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JÜLICH
FORSCHUNGSZENTRUM

Impact of disruption loads on plasma facing components

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many thanks to G. Arnoux (CCFE), N. Baumgarten (FZJ), J.W. Coenen (FZJ), R. Mitteau (IO), M. Sugihara (IO), A. Thornton (CCFE), M. Zlobinski (FZJ)

Outline

- **Heat loads**

  distribution
  impurity release
  runaway electrons

- **Forces**

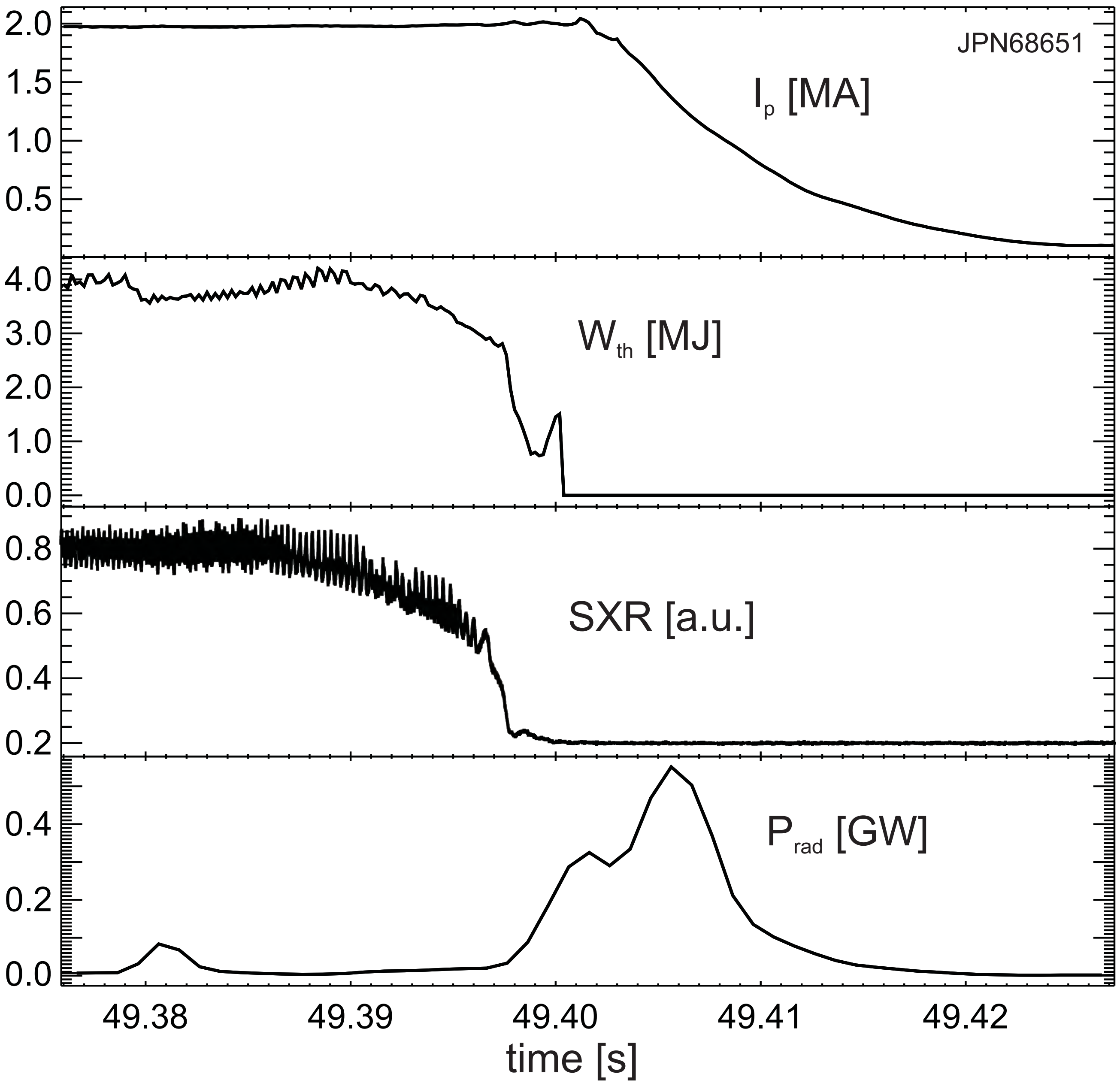
  eddy and halo currents

- **Mitigation and its consequences**

  massive gas injection

Disruption Sequence

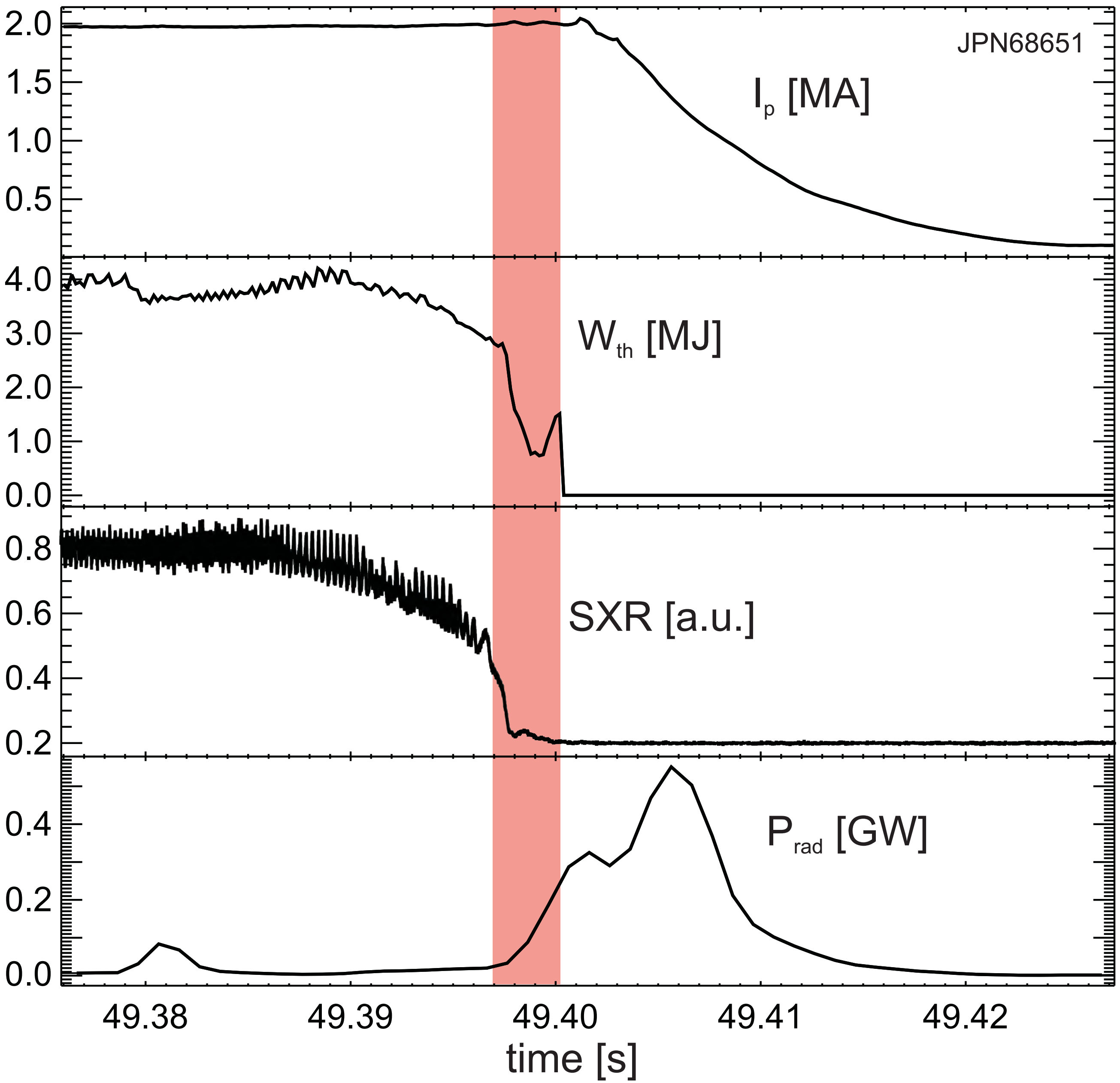
JET disruption



Disruption Sequence

JET disruption

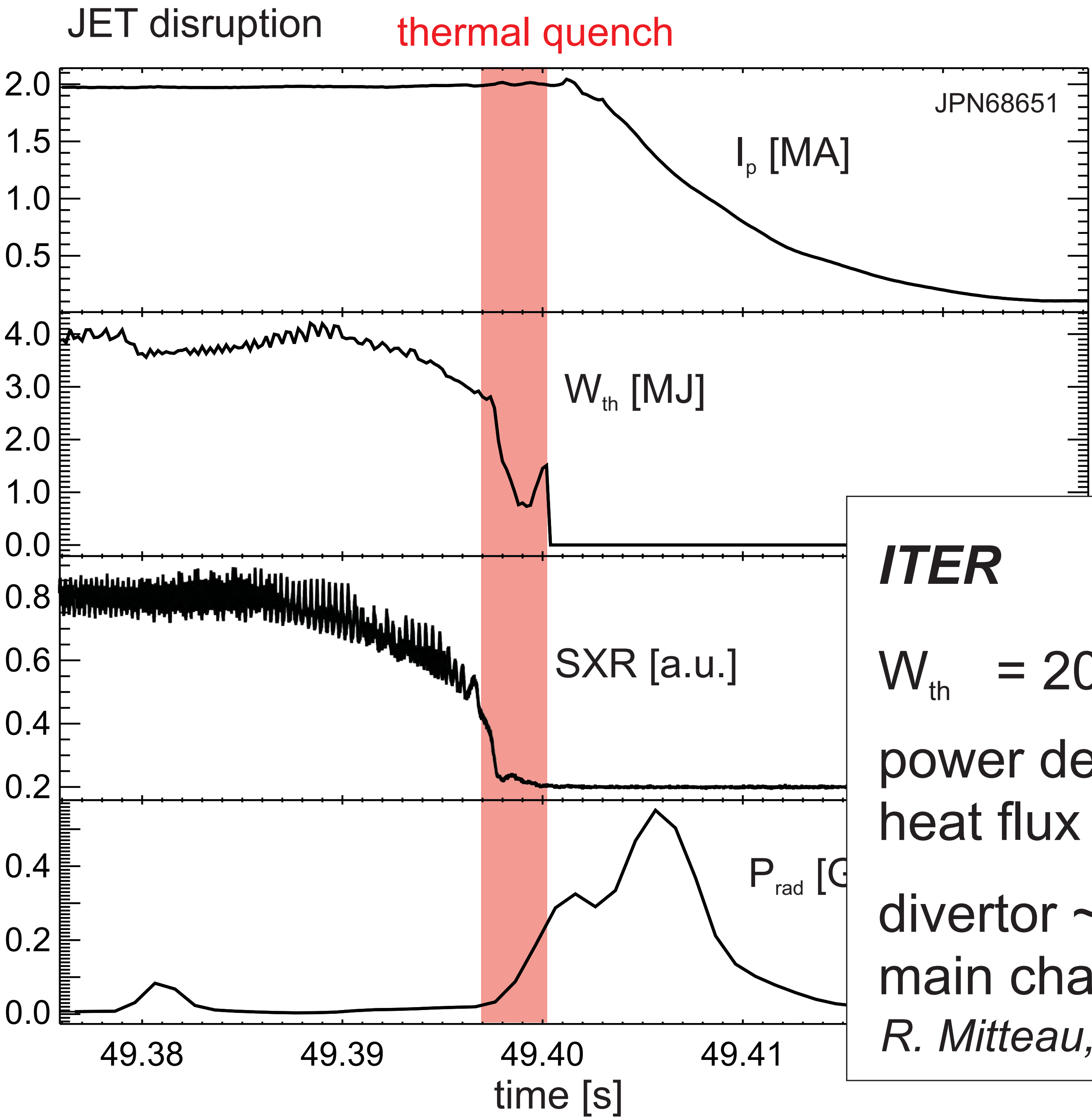
thermal quench



thermal quench:

loss of thermal energy ~ 1ms
high heat flux to PFC
impurity release from PFC

Disruption Sequence



thermal quench:

loss of thermal energy ~ 1ms
high heat flux to PFC
impurity release from PFC

ITER

W_{th} = 200-300 MJ

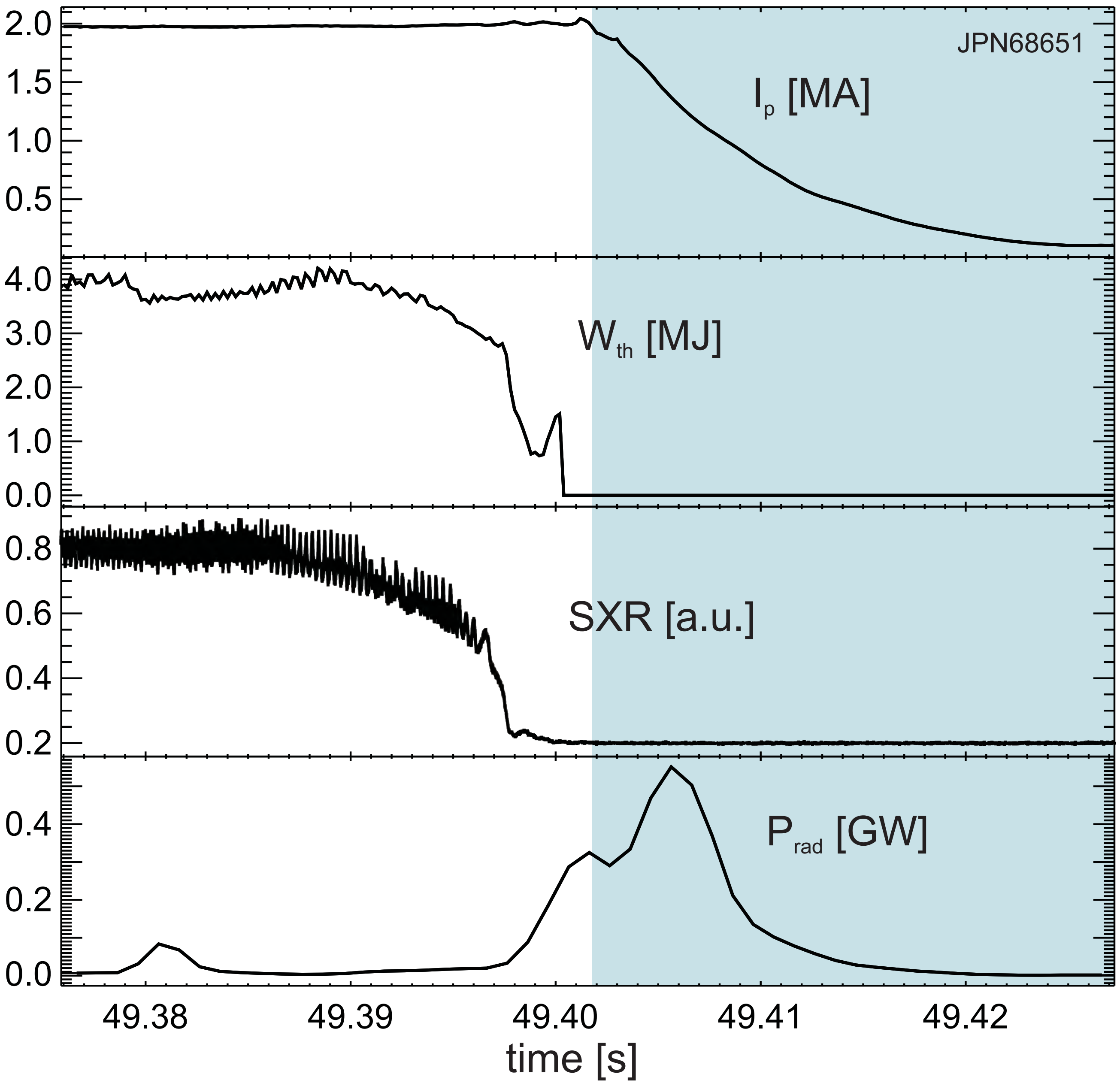
power decay length ~ 30-100mm
heat flux deposition time 1-10ms

divertor ~ 120-380 $MJm^{-2}s^{-0.5}$
main chamber (VDE) ~570 $MJm^{-2}s^{-0.5}$
R. Mitteau, I-05, tuesday

Disruption Sequence

JET disruption

current quench



current quench:

strong radiation

heat fluxes to PFC

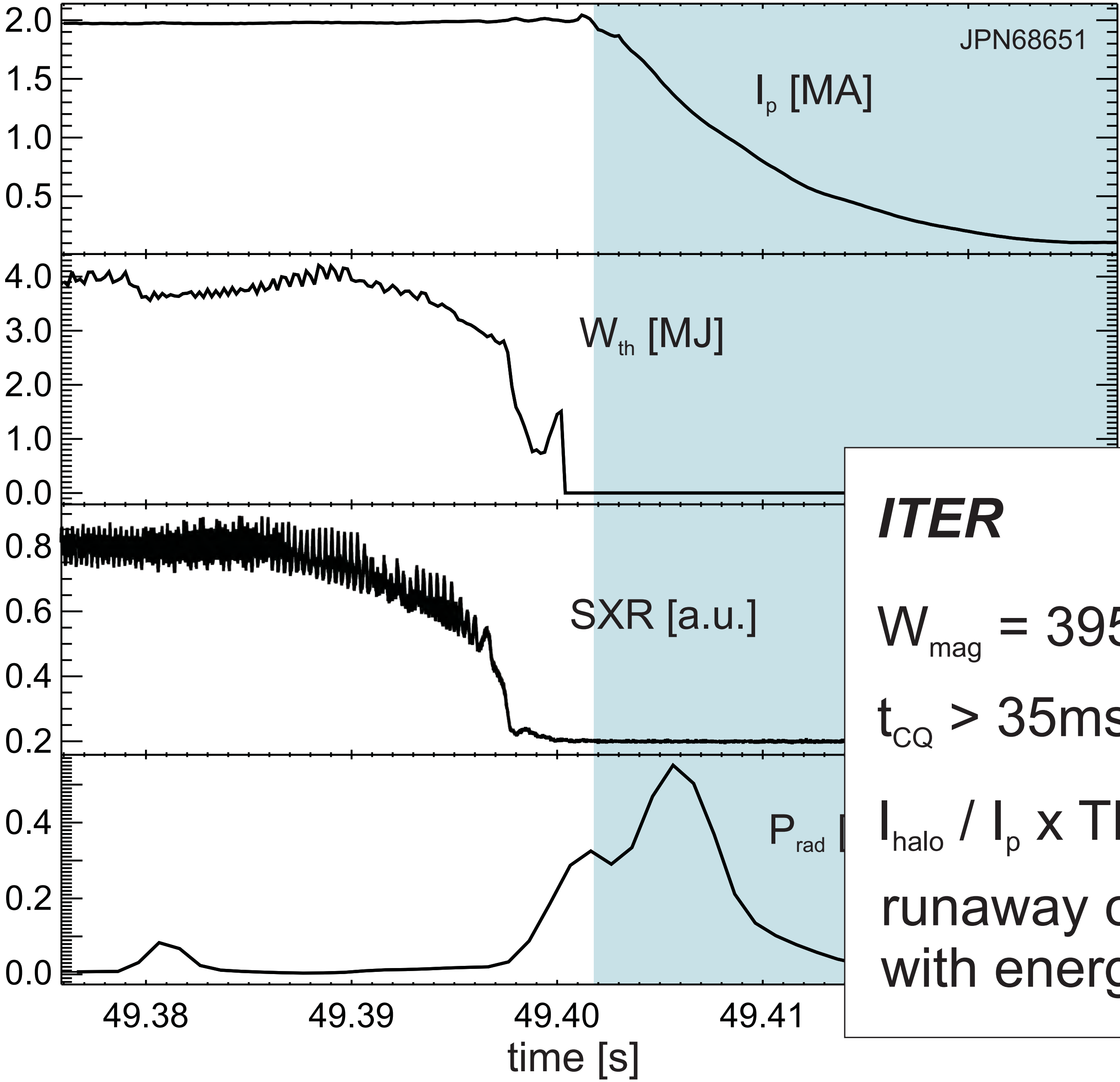
forces:
halo/eddy currents
sideways forces

runaway electrons

Disruption Sequence

JET disruption

current quench



current quench:

strong radiation

heat fluxes to PFC

forces:
halo/eddy currents
sideways forces

ITER

W_{mag} = 395 MJ (inside vessel)

t_{CQ} > 35ms (eddy current limitation)

