Plans & issues for MHD control in ITER

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On behalf of ITER International Team

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Outline

- **Disruption analysis**
- **ELM control considerations**

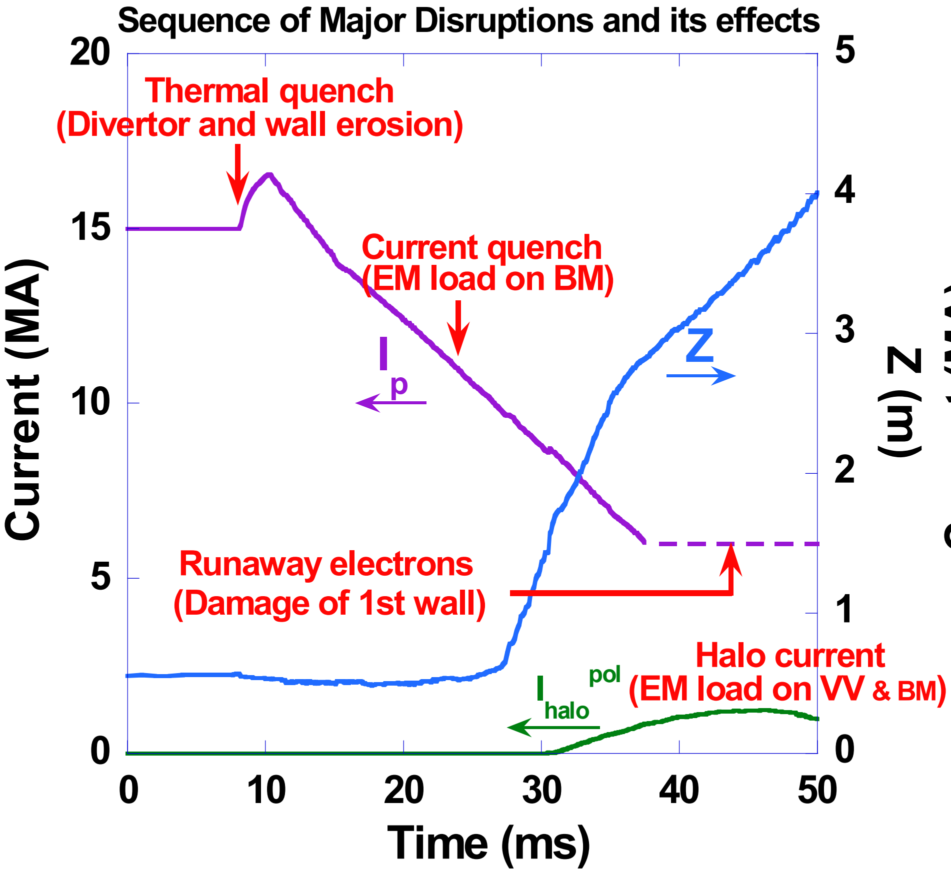
- Basic magnetic control* (CSD**)
- Error field correction (CSD**)
- NTM control (Zohm talk)
- RWM control (Navratil talk)

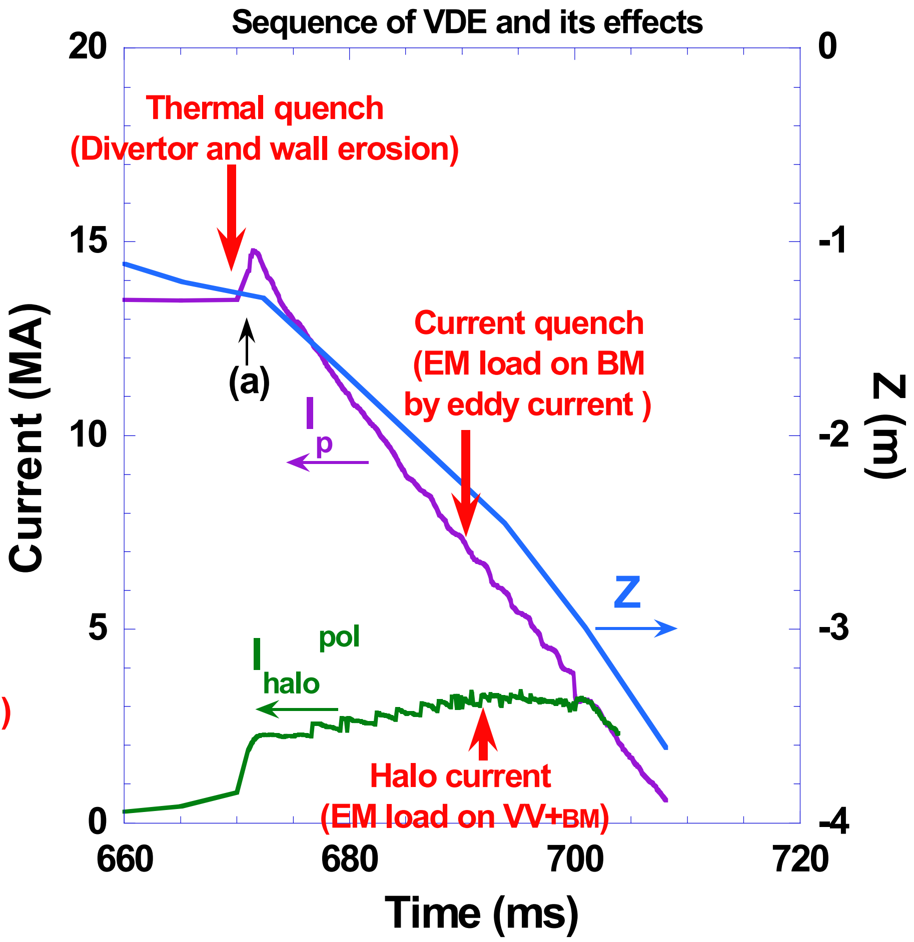
* Progress is being made in the start-up studies

