Termination of disruptions with runaway current plateau formation in present experiments and consequences for ITER

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Background

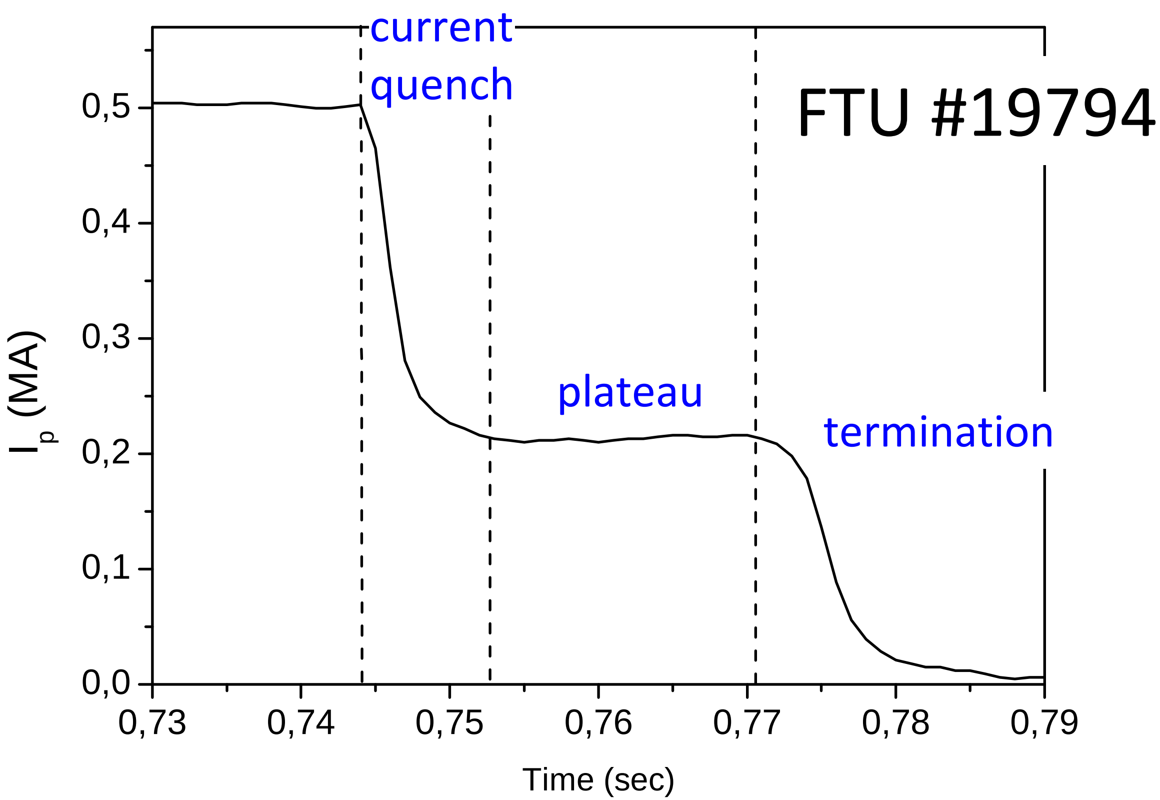
- Most of the work on disruption generated runaway electrons has focused on the mechanisms determining the generation of runaways during the current quench (CQ) of the disruption

- As much of two thirds of the predisruption plasma current has been predicted to turn into runaway current during an ITER disruption, mainly due to the avalanche mechanism

(L.G. Eriksson et al., Phys. Rev. Lett. ***92*** *(2004) 205004*)

- The estimated kinetic energy of the resulting runaway beam is W_{run}~ 10 - 30 MJ

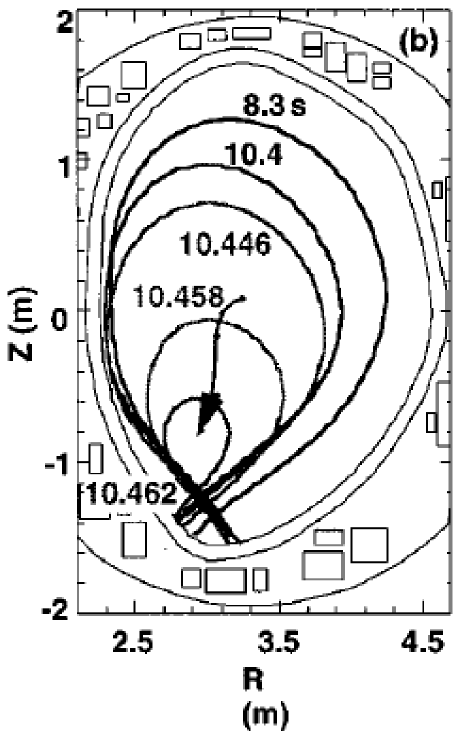
- Much less attention has been paid to the termination phase of the disruption when the runaway plasma becomes unstable, and the current and the runaway electrons are lost

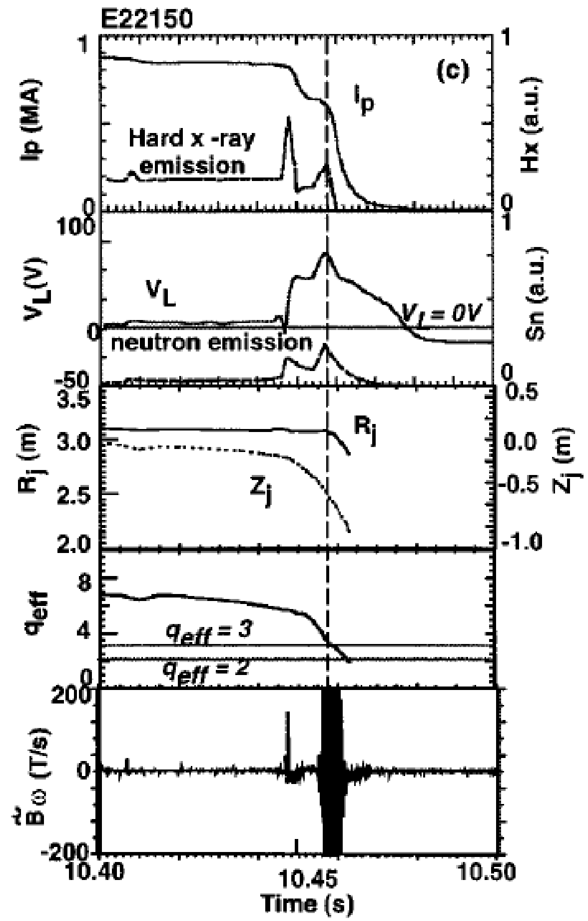


- The processes that lead to the runaway plateau instability are not well understood:

  - *movement of the plasma column leading to compression of runaway plasma against the wall and triggering MHD instabilities*

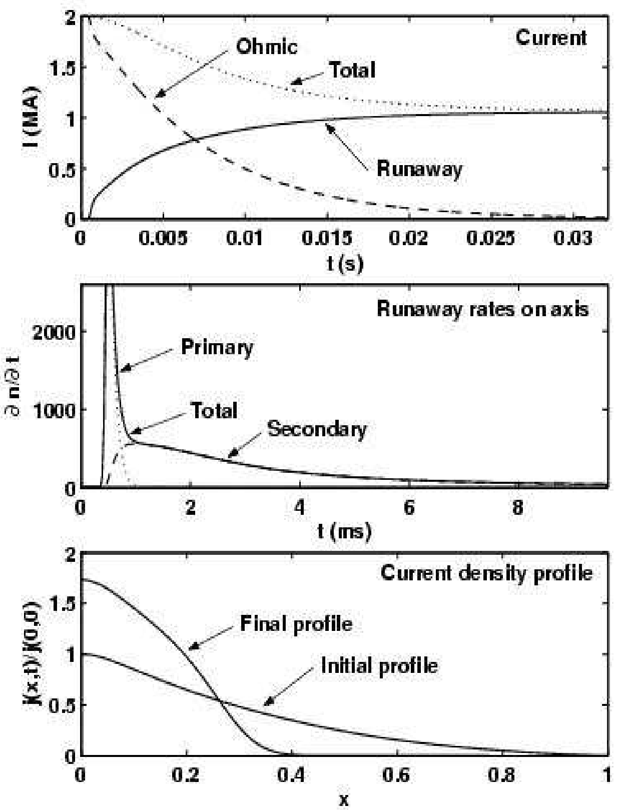
R. Yoshino and S. Tokuda, Nucl.Fusion. ***40*** *(2000) 1293*





