Analysis of Disruption Scenarios and Their Possible Mitigation in ITER

M. Sugihara[1], V. Lukash[2], Y. Kawano[3], R. Khayrutdinov[4],
N. Miki[3], A. Mineev[5], J. Ohmori[3], H. Ohwaki[6], D. Humphreys[7],
A. Hyatt[7], V. Riccardo[8], D. Whyte[9], V. Zhogolev[2],
P. Barabaschi[10], Yu. Gribov[1], K. Ioki[10], M. Shimada[1]

[1] ITER IT, Naka JWS,
[2] Kurchatov Institute,
[3] JAERI,
[4] TRINITI,
[5] Efremov,
[6] Keio Univ.,
[7] General Atomics,
[8] EURATOM/UKAEA,
[9] Univ. Wisconsin,
[10] ITER IT, Garching JWS

sugiham@itergps.naka.jaeri.go.jp

Purpose and outline

Design Philosophy for disruptions in ITER

- In-vessel components and vacuum vessel should be designed to withstand the expected Electro-Mechanical (EM) load by disruptions
- At the same time, to minimize the number of disruption event and its impact on machine by mitigation technique is highly desirable

1. **Analysis of Disruption Scenarios and EM Load (to check the robustness of the design)**
   - Database analysis and physics guidelines for current quench rate and halo current
   - Simulation of representative disruption scenarios by DINA code and EM load analysis
   - Trade-off between eddy and halo currents for EM load with respect to current quench rate

2. **Disruption mitigation by massive and moderate noble gas injection**
   - Assessment of current quench rate and runaway electron generation for various gas species and optimum amount of gas in ITER.
   - Optimization of response time, force on gas inlet valve and mitigation success / false rate based on neural network disruption prediction system.

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)

Current quench rate

- **Minimum □t(100%)/S are from JT-60U**
- **Definition of □t ;**

  $\square t_{max}(100\%) \equiv I_{p0}/(dI_p/dt)_{max}$

  $\square t_{max}(100\%)/S \approx 0.8(60\%)/0.6$

  $= 1.2\ ms/m^2$

  □ $\square t_{max}(100\%)_{ITER}$

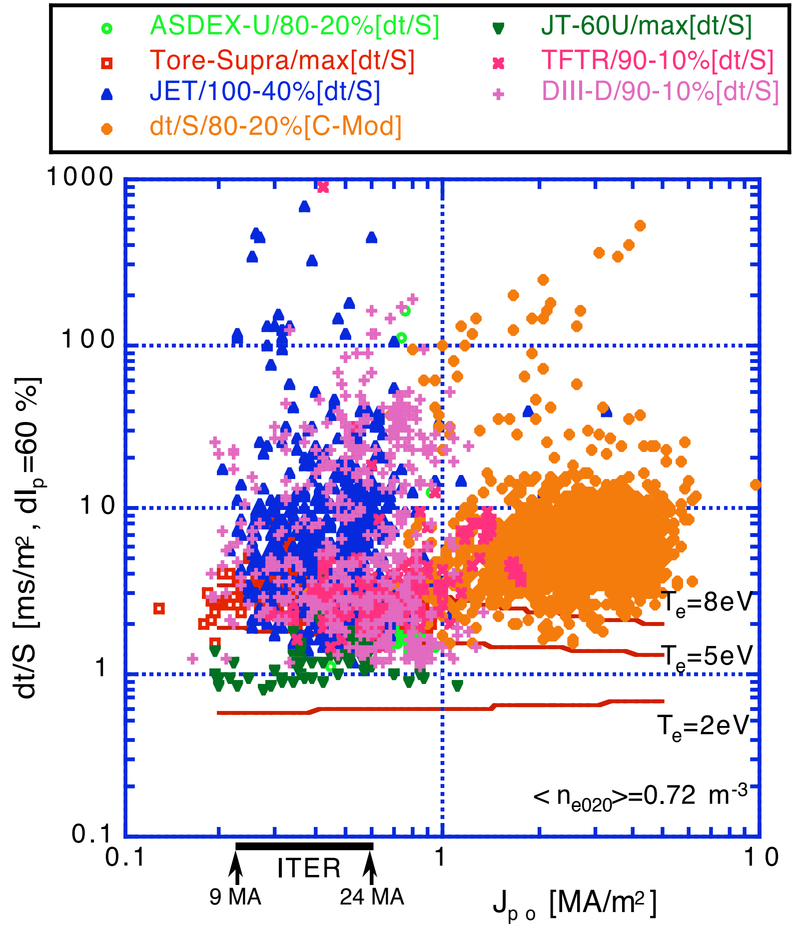
  $\approx 1.2\ ms/m^2 \square\ 21m^2 \approx 25\ ms$

- **However, $\square t_{max}(100\%) \approx 25$ ms cannot be applied to ITER. It should be always;**

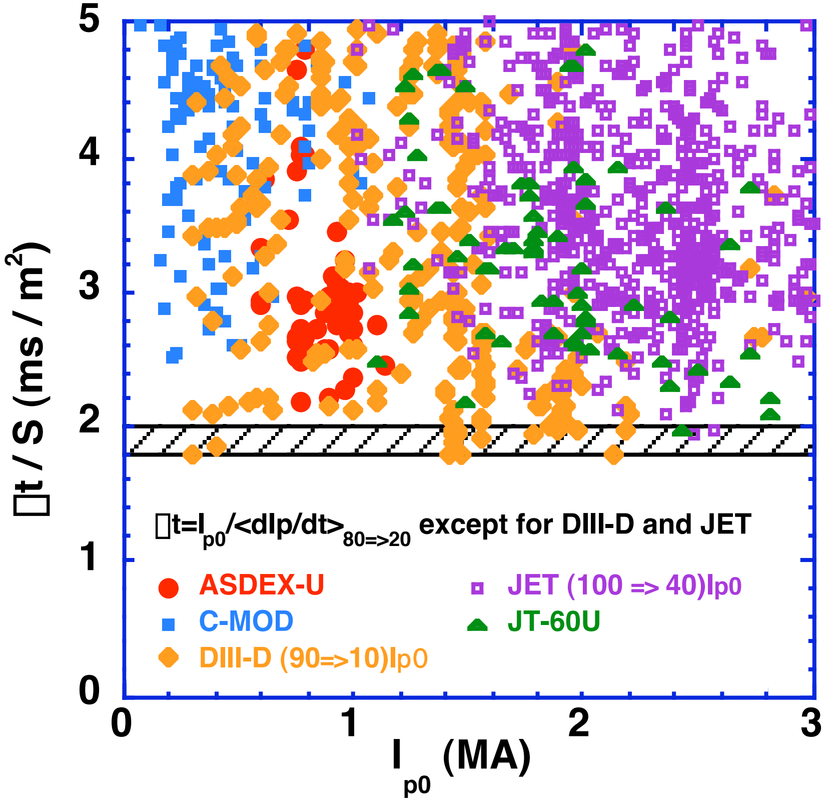
  $\square t(100\%) > \square t_{max}(100\%)$

From IPB [1]:

Different definitions are mixed



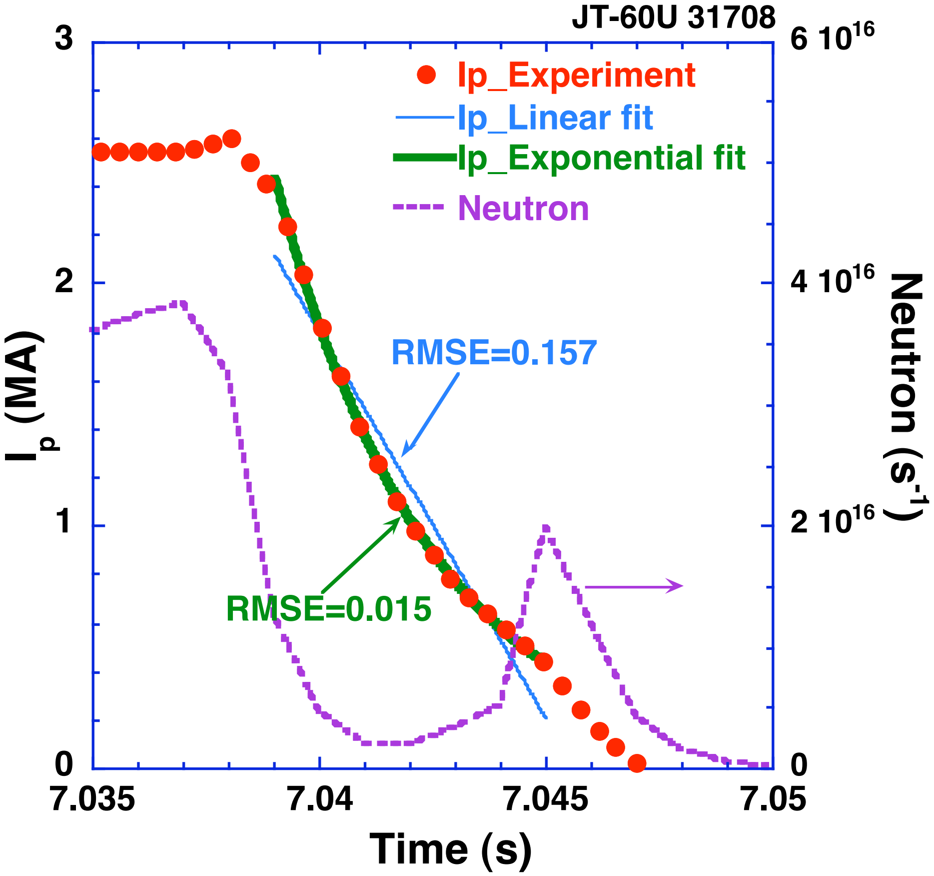
- **Good measure for quench time is to use average quench rate during (0.8-0.2)I_{p0} (recommendation by ITPS);**
  $\Box t(100\%) = I_{p0} / \langle (dIp/dt)_{80\Box\ 20} \rangle$
- **Presently available data (Fig.) [1] with this definition except for**
  DIII-D : $\langle (dIp/dt)_{90\Box\ 10} \rangle$
  JET : $\langle (dIp/dt)_{100\Box\ 40} \rangle$
  ($\langle (dIp/dt)_{80\Box\ 20} \rangle$ is smaller than $\langle (dIp/dt)_{100\Box\ 40} \rangle$ due to existence of runaway electron)



