ITER Disruption Issues

Michael Lehnen

Special thanks: K. Aleynikova, P. Aleynikov, Yu. Gasparyan[1], D. Kovalenko[2], R. A. Pitts, R. Roccella, P.C. de Vries

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Motivation


BRA 1-7 GER
90:58
90:00 +0:59 2'
BRAZIL
1 - 7
GERMANY
90' OSCAR
23' KLOSE
24' 26' KROOS
29' KHEDIRA
WISEUP
Itaú

Motivation

- ❑ **Design of the ITER Disruption Mitigation System**
  - Finding, validating and scaling of mitigation techniques
  - Final design review 2017

- ❑ **Preparation of ITER operation**
  - Disruption load validation / scaling
  - Disruption avoidance (prepare plasma control)
  - DMS commissioning and optimisation

- ❑ **Assessing risks during ITER operation**
  - Melt damage of plasma facing components
  - Dust generation
  - Avoiding critical EM loads

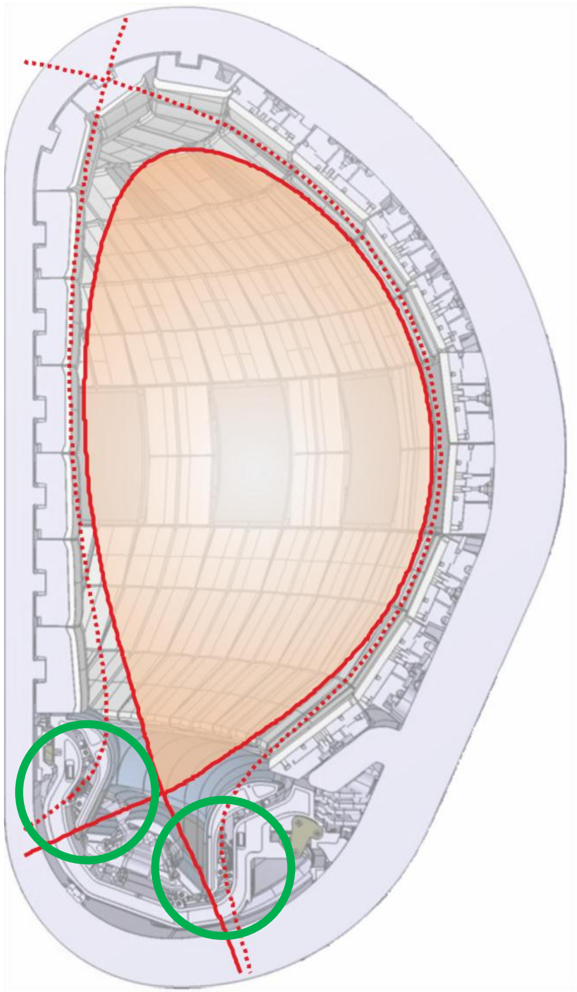
Outline

- Energy deposition during Thermal and Current Quench
- Energy deposition during Runaway impact
- Halo currents, Asymmetries, Rotation

