Disruption, VDE and Runaway Electron Conversion: Physics Basis and Issues for FIRE

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- Disruption Characteristics:
  - Thermal quench
  - Current quench

- VDEs and Halo Currents

- Runaway Electron Conversion

- Open Issues and R&D Needs

- Summary and Recommendations

Importance of Disruptions, etc.

- Disruptions and their consequences significantly impact the design and operation planning for DT-burning NSOs

- Plasmas with sufficient performance to achieve DT burn also have enough thermal and magnetic energy to put in-vessel (PFC) and torus vessel systems at risk from disruptions and/or loss of vertical equilibrium control (VDE)

- Since exploration of DT burn physics will entail ‘first-time’ entry into a self-heated plasma operation regime that lies near a number of MHD stability limits, disruptions will be frequent (10%-30% of pulses)

- Time to recover wall condition after disruption can adversely impact experimental program

- Time and cost to replace eroded PFCs and/or other failed components will be large

- There are potential regulatory issues

Effects of Disruptions, VDEs, RAe-, etc.

- **EM loading on toroidally and poloidally-conducting structures**
  - — Toroidal and poloidal induced currents
  - — Local 'loop' currents (j x B torque)
  - — In-vessel 'halo currents' and forces
  - — Global vertical and lateral force on VV, etc.

- **Thermal loading on PFCs, etc.**
  - — Divertor targets
  - — First wall
  - — Ohmic heating of connections

- **Erosion and/or structural damage of PFCs**

- **Redistribution of in-vessel material, wall deconditioning**

FIRE Disruption and Disruption-Related Design Basis Recommendations (cont'd)

Parameter	Value (Range)	Comment
Frequency	10% (10-30%) per pulse	30% for plasma development ≤ 10% for mature (repetitive) operation
Number (3,000 full performance attempts)	300 (900)	300 at full W_{th} and W_{mag}, balance at ≤ 0.5 W_{th} and full W_{mag}
Thermal energy	33 MJ	For typical 200 MW plasma
Thermal quench duration	0.2 (0.1–0.5) ms	Single or multi-step thermal quench
Fraction of W_{th} to divertor	80–100%	By conduction to targets, up to 2:1 toroidal asymmetry
Fraction of W_{th} to FW (baffle)	≤ 30%	By radiation (to FW) or conduction (to baffle)
In-divertor partition (inside/outside)	2:1 – 1:2	For SN plasmas. Significant uncertainty. No data for DN plasmas
Poloidal localization in divertor	3-x normal SOL; (1-x to 10-x)	Incident energy, with up to 2:1 toroidal asymmetry. Plasma shielding and re-radiation will likely redistribute in-divertor energy
Magnetic energy	35 (?) MJ	For 6.5 MA, total out to VV
Current quench duration	6 (2-600) ms	Duration ≥30 ms: more-severe VDE and halo current
Maximum current decay rate	3 MA/ms	May occur only during fastest part of current quench; typical maximum rate ~1 MA/ms
Fraction of W_{mag} to FW, by radiation	80–100%	By radiation, with poloidal peaking factor ~ 2
Fraction of W_{mag} to FW, by localized conduction	0-20%	From VDE: depends on VDE evolution and in-vessel halo current. Hot-plasma VDEs may also deposit ~0.2-1.0 W_{th} on localized portion(s) of FW. Toroidal alignment critical

Table Continues

FIRE Disruption and Disruption-Related Design Basis Recommendations (cont'd)

Parameter	Value (Range)	Comment
VDE frequency	TBD (??? 1% of pulses, or 10% of disruptions???)	Very uncertain. May be able to maintain vertical position control after thermal quench. But margin/noise sensitivity uncertain. Control failure yields VDE or loss of after-thermal-quench control
Halo current fraction $I_{h,max}/I_{p0}$	0.4 (0.01-0.50)	Highest value may apply (depends on passive stabilizer configuration)
Toroidal peaking factor	2 ($1.2 \leq TPF \leq 4$)	TPF up to 2 yields 'sinϕ' distribution; TPF > 2 yields 'localized filament'
$(I_{h,max}/I_{p0})$*TPF	≤ 0.50 (typical maximum)	Data bound is ≤ 0.75 (see text)
Runaway electron current (following disruption or fast shutdown)	50% I_p (0-50%)	Highly uncertain. I_{RA} > 1 MA requires ≥ 1 A seed source. Not expected in thermal plasma, but pellet shutdown may seed avalanche. MHD fluctuations may offset part or all of avalanche growth.
Runaway energy	~15 MeV	Limited by knock-on avalanche
Localization of runaway deposition	≤ 1 m^2	Poloidal localization to a ~0.1-m (poloidal) section of the FW or divertor target expected; toroidal localization depends on pfc and wall alignment to toroidal field