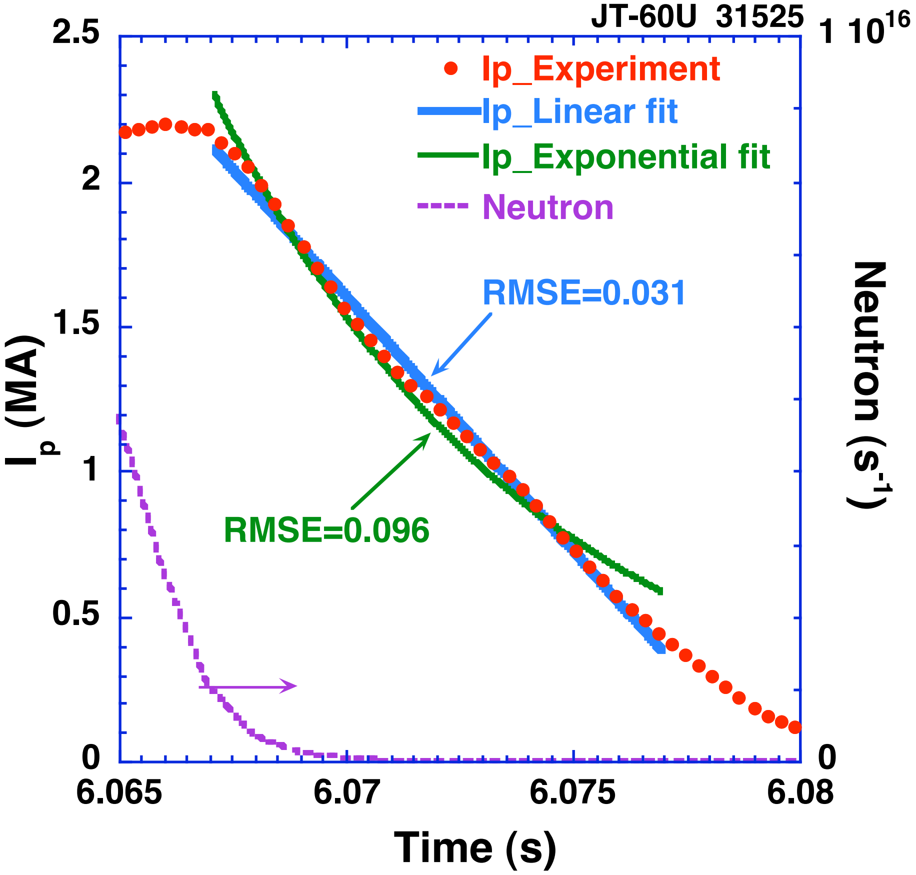
- **$(\Box t(100\%)/S)_{min} \approx 1.8\text{-}2$ ms/m^2 ==> □t(100%) ≈ 40 ms in ITER**
- **Linear waveform as simple choice**

- **Many fast quench disruptions have exponential-like waveform**
  - **- Runaway electron is associated with fast quench [2-4]**

Fast quench disruption



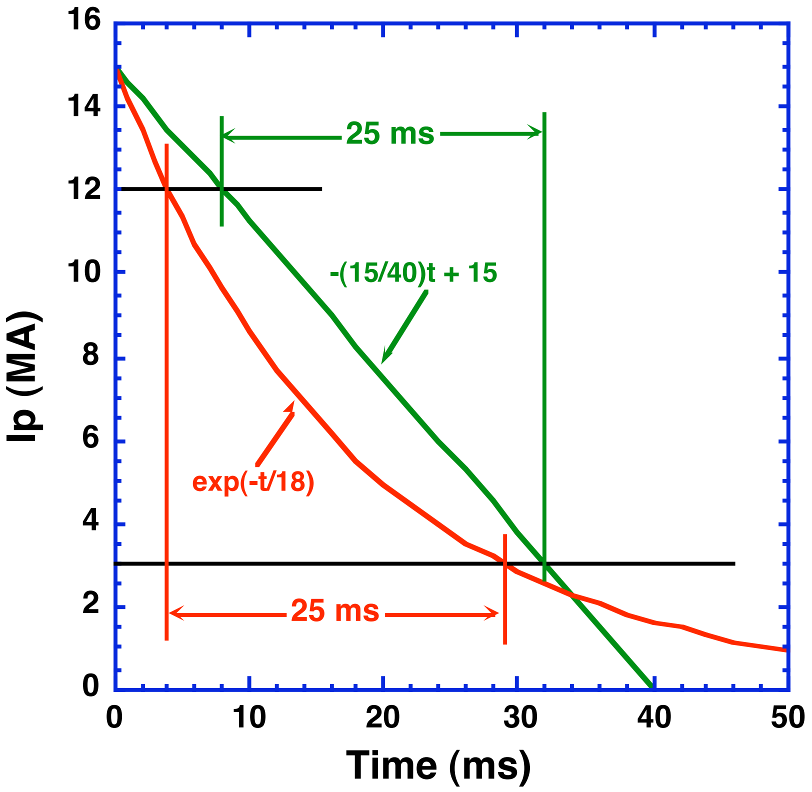
Slow quench disruption



- Time constant of exponential waveform consistent with the database

- Exponential waveform, which passes the 80% and 20% of I_{p0} for the linear waveform of the fastest current quench disruption (Δt(100%) ≈ 40ms)

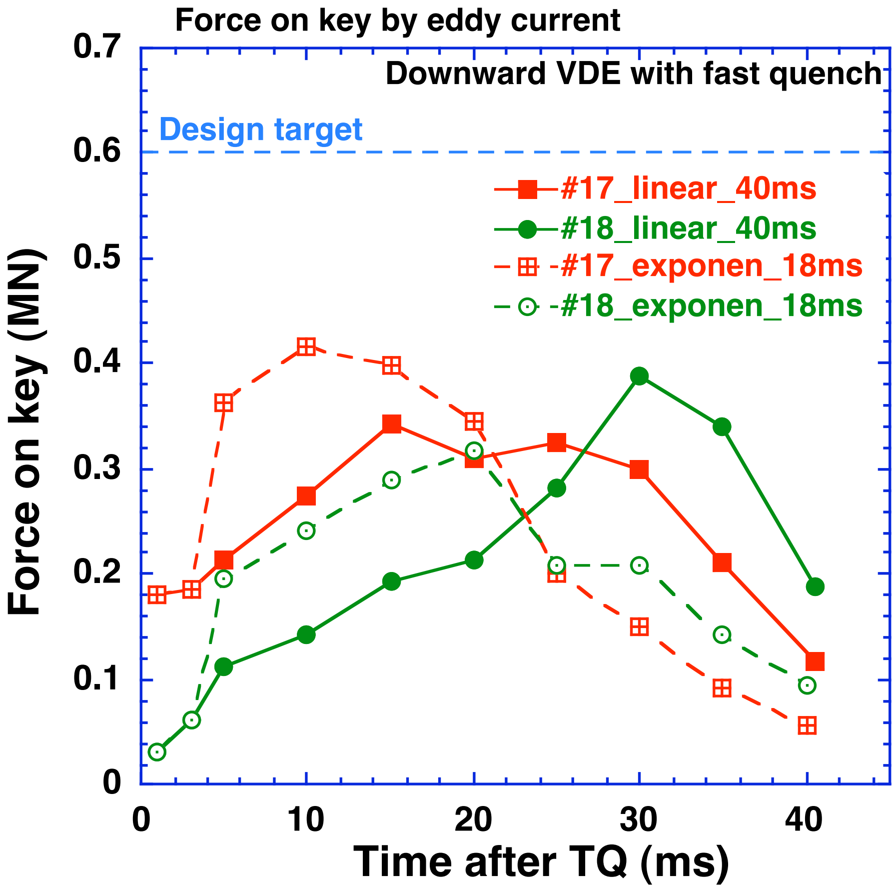
⇒ Exponential waveform with time constant of τ ≈ 18 ms in ITER



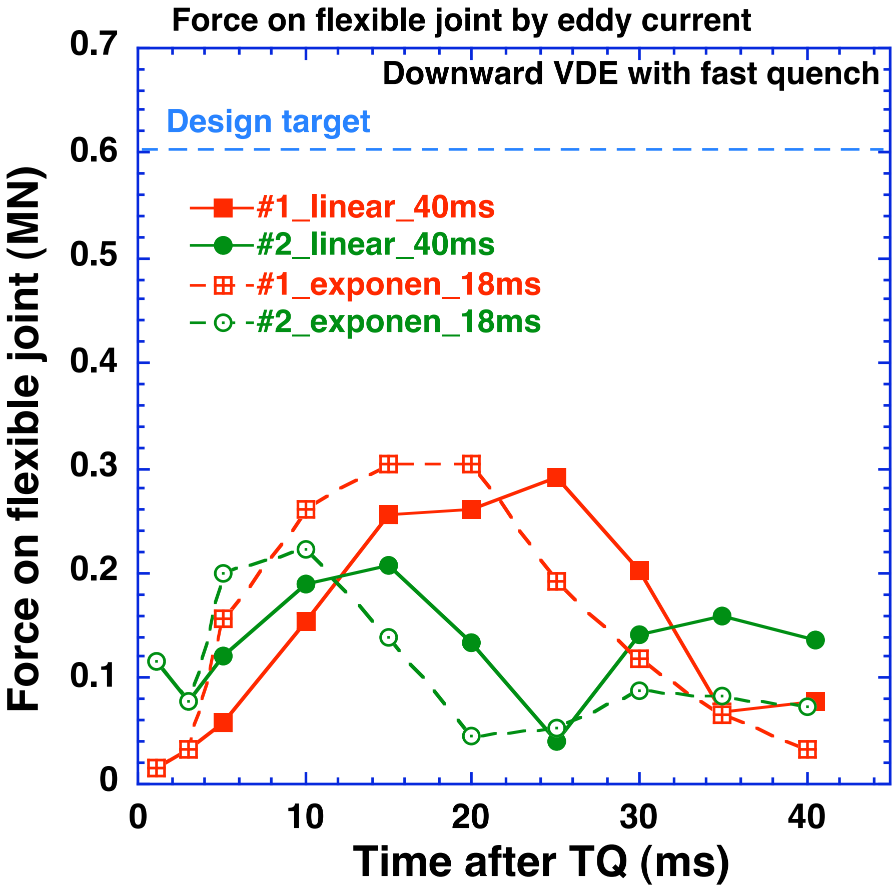
- Both linear and exponential waveforms are examined
- These linear and exponential waveforms have the same Δt(80-20%) and can be reasonable initial choice of the waveforms.