- Disruption Prediction

- Thermal Load mitigation
- RE suppression / mitigation

Energy deposition during Thermal and Current Quench



Major Disruption - Divertor

L-mode 7.5 MA 30 MJ

5 - 80 $MJm^{-2}s^{-0.5}$

H-mode 15 MA 350 MJ

100 - 2000 $MJm^{-2}s^{-0.5}$

W melt limit: 50 $MJm^{-2}s^{-0.5}$

Assumptions

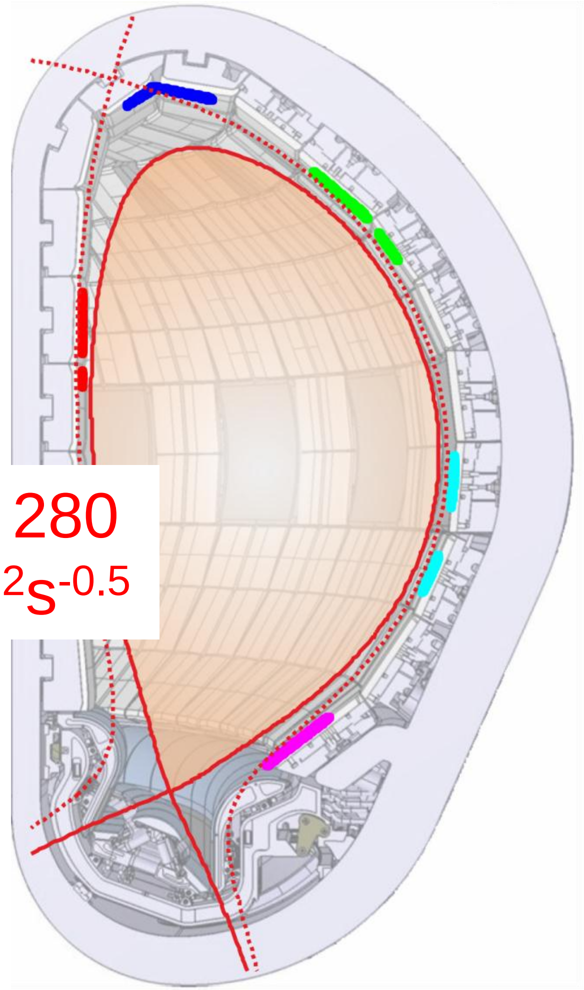
Footprint broadening:	*3-7*
Energy degradation:	*0-50%*
Divertor asymmetries:	*2:1 (in:out)*
Impact duration:	*1.5-3 ms*