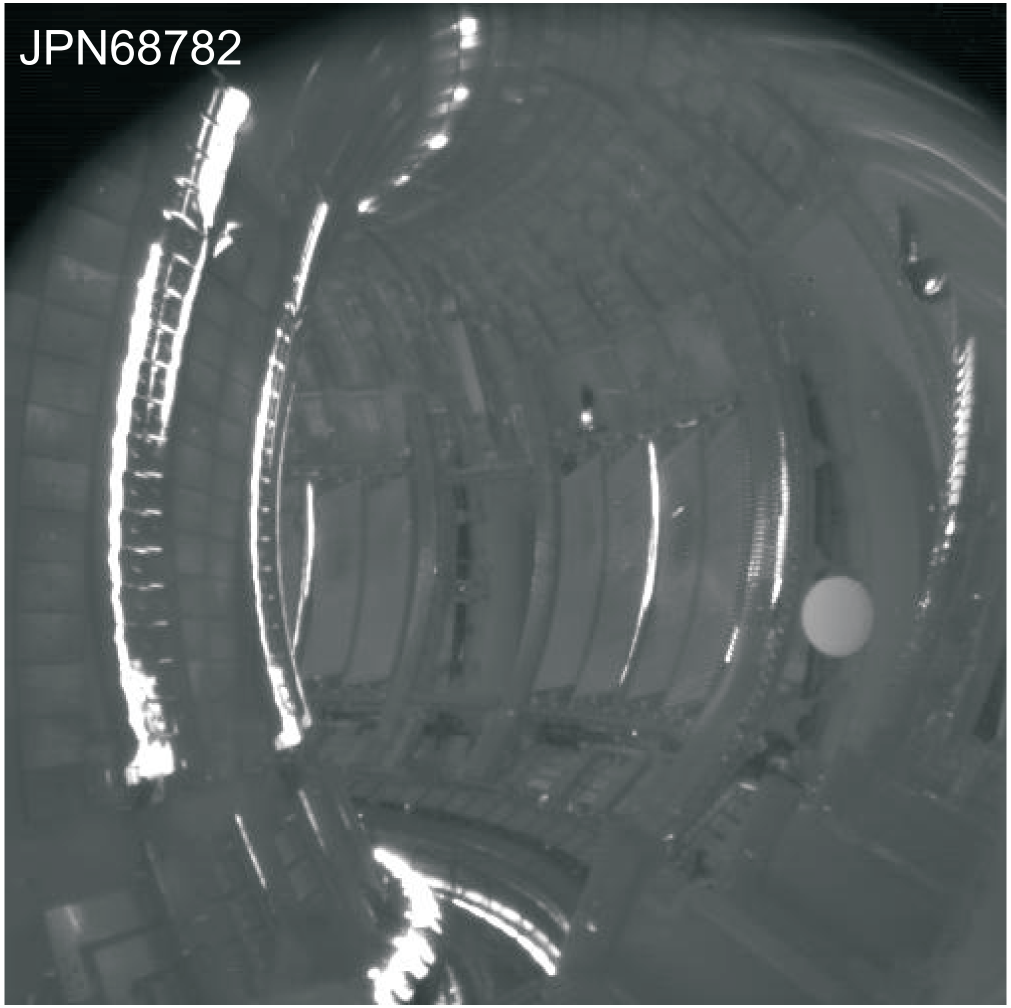
I_{halo} / I_p x TPF < 0.4 (design constraint)

runaway current up to 10MA
with energy 15-150 MJ

Thermal quench - heat flux distribution

Thermal quench - heat flux distribution

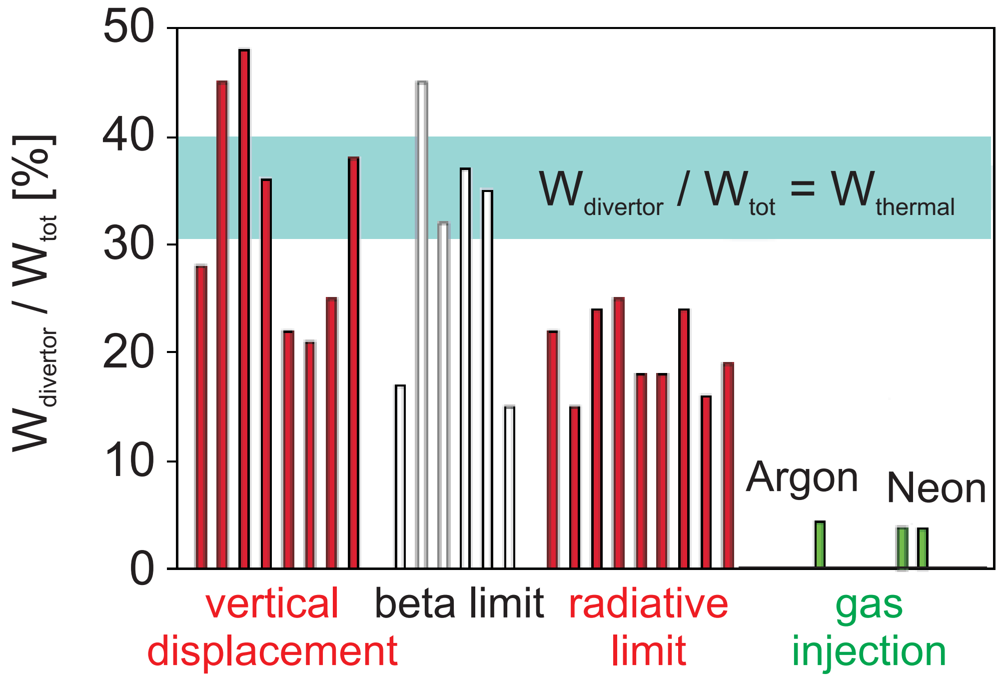
JET wide angle IR view



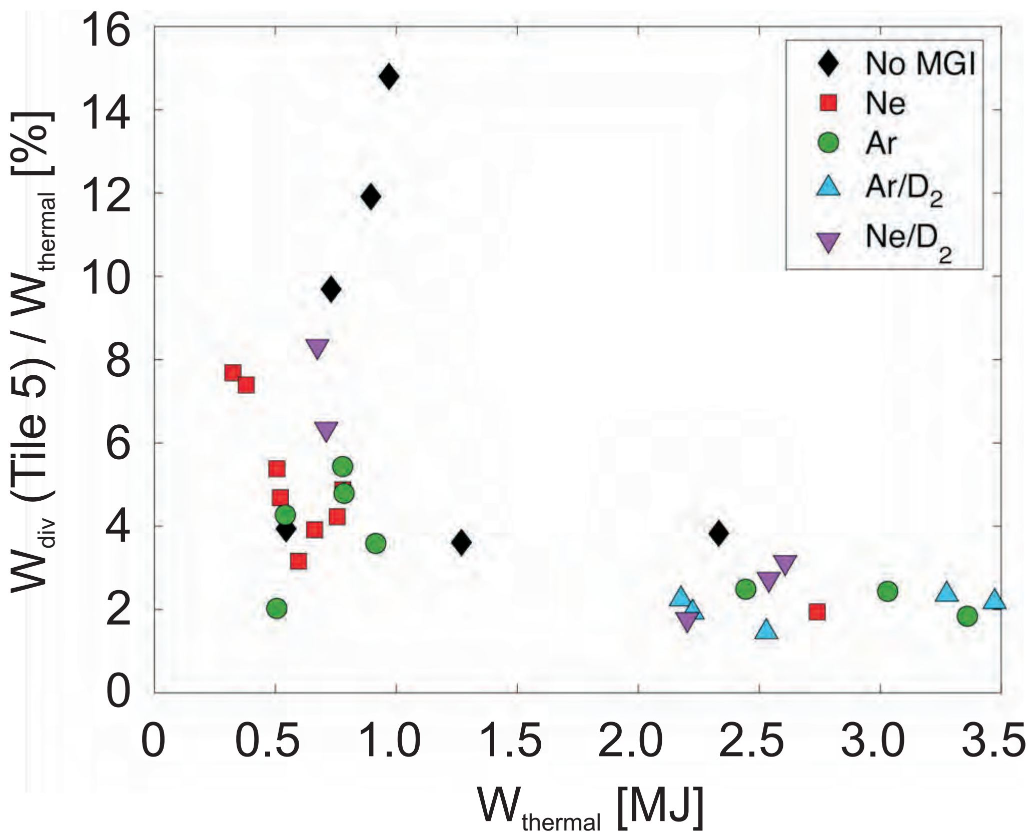
Thermal quench - heat flux distribution

energy deposition in the divertor

DIII-D [D. Whyte, PSI2002]



JET [G. Arnoux, EFDA-PWI 2010]



broad variation from a few % to 100% of thermal energy ariving in the divertor

remaining energy deposited on main chamber PFC or radiated

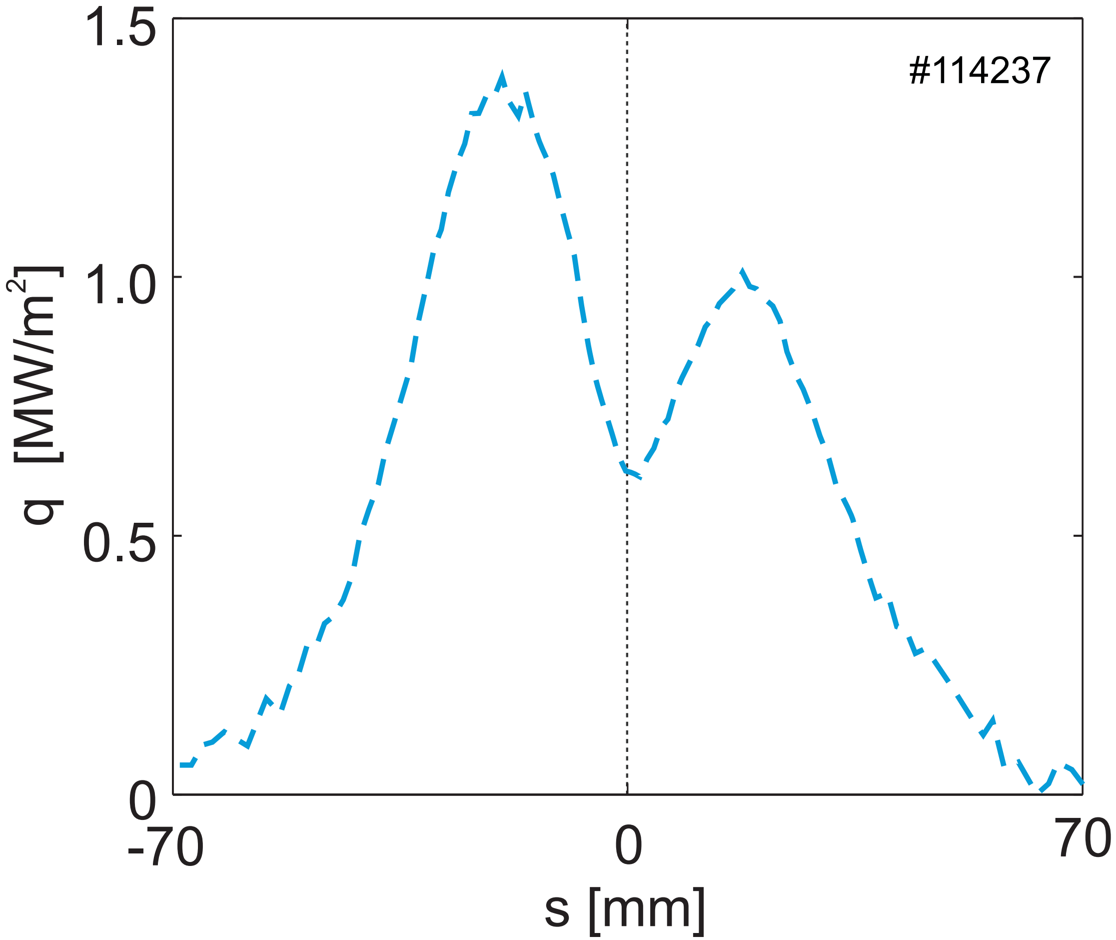
full energy balance challenging

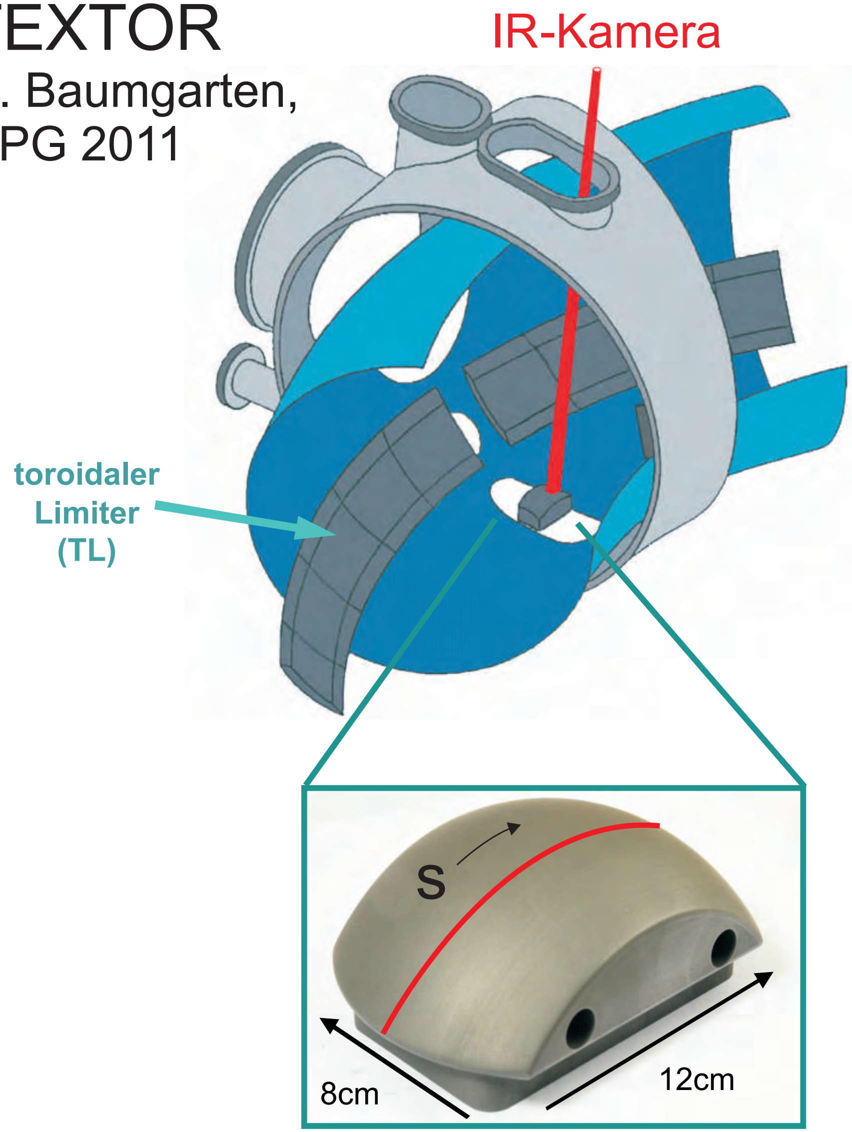
Thermal quench - heat flux distribution

radial energy distribution

TEXTOR
N. Baumgarten, DPG 2011

profile before disruption



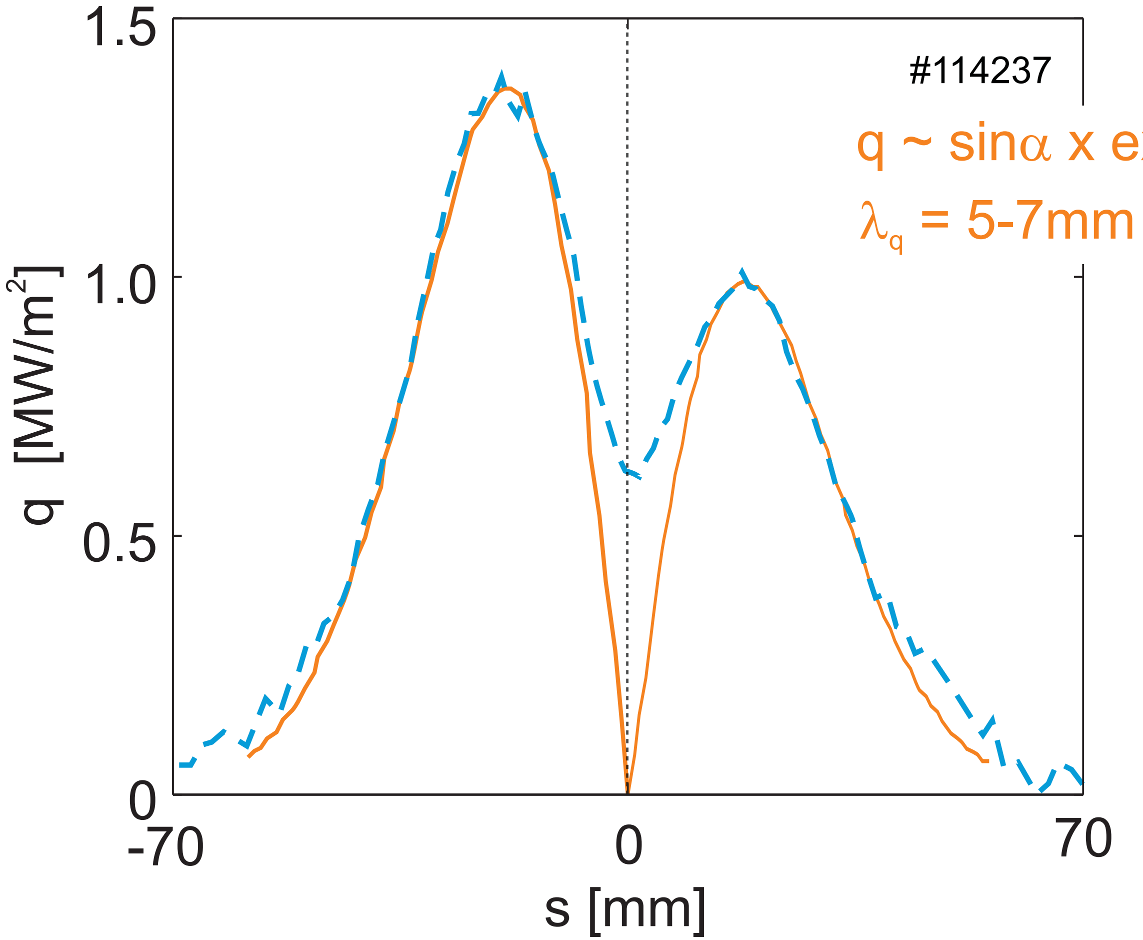


limiter tip @ LCFS (46cm)

Thermal quench - heat flux distribution

radial energy distribution

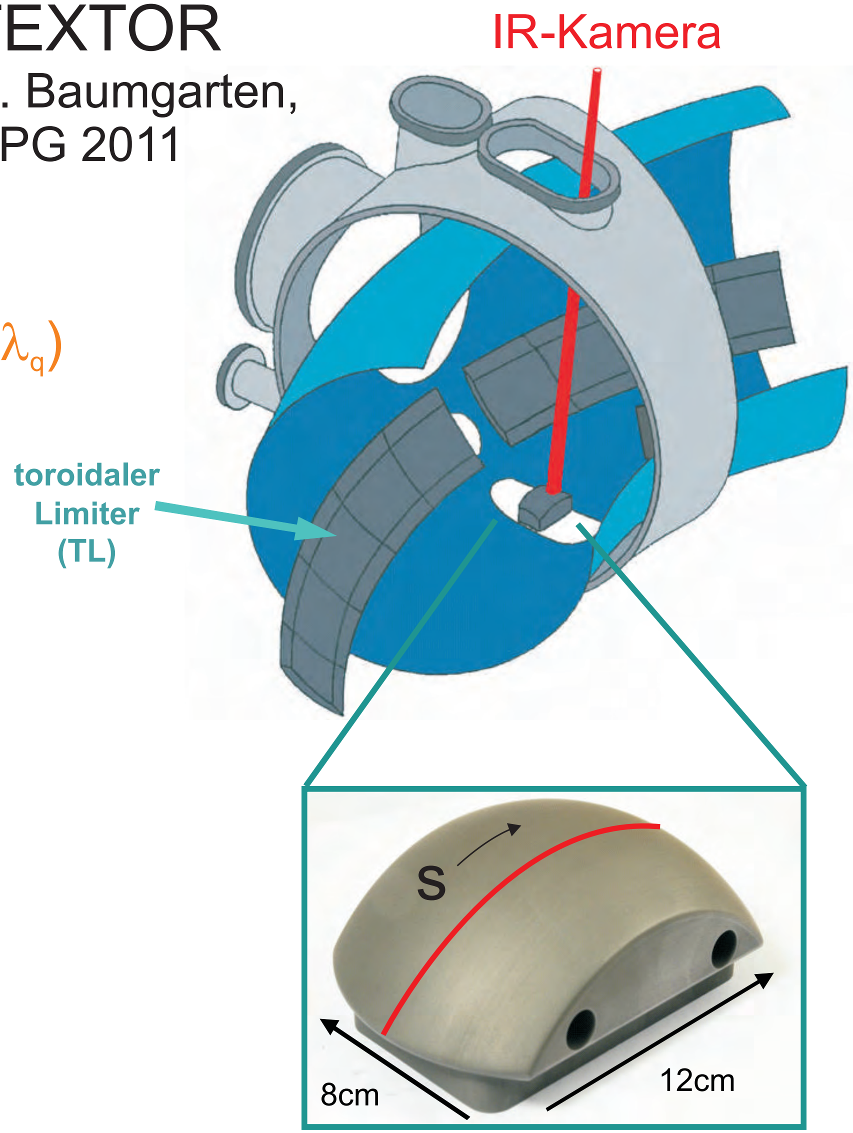
profile before disruption



$q \sim \sin\alpha \times \exp(-r/\lambda_q)$

λ_q = 5-7mm

TEXTOR
N. Baumgarten, DPG 2011

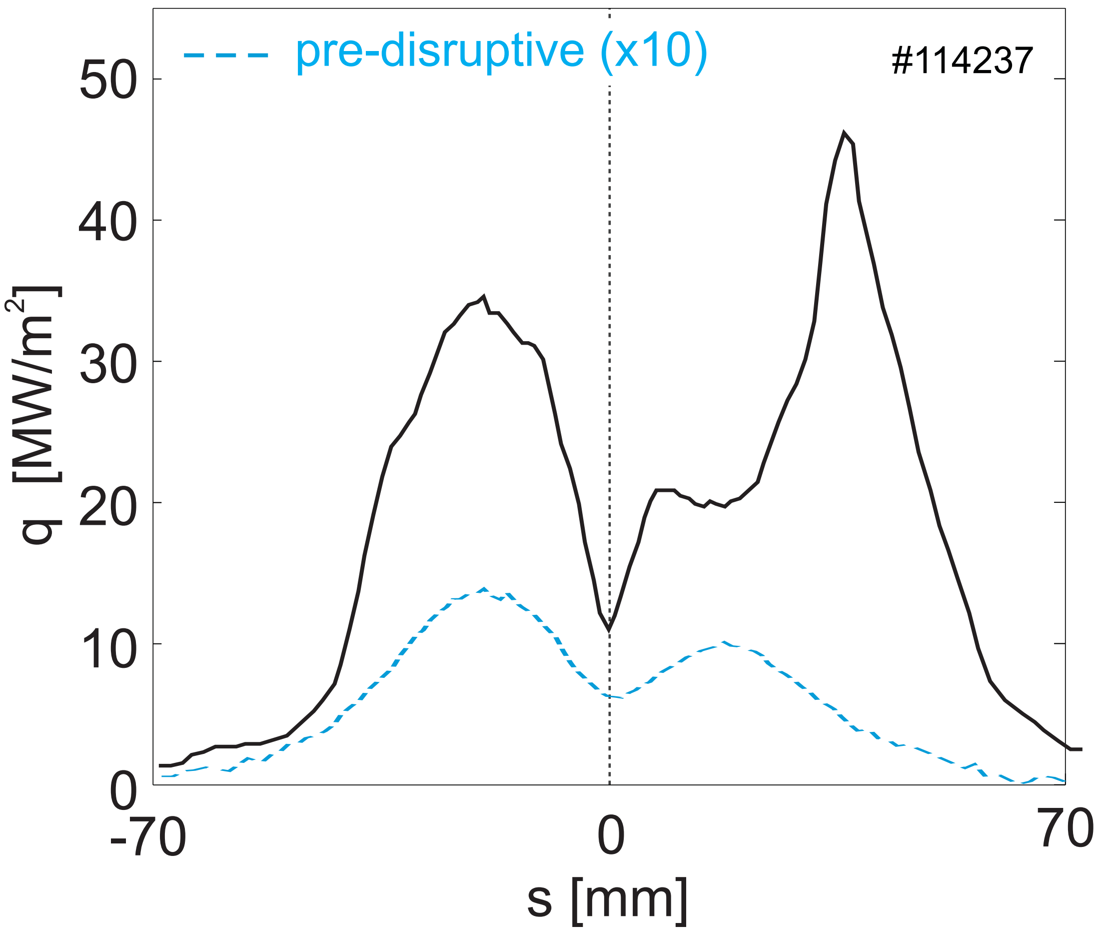


limiter tip @ LCFS (46cm)

