Member of the Helmholtz Association

TEC TRILATERAL EUREGIO CLUSTER

EFDA JET

JÜLICH FORSCHUNGSZENTRUM

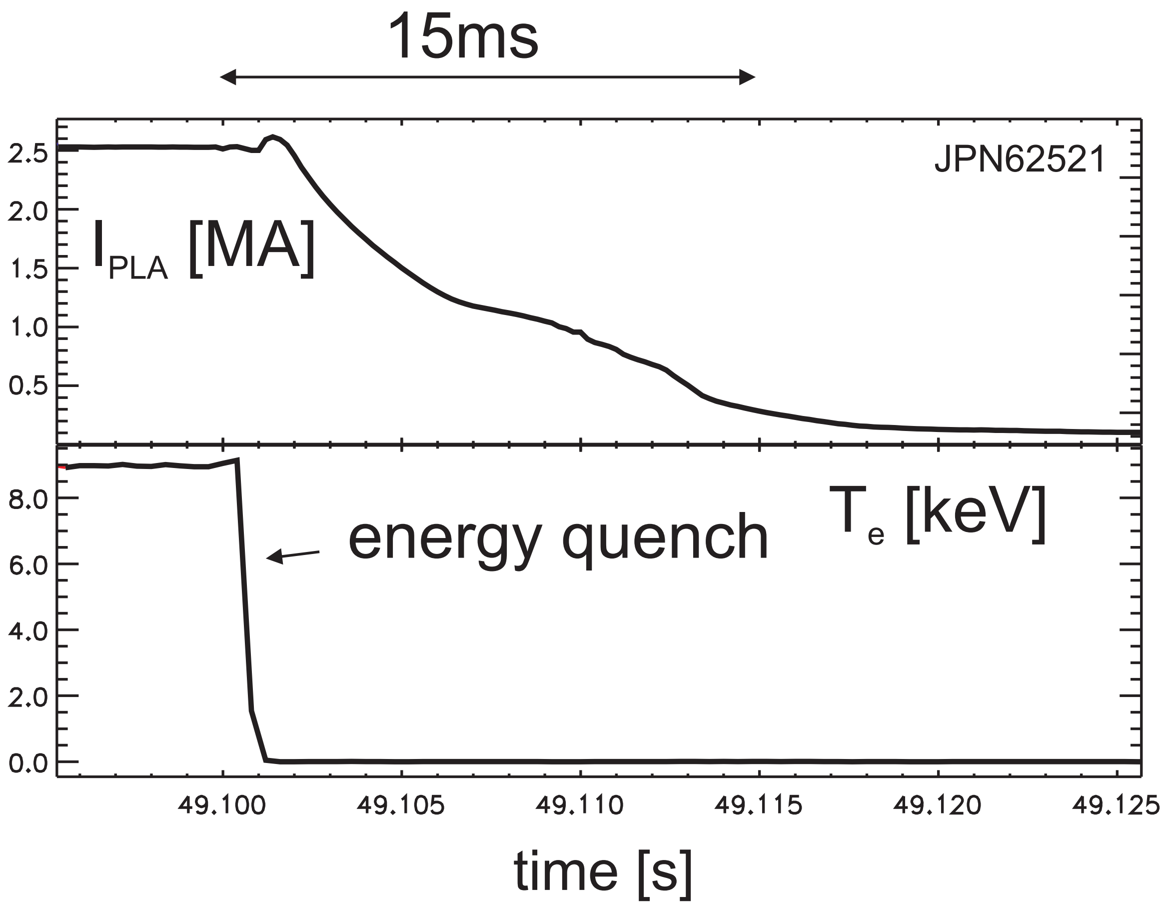
Disruption Control

M. Lehnen

Institute of Energy Research - Plasma Physics, Forschungszentrum Jülich GmbH

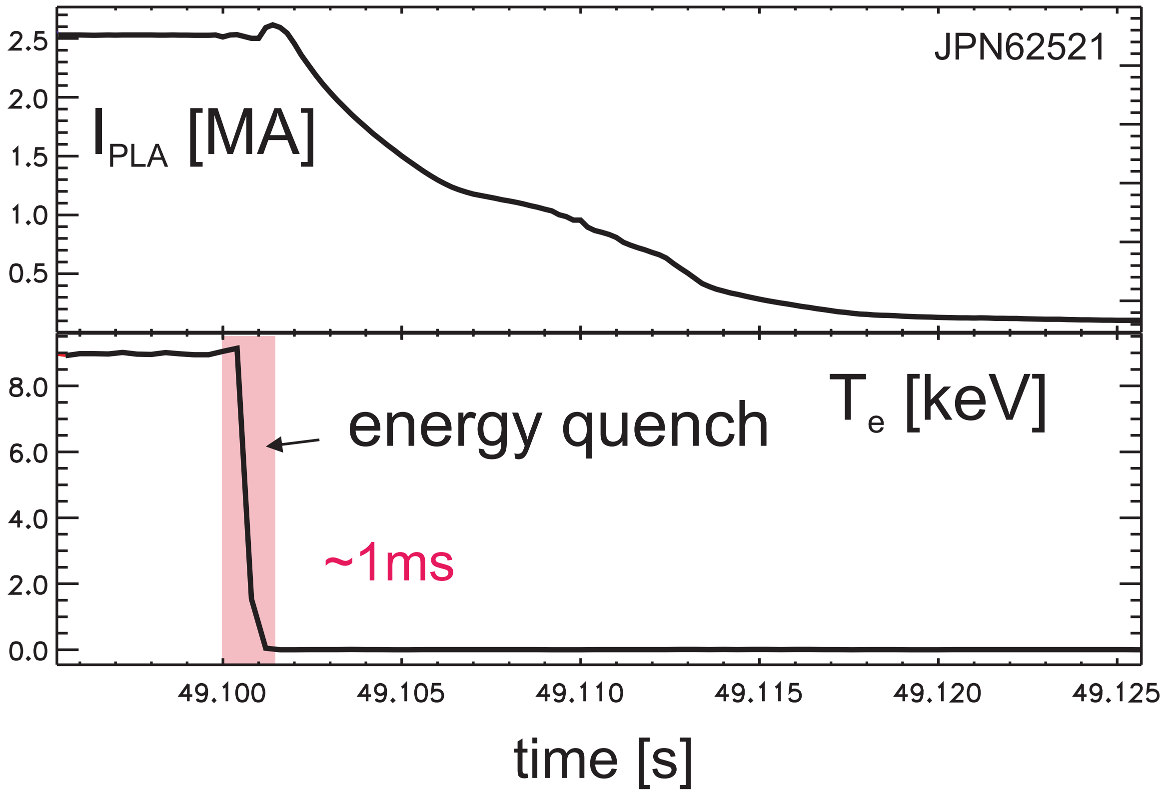
many thanks to
S.S. Abdullaev, A. Alonso, G. Arnoux, S.A. Bozhenkov, S. Brezinsek, S. Devaux, P. de Vries, T. Eich, B. Esposito, A. Huber, S. Jachmich, M.W. Jakubowski, U.Kruezi, P. D. Morgan, V.V. Plyusnin, C. Reux, V. Riccardo, G. Sergienko, JET EFDA contributors

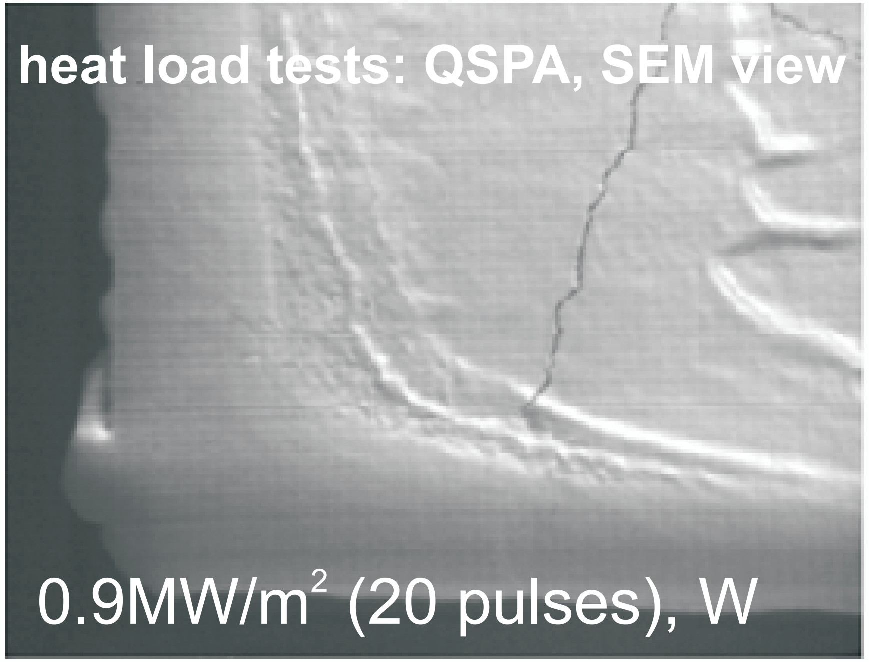
JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK
Association EURATOM-FZJ, 52425 Jülich, Germany
Laboratorio Nacional de Fusion, Asociacion Euratom CIEMAT, Madrid, Spain
Laboratoire de Physique des Plasmas-Laboratorium voor Plasmafysica, Association Euratom-Belgian State, ERM/KMS, B-1000 Brussels, Belgium
EURATOM/UKAEA Fusion Association, Culham, UK
CEA, IRFM, Association Euratom-CEA, F-13108 Saint-Paul-lez-Durance, France
Associazione Euratom-ENEA sulla Fusione, C.R. Frascati, C.P. 65, 00044-Frascati, Roma, Italy
Instituto de Plasmas e Fuso Nuclear /IST, Associacao EURATOM-IST, 1049-001 Lisbon, Portugal
Max-Planck-Institut für Plasmaphysik, Teilinistitut Greifswald, Germany



JET ITB Disruption

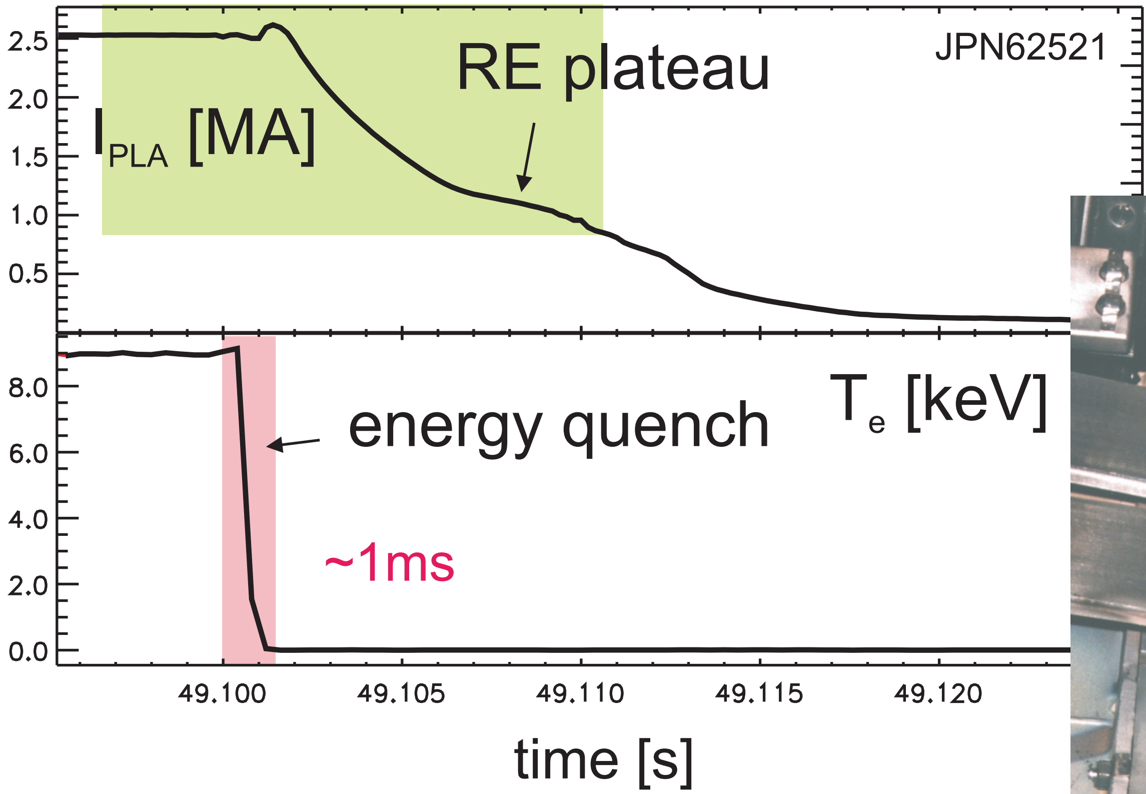
Loads during disruptions

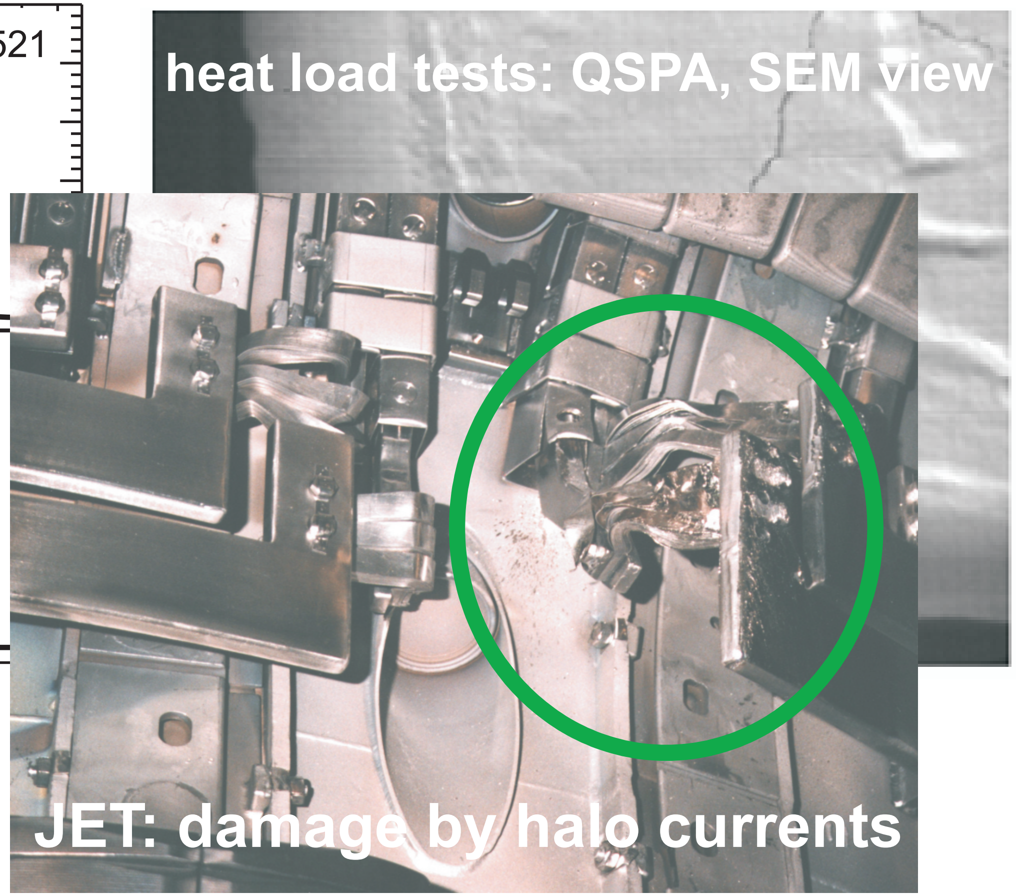




1) loss of thermal energy
to divertor/main chamber
(impurity influx)

Loads during disruptions

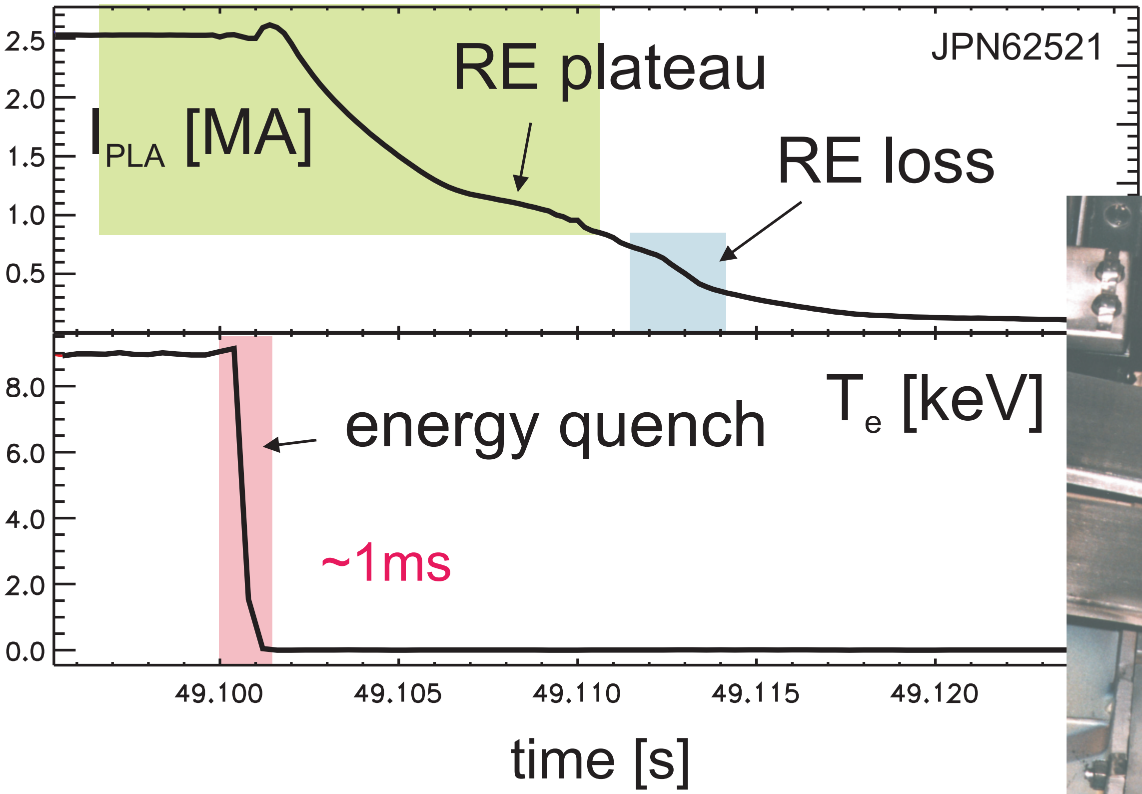


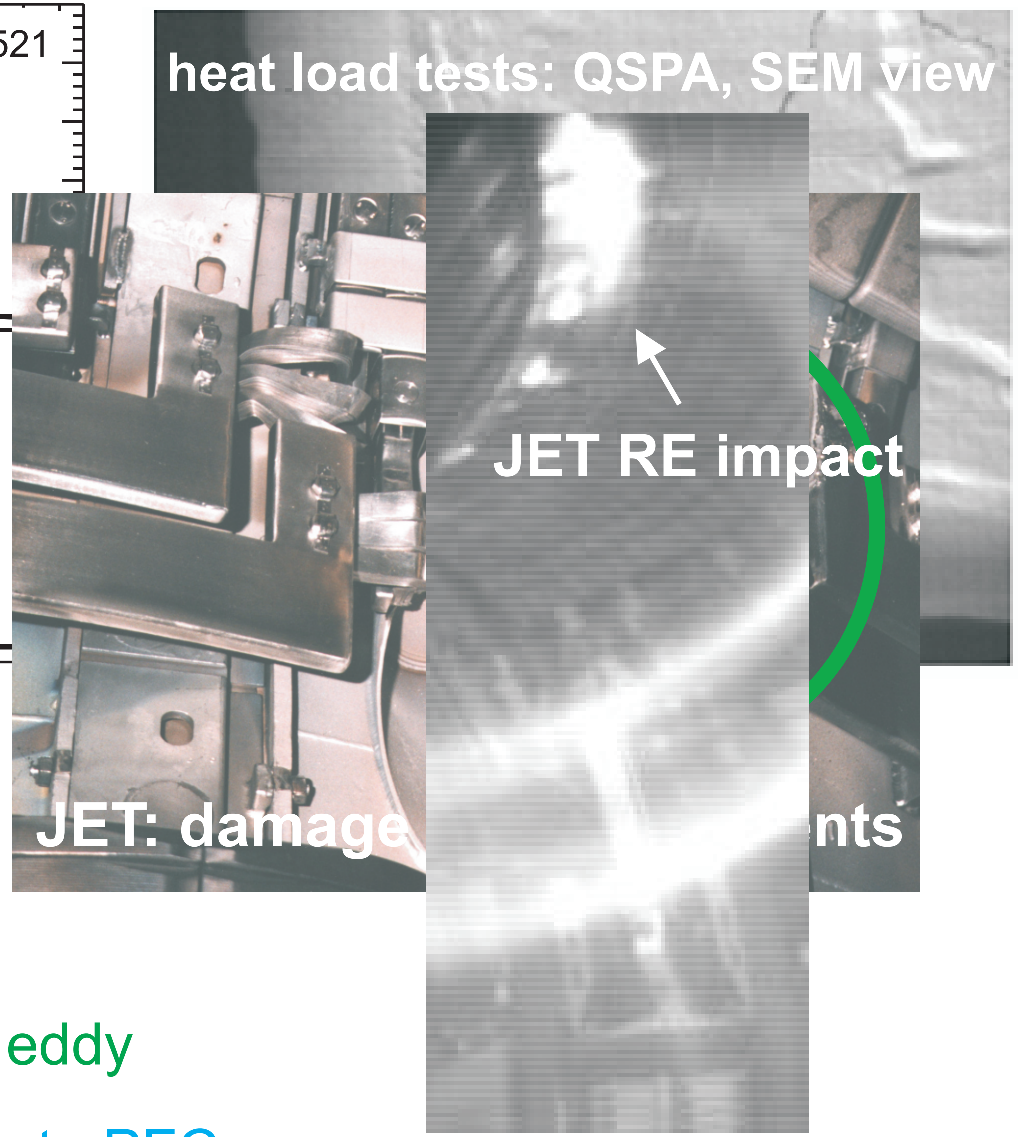


1) loss of thermal energy to divertor/main chamber (impurity influx)

2) forces by halo (VDE) and eddy currents

Loads during disruptions





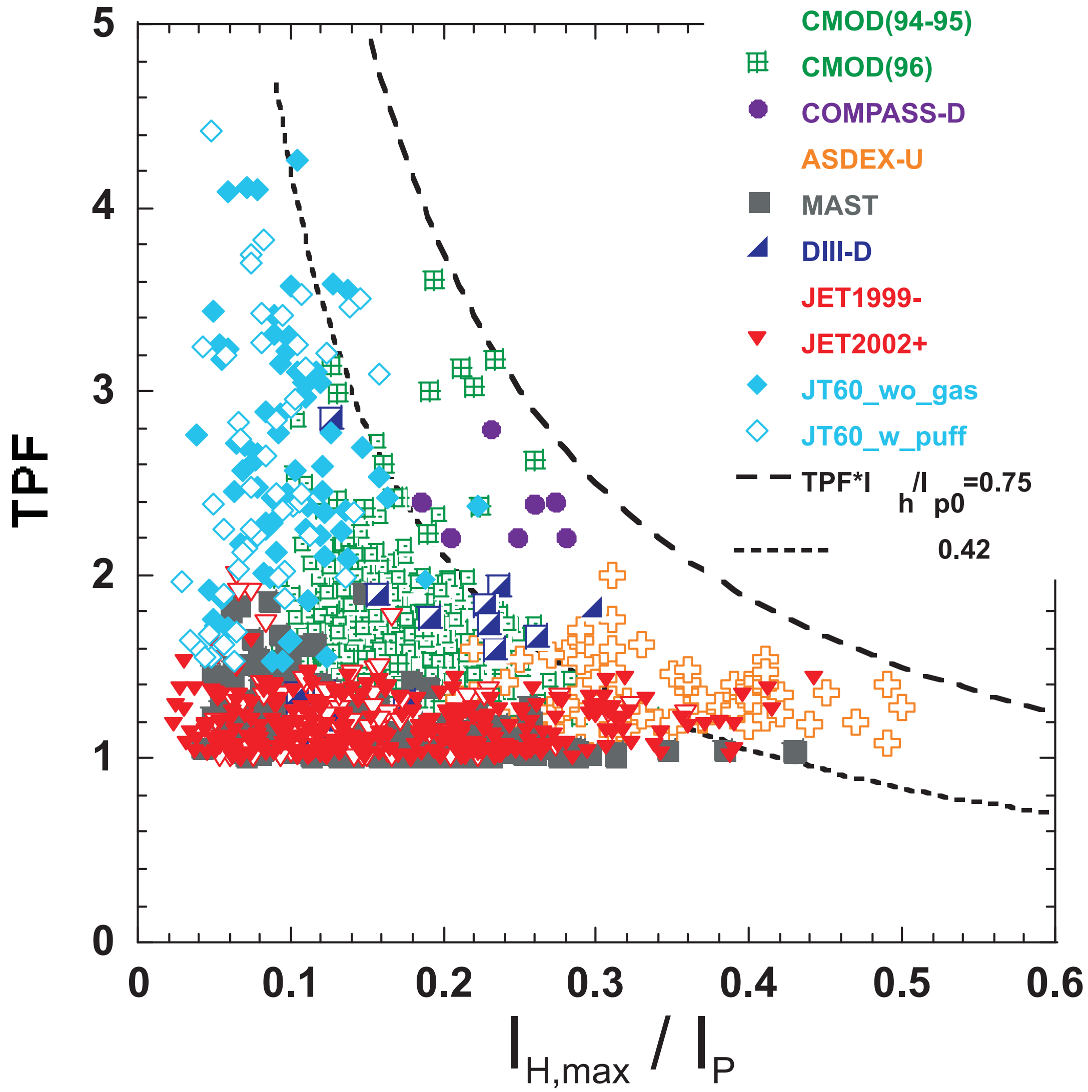
1) loss of thermal energy to divertor/main chamber (impurity influx)

2) forces by halo (VDE) and eddy currents

3) runaway loss to PFCs

Present state of the ITER requirements

Halo current



$0.42 < TPF \times I_H/I_P < 0.75$:
Cat. III event
detailed inspection is necessary

1-2 events / lifetime acceptable

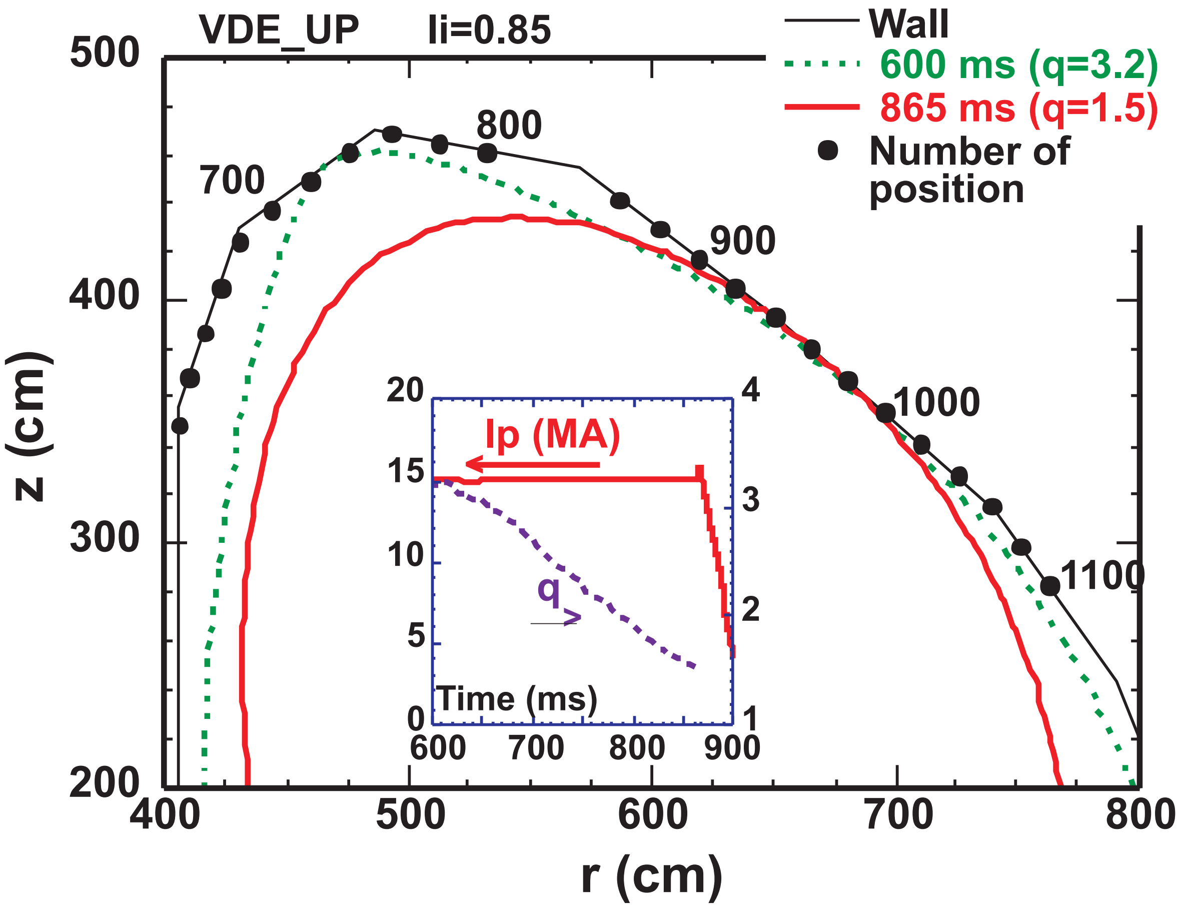
> reduction by a factor 2

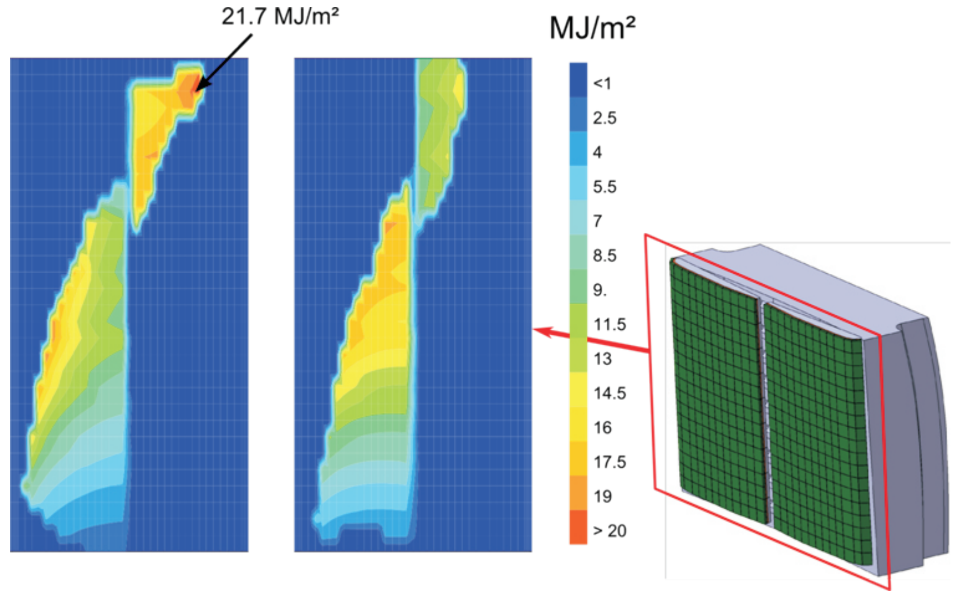
vertical / sideway forces
database presently revised
simulations

presented by M. Sugihara at the ITPA-MDC meeting in Korea 2009

Present state of the ITER requirements

Heat Load





Most severe case:
W_{th} at TQ 270 MJ, λ_q=3cm
> 22 MJ/m^2
> ε = 570 MJ/m^2/s$^{0.5}$(t=1.5ms)
(90 for ideal alignment)