- **EM load on blanket are similar for both waveforms.**

Force on key (only by I_{eddy})



Force on flexible joint



- **Global feature of EM load could be checked either by linear or exponential, but can depend on scenarios and components.**

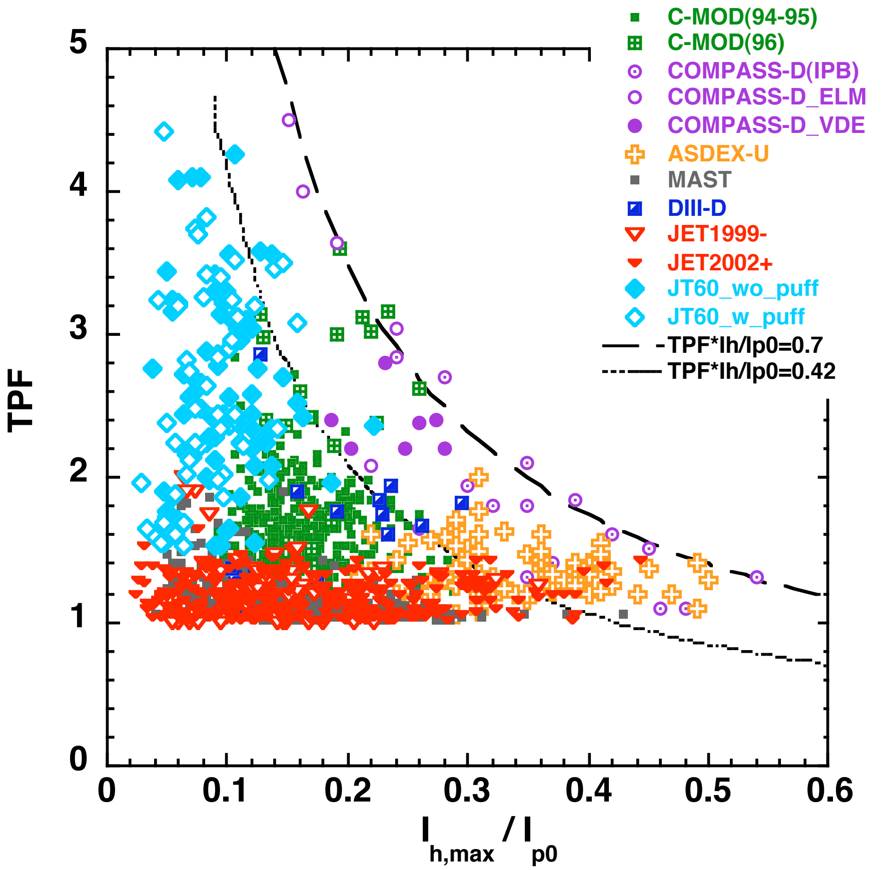
Halo current

- **Toroidal peaking factor; TPF**
- **Halo current fraction; $I_{h,max}/I_{p0}$**

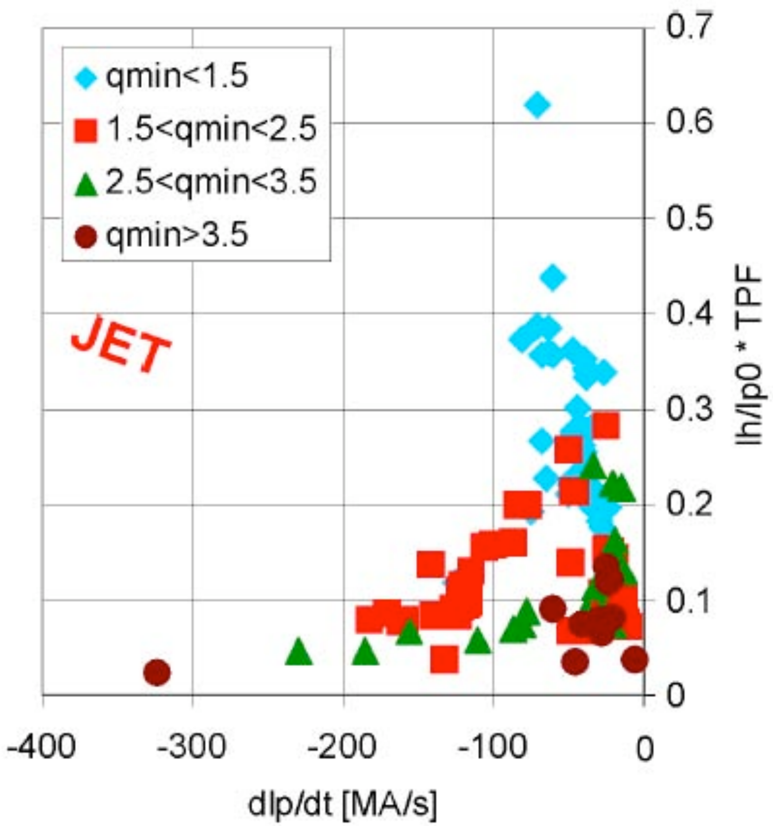
  Local max. halo current

  TPF□$I_{h,max}$
- **TPF□$I_{h,max}/I_{p0}$ < 0.7 for most of the machines [1,5,6]**
- **TPF□$I_{h,max}/I_{p0}$ depends on current quench rate (JET) [7];**

□ VDE with slow current quench has the largest TPF□$I_{h,max}/I_{p0}$



Data from IPB [1] + new data from JET, MAST and JT-60U



Specification for ITER

For VDE with slow current quench

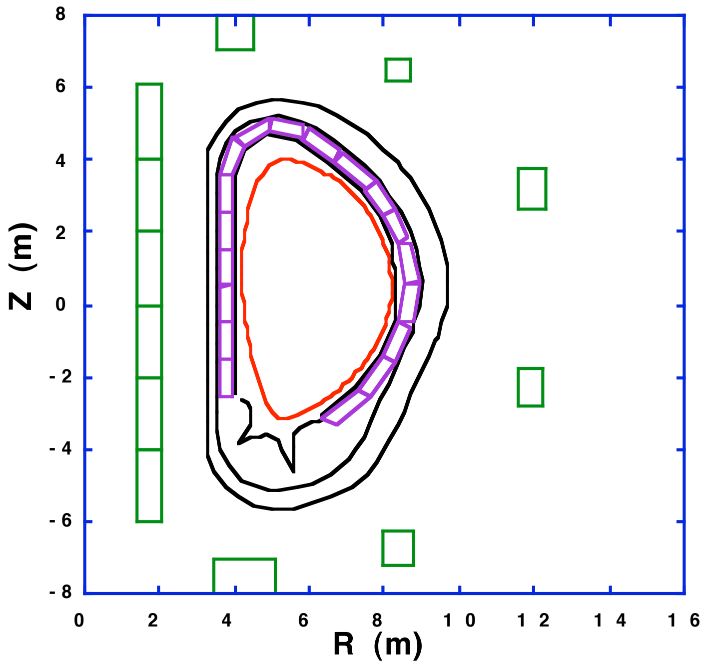
- TPF□$I_{h,max}/I_{p0}$≈0.7
- $I_{h,max}/I_{p0} \approx 0.44$
- TPF ≈ 1.6

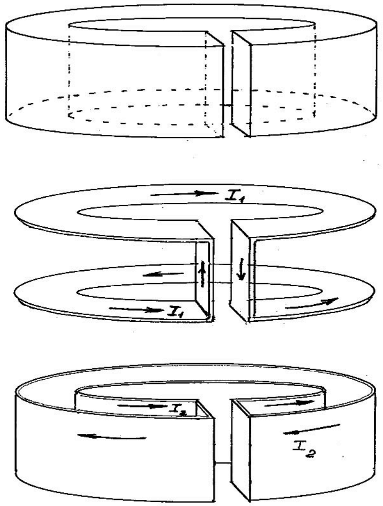
For VDE with fast current quench

- TPF ≈ 1.6 (same as slow)
- $I_{h,max}/I_{p0}$ is to be evaluated by simulation code
- TPF□$I_{h,max}/I_{p0} < 0.7$ (value depends on $I_{h,max}/I_{p0}$)

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 series of plates) and blanket (modeled by boxes;right lower figure)
- Divertor is not modeled yet





