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Disruption Scenarios, their Mitigation and Operation Window in ITER

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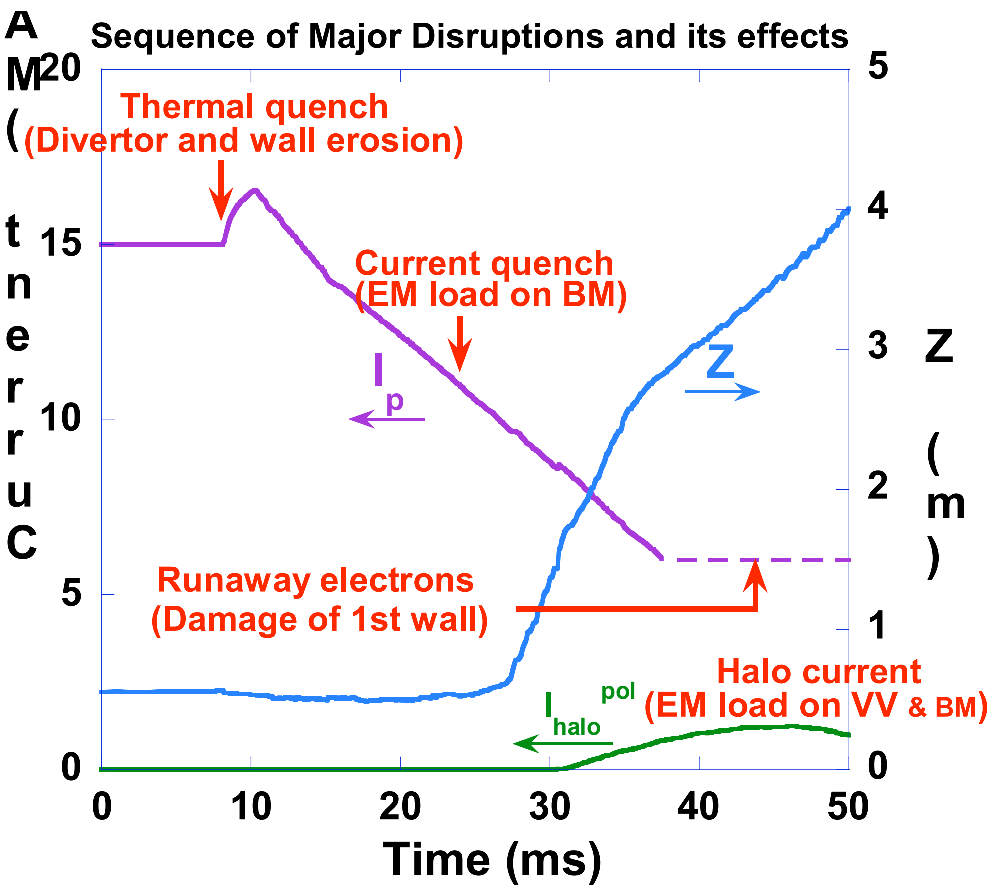
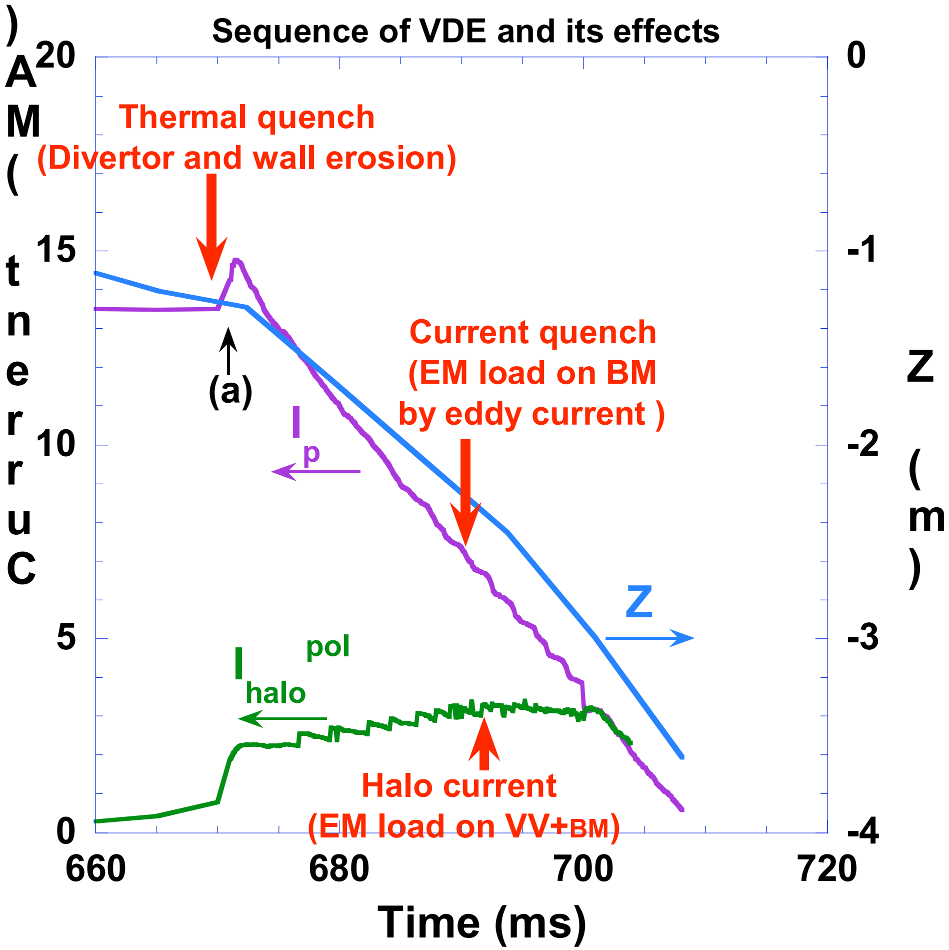
An extended version of this paper will be published by M. Sugihara et al. in Nuclear Fusion

Major disruption (MD) and Vertical Displacement Event (VDE)


Sequence of Major Disruptions and its effects


Sequence of VDE and its effects

Purpose and Outline

- Robustness of machine against various loads;
  - EM loads
  - Heat loads

  on in-vessel components and vacuum vessel during MDs and VDEs is essential for ITER to maintain wide operation window

- These loads are investigated to confirm the robustness using several representative disruption scenarios calculated with the DINA code based on the latest physics guidelines for
  - shortest current quench time [1-3]
  - maximum product of halo current fraction and toroidal peaking factor [1, 4-6]
  - energy deposition during vertical movement and thermal quench [7]

Robustness against EM loads

Representative disruption scenarios

- Fast current quench : VDE, Major Disruption (MD)
- Slow current quench : VDE (down & upward)

Note: VDE is a rare event

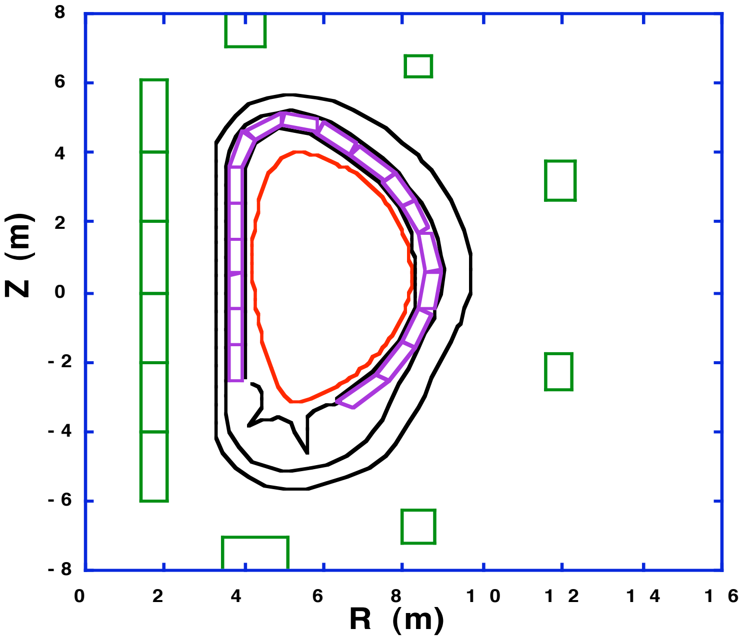
- failure of control
- break down of control system
- failure of mitigation system

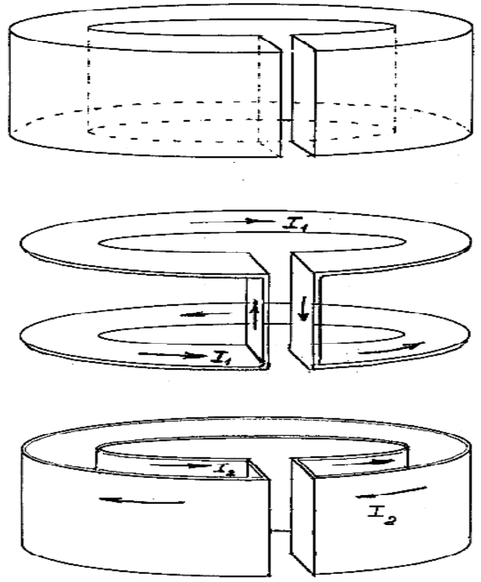
Origin of most severe EM load on each component

- Blanket & divertor : Eddy current + halo current
  (MD & VDE with fast current quench)
- Vacuum vessel : Halo current
  (VDE with slow current quench)

Disruption simulation by DINA code [8]

- 2D free boundary equilibrium calculation
- Transport and current diffusion in the plasma (1D averaged on flux surface) are solved
- Circuit equations for toroidal current in PF coils, vacuum vessel (modeled by a series of plates) and blanket (modeled by boxes with net toroidal current being forced zero;right lower figure)
- Divertor is not modeled yet