Critical value for melting of beryllium
ε_{melt} = 25 MJ/m^2/s$^{0.5}$

presented by M. Sugihara at the IEA Workshop on Disruptions, Culham, October 2009

Present state of the ITER requirements

Runaway Electrons

	Present day devices	**ITER**
source	Dreicer mechanism ($F_{friction}$ < eE)	Compton scattering, tritium decay
avalanche multiplication	$5x10^5$ (JET 4MA)	10^{21}-10^{22}
runaway current	1-2 MA	~10 MA
runaway energy	> 25 MeV	10-20 MeV
total energy	< 2-10 MJ	30-200MJ

wetted area for runaways ? (JET: ~0.3m^2)
penetration into PFC ? (depends on angle of incidence/fraction of $E_\perp$)
loss mechanism - scaling of loss times ? (JET: several events ~10-100μs)

methods for disruption mitigation (avoidance)

- **Controlled plasma shutdown**
  - reduce shaping
  - stop external heating
  - ramp down plasma current
  - stabilise vertical displacement / control runaway beam

slow time scale

- Local Heating
  - disruption avoidance/retardation by ECRH
  - curing (N)TM modes

not for all disruption types

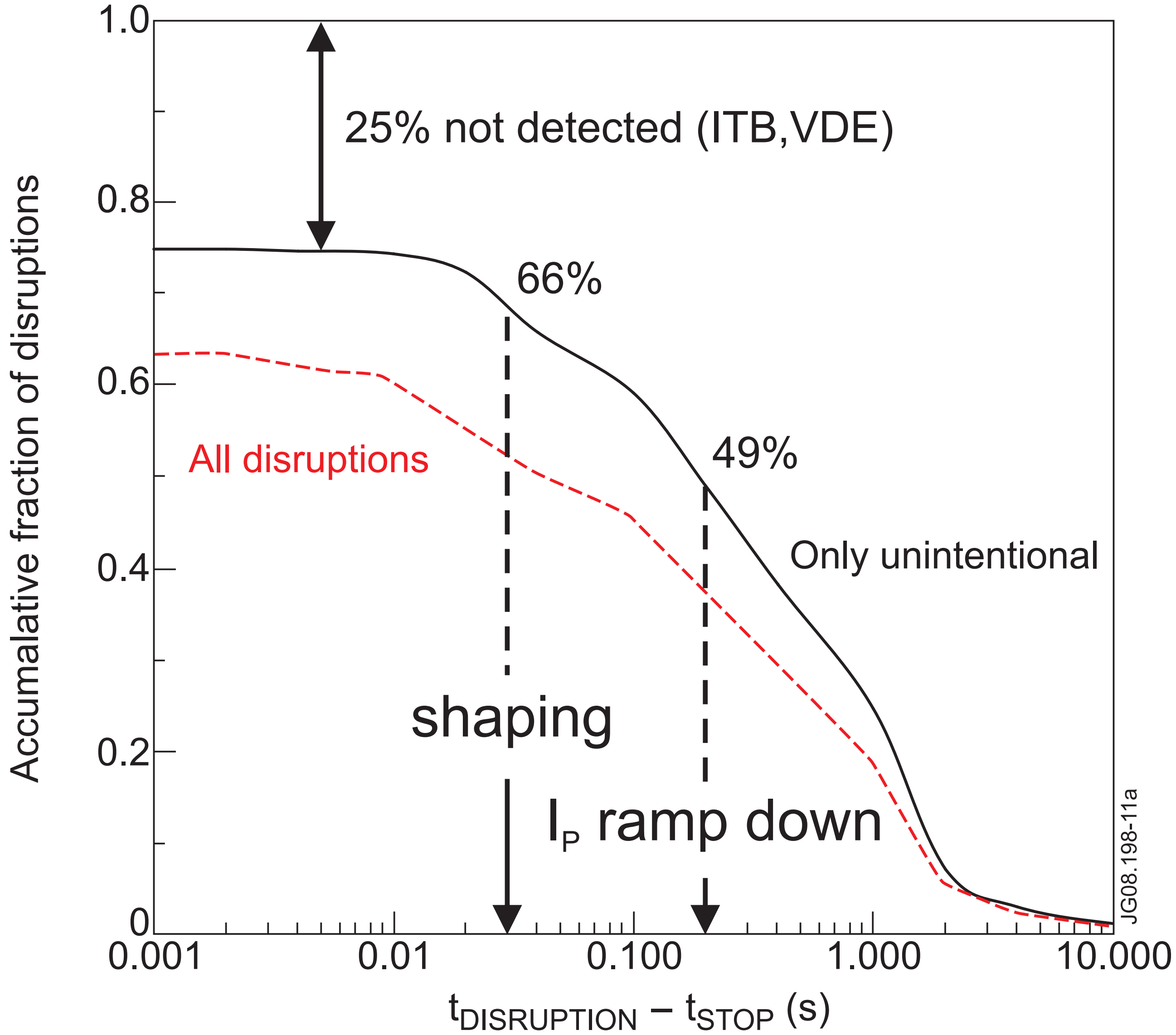
- Massive Material Injection
  - injection of gas, pellets, liquids
  - reduction of forces, heat loads
  - avoidance of runaways

last resort

- Magnetic Perturbations
  - de-confine runaway electrons

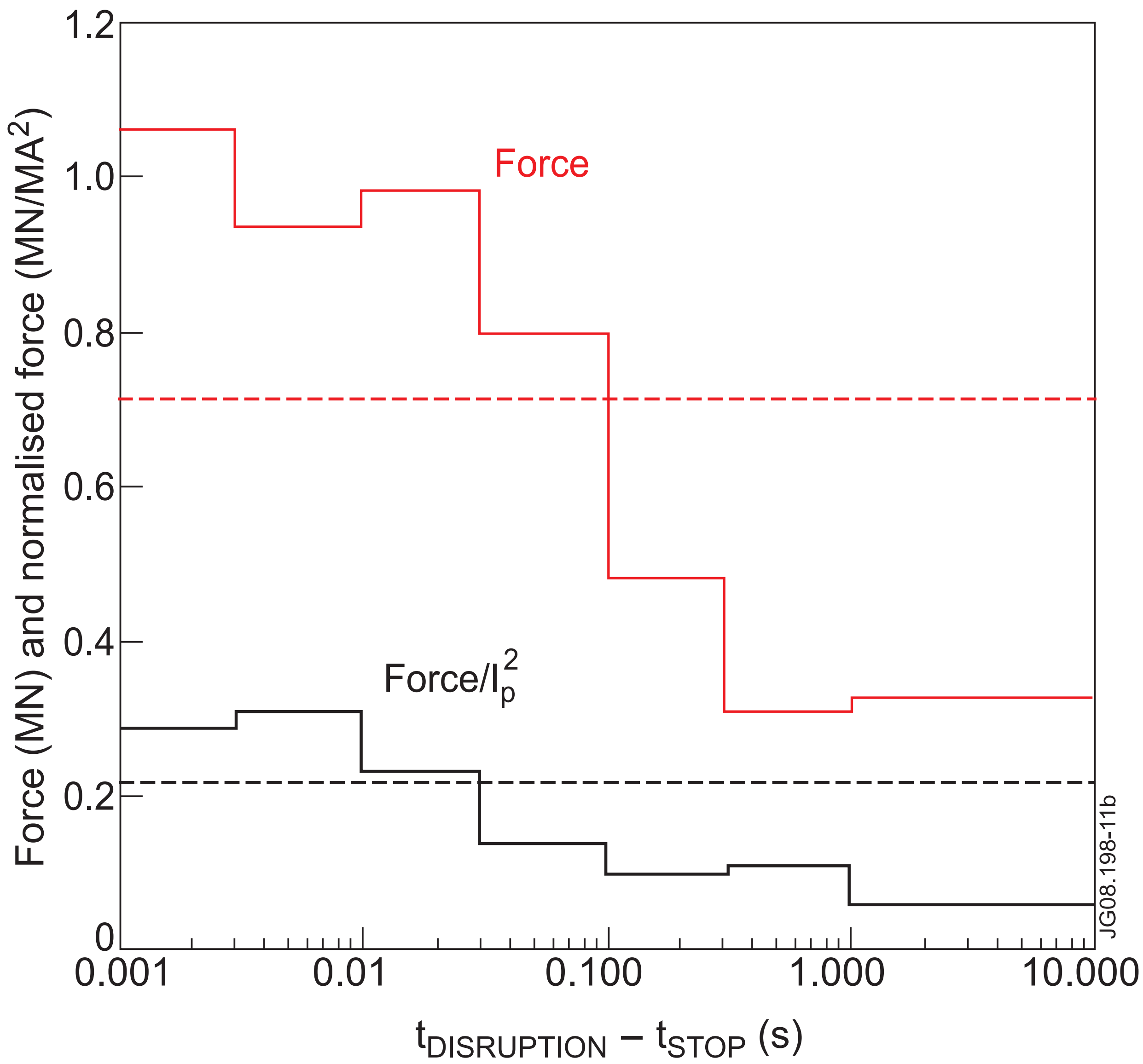
acts only on RE

warning time for JET disruptions



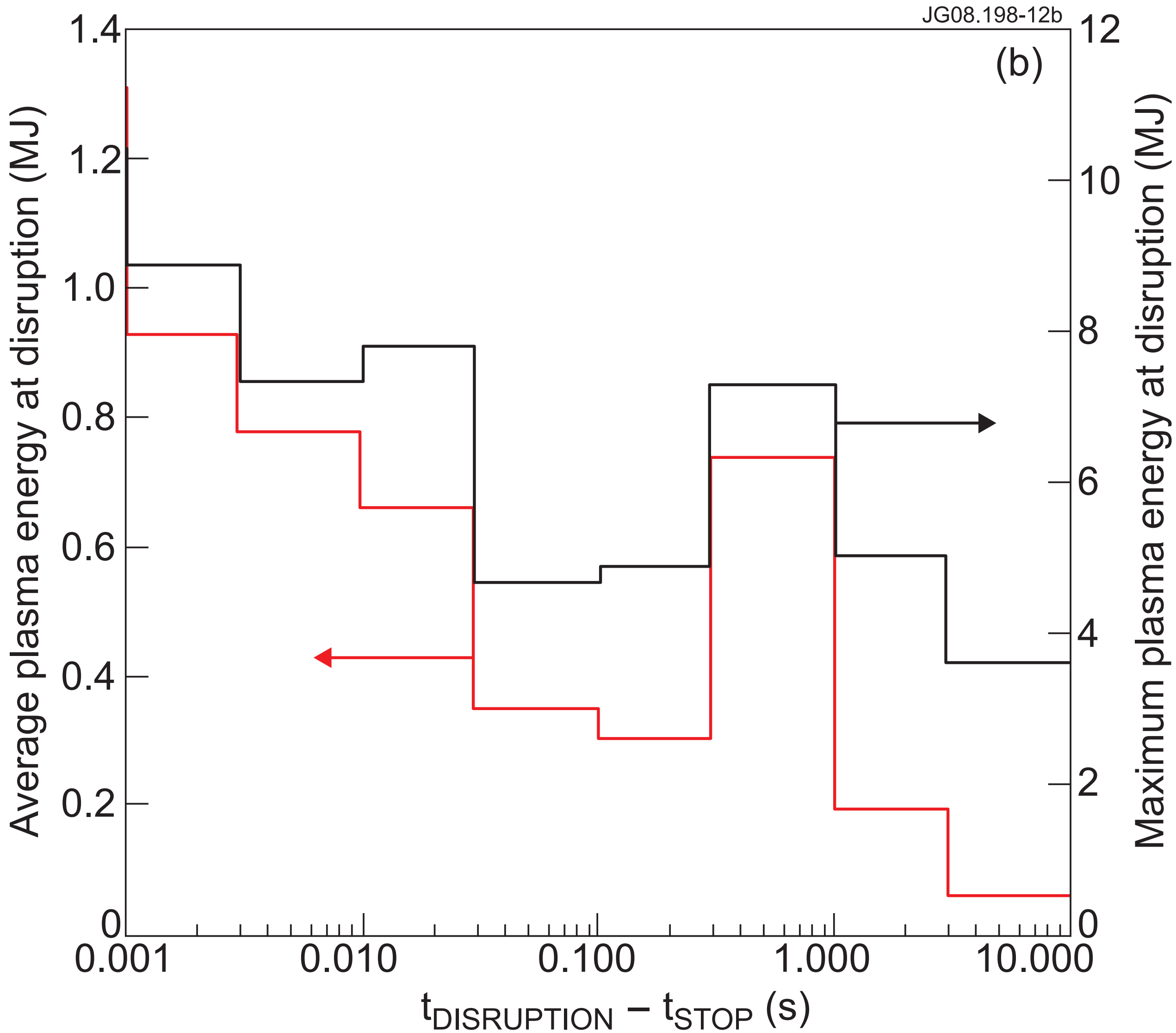
courtesy of
P. de Vries et al., EPS 2009, Nucl. Fusion **49** (2009) 055011

reduction of forces by the JET protection system



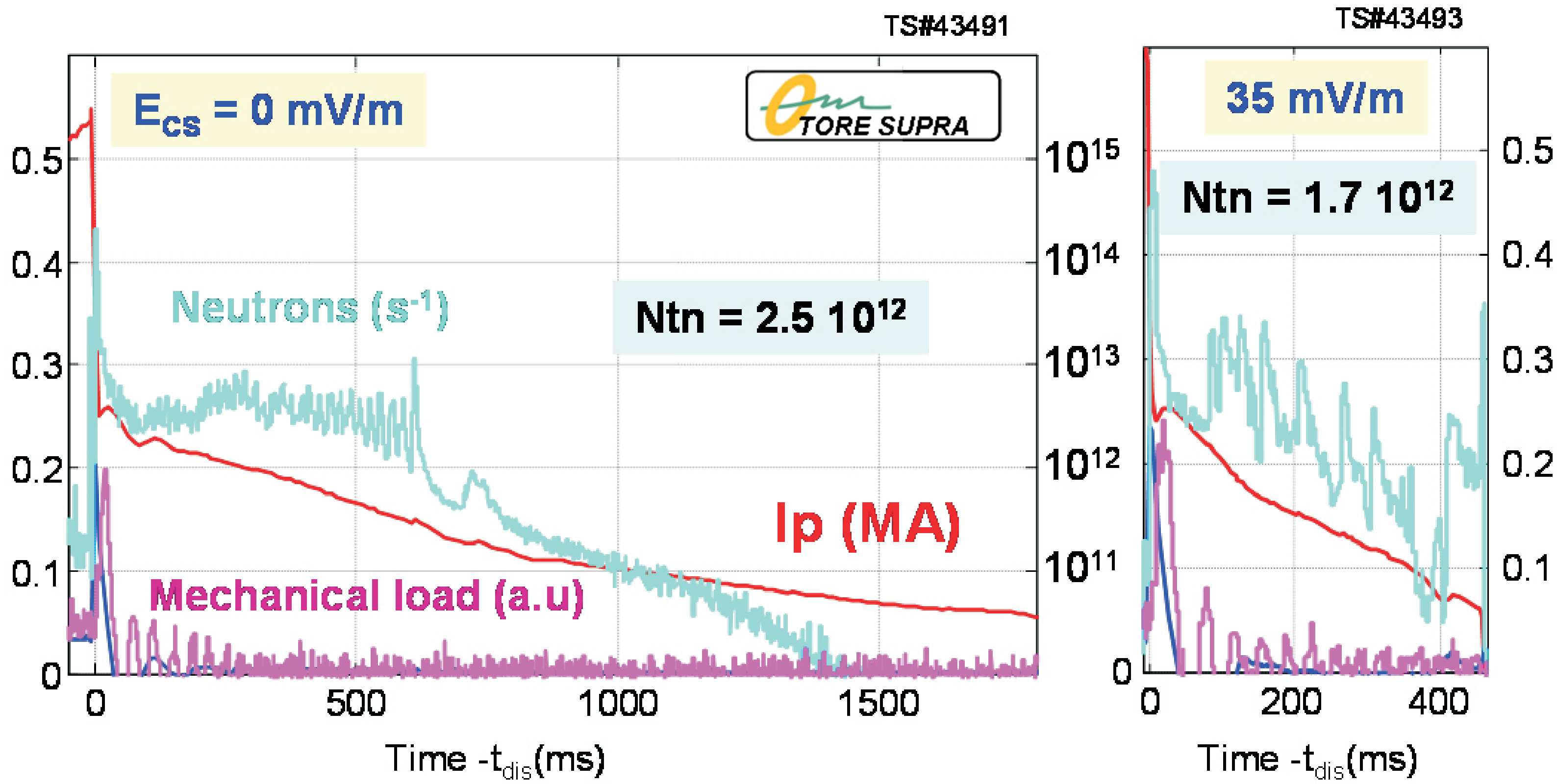
courtesy of
P. de Vries et al., EPS 2009, Nucl. Fusion **49** (2009) 055011

reduction of heat loads by the JET protection system



courtesy of
P. de Vries et al., EPS 2009, Nucl. Fusion **49** (2009) 055011

Tore Supra: Variation of the central solenoid voltage with RE beam position control



- **Reduction of the plateau duration** with a small voltage (~0.5 V/turn)
- Photoneutrons reduced (~30%) but still a neutron burst at the end
- Further studies required

C. Reux et al., EPS 2009
F. Saint-Laurent et al., EPS 2009

methods for disruption mitigation (avoidance)

- Controlled plasma shutdown
  - reduce shaping
  - stop external heating
  - ramp down plasma current
  - stabilise vertical displacement / control runaway beam

slow time scale

- **Local Heating**
  - disruption avoidance/retardation by ECRH
  - curing (N)TM modes

not for all disruption types

- Massive Material Injection
  - injection of gas, pellets, liquids
  - reduction of forces, heat loads
  - avoidance of runaways

last resort

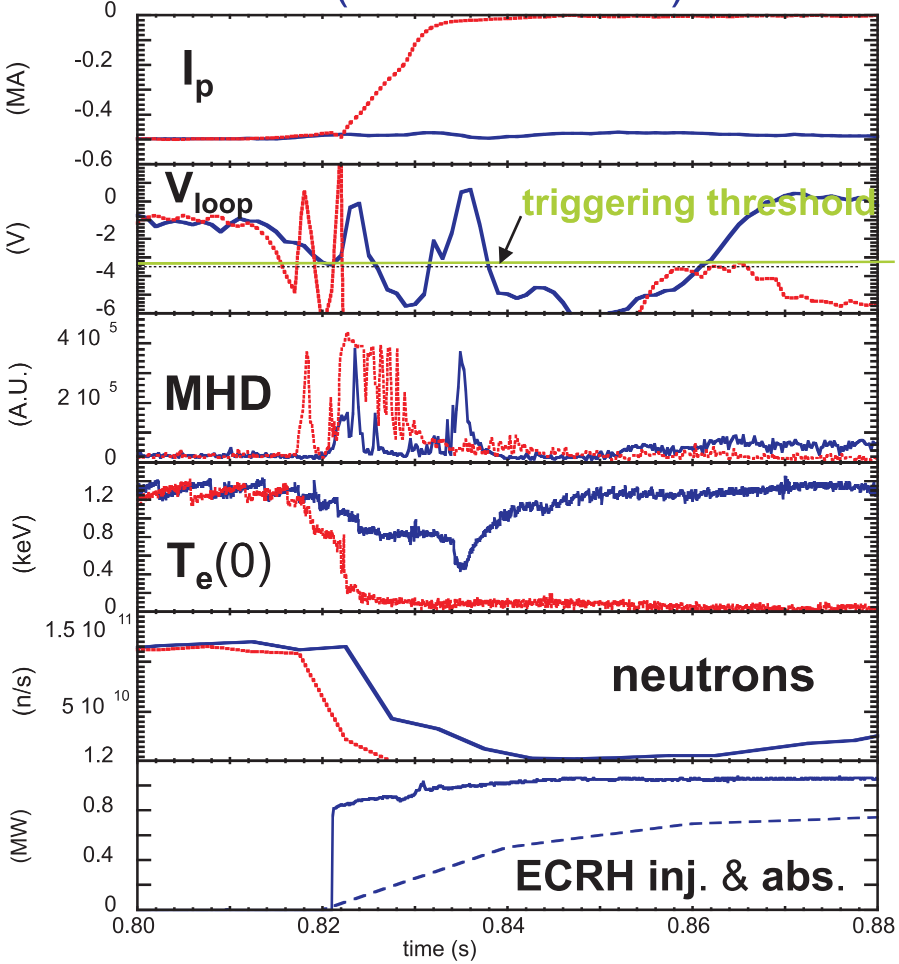
- Magnetic Perturbations
  - de-confine runaway electrons

acts only on RE

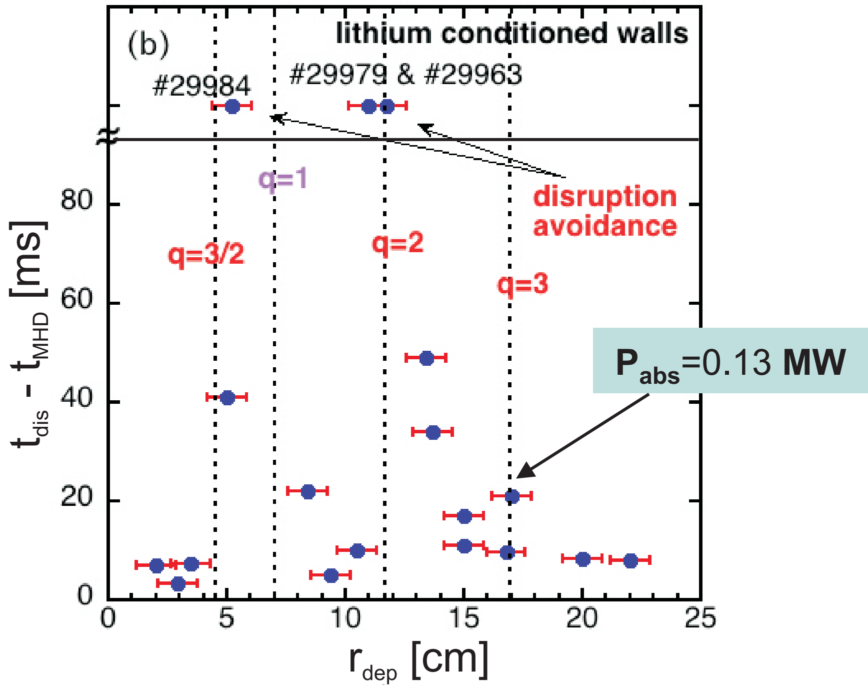
Associazione EURATOM ENEA sulla Fusione

FTU: Avoidance in LBO disruptions with ECRH

#29473 (no ECRH)
#29484 (off-axis ECRH)



Power Deposition Scan



Delay between MHD onset and I_p quench vs r_{dep} indicates that ECRH produces avoidance when $r_{dep} = r_{q=m/n}$

Modes are coupled, also in stabilizing phase

B. Esposito, G. Granucci et al., Phys. Rev. Lett. 100 (2008) 045006

methods for disruption mitigation (avoidance)

- Controlled plasma shutdown
  - reduce shaping
  - stop external heating
  - ramp down plasma current
  - stabilise vertical displacement / control runaway beam

slow time scale

- Local Heating
  - disruption avoidance/retardation by ECRH
  - curing (N)TM modes

not for all disruption types

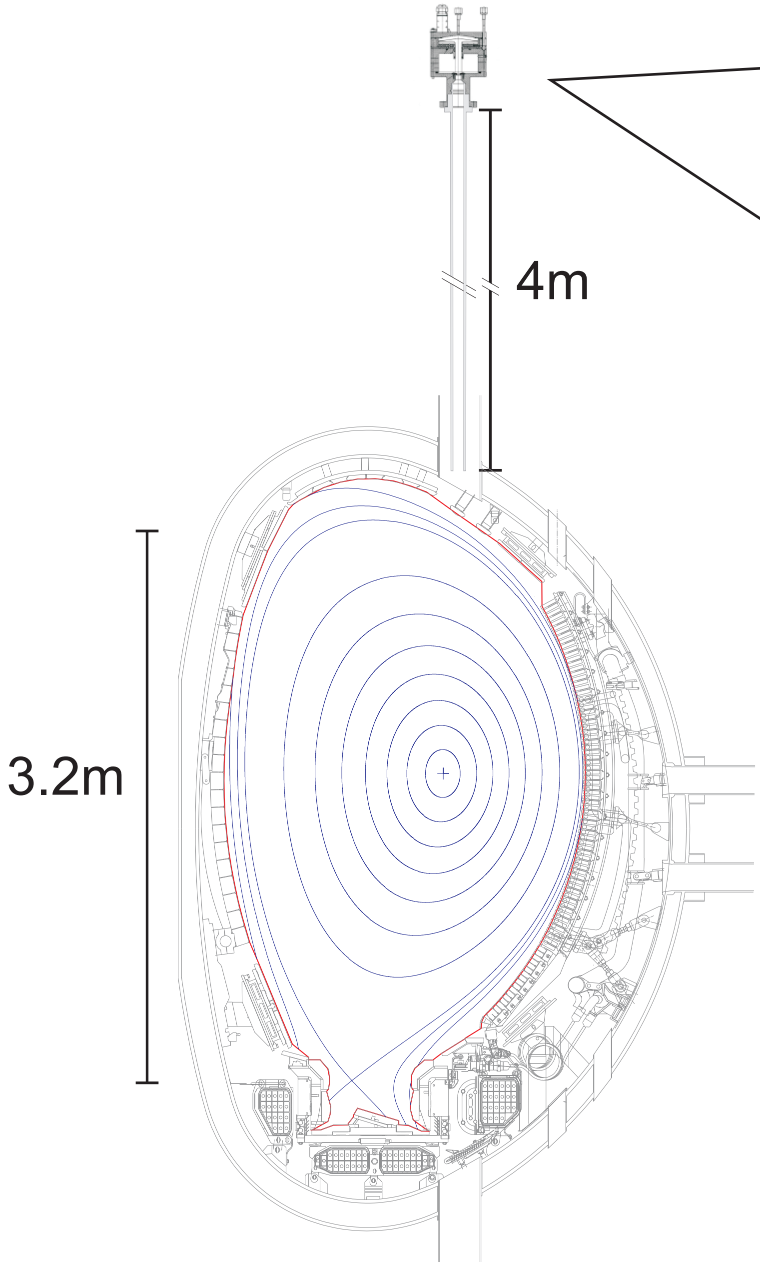
- **Massive Material Injection**
  - injection of **gas**, pellets, liquids
  - reduction of forces, heat loads
  - avoidance of runaways