➢ *MHD instabilities of the runaway beam itself*

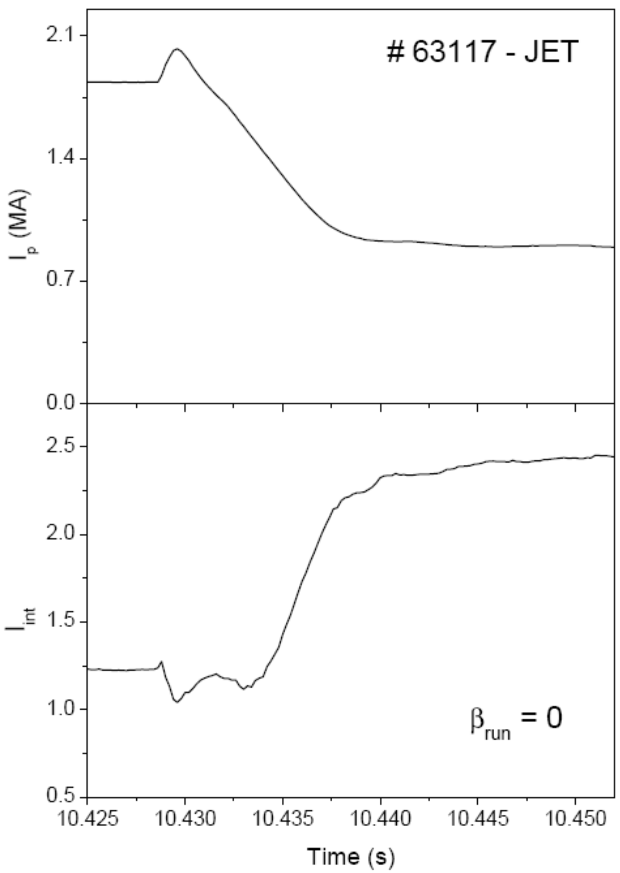
runaway current is predicted to be more peaked than pre-disruption current:



plasmas with steep current profiles
can be prone to tearing-mode instability

(P. Helander et al., Phys.Plasmas ***14*** *(2007) 122102)*

(L.G. Eriksson et al., Phys. Rev. Lett. ***92*** *(2004) 205004)*



*(A. Loarte et al., Nucl. Fusion **51** (2011) 073004)*

plasma equilibrium reconstruction with EFIT

↓

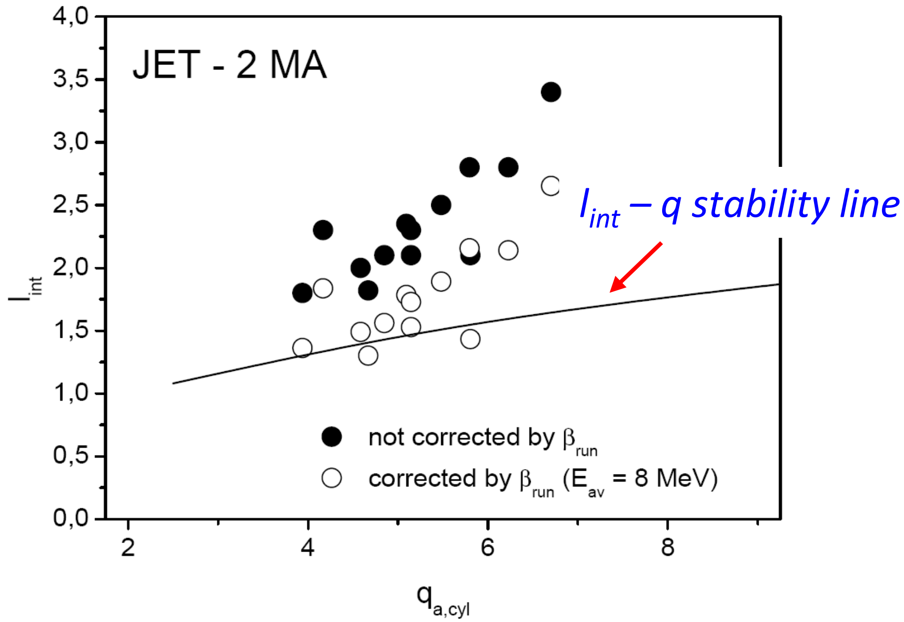
Shafranov Λ

↓

$$l_{\text{int}} = 2\left(\Lambda - \beta_{run}\right)$$

↓

β_{run}: poloidal β due to the runaways: $\beta_{run} \approx \gamma \frac{I_{A0}}{I_r}$



- During current termination conversion of magnetic energy into runaway kinetic energy may occur, and the energy gained by the runaway electrons can substantially increase in comparison with the energy gain during the CQ only

in ITER, the magnetic energy stored in the plateau runaway beam, $W_{mag}^{tot} = L\, I_r^2/2 \sim 800$ *MJ* ($I_r \sim 10$ *MA), much larger than* W_{run}

- Experimental evidence that such a conversion takes place has been reported for the first time in JET, where it has been shown that conversion of a few tenths of the magnetic energy into runaway kinetic energy is likely occuring

*(A. Loarte et al., Nucl. Fusion **51** (2011) 073004)*

JET disruptions *($R_0 \sim 3$ m; $a \sim 1$ m)*

both, accidental and purposely triggered disruptions by impurity puffing

Pre-disruption plasma current ~ 1 – 6 MA; Plateau runaway current ~ 0.3 – 3 MA

DIII-D disruptions *($R_0 \sim 1.67$ m; $a \sim 0.6$ m)*

purposely triggered disruptions by Ar pellet injection

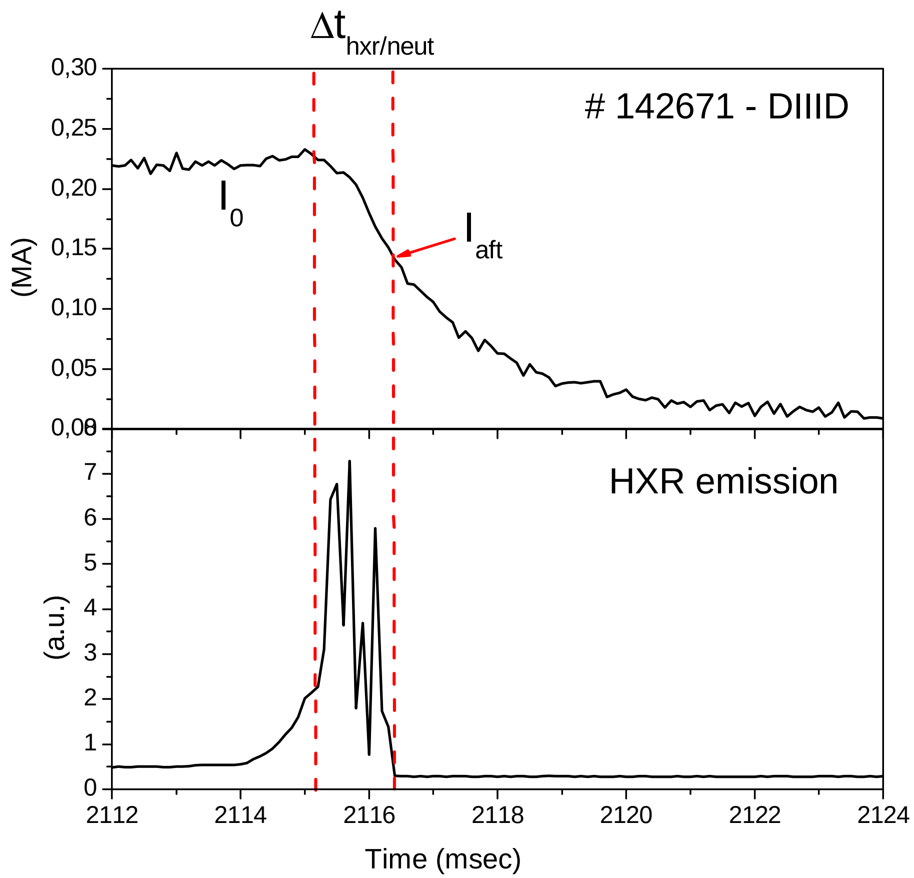
Pre-disruption plasma current ~ 1 MA; Plateau runaway current ~ 0.05 – 0.4 MA