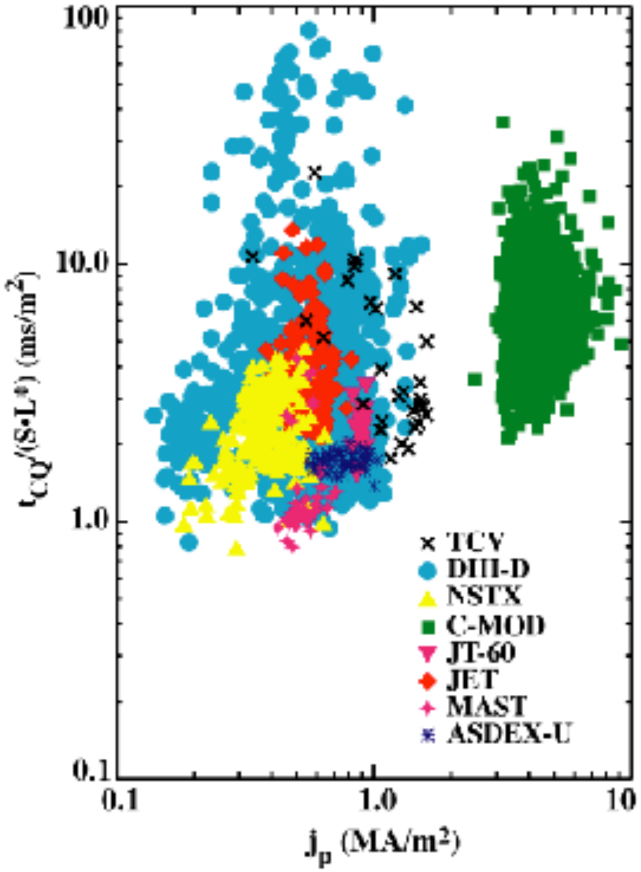




Physics guidelines for simulations

Representative scenarios Pysics guidelines	Major Disruptions (MD)	Down/upward VDE with fast and slow *Ip* quench
1. Current quench waveform and time (fast quench)	Linear *36 ms* and Exponential *16 ms* [2,3,9-11]	⇐
2. Thermal quench (T.Q.) time duration	Beta drop : *1 ms* [1] *j* flattening : ≈*3 ms*	⇐
3. Surface *q* value at T.Q.	*3*	*1.5 – 2* [12]
4. Beta drop during T.Q.	≈ *0.72 - 0.75*	≈ *0.75 - 0.4*
5. *li* change during T.Q.	*0.15 - 0.2*	⇐
6. $f_h \equiv (I_{h,max}/I_{p0}) \times TPF$ for VDE with slow current quench		*0.7* for downward VDE with slow quench

Revised physics guideline on current quench time has been recommended by ITPA MHD Topical Group



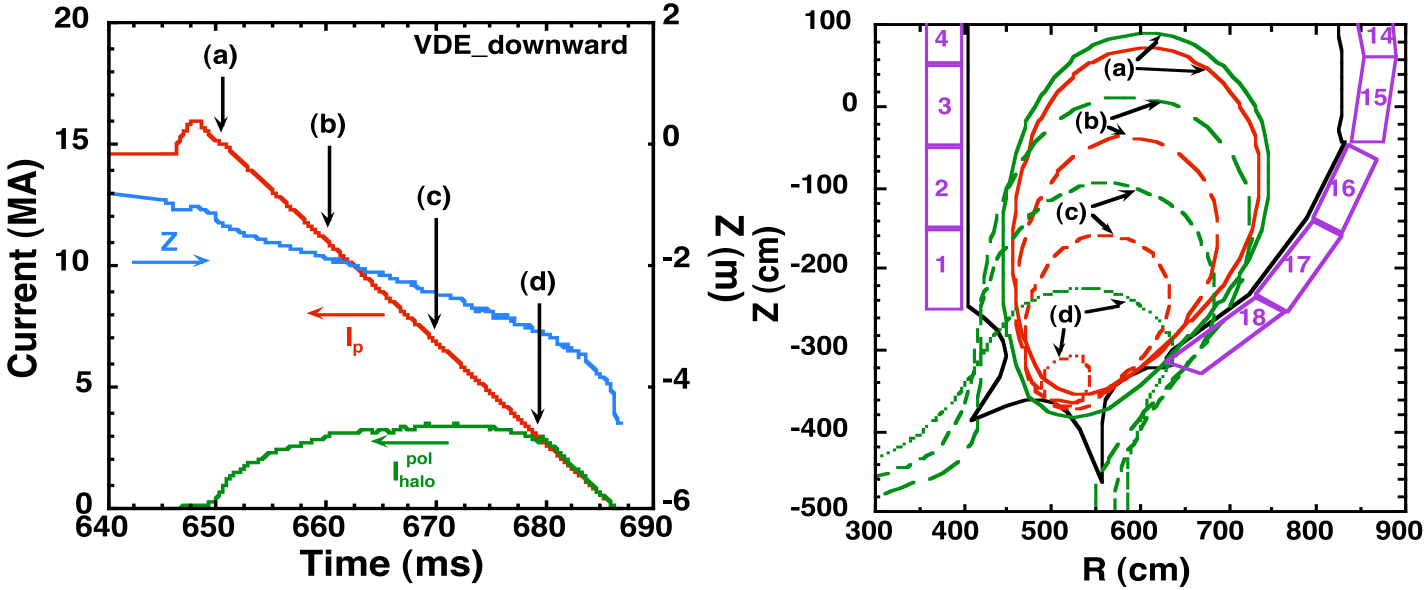
Note that there is a large range of values

For details,
J. Wesley et al., “Disruption Characterization and Database activities for ITER”, this conference, IT/P1-21

