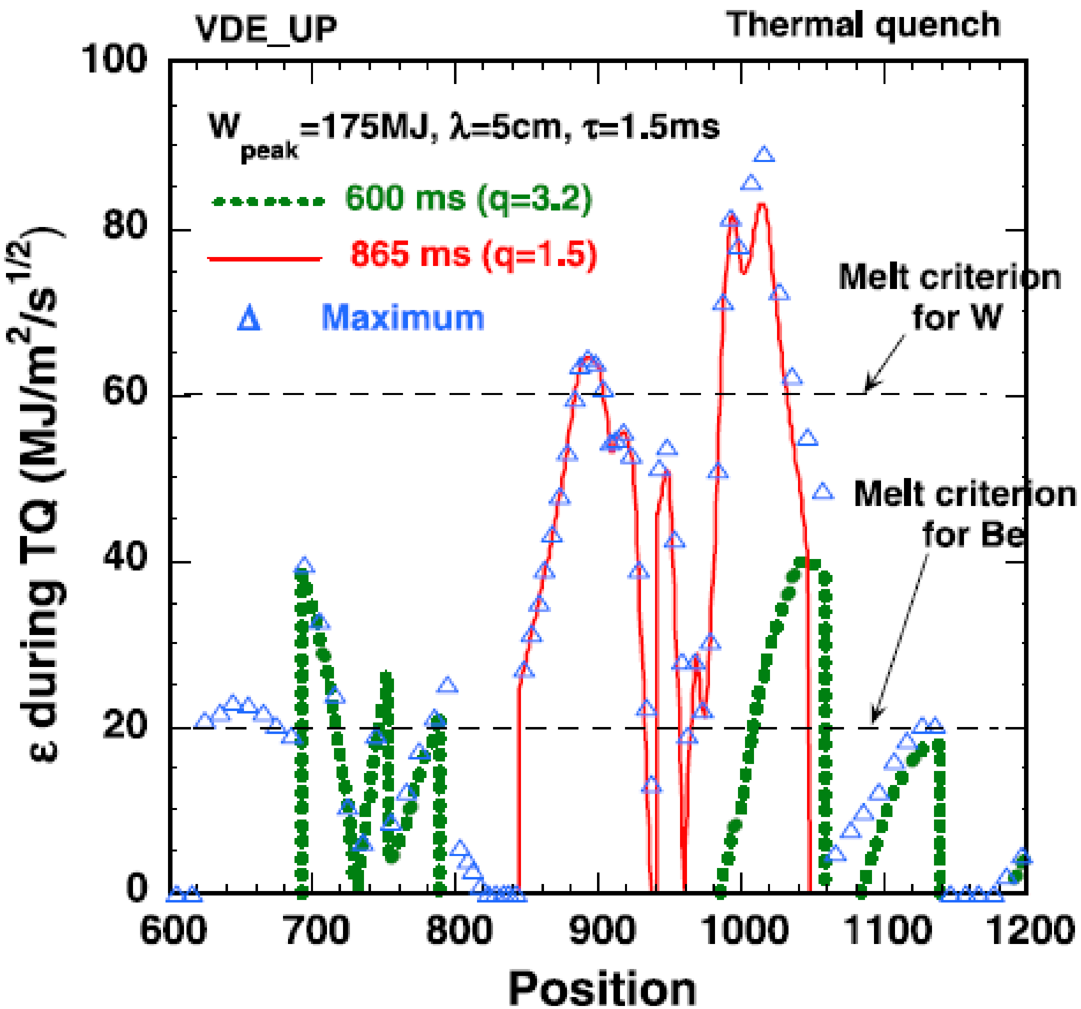
Thermal Loads - MDs

- Melting and Sublimation thresholds (ε) are reported in units of MJ m^{-2} $s^{-1/2}$
- The Beryllium melting criterion is:

  ~20 MJ m^{-2} $s^{-1/2}$
- ε for ITER is in the range 8.2–75 MJ m^{-2} $s^{-1/2}$ for a deposition time of 1.5–3 ms
- Loss of Be thickness is ~30–100 *μ*m/event for 1–2 MJ m^{-2}
- Total allowable MDs ~ 100-300