** Control System Assessment and Design (CSD)

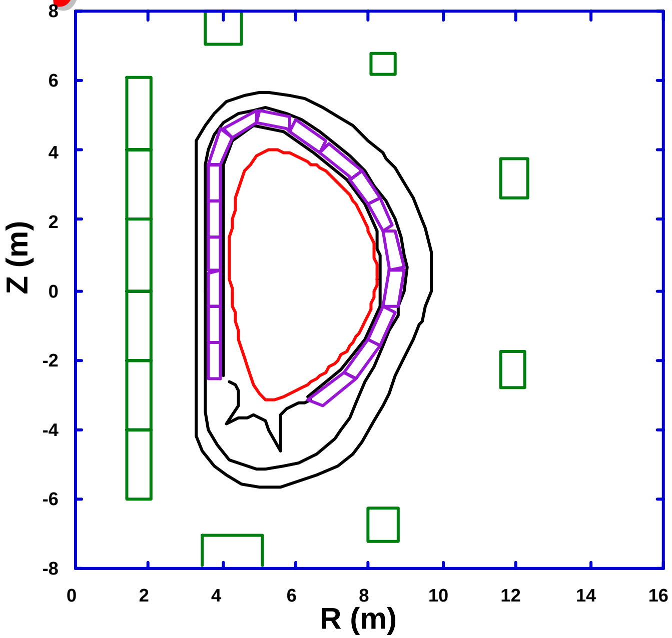
Disruption analysis

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

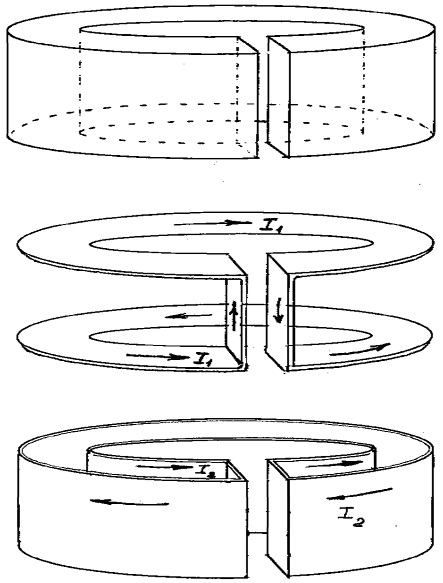

Sequence of Major Disruptions and its effects


Sequence of VDE and its effects

Disruption simulation by DINA code



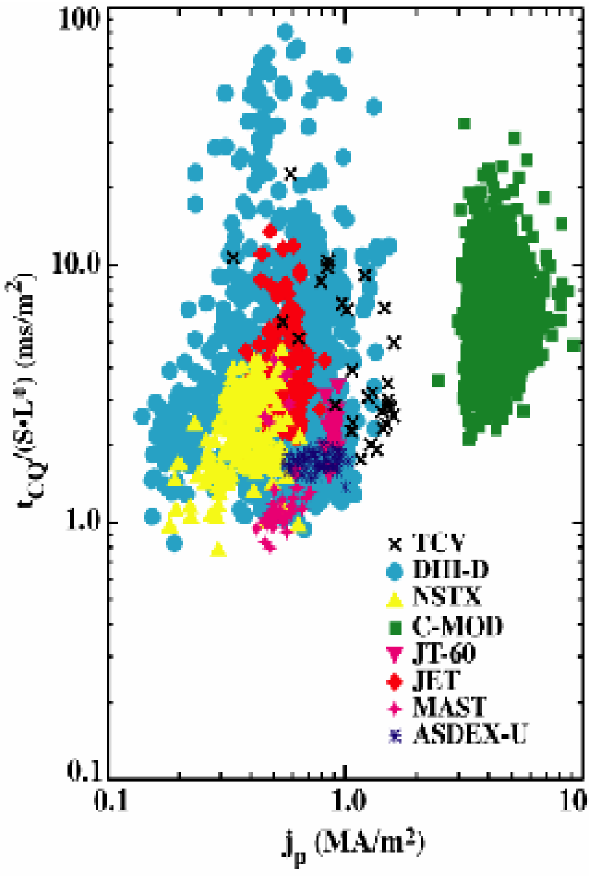
- 2D free boundary equilibrium calculation
- Transport and current diffusion in the plasma (1D averaged on flux surface) are solved
- Circuit equations for toroidal current in PF coils, vacuum vessel (modeled by a series of plates) and blanket (modeled by boxes with net toroidal current being forced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



Physics guidelines for simulations

Representative scenarios Physics guidelines	Major Disruptions (MD)	Down/upward VDE with fast and slow *Ip* quench
1. Current quench (CQ) 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 CQ		*0.7* for downward VDE with slow quench

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



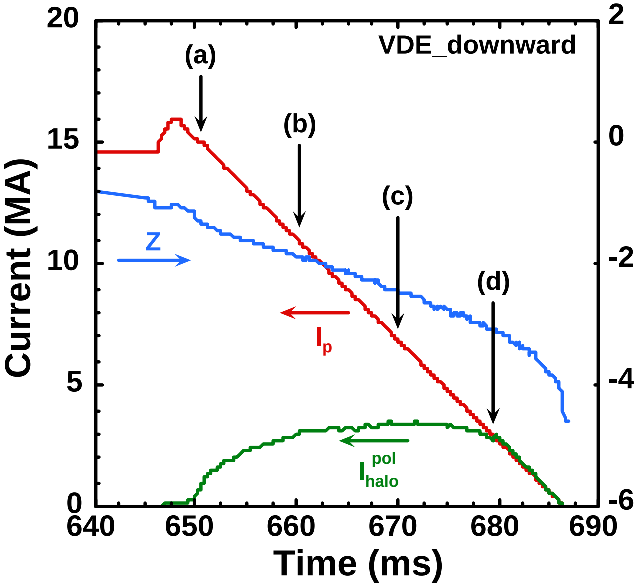
Note that there is a large range of values

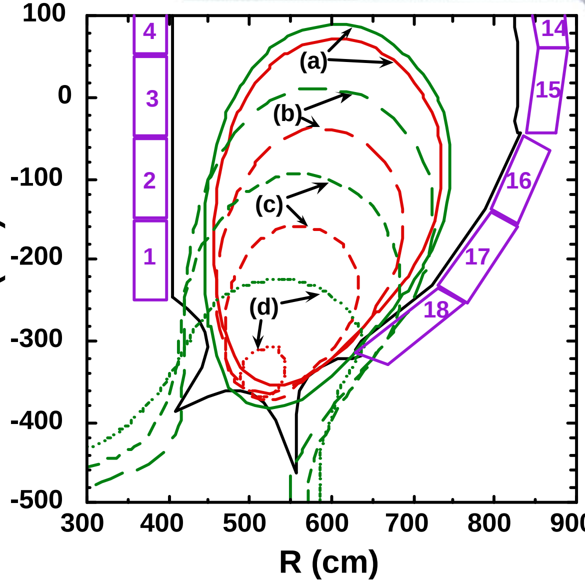
For details,
J. Wesley et al., “Disruption Characterization and Database activities for ITER”, IAEA FEC 2006, IT/P1-21