Calculation results

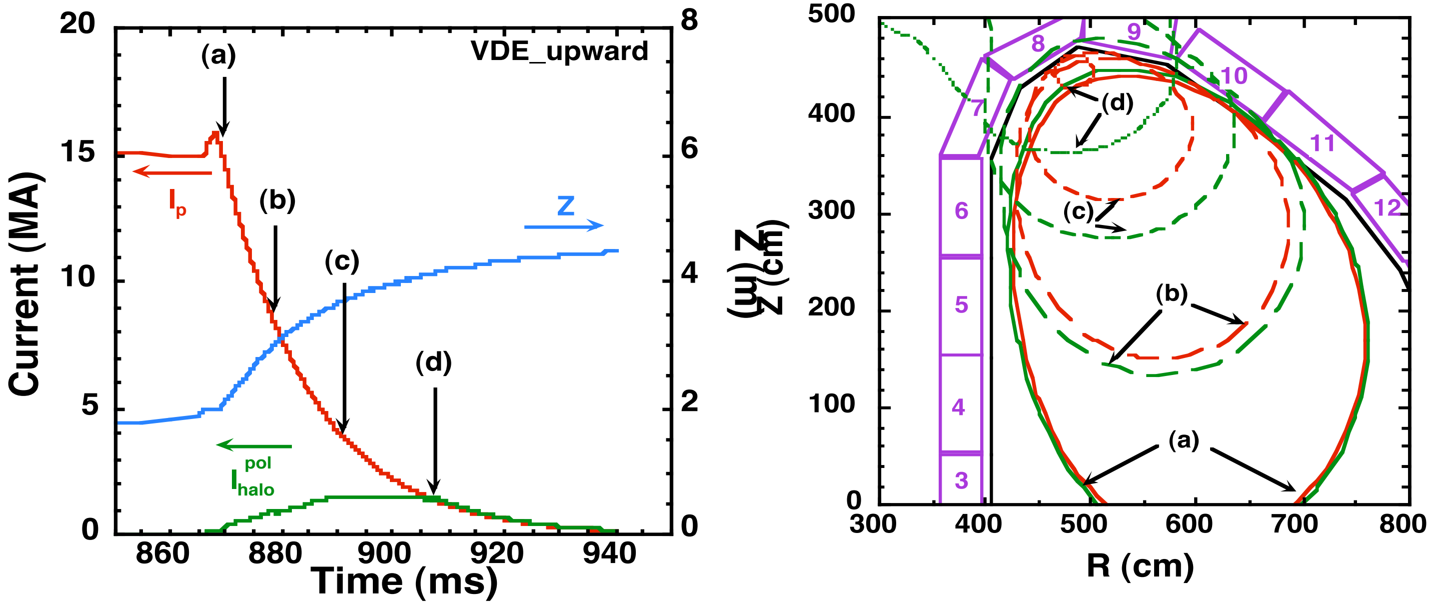
Downward VDE with fast quench

Linear waveform with *36 ms* full current decay time



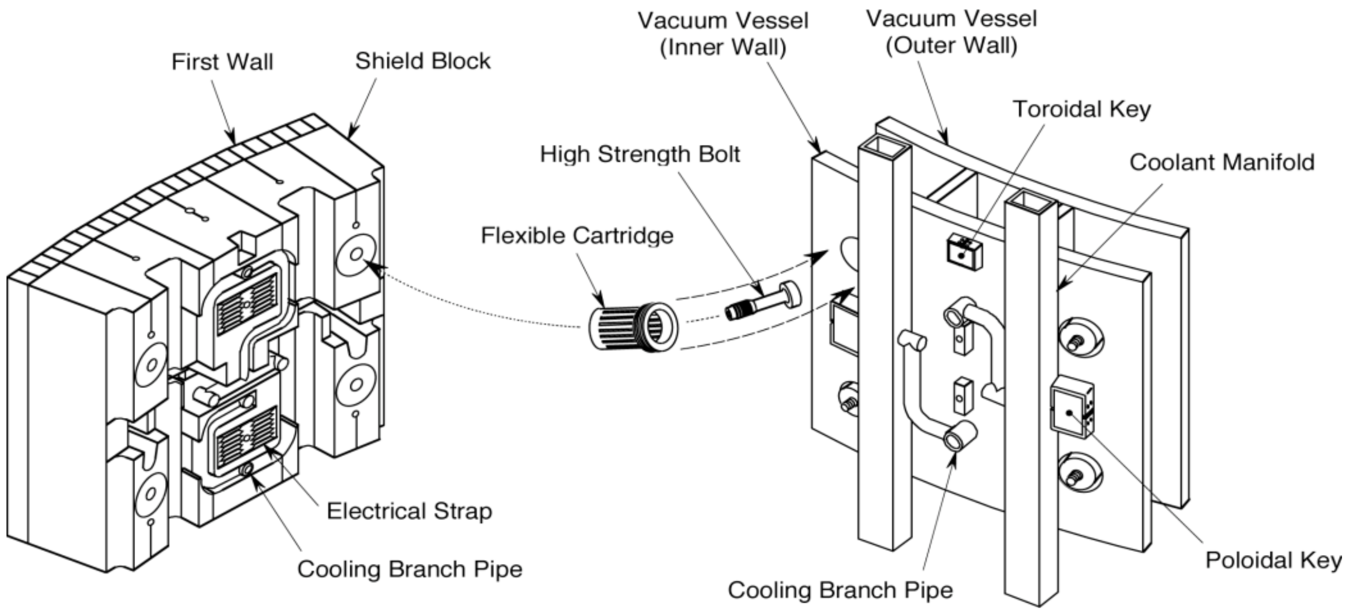
Upward VDE

Exponential decay waveform with *16 ms* time constant



Support of blanket modules on VV by

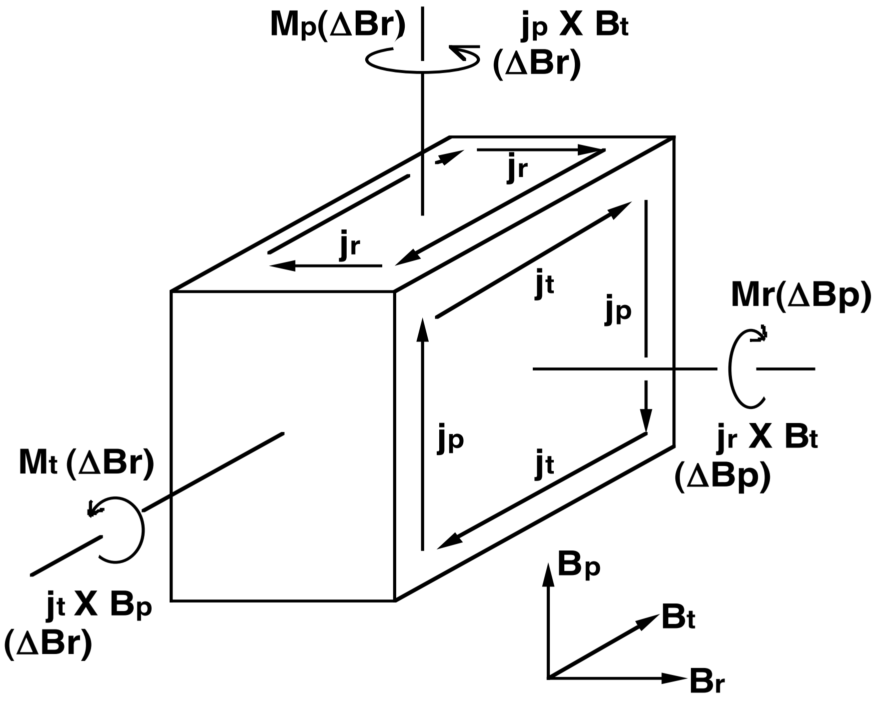
- Key for *Fp*
- Flexible joint for *Fr*



- **Moments *Mr, Mp, Mt* are calculated by FEM (induced eddy current)**
- **Force on each module**