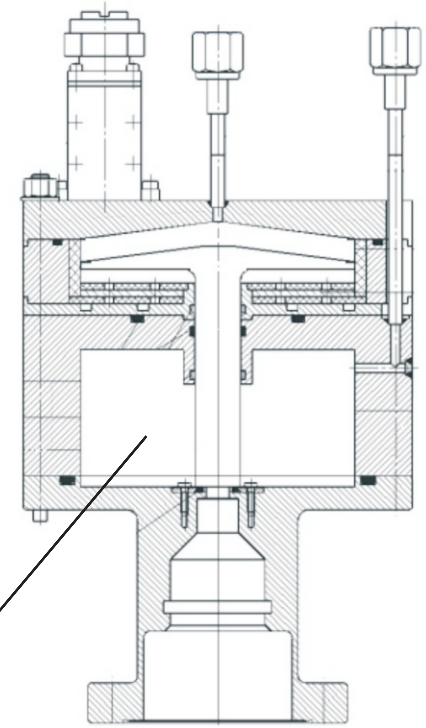
last resort

- Magnetic Perturbations
  - de-confine runaway electrons

acts only on RE

Massive Gas Injection: Set-up at JET





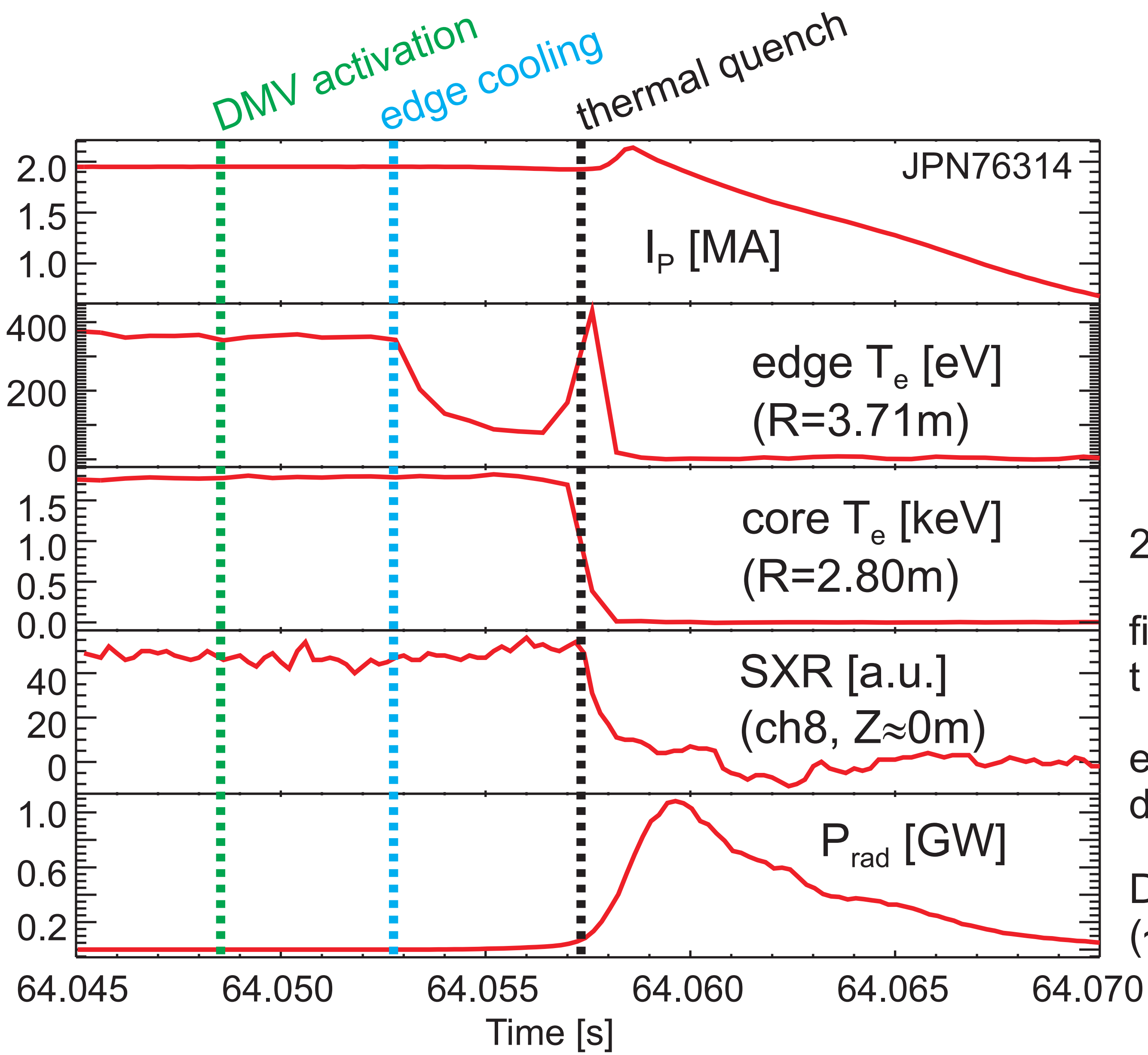
Injection Volume = 650 ml

Maximum Pressure = 36 bar

Injected Particles = $2.5x10^{23}$

Injected species: Ar, Ne, He, D_2

MGI Disruption Sequence



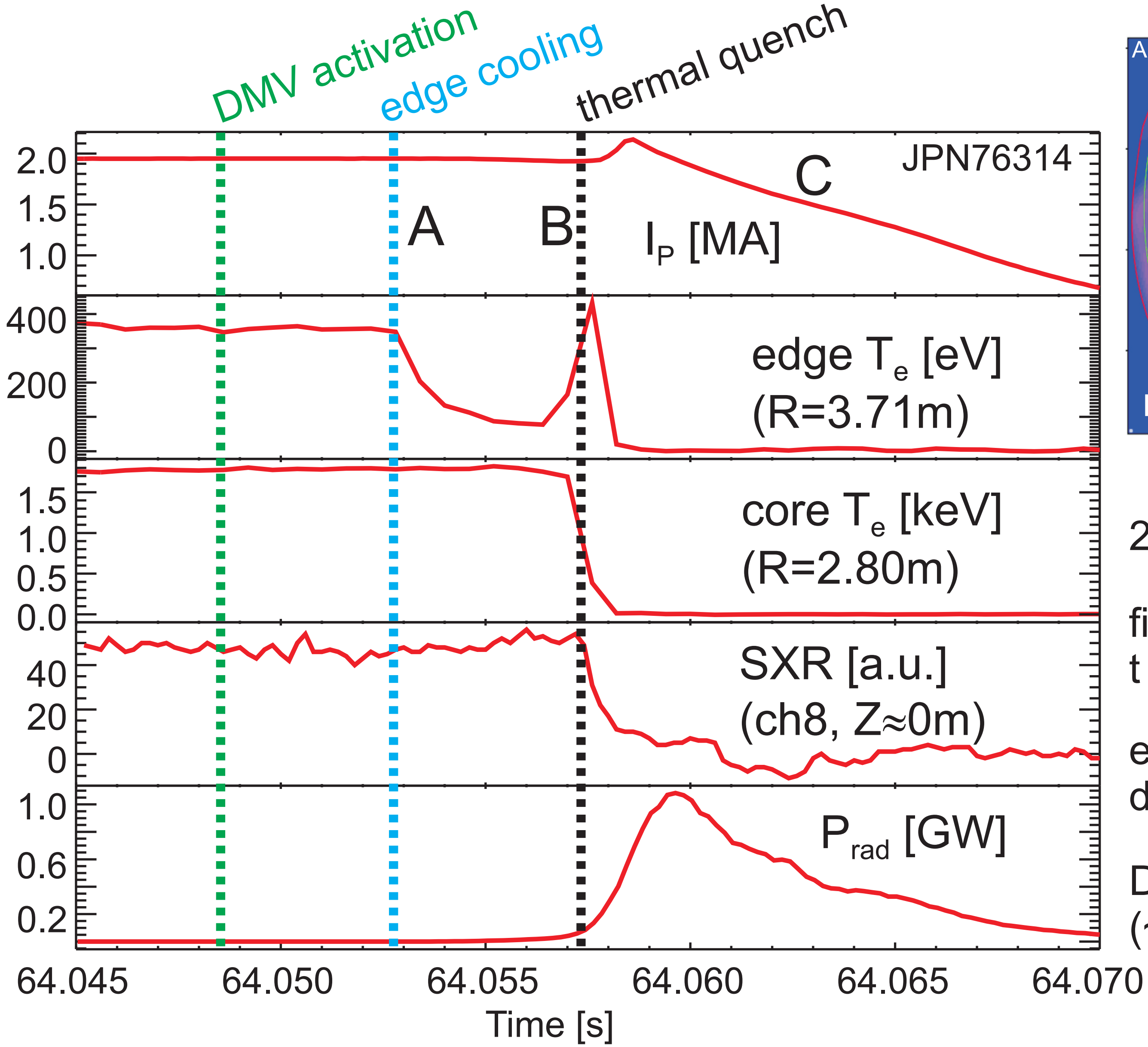
2.0MA, 1.8T, OH, Neon

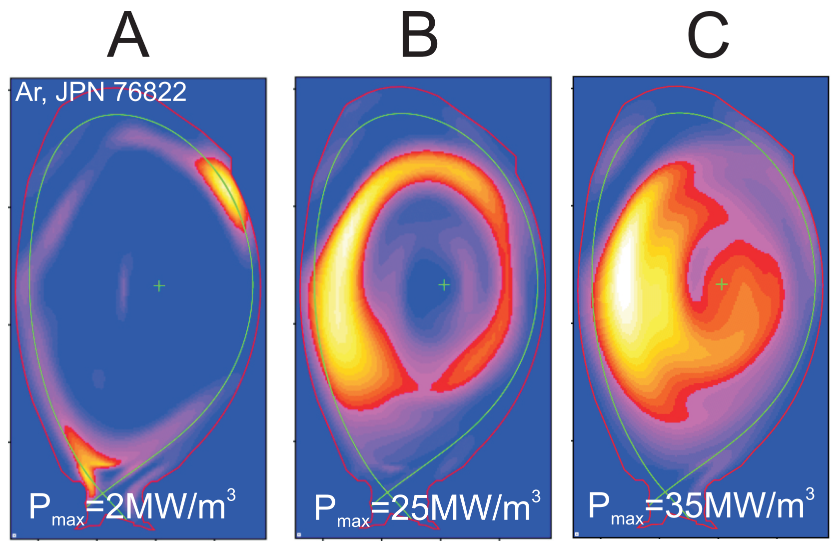
first gas visible in plasma at $t \sim 4m / 2.5\ c_0$

edge cooling time is 4-9ms depending on q95 and DMV pressure

DMV request at 64.0s (~40-50ms delay by NBI interlock)

MGI Disruption Sequence





2.0MA, 1.8T, OH, Neon

first gas visible in plasma at
t ~ 4m / 2.5 c_0

edge cooling time is 4-9ms
depending on q95 and DMV pressure

DMV request at 64.0s
(~40-50ms delay by NBI interlock)

Timescales

reaction time of the valve / time of flight

defines system delay - to be minimised

cooling duration (delay from gas arrival to thermal quench)

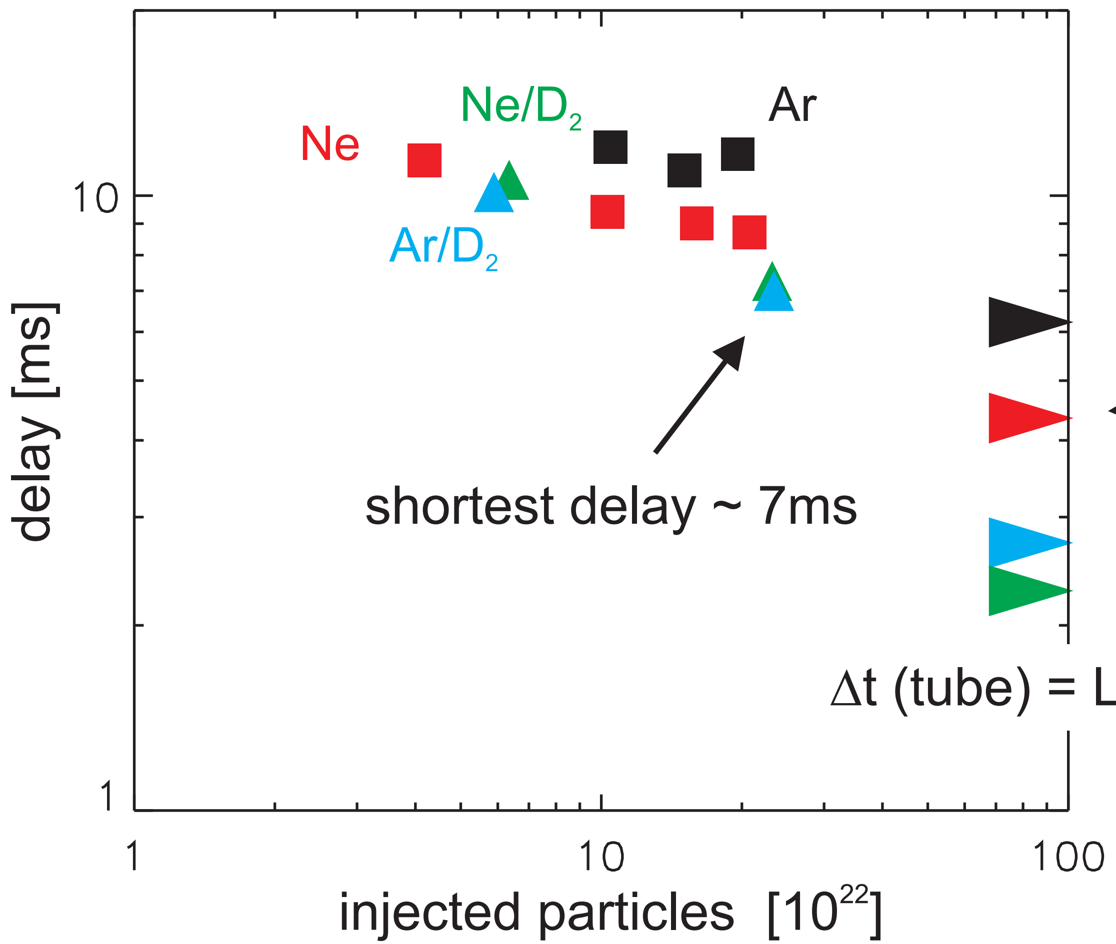
deposition of the gas in the plasma edge

current quench time

fast enough to minimise halo currents -
slow enough to avoid excessive eddy currents

Timescales

Delay from DMV activation to thermal quench



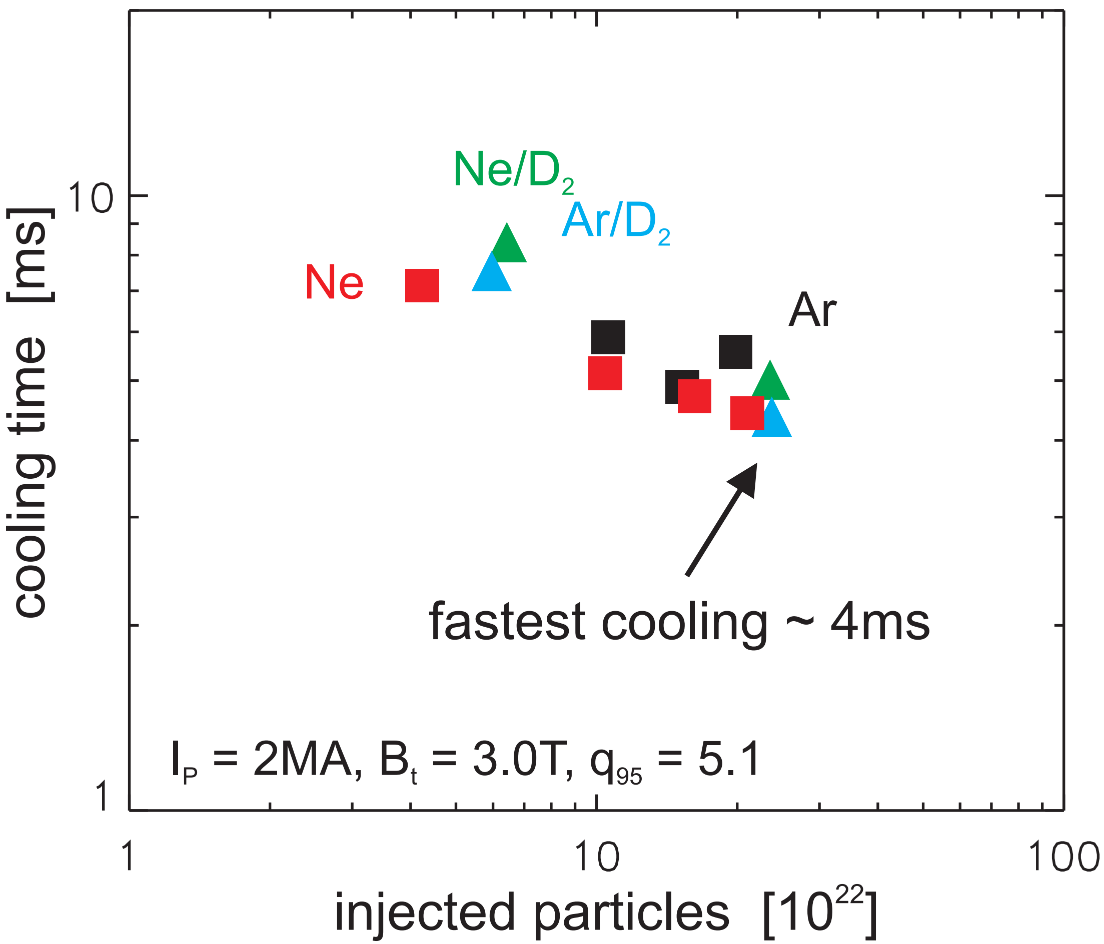
delay =
time of flight + cooling phase

time of flight (4m tube)

Δt (tube) = $L / 2.5\ c_0$

additional delay by machine protection
up to 50ms

Duration of cooling phase

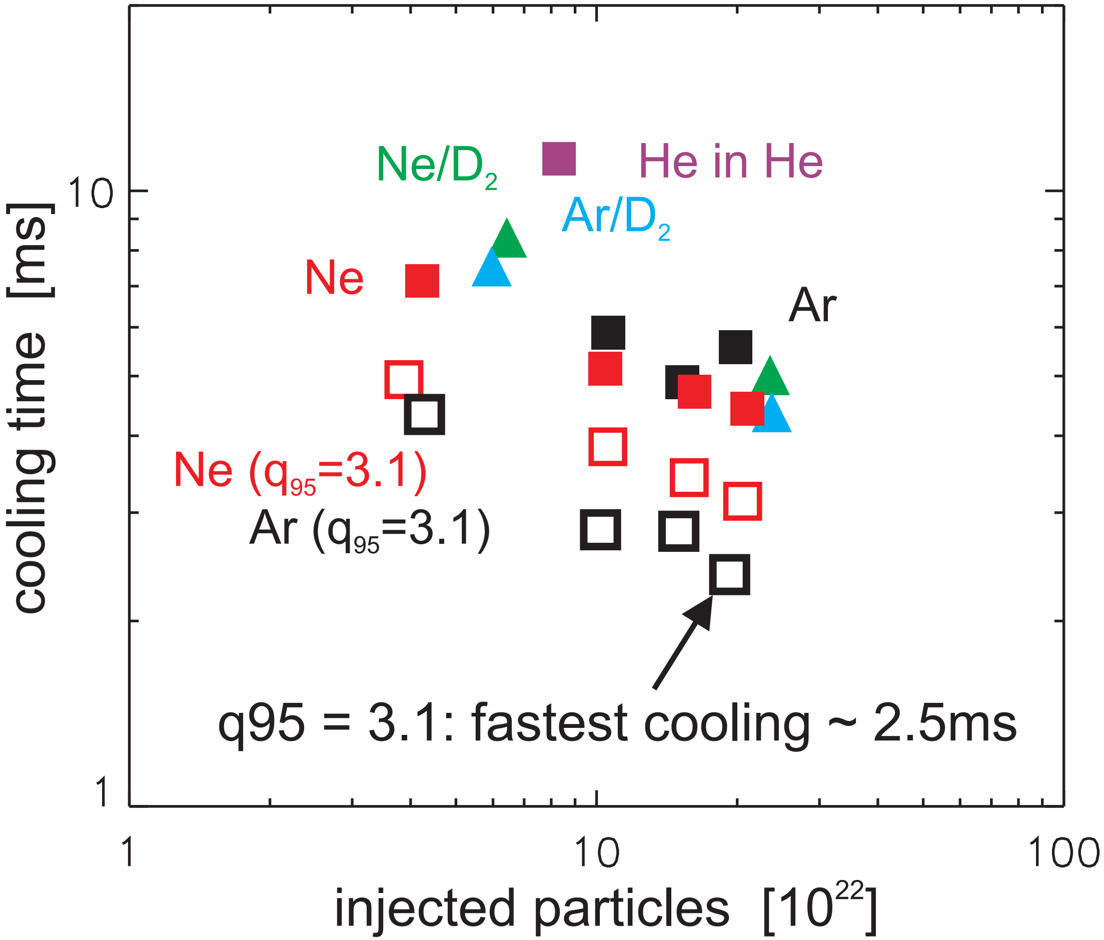


gas to be injected before TQ!

extrapolation to ITER:
scaling with machine size,
thermal energy in plasma boundary

Timescales

Duration of cooling phase



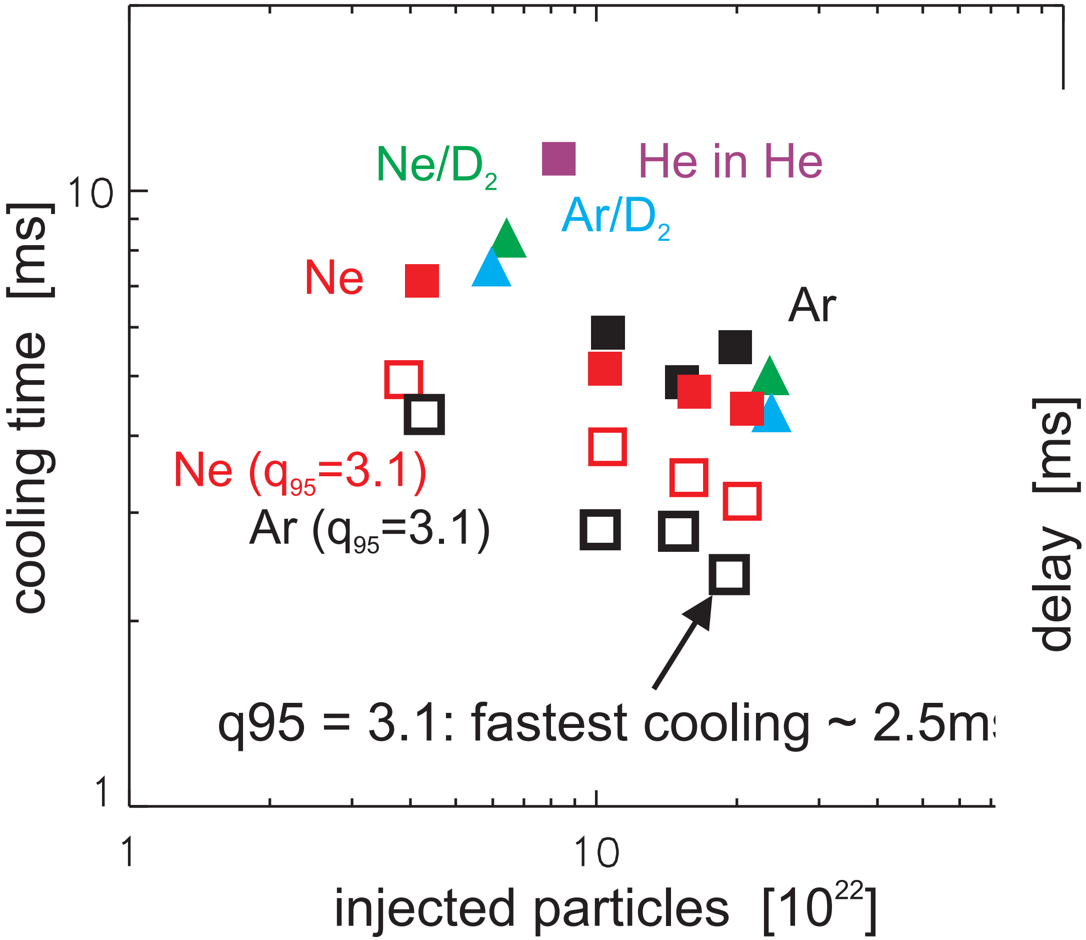
gas to be injected before TQ!

extrapolation to ITER:
scaling with machine size,
thermal energy in plasma boundary

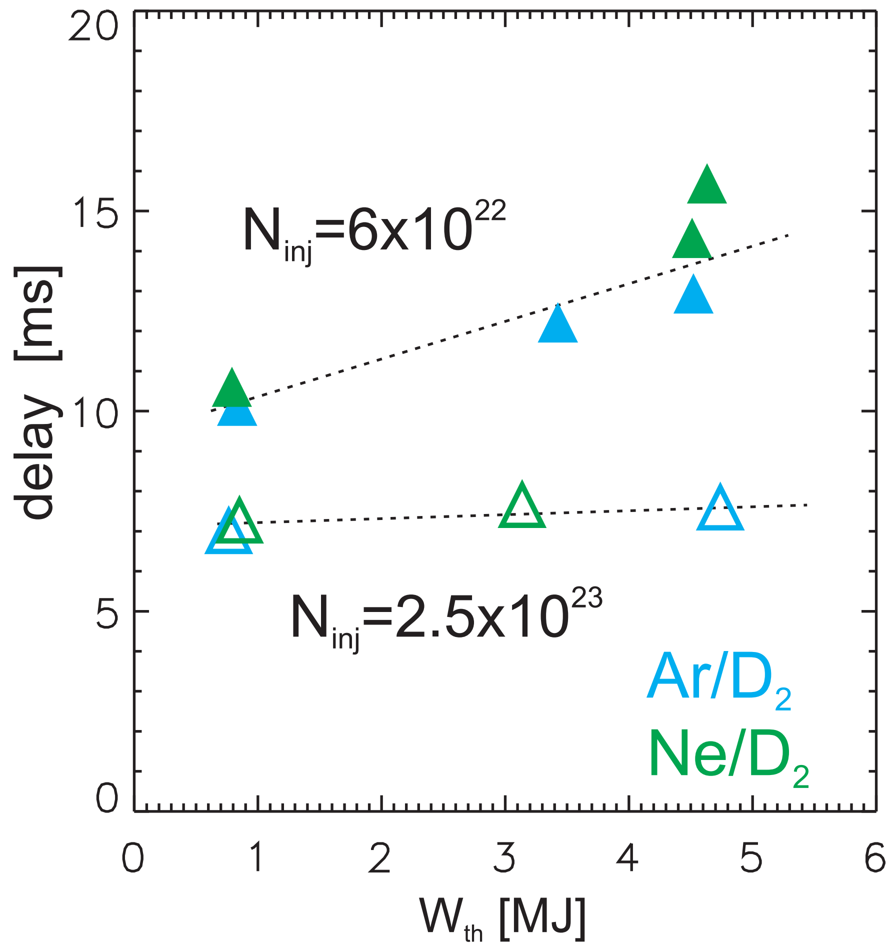
shorter cooling phase for low q95

He injection: long cooling duration

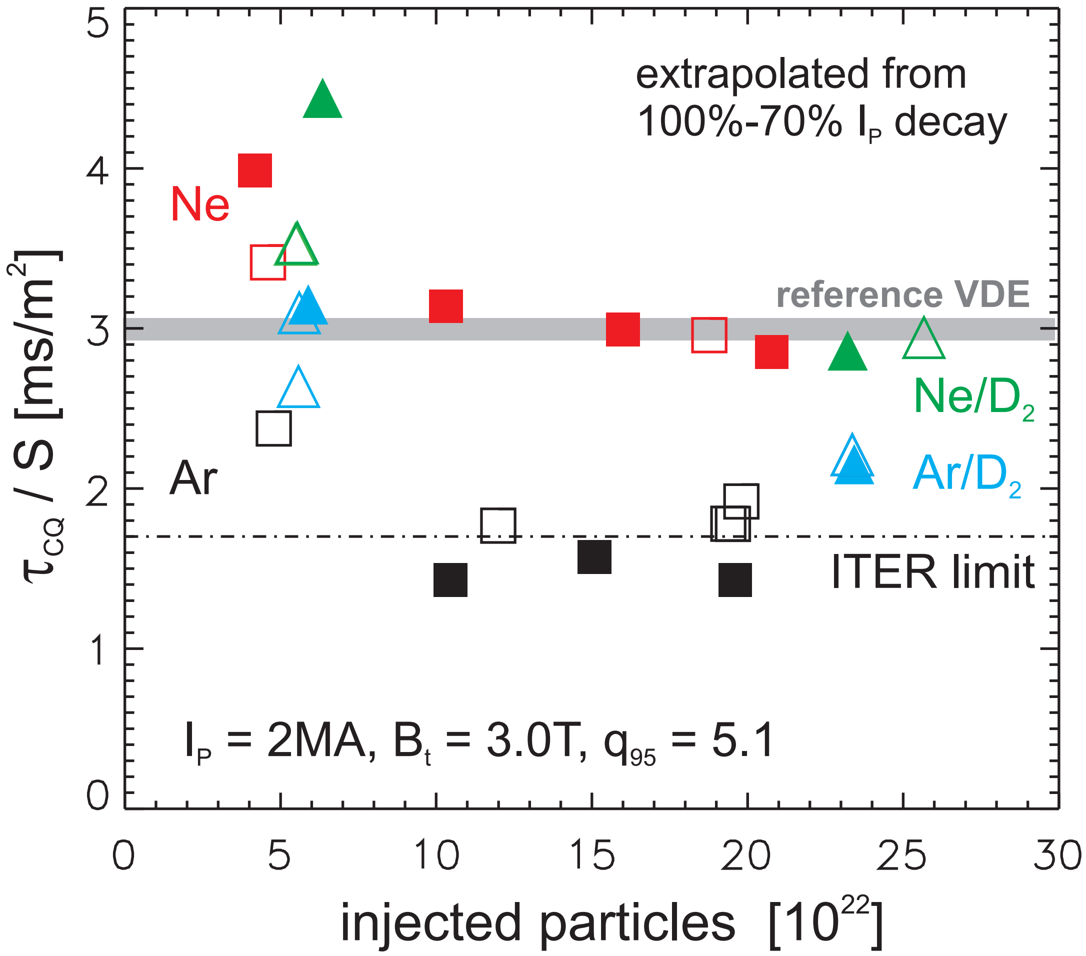
Duration of cooling phase



only small effect of W_{th}



Current decay rate - eddy current limit



Ne and Ne/D_2
almost no difference in current decay

Ar
fastest decay

Ar/D_2
between pure Ar and Ne

He: 6ms/m^2

OH / NBI		
■	□	Ne
▲	△	Ne/D_2
■	□	Ar
▲	△	Ar/D_2

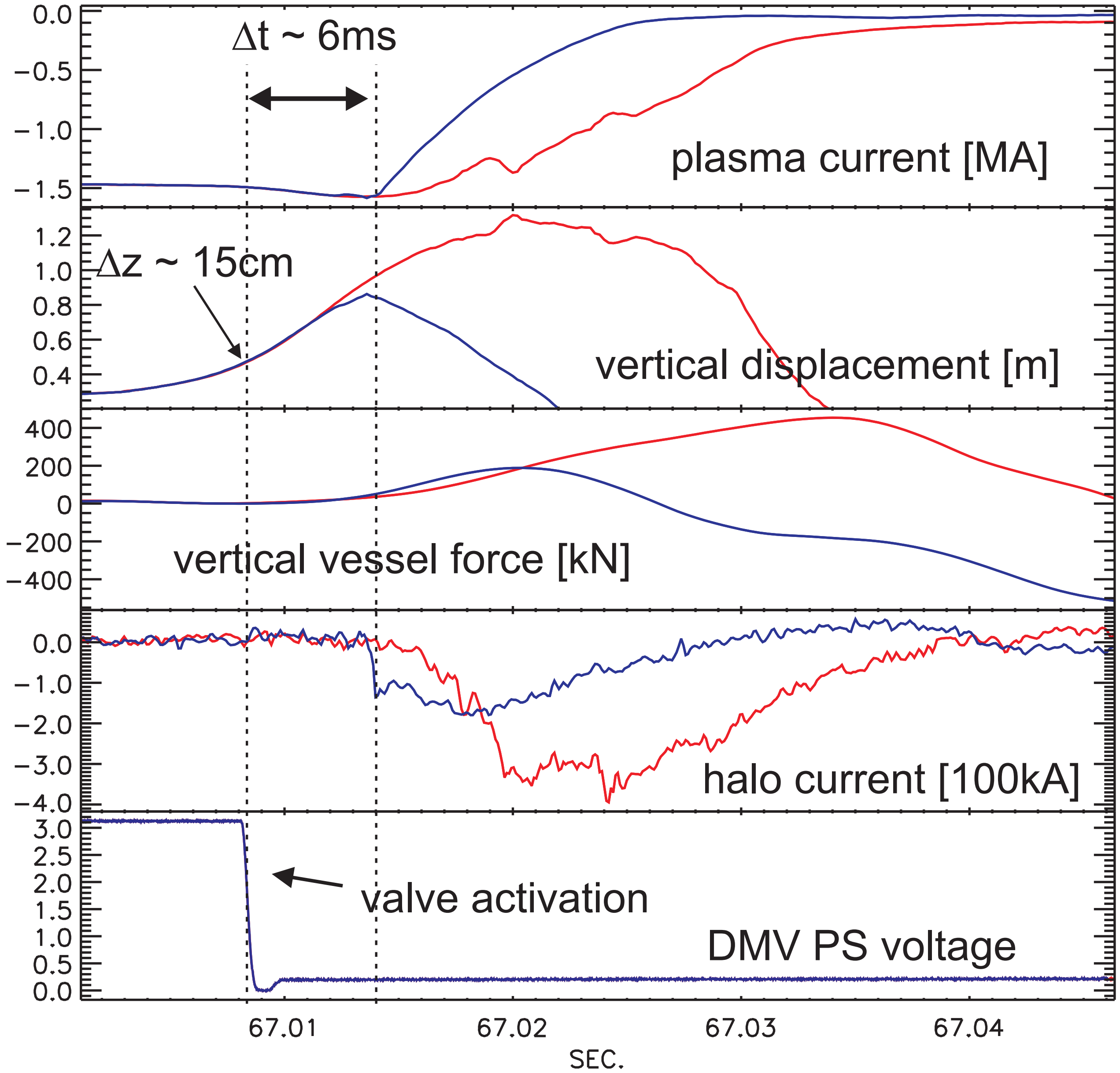
Reduction of halo currents / forces

initiation of the thermal quench on the timescale of the vertical displacement

aim for short overall reaction time (ITER: VDE slower)