M. Sugihara, et. al., 2007

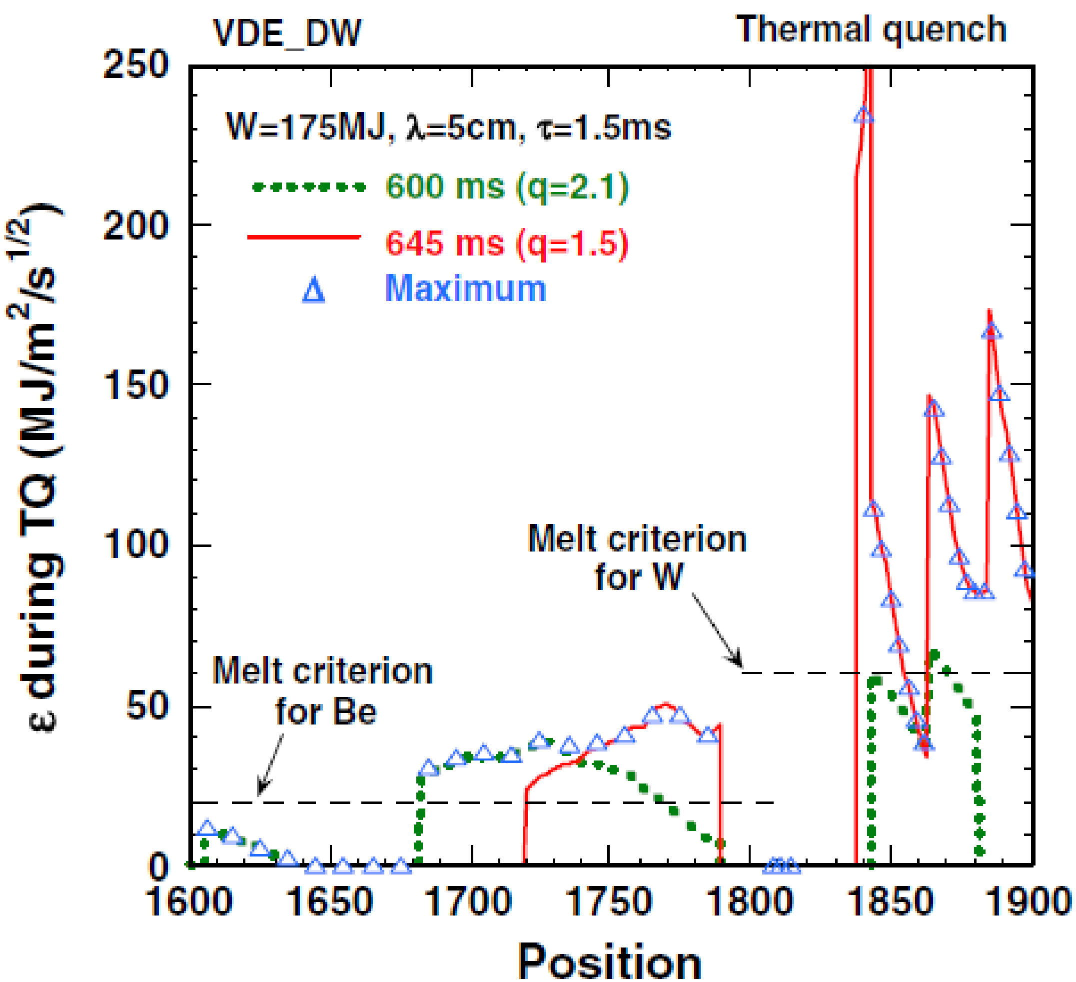
Thermal Loads – Upward VDEs



- Energy load during the vertical movement is 3-4 MJ m^{-2} $s^{-1/2}$ which is comfortably low
- The problem occurs during the thermal quench of the VDE when an additional load of 2 GW/m^2 is deposited on the wall
- Be loss of thickness is ~140 μm/event
- This VDE was examined using three different l_i values ~ 0.7, 0.85 and 1 with little difference observed