  $Fp \Leftarrow Mr + (Fp \text{ by halo})$

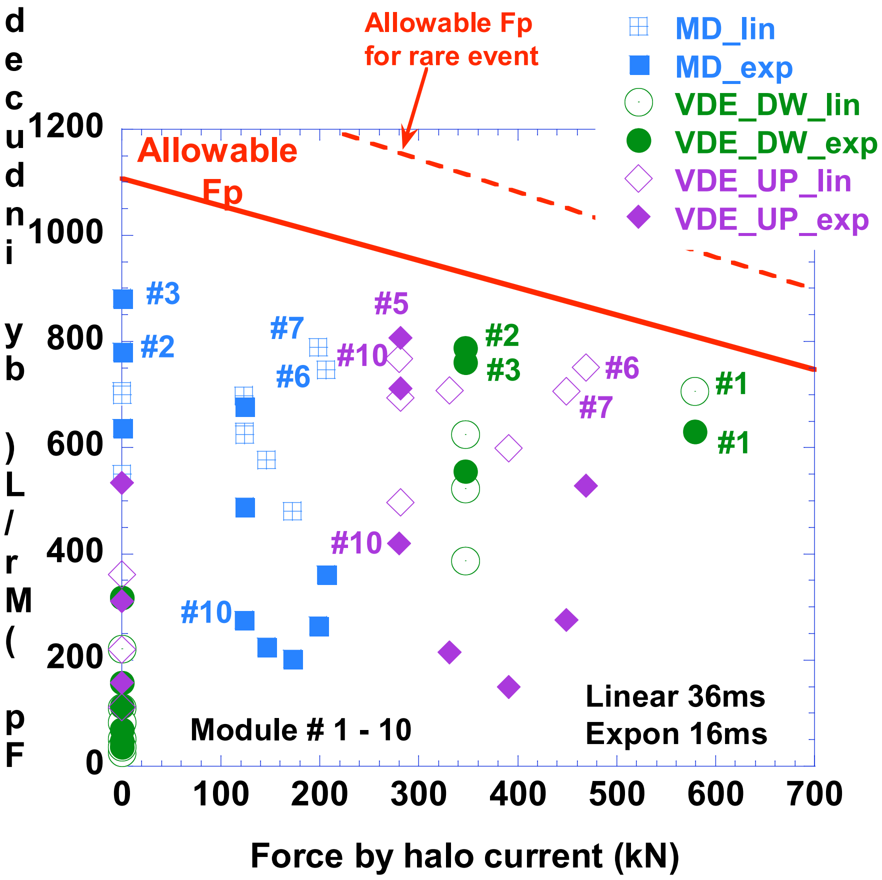
  $Fr \Leftarrow Mp + Mt$

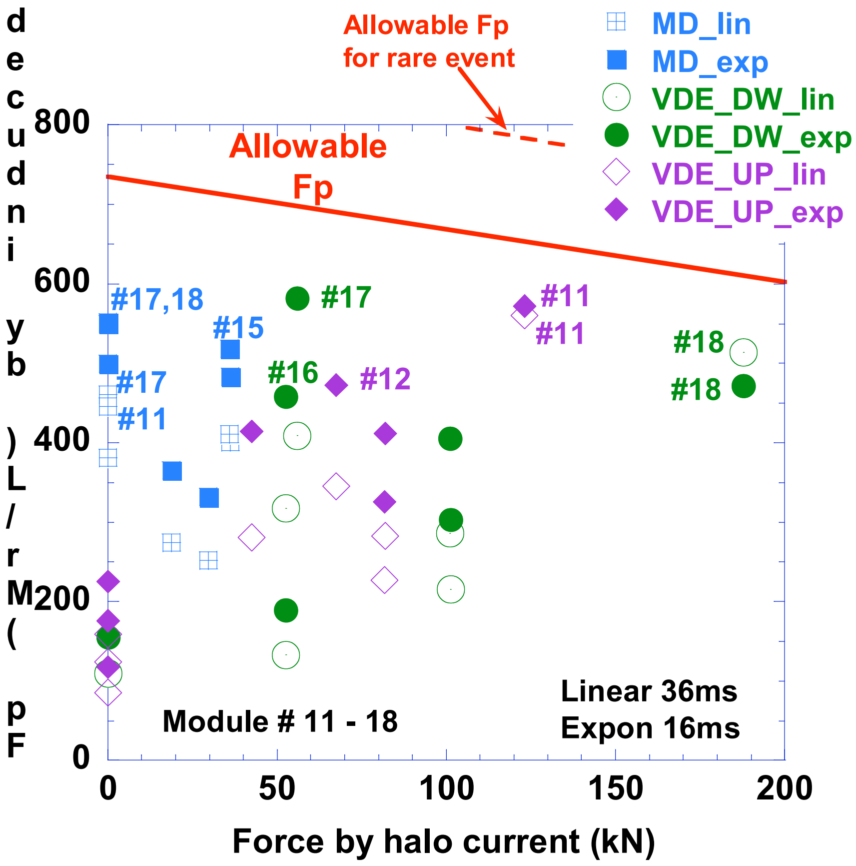


Force on Key

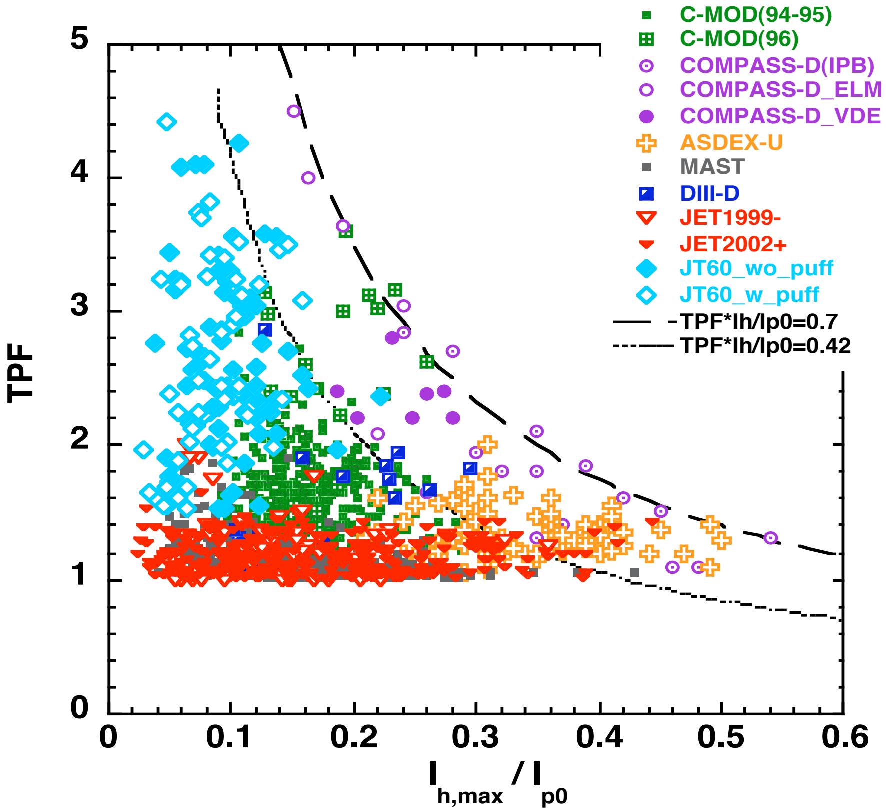
- Force by eddy current is dominant but force by halo is also significant for the peak force

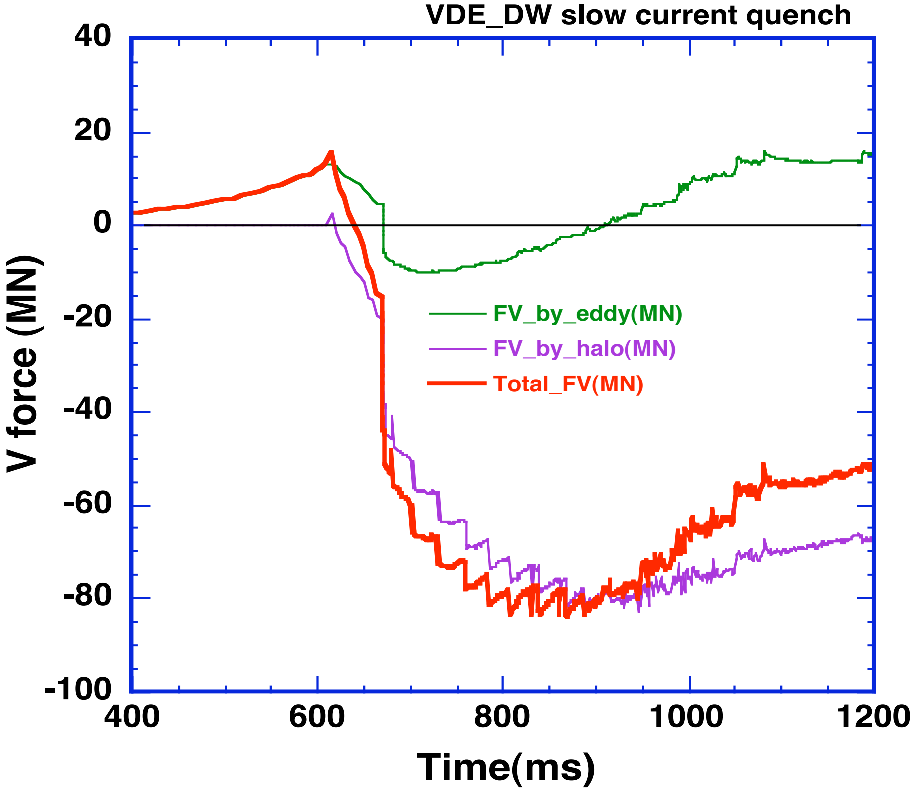
- EM loads are within the allowable limit for all these representative scenarios, but the margins are not very large





Vertical Force on VV by Downward VDE with Slow Ip Quench





- *TPF×Ih,max/Ip0 < 0.7* for most of the machines
  - *TPF×Ih,max/Ip0≈0.7*
  - *Ih,max/Ip0 ≈ 0.44*
  - *TPF ≈ 1.6*

- V force by eddy current slightly increases total V force
- The total force is marginally within the design limit

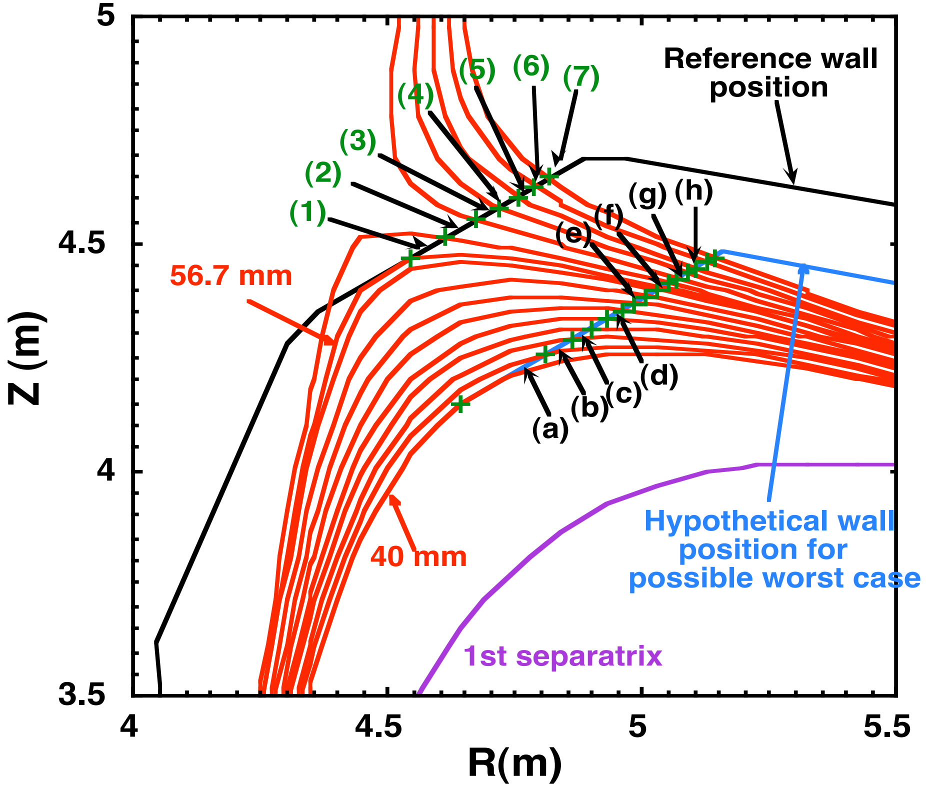
Heat Load on PFC during Vertical Movement and TQ for MDs and VDEs

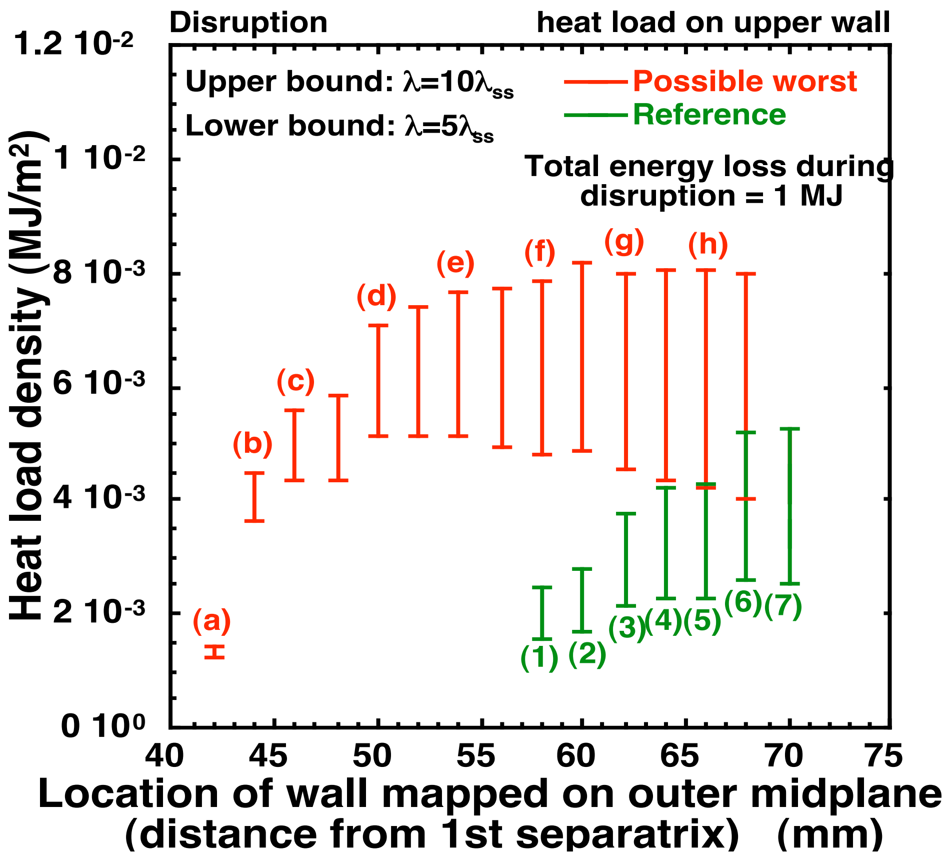
- Assessment of melt layer thickness of beryllium first wall and tungsten baffle due to TQ for MDs and plasma contact during vertical movement and TQ thereafter for VDEs.
- Criterion for melting $\varepsilon\ (MJ/m^2/\ s^{1/2}) \approx 20$ for Be
  60 for W
- Database of heat load during the TQ is very limited. Most systematic database so far available is in [7].