Mitigation of forces from halo / eddy currents

Mitigation of fast VDE

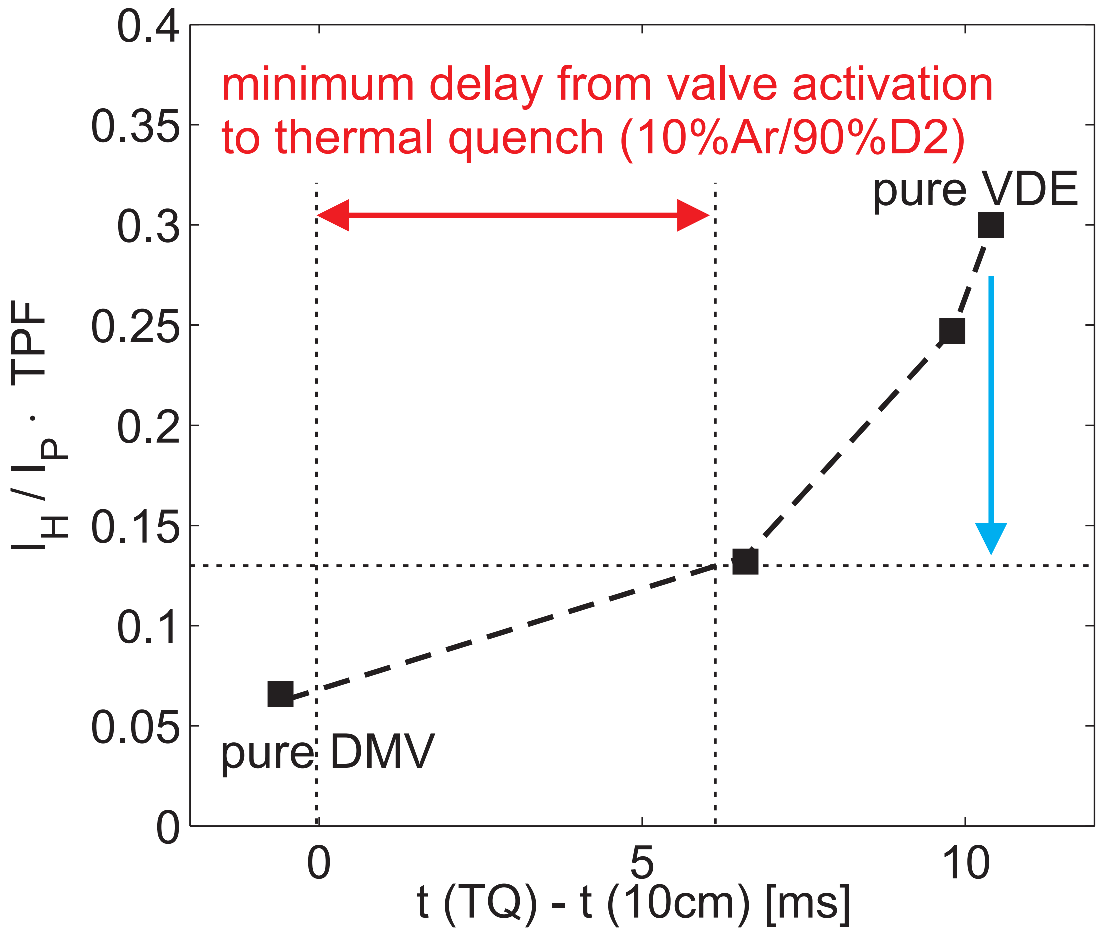


pure VDE (79538)
VDE + DMV (79541)

ITER_ZSIRSO
1.5MA
1.7T

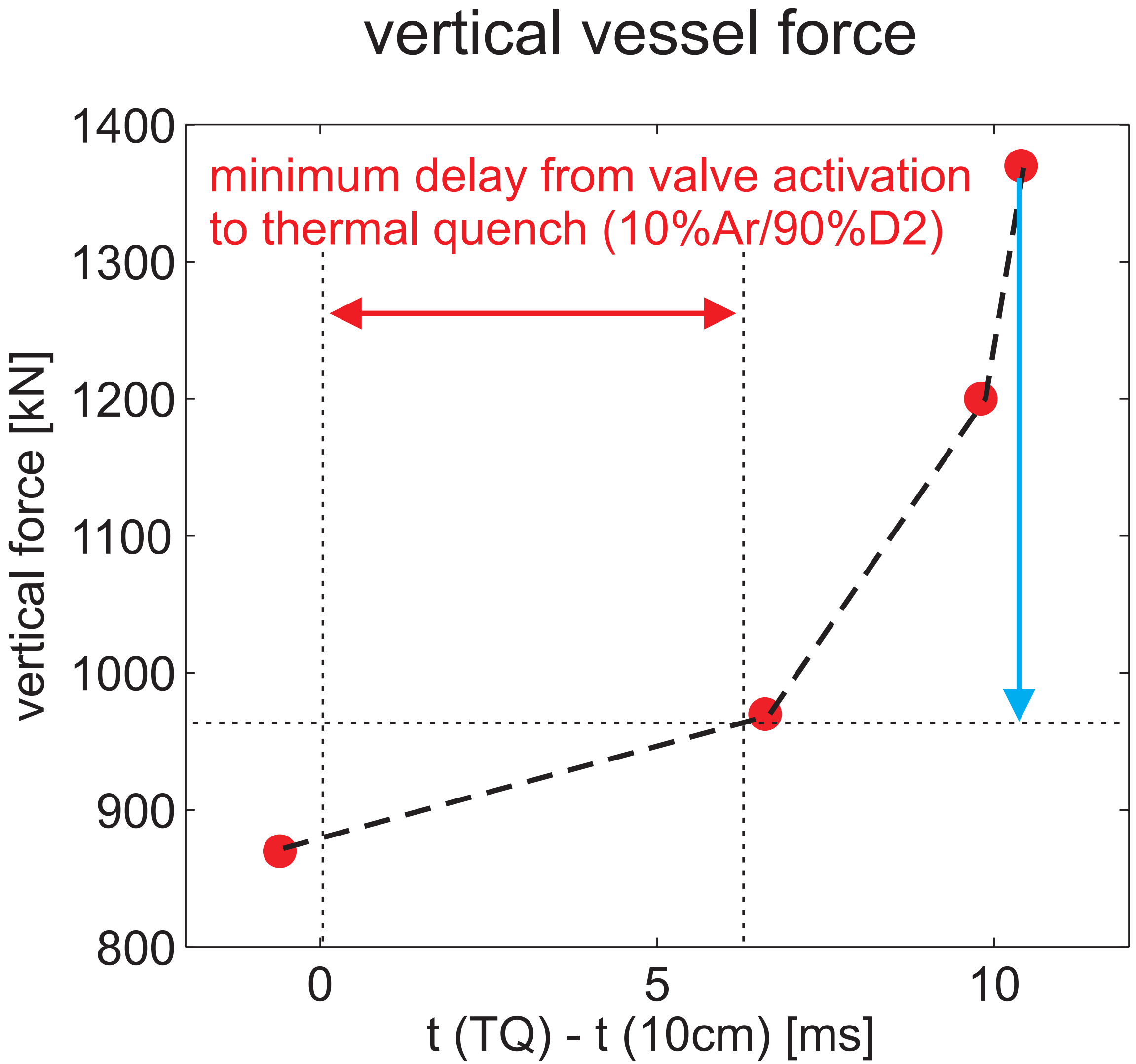
Mitigation of forces from halo / eddy currents

halo current fraction x toroidal peaking factor



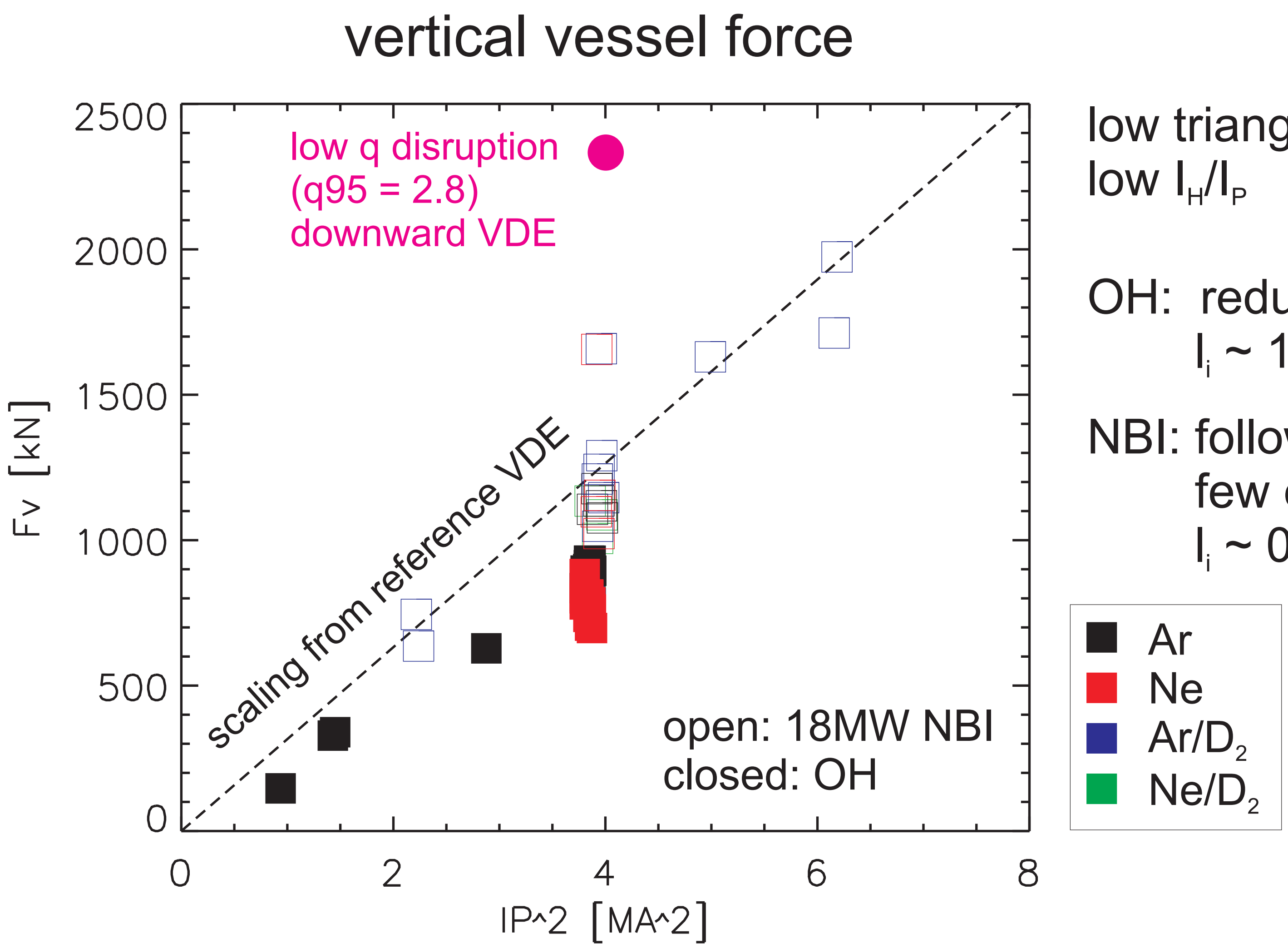
reduction by a factor 2.5
if DMV is activated at Δz = 10cm

Mitigation of forces from halo / eddy currents



reduction by ~30%
if DMV is activated at Δz = 10cm

Mitigation of forces from halo / eddy currents



low triangularity/elongation

low I_H/I_P

OH: reduction by 30%

$l_i \sim 1.25$

NBI: follows scaling for VDE (OH)

few exception with higher force

$l_i \sim 0.9$

Reduction of heat loads

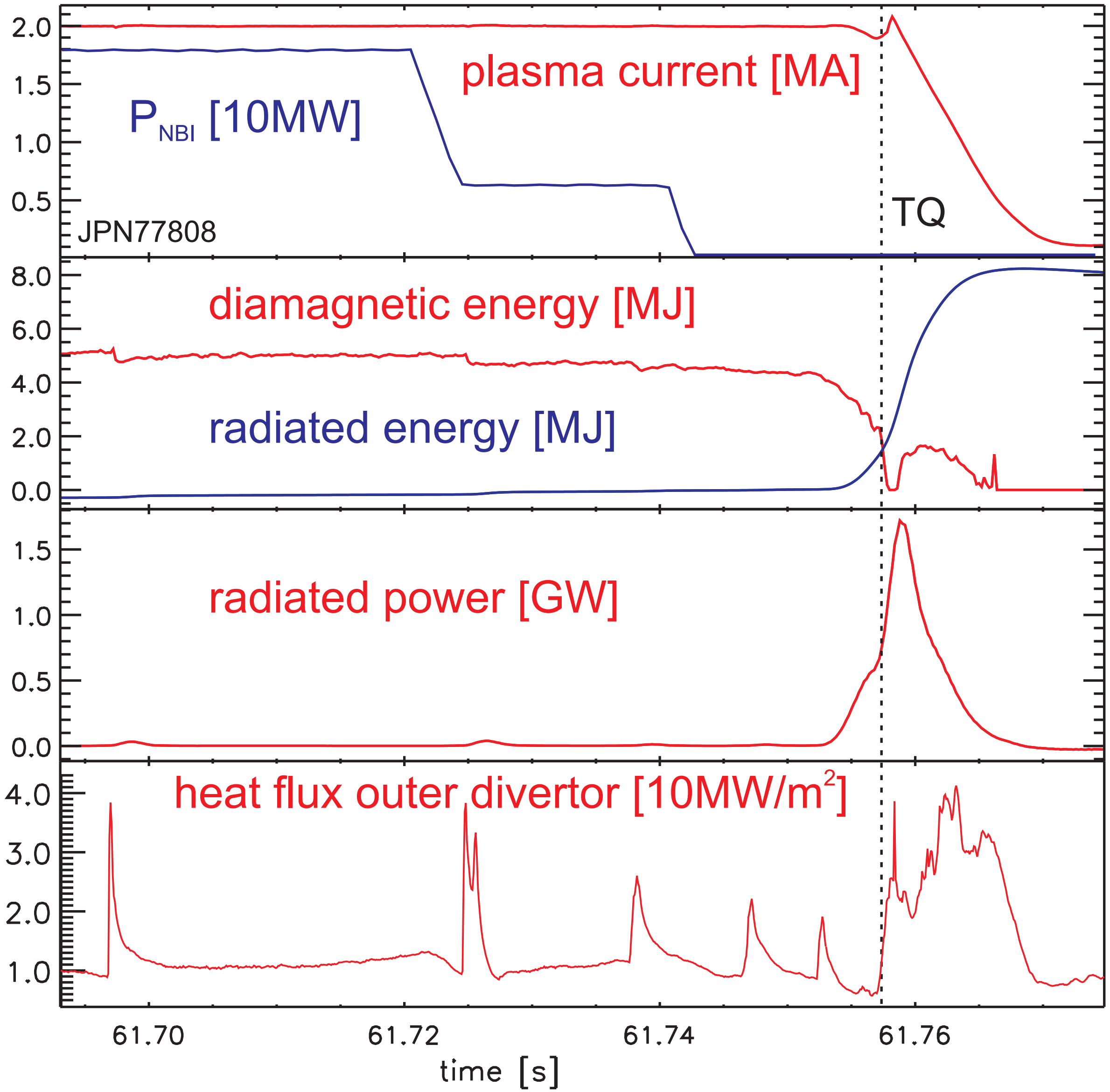
maximise the fraction of radiated power before and during the thermal quench

high radiation efficiency (Ne, Ar)

maximise impurity deposition before the thermal quench

Mitigation of Heat Loads

Ar/D2 injection ($N=3x10^{23}$)



peak heat flux in TQ (ΔW > 2MJ) comparable to ELMs (ΔW~0.3MJ)

background to be corrected during CQ

Mitigation of Heat Loads

direct measurements of heat loads difficult:

- only small fraction detected in divertor (energy distribution to be analysed)
- strong background radiation from inside the plasma

energy balance during disruption

$$W_{rad} = f_{mag} \times \left(W_{mag} - W_{mag}^{structure} - W_{mag}^{RE}\right) + f_{th} \times W_{th}$$

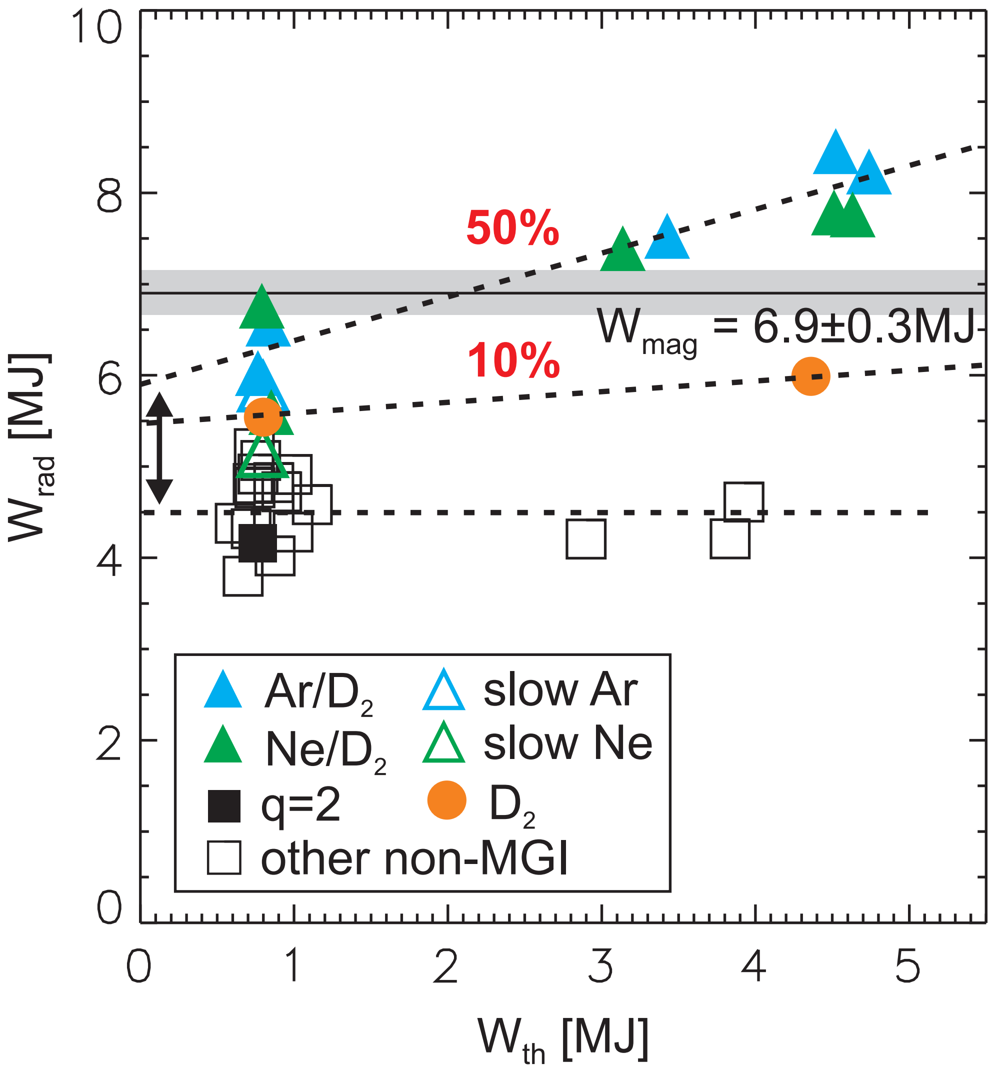
f_{mag}: ≈ 1.0

W_{mag}: keep constant

$W_{mag}^{structure}$: assume constant

W_{mag}^{RE}: no RE

Mitigation of Heat Loads



significant more energy is radiated during MGI compared to reference disruptions

Ar/Ne+D_2 MGI

$$\mathbf{W_{rad} \approx 0.85 \times W_{mag} + 0.48 \times W_{th}}$$

reference*

$$\mathbf{W_{rad} \approx 0.65 \times W_{mag}}$$

most non-MGI disruptions:
W_{th} degrades before TQ

*cf. V. Riccardo 2002, J. Paley 2005:

$W_{rad} \approx 68\%\ W_{mag}$

$f_{mag} \approx 0.94$

$$W_{rad} = f_{mag} \times \left(W_{mag} - W_{mag}^{structure} - W_{mag}^{RE}\right) + f_{th} \times W_{th}$$

TRILATERAL EUREGIO CLUSTER

JÜLICH FORSCHUNGSZENTRUM

Suppression of runaways

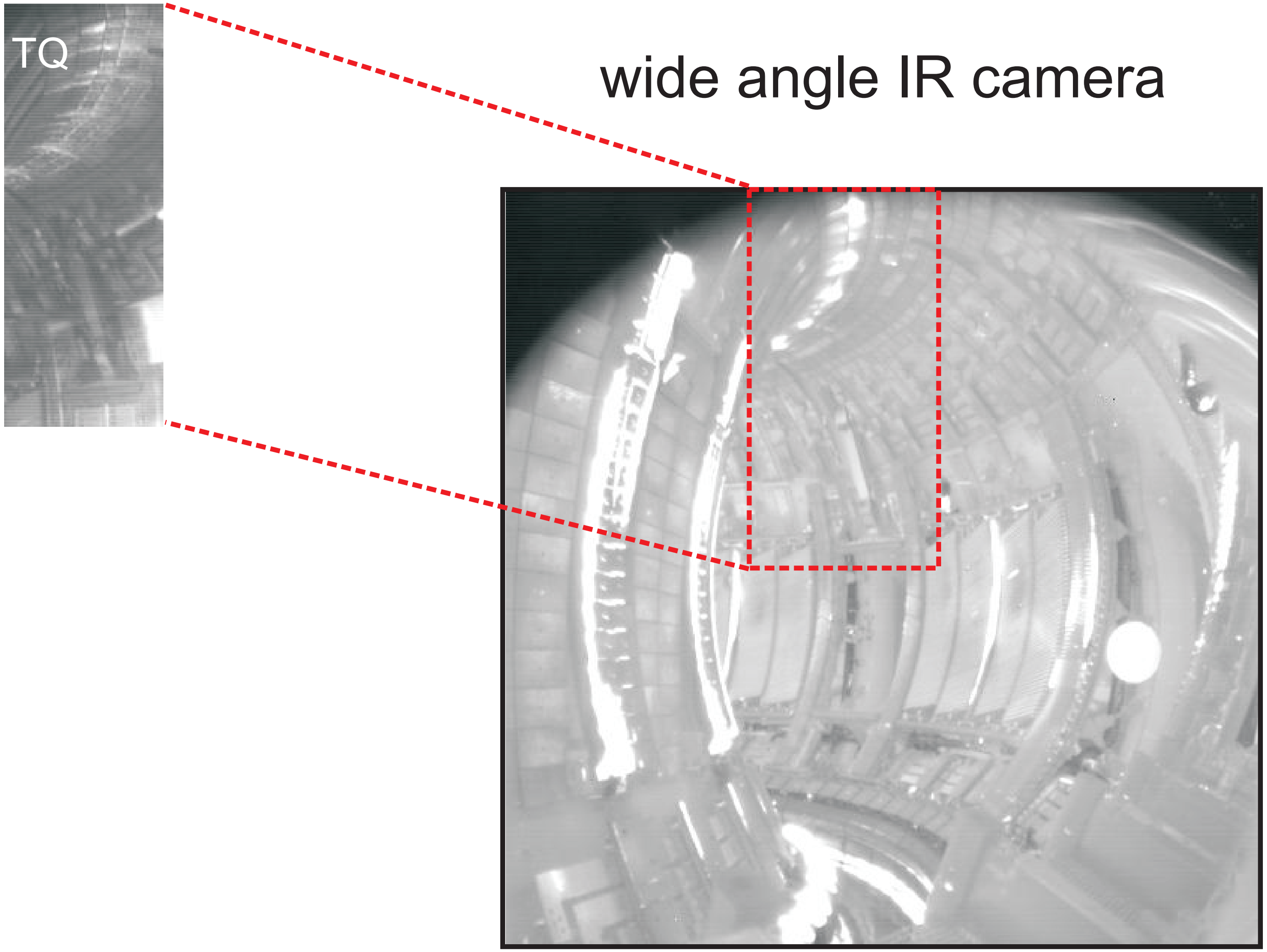
high electron density in the current quench

high fuelling efficiency

maximise deposited impurities before the thermal quench

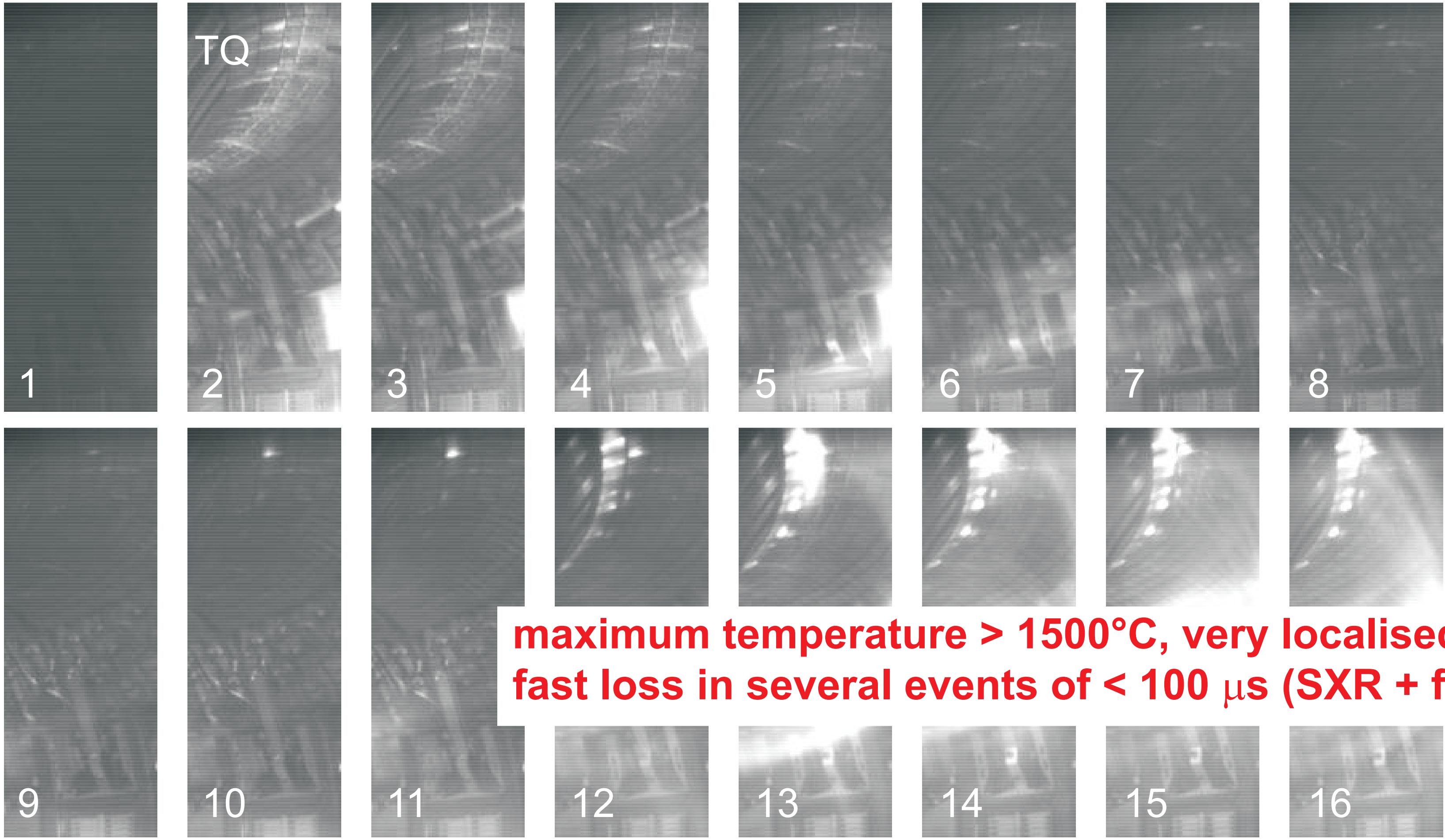
Heat loads by runaways

wide angle IR camera

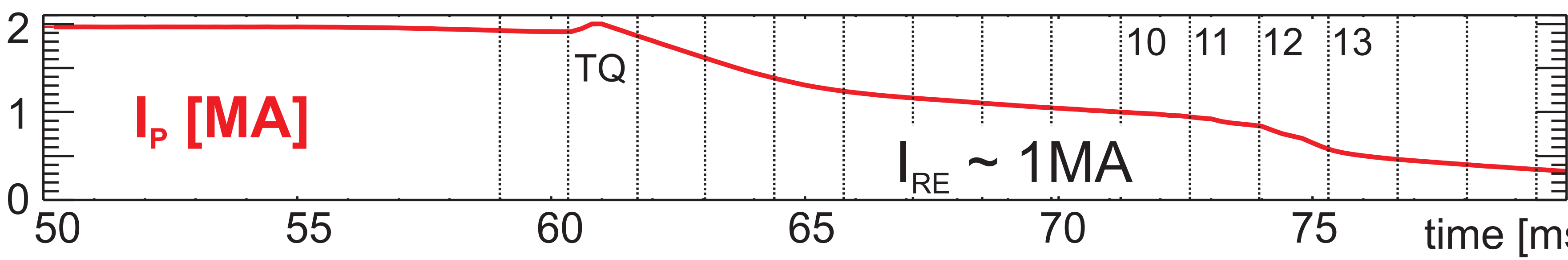


Heat loads by runaways

wide angle IR camera, #76533 Δt ~1.3ms, Ar injection



maximum temperature > 1500°C, very localised
fast loss in several events of < 100 μs (SXR + fast visible)