Thermal quench - heat flux distribution

radial energy distribution

profiles during thermal quench



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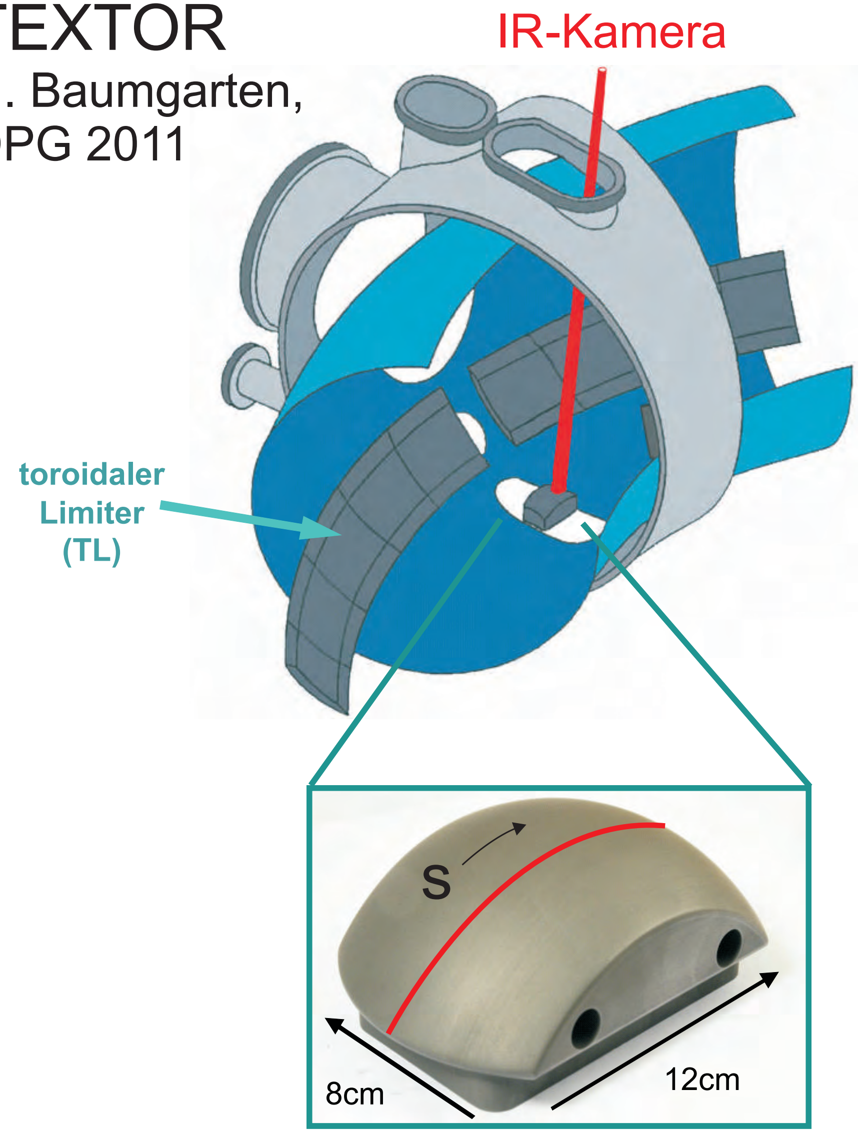
N. Baumgarten, DPG 2011

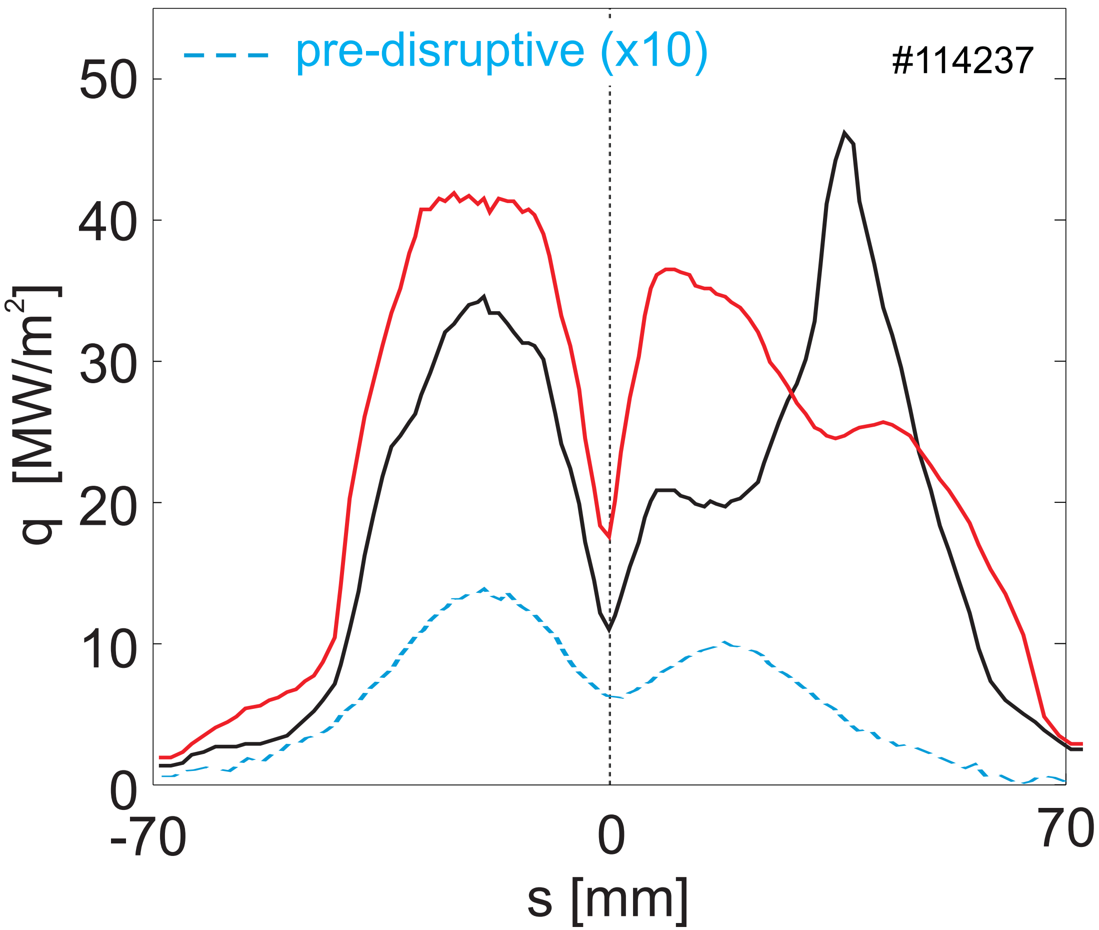


limiter tip @ LCFS (46cm)

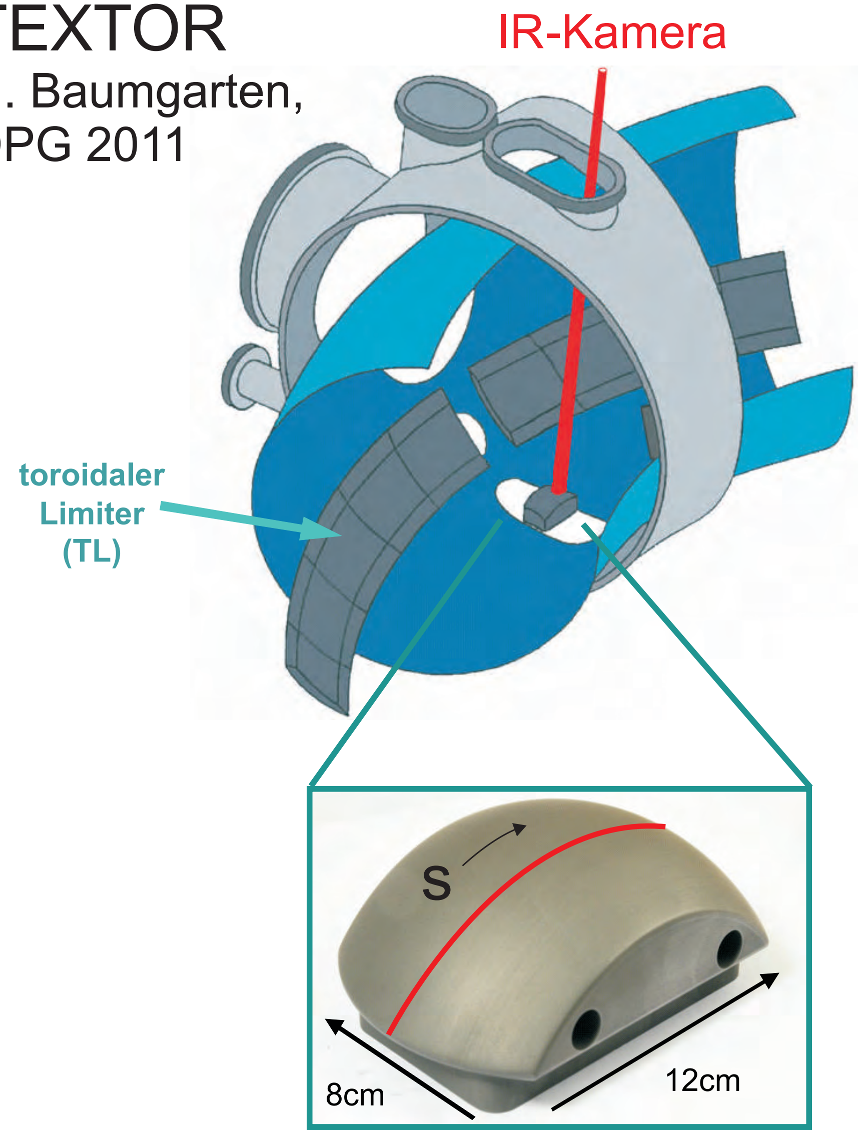
Thermal quench - heat flux distribution

radial energy distribution

profiles during thermal quench



TEXTOR
N. Baumgarten,
DPG 2011



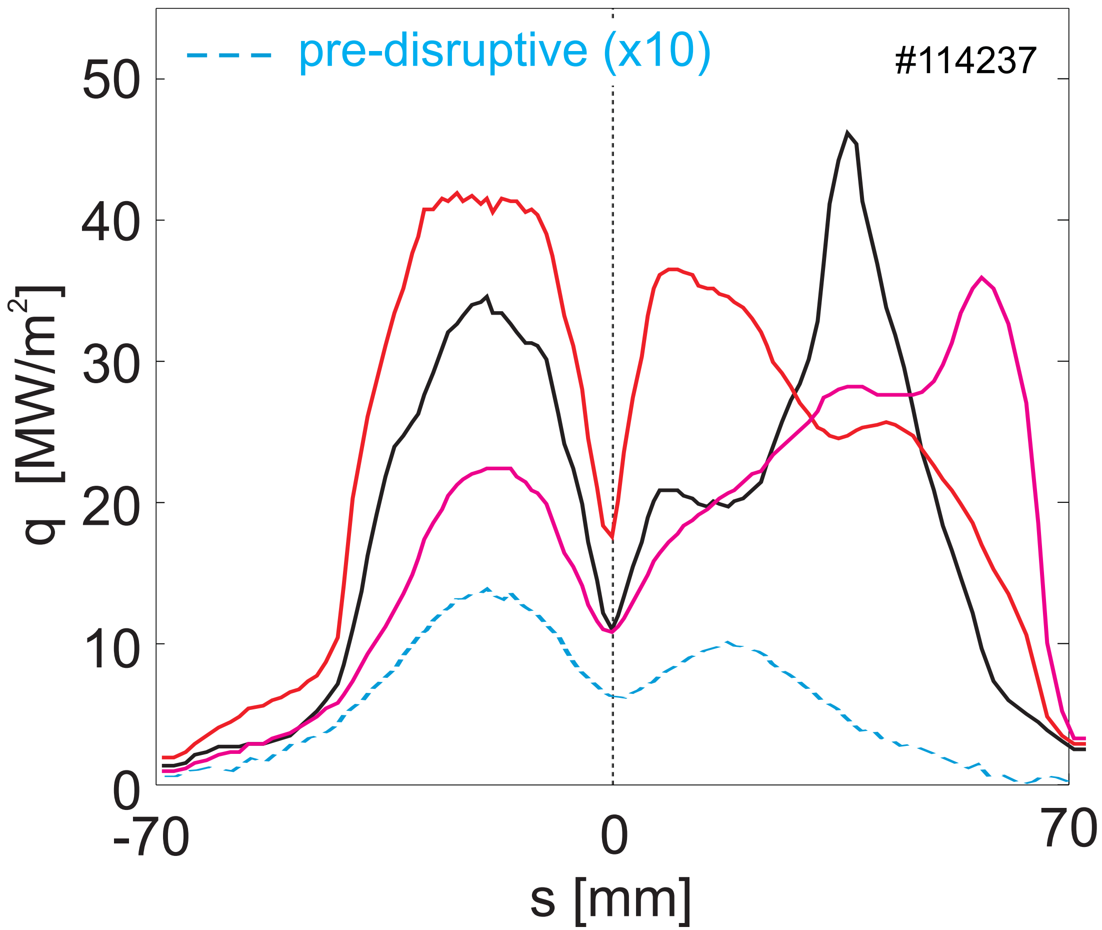
limiter tip @ LCFS (46cm)

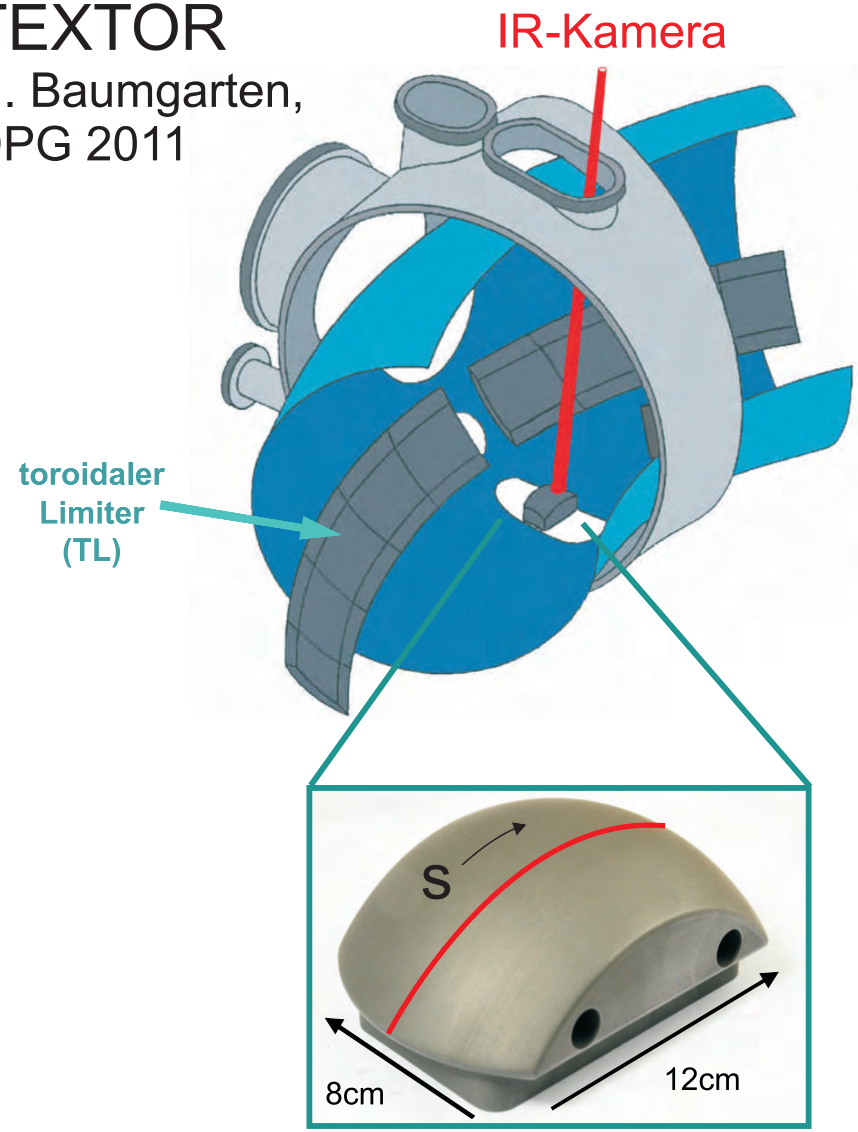
Thermal quench - heat flux distribution

radial energy distribution

TEXTOR
N. Baumgarten, DPG 2011

profiles during thermal quench





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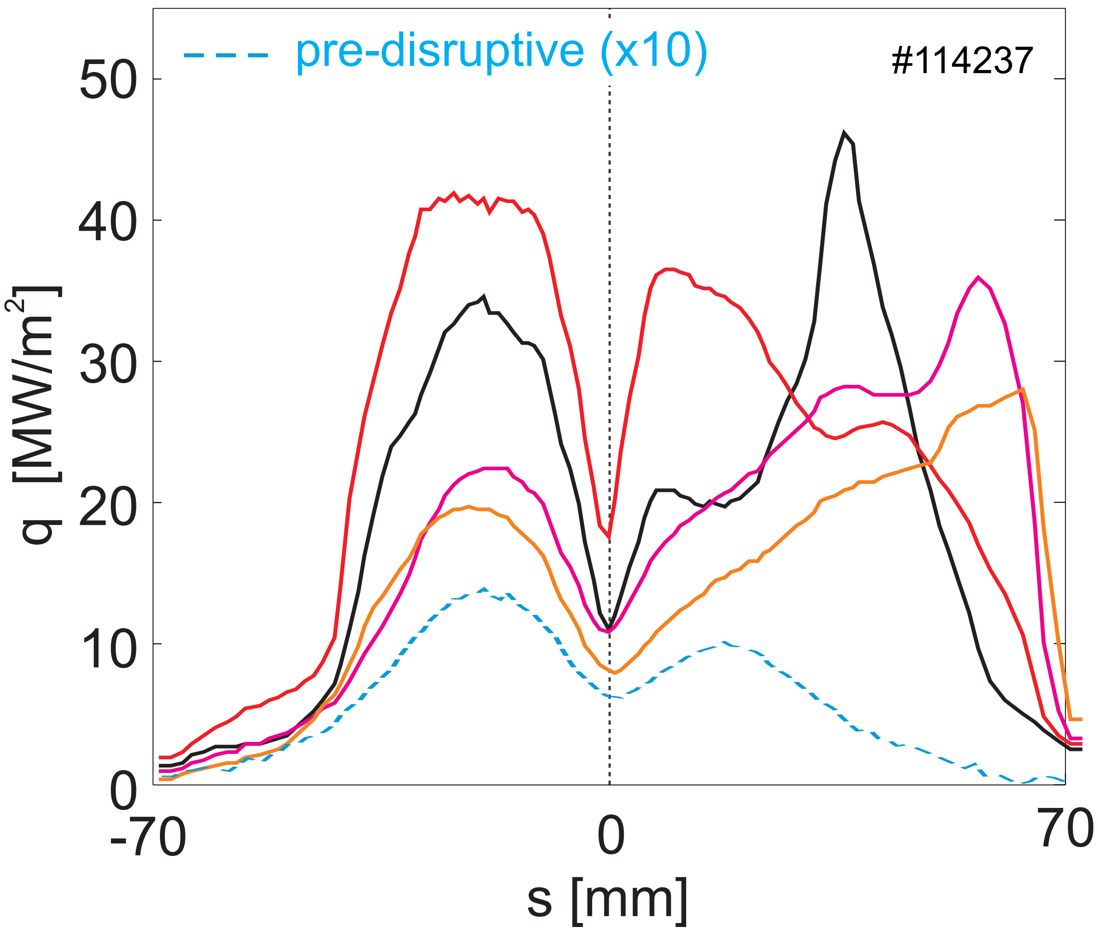
Thermal quench - heat flux distribution

radial energy distribution

profiles during thermal quench



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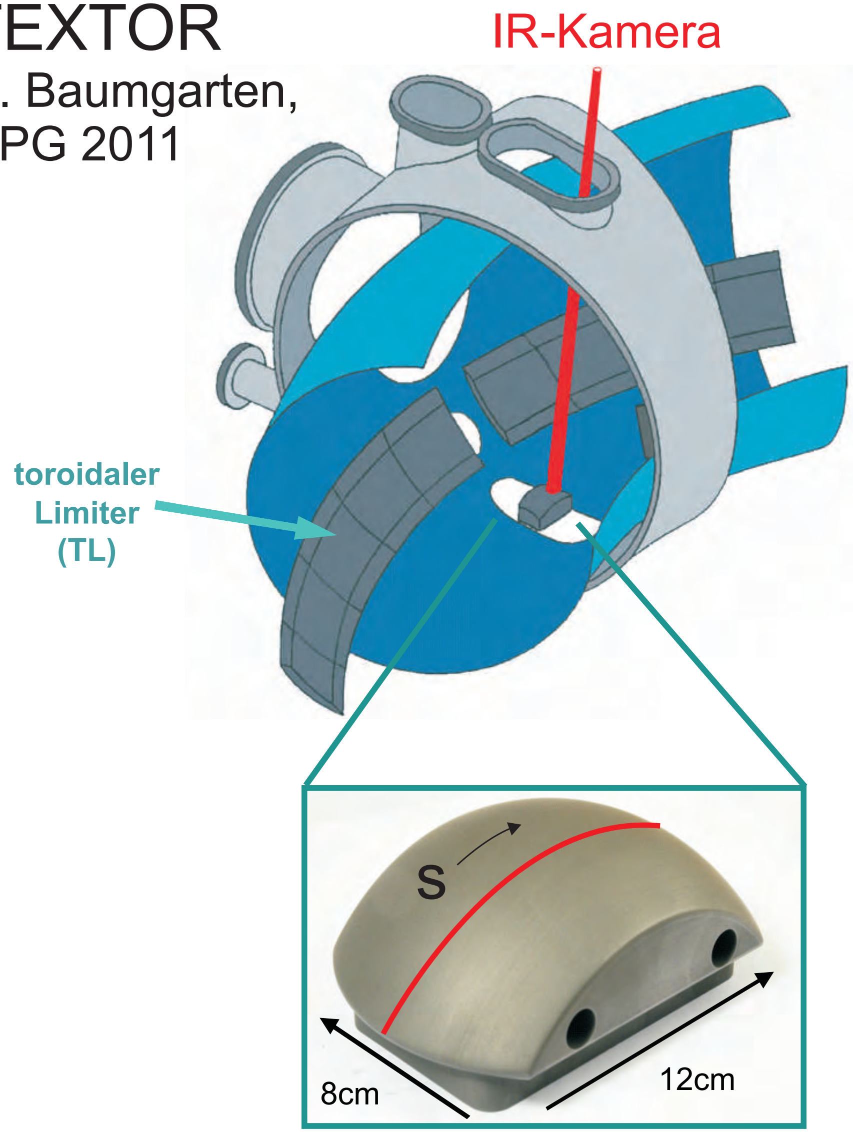