Calculation results

Downward VDE with fast quench

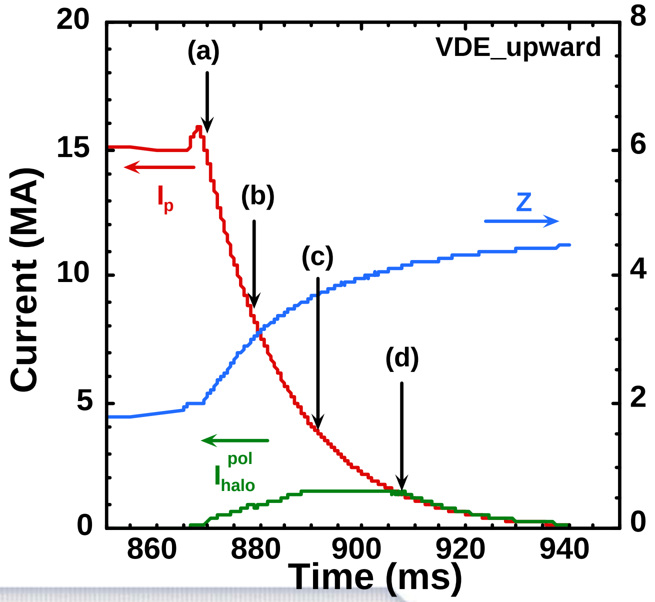
Linear waveform with *36 ms* full current decay time

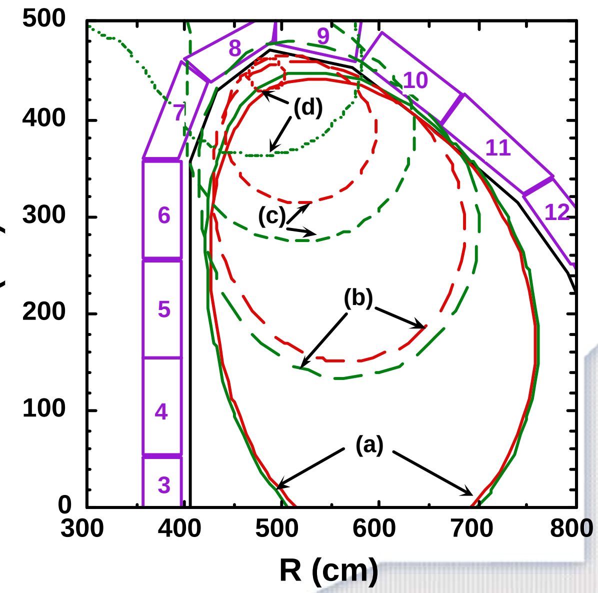




Upward VDE

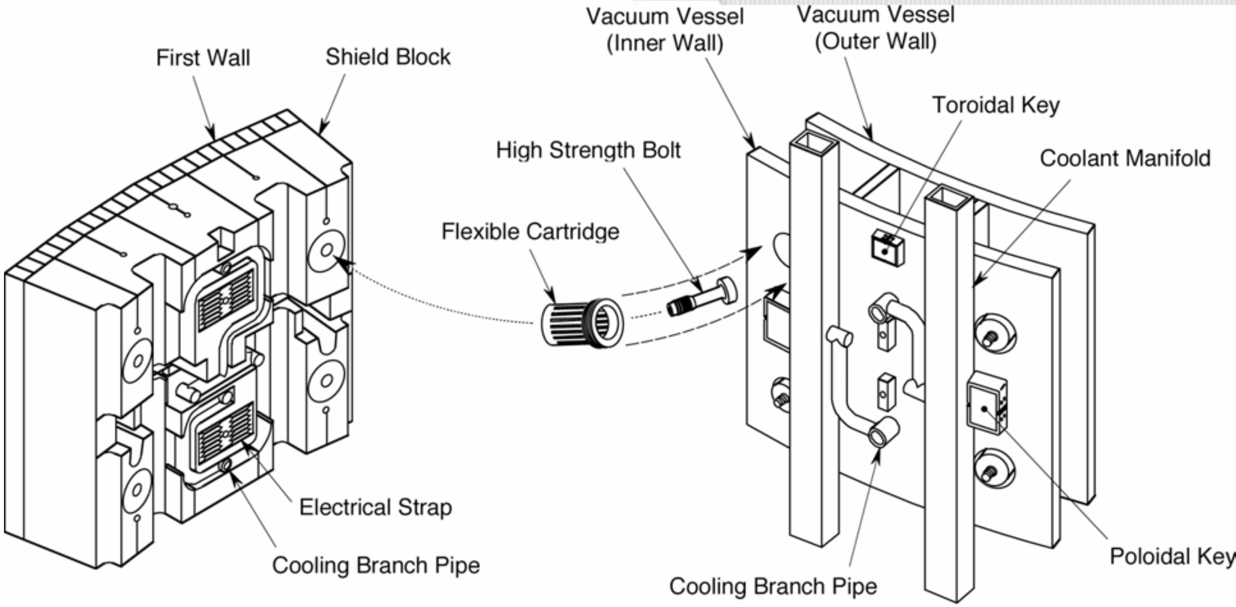
Exponential decay waveform with *16 ms* time constant





Support of blanket modules on VV by

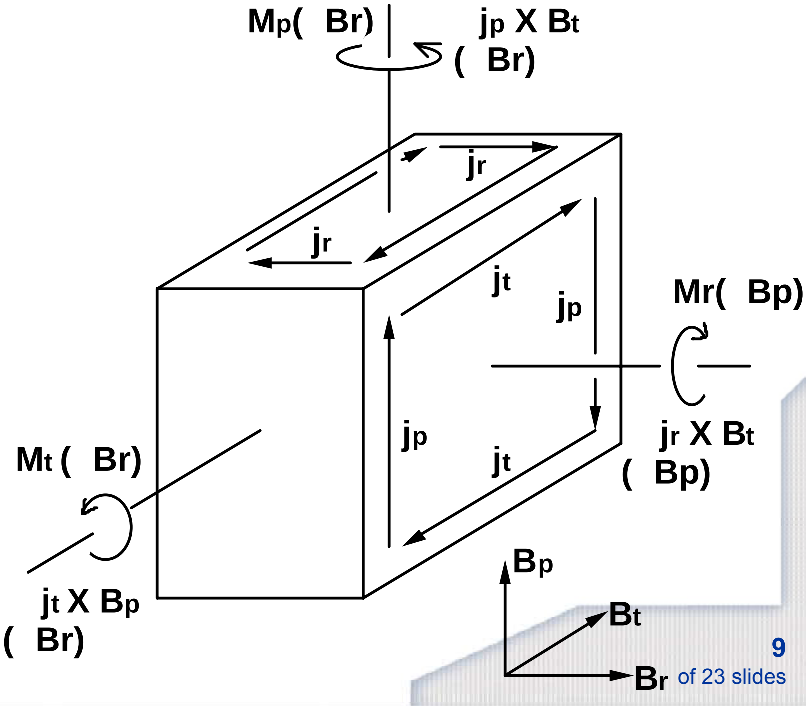
- Key for *Fp*
- Flexible joint for *Fr*