FTU disruptions *($R_0 \sim 0.935$ m; $a \sim 0.3$ m)*

most runaway plateaus are observed in disruptions occurring during LHCD or the current ramp-up

Pre-disruption plasma current ~ 0.3 – 0.5 MA; Plateau runaway current ~ 0.1 – 0.2 MA

Runaway plateau terminations



- Runaway plasma becomes unstable and runaways are lost: the signature is the HXR or photoneutron emission when the runaways hit the PFC
- After $\Delta th_{hxr/neut}$ all the current is ohmic and decays resistively

I_0 = plateau runaway current
I_{aft}= ohmic current after runaway loss
$\Delta t_{hxr/neut}$ = runaway loss interval

- during $\Delta t_{hxr/neut}$ conversion of magnetic energy into runaway kinetic energy may occur

current decay ($dI_p/dt < 0$)

↓

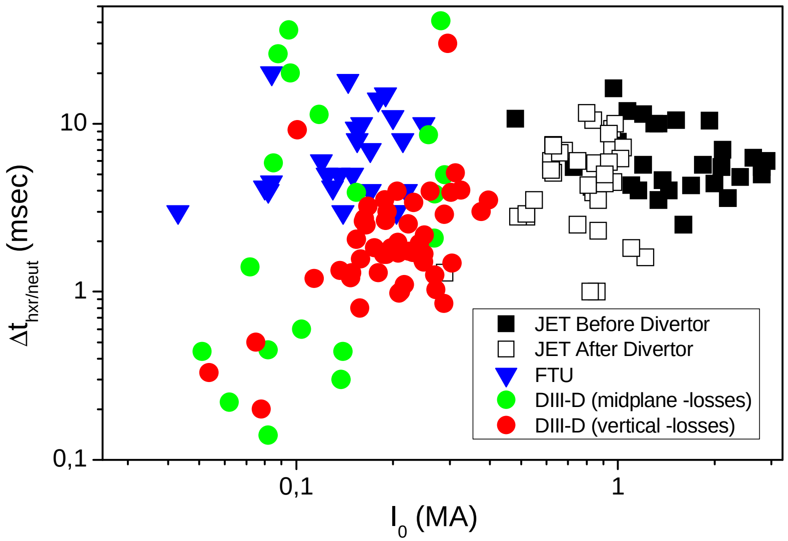
$E_{//}$

↙ ↘

runaway acceleration and generation (W_{run})

induced ohmic current (ohmic dissipation) (W_{OH})

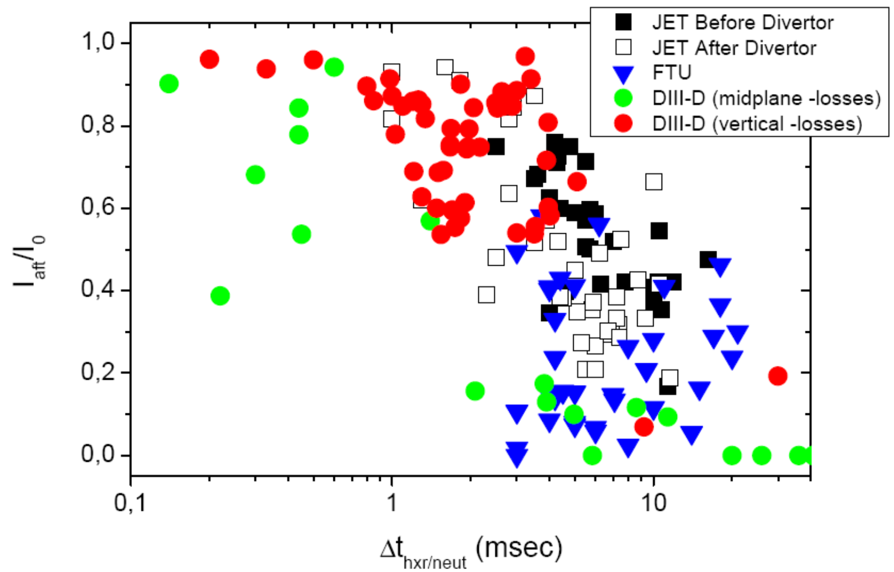
- the balance between these two effects will determine how much of the initial magnetic energy is converted into runaway kinetic energy, W_{run}, or ohmically dissipated, W_{OH}



typical duration of the runaway loss: $\Delta t_{hxr/neut} \sim 1 – 10$ ms

lower ohmic conversion, I_{aft}/I_0 , for slow terminations

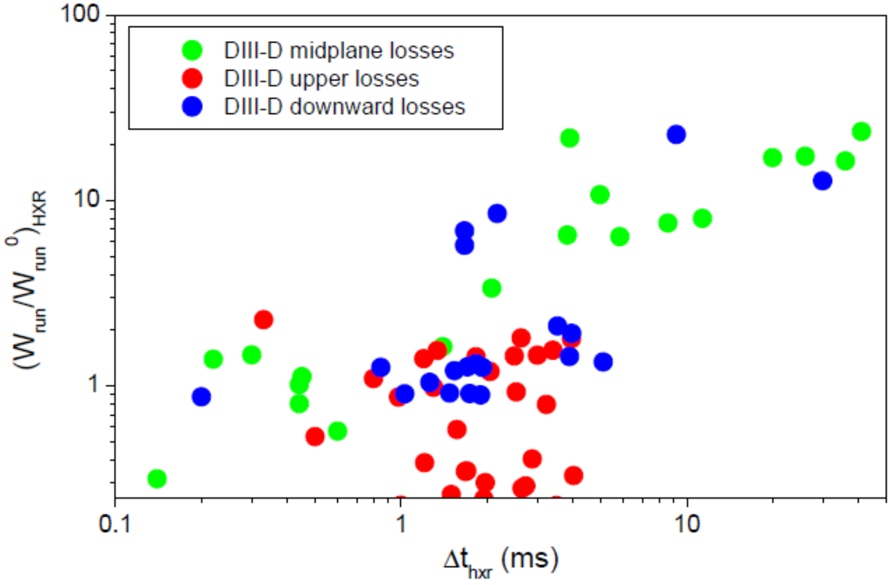
(suggesting lower ohmic dissipation and larger energy conversion into runaway kinetic energy)



magnitude of HXR in DIII-D flashes points out up to 10x conversion of magnetic to kinetic RE energy in slow RE-wall strikes

- W_{run}: total energy deposited on the runaway electrons

- W_{run}^{0}: plateau runaway kinetic energy



(E. Hollmann et al., EX/9-2, 24th IAEA Conf., San Diego (2012))

suggests up to 10x increase in RE beam kinetic energy for long interaction times!