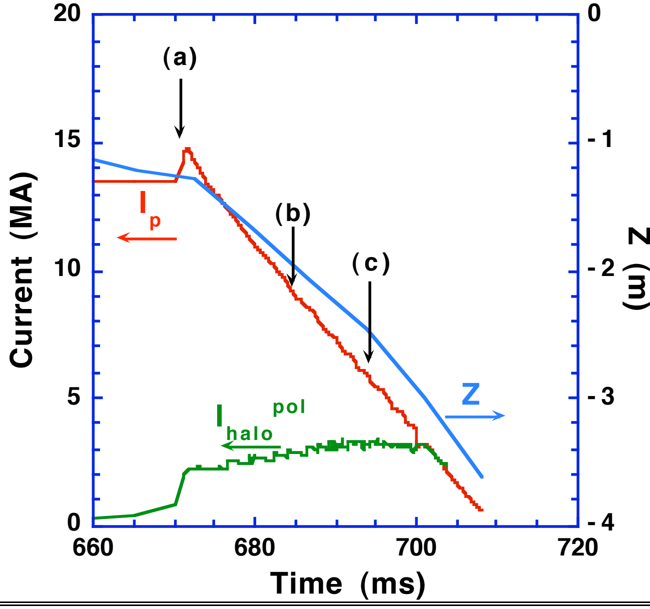
Physics guidelines for simulations

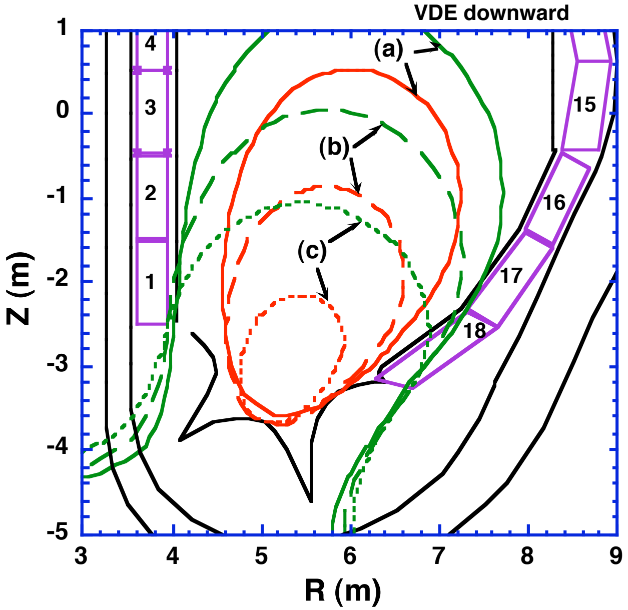
Representative scenarios Physics guidelines	Major Disruptions (MD)	Down/upward VDE with fast and slow Ip quench
1. Current quench waveform and time (fast quench)	Linear 40ms and Exponential 18 ms	□
2. Thermal quench (T.Q.) time duration	Beta drop : 1 ms [1] j flattening : ≈ 3 ms	□
3. Surface q value at T.Q.	3	1.5 – 2 [9]
4. Beta drop during T.Q.	≈ 0.72 - 0.75	≈ 0.75 - 0.4
5. Change of li during T.Q.	0.15 - 0.2	□
6. $f_h \equiv (I_{h,max}/I_{p0}) \square TPF$ for VDE with slow current quench		0.7 for downward VDE with slow quench

Calculation results

Downward VDE with fast quench

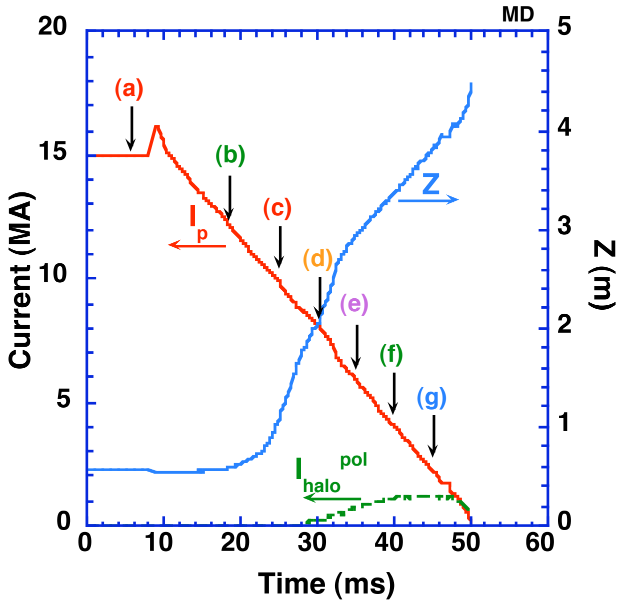
EM load on BM & divertor due to eddy and halo is expected most severe

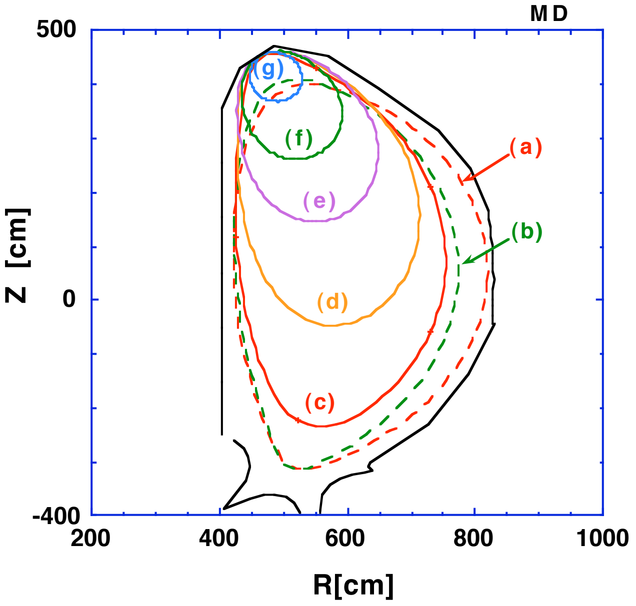




Major Disruption

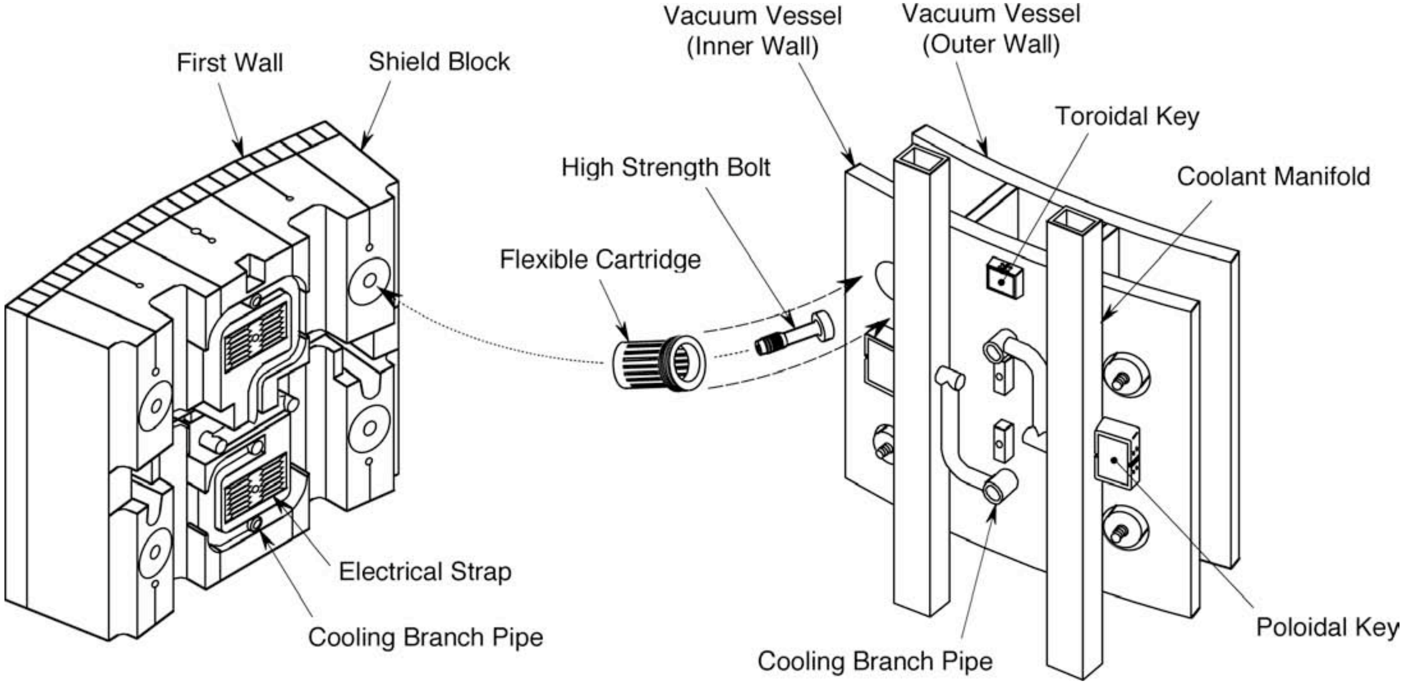
EM load on BM & div. due to eddy and halo is less severe than VDE but number of disruption is large





Support of blankets on vacuum vessel by

- Key (Fp)
- Flexible joint (Fr)

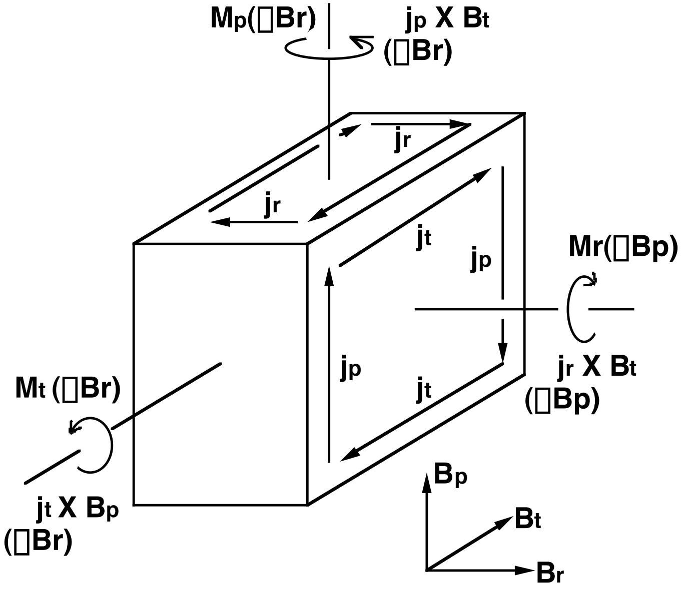


Moments Mr, Mp, Mt are calculated by FEM (induced eddy current)