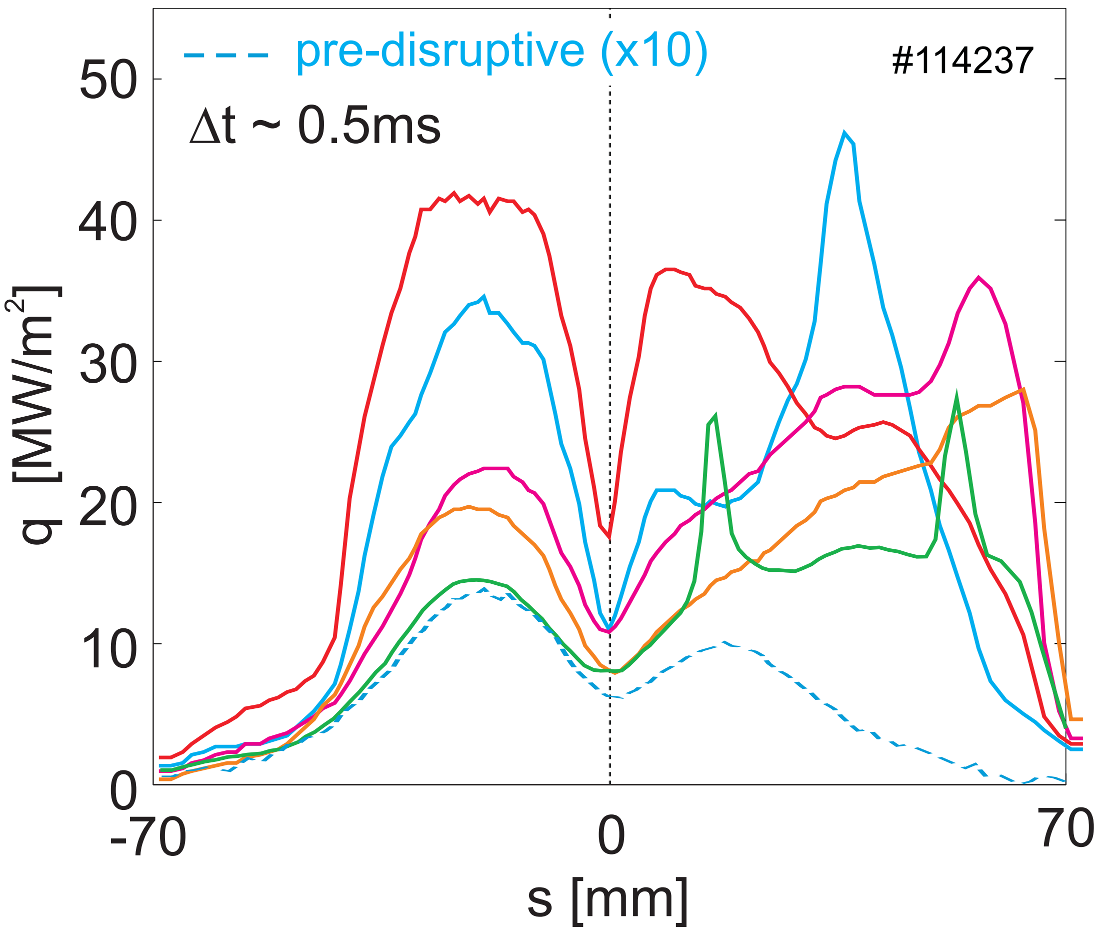
limiter tip @ LCFS (46cm)

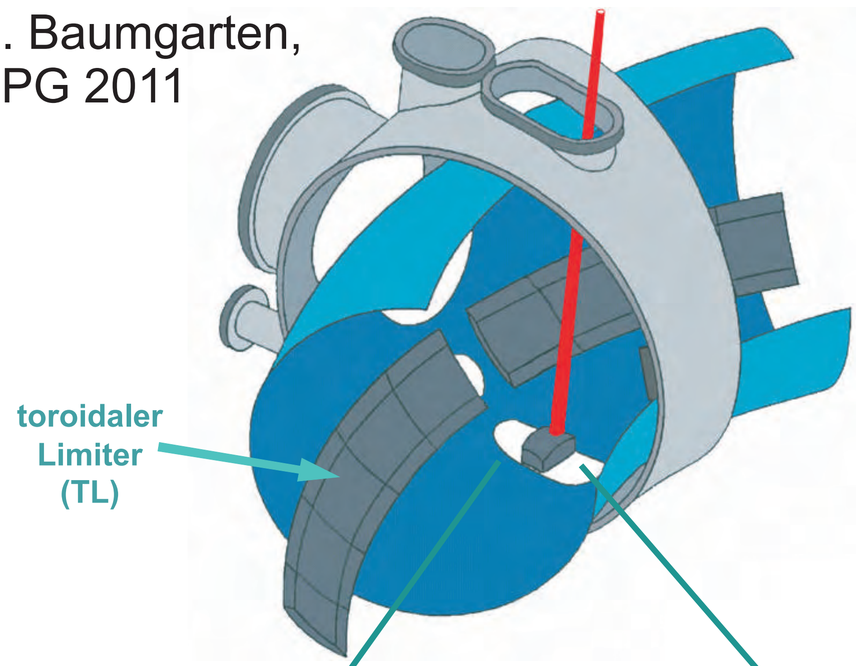
Thermal quench - heat flux distribution

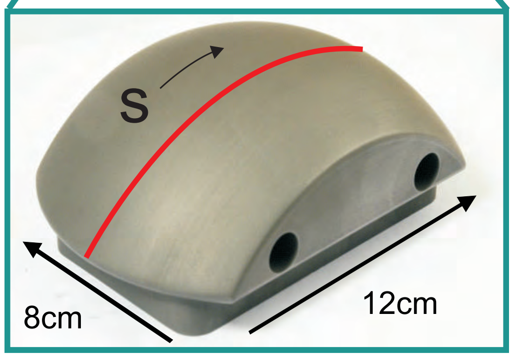
radial energy distribution

TEXTOR
N. Baumgarten, DPG 2011

profiles during thermal quench





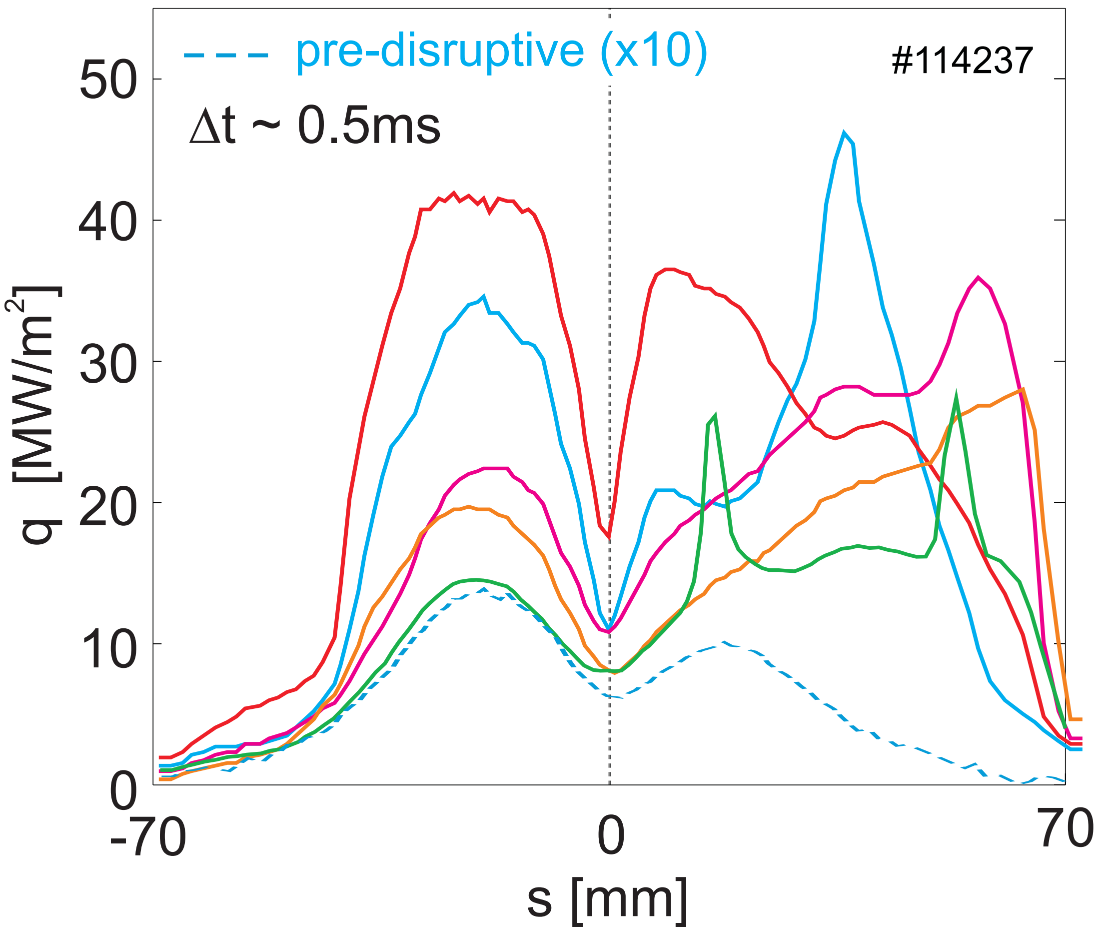


limiter tip @ LCFS (46cm)

Thermal quench - heat flux distribution

radial energy distribution

profiles during thermal quench



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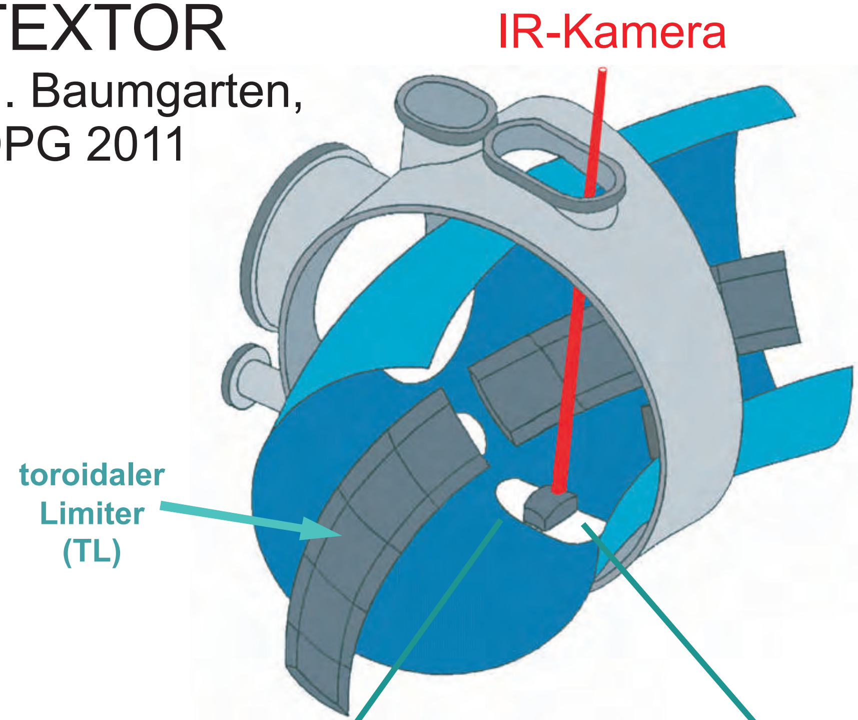
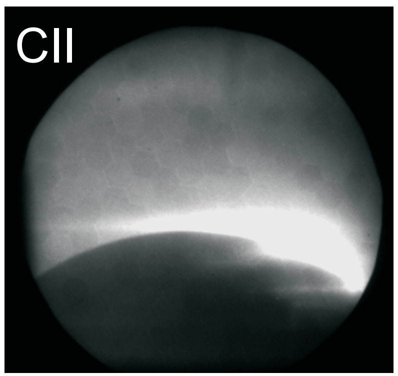
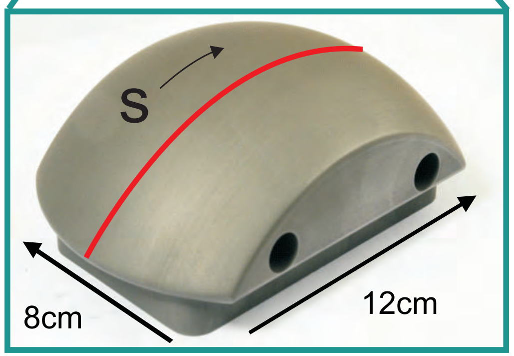




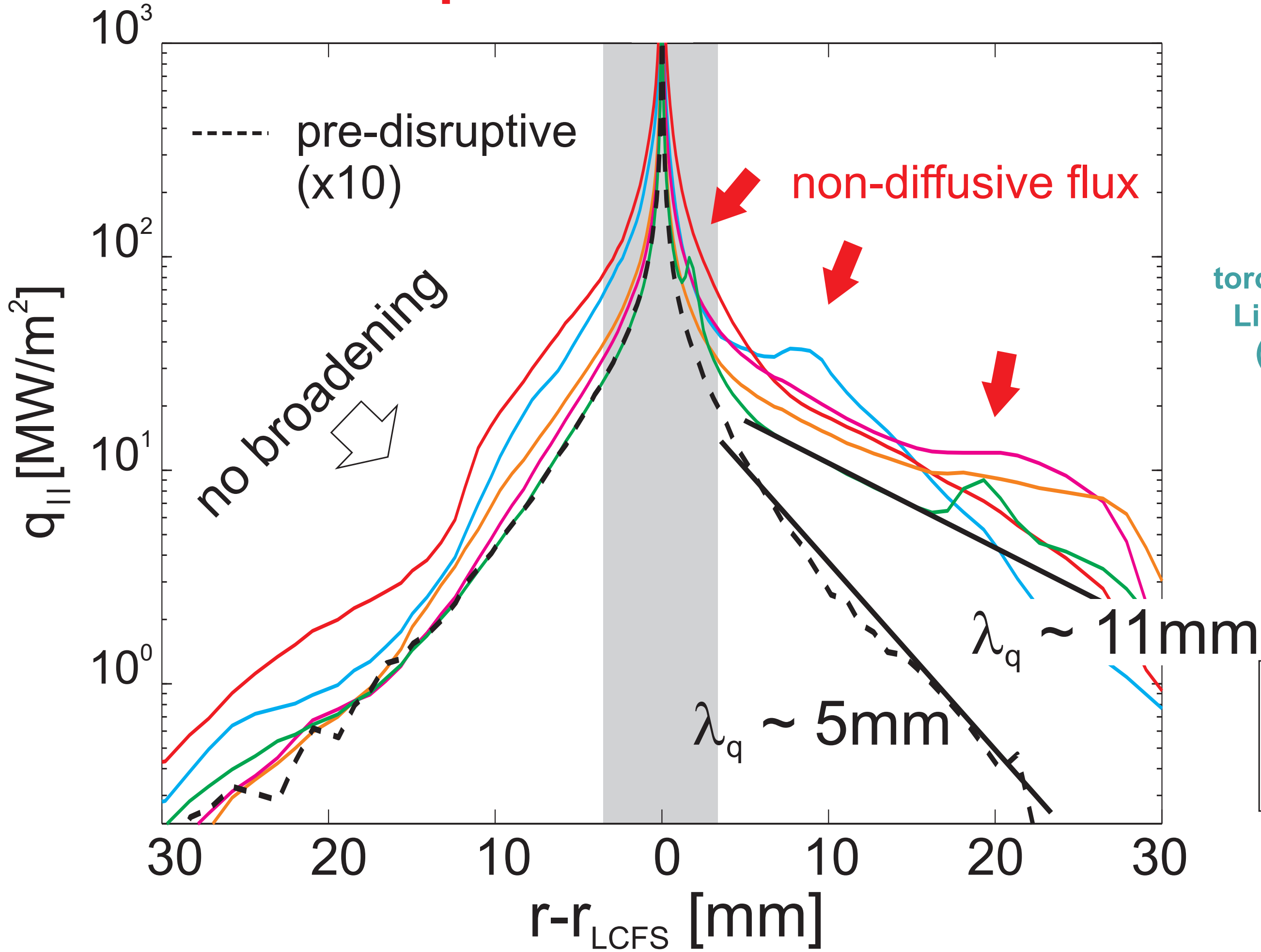


limiter tip @ LCFS (46cm)

Thermal quench - heat flux distribution

radial energy distribution

parallel heat flux



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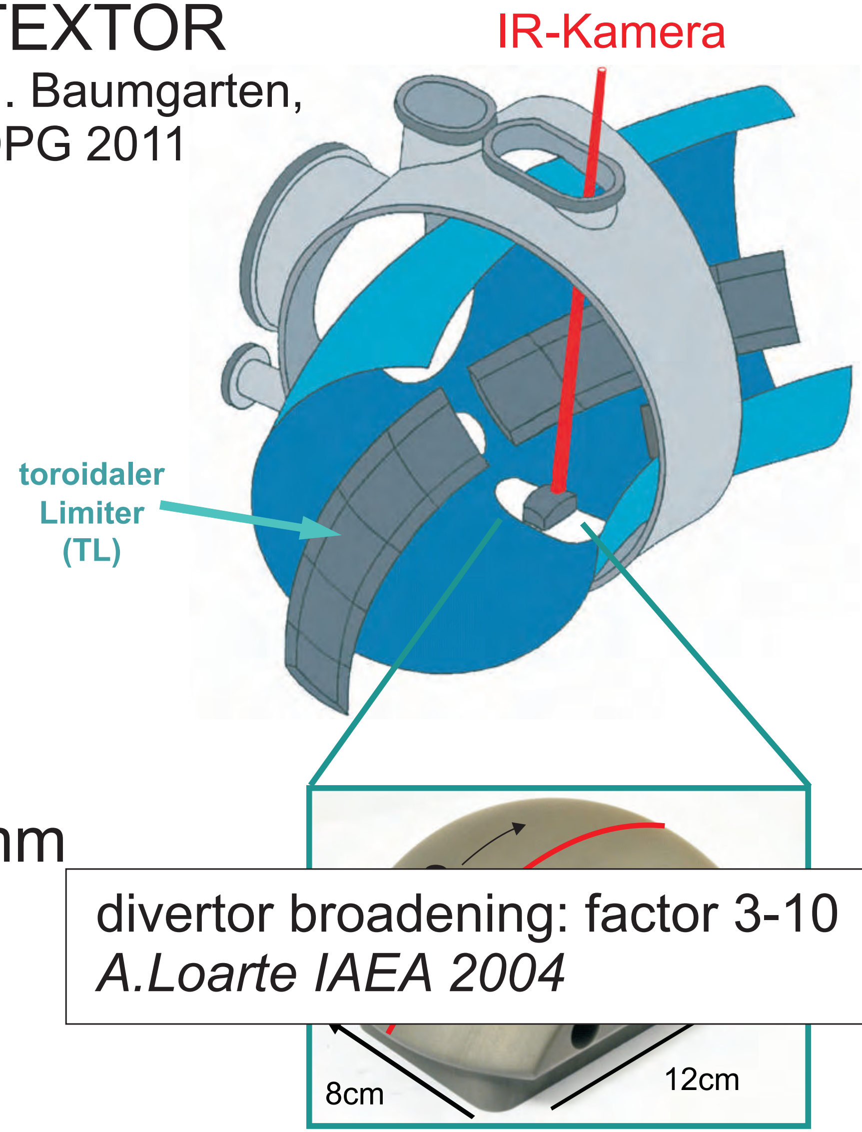


divertor broadening: factor 3-10
A.Loarte IAEA 2004

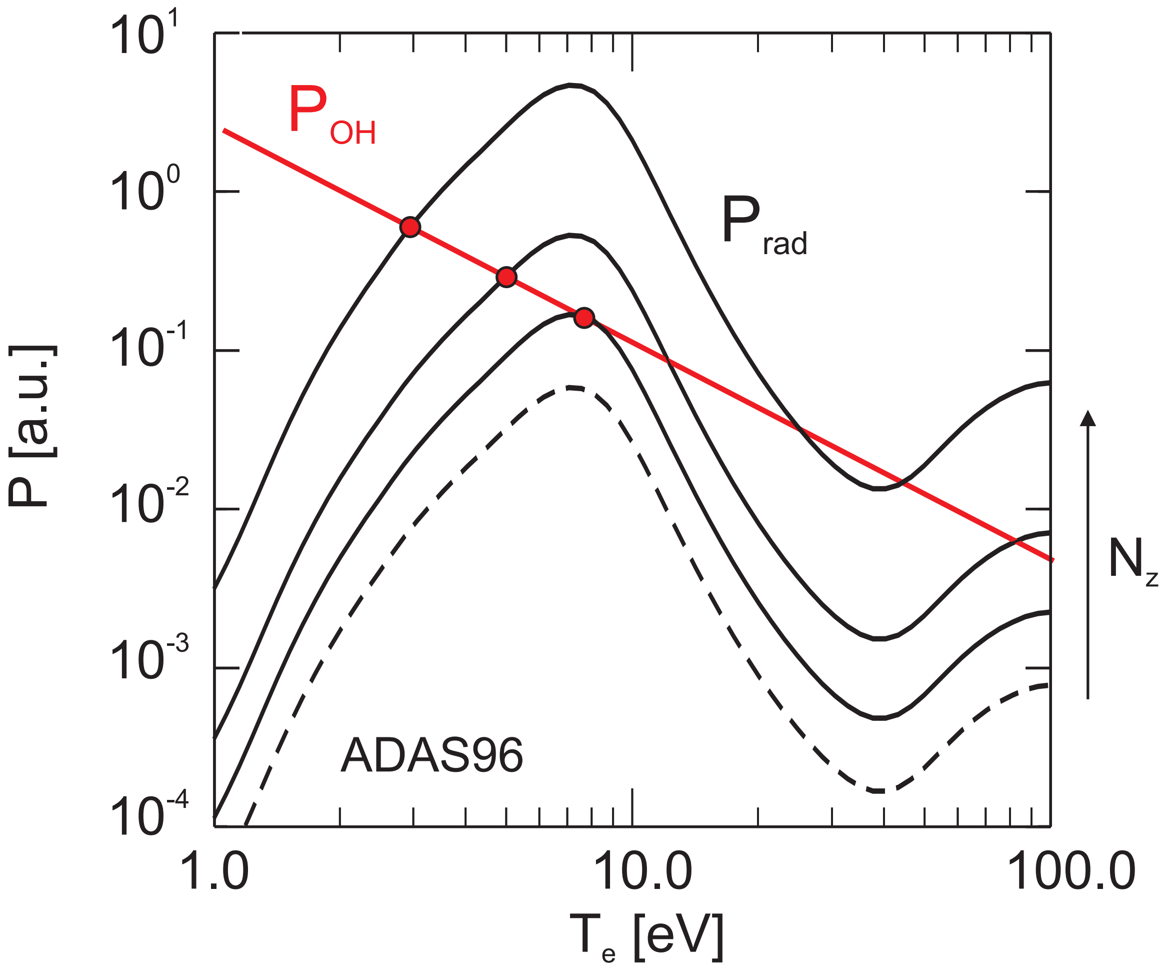
limiter tip @ LCFS (46cm)