Mechanisms determining energy conversion

it is suggested that a fundamental parameter determining ohmic conversion, I_{aft}/I_0 , during current terminations is given by the ratio of the ohmic decay time of the residual current, I_{aft}, to the runaway loss interval, $\Delta t_{hxr/neut}$

$$E_\parallel \sim \frac{L}{2\pi R}\frac{dI_p}{dt} \sim \frac{L}{2\pi R}\frac{I_0 - I_{aft}}{\Delta t_{hxr}}$$

$$E_\parallel \sim \eta\, j_{OH} \sim \eta \frac{I_{aft}}{\pi a^2}$$

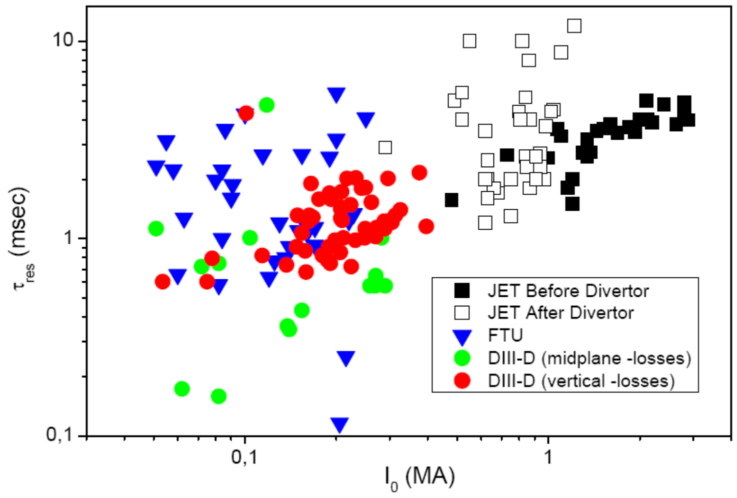
$$\tau_{res} = \frac{L_p}{R_p}; \quad R_p \approx \eta \frac{2R_0}{a^2}$$

$$\frac{I_{aft}}{I_0} \sim \frac{(\tau_{res}/\Delta t_{hxr})}{1+(\tau_{res}/\Delta t_{hxr})}$$

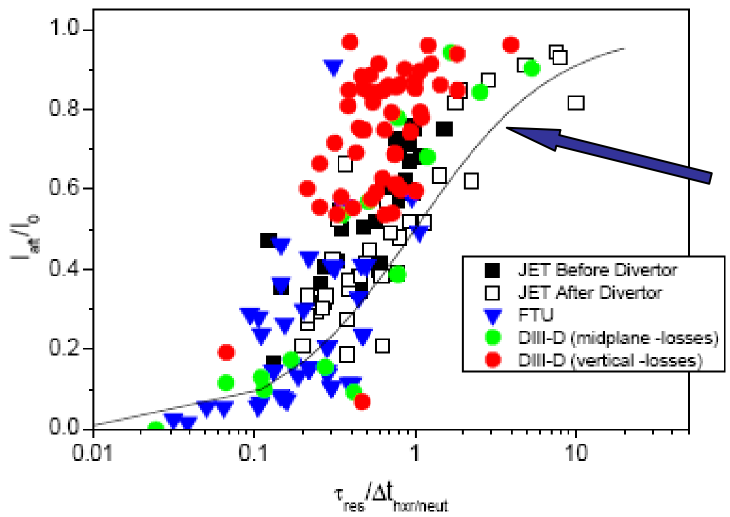
ohmic conversion increases with $\tau_{res}/\Delta t_{hxr}$

energy conversion into runaway kinetic energy decreases with $\tau_{res}/\Delta t_{hxr}$

$$\tau_{res} \approx \frac{I_{aft}}{\left(dI_p / dt\right)_{aft}}$$



…which seems to be supported by experiment…



$$\frac{I_{aft}}{I_0} \sim \frac{\left(\tau_{res} / \Delta t_{hxr}\right)}{1+\left(\tau_{res} / \Delta t_{hxr}\right)}$$

simple 0-D modelling, neglecting runaway generation during current termination, and taking only into account acceleration by the electric field of the plateau runaway electrons, confirms the above picture

$$2\pi R_0 E_{\parallel} = -\frac{d}{dt}\left(L_p I_p\right)$$

$$E_{\parallel} = \eta\left(j_p - j_r\right) \approx \frac{\eta}{\pi a^2}\left(I_p - I_r\right)$$

$$\frac{dI_r}{dt} \approx -\frac{I_r}{\tau_{diff}}$$

→

$$I_p = \frac{I_0\ \tau_{res}}{\tau_{res} - \tau_{diff}}\left(e^{-t/\tau_{res}} - \frac{\tau_{diff}}{\tau_{res}} e^{-t/\tau_{diff}}\right)$$

$$I_{OH} = \frac{I_0\ \tau_{res}}{\tau_{res} - \tau_{diff}}\left(e^{-t/\tau_{res}} - e^{-t/\tau_{diff}}\right)$$

$$I_r = I_0\ e^{-t/\tau_{diff}}$$

$$\tau_{res} = \frac{L_p}{R_p} \approx \frac{a^2 L_p}{2R_0 \eta}$$

$$\left(R_p \approx \eta \frac{2R_0}{a^2}\right)$$

- *Estimate of I_{aft} :*

I_{aft} is defined as the plasma current when the runaway population is lost:

$$\frac{I_r}{I_0} = f$$

(f is a small value, chosen as f ≈ 1-5%)

$$\frac{I_r}{I_0} = e^{-t_f/\tau_{diff}} = f \quad \longrightarrow \quad t_f \approx \Delta t_{hxr/neut} = -\tau_{diff} \ln f$$

$$I_p = \frac{I_0\, \tau_{res}}{\tau_{res} - \tau_{diff}} \left(e^{-t/\tau_{res}} - \frac{\tau_{diff}}{\tau_{res}} e^{-t/\tau_{diff}} \right)$$

$$\frac{I_{aft}}{I_0} \equiv \frac{I_p(t_f)}{I_0} = \frac{R}{R-1} \left(f^{1/R} - \frac{f}{R} \right)$$

$$R \equiv \frac{\tau_{res}}{\tau_{diff}} \approx \frac{a^2 L_p}{2R_0 \eta\, \tau_{diff}}$$

- *Fraction of energy into runaways:*

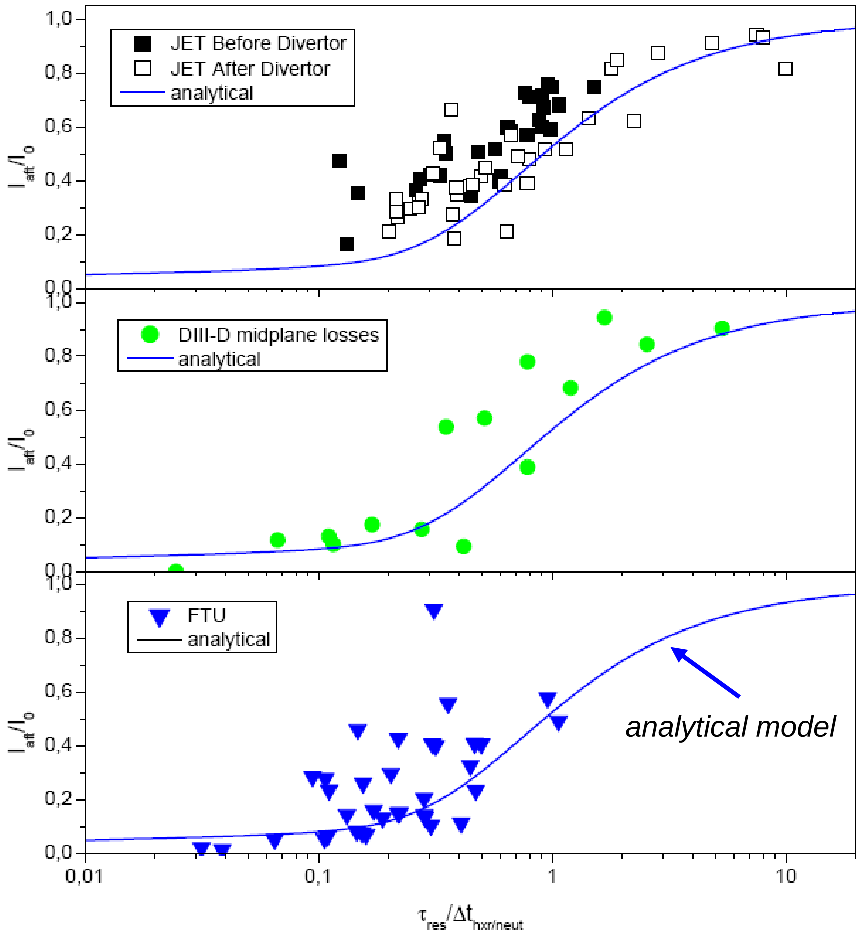
$$\Delta W_{run} \approx 2\pi R_0 \int_0^{\infty} E_{\parallel} I_{run}\, dt \approx R_p \int_0^{\infty} I_{OH}\left(I_p - I_{OH}\right) dt$$