Energy release at TQ (relative to peak stored energy W_{peak})	$(0.5\text{-}1.0)W_{peak}$
Expansion factor of heat load width from the steady heat load width λss	*5-10*
Time duration of heat deposition on divertor/wall	*(1.5-3) ms*

Heat Load during Major Disruptions

- Largest heat load on the beryllium first wall is that on the upper wall, since half of the heat flux across the second separatrix
- Range of *8.2-75 $MJ/m^2/s^{1/2}$* for deposition time duration of *1.5-3 ms* =>melting of Be is expected in many MD cases.





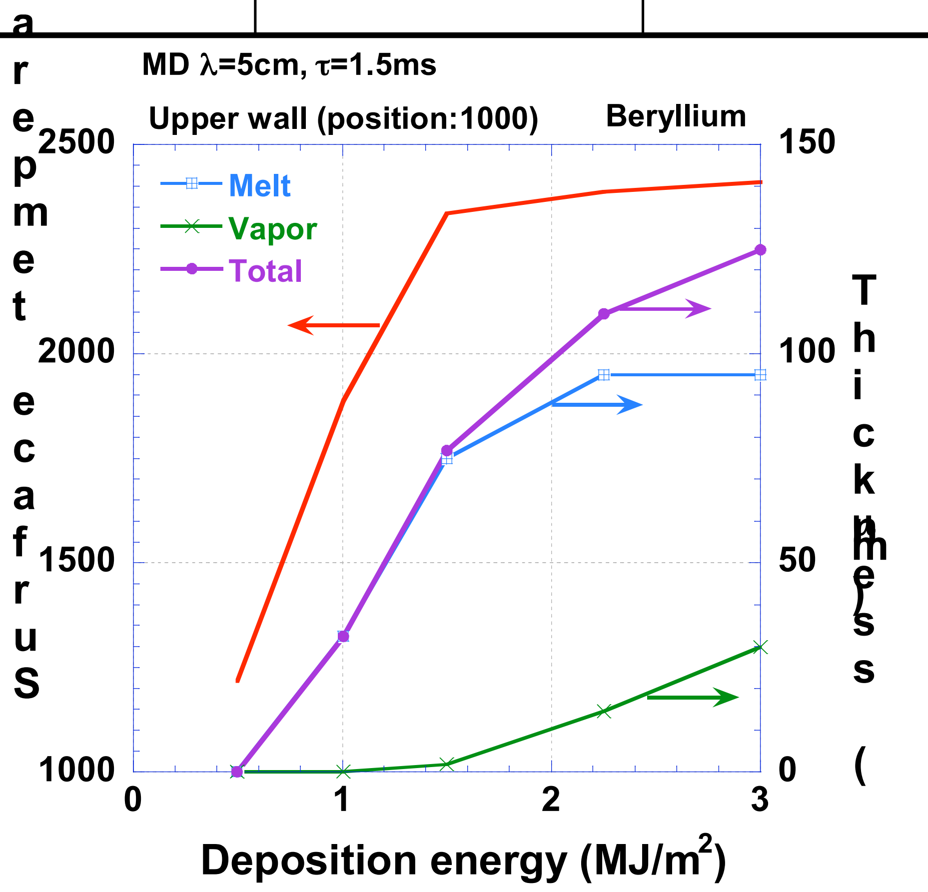
Energy loss / disruption Case and peak location	*175 MJ*	*350 MJ*
Reference : peak location (6) – (8) *(MJ/ m^2)*	*0.45 - 0.92*	*0.9 - 1.84*
Possible worst : peak location (f) - (g) *(MJ/ m^2)*	*0.9 - 1.44*	*1.8 - 2.9*

Heat conduction calculations

- Loss of Be thickness for most likely MDs with somewhat reduced stored energy and reference case

  ≈30 μm/event for 1MJ/m^2

  even if whole melt layer is lost



- **Mitigation by e.g., massive gas injection [13] is very effective at increasing the lifetime of Be first wall, but**

- **Several tens of unmitigated TQs must be expected out of ≈*3000* MDs (≈10 % of $3x10^4$ total shots) in ITER.**

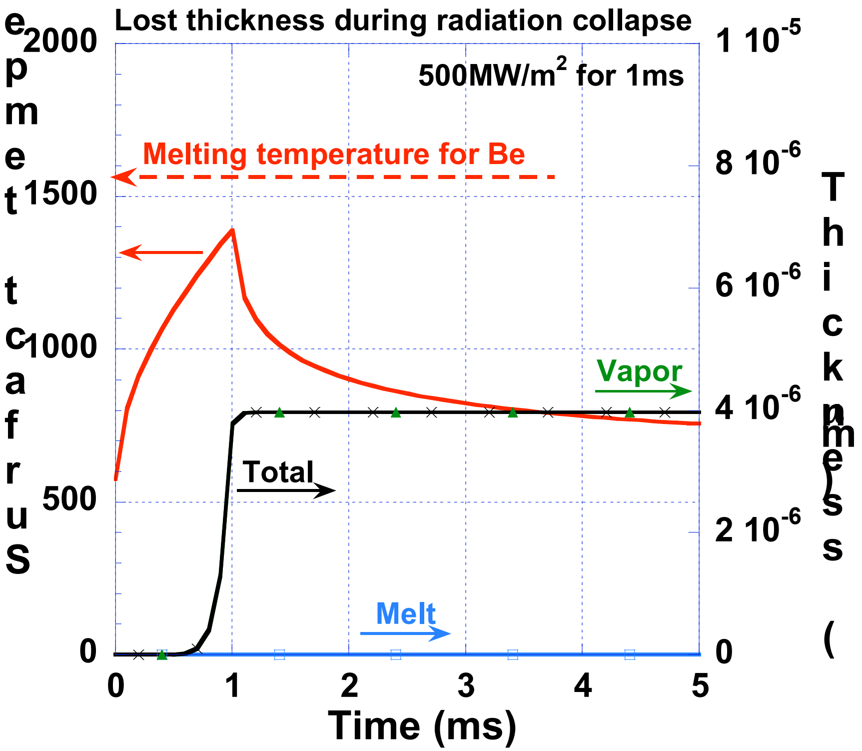
- **Missed rate of prediction > a few *%* even with the most advanced algorithm of neural network [14].**
  In particular, for high beta plasmas, the missed rate is further increased up to ≈*20%* [15, 16].

Beryllium would not melt during mitigation if
- radiation is not strongly toroidally peaked
- radiation duration ≈1ms