Force on each module

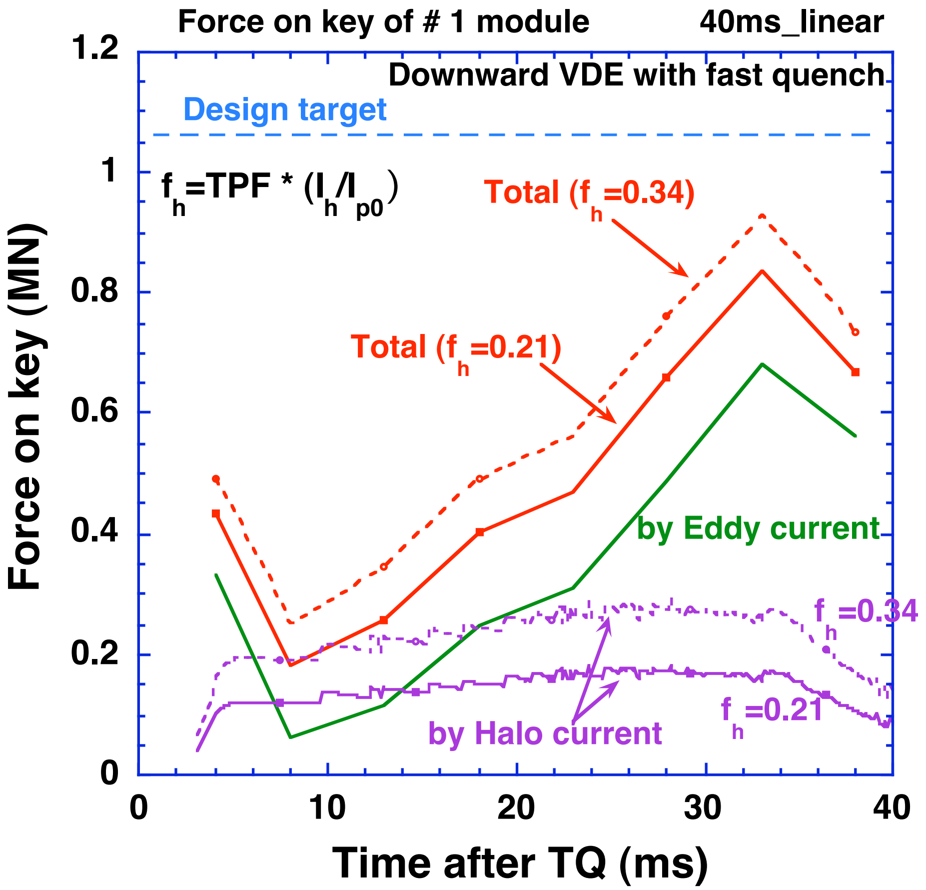
Fp □ Mr + (Fp by halo)

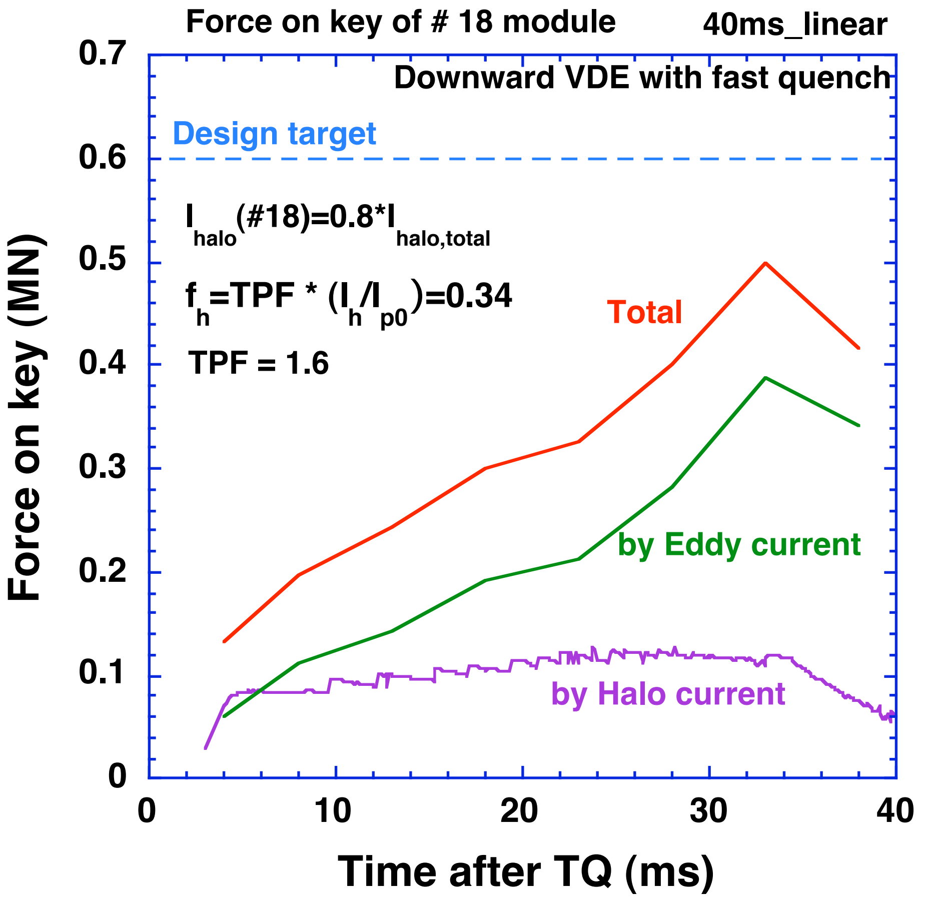
Fr □ Mp + Mt



Force on Key

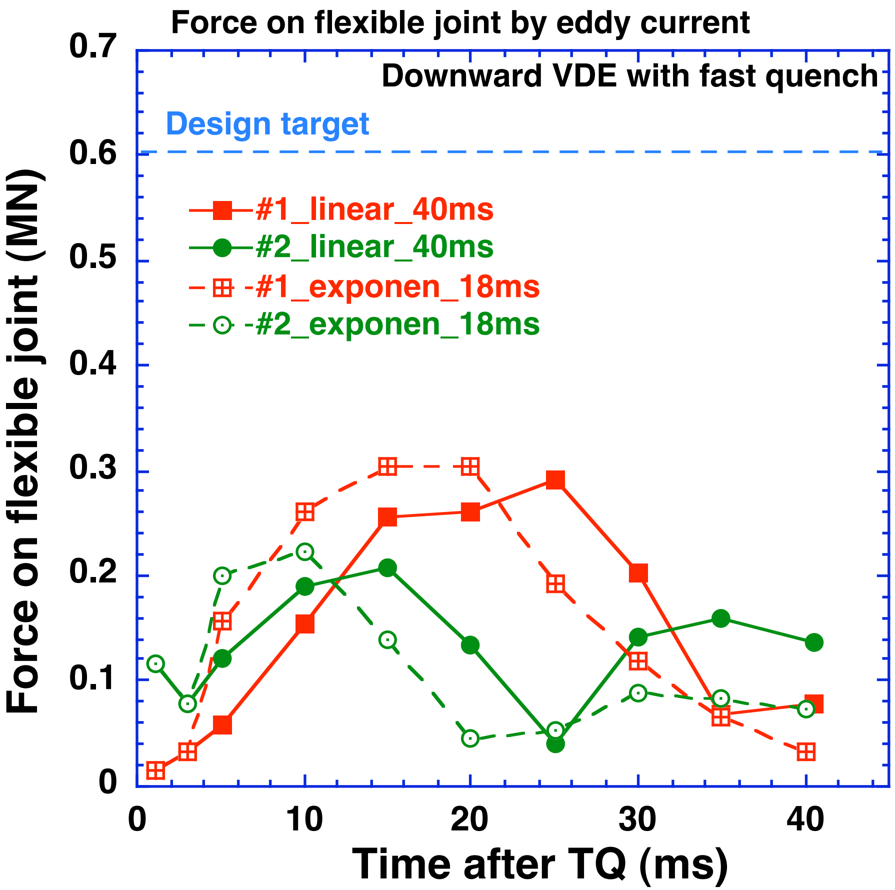
- Force by eddy current is dominant but force by halo is also significant for the peak force
- Nr. 1 and 18 BM are close to design target. There is some margin, but not so large.