- **Basis: ITER EDA /EG and *ITER Physics Basis, Chapter 3***
- **Lacks for FIRE: thermal quench data, DN data**

Thermal Quench Duration Basis

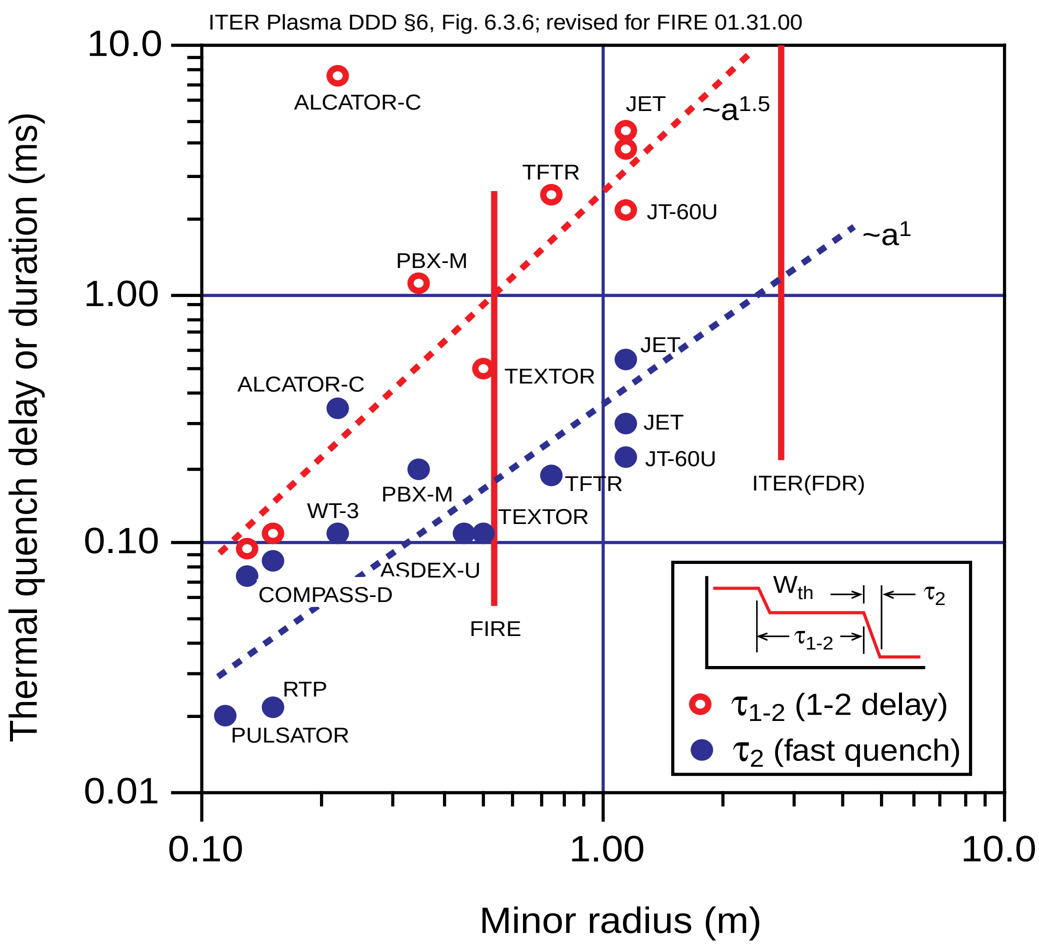