$$\frac{\Delta W_{run}}{L_p I_0^2 / 2} \approx \frac{1}{R+1}$$

$$R \equiv \frac{\tau_{res}}{\tau_{diff}} \approx \frac{a^2 L_p}{2 R_0 \eta\, \tau_{diff}}$$

conversion of magnetic into kinetic runaway energy is determined by τ_{res}/τ_{diff}

C.R. Frascati



$$\frac{I_{aft}}{I_0} = \frac{R}{R-1}\left(f^{1/R} - \frac{f}{R}\right)$$

$$R \equiv \frac{\tau_{res}}{\tau_{diff}}$$

more accurate modelling and comparison with the experiment demands including runaway generation, induced currents in the vessel and penetration of the externally stored magnetic energy during termination

$$2\pi R_0 E_{\|} = -\frac{d}{dt}\left(L_p I_p + M I_v\right)$$

current decay

$$\frac{d}{dt}\left(M I_p + L_v I_v\right) = -R_v I_v$$

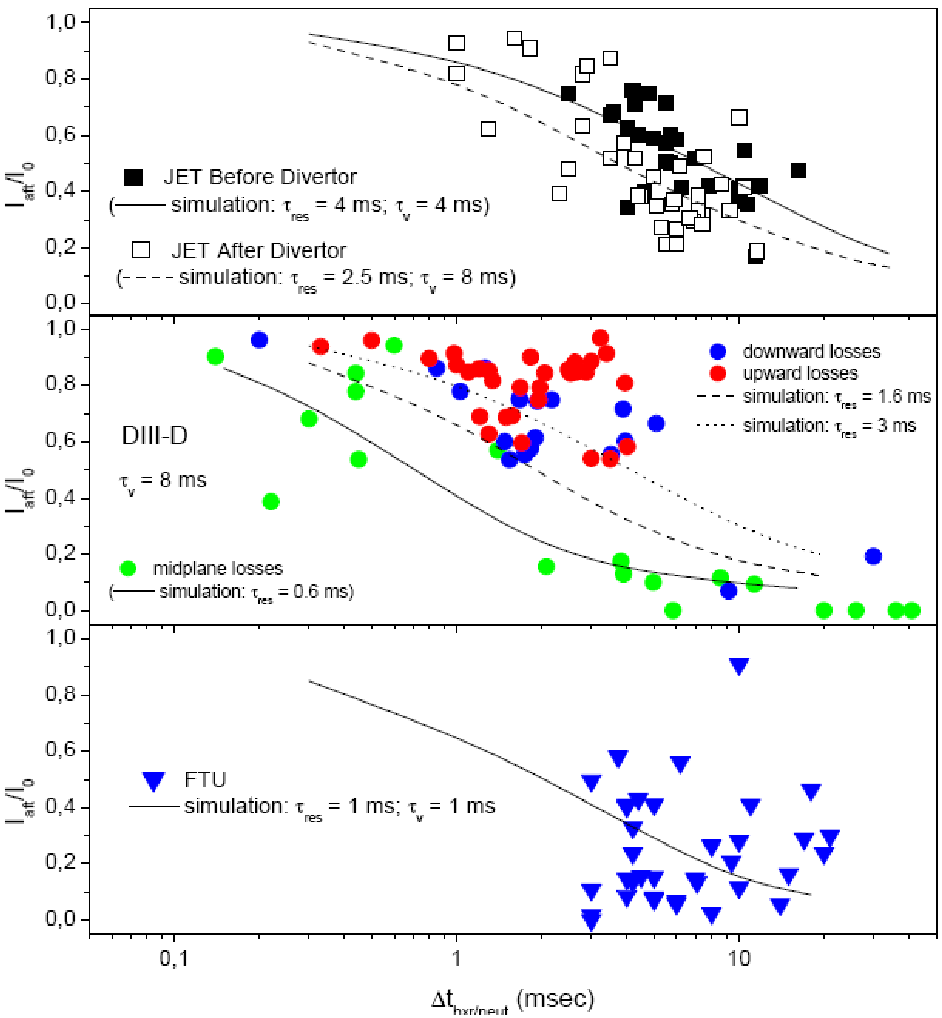
vessel induced current

$$E_{\|} = \eta\left(j_p - j_r\right)$$

electric field

$$\frac{dI_r}{dt} = \left(\frac{dI_r}{dt}\right)_{Dreicer} + \left(\frac{dI_r}{dt}\right)_{secondary} - \frac{I_r}{\tau_{diff}}$$

runaway generation and loss



Input data:

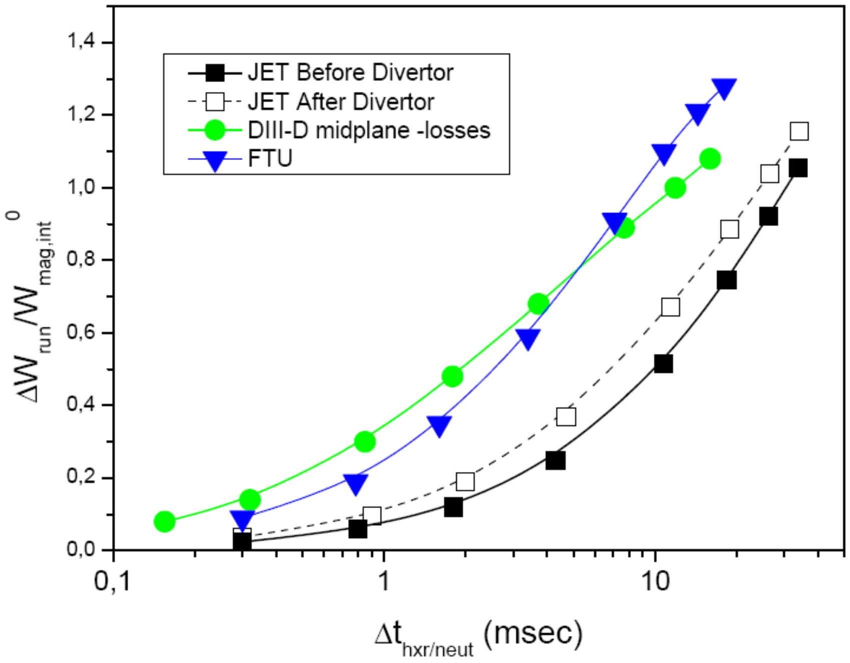
measured τ_{res}

measured τ_v ($\equiv L_v/R_v$)

$$L_p \cong \mu_0 R_0 \left(\frac{l_{int}}{2} + \ln\left(\frac{8R_0}{r_w}\right) - 2 \right)$$

$$L_v \approx M \approx \mu_0 R_0 \left(\ln\left(\frac{8R_0}{r_w}\right) - 2 \right)$$