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

  Fp ⇐ ***Mr* + (*Fp* by halo)**

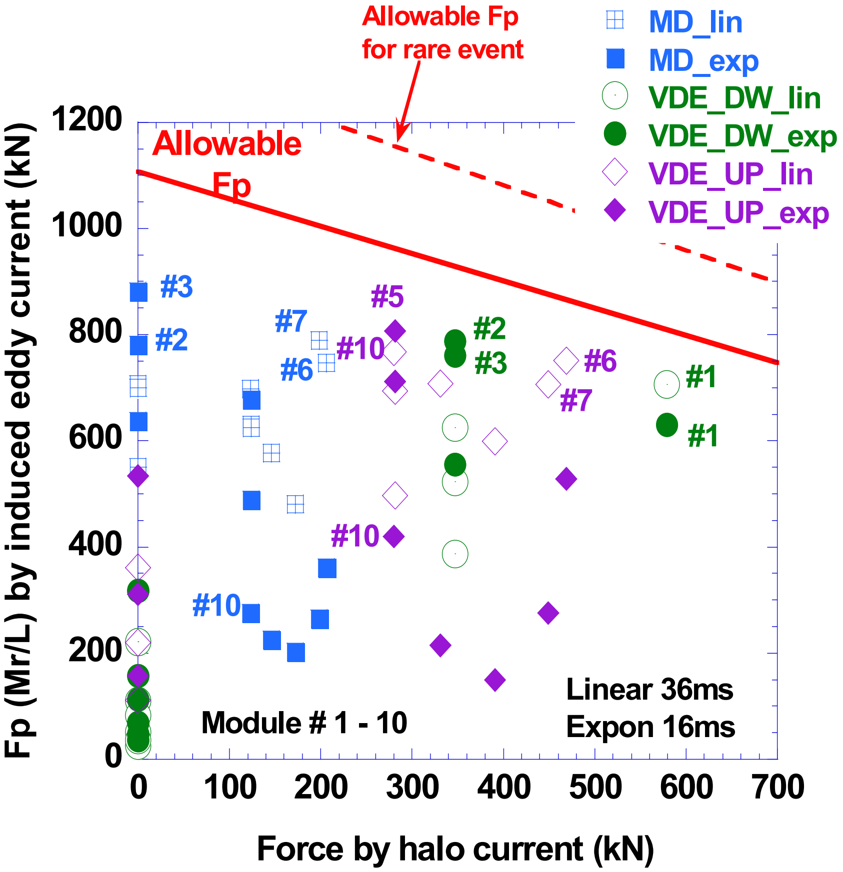
  Fr ⇐ ***Mp* + *Mt***

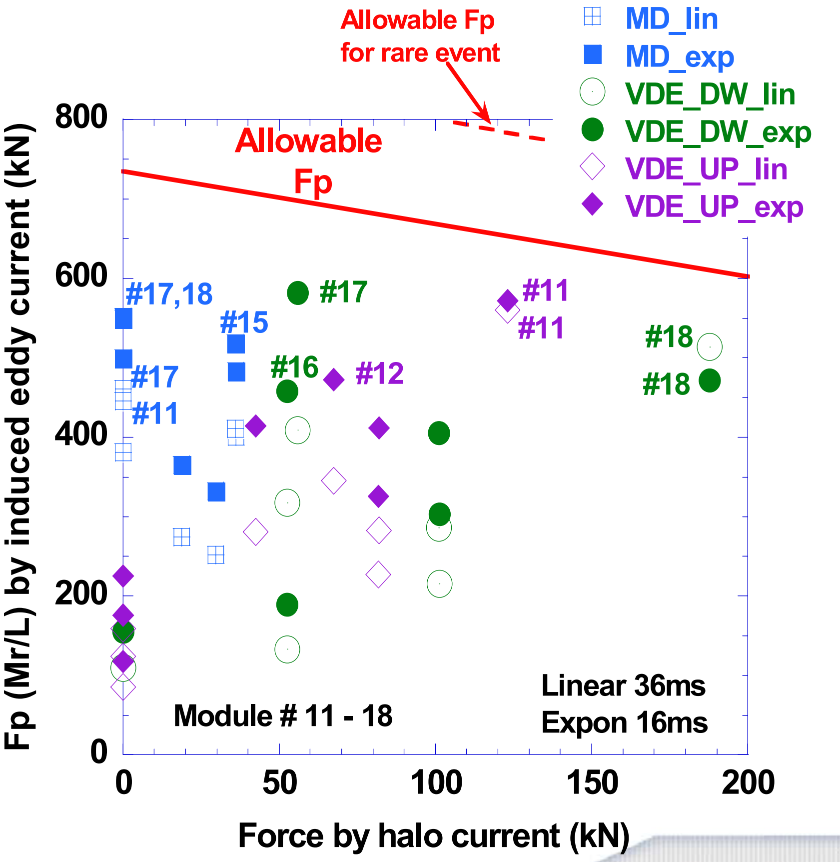


Force on Key

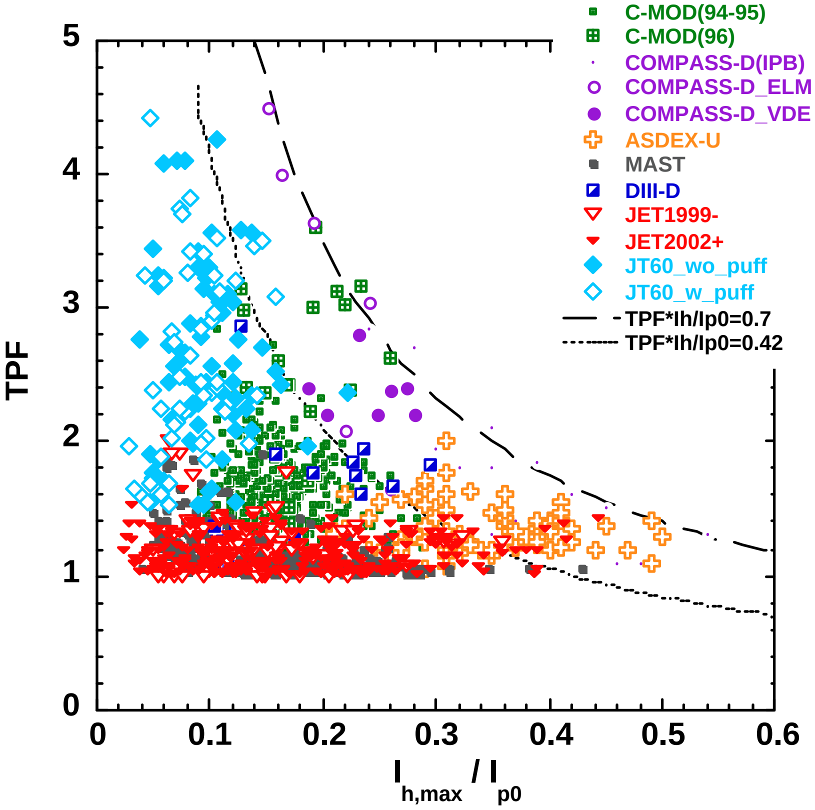
- Force by eddy current is dominant but force by halo is also significant for the peak force