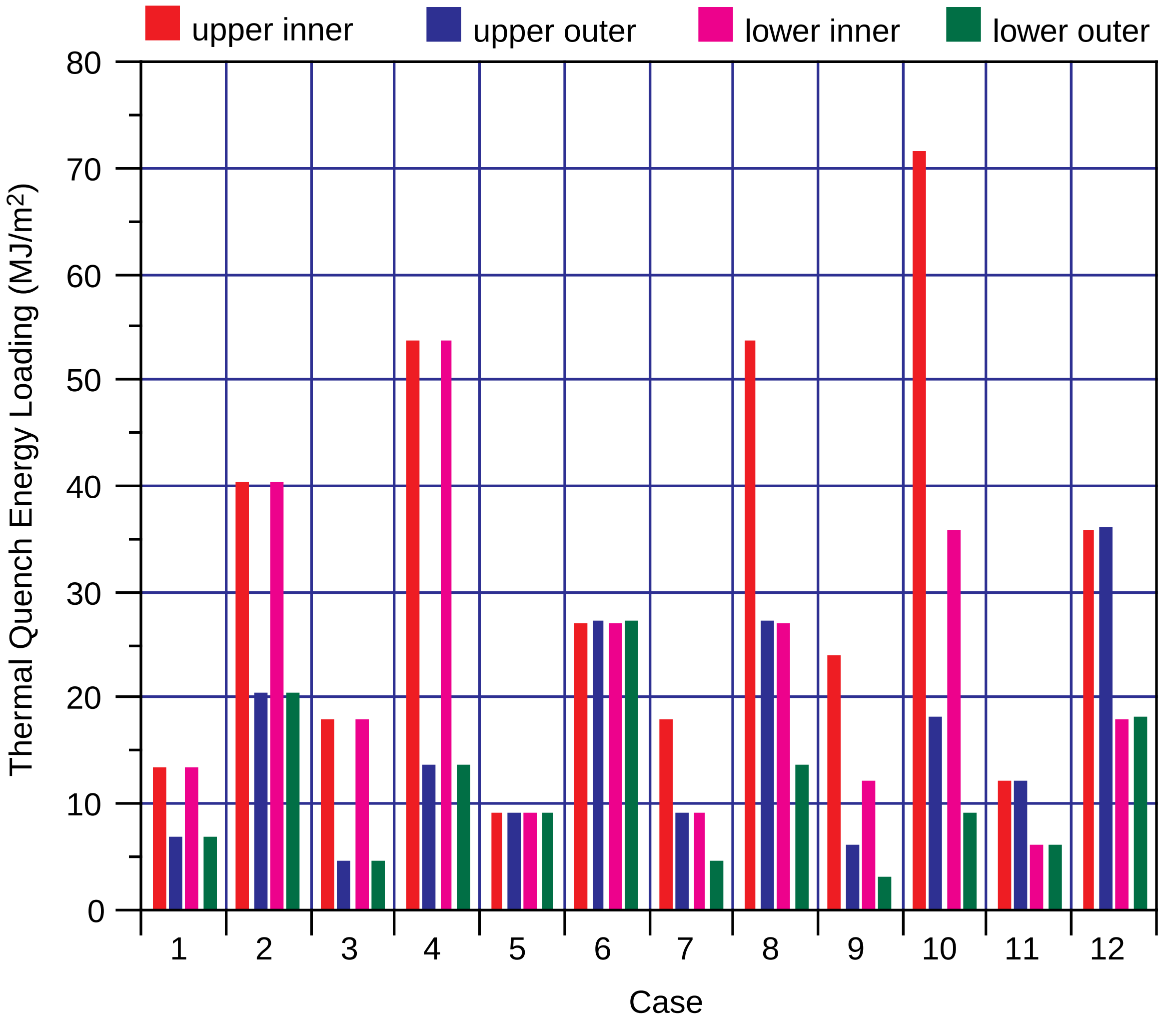


Fig. 1. Thermal quench data with application to FIRE
(empirical scaling, from *ITER Physics Basis*, Chapter 3)