EUREGIO CLUSTER
JÜLICH
FORSCHUNGSZENTRUM

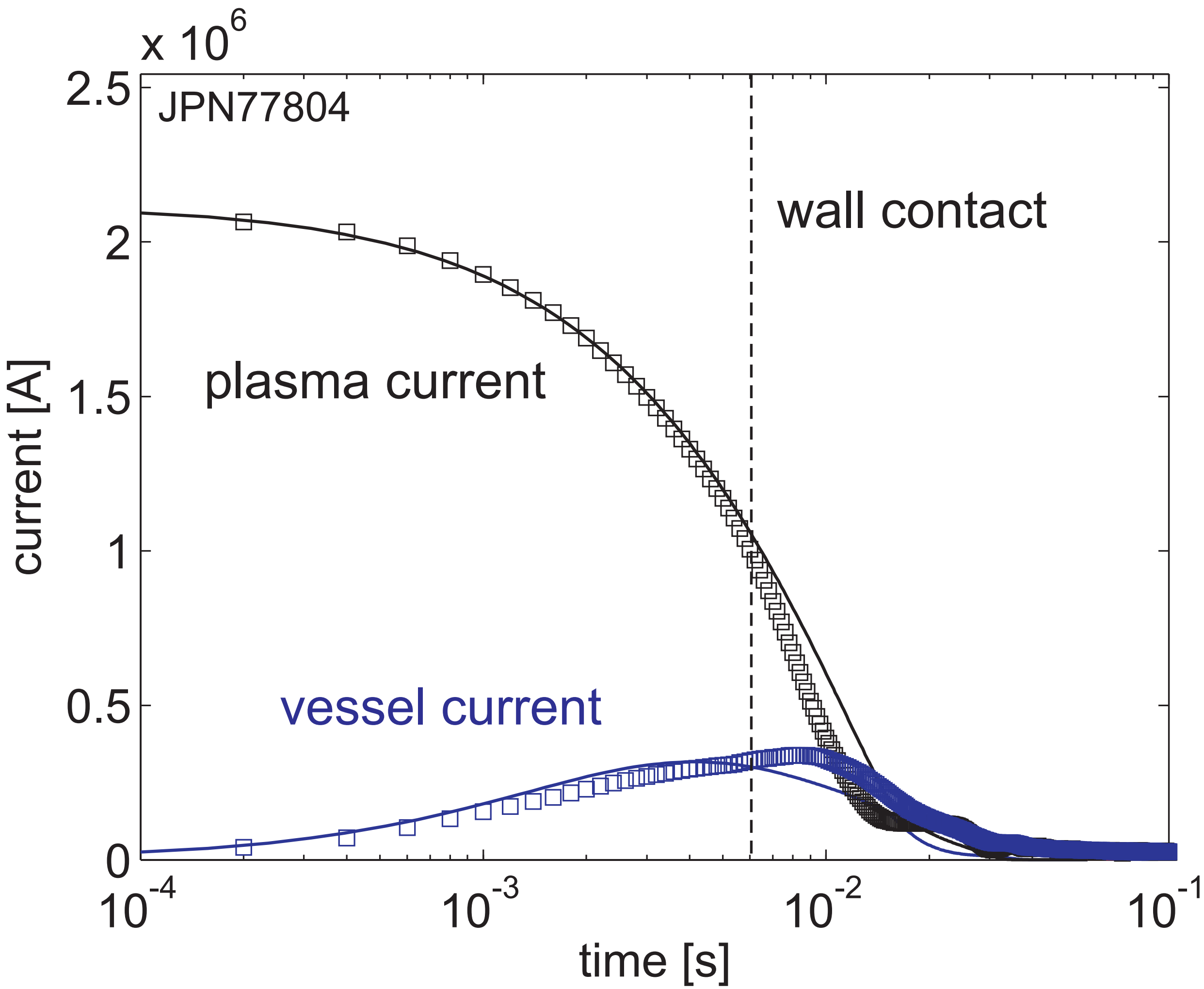
Mitigation of runaways

RE generation: $E > 0.01 \times E_{Dreicer}$; $E_{Dreicer} \sim n_e / T_e$

Avalanche suppression: $E < E_C = 10^{-21}\ Vm^2 \times n_e^{tot}$

⇨ **increase density**

Density estimate from 0-d model*



Plasma Current

$$\frac{dI_P}{dt} = -\frac{2\pi R\eta}{A(L-L_v)} I_P - \frac{I_v}{\tau_v(1-L/L_v)}$$

Vessel Current

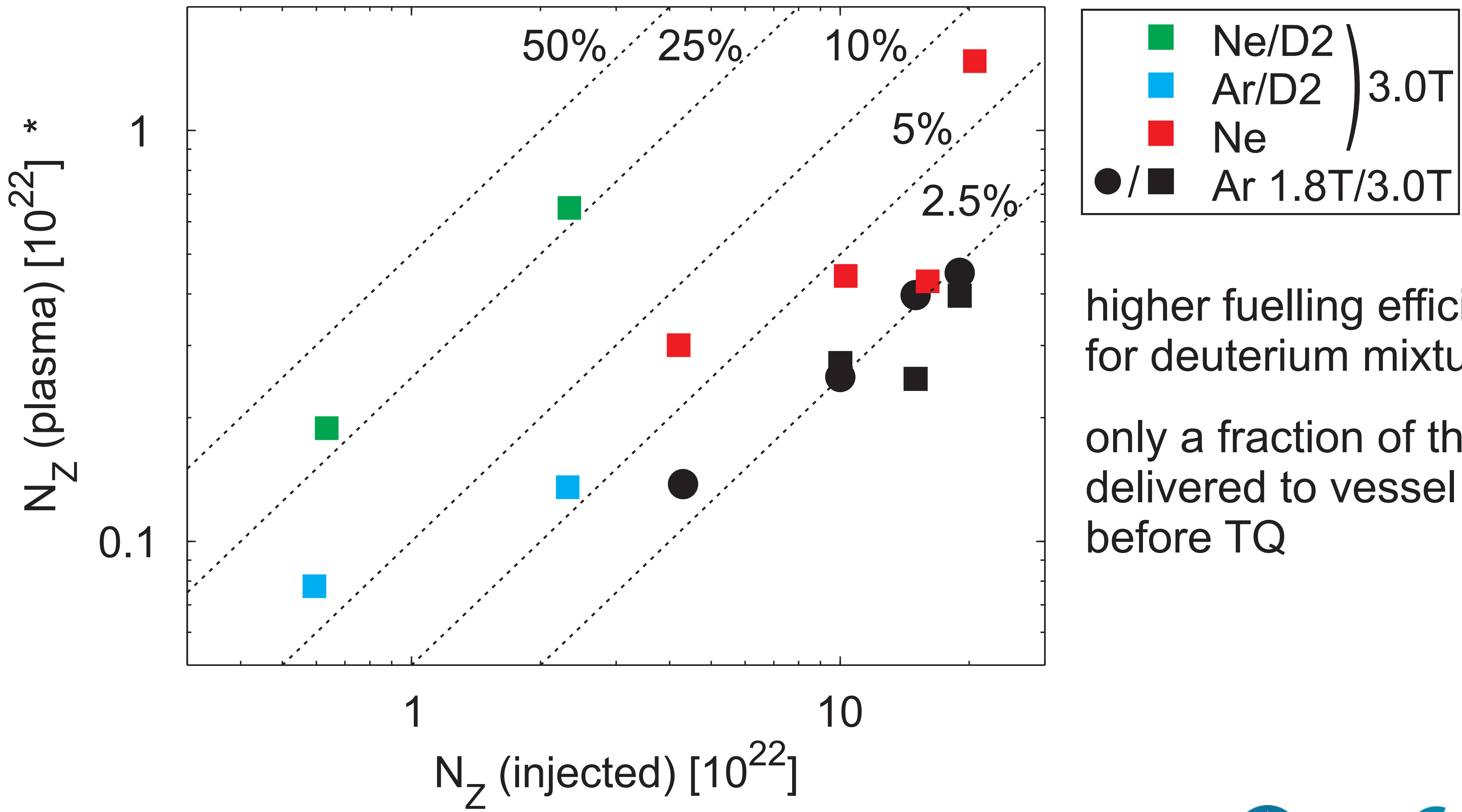
$$\frac{dI_v}{dt} = -\frac{I_v}{\tau_v} - \frac{dI_P}{dt}$$

radiated power = ohmic power

$$n_e n_Z L_{rad}(T_e) = \frac{\eta(T_e) I_P^2}{A^2}$$

*S.A. Bozhenkov et al., PPCF 2008, RE not considered here

Fuelling Efficiency

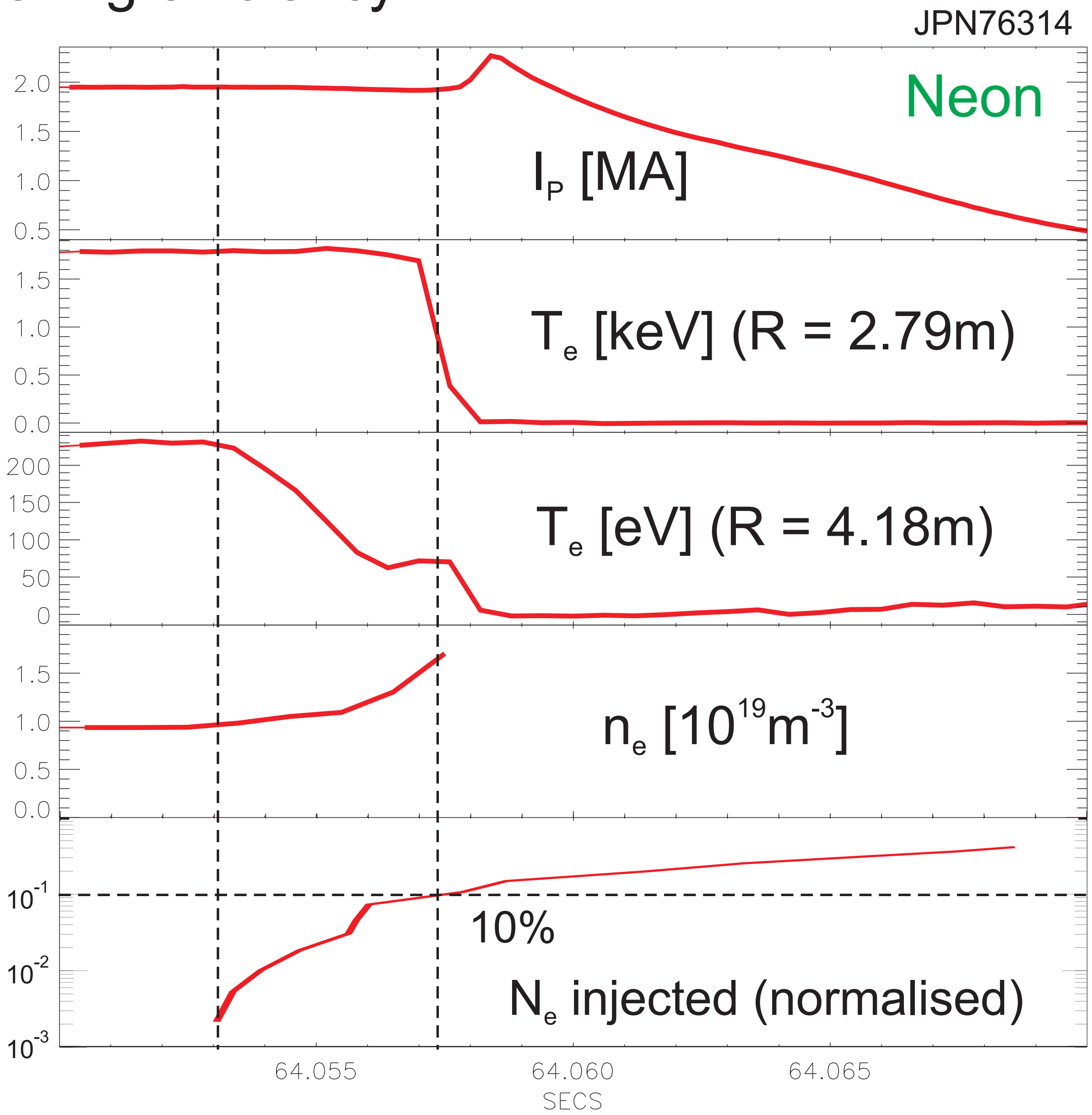


higher fuelling efficiency for deuterium mixtures

only a fraction of the gas delivered to vessel before TQ

* estimated from 0-d current quench model

Fuelling efficiency



density increase before TQ:
2-3% in plasma

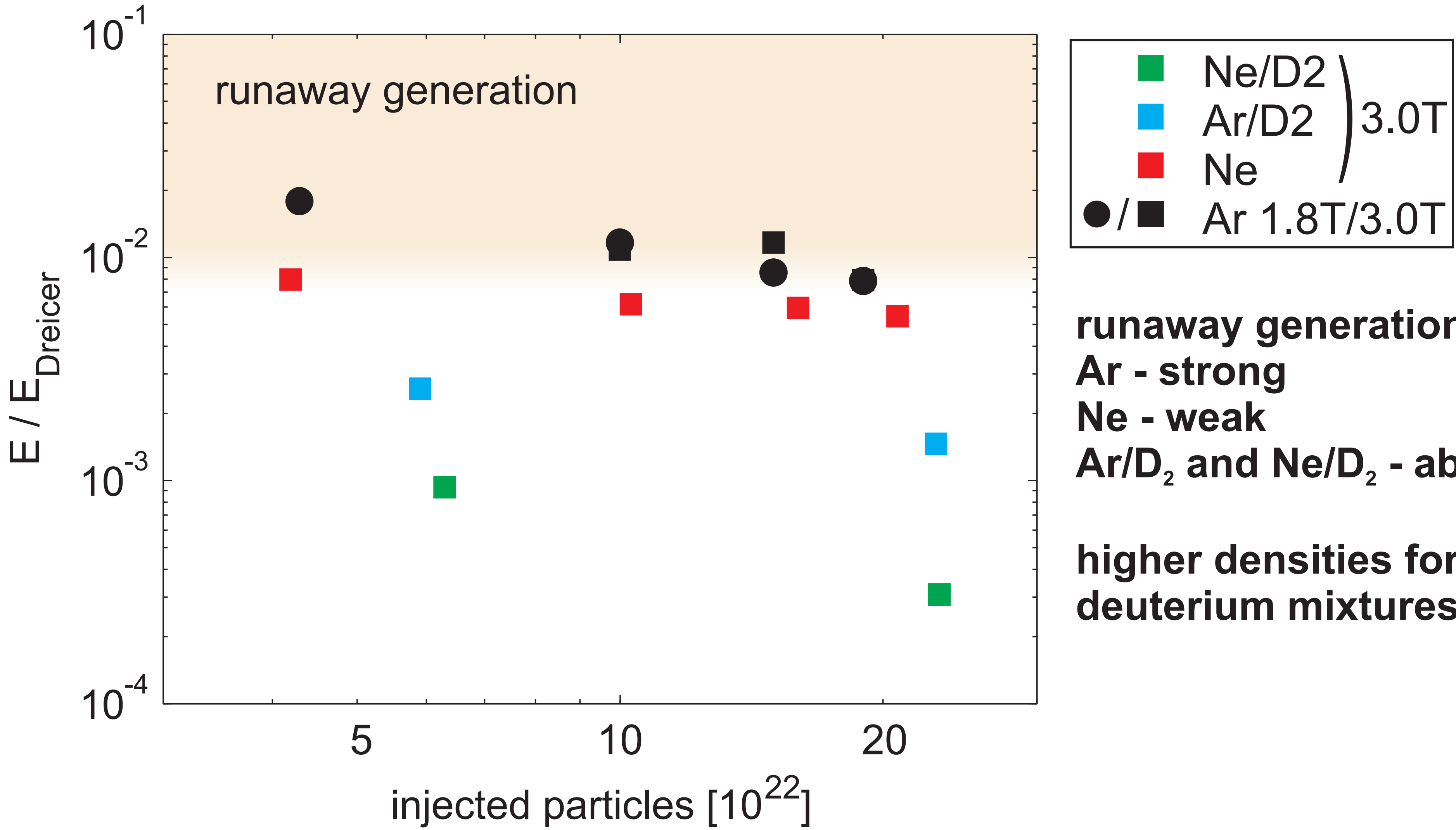
fuelling efficiency found from
CQ analysis: ~ 5%

lab measurements:
~ 10% injected at TQ

main cause for low f.e.
> gas flow dynamics (4m tube!)

Mitigation of runaways

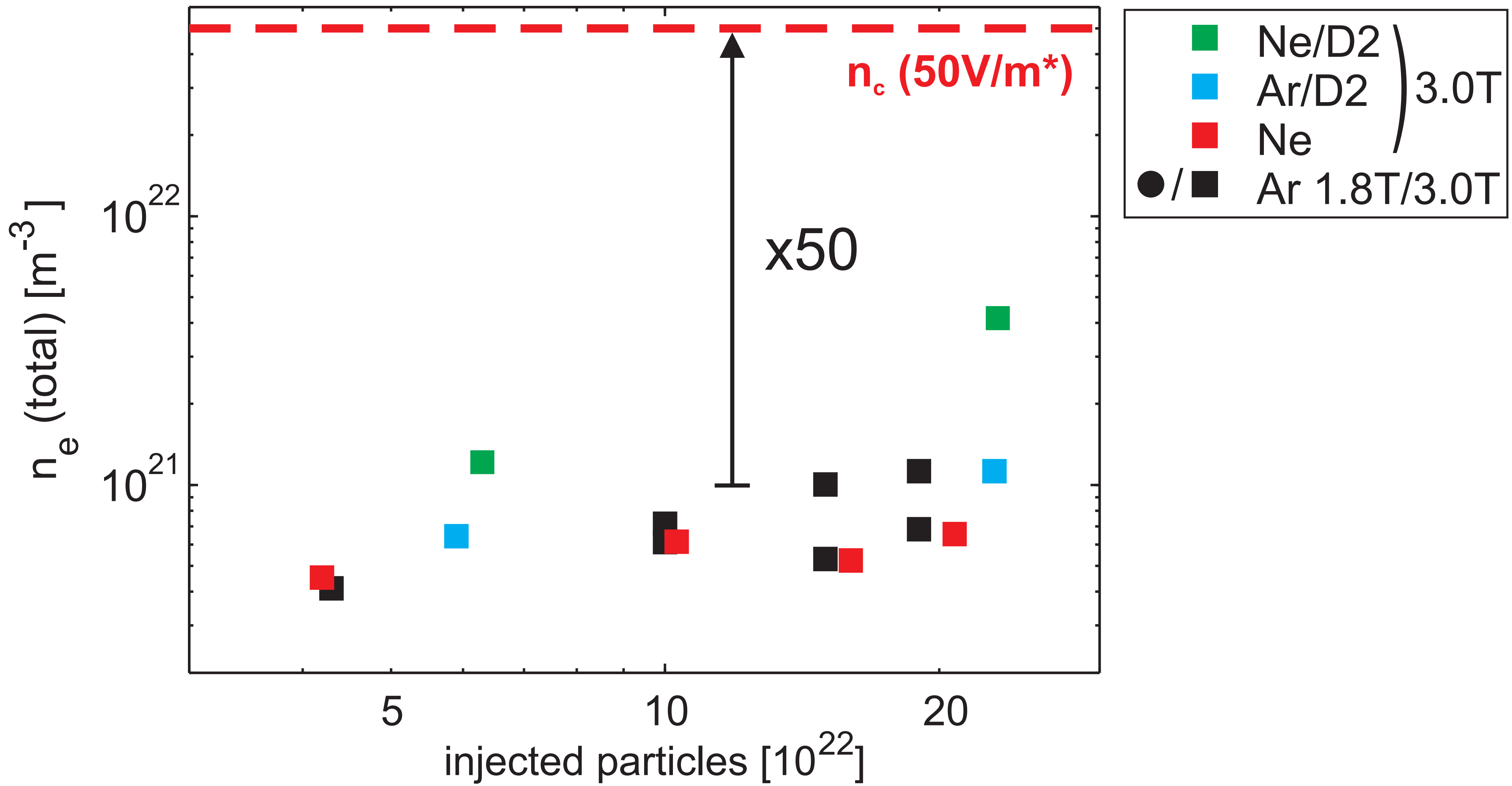
Electric Field



runaway generation:
Ar - strong
Ne - weak
Ar/D_2 and Ne/D_2 - absent

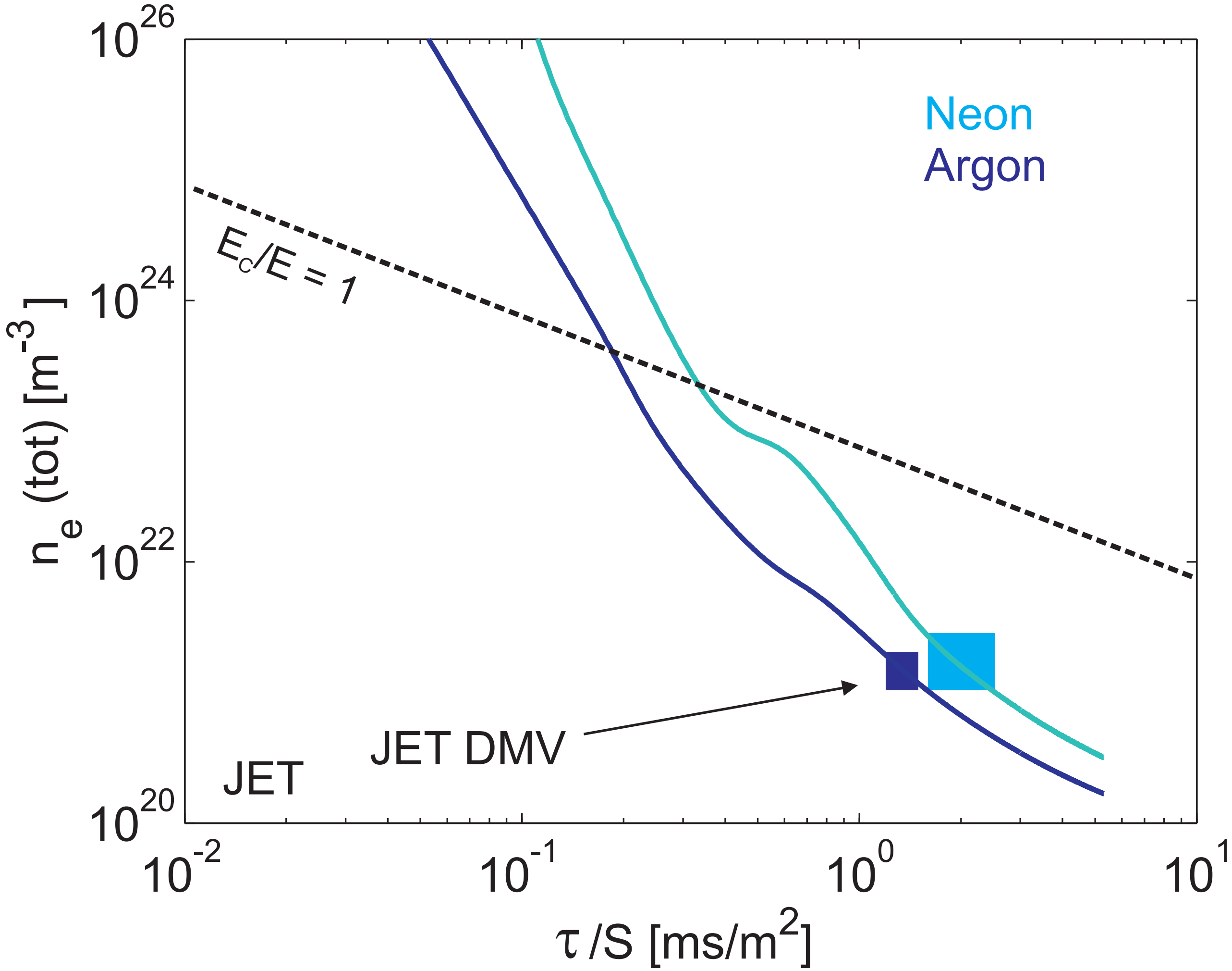
higher densities for deuterium mixtures

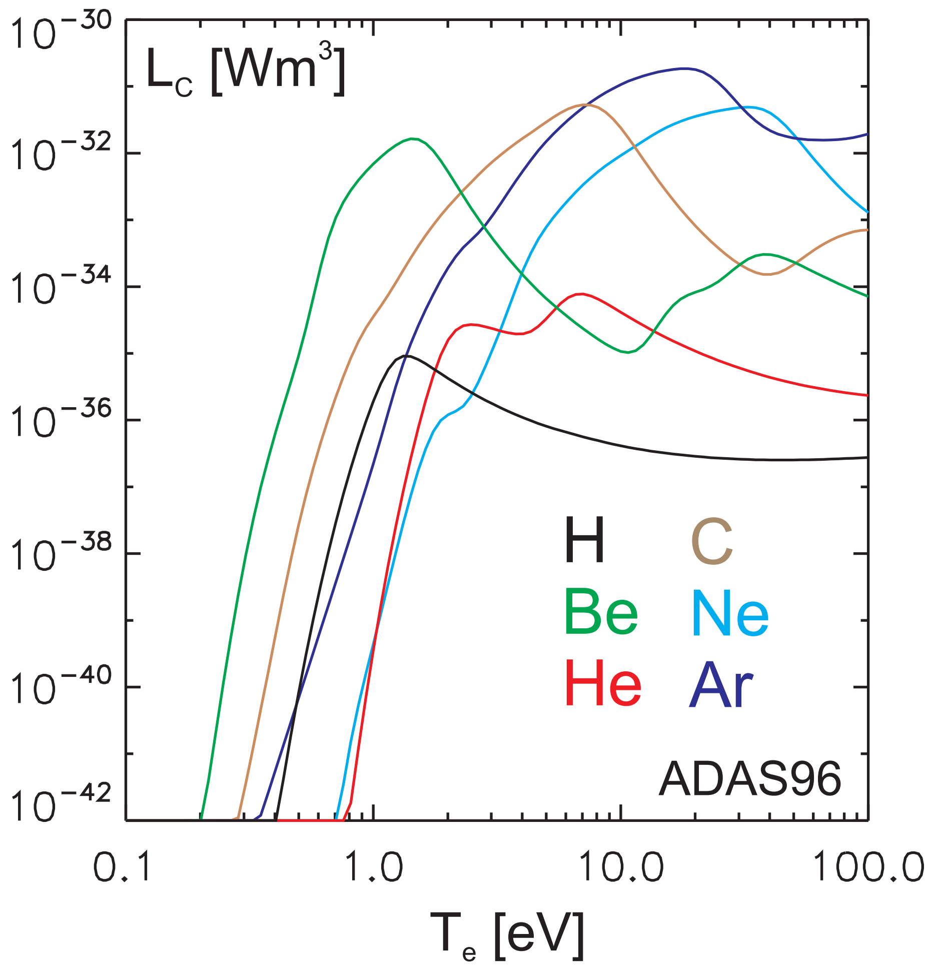
Avalanche Suppression



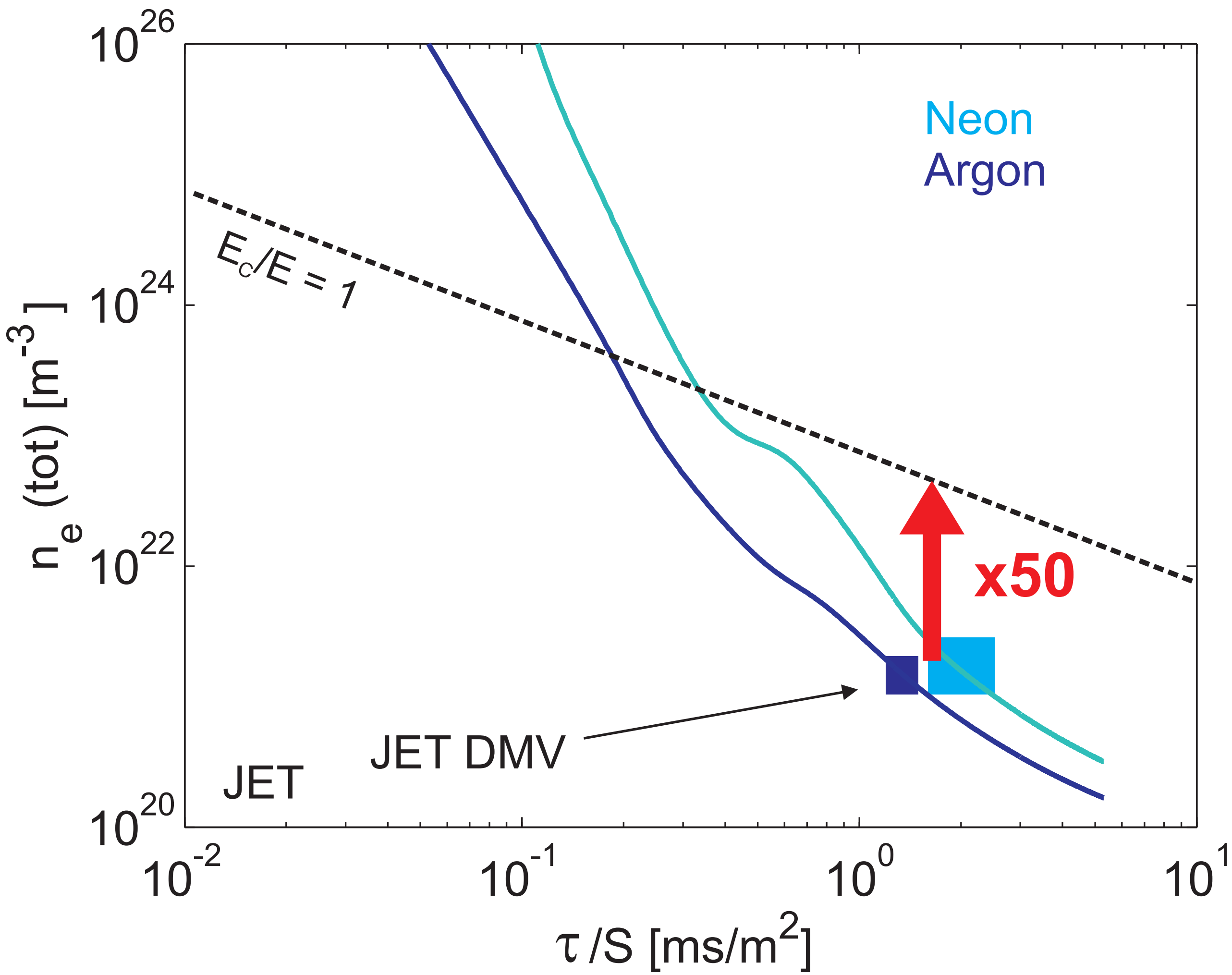
*impurity injection can lead to higher E