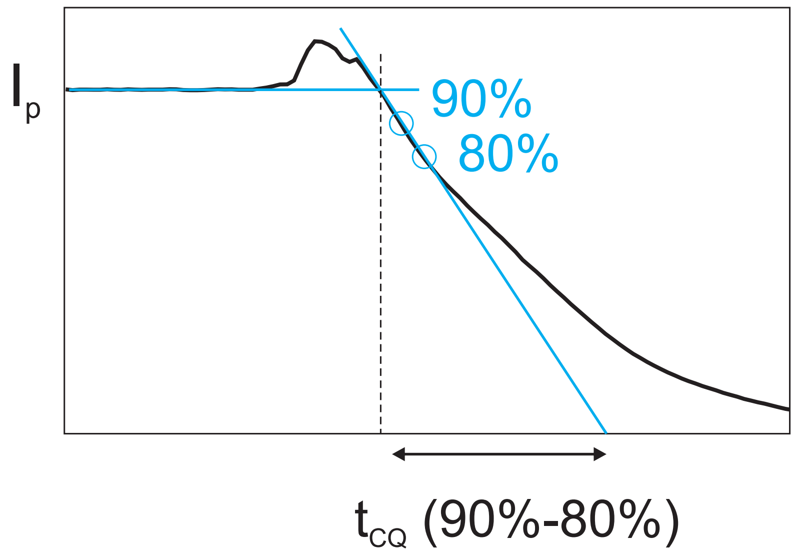
Thermal quench - impurity release

Thermal quench - impurity release

quantification by current decay during current quench

0-d model assumption: $P_{OH} = P_{rad}$

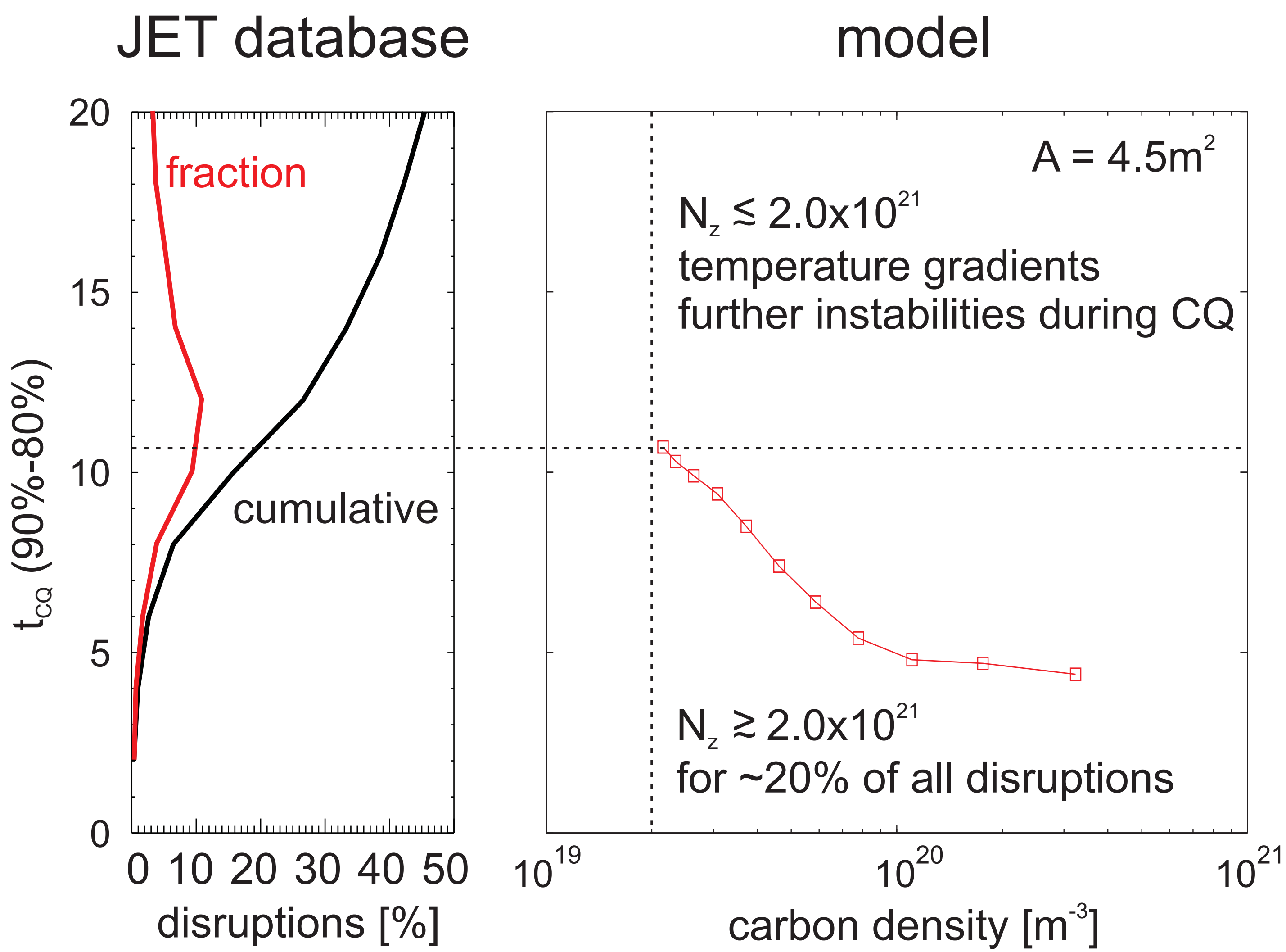




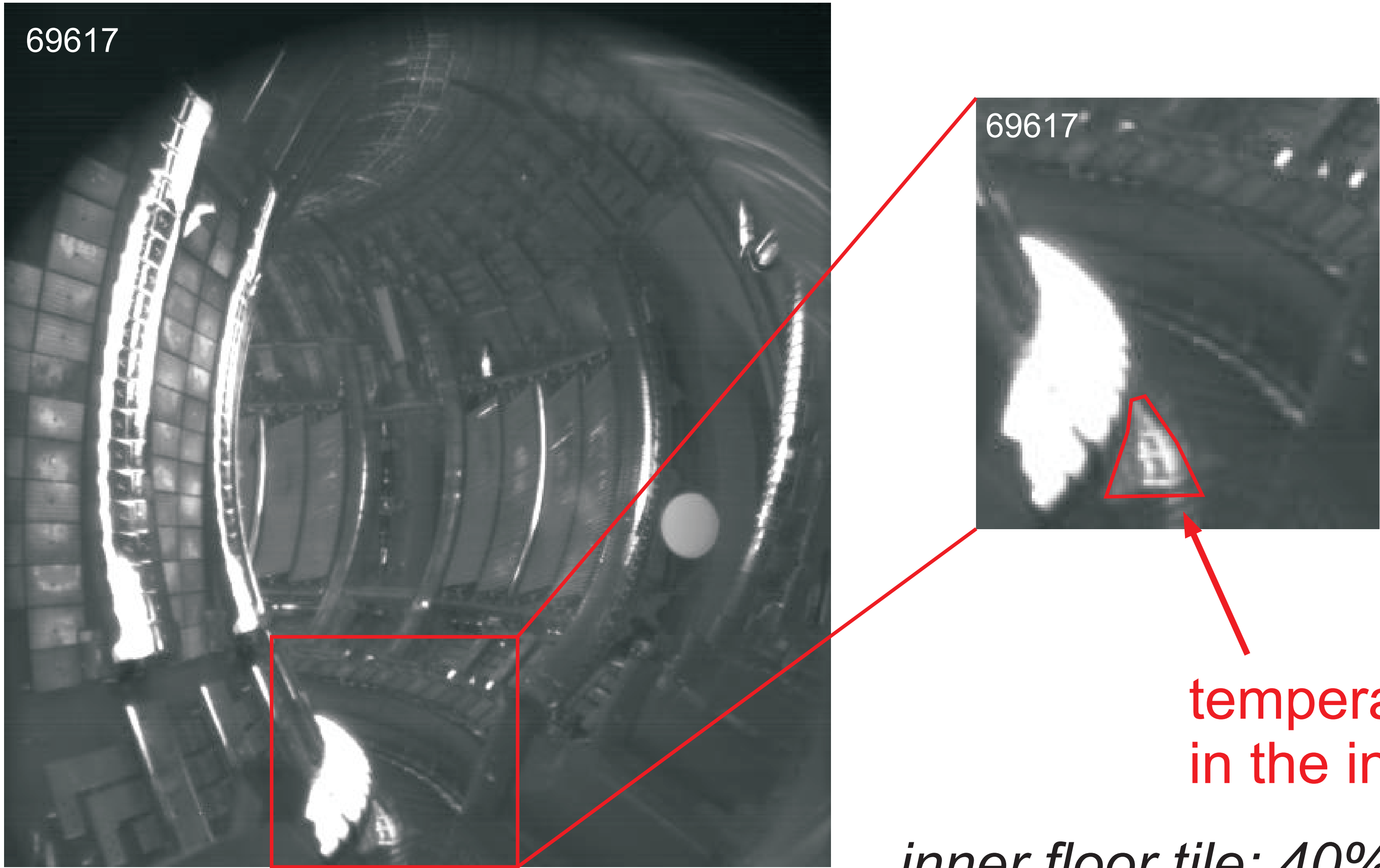
corona equilibrium can be applied as $n_e \times t > 10^{17}$ s m^{-3}

Thermal quench - impurity release

quantification by current decay during current quench



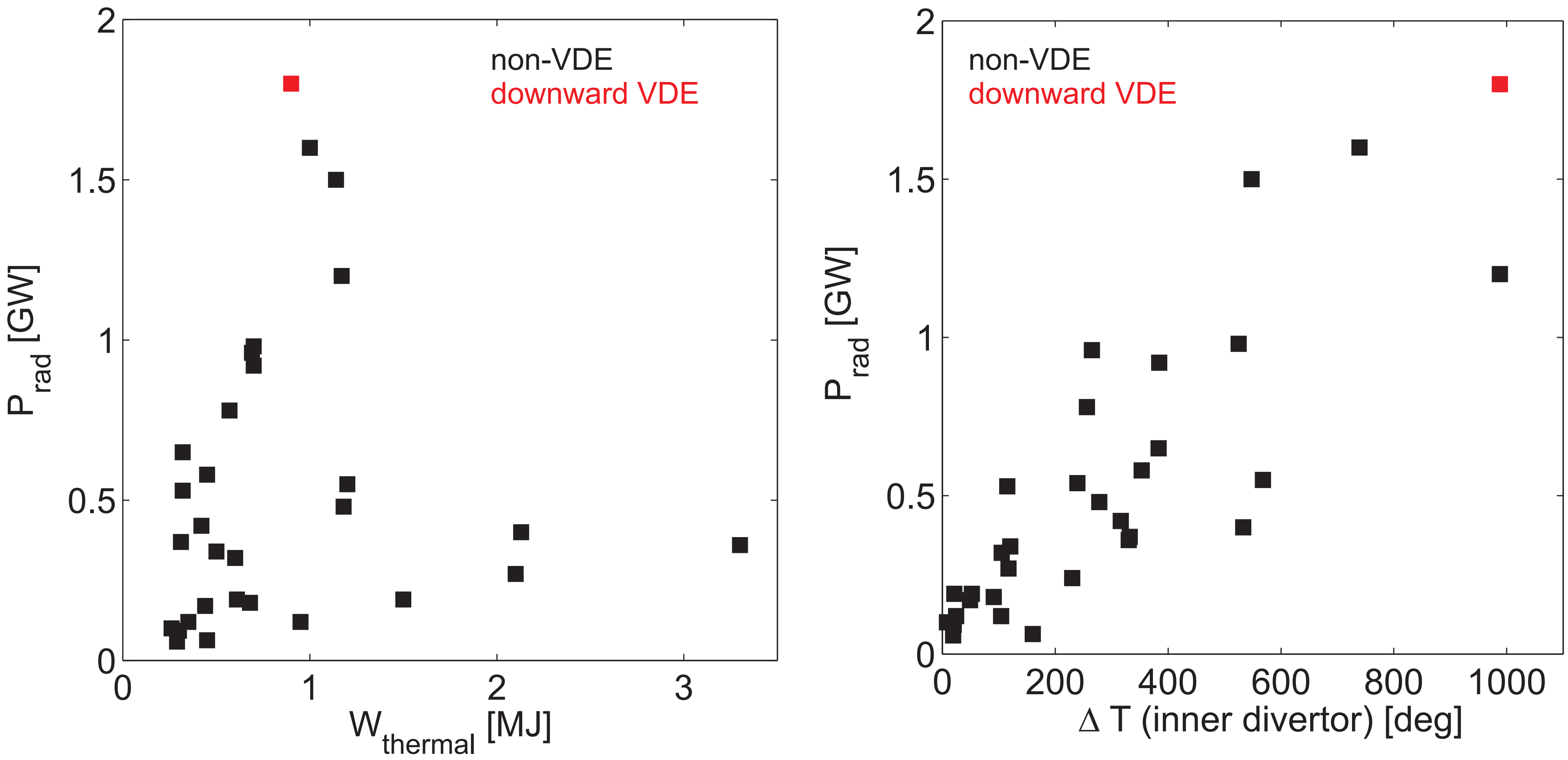
JET wide angle IR view



temperature rise
in the inner divertor

inner floor tile: 40% of retention
J. Likonen, JNM 2009

JET - peak radiated power during CQ

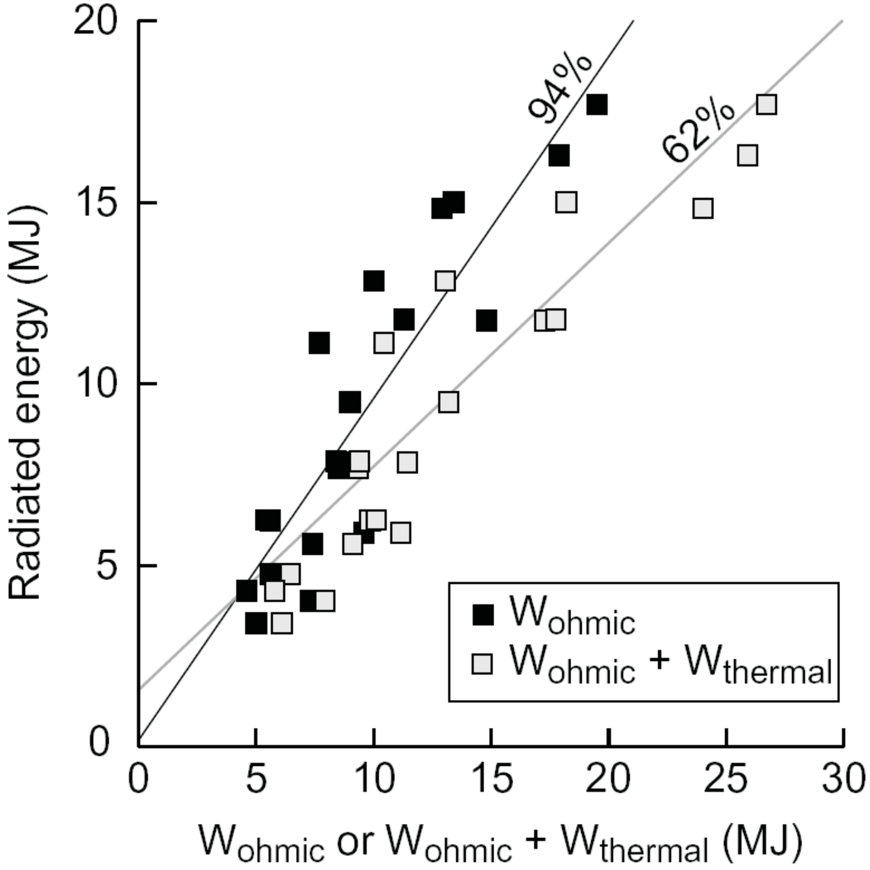


- no clear correlation to thermal energy loss
- spatial distribution of energy is important for C release (or existance of C-layers)

Current quench - dissipation of magnetic energy

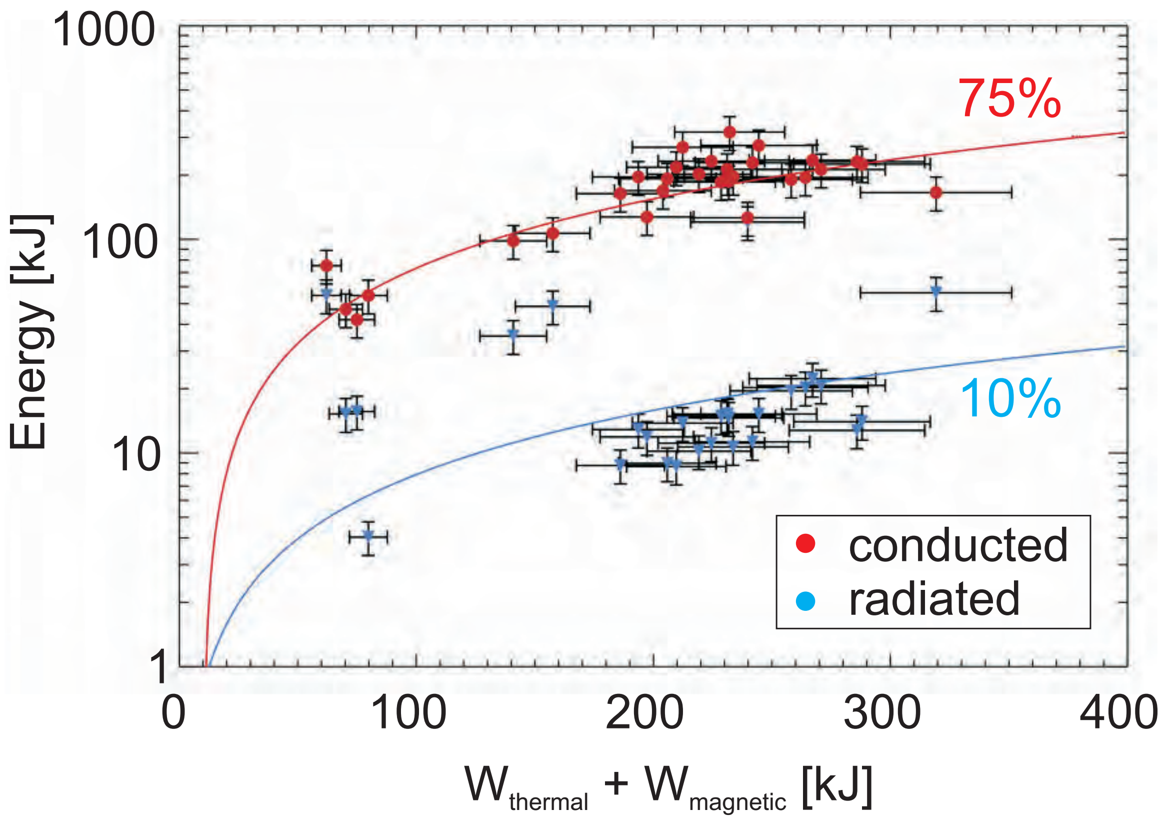
Current quench - dissipation of magnetic energy