Thermal Quench Energy Deposition

- ~80-100% W_{th} to active PFCs (divertor targets)
- ~3-x SOL expansion (1-x to 10-x); 0-30% to baffle (depends on configuration)
- Up to 2: 1 toroidal peaking + MHD
- In/out split for SN ~1:1 (2:1 to 1:2); no DN data
- Up/down split for DN depends on symmetry; design basis assumption 1:1 to 2:1 (CDA!)
- Combination of uncertainties yields 3-72 MJ/m^2 on divertor; 'mean' = ~20 MJ/m^2
- Lack of systematic TQ data and good energy accountability for SN disruptions identified as R&D need by ITER EG; FIRE needs data for DN and near-DN therrmal quench

Combination of TQ Basis Parameters



Current Quench Basis

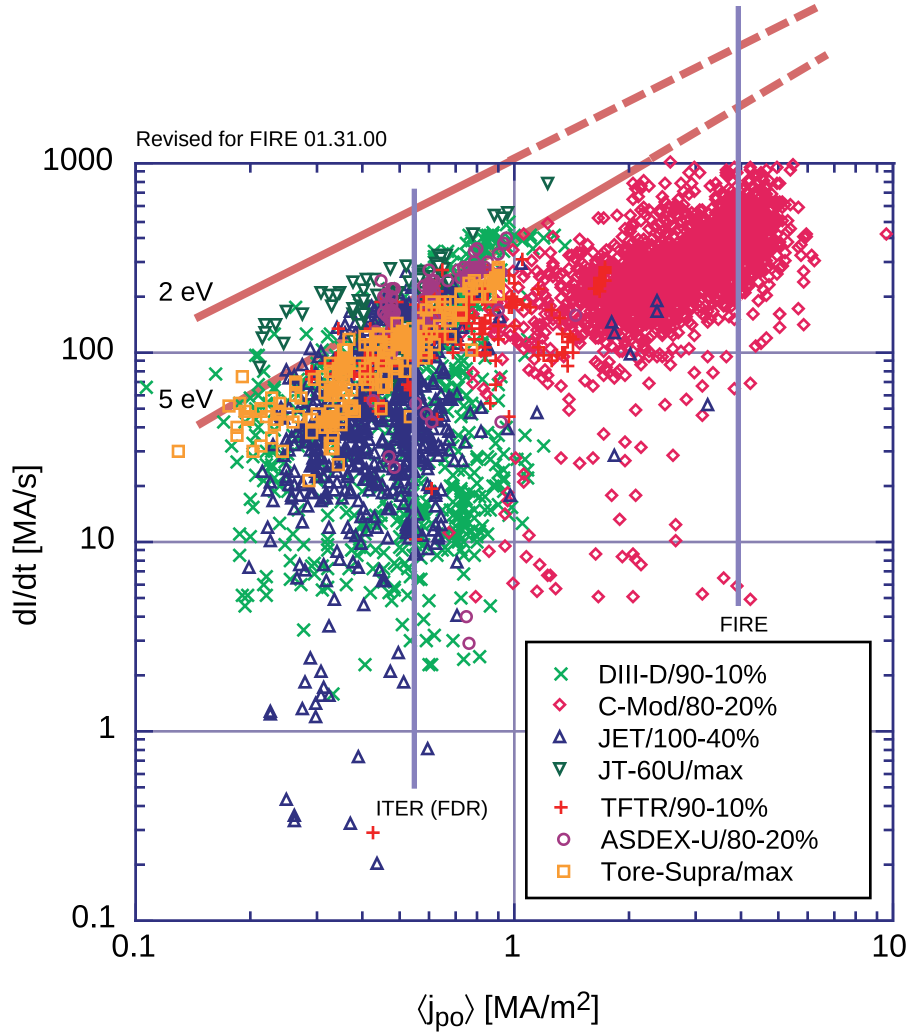


Fig. 3. Current quench database (various tokamaks), with contours of corresponding electron temperature superposed (calculated per Ohmic heating/radiation loss power balance model)