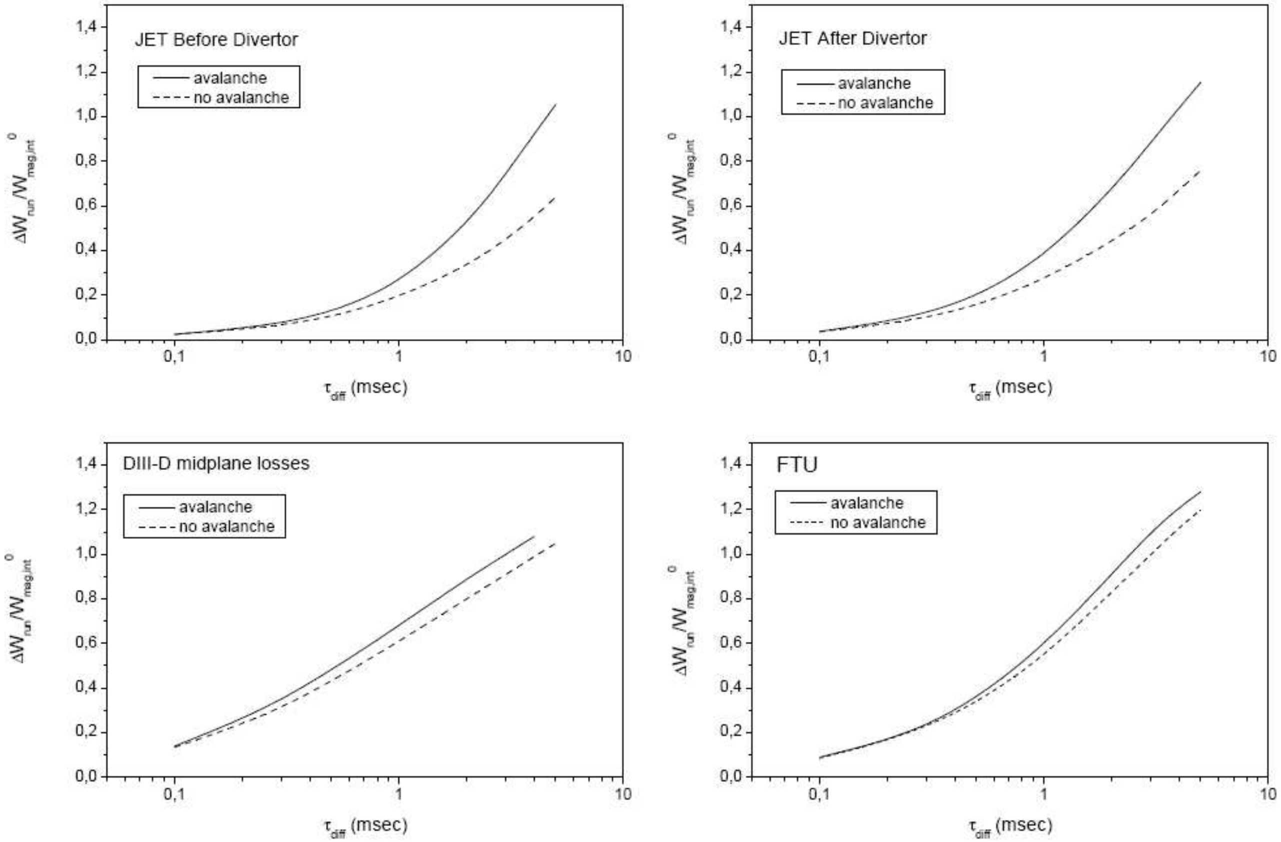
τ_{diff} = 0.1 – 5 ms



(W^0 $_{mag,int}$: internal magnetic energy of the plateau runaway beam)

- lower conversion into runaway kinetic energy in JET is mainly due to the larger ohmic decay time, τ_{res} , corresponding, for similar characteristic runaway loss times, to larger τ_{res}/τ_{diff}

- *Energy conversion and avalanche runaway generation:*



energy conversion due to the generation of runaways increases with the plateau current and for slow terminations

Summary

- Termination of the current and the loss of runaway electrons following runaway current plateau formation in JET, DIII-D and FTU disruptions has been investigated

- Substantial conversion of magnetic energy into runaway kinetic energy is likely occurring for the slowest terminations

- Simple modelling and experiment suggest that energy conversion in actual devices is determined to a great extent by τ_{res}/τ_{diff}, and that, for large enough currents, avalanche generation of runaway electrons can increase substantially the amount of energy deposited on the runaway population

ITER disruption terminations:

- Extrapolations to ITER are subject to large uncertainties mainly due to our incomplete understanding of the thermal plasma and the runaway beam characteristics after the current quench phase of the disruption as well as of the instabilities leading to the runaway loss and current termination

- *τ_{res} ~ 50 – 150 ms, τ_v ~ 500 ms $\rightarrow$ lower conversion efficiency, $\Delta W_{run}/W_{mag,int}^0$, than in actual devices*

however…

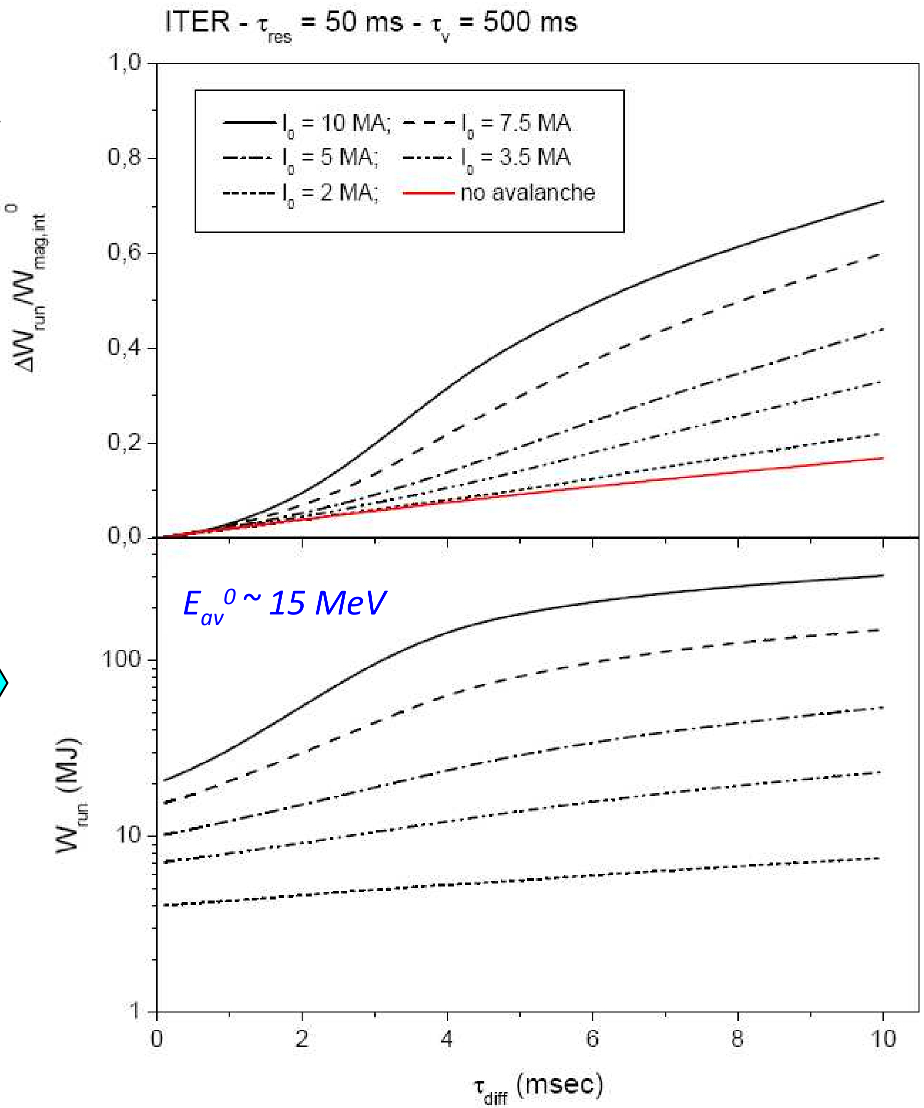
- *much larger magnetic energies ($W_{mag}^0 \propto I_0^2$)*