JET: most of W_{ohmic} is radiated



J. Paley, JNM 2005

MAST: major fraction of W_{mag} conducted to divertor



A. Thornton, EFDA-PWI 2010

Current quench - dissipation of magnetic energy

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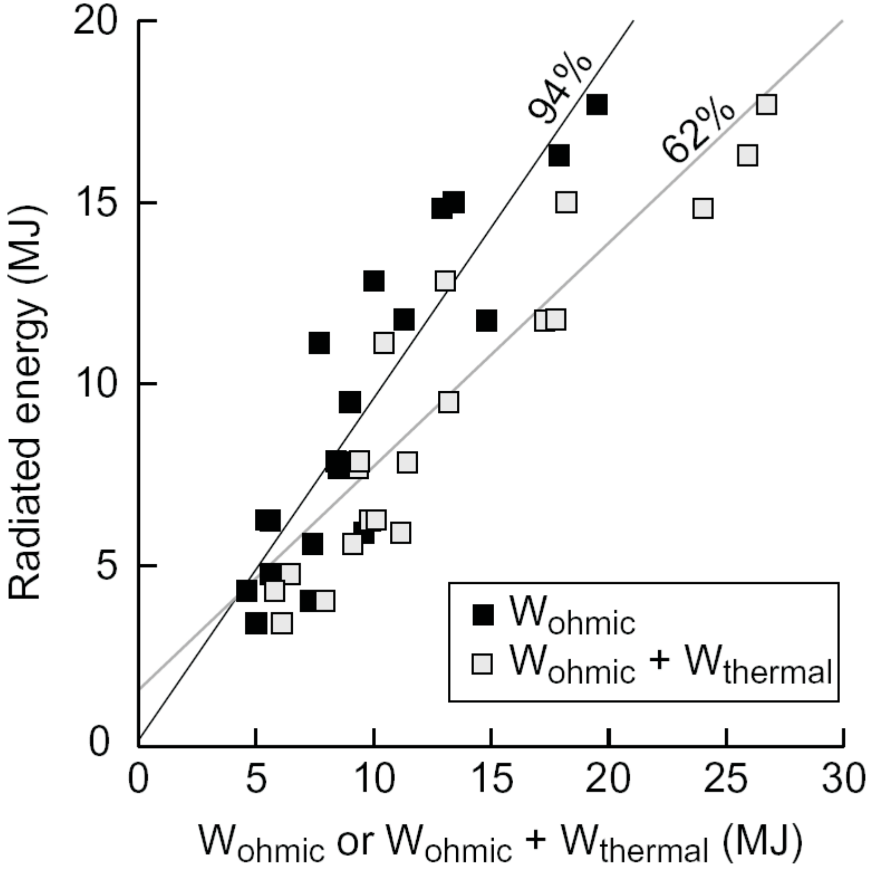

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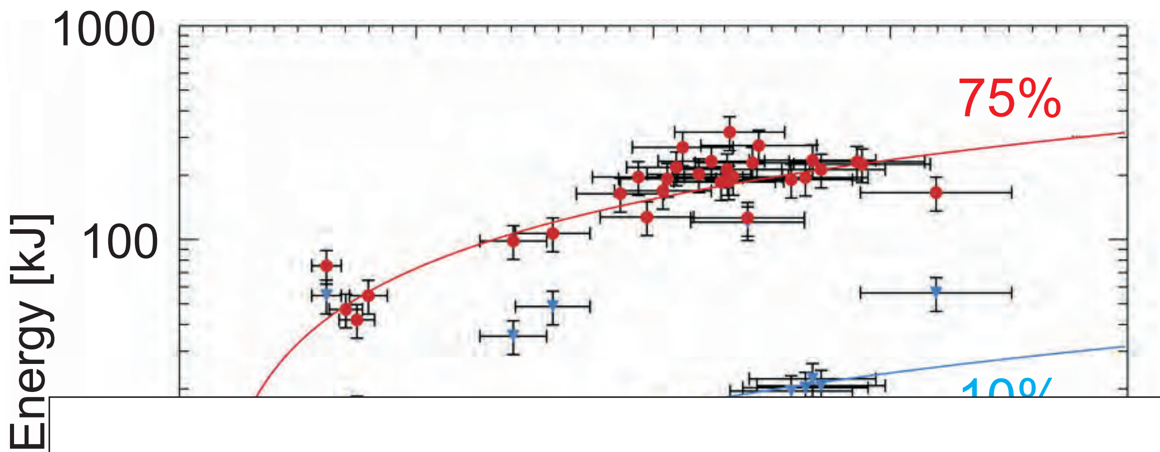


ITER

W_{mag} = 395 MJ (inside vessel)

t_{CQ} > 35ms (eddy current limitation)

heat impact factor < 85 $MJm^{-2}s^{-0.5}$
(„broadening“ of a factor 7)

Excursus - Disruption induced fuel release

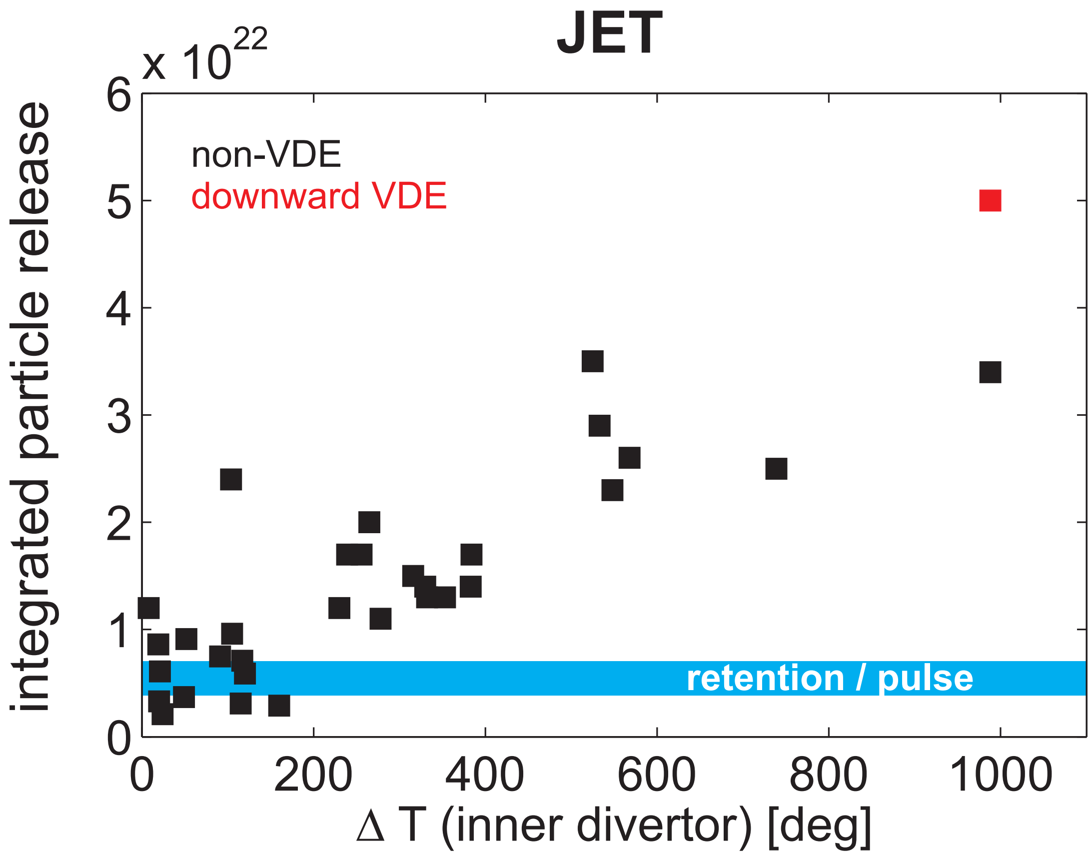
Disruption induced fuel release

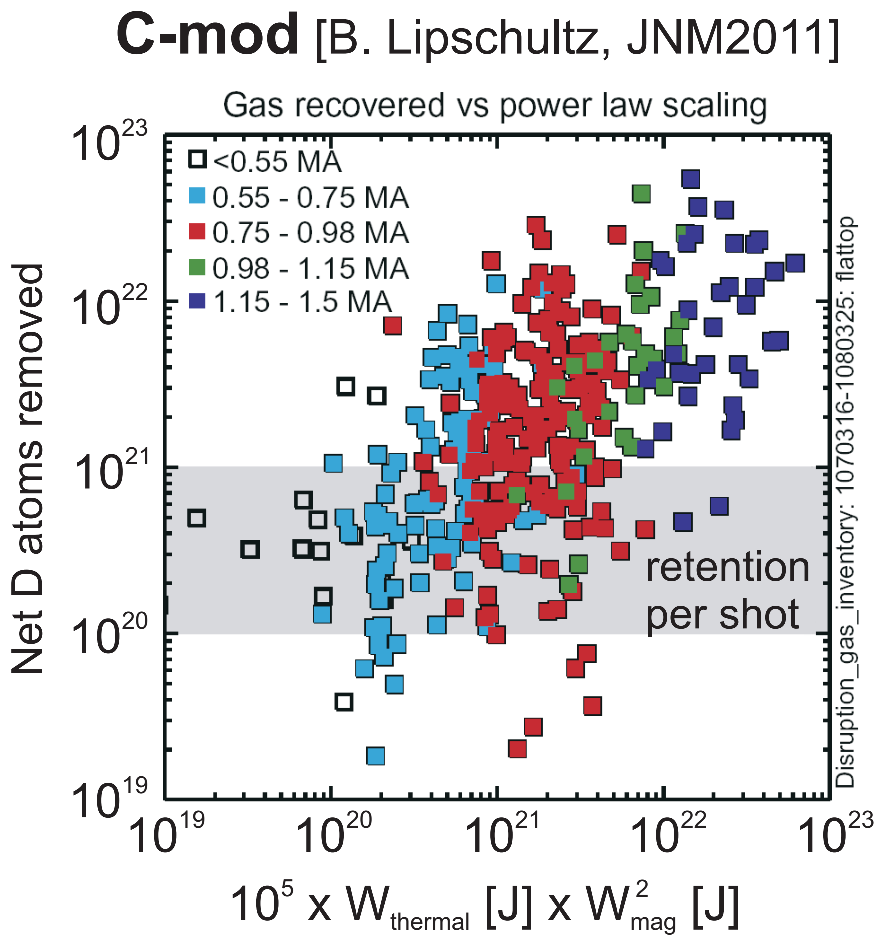
Desorption by heating

(a) heating by convection/conduction during thermal quench and/or current quench

heat flux distribution not yet understood, radiation during CQ to be controlled, high ΔT possible

(b) radiation heating during current quench
does not reach remote divertor areas, ΔT(ITER) ~ 200-300K





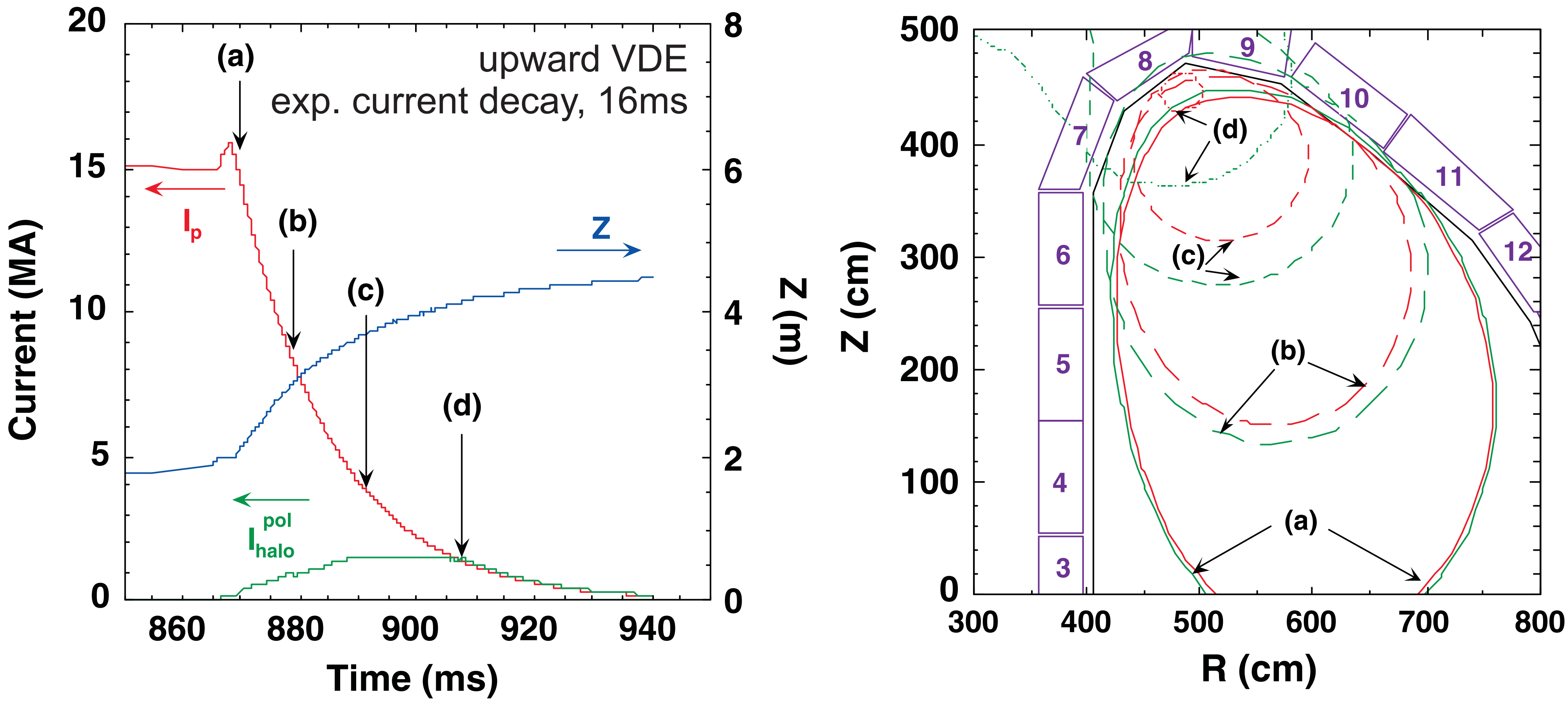
Current quench - mechanical loads

Current quench - mechanical loads

plasma intersected by the first wall ⇨ halo currents

fast current quench ⇨ eddy currents

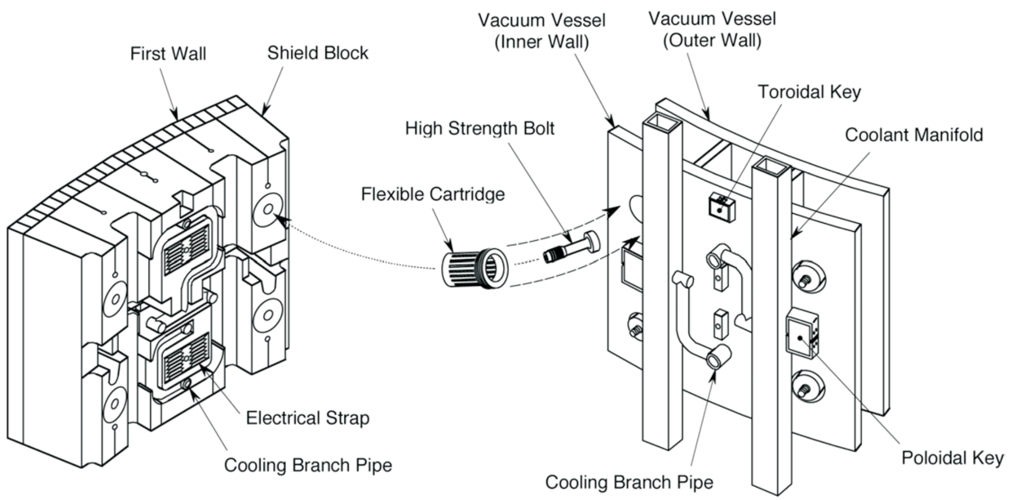
DINA simulation for ITER, M. Sugihara, NF 2007

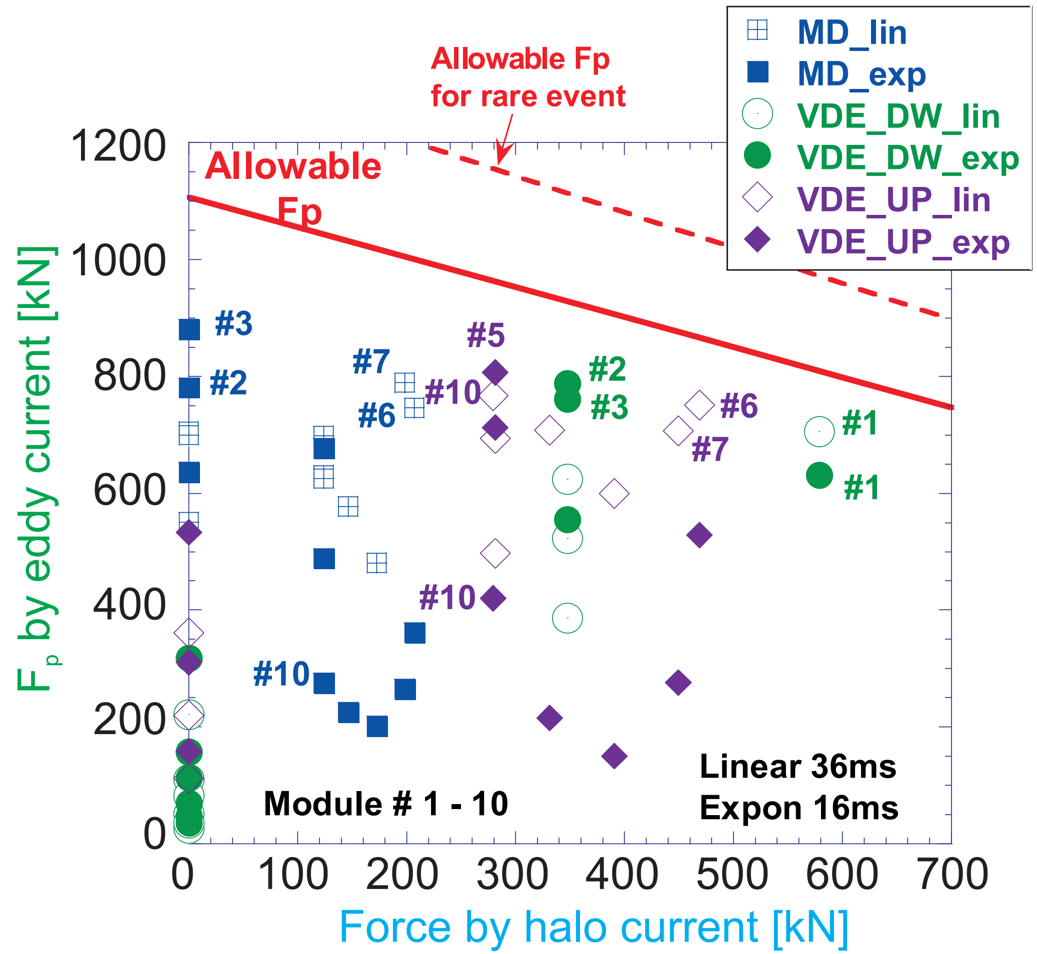


Current quench - mechanical loads

Forces on ITER blanket modules by halo and eddy current

ITER blanket module



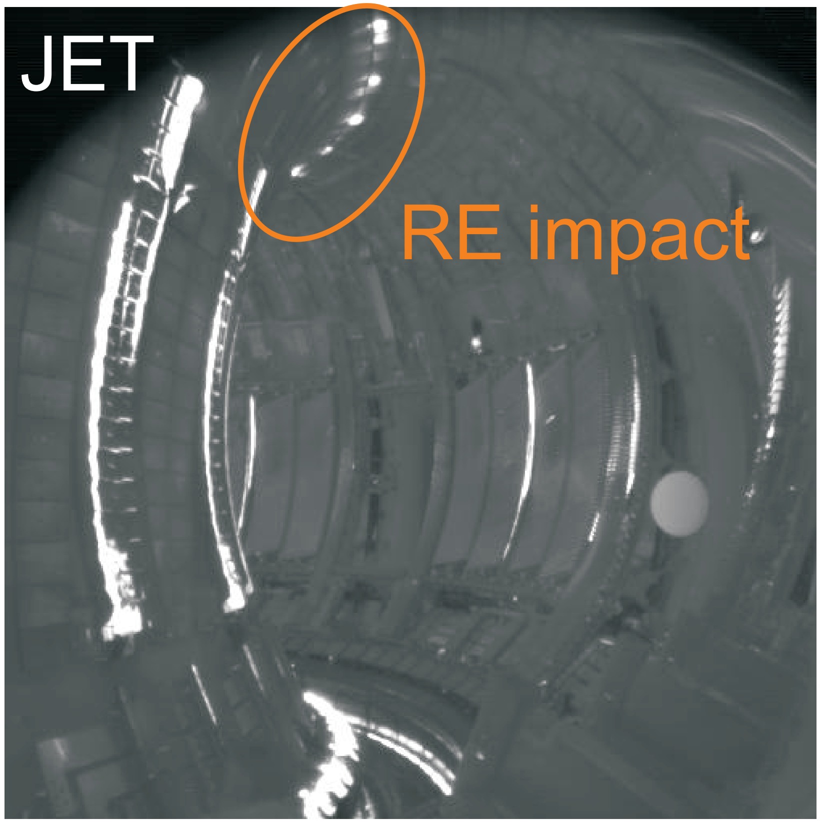


M. Sugihara, NF 2007

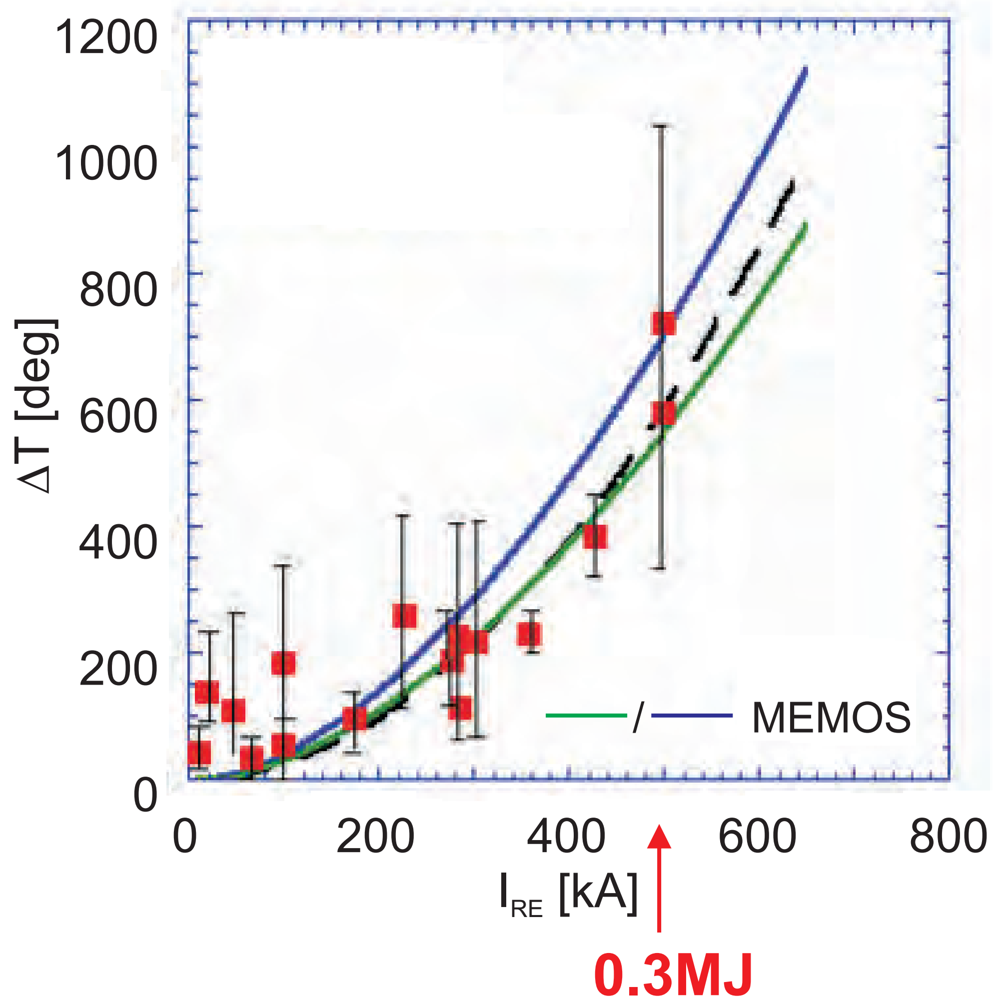
➡ ITER-like wall: I-06 Ph. Mertens, Tuesday