M. Sugihara, et. al., 2007

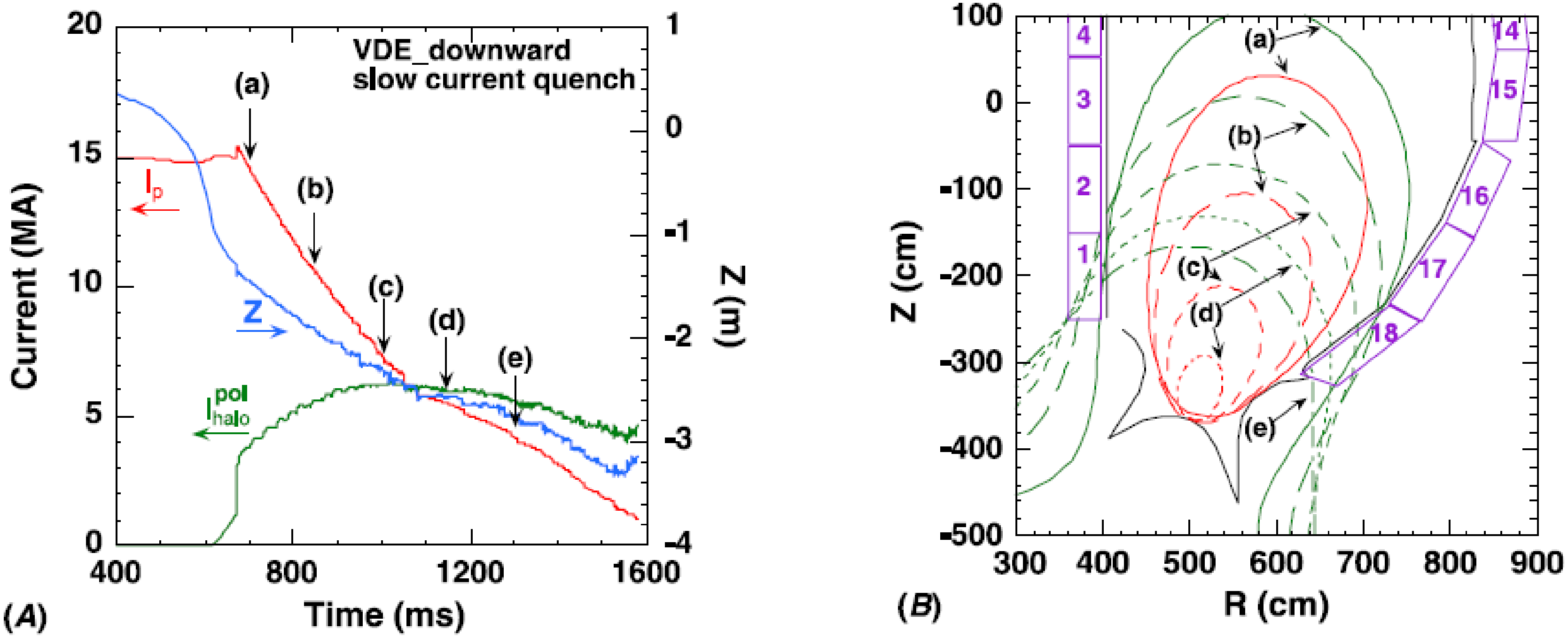
Thermal Loads – Downward VDEs



- ε still exceeds the critical Be melting value, but is less than for the upward VDEs
- In the tungsten baffle region, a considerably larger ε is expected.
- The wall's heat load is 17.5 MW m^{-2} before the TQ
- The heat load during the TQ is 6.54 GW m^{-2}
- The surface temperature reaches 750 K before the TQ, but 6760 K during the TQ
- Expected loss of W at the baffle is ~230 μm/event

M. Sugihara, et. al., 2007

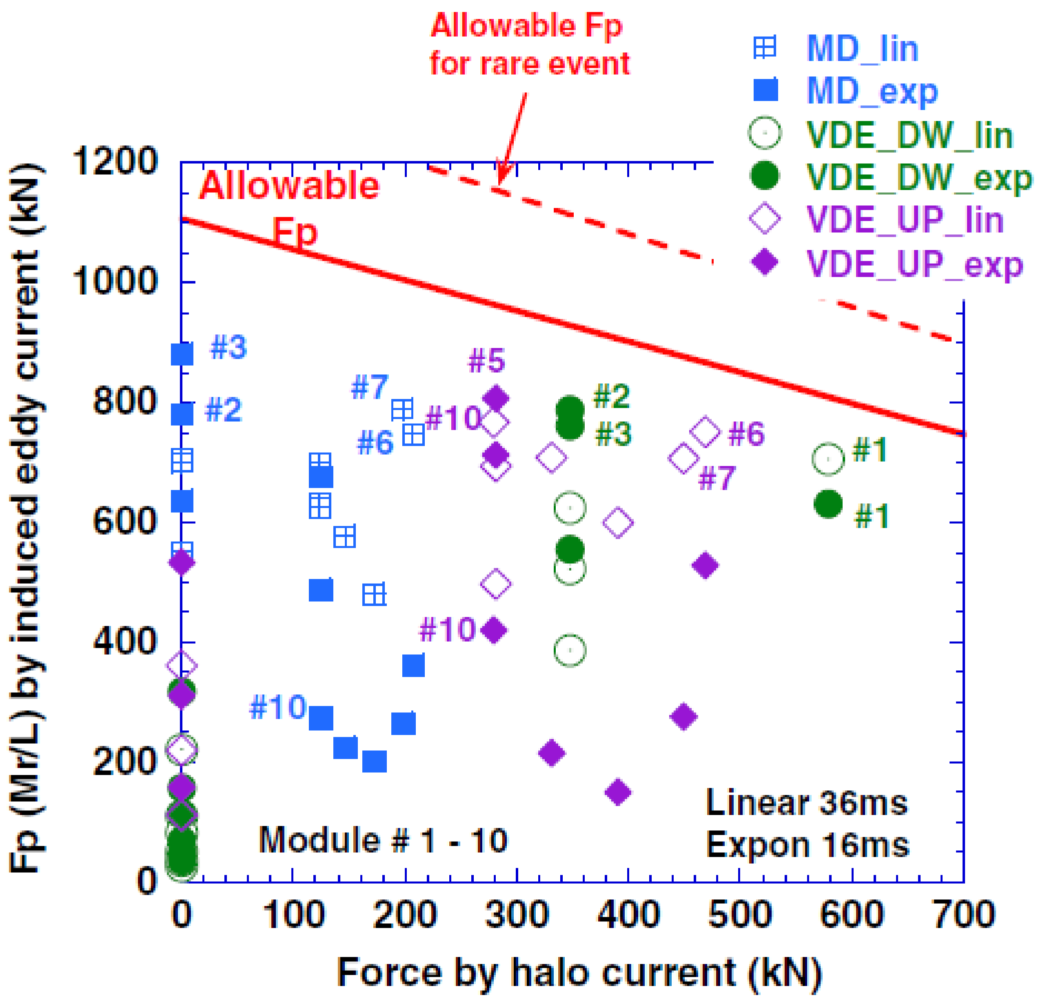
EM Load Analysis



- The fastest current quench time and the maximum toroidal peaking factor (TPF) were determined from the IDDB
- A 3D finite element code was used to calculate the induced eddy and halo currents