- *larger runaway generation due to the avalanche mechanism* *fraction of internal magnetic energy converted into runaway kinetic energy*

$$\Delta W_{run} \approx 2\pi R_0 \int_0^\infty I_{run}\left(E_\parallel - E_R\right) dt$$

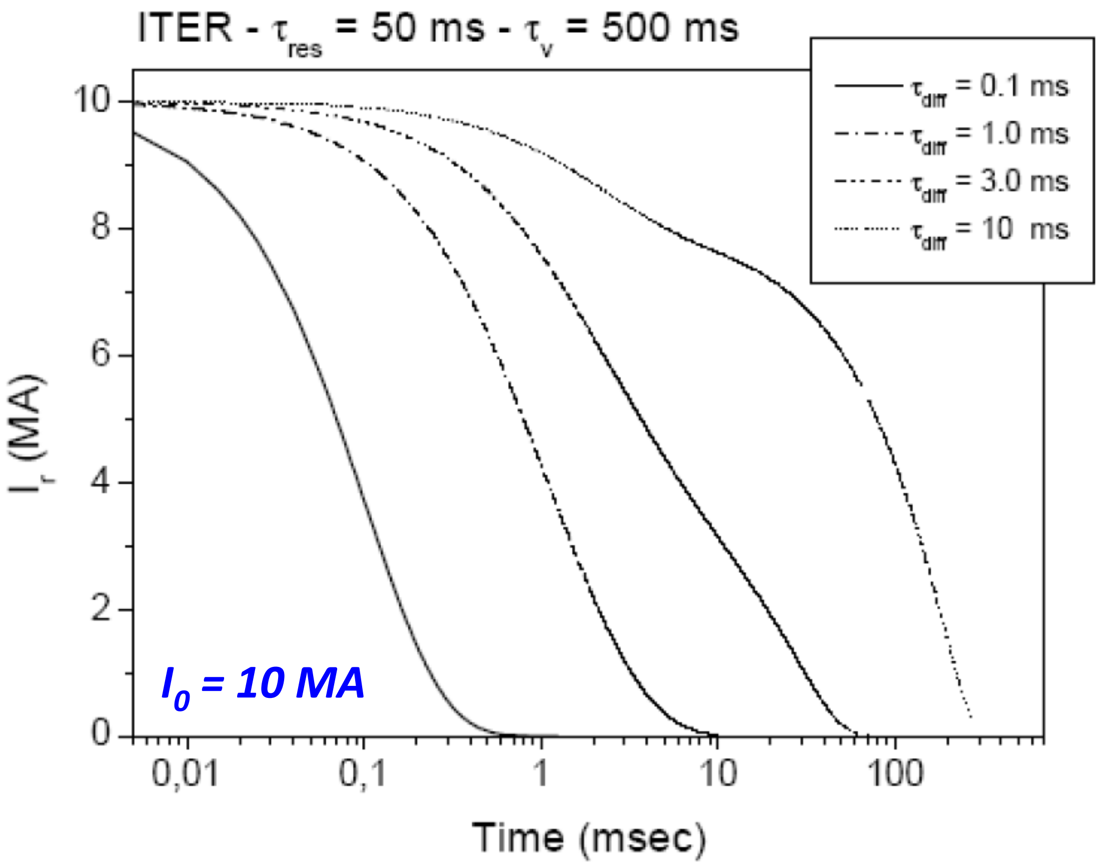
total energy deposited in the form of runaway kinetic energy during disruption termination

$$W_{run} = W_{run}^0 + \Delta W_{run}$$

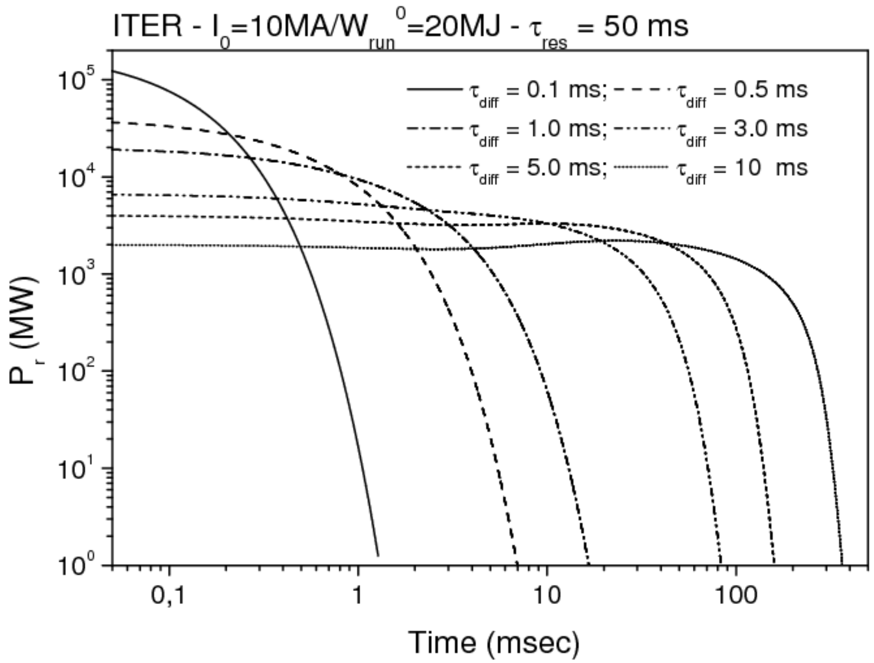


(W_{run}^0: *plateau runaway kinetic energy*, *assumed proportional to the plateau current* ~ $I_0 E_{av}^0$)

…moreover, the time for the loss of the runaway current increases substantially with τ_{diff} mainly due to the avalanche generation of runaways



Power deposited by the runaway electrons:



- *for fast terminations, the total deposited energy is namely the plateau kinetic energy, with only a small fraction of the magnetic energy converted into runaway kinetic energy, but the peak power is the highest*

- *for slow terminations, the peak power load is substantially lower but the plasma facing components (PFC) are exposed for a significantly longer time and the total amount of deposited energy increases due to energy conversion*

Estimate of surface temperature increase:

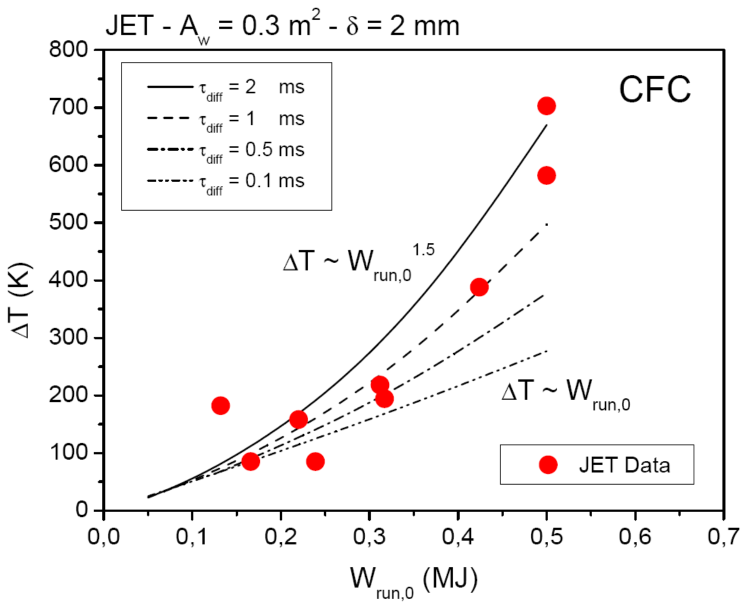
$$q(x,t) \approx q_0(t)\, e^{-x/\delta}$$