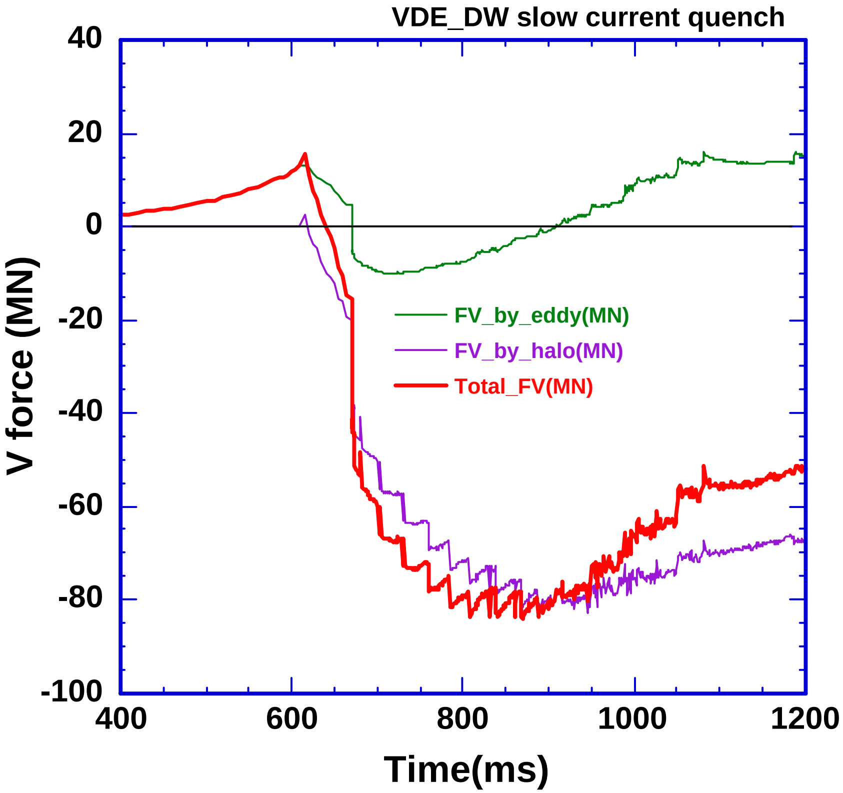
- EM loads are within the allowable limit for all these representative scenarios, but the margins are not very large





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 ε ($MJ/m^2/\ s^{1/2}$) $\approx$ *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***

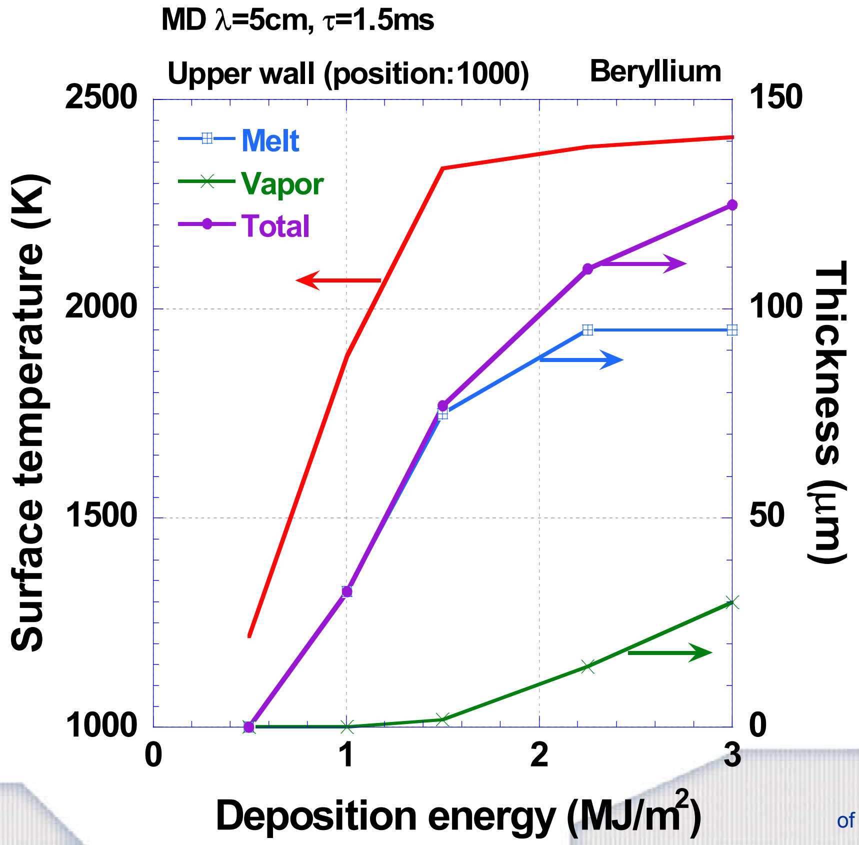
Energy loss / disruption Case and peak location	*175 MJ*	*350 MJ*
Reference : peak location (6)–(8) *(MJ/ m²)*	*0.45 - 0.92*	*0.9 - 1.84*
Possible worst : peak location (f)-(g) *(MJ/ m²)*	*0.9 - 1.44*	*1.8 - 2.9*