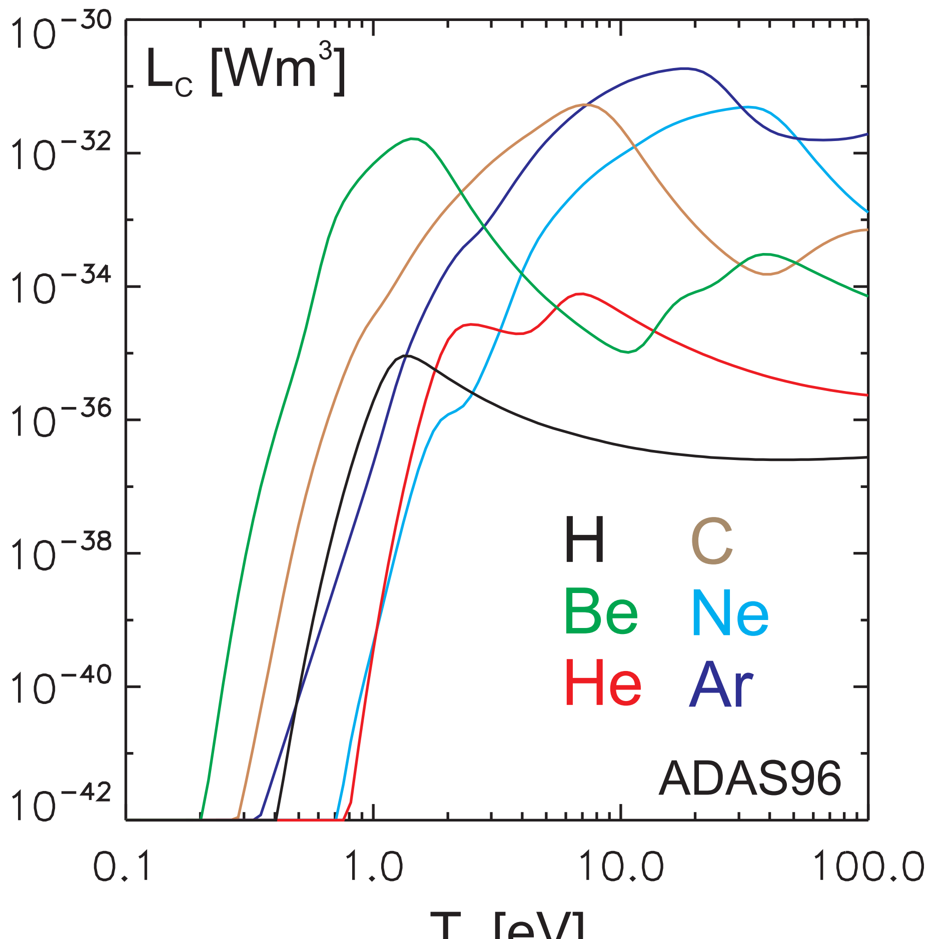
current quench times - consequences for avalanche suppression





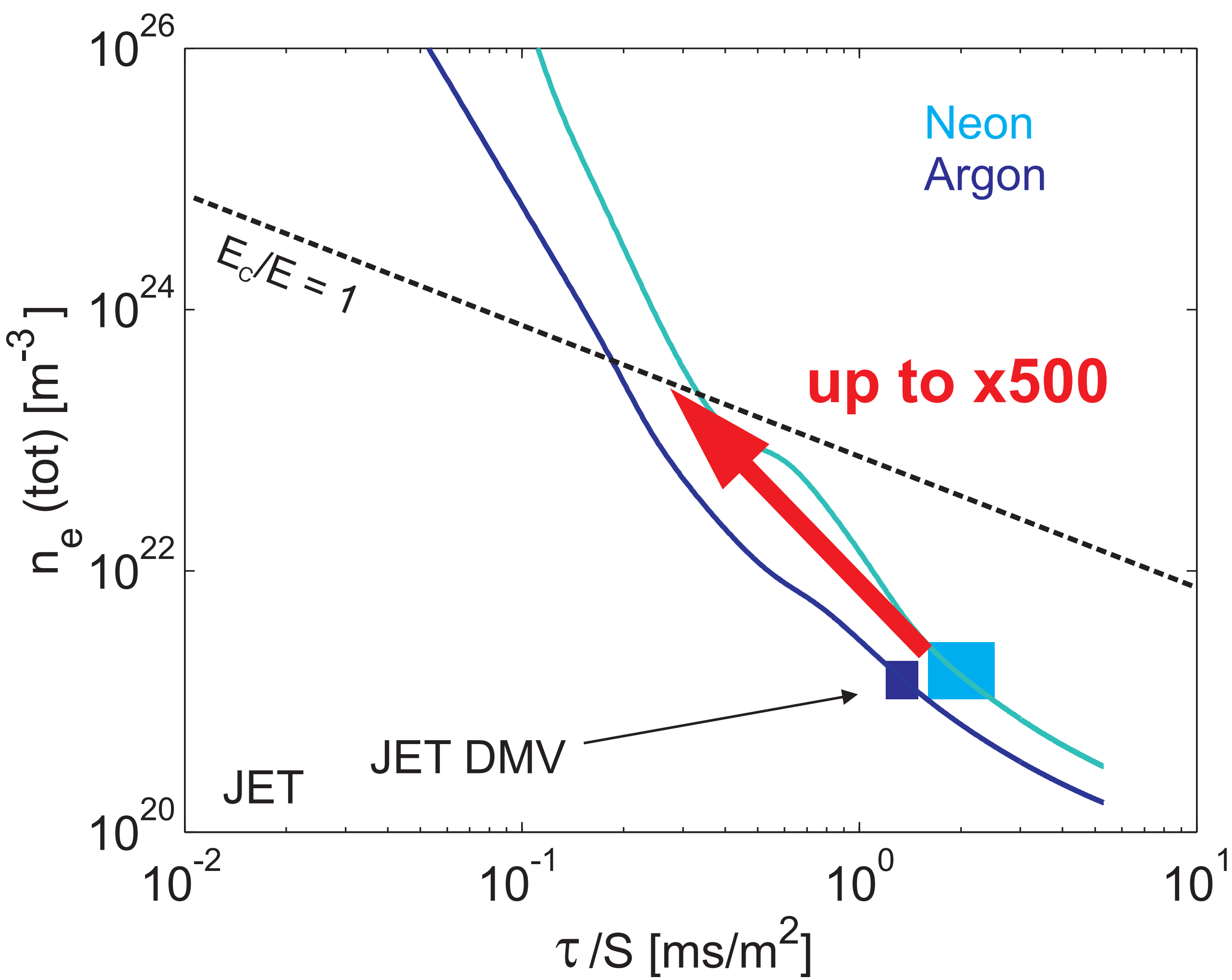
current quench times - consequences for avalanche suppression

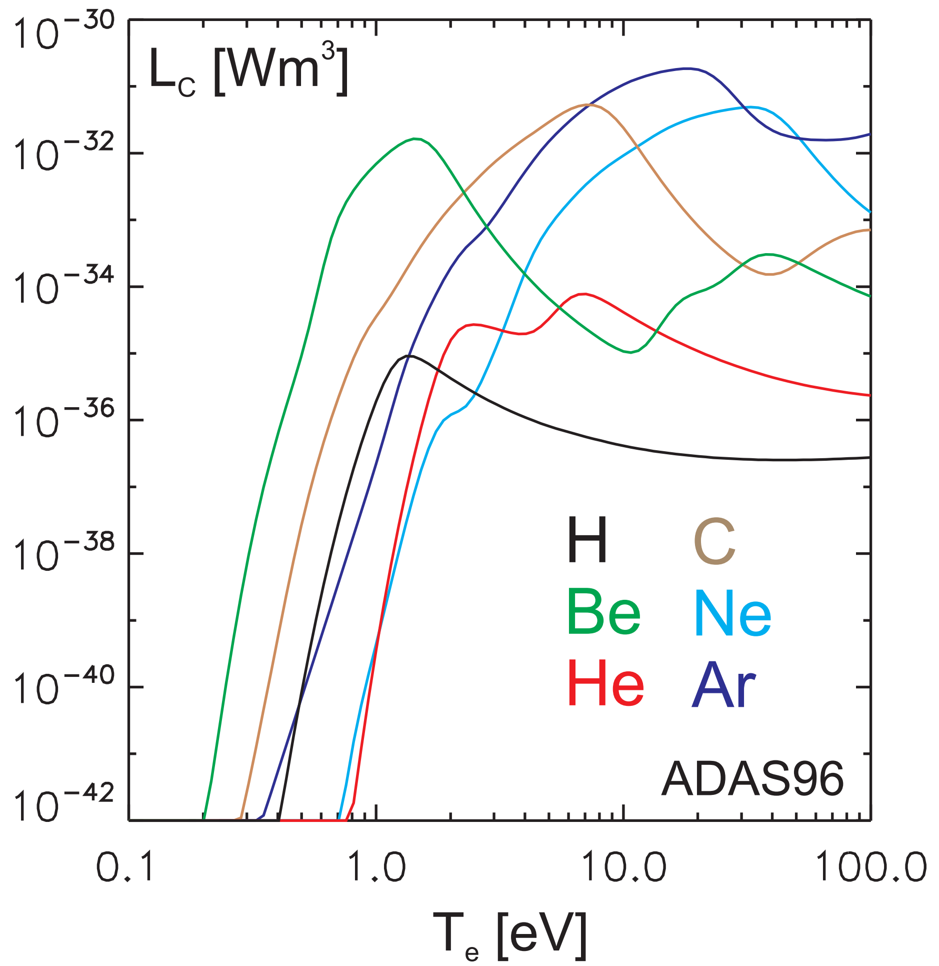




Mitigation of runaways

current quench times - consequences for avalanche suppression

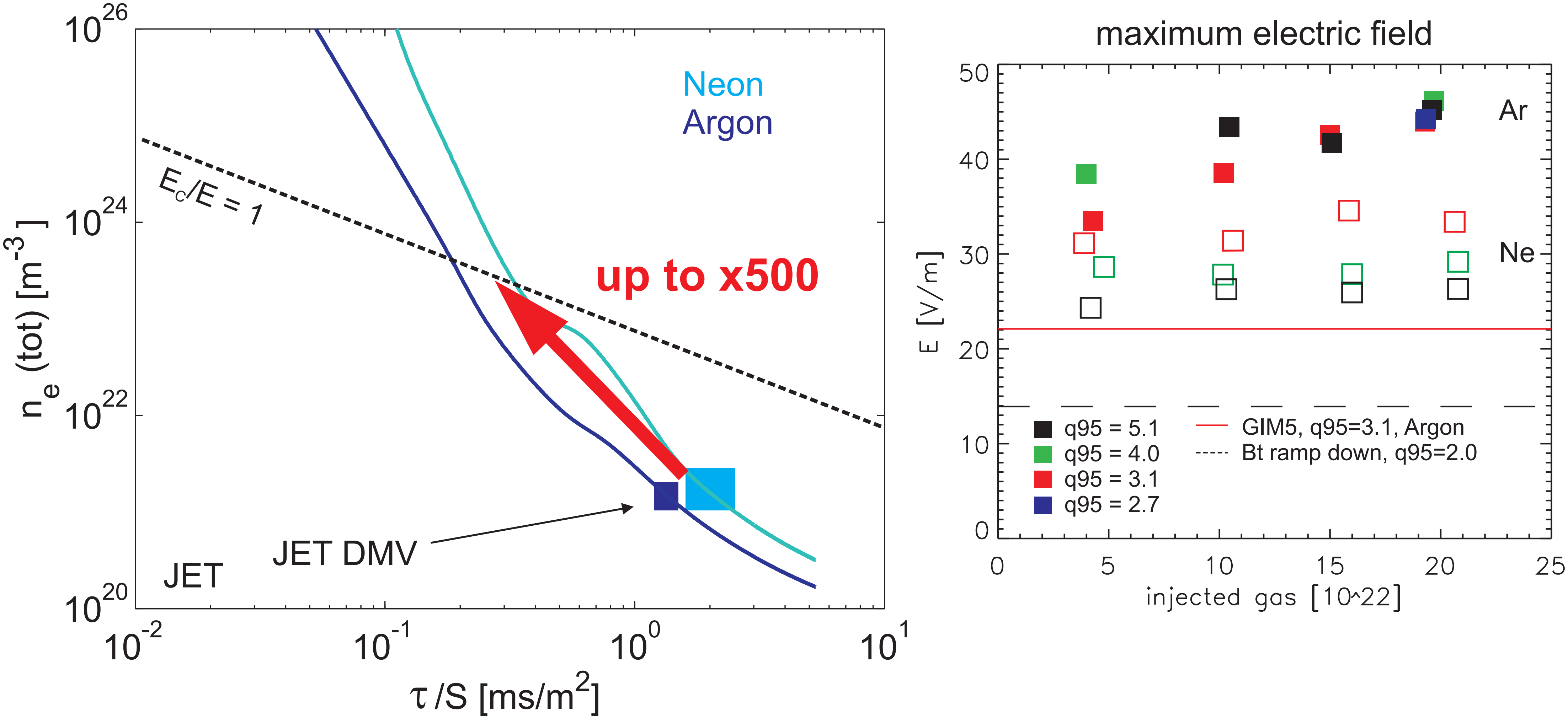




opacity could lead to stagnation in the reduction of τ_{CQ}
(seen in AUG, JET data not clear)
more sophisticated model needed

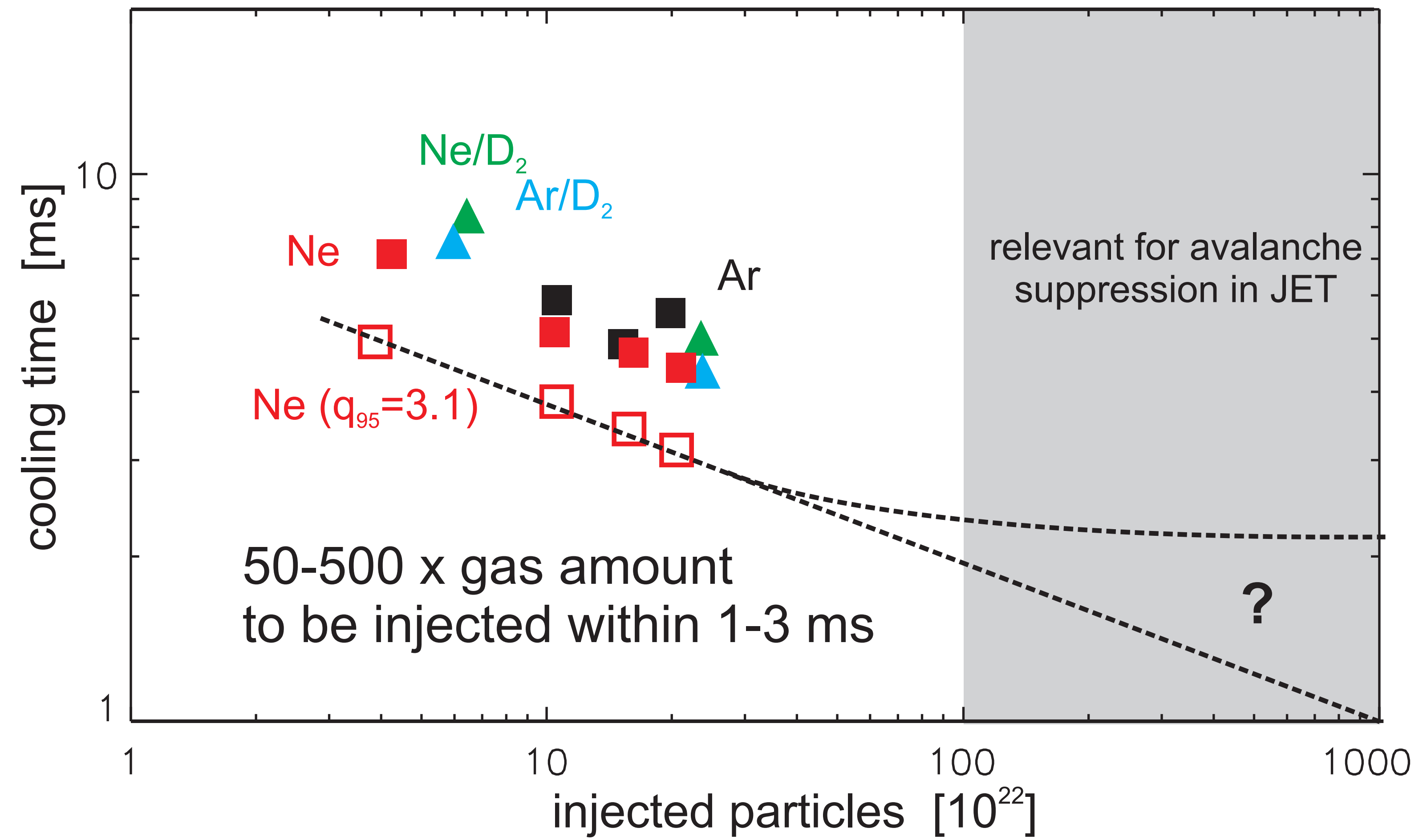
Mitigation of runaways

current quench times - consequences for avalanche suppression



opacity could lead to stagnation in the reduction of τ_{CQ}
(seen in AUG, JET data not clear)
more sophisticated model needed

Timescale and amount of gas for avalanche suppression in JET



methods for disruption mitigation (avoidance)

- Controlled plasma shutdown
  - reduce shaping
  - stop external heating
  - ramp down plasma current
  - stabilise vertical displacement / control runaway beam

slow time scale

- Local Heating
  - disruption avoidance/retardation by ECRH
  - curing (N)TM modes

not for all disruption types

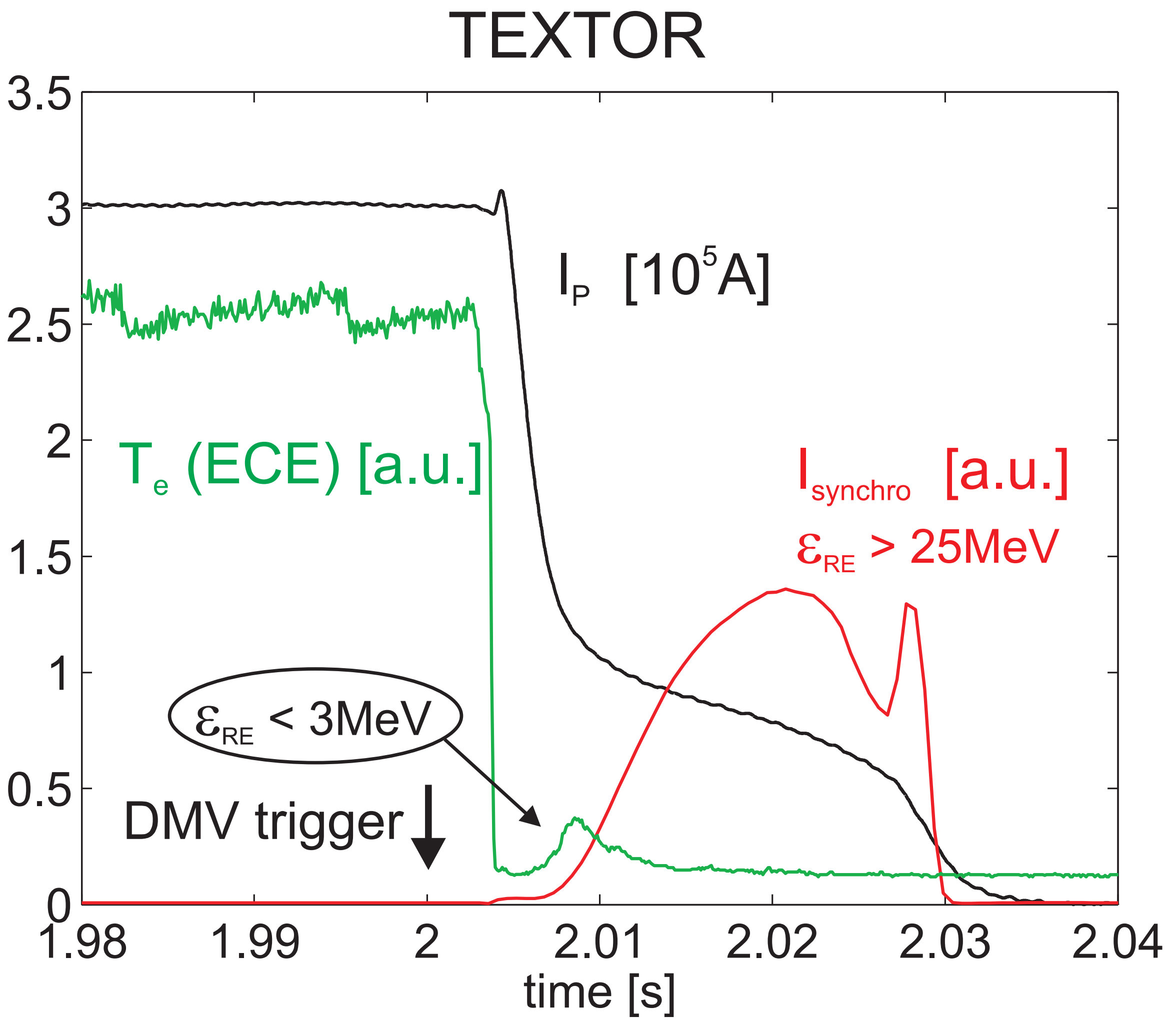
- Massive Material Injection (Gas, Pellets, Liquids)
  - injection of gas, pellets, liquids
  - reduction of forces, heat loads
  - avoidance of runaways

last resort

- **Magnetic Perturbations**
  - de-confine runaway electrons

acts only on RE

Runaway generation by Argon injection



3×10^{21} injected Argon atoms

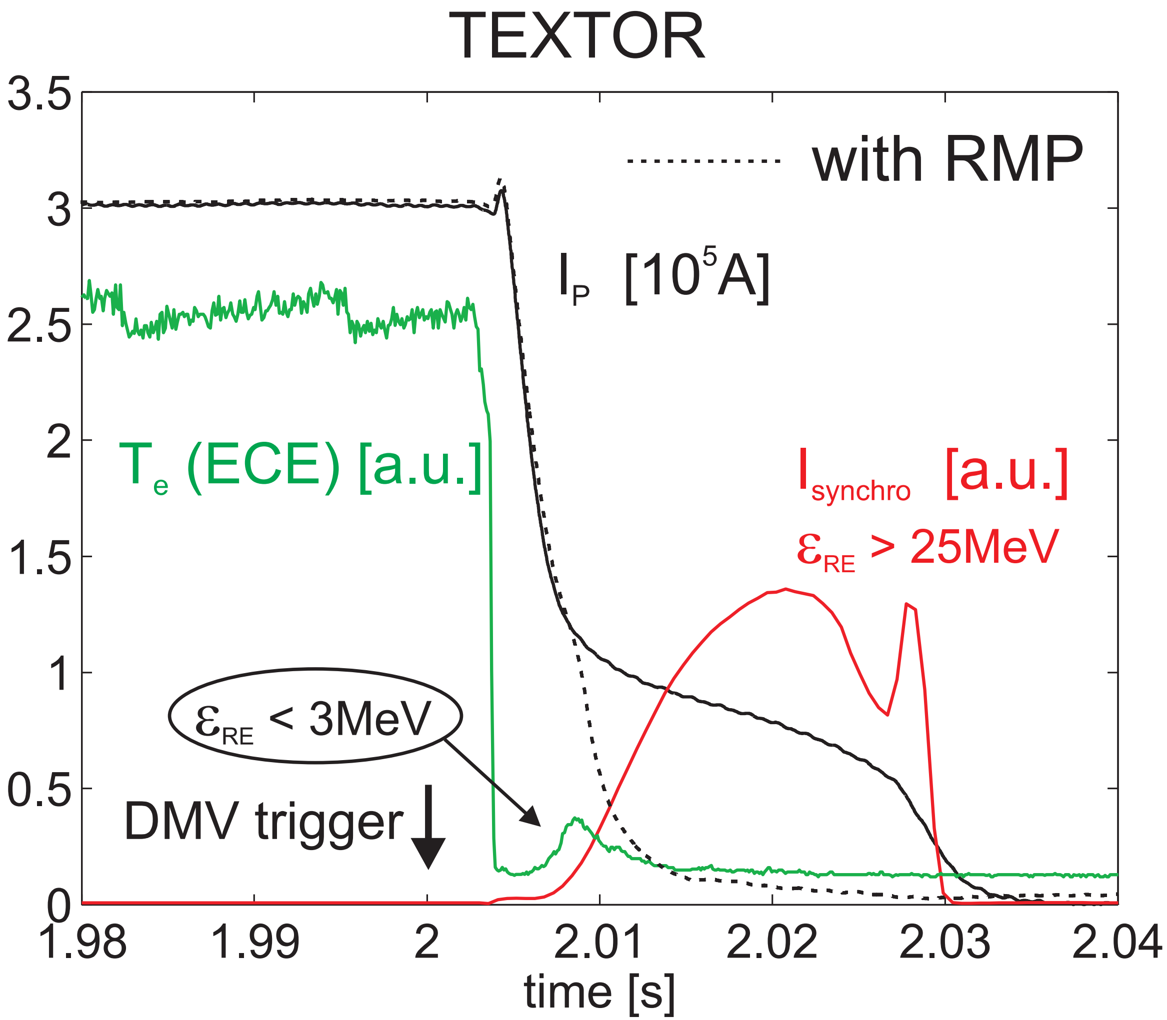
I_P = 0.3 MA
B_t = 2.25T
ohmic

E^{max} ~ 20 V/m

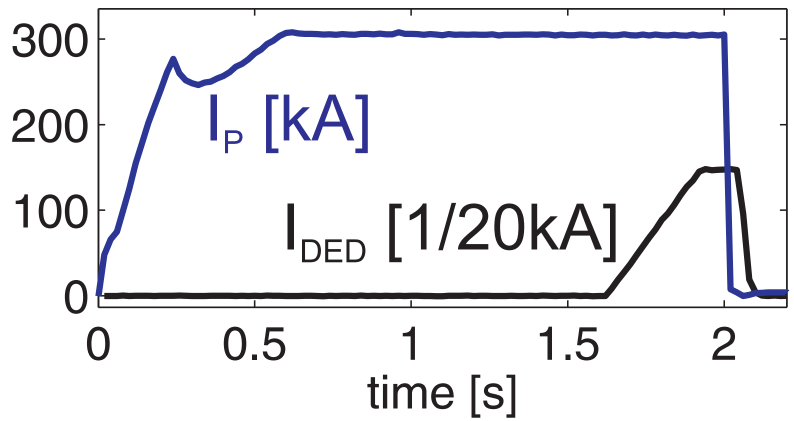
RE diagnostic

IR camera (synchrotron radiation)
Neutrons
ECE
current plateau

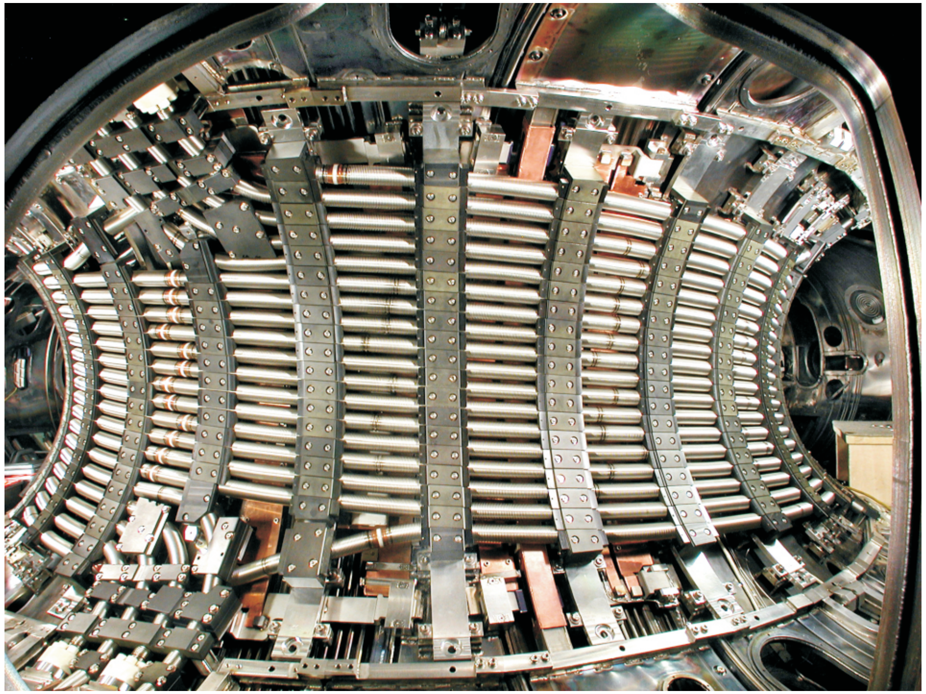
Runaway generation by Argon injection

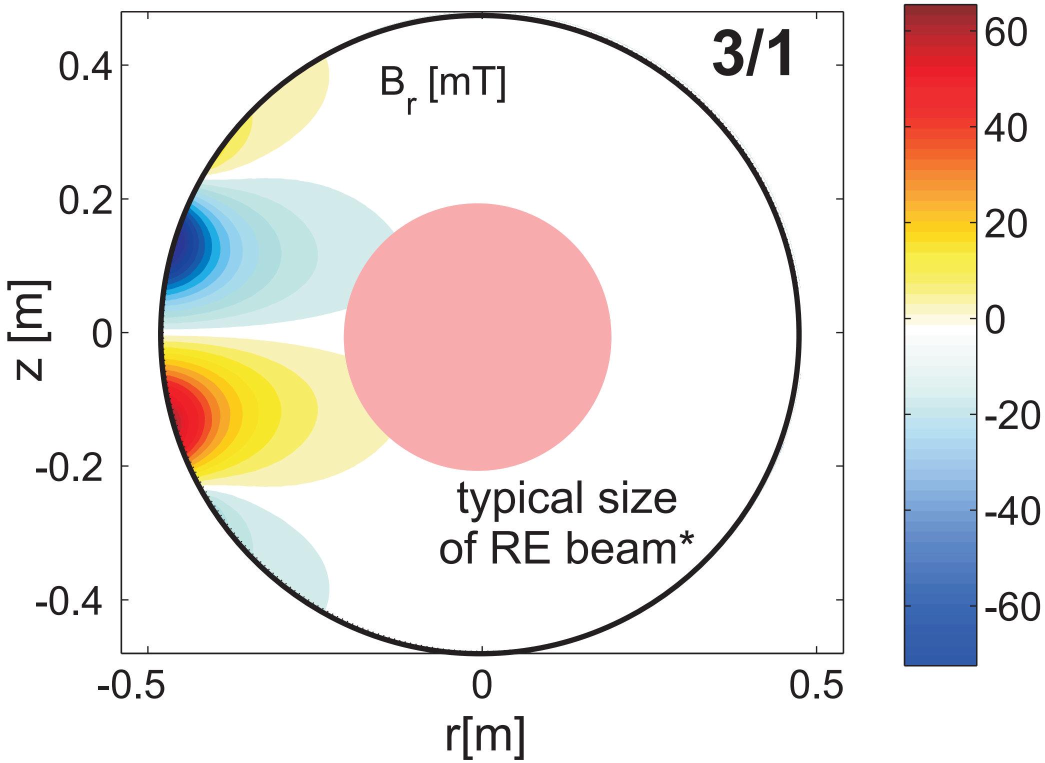


Perturbation Field switched on 200ms before DMV trigger



Dynamic Ergodic Divertor (DED)