(runaway heat source)

$$\Delta T \approx \frac{\alpha}{K\,\delta}\int_0^t \frac{P_r(t')}{A_w}\, e^{\alpha\,(t-t')/\delta^2}\, erfc\left(\frac{1}{\delta}\sqrt{\alpha\,(t-t')}\right) dt'$$

$$\alpha \equiv \frac{K}{\rho\, C}$$

➢ Example: JET runaway heat loads



- *at low τ_{diff}, conversion of magnetic into runaway kinetic energy is negligible and the thermal loads increase linearly with I_0 (deposited energy: $W_{run} \sim W_{run}^0 \propto I_0$)*
- *for increasing τ_{diff}, energy conversion is stronger and, if I_0 is high enough, magnetic energy conversion will dominate the runaway energy, showing a trend to increase with the square of I_0*

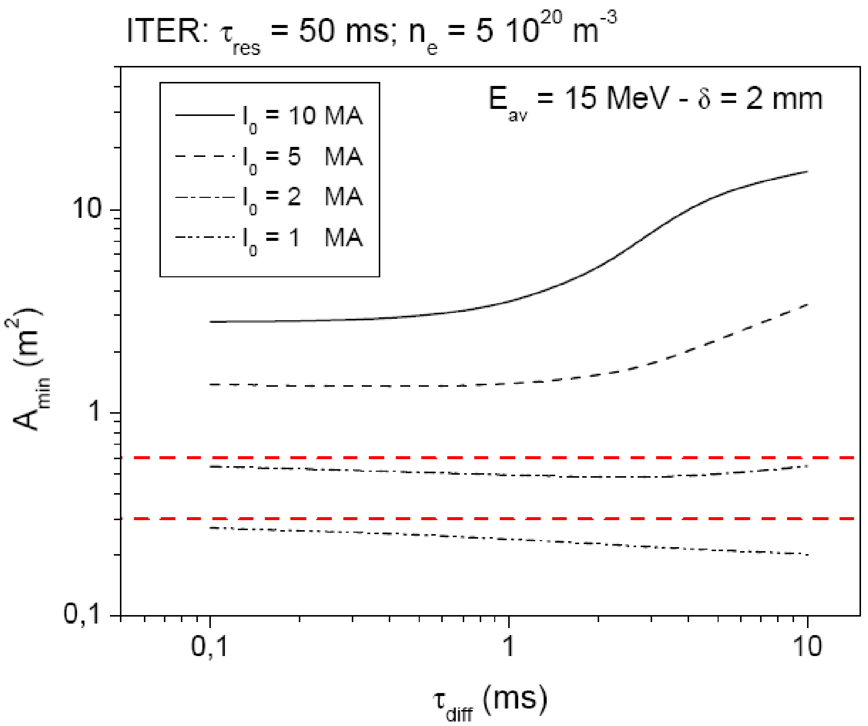
(for the simulations: $W_{run}^0 \propto I_0$ with 0.5 MJ for 1 MA, i.e., $E_{av}^0 \sim 8$ MeV)

(JET Data: V. Riccardo et al., Plasma Phys. Control. Fus. ***52*** *(2010) 124018)*

Minimum wetted area for Be melting avoidance:

$$A_{\min} \equiv \frac{\Delta T_{A_w=1m^2}}{\Delta T_{melting}}$$

- ΔT_{max} : calculated ΔT during termination for A_w = 1 m^2
- $\Delta T_{melting}$: ΔT for Be melting (~ 1000 K)



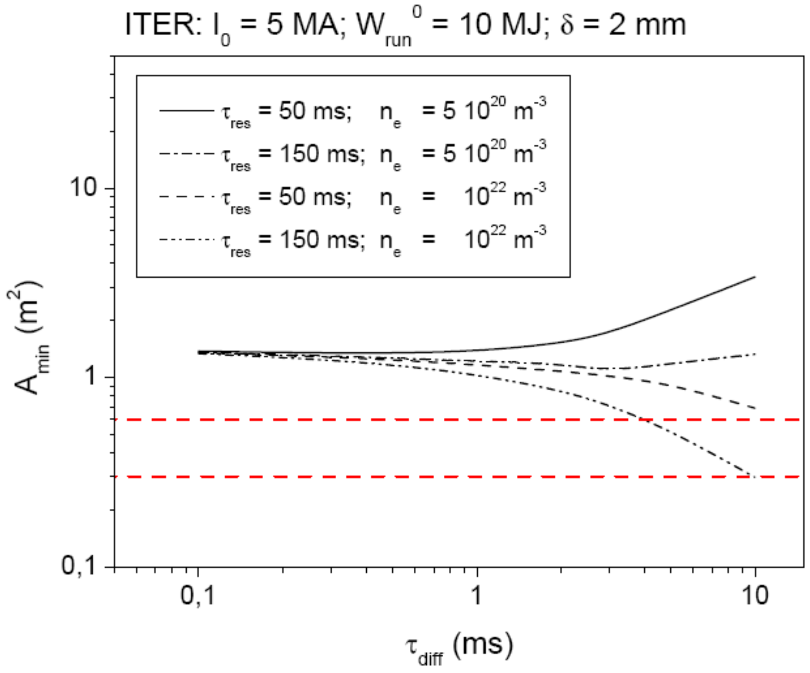
} *runaway wetted area estimated for ITER (~0.3 – 0.6 m²)*

under these assumptions, the plateau runaway current should be reduced to ~ < 2 MA in order to avoid damage on the first wall

Control of the runaway heat loads:

the amount of deposited power might be reduced:

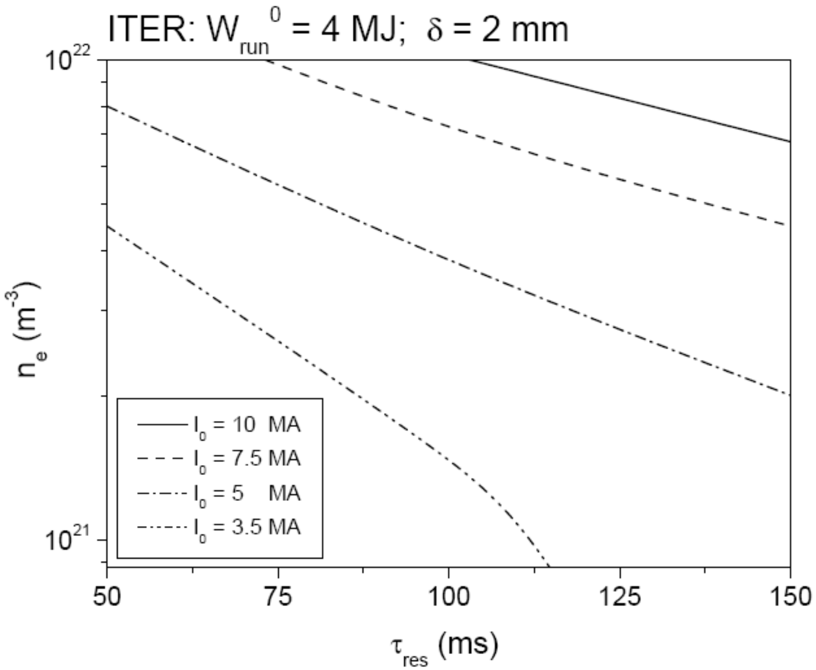
- *increasing the density (collisional dissipation)*
- *increasing the ohmic decay time, τ_{res} (less energy conversion)*



** not efficient for rapid terminations*

** fast terminations can only be controlled reducing W_{run}^{0}:*

hence, in order to keep $A_{min} < 0.6\ m^2$ during fast terminations, the plateau runaway energy must be lower than ~4 MJ *control of the runaway damage on the first wall for both fast and slow terminations demands a combination of a low enough energy of the plateau runaway beam together with high enough n_e and τ_{res} to prevent large conversion of magnetic into runaway kinetic energy*



Minimum required n_e for A_{min} < 0.6 m^2 and terminations in the range 0.1 < τ_{diff} < 10 ms