Current quench - Runaway electrons

Current quench - Heat loads by runaway electrons

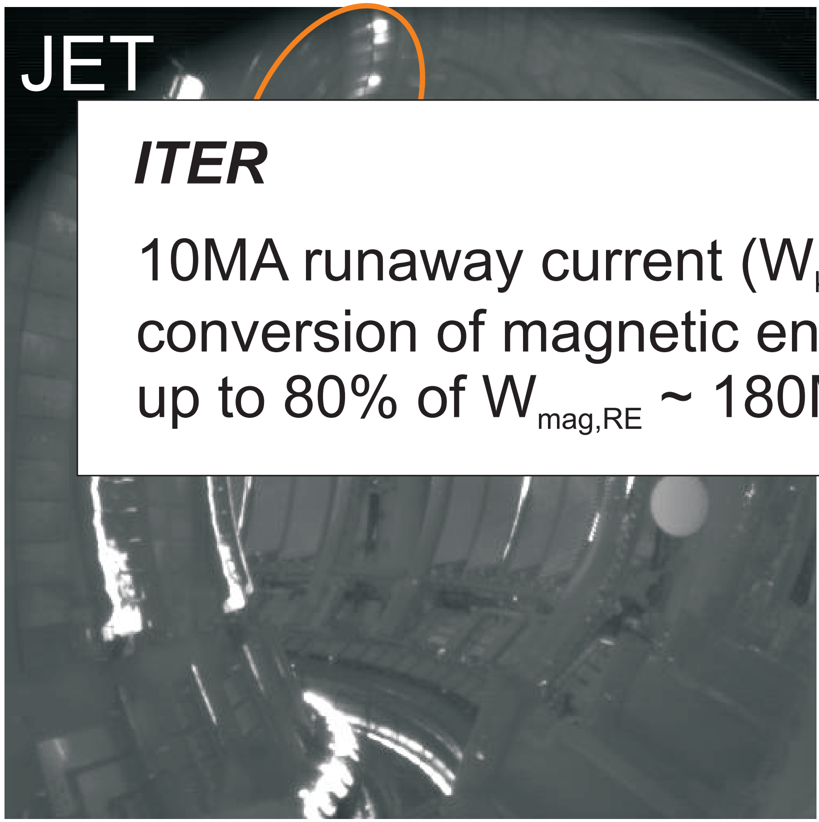


Temperature rise at upper dump plate



M. Lehnen, PSI 2008,
G. Arnoux, B. Bazylev PSI 2010

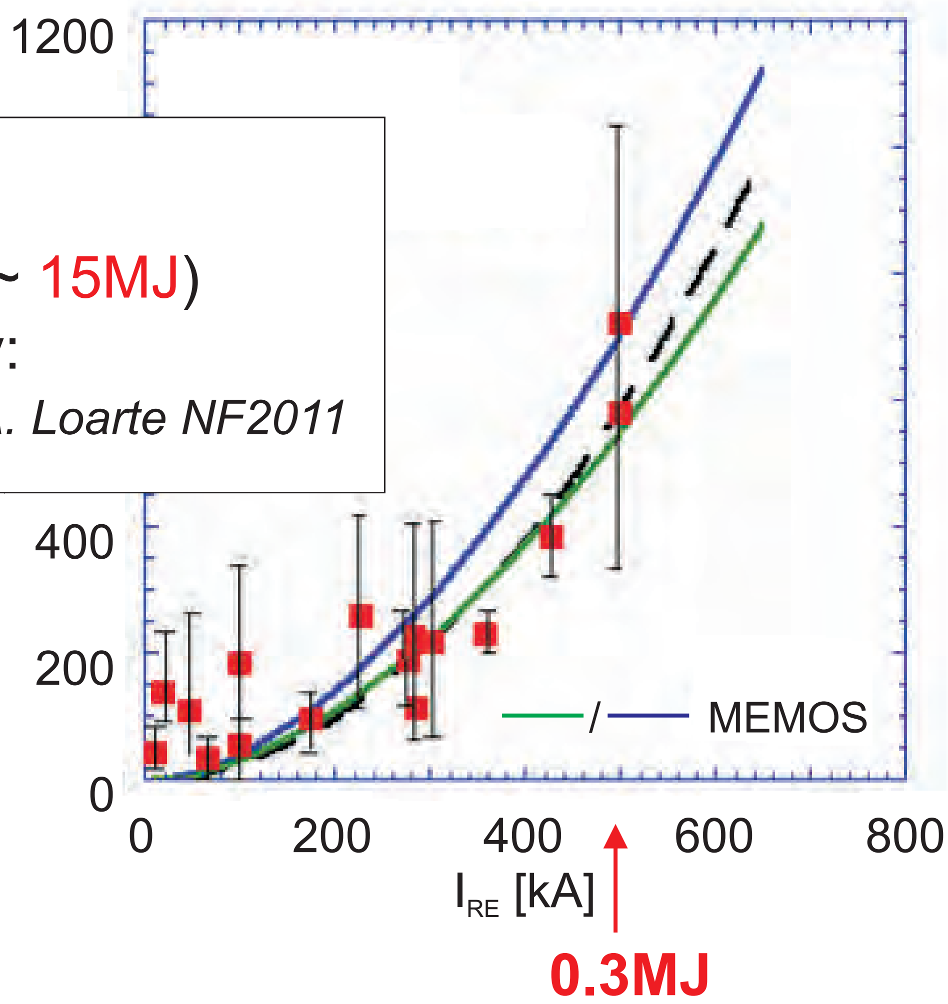
Current quench - Heat loads by runaway electrons



ITER

10MA runaway current ($W_{kin,RE}$ ~ 15MJ)
conversion of magnetic energy:
up to 80% of $W_{mag,RE}$ ~ 180MJ *A. Loarte NF2011*

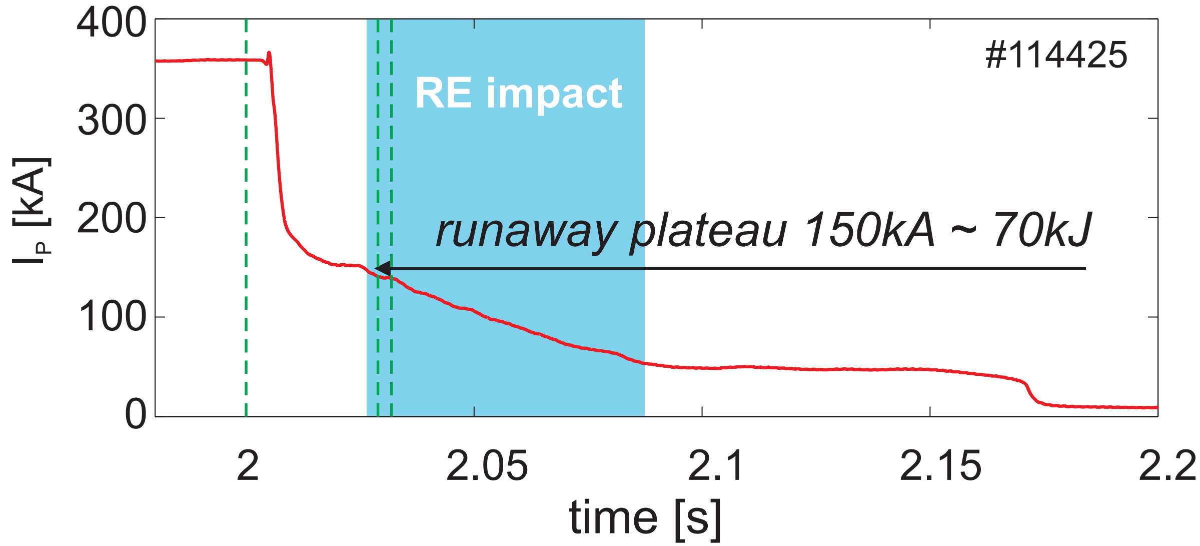
Temperature rise at upper dump plate



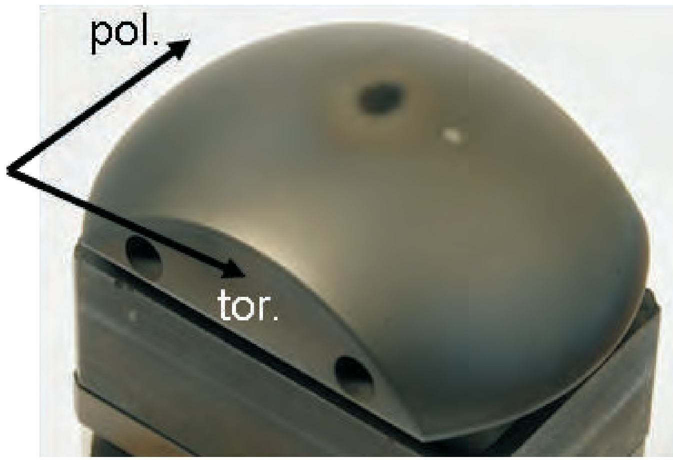
M. Lehnen, PSI 2008,
G. Arnoux, B. Bazylev PSI 2010

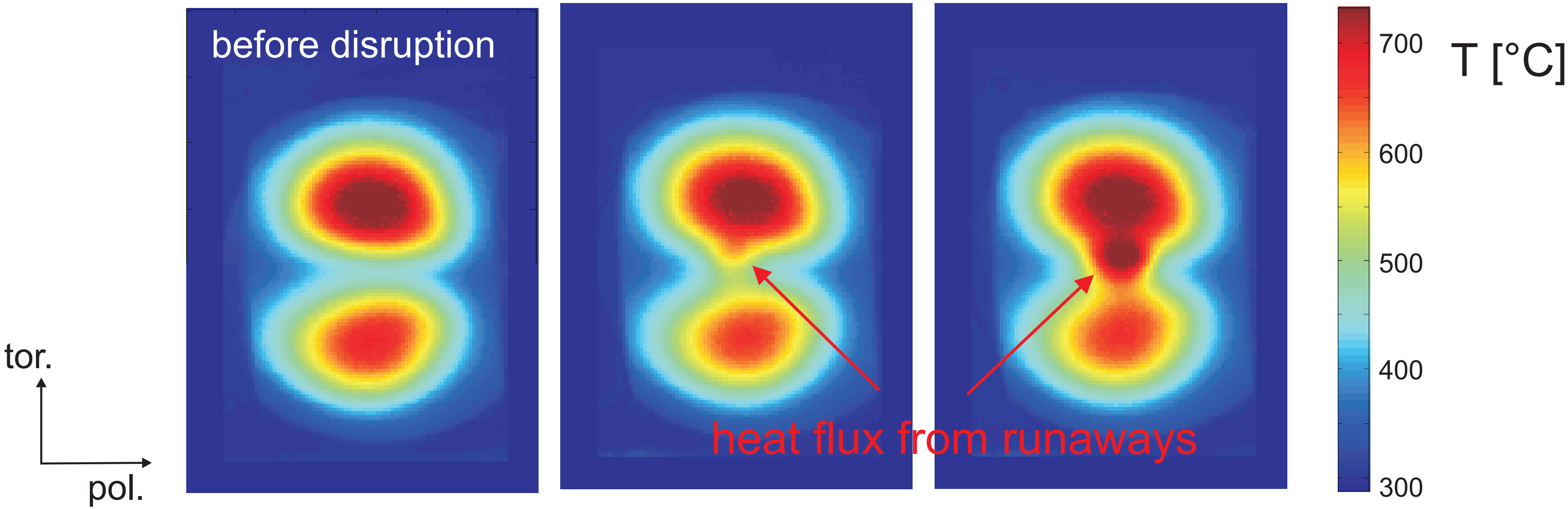
Current quench - Heat loads by runaway electrons

TEXTOR deliberate RE generation

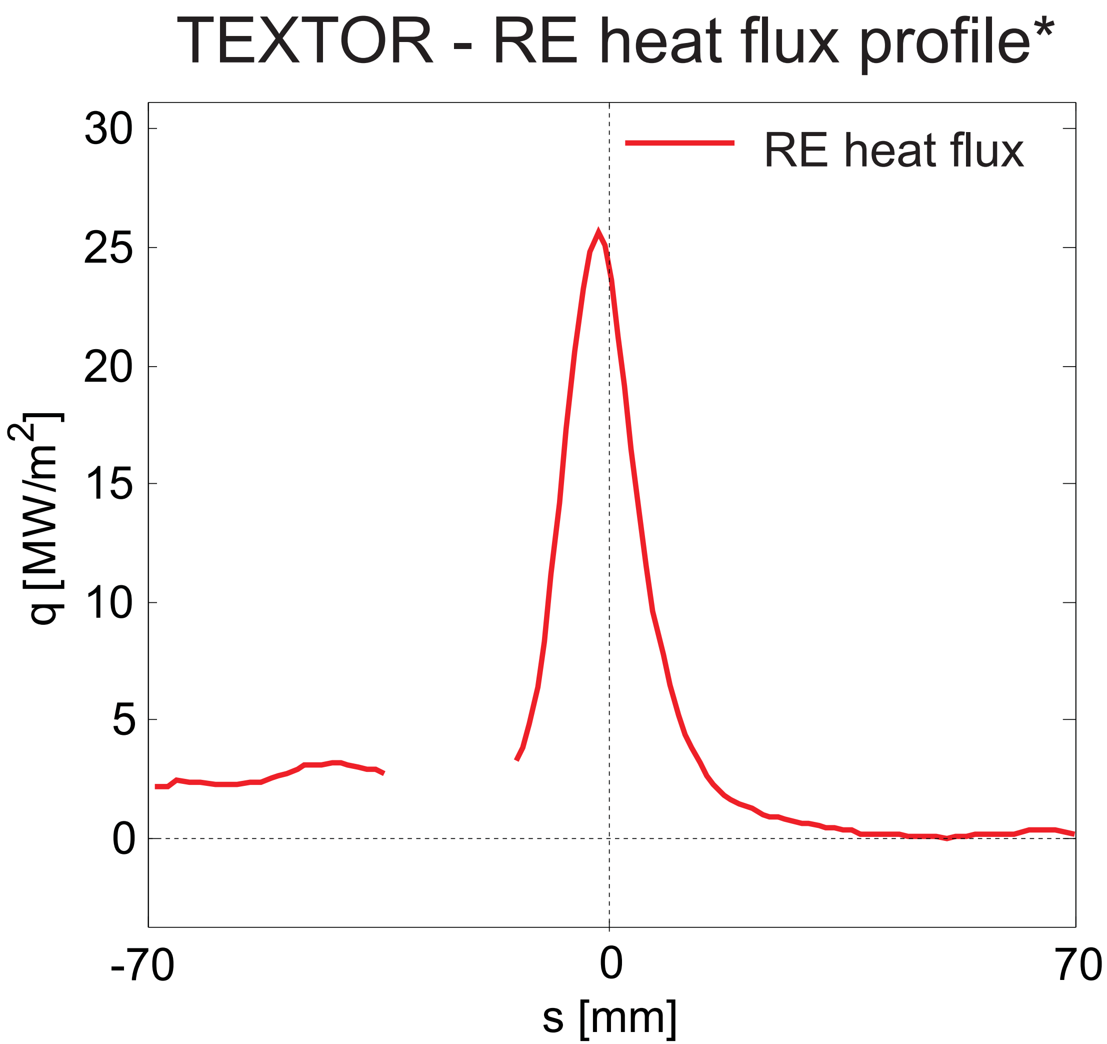


pyrometer: > 2500°C





Current quench - Heat loads by runaway electrons

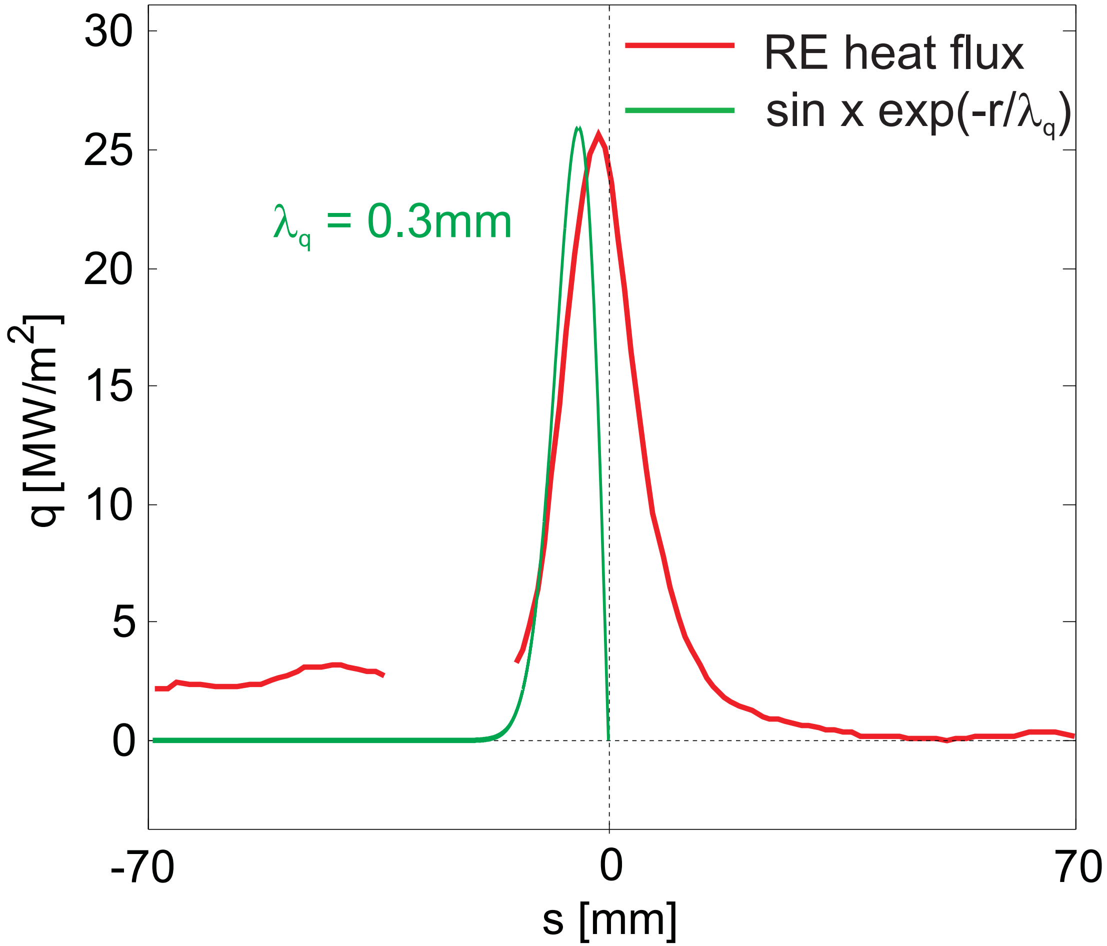


*at the start of runaway loss estimated mean heat flux: 150MW/m^2

N. Baumgarten, DPG 2011

Current quench - Heat loads by runaway electrons

TEXTOR - RE heat flux profile*



*at the start of runaway loss estimated mean heat flux: $150 MW/m^2$

e-folding length ~ gyro radius

$E_{perp}/E_{par} \sim 0.1 \Rightarrow \rho \sim 3mm$

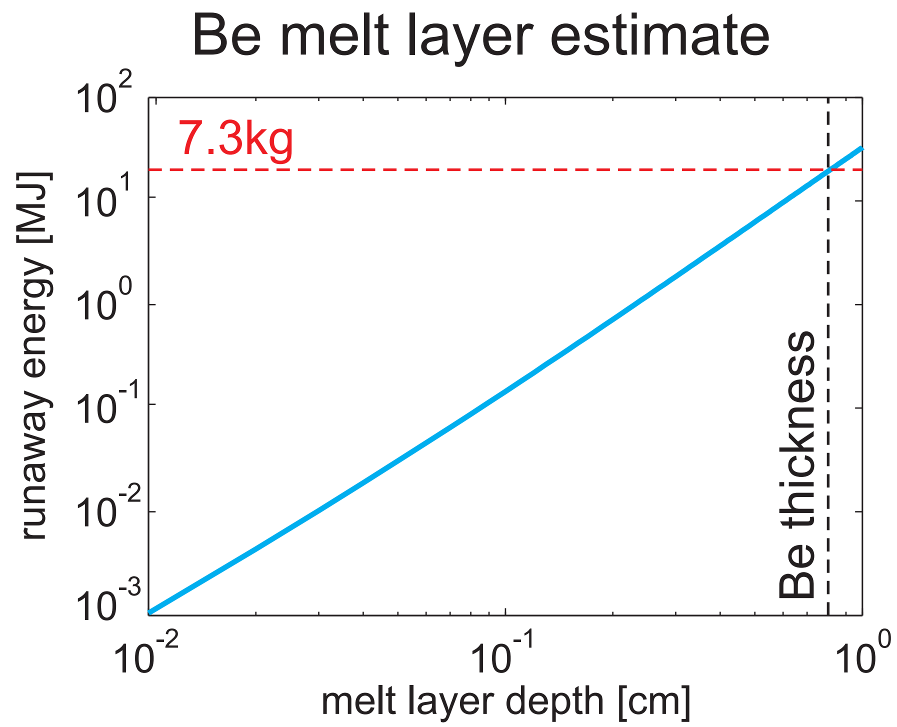
parallel penetration depth: ~10 cm (12.5 MeV) !