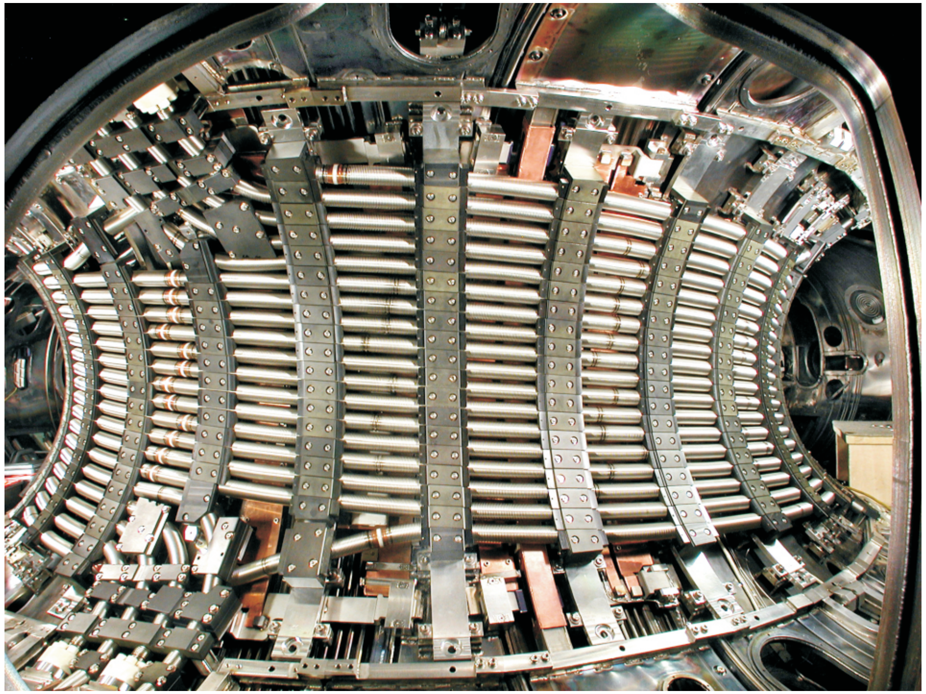


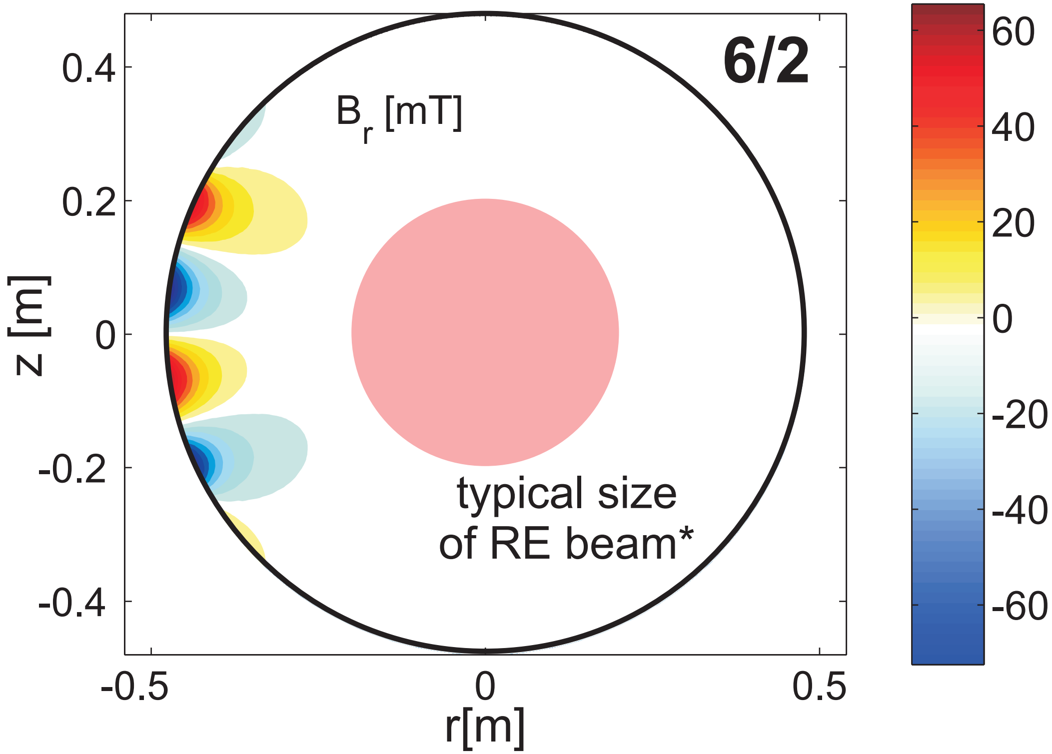
16 coils at the HFS: m/n = 12/4, 6/2, 3/1

current / coil $\leq$ 15kA $\longrightarrow$ B_{DED}/B_{ϕ} ~ 1%

* as measured by SXR

Dynamic Ergodic Divertor (DED)



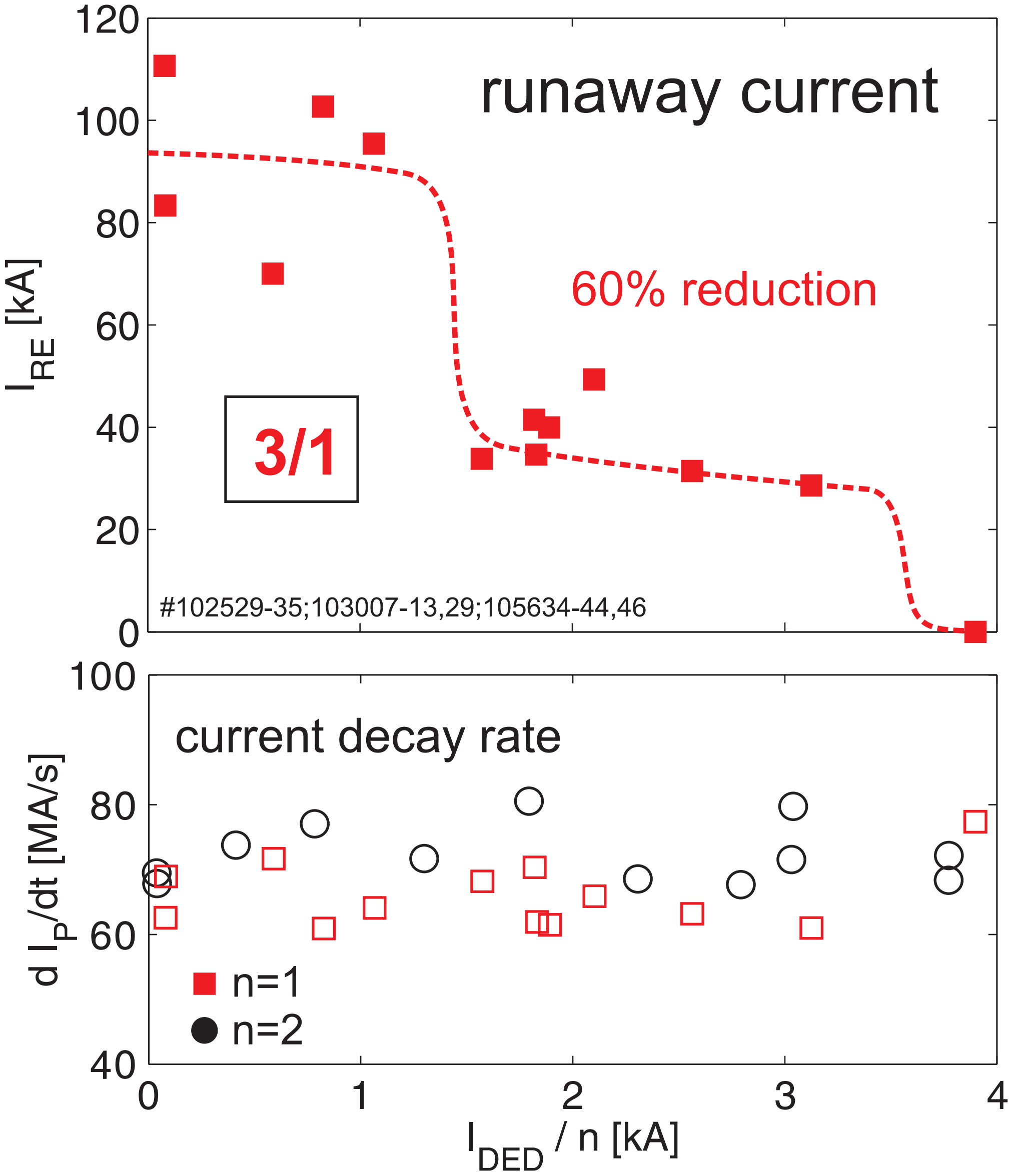


16 coils at the HFS: m/n = 12/4, 6/2, 3/1

current / coil ≤ 15kA → $B_{DED}/B_{\phi} \sim 1\%$

* as measured by SXR

RE suppression with n=1 RMP



strong reduction of RE current for $I_{DED}/n > 1.4$kA

current decay rate unaffected

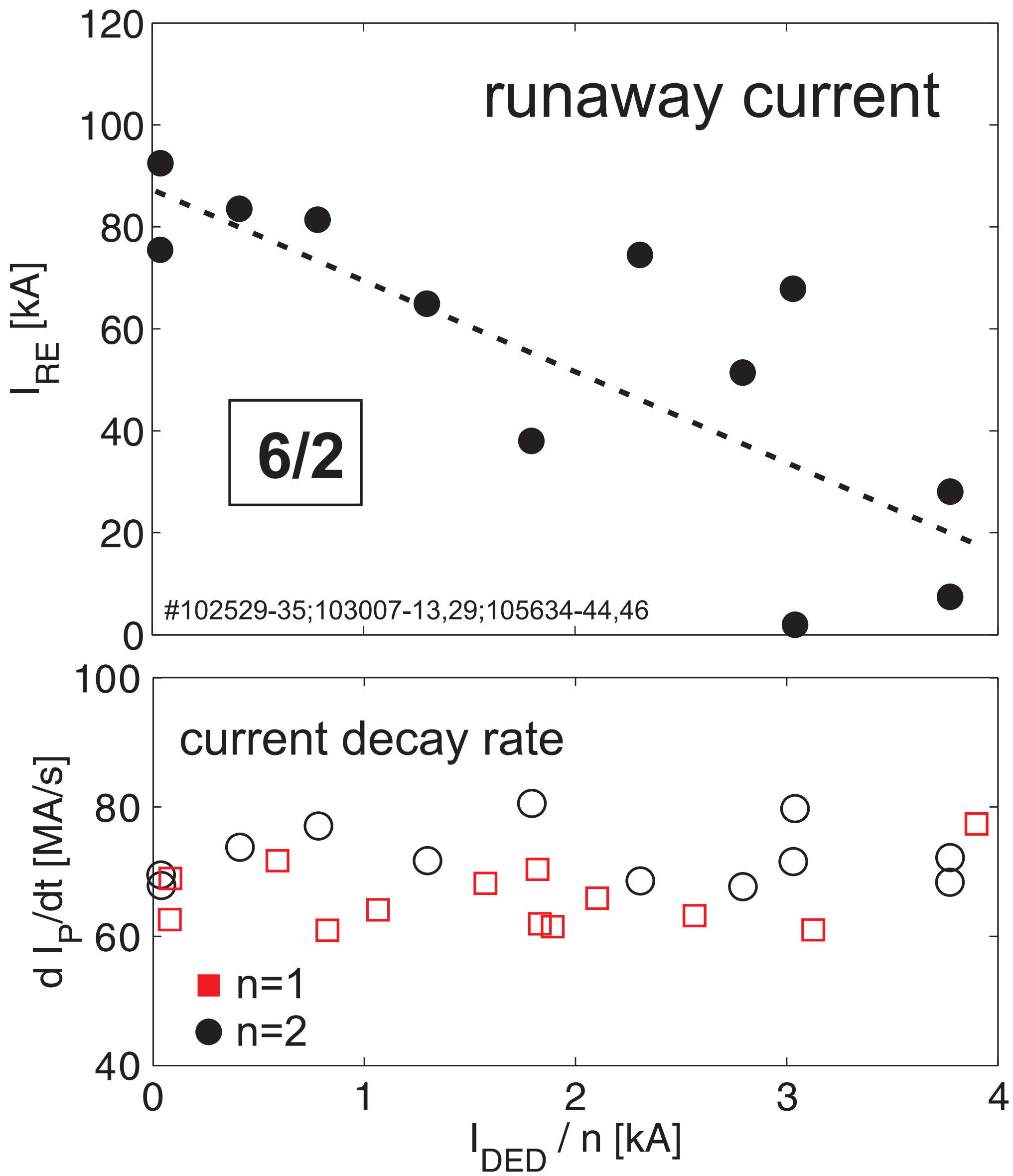
$I_{DED} = 1.4$kA

⇩

B_{m1} (r=a) = 2.5-3.5 mT (m=2,3,4)

M. Lehnen et al, PRL 100, 255003 (2008)

RE suppression with n=2 RMP

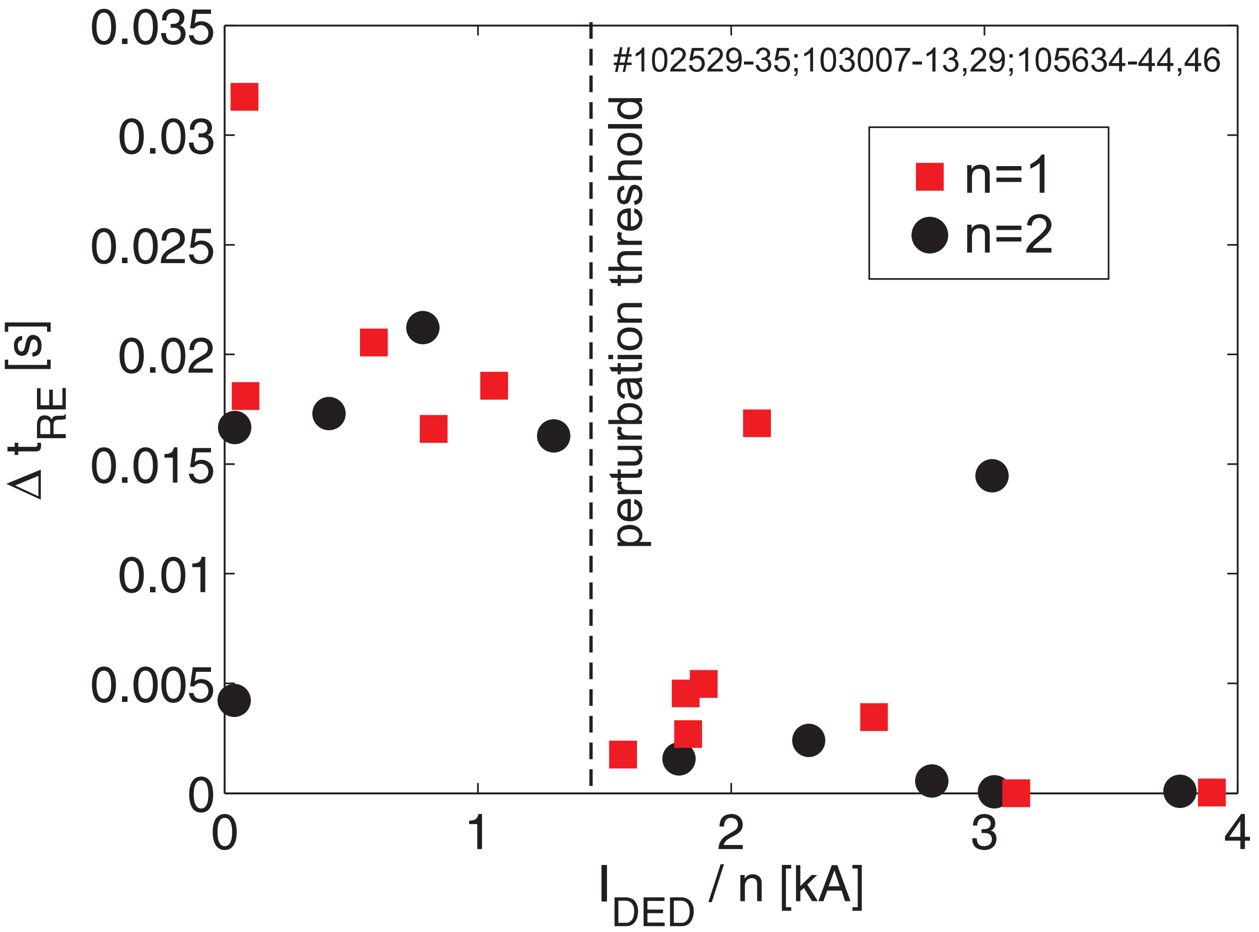


reduction of RE current

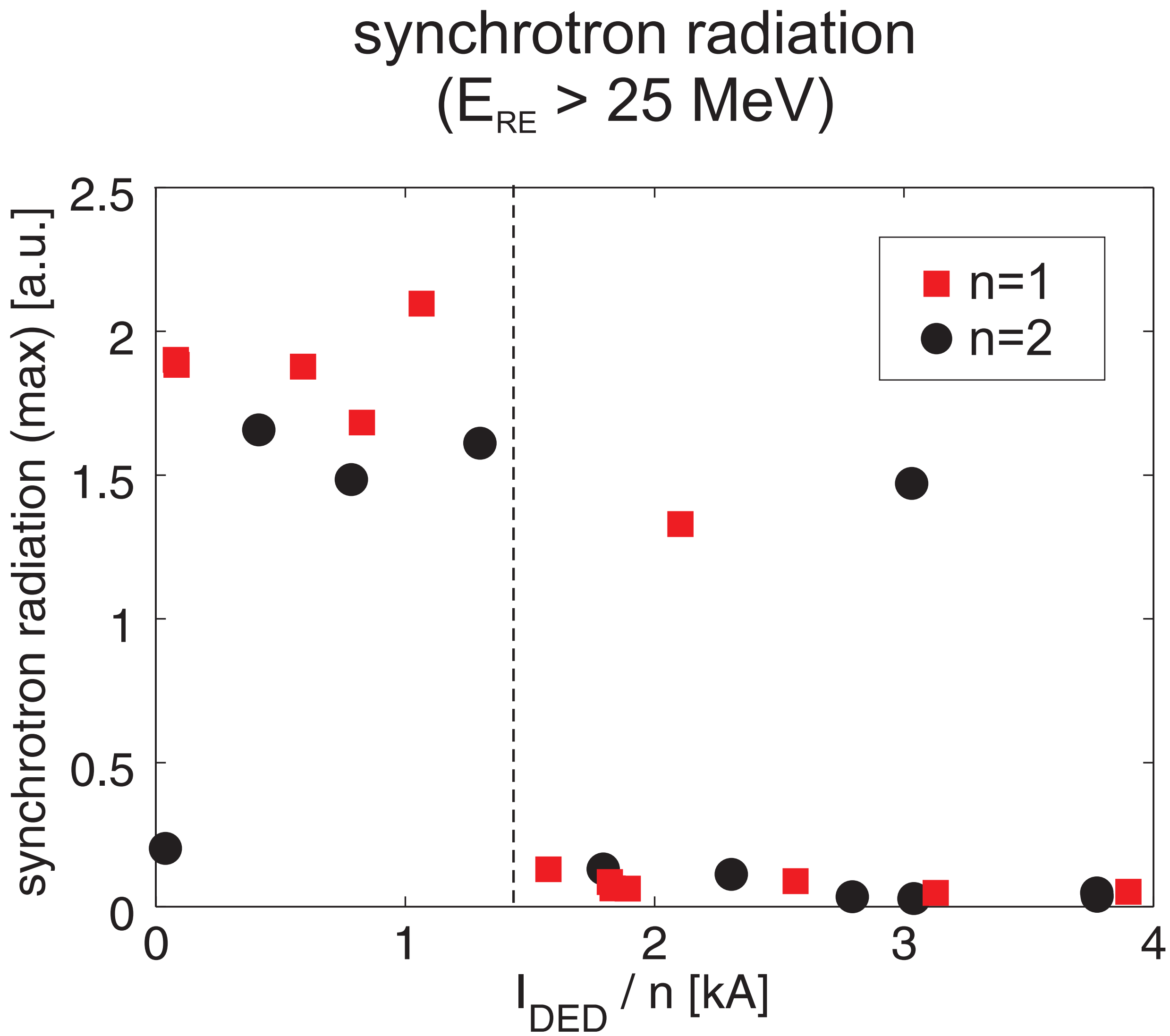
6/2: more shallow penetration B_r

M. Lehnen et al, PRL 100, 255003 (2008)

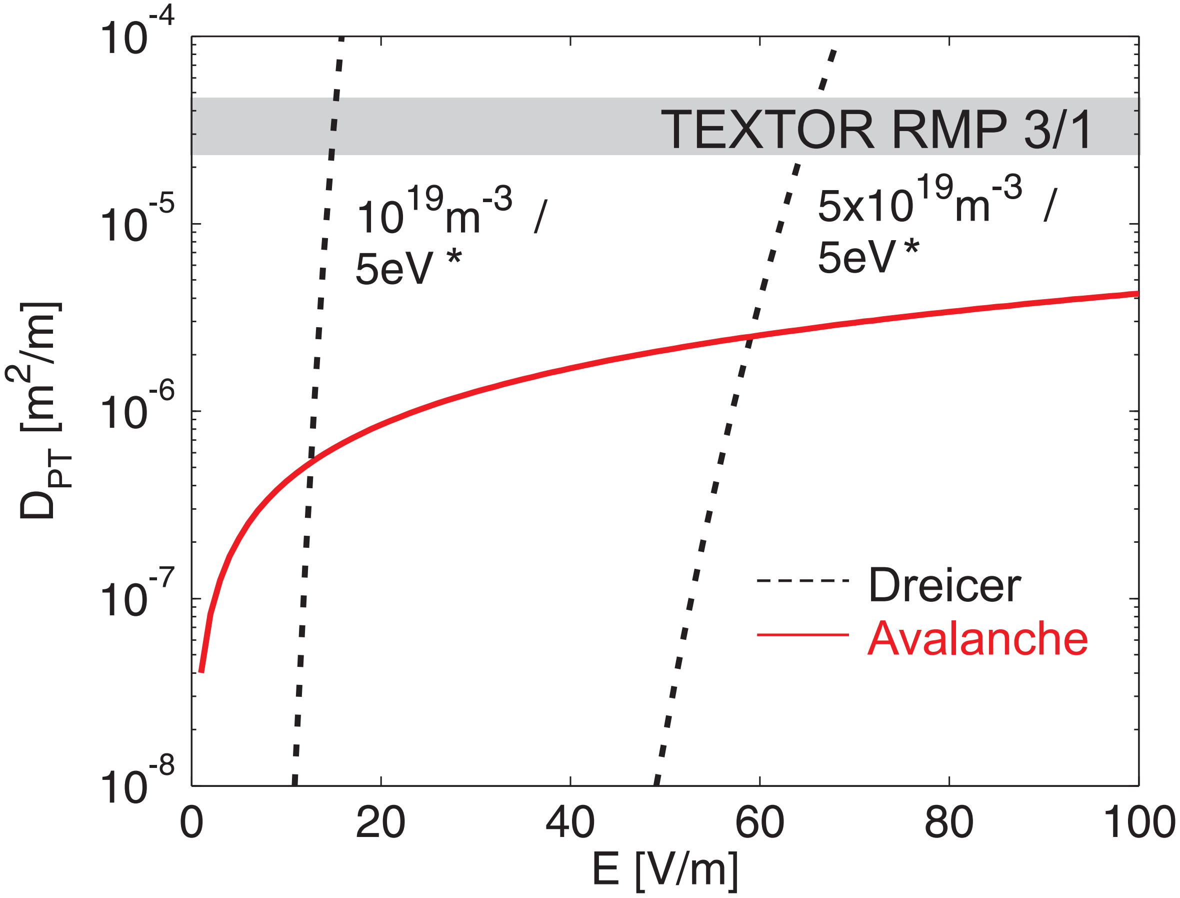
RE plateau length with RMP



suppression of high energetic runaways



critical diffusion for runaway suppression



$$D_\perp \partial^2 n_{RE}/\partial r^2 = G_{RE}$$

$$D_\perp = c\, D_{PT}$$

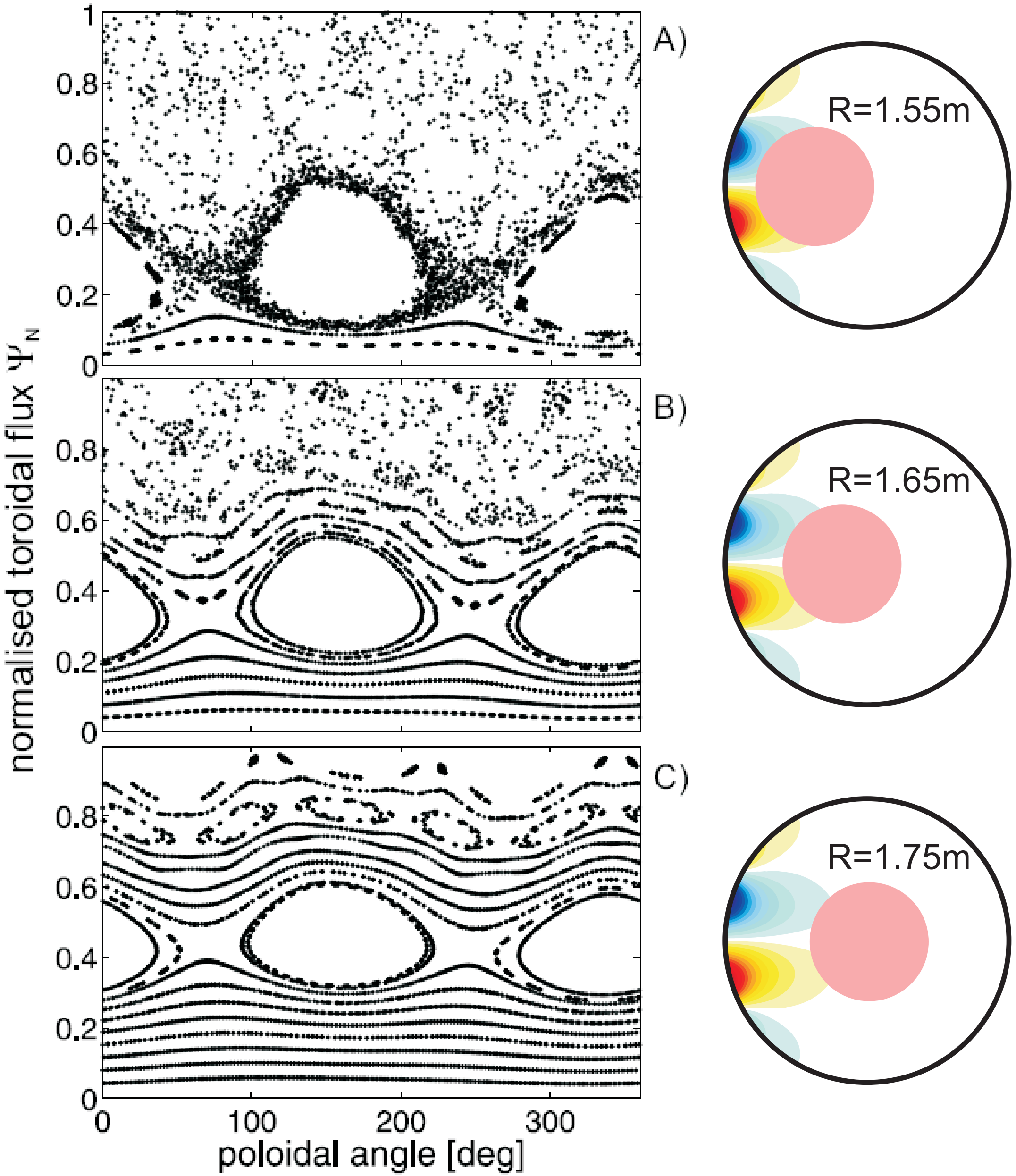
Primary RE (Dreicer)

$$G_{RE} \sim \exp(E/E_D)$$

Avalanche

$$G_{RE} \sim E/E_c$$

* I_{RE} = 10kA



Mapping of particle trajectories* for DED 3/1 configuration

high degree of ergodisation, if RE beam close to the DED

<u>case A</u>

$D_{PT} = 2.8\text{x}10^{-5}$ (Ψ_N=0.4)

$D_{PT} = 4.5\text{x}10^{-5}$ (Ψ_N=1.0)

⇨ $D_{RE} \sim 10^4\ m^2/s$

$$j \sim (1-\rho^2)^\nu$$

$\nu = 1.5$

$q_0 = 1.5$

$r_{RE} = 0.2m$

$E_{RE} = 5MeV$

$I_{DED} = 3.75kA$

*details: contact S.S. Abdullaev

Conclusions/Summary/Questions

- **Controlled plasma shutdown**
  - acts on a relatively slow time scale
  - forces can be reduced
  - runaways could be reduced, if plasma current is ramped down
  - reduction of heat loads less effective due to energy confinement
- **Local Heating**
  - (N)TM can be healed in LBO and high β_N disruptions (see talk by M. Maraschek)
  - detection by loop voltage or directly by ECE
  - efficiency depends strongly on position of heat deposition

Conclusions/Summary/Questions

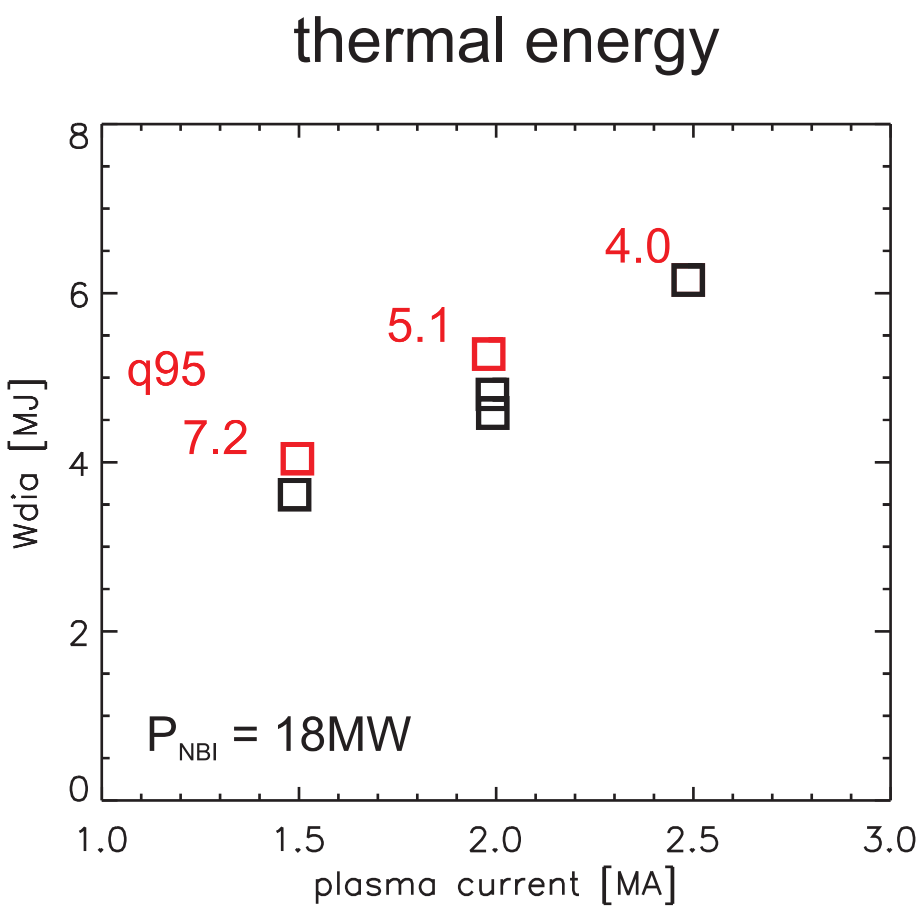
- **Massive Material Injection (Gas)**
  - reduction of forces has been achieved by MGI in JET mainly by halo current mitigation
  - heat loads are reduced (50% of thermal energy is radiated)
  - distribution of the remaining energy is to be analysed
  - runaway generation is avoided with Ar or Ne + D2 mixture
  - cooling duration - critical timescale for fuelling efficiency
  - eddy currents might become critical for strong MGI (maybe saturation caused by opacity)
  - extremely high gas rates for avalanche suppression ($5x10^{24}$ in a few ms)
  - heat load by radiation to be assessed (number of gas inlets)
  - a short distance valve-plasma is needed for faster reaction time and a higher fuelling efficiency