Heat conduction calculations

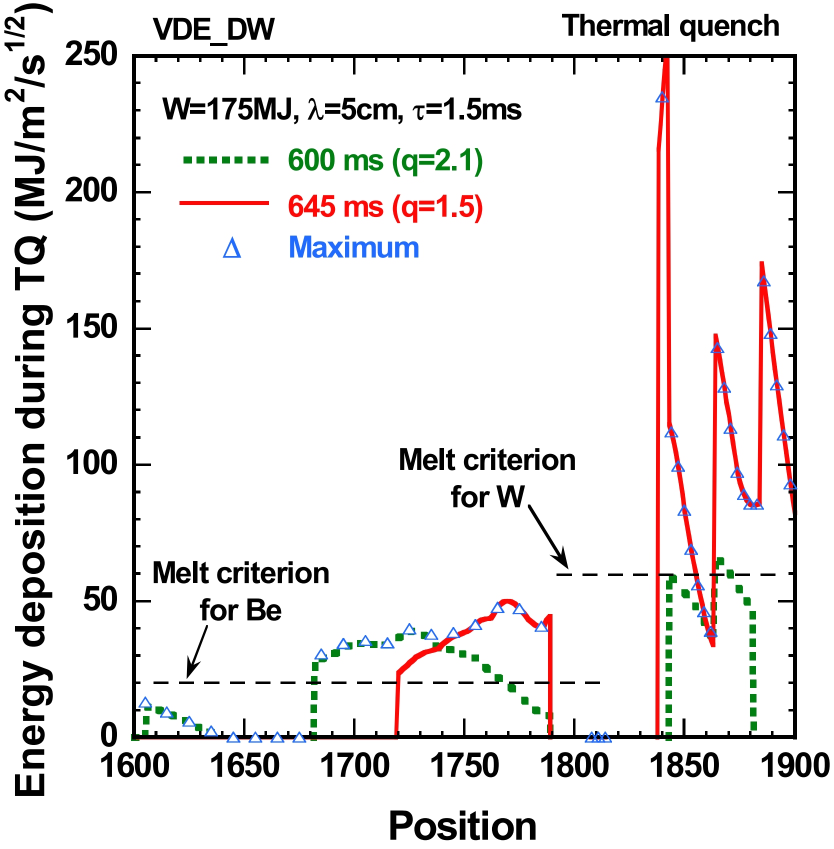
- **Loss of Be thickness for most likely MDs with somewhat reduced stored energy and reference case**

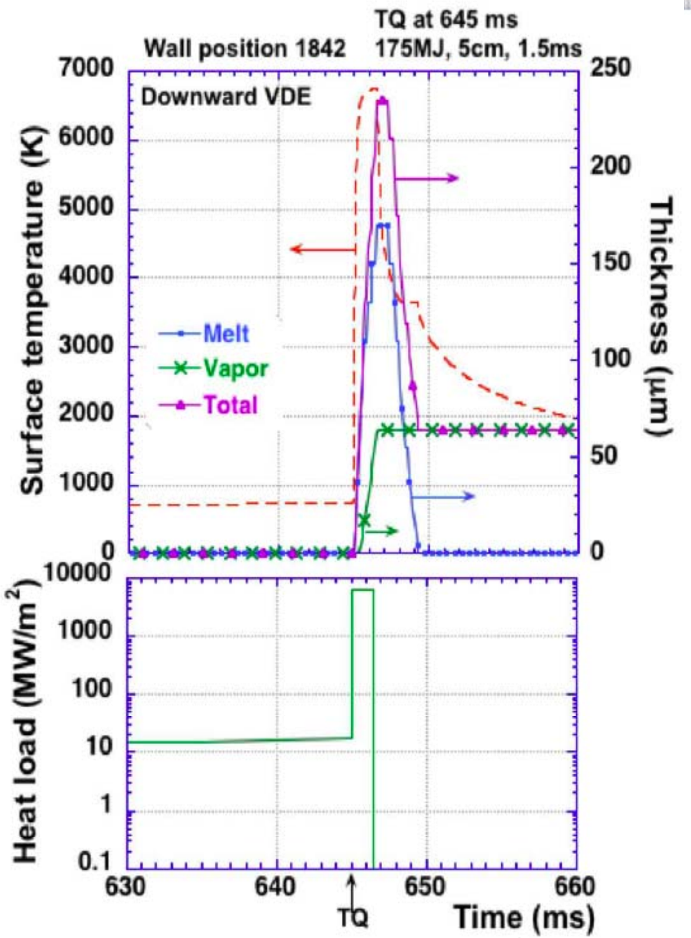
≈30 μm/event for 1MJ/m²

even if whole melt layer is lost



Heat load by TQ during downward vertical mover





- 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***.

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 $_N$) 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 m at first wall	~ 200 m at tungsten baffle
# of unmitigated events (30,000 discharges) (goal)	~ 80 – 300	<10

Highly reliable system for disruption control is essential for high availability of ITER

ELM control

- Pacemaking with pellets
- Edge ergodisation

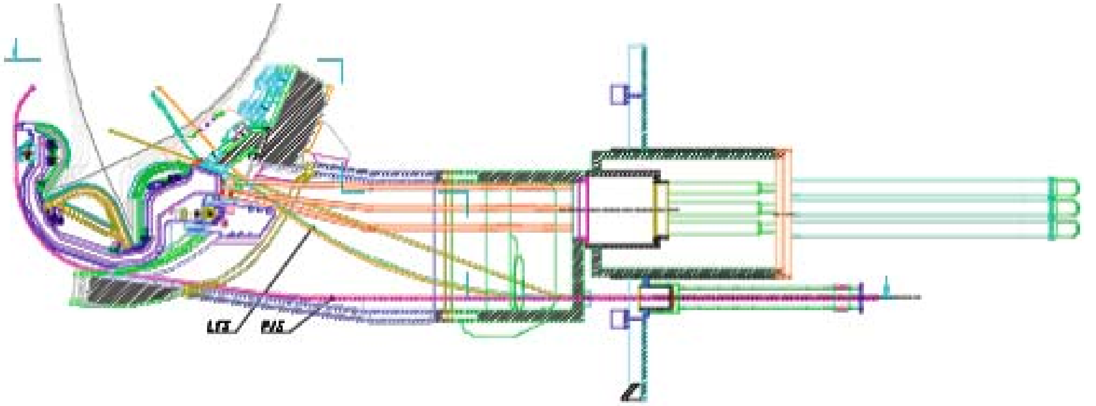
Pellet injectors for fuelling and ELM control

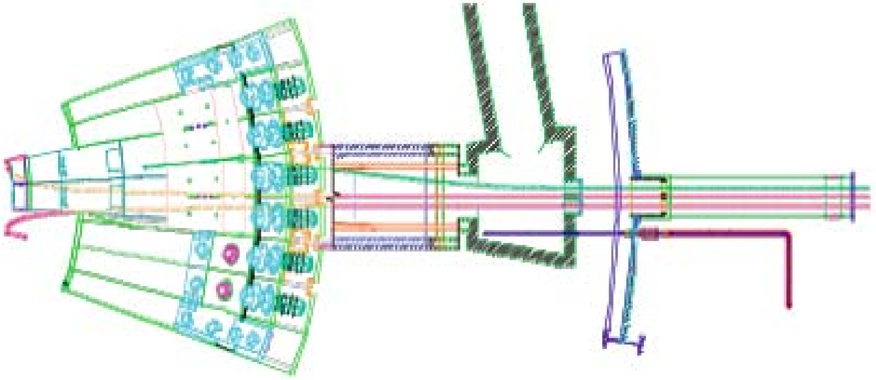
Fuelling
HFS

ELM control
HFS / LFS

If fuelling pellet from HFS injection is enough for ELM control,

It is beneficial for
- system simplicity
- overall cost





LFS injection accommodates uncertainties in τ_p* and provides deep penetration (Δ_{pel}) for triggering ELMs