Halo Current Magnitude

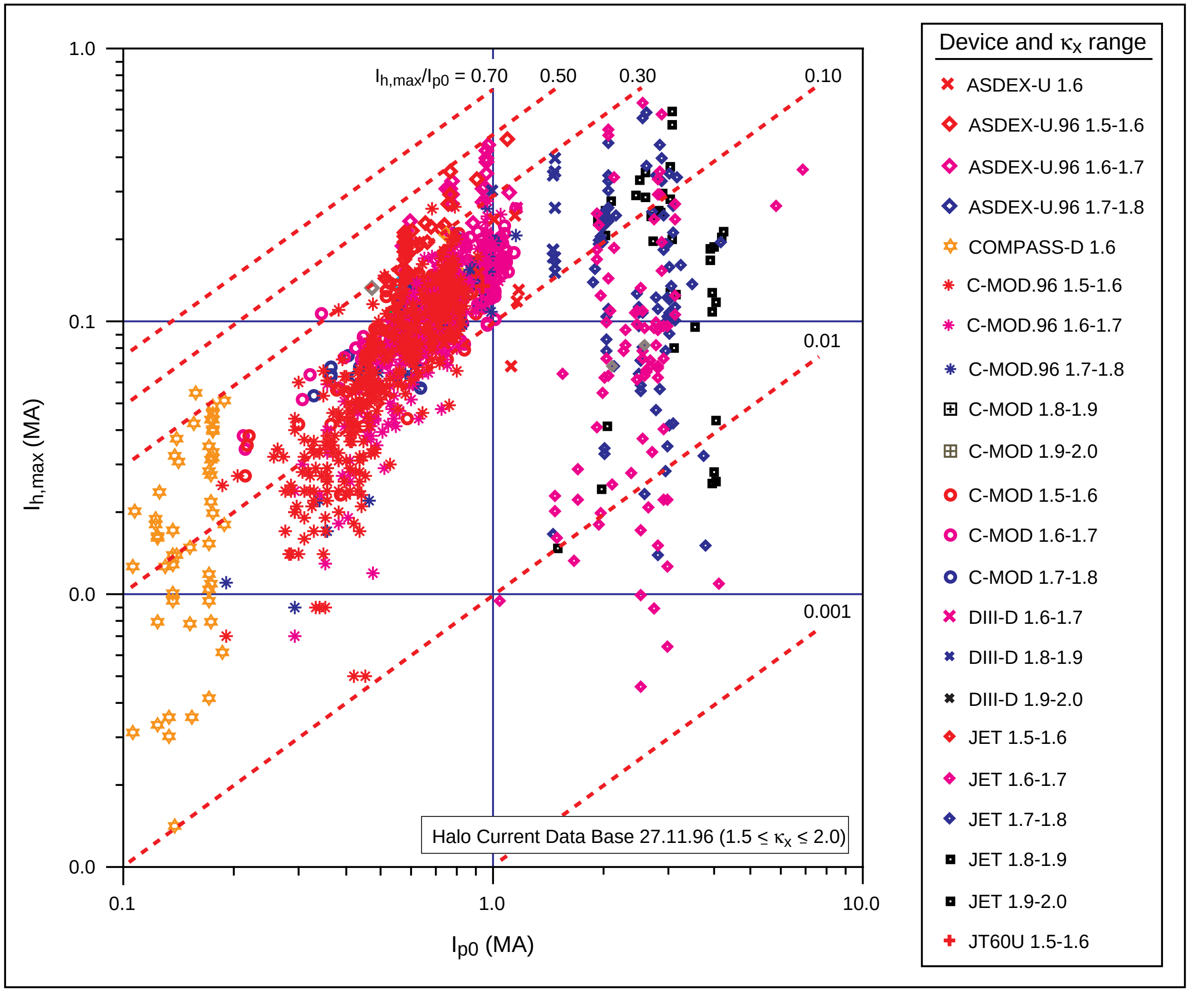


Fig. 6. Peak total halo current ($I_{h,max}$) versus pre-disruption plasma current (I_{p0}) for disruptions in elongated tokamaks. For plasmas with vertical elongation $1.5 \leq \kappa_X \leq 2.0$, where κ_X is the elongation at the separatrix.