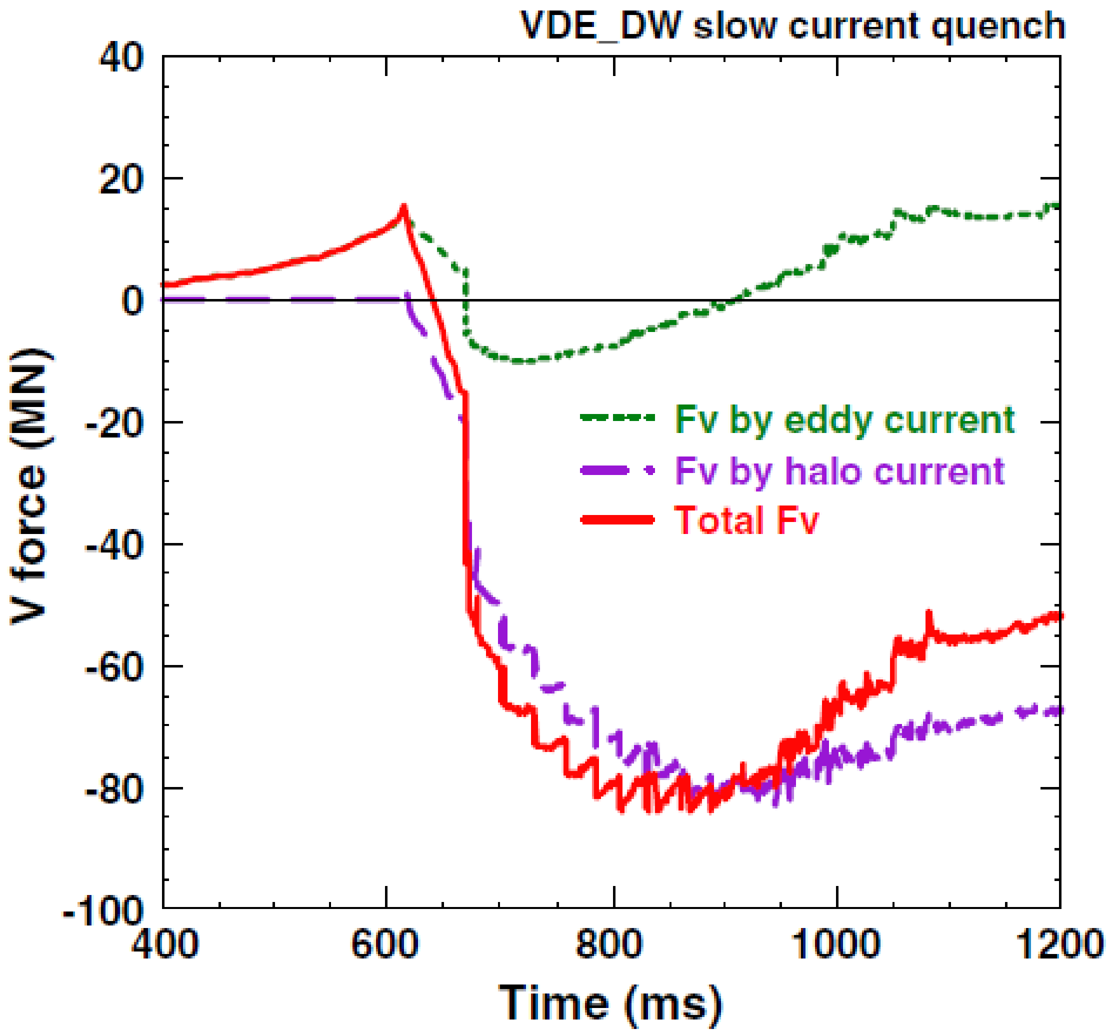
M. Sugihara, et. al., 2007

EM Load Analysis



- Poloidal Forces are within allowable values

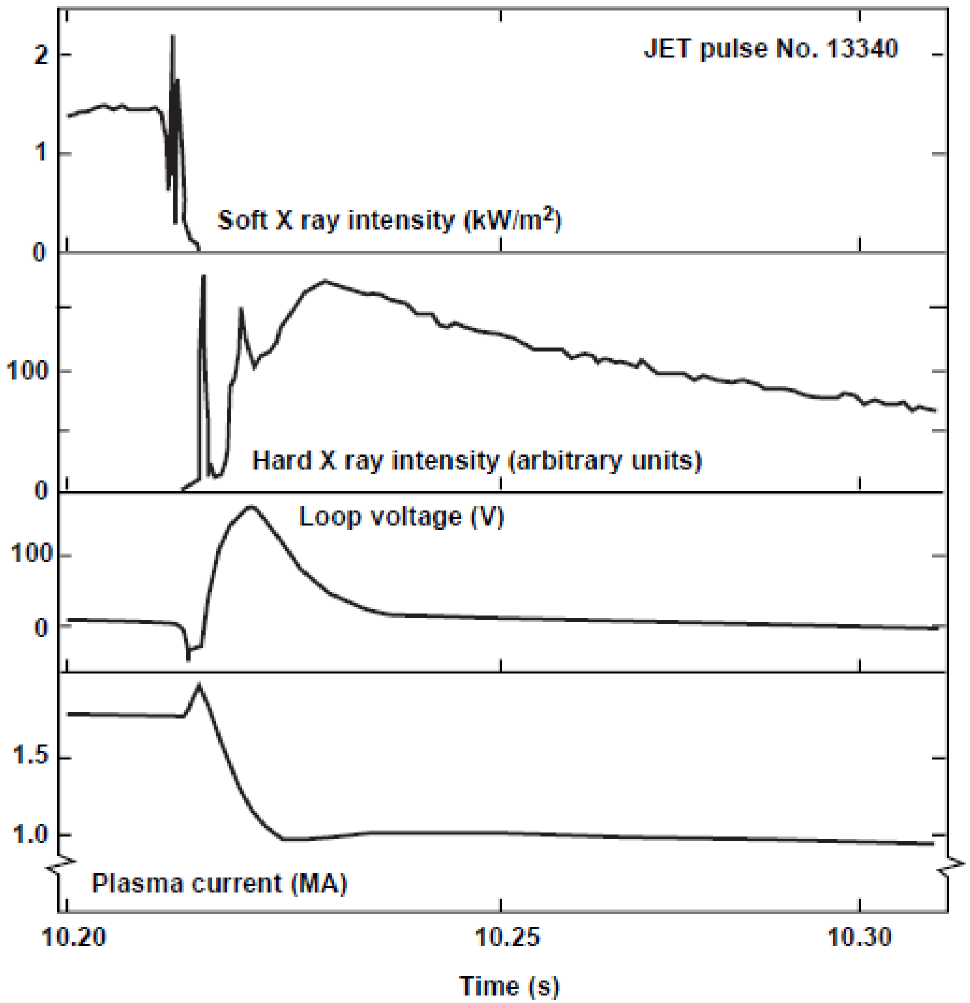
EM Load Analysis



- Downward VDEs are expected to have the largest halo currents ~6.4 MA at the maximum
- Maximum total vertical force is marginally within the design limit (80 – 85 MN)

M. Sugihara, et. al., 2007

Runaway Electrons



- High in-plasma electric fields are created during the CQ.
- These electric fields generate runaway electrons with energies from 10 to 100 MeV
- Runaway electrons are expected to stay confined for 130-230 ms in ITER
- Avalanche multiplication allows for the creation of further runaway electrons