- **ELM frequency and energy loss:**

$$f_{ELM} \; W_{ELM} \quad 0.4 P_{loss} \qquad\qquad f_{ELM} \quad 0.4 P_{loss} / \; W_{ELM}$$

$f_{ELM} \quad 1.6 Hz$ **for natural ELM with** $P_{loss} \quad 80MW$, $W_{ELM} \quad 20MJ$

- **ELM energy loss deposited on divertor:**

$$W_{ELM}^{div} \quad 0.65 \; W_{ELM} \quad 0.65 \quad 20 \quad 13MJ$$

- **Allowable energy loss during ELMs (** $P_{ELM}^{limit} \quad 1MJ/m^2$ **from** $T_{surf} \quad T_{critical}$**):**

$W_{ELM} \quad S_{pl} P_{ELM}^{limit} \qquad\qquad W_{ELM} \quad 5MJ$ **for** $S_{pl} \quad 5m^2$

- **Minimum required pellet injection frequency:**

$$f_{ELM}^{pellet} \quad 1.6 \quad (13/5) \quad 4Hz$$

- **Pellet injection of size** d_{pel} **with this frequency** f_{ELM}^{pellet} **must be consistent with the particle balance:**

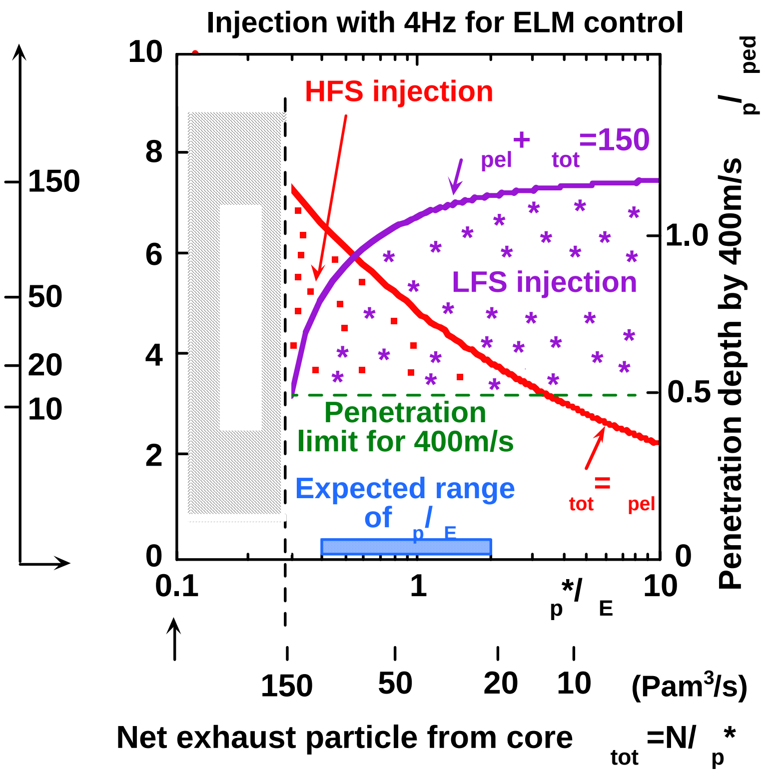
$$(\quad /4) d_{pel}^3 N_a f_{ELM}^{pellet} \quad n \quad V / \quad {}_p^* \qquad\qquad d_{pel} \quad (0.086 \frac{n \quad V}{N_a (\quad {}_p^* / \quad {}_E)})^{1/3}$$

${}_p^*$ **: (global) particle confinement time,**

$N_a \quad 6 \quad 10^{28} m^{\;3}$**: hydrogen density in a pellet**

LFS injection provides ELM pace-making for a wide parameter range

ELM trigger: $_{p}$ $(0.5 \sim 1)$ $_{ped}$



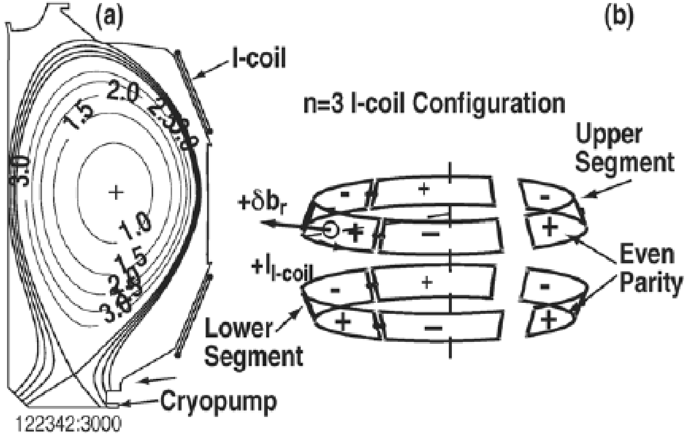
LFS injection can cover the expected range of $\tau_p{}^*/\ \tau_E$ and the required λ_p

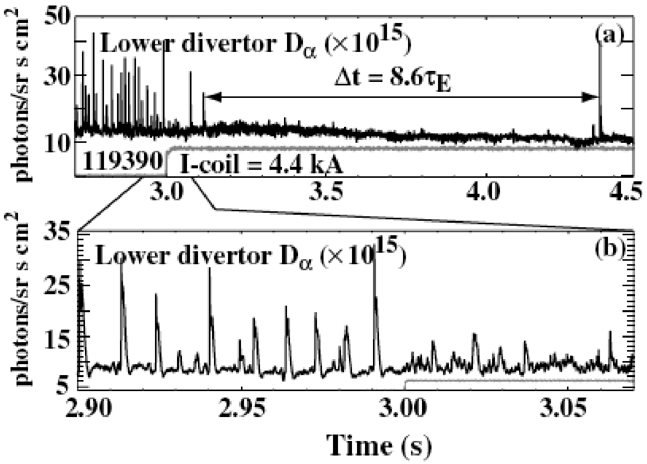
The operation window is wider for LFS injection than that for HFS injection

Independent control of EL M and fueling is possible and more flexible

ELM control with resonant magnetic perturbation (RMP):