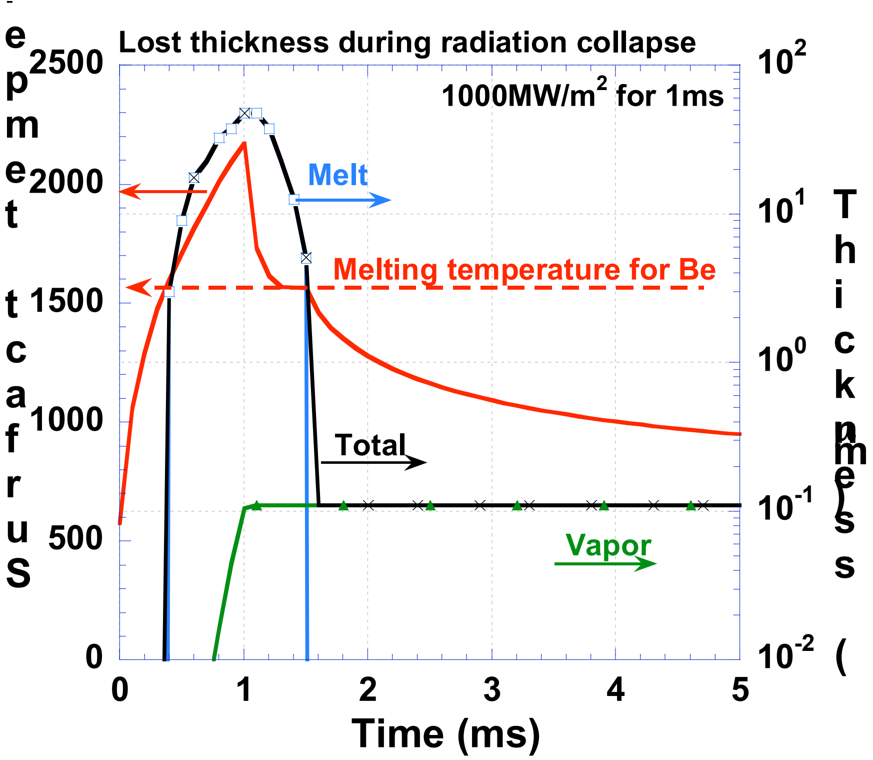
Heat conduction calculation

Radiation duration=1ms, Total energy radiated=350MJ

Uniform



Factor of 2 peaking



Heat Load during VDEs

Heat load due to hot plasma touching the wall during the vertical movement

Assumptions

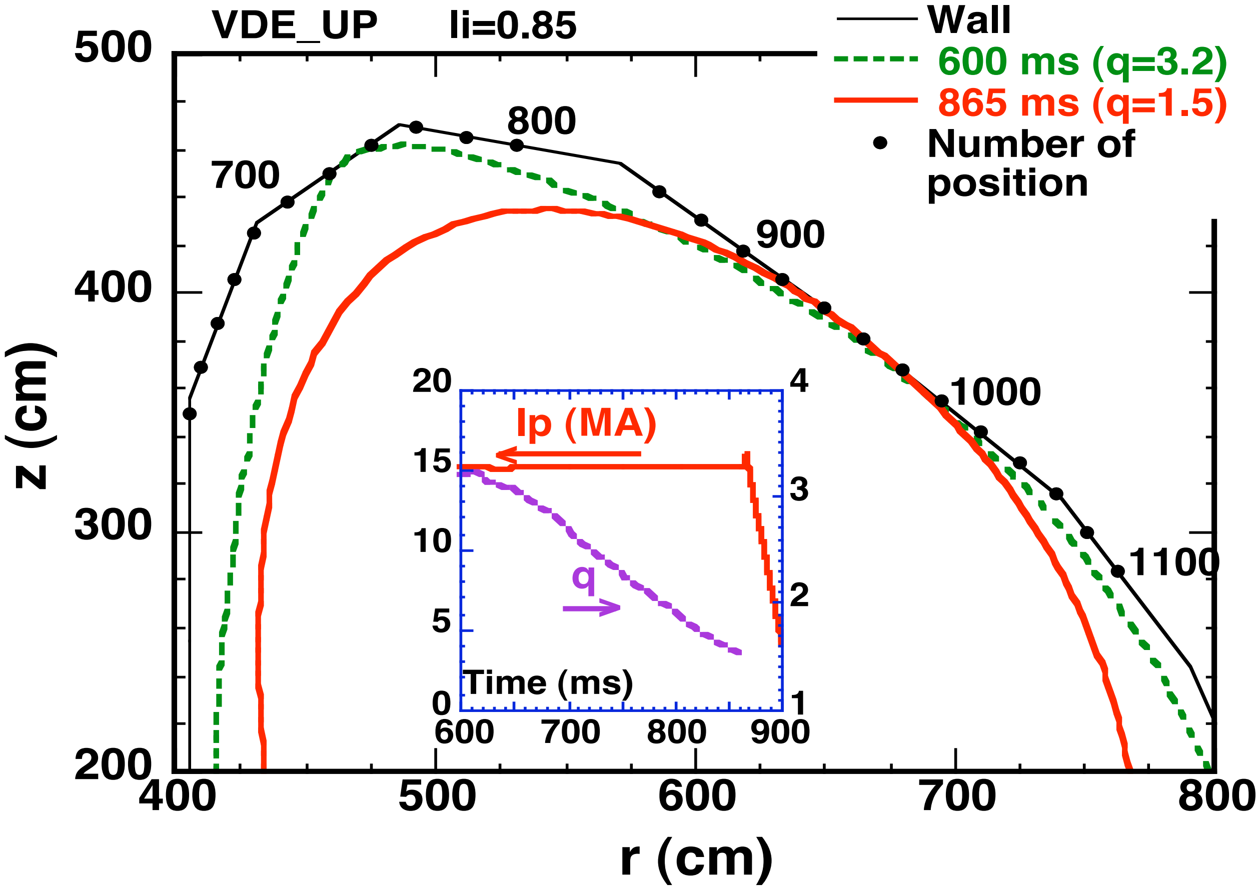
- **After touching the wall, plasma transits back to the L mode and the heat flow across the LCFS is *200 MW* (more than twice of the H mode phase)**
- **λ_{ss} is assumed wider than that of H mode phase, and thus, ≈*1 cm* is assumed as a typical value**

Heat load due to TQ at some moment during plasma vertical movement

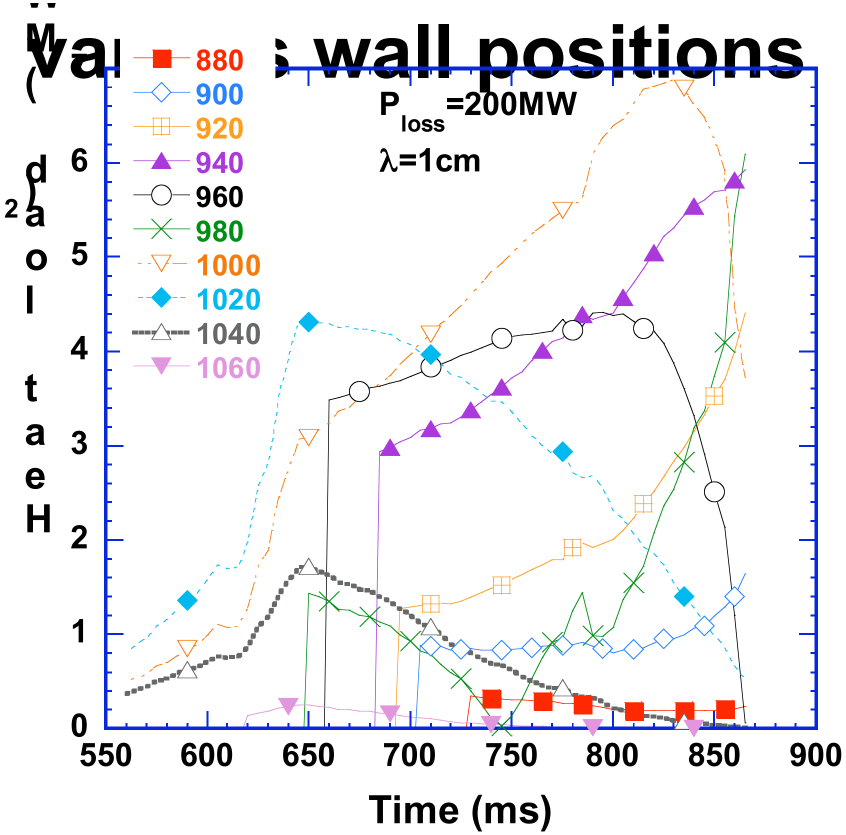
Same assumptions for MDs

Upward VDEs

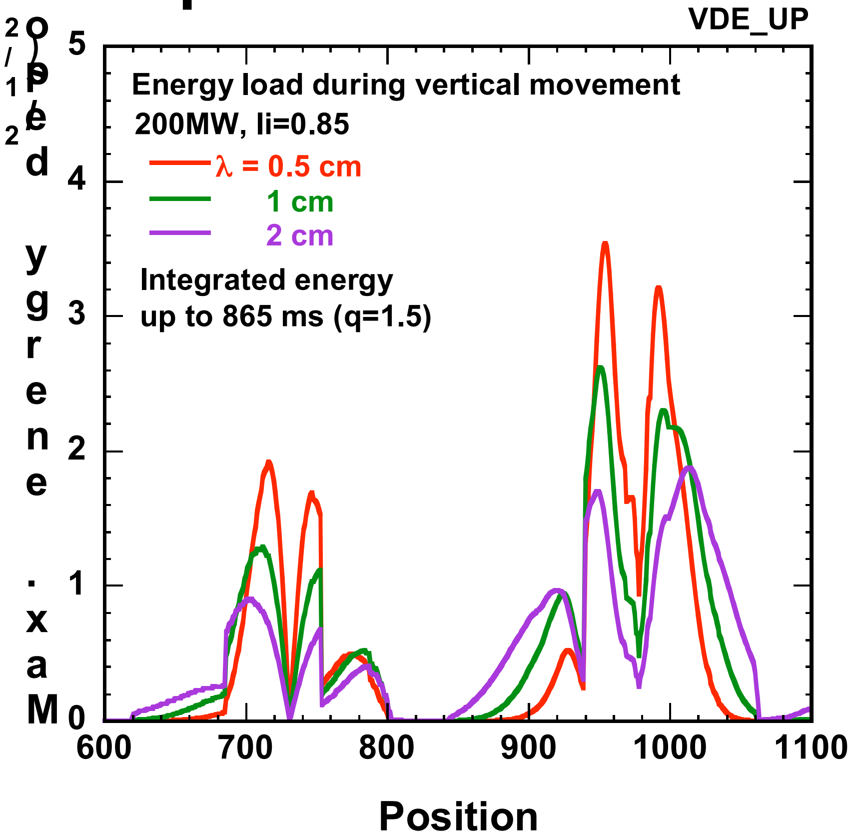
Equilibrium configurations during upward vertical movement :
- at *600 ms* (early phase of plasma touching upper wall)
- at *865 ms* (just before TQ at *q=1.5*).



Waveform of heat load on various wall positions



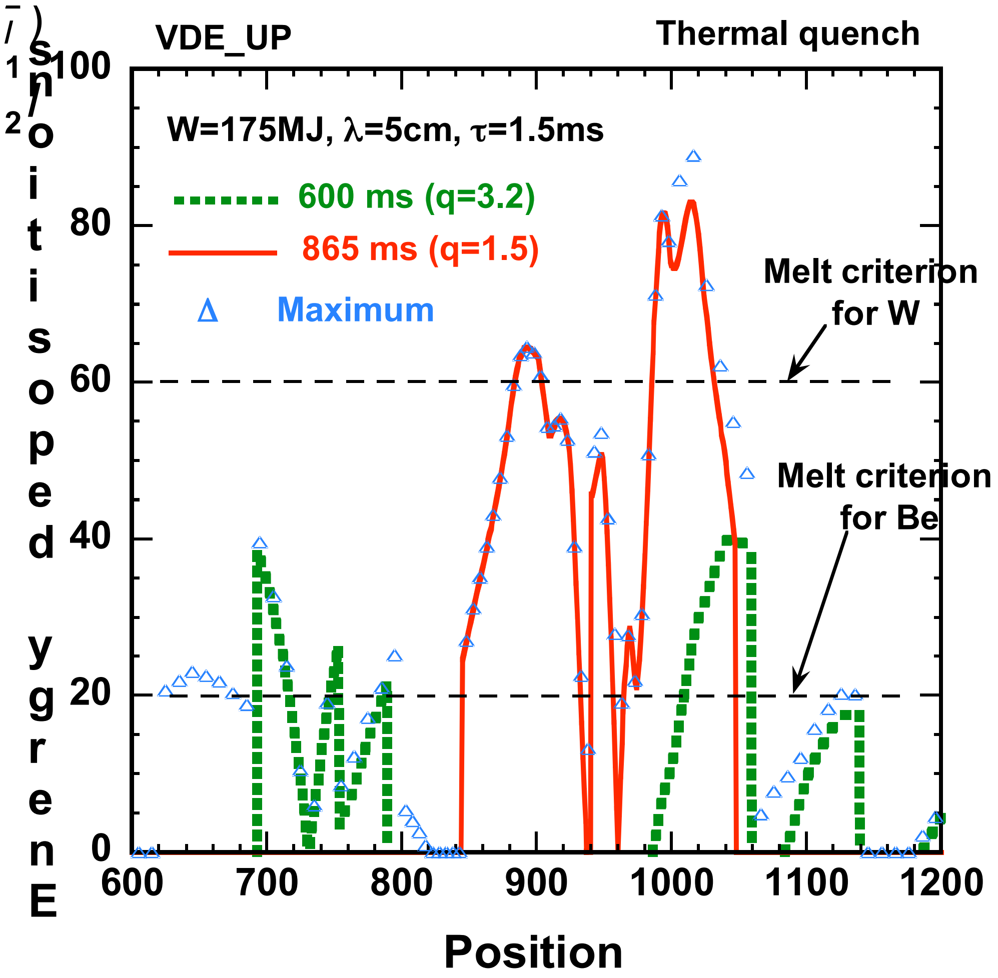
Integration of each waveform for heat load (ε) on various wall positions