- A 15 MA discharge in ITER could allow for 70% of the initial thermal current to be converted into runaway electrons

ITER Physics Basis, 1999

Runaway Electrons

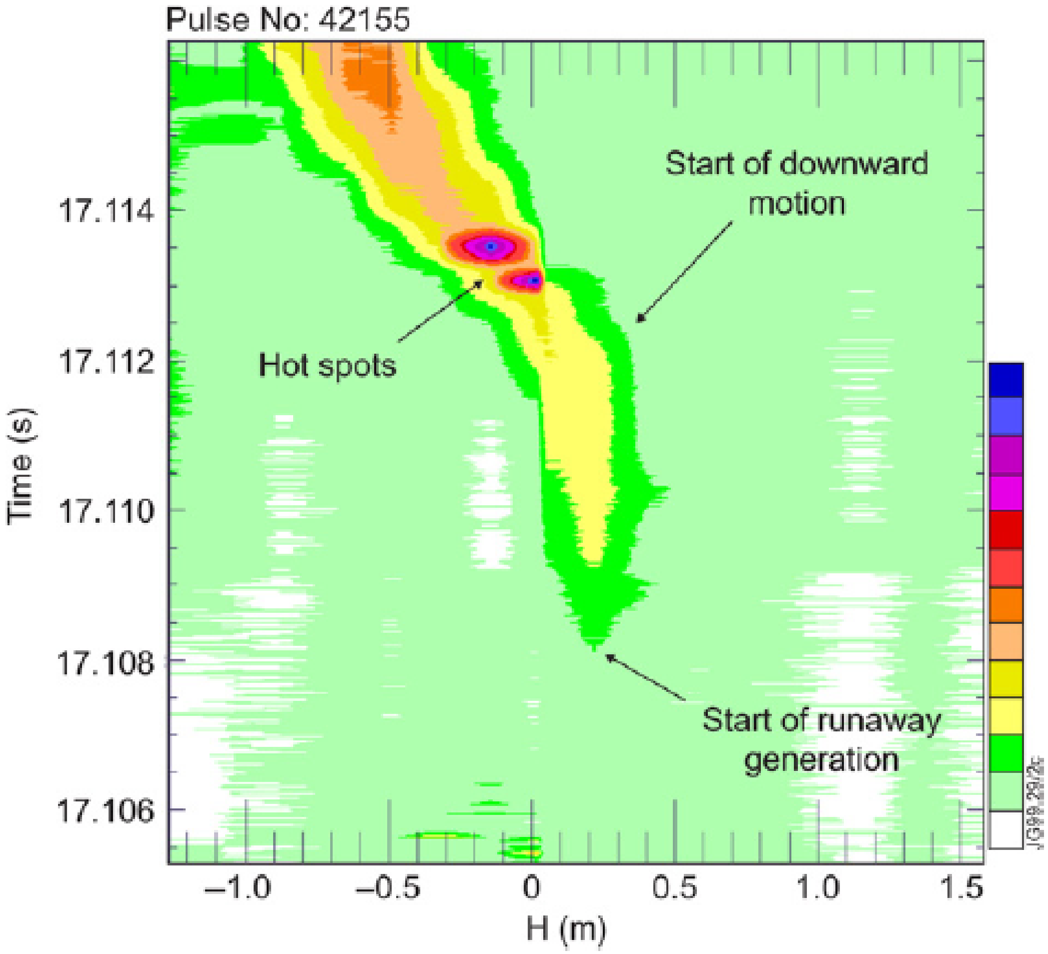


Figure 49. Observation of soft x-ray image of runaways in JET. The downward motion (towards the divertor) is clearly seen. The runaways are first generated 4ms after the start of the disruption

- Vertical instability of the runaway electron current channel will cause the energy to be deposited on the upper or lower first-wall or perhaps in the divertor.
- A deposition depth of ~2.5 mm for beryllium and copper and ~0.2 mm for tungsten is estimated.