Halo Current Asymmetry (TPF)

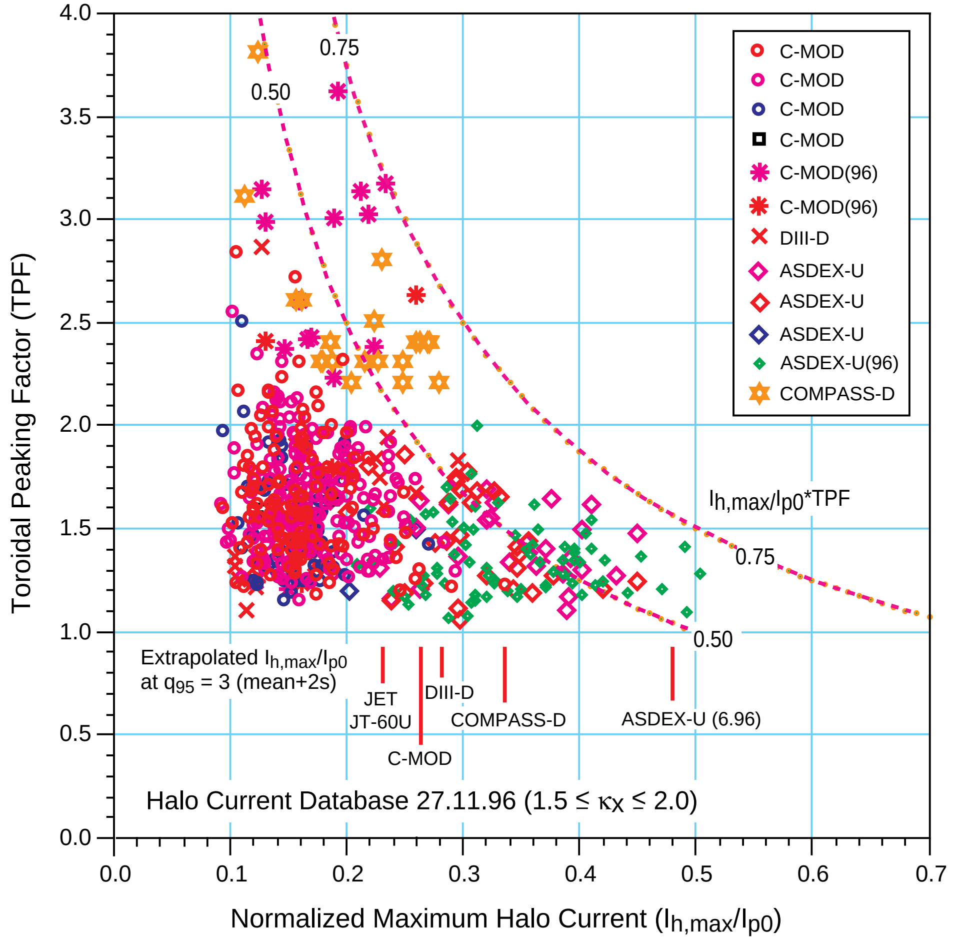


Fig. 9a. Toroidal peaking of halo currents in tokamaks, for plasmas with $1.5 \leq \kappa_X \leq 2$. High peaking factors occur only at low halo current fraction. The hyperbolic curves show limiting bounds for the data. Bounds on the normalized maximum halo current at $q_{95} = 3$ derived from the data in Fig. 3 are also shown.

Halo Current Asymmetry (TPF)