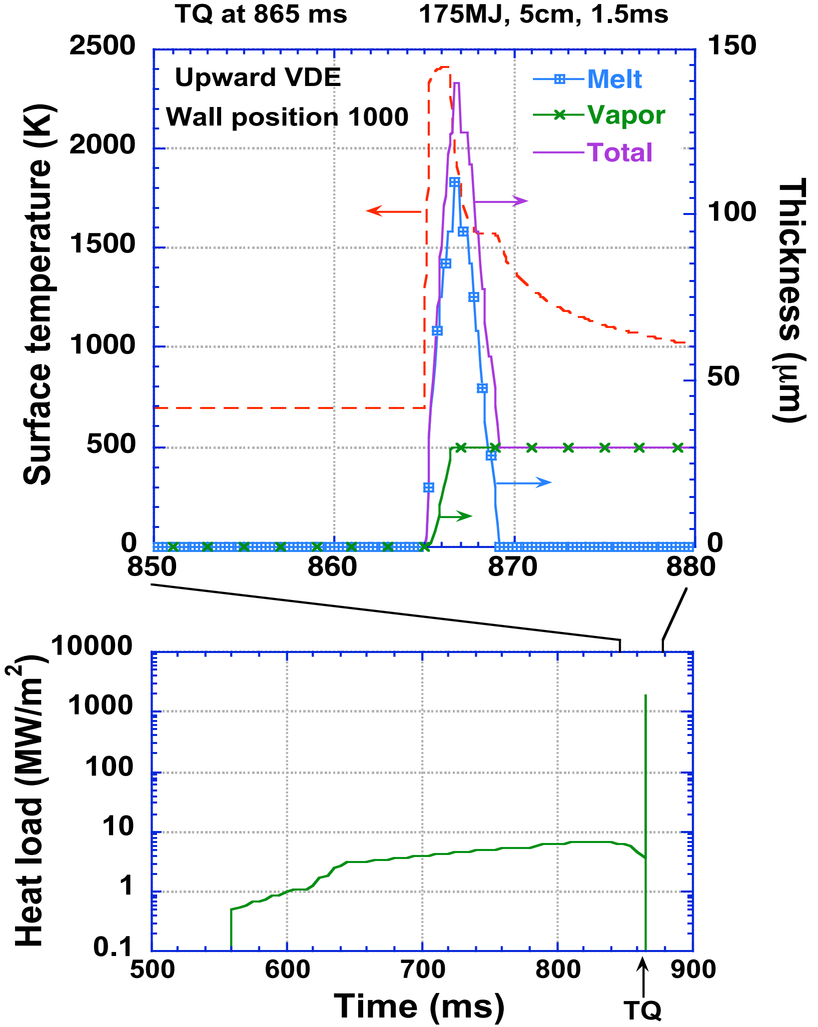


Peak values of ε are significantly smaller than critical value for melting even for smallest $\lambda ss=0.5$ cm

==> Melting of Be will not occur during vertical movement phase

Heat load by TQ during upward vertical movement



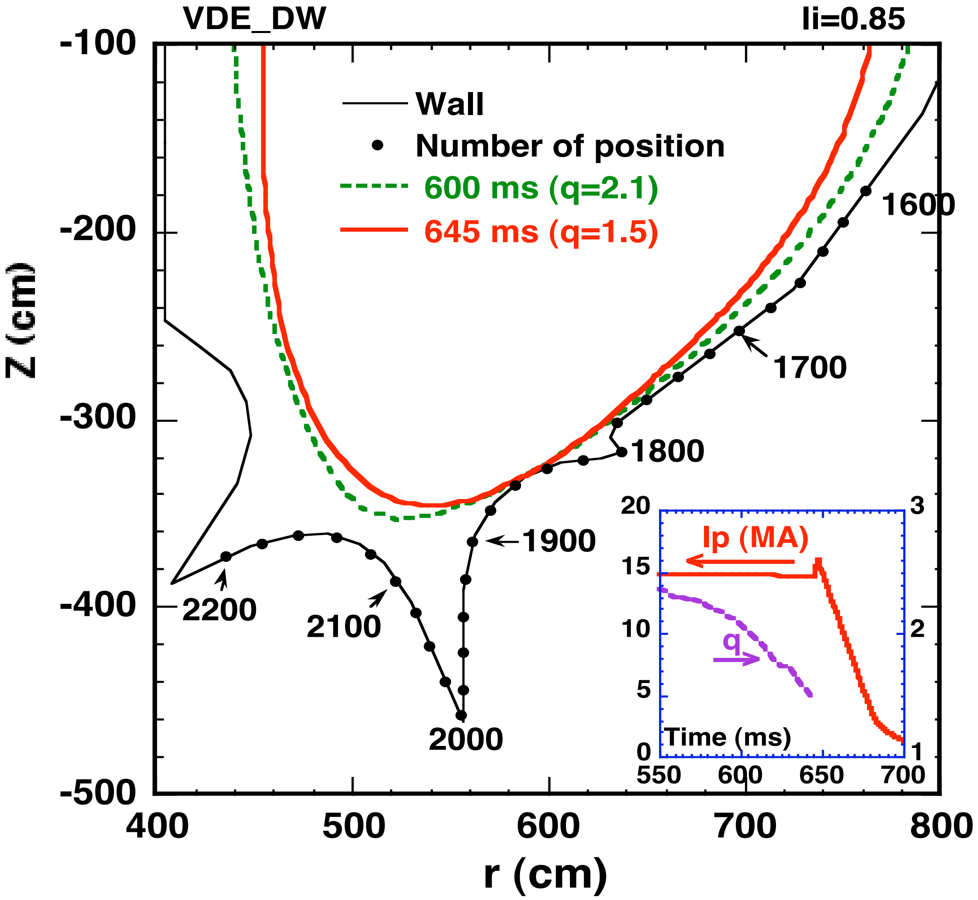


- Wide region of the wall receives the heat in the early phase but ε exceeds the critical value in limited regions.
- In the later phase, ε significantly exceeds the critical value in some regions; loss of $\approx$*100 μm/*event

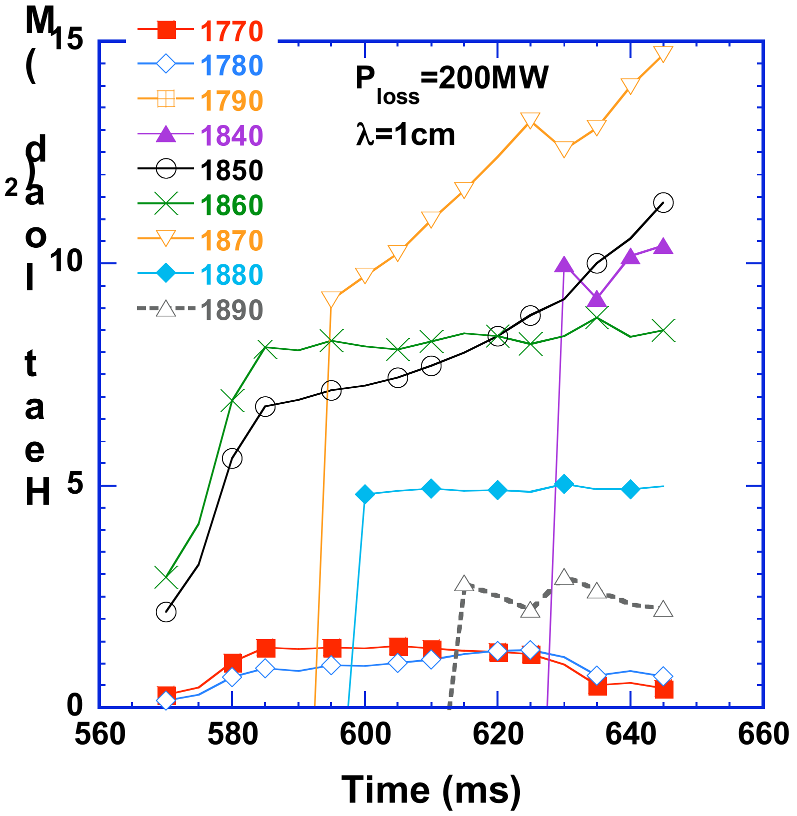
Downward VDEs

Equilibrium configurations during downward vertical movement :