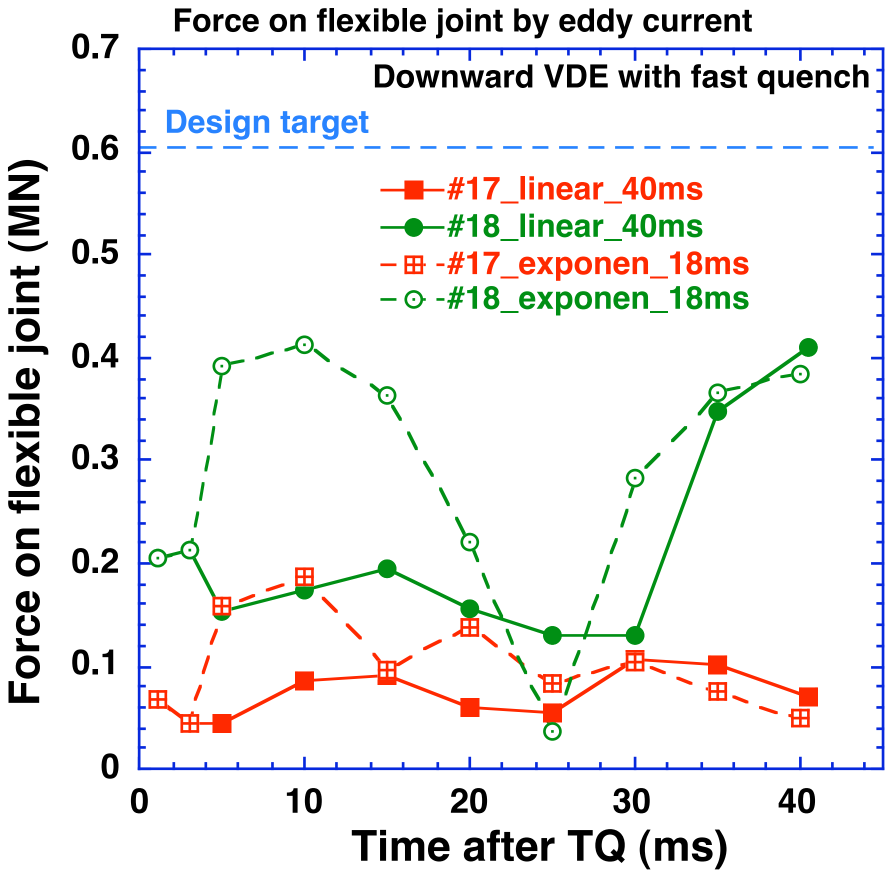




Force on Flexible joint

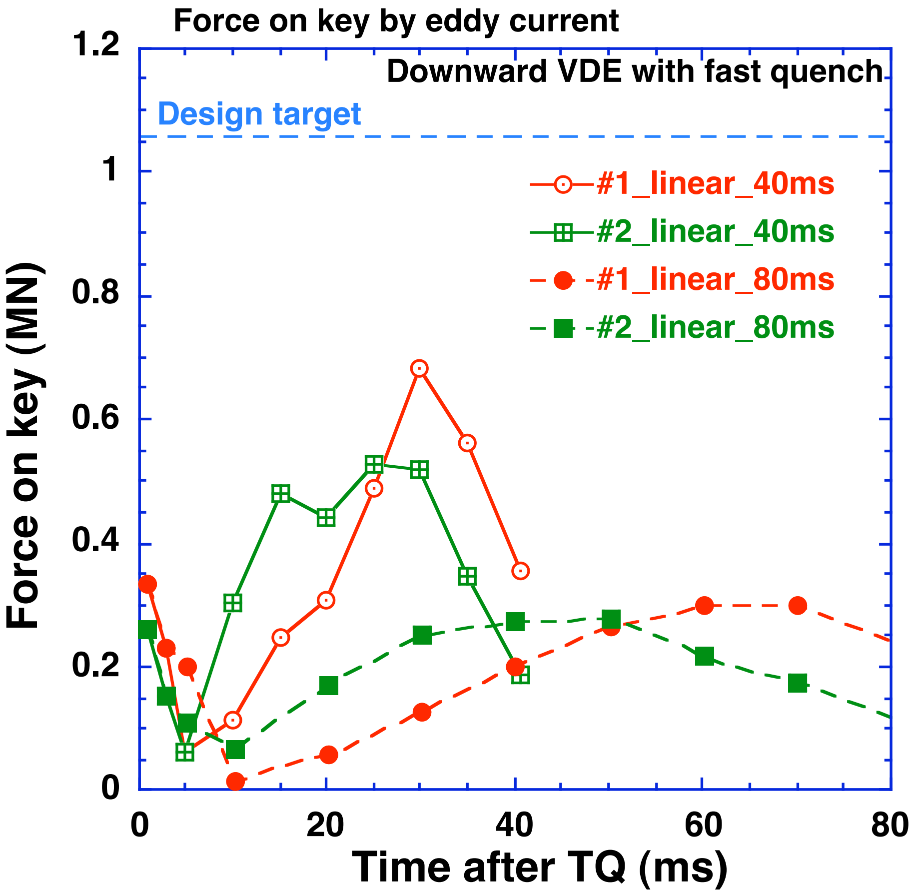
- Dominant force is by eddy and force by halo is small



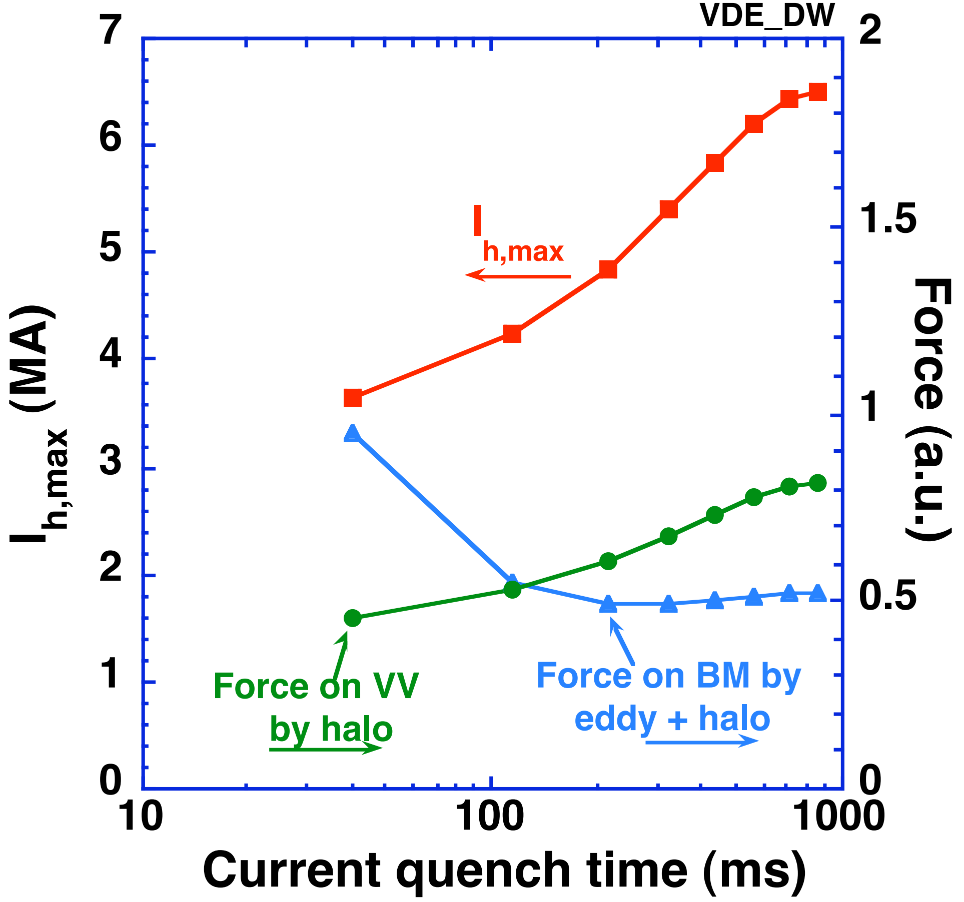


Force by eddy current can be reduced significantly with increase of current quench time by factor of 1.5-2

Force on key due to eddy : Linear 40 vs 80 ms (Downward VDE)



Reduction of eddy current Is significant but increase of halo current is very small



- This feature can be a good basis for the optimum current quench time for disruption mitigation

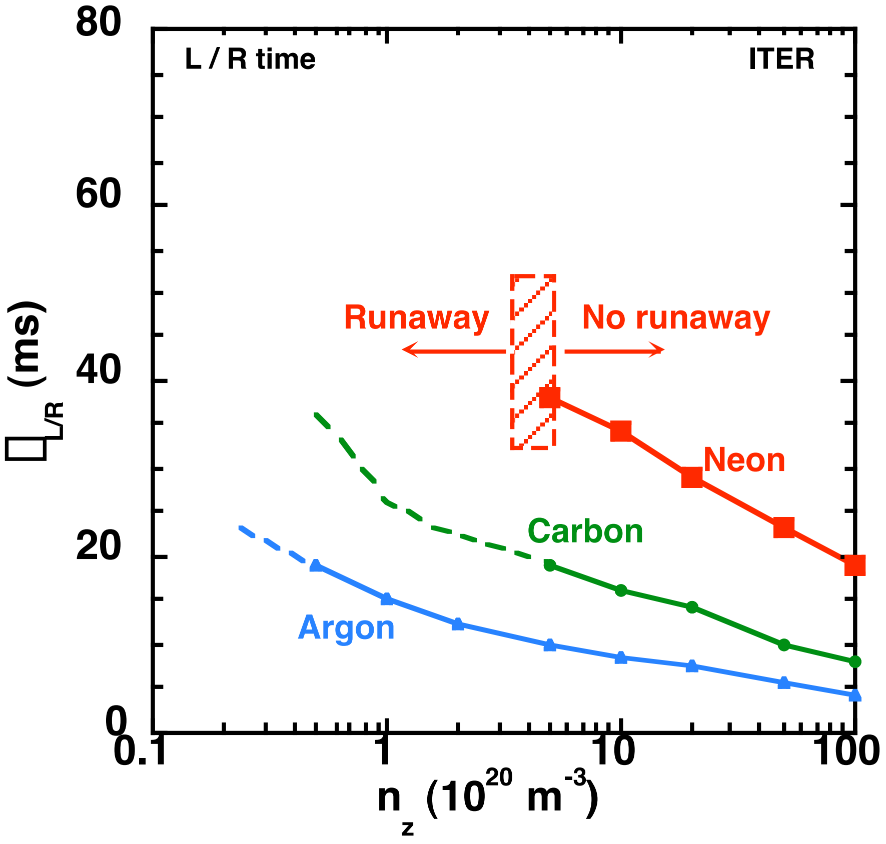
Possible disruption mitigation in ITER

-Massive [10] or moderate [11] noble gas injection

- **Choice of Neon as an optimum injection gas species**
- **$\square_{L/R}$ is evaluated by the coupled time dependent equations [12]:**
  - **Impurity rate eq.**
  - **Plasma power balance eq. (radiation & joule power)**
  - **Plasma circuit eq.**
  - **Avalanche & Dreicer R.E. eq.**
- **Current quench time can be longer by factor of 1.5-2 than that of unmitigated disruption (18ms L/R time) or argon case for**