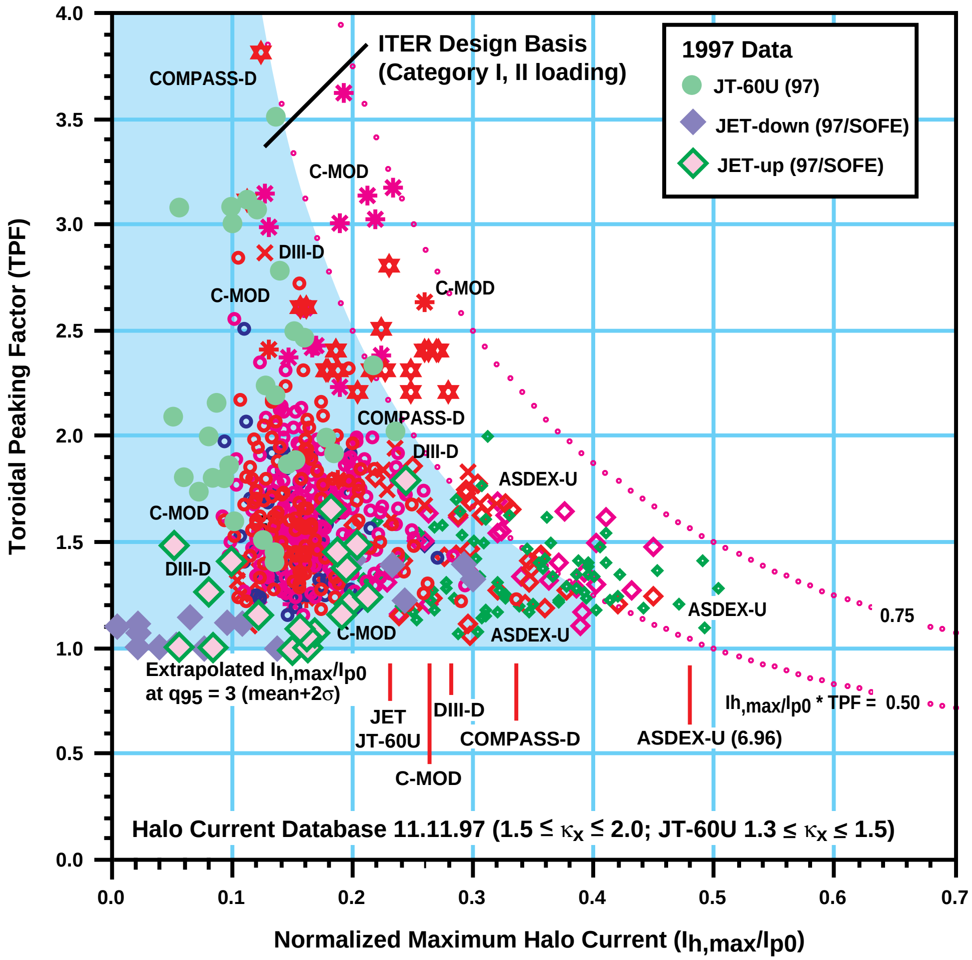


Fig. 9b. Halo current database, selected for $1.5 \le \kappa_X \le 2.0$. Recent data reported by JET and JT-60U added. The shaded $I_{h,max}/I_{p0}$ vs. TPF domain shows the loading condition envelope established for ITER in-vessel and vessel component design for so-called Category I and II loading conditions (routine/normally-expected events)

Vertical and Lateral Forces (VV and In-VV)

- Maximum vertical force (B_T*I_h*2a_o) ≤ 32 MN (320 tonnes)
  - Likely vertical force ~16 MN (160 tonnes)
  - Lateral force = 1/3 F_z: ~6 MN (60 tonnes)
  - Estimates are for 10 T and 50% halo current (or 12 T and 40% halo current)
- Need B_R(Z) calculation and TSC (distribution, dynamics)
  - Localization, asymmetry in passive stabilizer(s), effect of plasma 'bridging' to divertor?
  - 3-D plasma model, detailed predictive basis lacking!

Runaway Electron Conversion

• Knock-on avalanche is possible following FIRE disruption or VDE: growth rate is $1000 \leq \gamma_{RA}(s^{-1}) \leq 10000$

• Conversion gain is low: only (!) 10^6 (cf 10^{19} for ITER)

• Need ~1 A of seed current to have RAe trouble

• Seed level in FIRE uncertain:
pellet 'interchange' mechanism a risk?

• MHD losses can offset avalanche growth:
what are fluctuation levels in
post-thermal-quench plasma?

• Runaway strike will be poloidally and toroidally localized.
Toroidal alignment is critical (RA SOL ~1 mm)
ITER calculations yield ~mm damage

Summary and Conclusions

- Disruption, halo current and RAe- characteristics have been specified (based upon ITER Physics Basis); VV and in-VV response TBD
- Thermal quench data (SN) quality is poor; DN data wholely lacking (R&D for C-Mod and DIII-D)
- Divertor plasma shielding and radiative energy redistribution is critical divertor response issue
- Halo current magnitude and VV force estimated: need TSC and toroidal asymmetry model (3-D plasma) for details; passive stabilizer role and asymmetry needs further physics R&D (ASDEX-U)
- Possibility of after-TQ VDE stabilization TBD
- Outcome of RAe- uncertain (seed and MHD levels); potential for serious in-vessel surface damage