T.C. Hender, et. al., 2007

Runaway Electrons

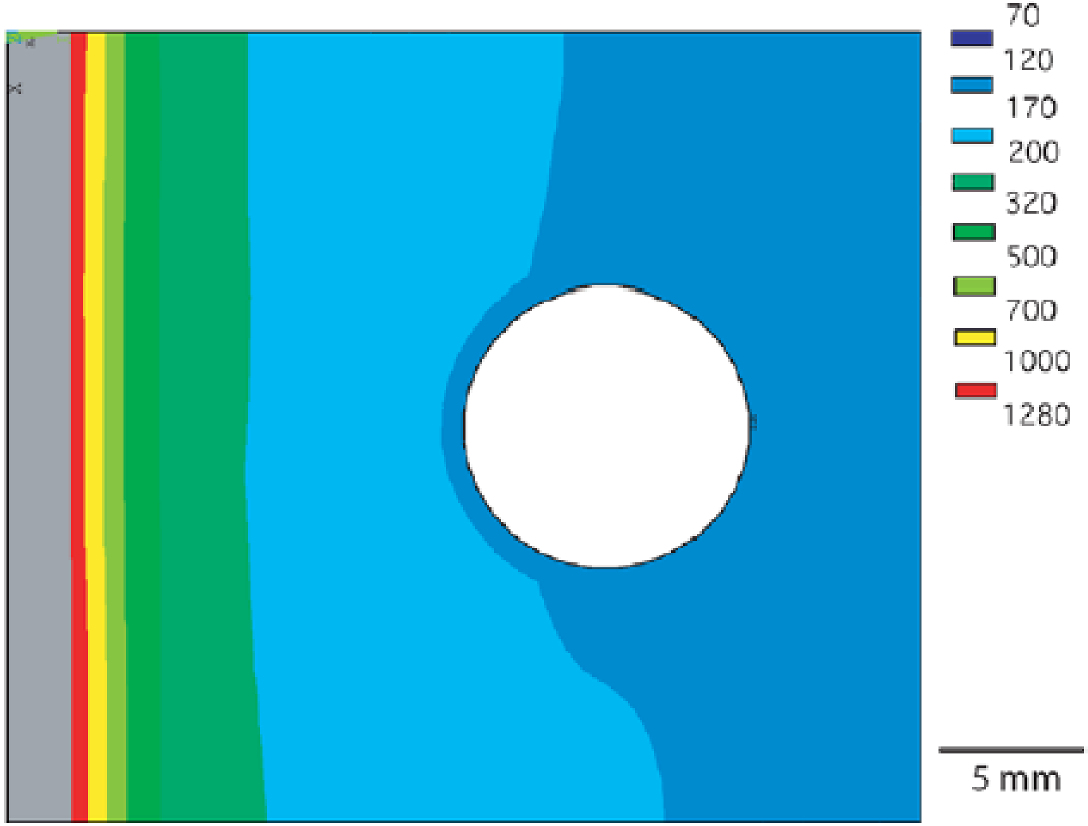


Figure 51. Numerical simulation of the ITER first-wall temperature (in ◦C), just after energy deposition by 10MeV runaway electrons, with 50 MJm−2, deposition time =0.1 s. From the lefthand side, the simulation geometry comprises 10mm of beryllium armour, 22mm of copper heat sink and a 10mm inner-diameter copper cooling water tube (lateral spacing = 28 mm). The ~2mm thick grey zone indicates material attaining temperature larger than the beryllium melting point.

- DINA simulations estimate 15-65 MJ m^{-2} deposited on an area of 0.8 m^2 for 50 MJ runaway energy content
- Beryllium and tungsten will both experience melting in the 15 MJ m^{-2} estimate and there will be ablation with the melting in the 65 MJ m^{-2} case
- In a single runaway interaction event, Monte Carlo simulations predict several kg of molten material can be produced and mobilized by JxB forces
- Graphite will also undergo ablation for >35 MJ m^{-2}

T.C. Hender, et. al., 2007

Runaway Electrons

- Runaways could be suppressed if two conditions are met:
  - The electron density is at least:

    $$n_{RB} \approx 4.2 \times 10^{20}\ m^{-3}$$

  - The electric field is below the critical electric field:

    $$E_c = \frac{4\pi e^3 n_e \ln\Lambda}{mc^2} \approx 38\ V\ m^{-1}$$

M.N. Rosenbluth and S.V. Putvinski, 1997
T.C. Hender, et. al., 2007

Mitigation – Neural Nets

- Mitigation requires proper early detection of disruptions
- Neural network predictors have been developed and tested on ADITYA, ASDEX Upgrade, DIII-D, JET, JT-60U and TEXT
- Performance is quantified by success rate, SR, failure rate (or missed alarm), MA, and false alarm rate, FA
- NNs require training with shots and information specific to input NN data set, operation modes and attributes of the tokamak

T.C. Hender, et. al., 2007

Neural Net - DIII-D

- Trained to predict the maximum β_N at the disruption
- Uses 33 input parameters
- Prediction is tens of milliseconds in advance
- 90% SR accuracy
- 20% FA on non-disrupting shots