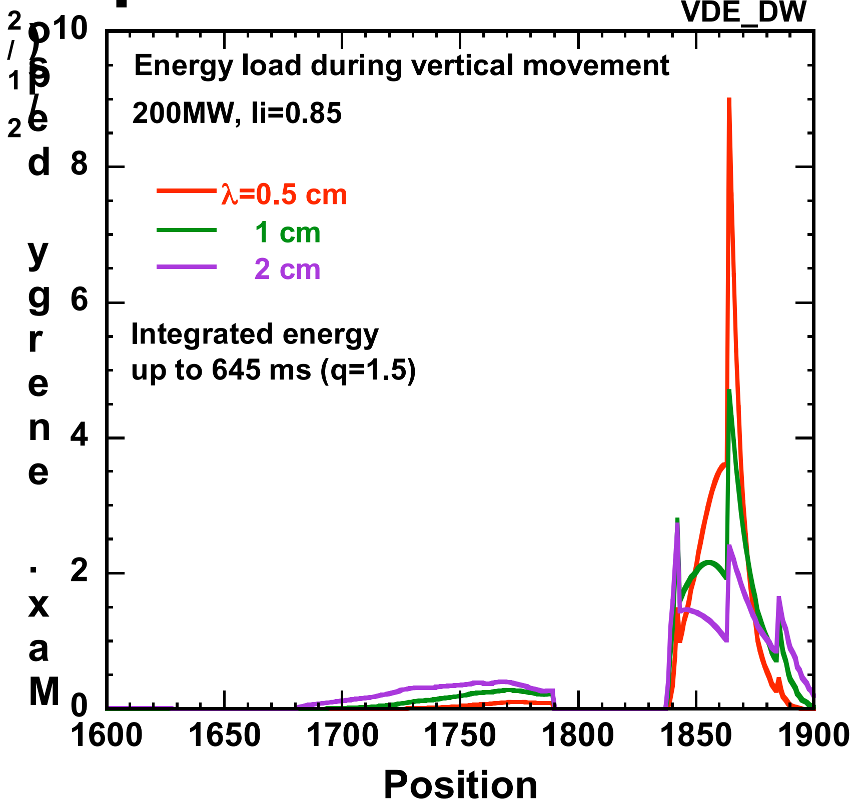
- **at *600 ms* (early phase of plasma touching upper wall)**
- **at *645 ms* (just before TQ at *q=1.5*).**



Waveform of heat load on various wall positions



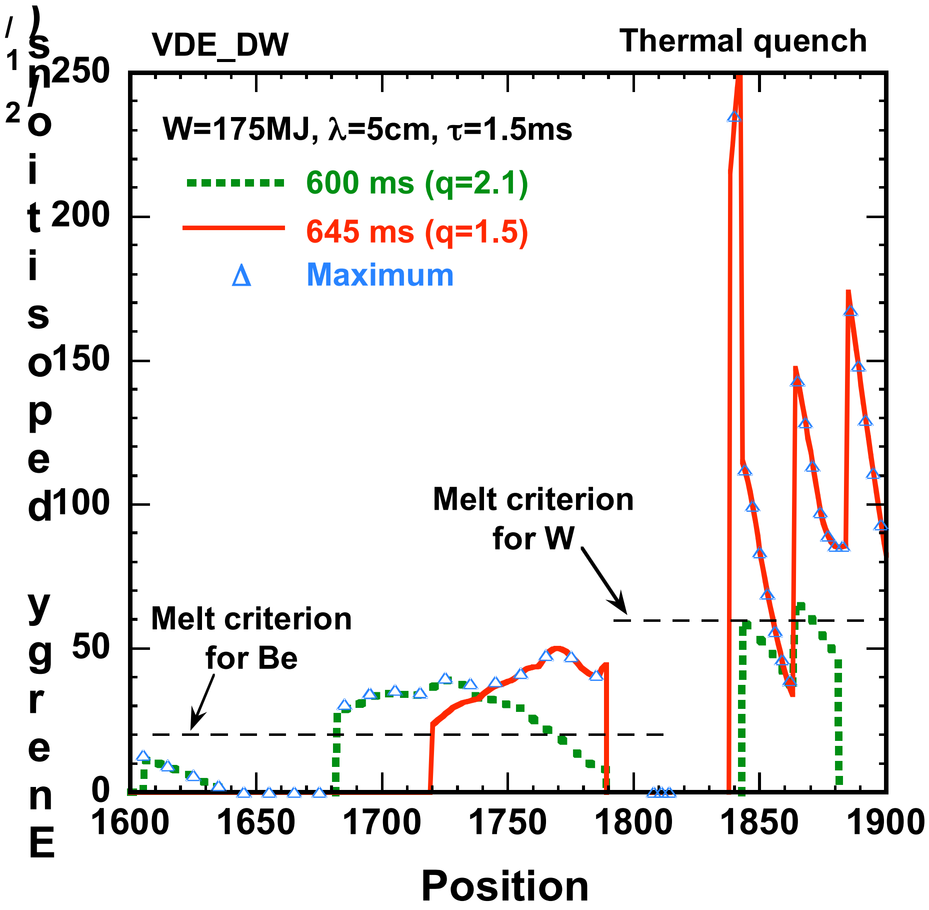
Integration of each waveform for heat load (ε) on various wall positions

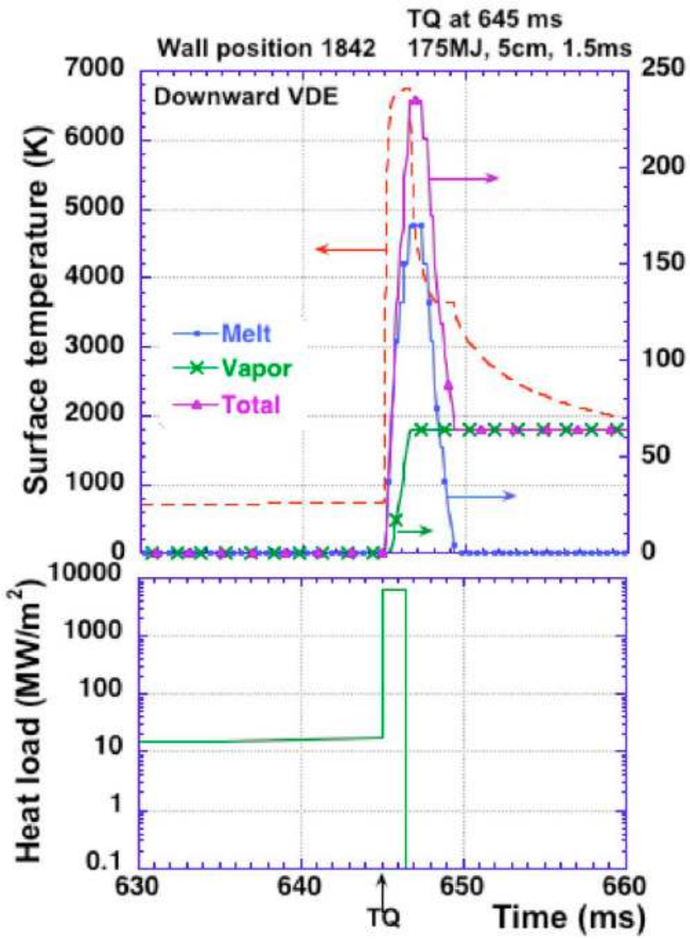


Peak values of ε are significantly smaller than critical value for melting even for smallest *λss=0.5 cm*

==> Melting of W and Be will not occur during vertical movement phase

Heat load by TQ during downward vertical movement





- ε exceeds the critical value, but somewhat smaller on Be first wall than upward VDE case.
- ε significantly exceeds the critical value (*60 MJ/m^2/s$^{1/2}$* for tungsten baffle region), and the loss of W baffle is *≈200 μm*/event.

Conclusions

- **Several representative disruption scenarios are specified and disruption simulations are performed with the DINA code and EM load analyses with a 3D FEM code for these scenarios based on newly derived physics guidelines for the shortest current quench time and their waveforms ($\Delta t \approx 36\ ms$ linear and $\tau \approx 16\ ms$ exponential waveforms), as well as the maximum product of halo current fraction and toroidal peaking factor (maximum $f_h \approx 0.7$) expected in ITER.**

- **Some margins are confirmed in the EM loads on the in-vessel components for all of the representative scenarios, further efforts both from the physics and engineering sides are needed to enlarge the margins.**

- **Heat load on various parts of the first wall due to vertical movements and TQs is calculated based on the database of heat deposition during disruptions and simulation results with the DINA code. It is concluded that melting of Be wall will not occur during the vertical movement. Melting is anticipated at TQ during VDE.**

- **Its impact could be reduced substantially by implementing a reliable detection and mitigation system, e.g., massive gas injection. Latest experiments show that radiative heat load on the first wall due to the massive gas injection will not be so localized and ε is marginally below the critical value for melting [17].**

- **More severe melting is anticipated due to MDs, for which at least several tens of unmitigated disruptions must be considered even if an advanced prediction/mitigation system is implemented. With these unmitigated MDs, the loss of Be layer is expected to be $\approx$*30 μm*/event.**

Summary

	Major Disruption (MD)	Vertical Displacement Event (VDE)
Cause; frequency	Tearing mode, kink mode, etc.; ~10 %	Loss of vertical control (failure in power supply or diagnostics); Very rare
Prediction/detection	~97-98 % (80 % @ high β_N) with neural network	Very high reliability (the motion is slow: ~0.5 s)
Consequence	Halo+eddy current, heat load, runaway electron	
Electromagnetic force	Within allowable limit, but the margin is not large	
Melting at thermal quench @175 MJ	~ 30 μm at first wall	~ 200 μm at tungsten baffle
# of unmitigated events (30,000 discharges) (goal)	~ 80 – 300	<10

Highly reliable system for disruption prediction/mitigation/ avoidance is essential for high availability of ITER

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