  n_{Neon} □ $(3\text{-}5)\square10^{21}$ m^{-3}
- **R.E. is not generated for**

  $n_{Neon} \geq (0.5\text{-}1)$ $\square10^{21}$ m^{-3}



Species: Neon

Amount: $n_{Neon} \approx (1\text{-}2)\square10^{21}$ m^{-3}

Response time Δt , Force on gas inlet valve & Success rate

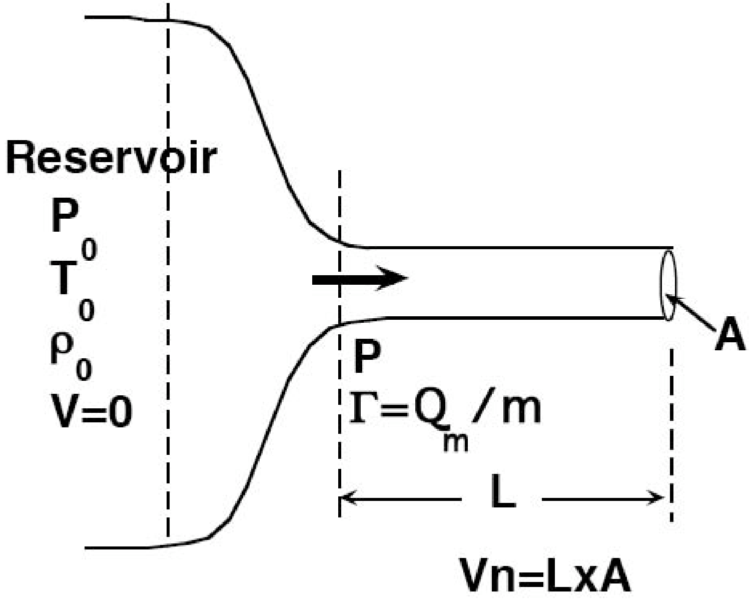
- **Assumption : neutral gas pressure $P_n \approx \overline{P}_p \equiv 0.29\ MPa$ for penetration to plasma center**

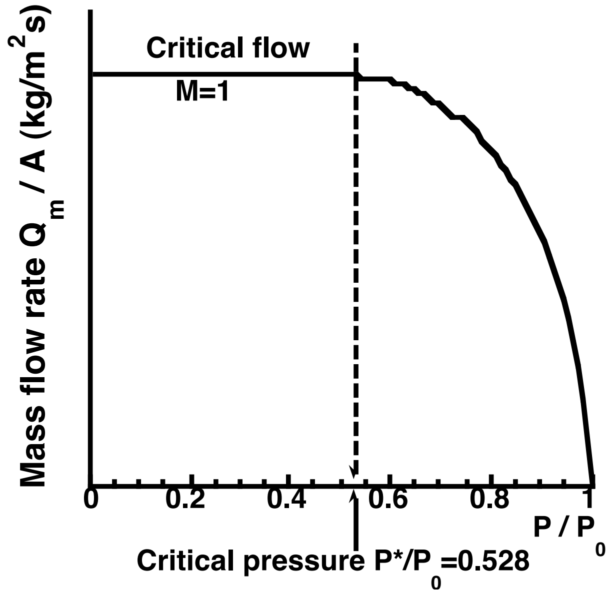
- **Required time Δt for neutral gas pressure to reach required value $\overline{P}_p$ can be evaluated by solving the following flow eqs. (gas flow is critical at the valve: Mach=1)**

$$\frac{V_n}{kT_0}\frac{dP_n}{dt} = \frac{A}{m}\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} P_0\rho_0}\quad \text{(for } P_n<P^*\text{)}$$

$$\frac{V_n}{kT_0}\frac{dP_n}{dt} = \frac{A}{m}\sqrt{\frac{2\gamma}{\gamma-1} P_0\rho_0\left(\frac{P_n}{P_0}\right)^{\frac{2}{\gamma}}\left(1-\left(\frac{P_n}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

(for $P_n > P^*$)



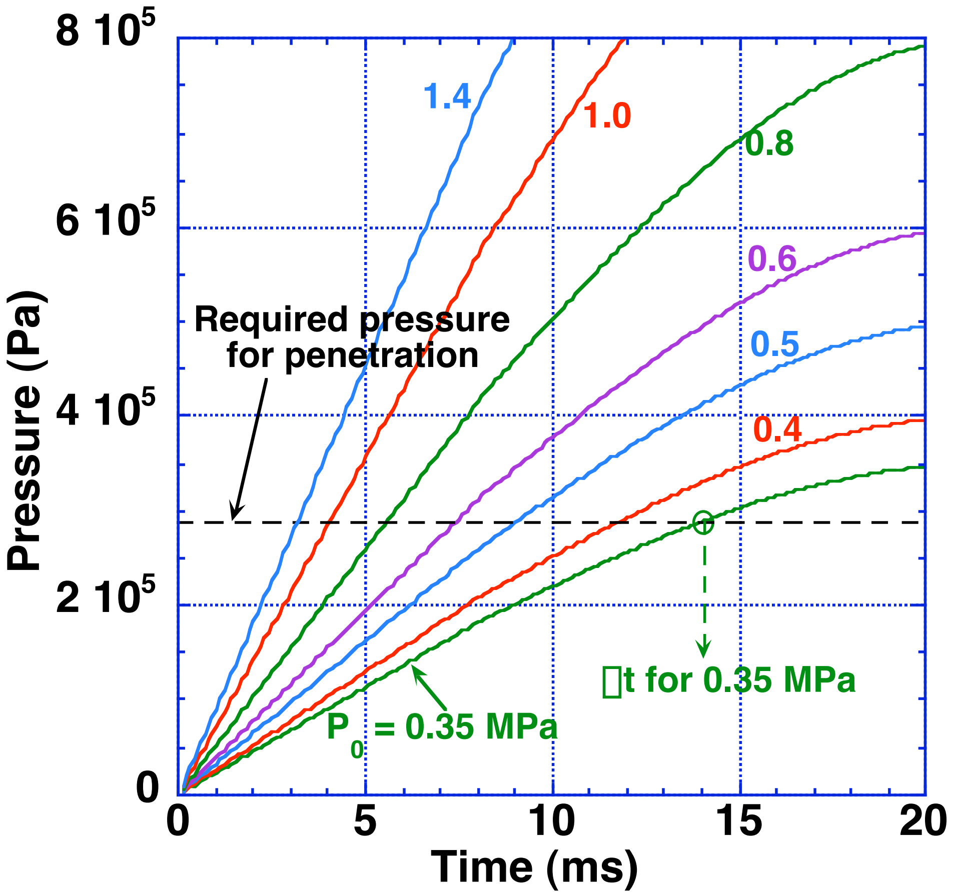


Solution

- □*t* decreases with increase of reservoir gas pressure P_0

  □ quick response is achieved by increasing reservoir gas pressure P_0

- On the other hand, force on the gas inlet valve $F_0 = P_0 A$ increases to achieve faster response (decreasing □*t*)

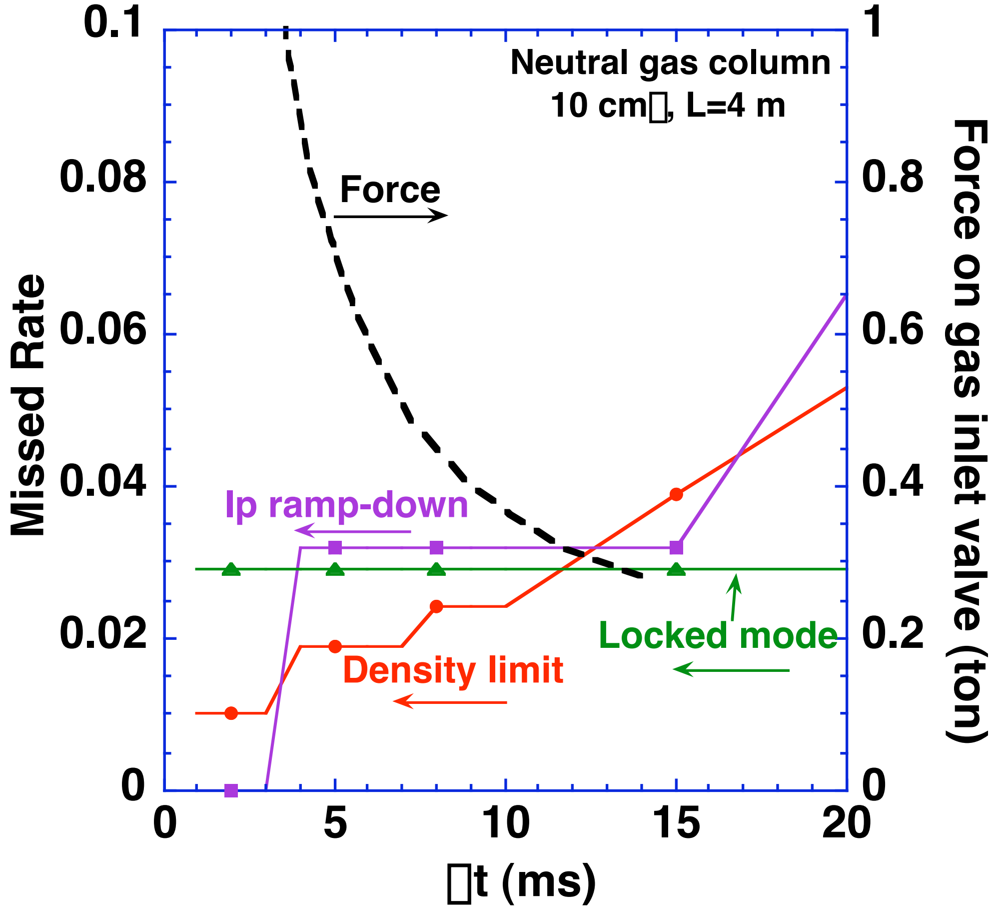


Success rate of mitigation can be increased with decreasing *□t* (with increasing force on gas inlet valve F_0)