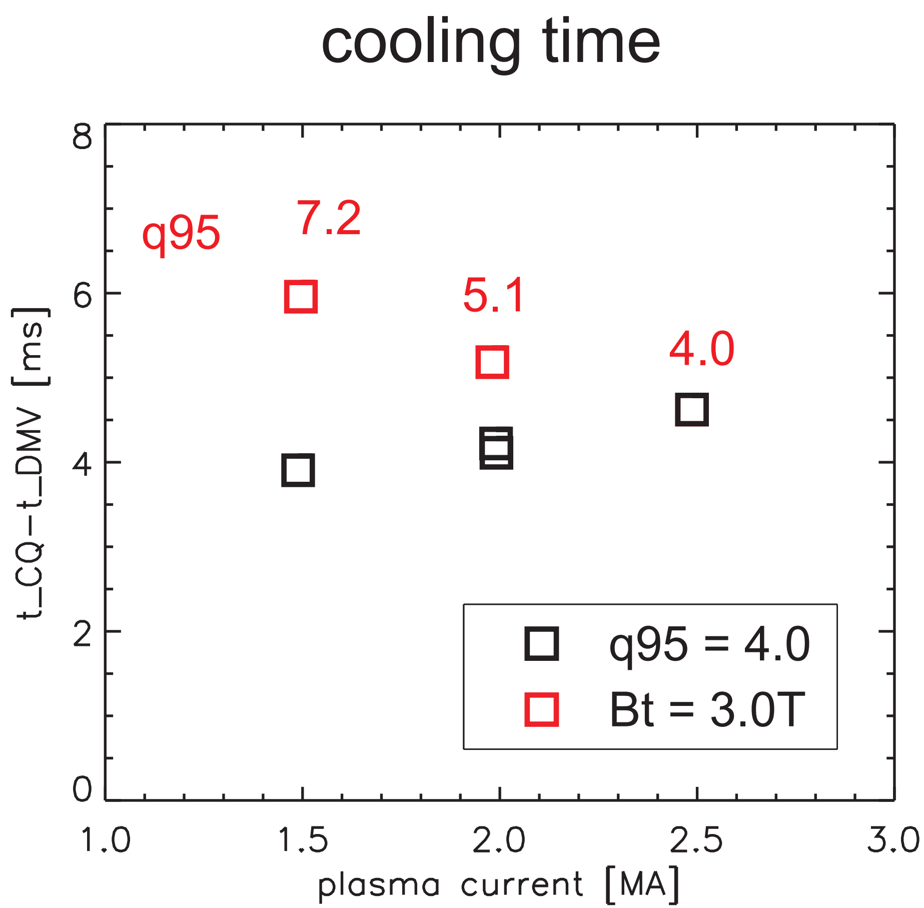
Reliable for the reduction of forces and heat loads
Suppression of the runaway avalanche needs much more work

Conclusions/Summary/Questions

- **Magnetic Perturbations**
  - suppression of the runaway avalanche has been shown in TEXTOR (but not 100% reliable)
  - scaling to ITER challenging and needs further analysis of the mechanism no additional coils foreseen > perturbation coils for ELM mitigation

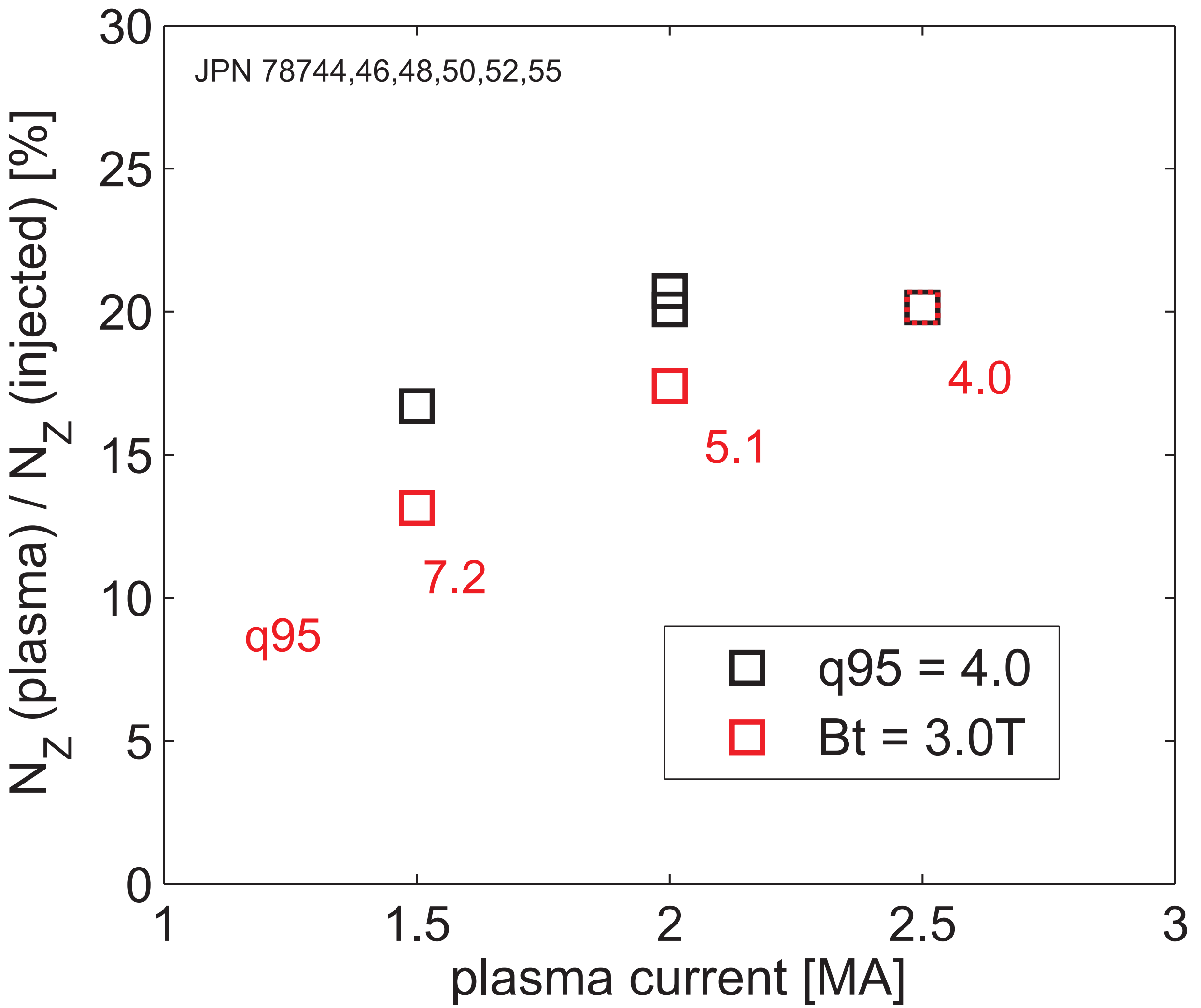
Fuelling Efficiency





to be checked: ELM size, pedestal parameters,...

q_{95} / B_t / I_P scan: fuelling efficiency

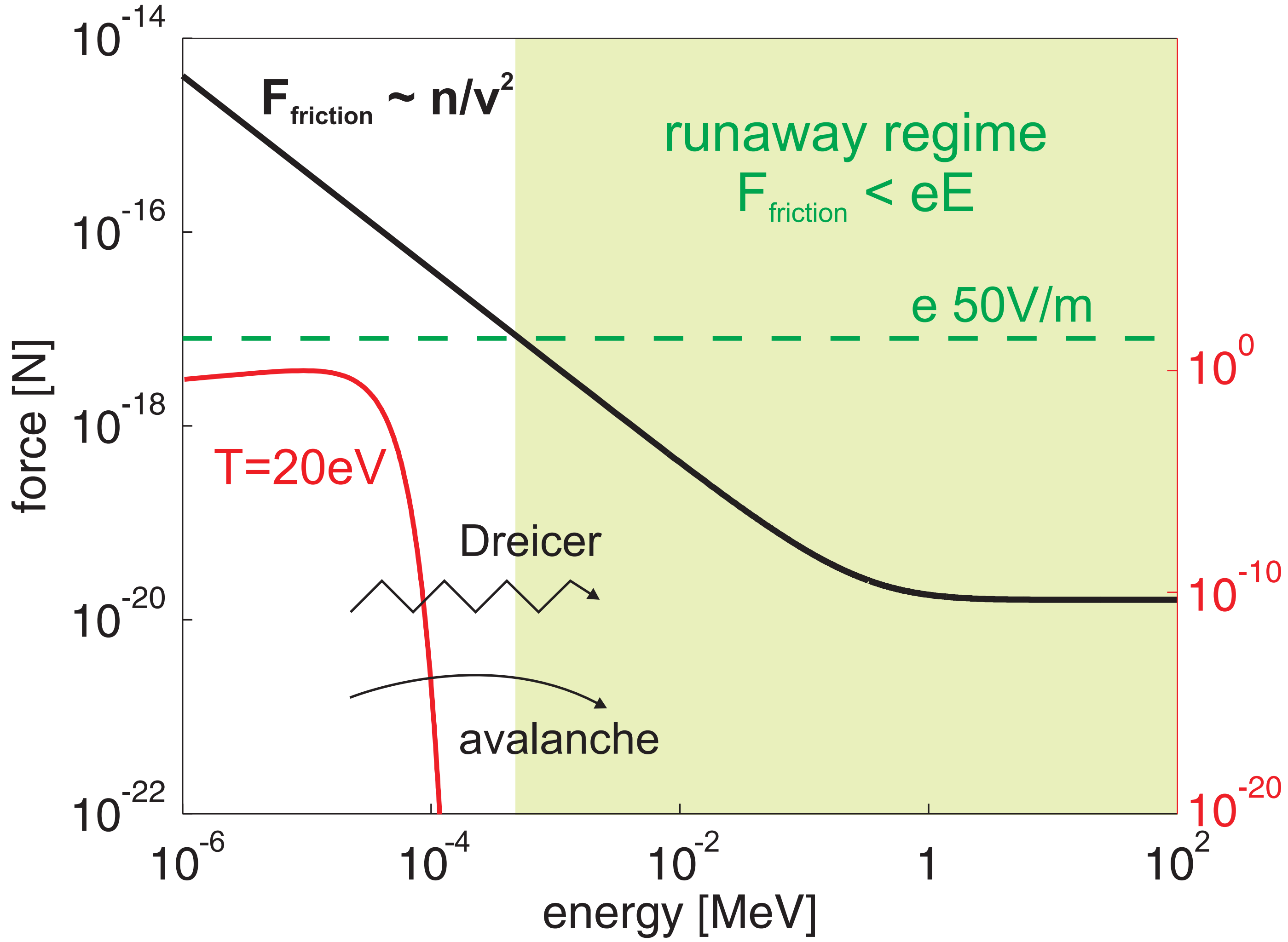


H-Mode

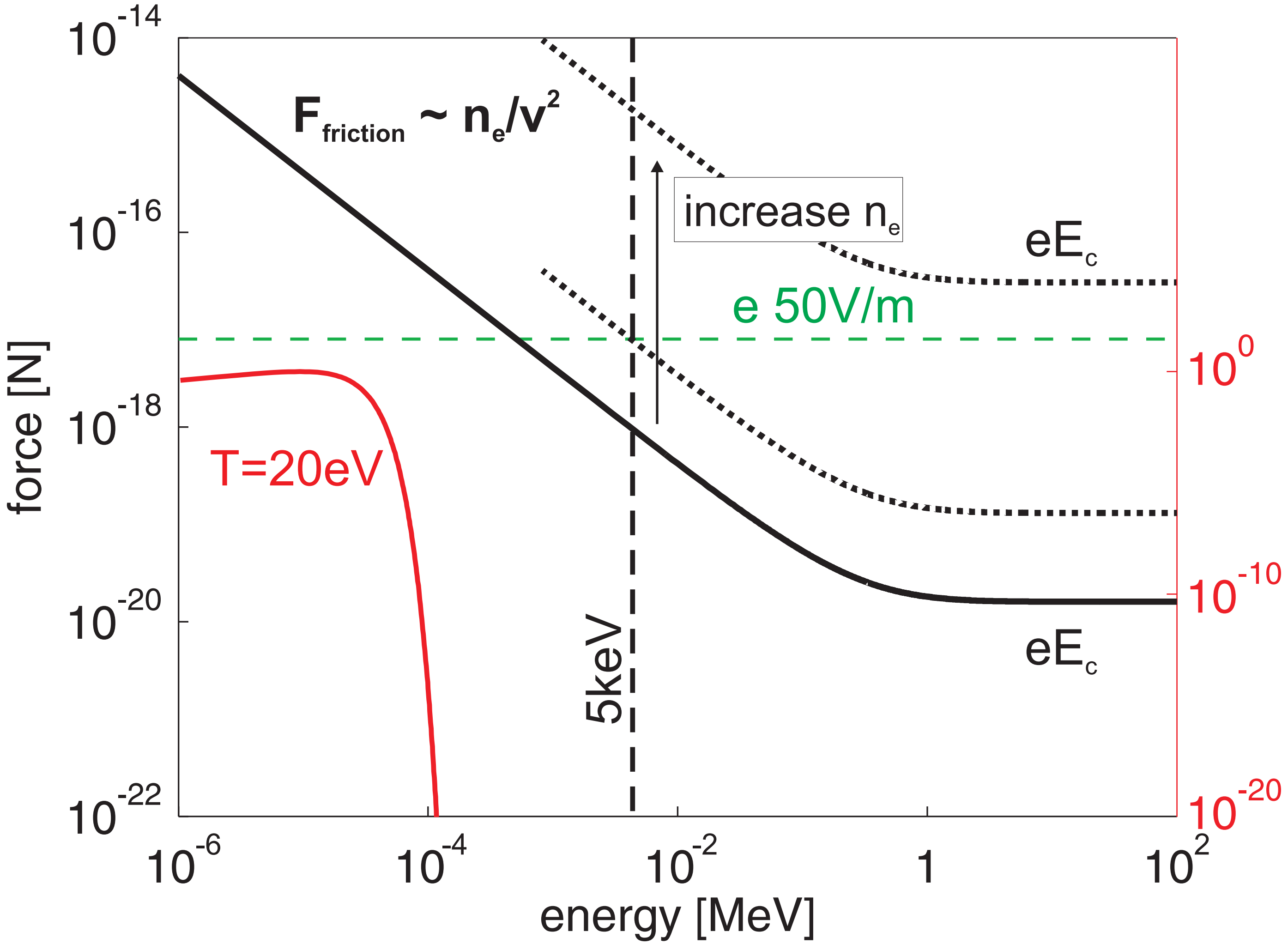
10%Ar in D2 injection @ 30bar

P_{NBI} = 18 MW

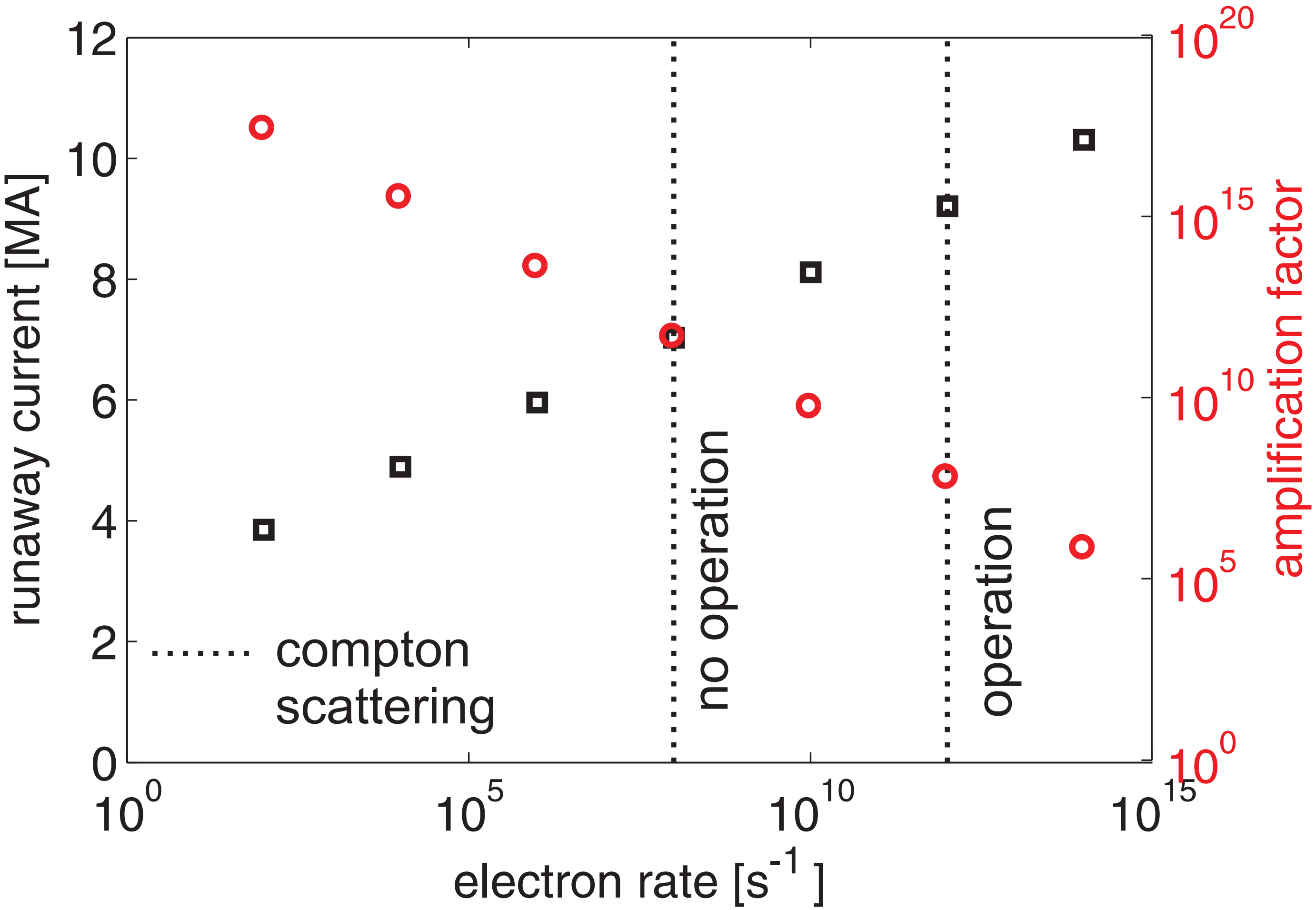
Runaway generation



Primary runaway generation by Tritium decay



mean energy E < 6keV: critical density is $1x10^{21}m^{-3}$, instead of $5x10^{22}m^{-3}$ for unconditional suppression main source for primaries: electrons from compton scattering



operation:
DT operation at full performance

no operation:
maximum radiation level immediately after DT operation at full performance

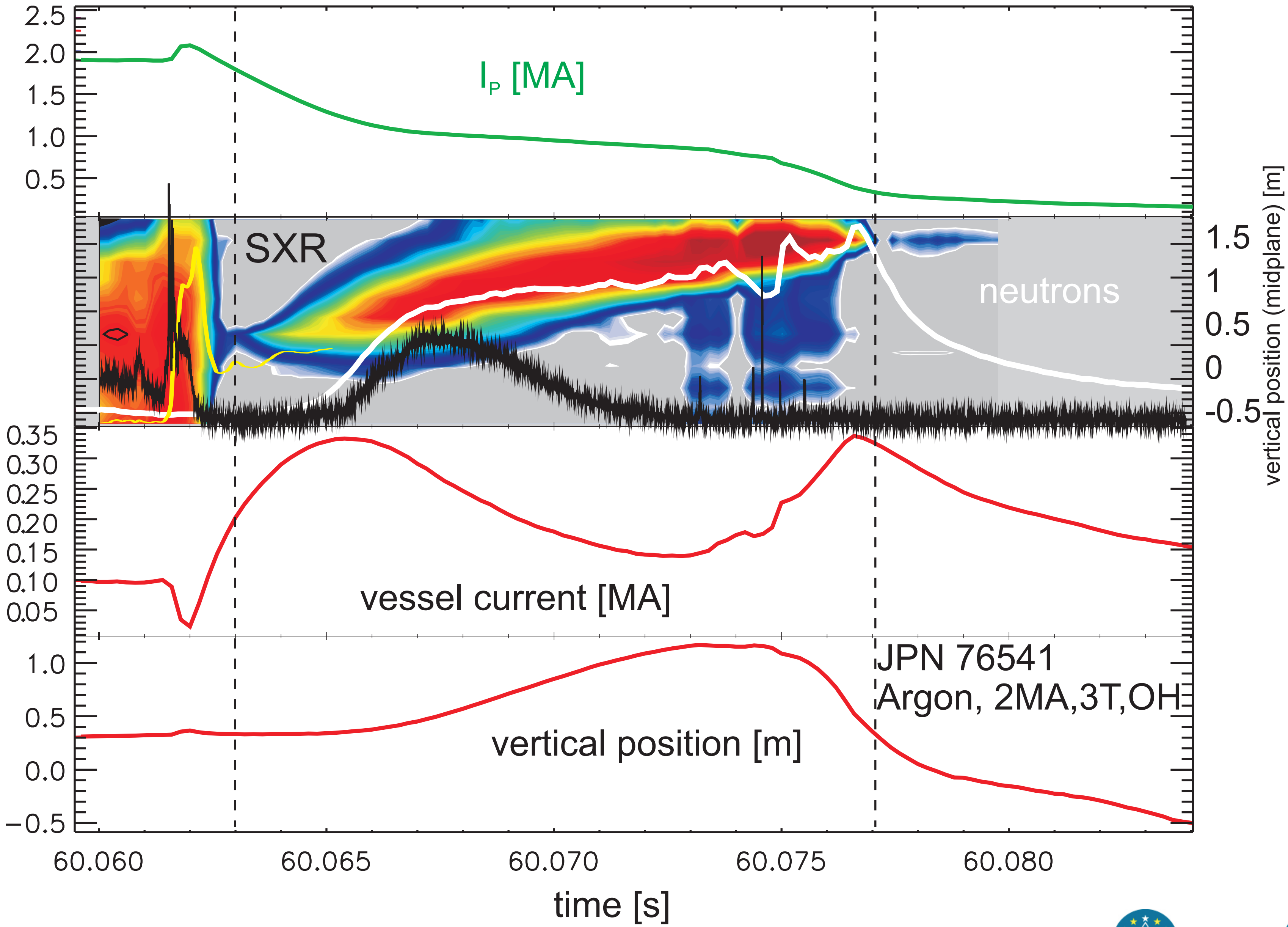
Reference:
NUCLEAR ANALYSIS REPORT
G 73 DDD 2 W 0.2

$$rate = \Gamma_\gamma \, \sigma \, N_e$$

$$\sigma = 6 \times 10^{-29} \, m^2$$

r_{RE} = 1m

Runaway generation



Comparison with inflow model

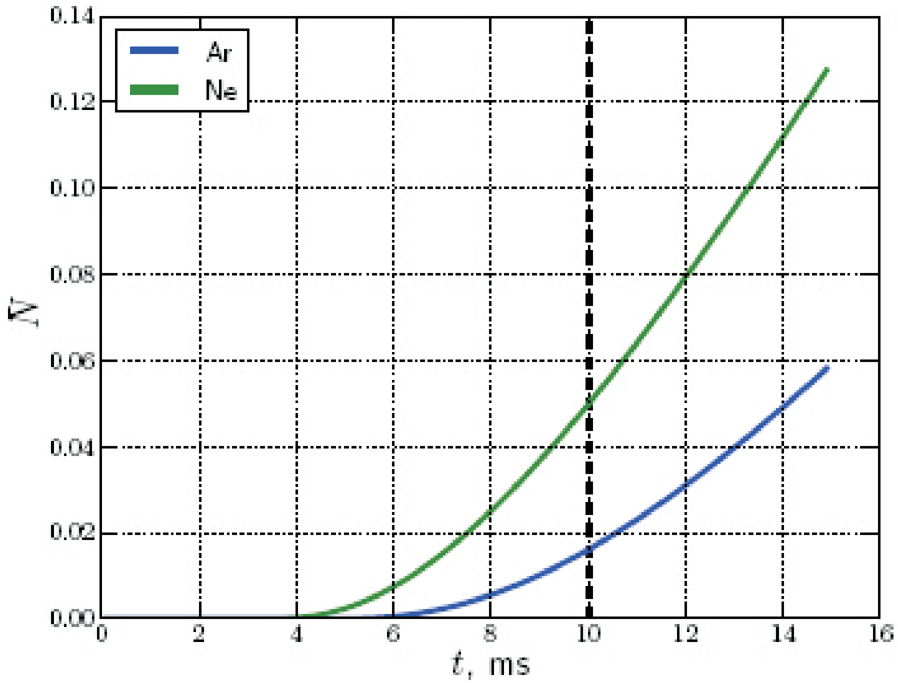


Figure: *An estiation of the number of delivered particles from the ideal model.*

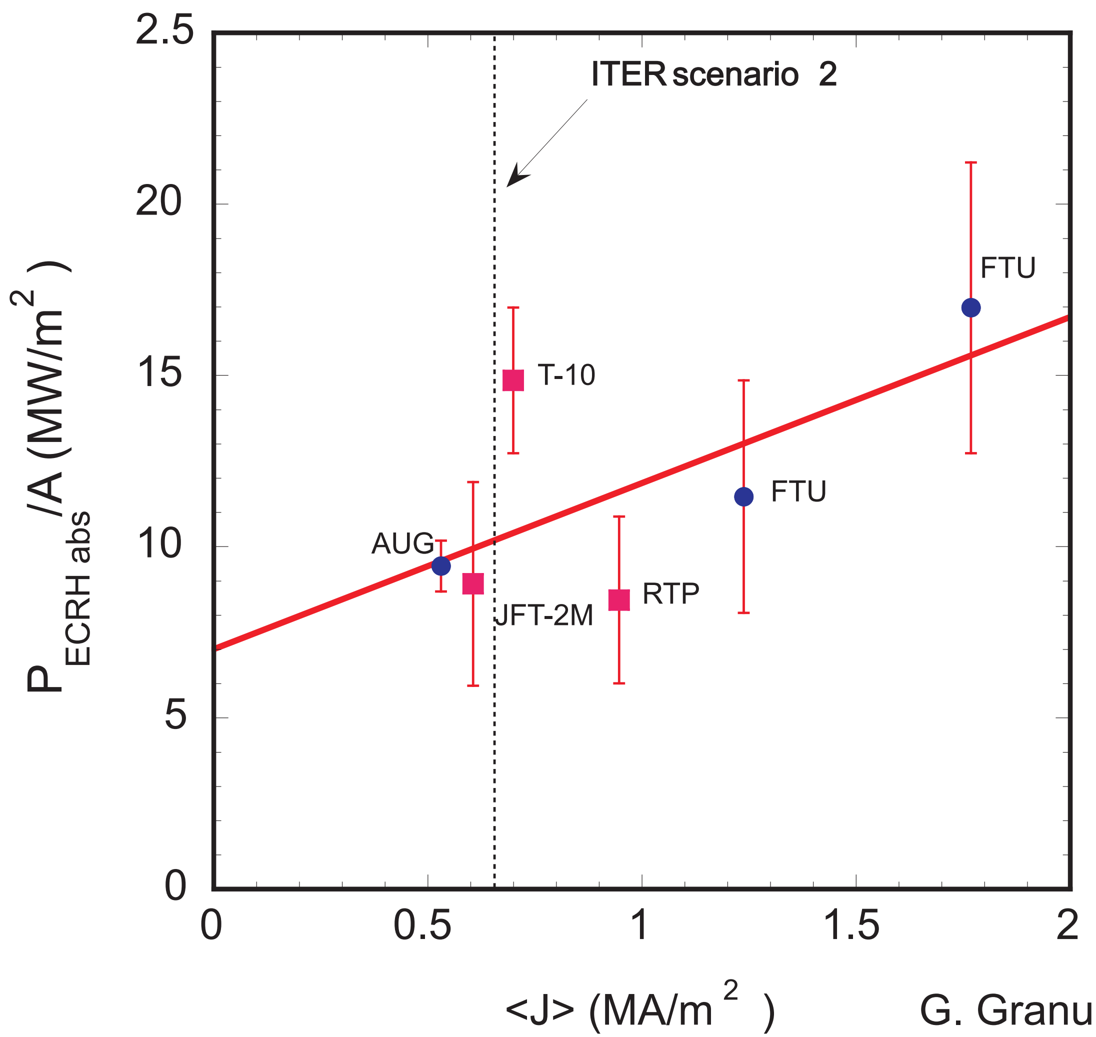
- The number of particles delivered before the current quench gives the correct magnitude.
- The model notation: A - the cross-sectional area, K - a correction factor, x - distance from the valve to plasma, V - the valve volume, $n = 2/(\gamma - 1)$, $\xi = x/(c_0 t)$, $\bar{N} = N/(n_0 V)$.

$$\bar{N}(t) = \frac{A \cdot K \cdot x}{V} \cdot \frac{n^n}{(n+1)^{n+1}} \cdot \sum_{k=0}^{n+1} \frac{(-1)^{k-1} \cdot (n+1)!}{(n-k+1)! \cdot k!} \cdot \left(1 - \left(\frac{\xi}{n}\right)^{k-1}\right)$$

Associazione EURATOM ENEA sulla Fusione

Max-Planck-Institut für Plasmaphysik

Power Threshold Analysis



Data considered are for **q**=2 stabilization

Error bars indicate the range between the saved case and the unsaved case

The EC power density is taken from the absorbed power divided by the q=2 corona (width=FWHM)

The minimum required power in ITER is 4 **MW** of absorbed power (assuming FWHM~3.75 cm)

G. Granucci et al., RF Topical Conference 2009, „ECRH: A Tool To Control Disruptions In Tokamaks.“