λ_q (RE) ~ 5% λ_q (s.s.)

N. Baumgarten, DPG 2011

TEXTOR - RE heat flux profile*

ITER



rough estimate:
20 MJ melt 7.3kg of Be
melt depth marginally down to Cu interface

calculated molten Be mass
roof geometry considered
r_{RE} = 0.5 m
λ_q < 1.0 mm

symmetric impact and
no conversion of W_{mag}

q [MW/m^2]

-70 0 70
s [mm]

N. Baumgarten, DPG 2011

Disruption Mitigation - Massive Gas Injection (MGI)

MGI is applied when a forthcoming disruption is detected and cannot be avoided by any control means

MGI aims at

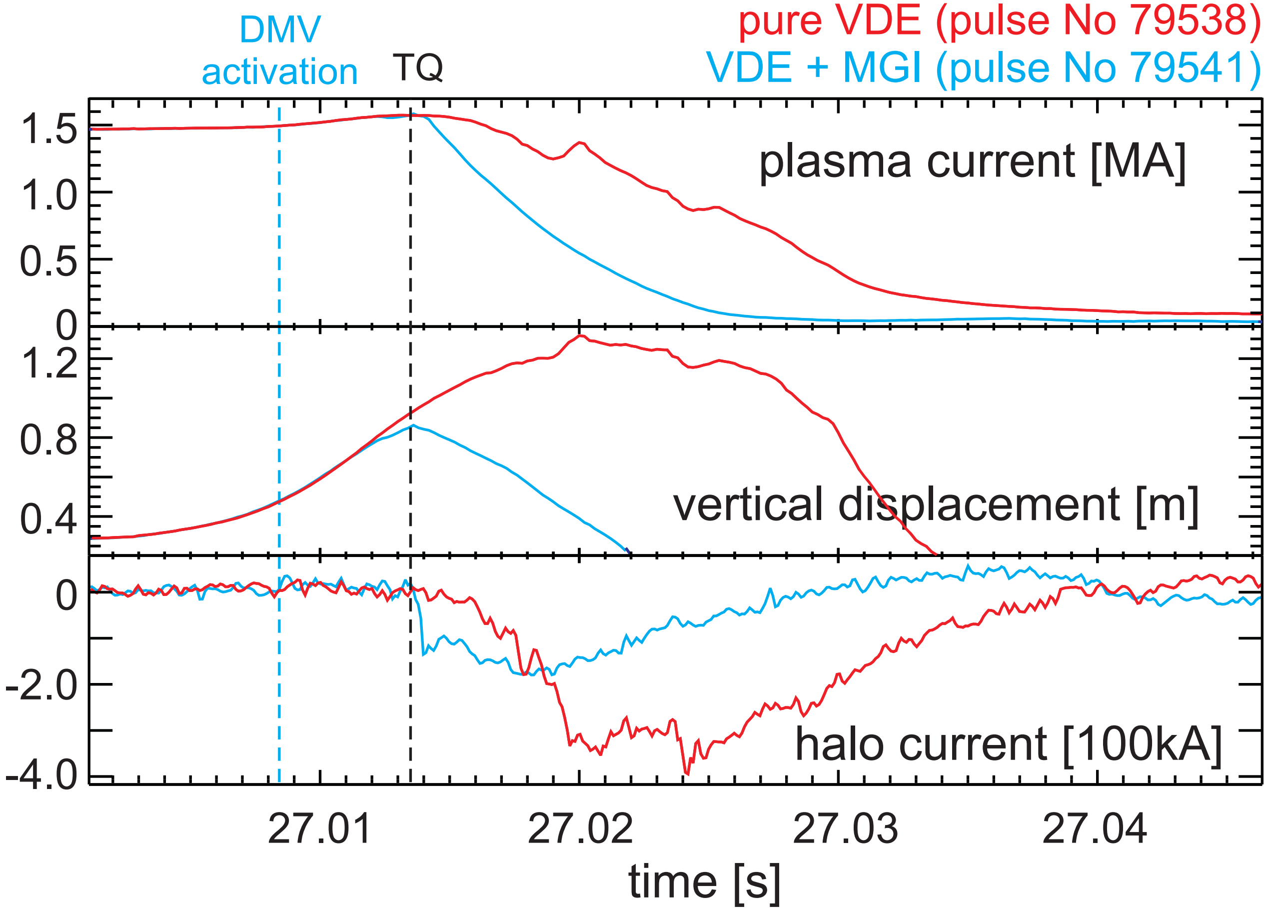
a) reduce thermal loads by increasing radiation ✓
b) reduce forces by controlling the current decay ✓
c) suppress runaways by densification ✗ (30% of n_{crit} in AUG)

ITER

species: He, Ne, Ar (to be defined)
injection of ~10^{23-24} atoms to mitigate heat loads and forces
injection of ~10^{25-26} atoms for suppression of runaways
timescale: < 10ms

Disruption Mitigation - Reduction of forces

JET: MGI into VDE



Reduction of

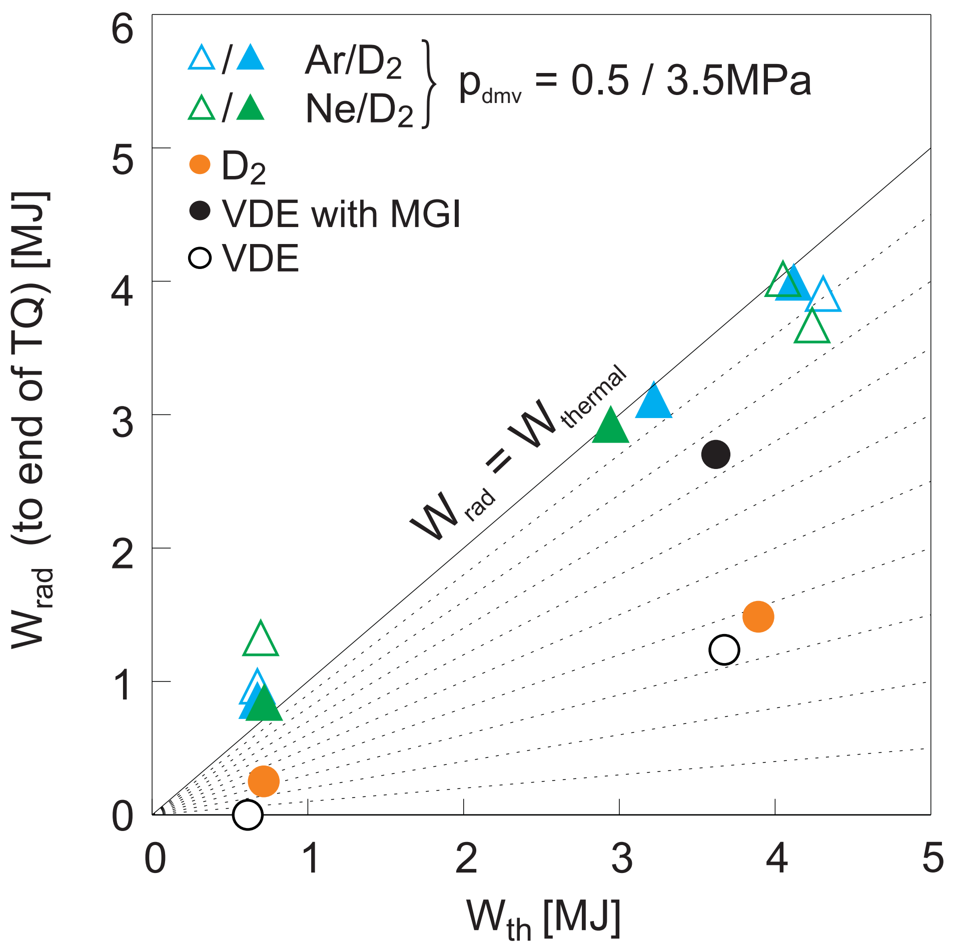
halo currents: factor 4
sideways forces: factor 10

t_{CQ} / S > 1.7 ms/m^2

corresponds to
t_{CQ} > 36ms for ITER (S=21m^2)

Disruption Mitigation - Reduction heat loads

JET: fraction of radiated thermal energy

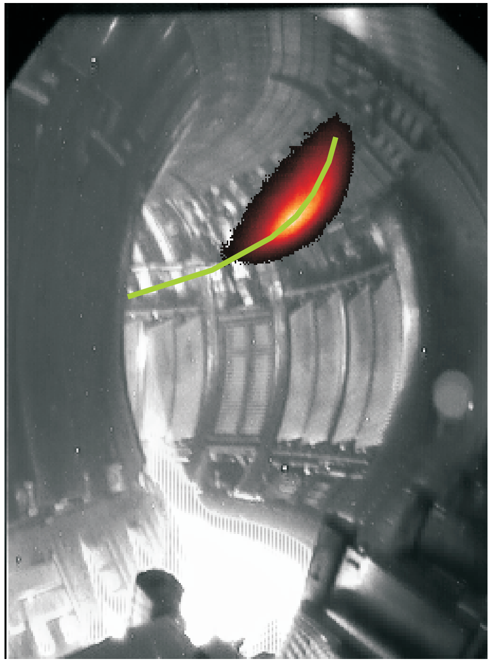


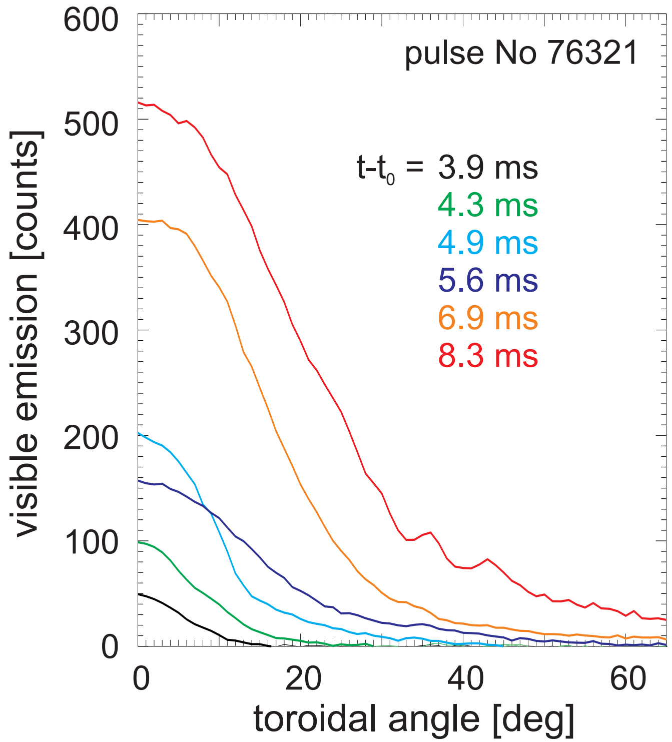
significant amount of $W_{thermal}$ is radiated

uncertainties because of diagnostic time resolution and smooth transition from thermal to current quench

Disruption Mitigation - Radiation heat load

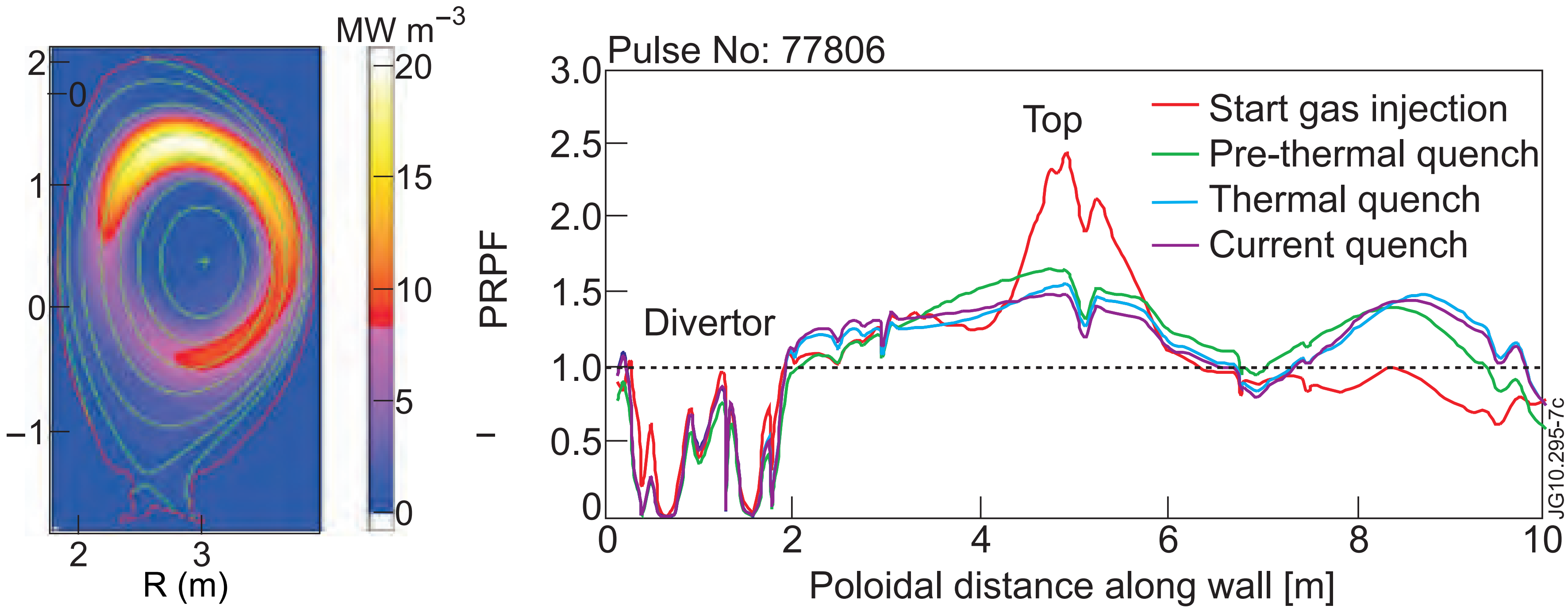
JET - toroidal peaking from visible: 5-7





Disruption Mitigation - Radiation heat load

JET - poloidal peaking from bolometry: 1.5-2.0



Disruption Mitigation - Radiation heat load

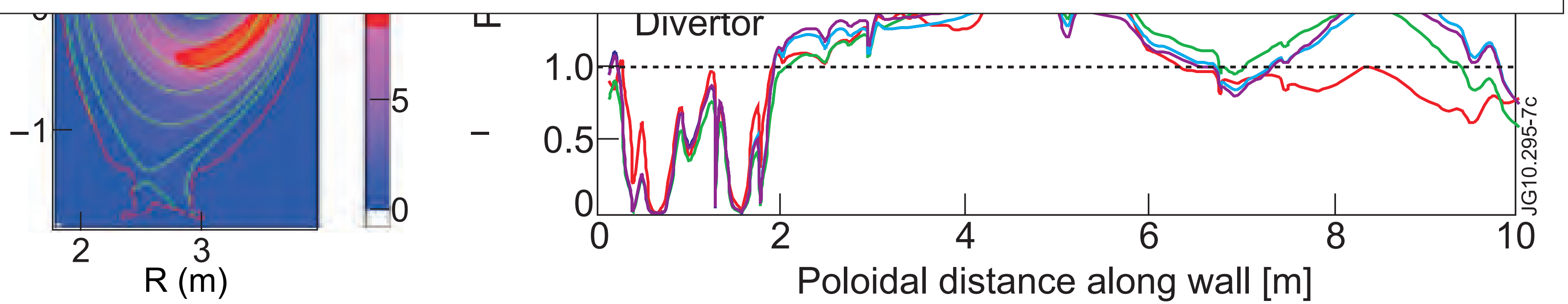
ITER *pre-TQ:* 180 MJ radiated in 7 ms ⇨ ΔT = 140° (3.1 $MJs^{-0.5}m^{-2}$)

TQ: 180 MJ radiated in 1-3 ms ⇨ ΔT = 210-360° (4.8-8.4 $MJs^{-0.5}m^{-2}$)

tolerable peaking: 5 (pre-TQ) / 1.8-3 (TQ) *(not combined)*

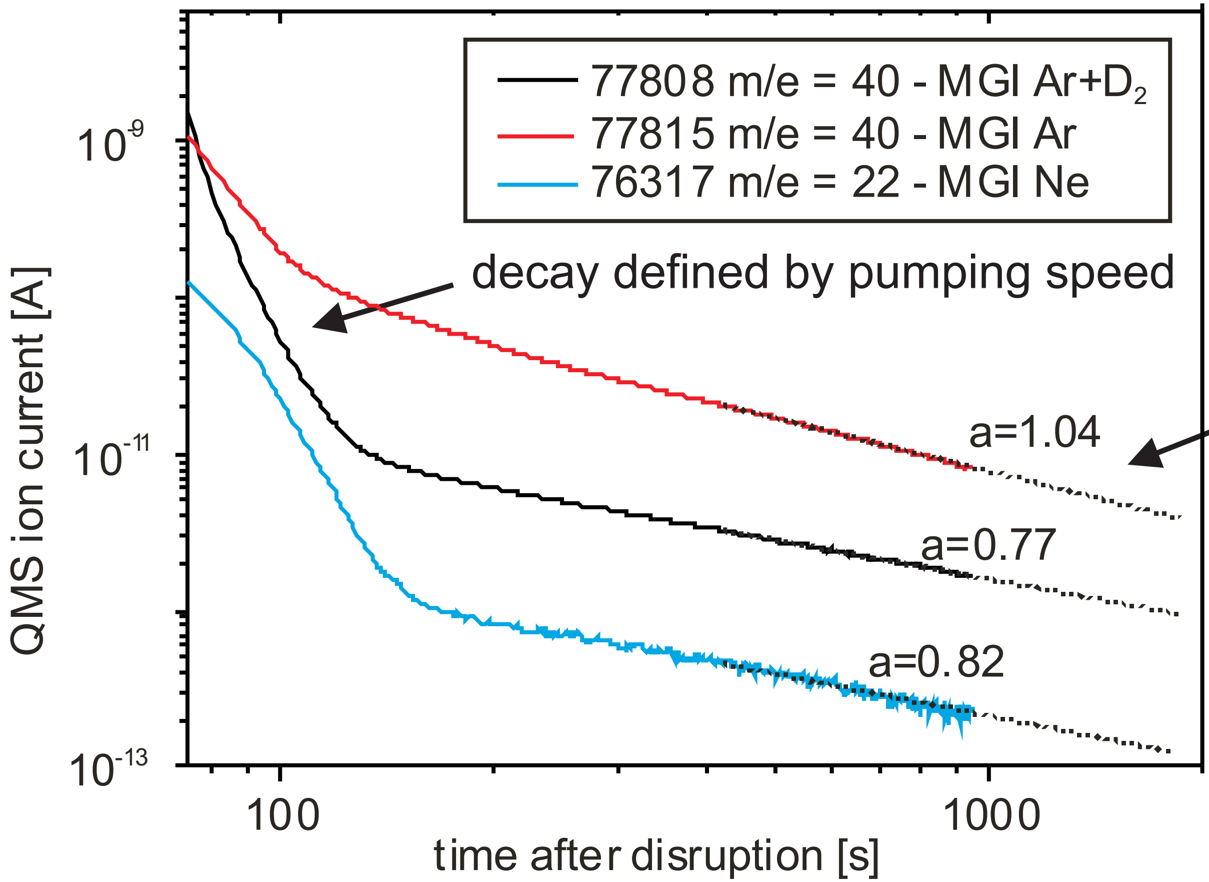
⇨ JET data suggests ~ 4 injection ports

(inter-machine is prepared within ITPA)



Disruption Mitigation - Impurity retention

Impurity neutral pressure after MGI in JET



Legacy effect observed

Wall cleaning / conditioning necessary after MGI

decay defined by wall release
$\sim (t-t_{disr})^{-a}$

U. Kruezi, JNM 2011

Summary and conclusions

- Energy is distributed in a complex manner to PFC
  - heat loads at remote areas / main chamber have to be expected
- Carbon and fuel release observed during disruptions - related to layers in the inner divertor
- Released impurities determine the radiation during the current quench insufficient radiation of magnetic energy leads to conductive loss
- Eddy and halo currents arising during the current quench cause high forces on components, margins to limits are small in ITER
- Runaway electrons constitute the most critical load because of strongly localised impact with deep penetration
- Massive gas injection can reduce loads (RE suppression challenging) Implies need for conditioning, high load on gas handling, can cause critical radiation heat loads

Disruptions in ITER will be a new class and will have significant impact on the lifetime and efficiency of components.

A reliable system for disruption detection, avoidance and - as a last resort - mitigation is indispensable for ITER.