- Employ neural network system by Yoshino as example [13]

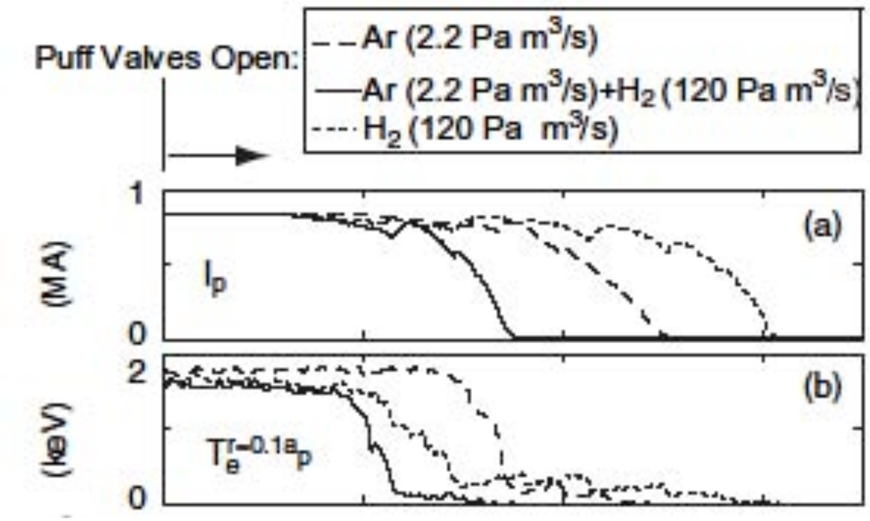
In the case of massive injection

With increasing □t, missed rate increases gradually, but for □t≈15ms, missed rate can be still very low (3-4%) for LM, DL, high li (Ip ramp-down) disruptions. Force on the gas inlet valve reduces significantly (≈ 300kg; needs design study).

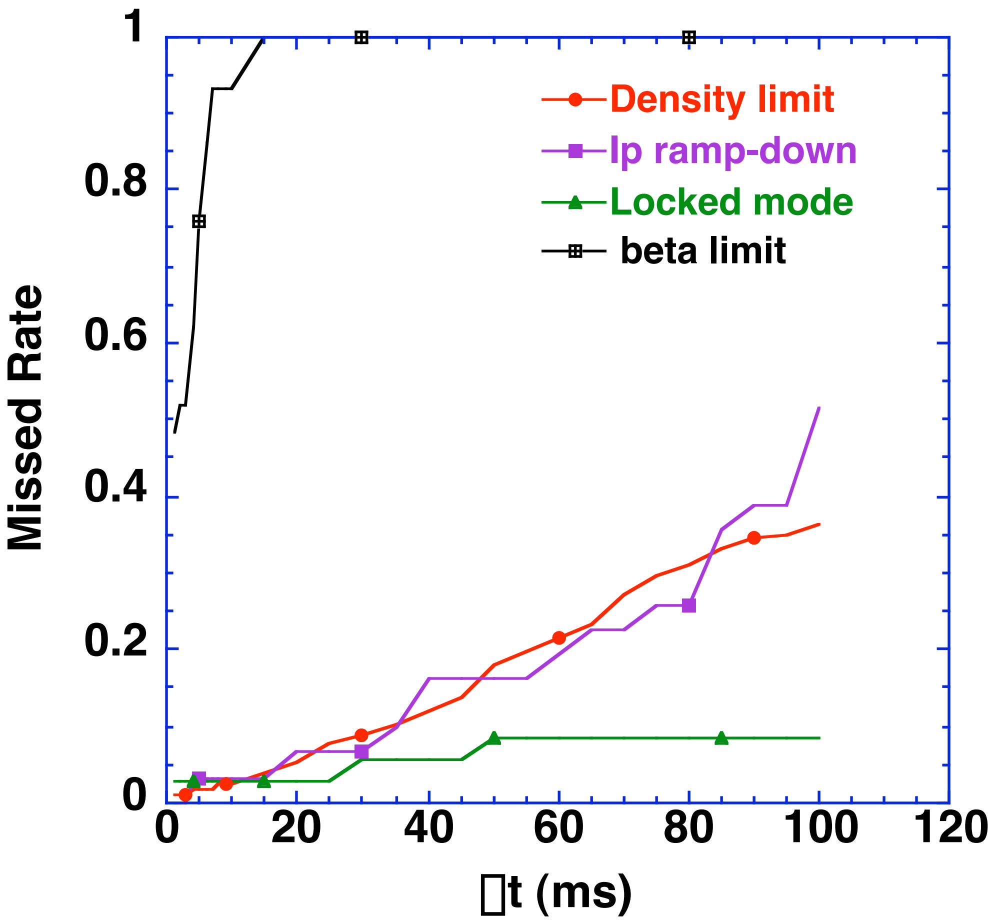


In the case of mild gas puff

Response is very slow, i.e., thermal quench occurs ≥ 100 ms after puff valve open;



Bakhtiari, NF 42 (2002) 1197



More than 40% of disruption will be missed, while force on the gas inlet valve is not an issue.

ITER value for massive and mild injection

	Massive injection	Mild injection
Δt (ms)	15	100
Missed rate (%)	3-4	40
False rate (%)	2	2
Force on gas inlet valve (kg)	300	Not an issue

- **In this system, by optimizing the alarm level, the false rate can be reduced significantly;**
  with Alarm level: 0.98 => False rate ≈ 2 %

- **Increasing alarm level can further reduce the missed rate but the false rate significantly increases.**

Total shots: 10^4

Disruptive shots : 10^3

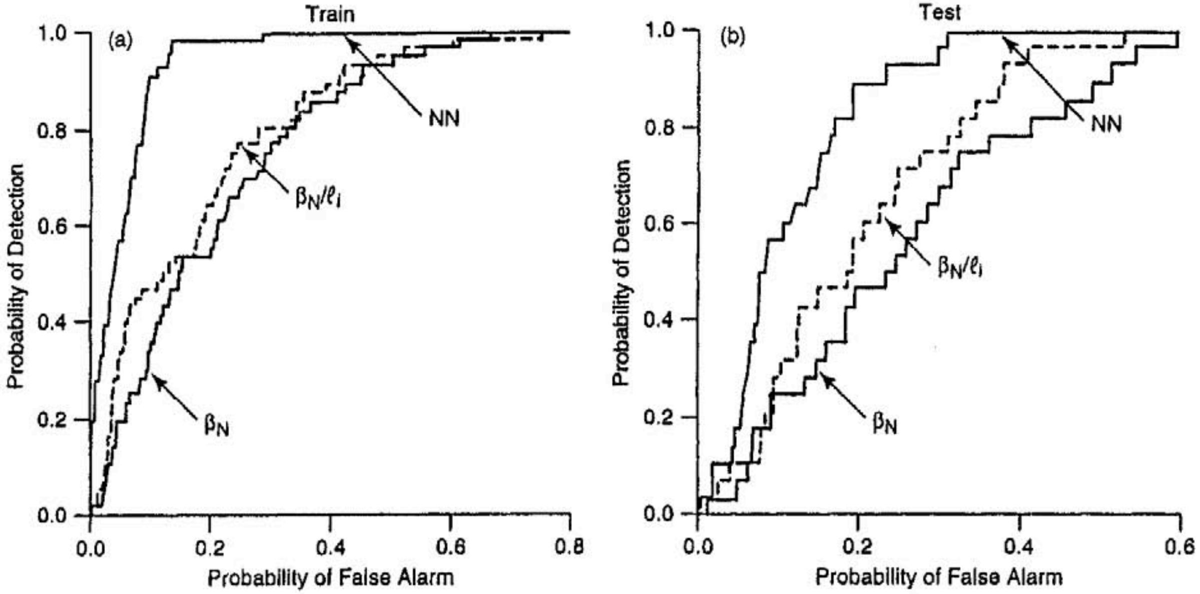
	Massive injection	Mild injection
Success shots	970-960	600 (≈ 700)
Missed shots	30-40	400 (≈ 300)
False shots	200	200 (≥ 500)

( ) ; rough estimation for alarm level=0.99

- **Key point to enhance the effectiveness of mitigation:**

Increase of success rate for disruptions close to beta limit and ITB [13,14].

- Success rate cannot be increased without increasing false rate (algorithm by DIII-D)



DIII-D; Wroblewski et al., NF 37 (1997) 725

Conclusions

- **Physics guideline for the current quench time (□t=40 ms linear , time constant of □=18 ms exponential waveform) and halo current (TPF□$I_{h,max}/I_{p0} < 0.7$) are derived from disruption database.**

- **Representative disruption scenarios are analyzed by the DINA code and EM load on the blanket modules and vacuum vessel are analyzed by FEM code. There is some margin, but the margin is not so large, which indicates the importance of mitigation.**

- **Increasing current quench time by a factor of (1.5-2) can decrease the EM load due to eddy currents significantly, at the expense of small increase of the EM load due to halo currents.**

- Such mitigation can be achieved either by massively or mildly injecting (1-2)x10^{21} m^{-3} of Neon gas without runaway electron generation.

- Success rate of mitigation can be increased with increasing the pressure of gas reservoir (decreasing the response time) at the expense of increasing the force on gas inlet valve.

- Coupled with a neural network disruption prediction system, it is found that the success rate can be >95% for massive injection with moderate force of gas inlet valve (≈ 300 kg). However, only ≈ 60% of disruptions can be mitigated successfully for mild injection method due to its longer response time.

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