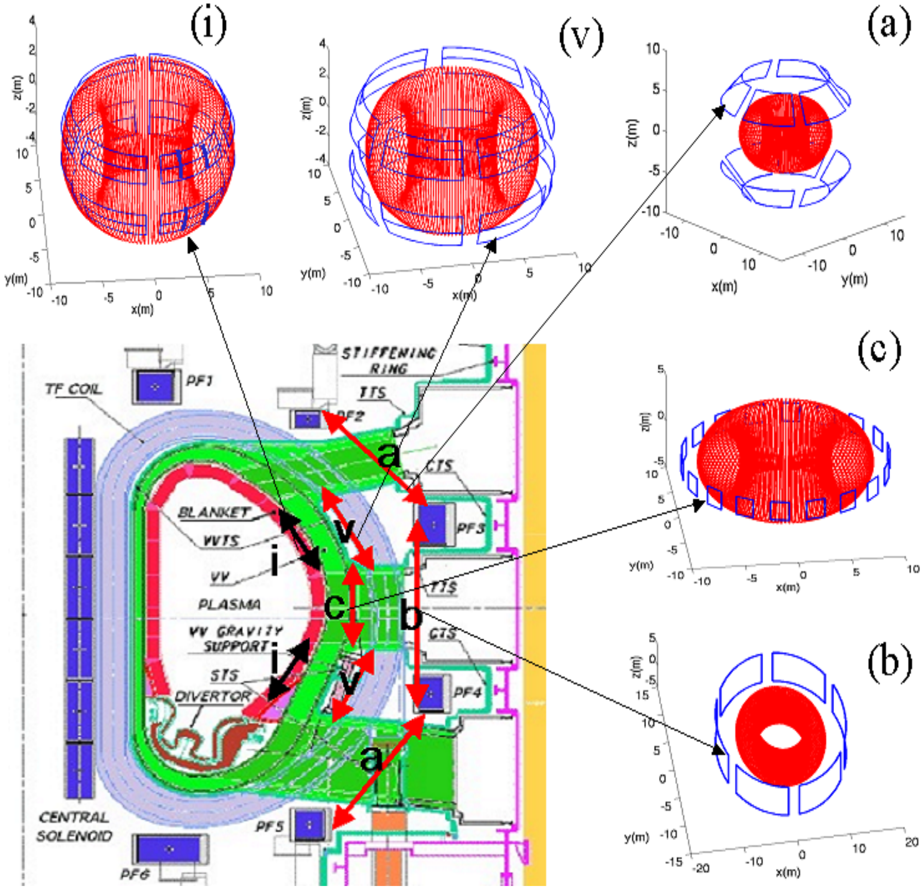
DIII-D experiments



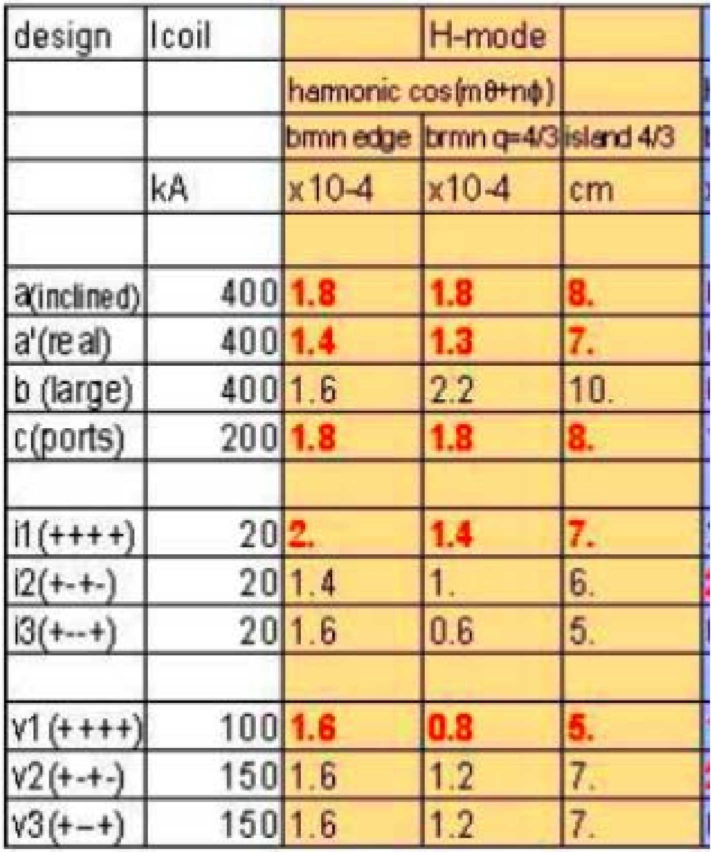


P can be just below (P)$_{\text{critical}}$

ITER application (Becoulet)



Summary of results



design	Icoil		H-mode	
		harmonic cos(mθ+nφ)		
		bmn edge	bmn q=4/3	island 4/3
	kA	x10-4	x10-4	cm
a(inclined)	400	**1.8**	**1.8**	**8.**
a'(real)	400	**1.4**	**1.3**	**7.**
b (large)	400	1.6	2.2	10.
c(ports)	200	**1.8**	**1.8**	**8.**
i1(++++)	20	**2.**	**1.4**	**7.**
i2(+-+-)	20	1.4	1.	6.
i3(+--+)	20	1.6	0.6	5.
v1 (++++)	100	**1.6**	**0.8**	**5.**
v2(+-+-)	150	1.6	1.2	7.
v3(+--+)	150	1.6	1.2	7.

Remarks

Island width at $\Psi^{1/2}$=0.7 is large even for i-coil.

No substantial difference between a' coil and i-coil => Coils for RWM can be used ??

b_{mn} (10-4) : 1.4 vs (1.4-2)

Δ_{island} (Δ_{island} /a) : 5 cm (0.025) vs 7 cm (0.035)

cf; DIII-D case 2 cm (0.033)

Physics issues

Effectiveness for the ITER reference scenario with q_{95} 3

On which scenario the emphasis should be placed ??

- Reference inductive scenario with large type-I

- Hybrid mode

Avoidance of possible deleterious effects on NTM and mode locking by lower m harmonic components

Confirm no trigger of large ELMs by fuelling pellet under ELM control condition by RMP

Engineering issues

eg., Disruption load for i-coil case

Engineering issues of In-vessel coils

- MI cables contain gas; they do not stand high voltage (> 100 V)
- MI conductors have limited capability to support high electromagnetic forces (local IxB)
- Conductor cooling is a requirement to remove heat from nuclear and joule heating. If multiple parallel cooling loops are required, insulating breaks in the cooling pipes become a design issue

- In addition, if the coils are wound around the blanket modules, the coils need to avoid shorting the slits (the EM forces are already marginal)

It is highly recommended to investigate approaches other than in-vessel coils

Conclusions

Disruption study

- Electromagnetic load for the worst-case unmitigated disruptions is estimated to be within the design target, but the margin is not large
- The first wall melting expected at unmitigated disruption is ~ 30 m/event
- This indicates that more work is required in the studies of disruption prediction, mitigation and avoidance

ELM control

- Both HFS and LFS pellet injectors are required for fueling and ELM control
- The results on ELM elimination with in-vessel coils are spectacular; however, in-vessel coils are very difficult to implement in ITER