Neural Net – ASDEX Upgrade

- Trained to predict the time before a density limit disruption for killer pellet injection
- An alarm is activated for $t_{nn} < 50$ ms
- Uses 13 input parameters
- Trained from 99 disruptive shots and 386 non-disruptive shots
- 85% SR (55/65 disruptive shots)
- 1% FA for 500 non-disruptive shots

T.C. Hender, et. al., 2007

Neural Net - JT-60

- Trained to predict the occurrence of a disruption by calculating a “stability level”
- Trained in two steps:
  - First with 12 disruptive and 6 non-disruptive shots
  - Second with modifications of the 12 disruptive shots based on the output
- Tested against 300 disruptive and 1008 non-disruptive shots from over 9 years
- SR was 97-98% except for certain cases with a 10 ms advance warning
- FA was 2.1% for non-disrupting shots

T.C. Hender, et. al., 2007

Cross-Machine Neural Nets

- While there is difficulty in extrapolating a neural network, a cross-machine prediction of disruptions was attempted between JET and ASDEX Upgrade
- The NN was programmed using 7 normalized dimensionless parameters and normalized time
- The NN trained on JET and tested on ASDEX had a SR of 67%
- The NN trained on ASDEX and tested on JET had a SR of 69%

T.C. Hender, et. al., 2007

Mitigation Methods

- Plasma control actions
  - Experiments on JT-60 demonstrated that a VDE could be mitigated by a rapid shift of vertical displacement after the thermal quench is detected
- Pellet Injection
  - Uses cryogenic H_2, D_2, Ne, Ar, Xe, etc
  - Reduces 25-95% thermal flux to divertor
  - 50-75% reduction in halo current
  - Unfortunately, causes runaway electrons

T.C. Hender, et. al., 2007

Massive Noble Gas Injection

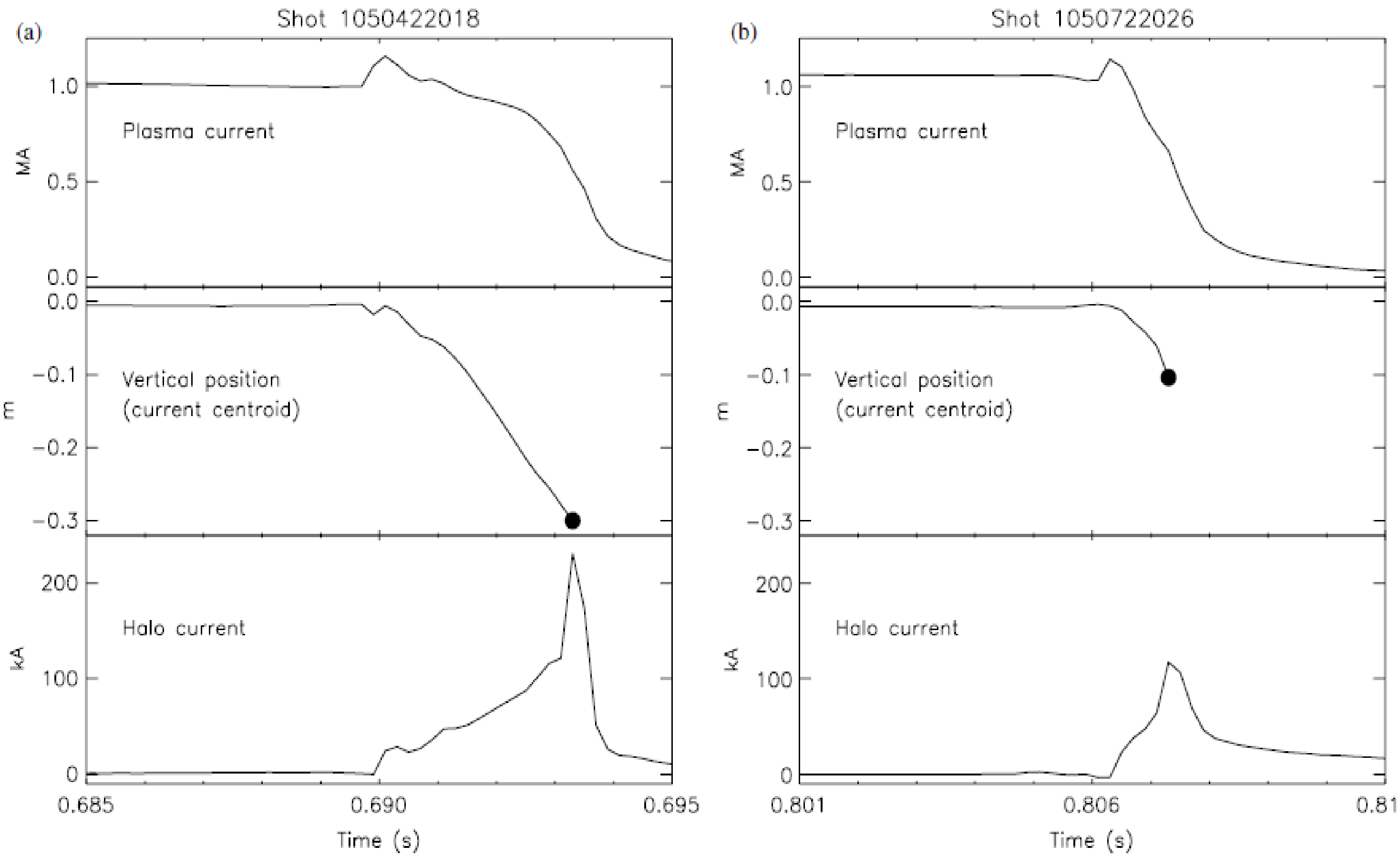
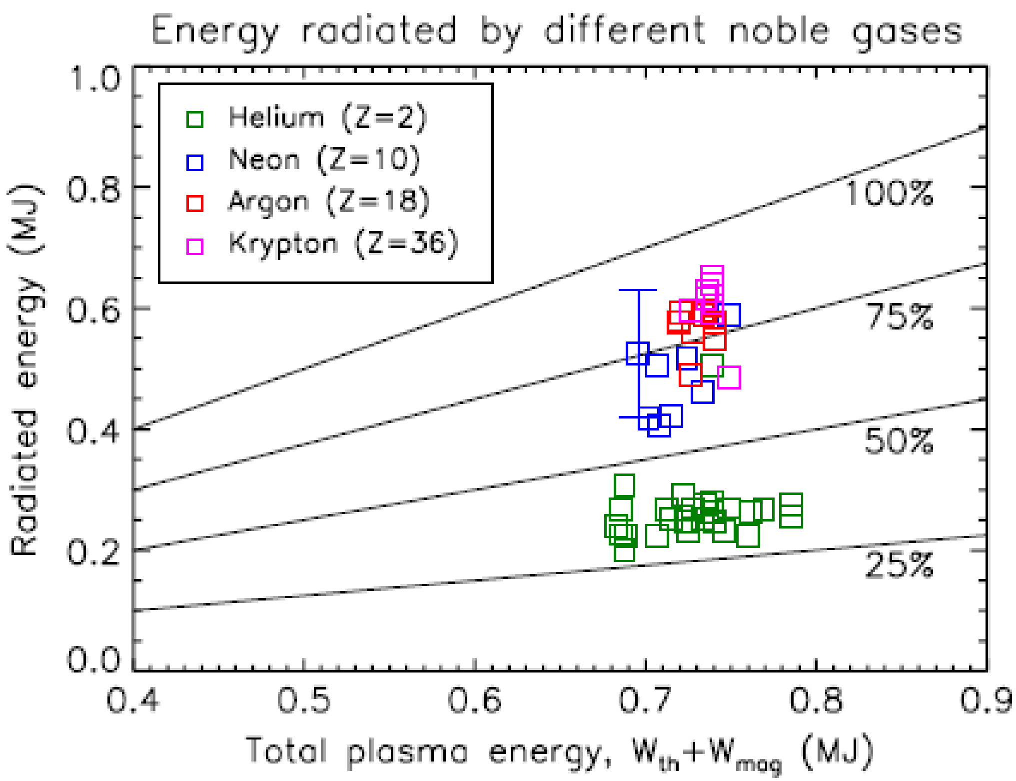


Figure 1. Comparison of an unmitigated current quench (left) with an argon gas jet case (right) in C-Mod. The argon significantly shortens the current quench, resulting in much less vertical displacement and half the halo current. (The dot at the end of the displacement signal indicates the last time for which closed flux surfaces exist.)

Massive Noble Gas Injection



- Runaway electrons were negligible in Alcator C-Mod and DIII-D experiments
- Lowering the temperature can speed up the current quench due to the increased resistivity.
- Total halo current is reduced by about 50%
- A substantial fraction (50-95%) of the thermal energy is radiated

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R.S. Granetz, et. al., 2007

Gas Jet on ITER

Table 13. Parameters for a single-species ITER MGI system.

Value or requirement	Units	D_2	Ar	Basis or assumption
Sound speed (v_s)	$m\,s^{-1}$	935	320	300 K
Time to reach plasma surface	ms	3.1 (5.3)	9.4 (15.6)	3 m (5 m) to plasma; propagation at v_s
Additional delay	ms	2	2	Valve trigger and opening delay, etc
Minimum look-ahead time for pre-emptive action	ms	5.1 (7.3)	11.4 (17.6)	Sum of propagation and delay times, assumes deployment before natural TQ onset is required
N_{RB}	Atoms or molecules	1.75×10^{25}	1.94×10^{24}	To achieve $n_e = n_{RB}$, for 830 m^3 plasma volume, 100% assimilation
Delivery time (t_{del})	ms	9	9	$4^* t_{del} = t_{CQ} = 36$ ms; $t_{CQ}/S^* = 1.7\,ms\,m^{-2}$
Required average flow rate	s^{-1}	1.94×10^{27}	2.16×10^{26}	Assumes prompt rise
Required average flow rate	$Pa\,m^3\,s^{-1}$	7.2×10^6	8.0×10^5	Assumes prompt rise
Required average flow rate	$Torr\,L\,s^{-1}$	5.5×10^7	6.1×10^5	Assumes prompt rise

Delivery time needs to be 9ms – 1/4 the t_{CQ}

N_{RB} has to be ~10^{24} atoms to achieve n_e=n_{RB}

Minimum look-ahead time: 5.1 or 11.4 ms

T.C. Hender, et. al., 2007

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