R.A. Pitts, JNM 2013; S. Carpentier-Chouchana, Phys.Scr. 2014

Energy deposition during Thermal and Current Quench

$80 - 320\ MJm^{-2}s^{-0.5}$

PFCFLUX



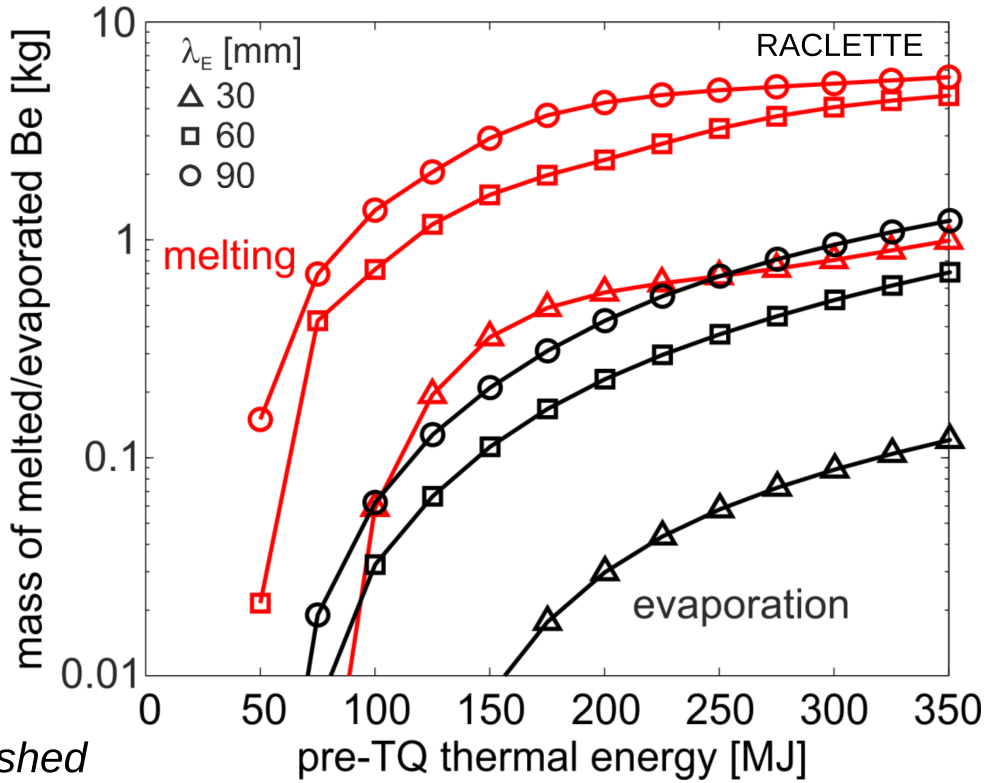
$130 - 280\ MJm^{-2}s^{-0.5}$

Major Disruption – First Wall

H-mode 15 MA 350 MJ

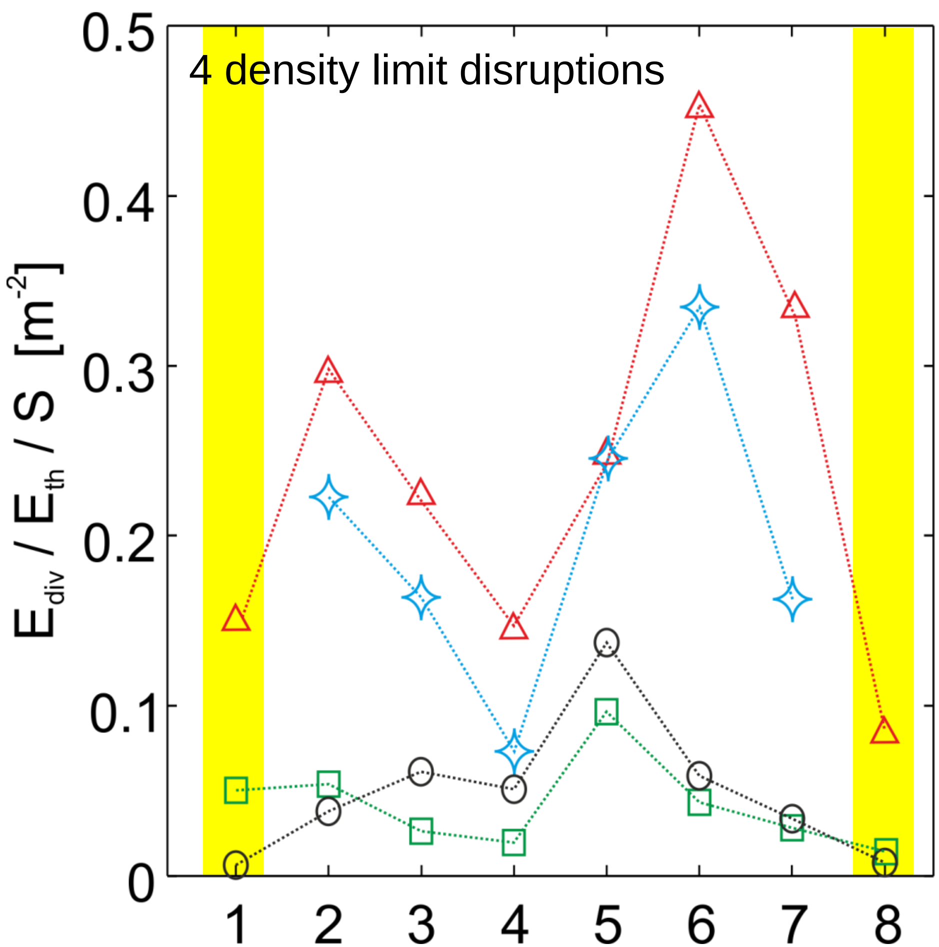
Be melt limit: 25 $MJm^{-2}s^{-0.5}$

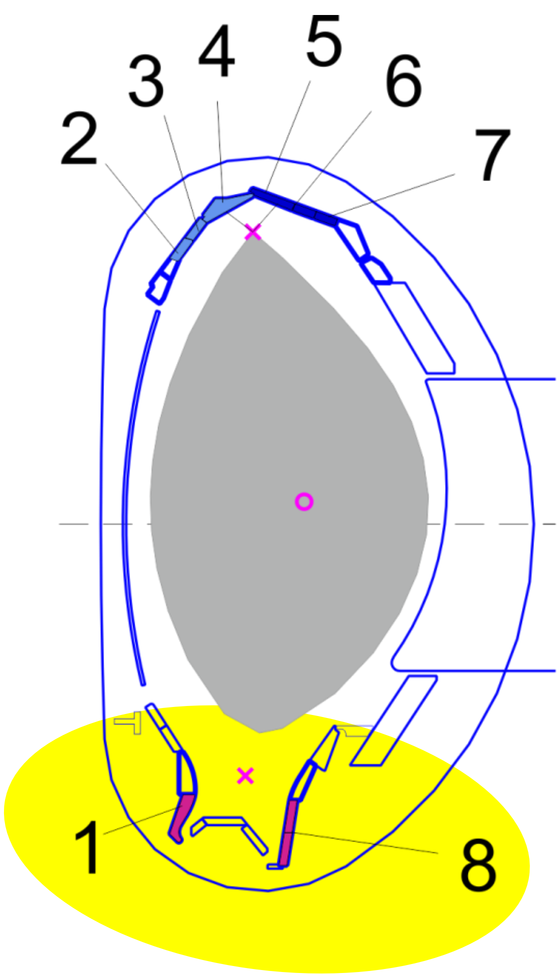
λ_E = 30 - 90 mm ➡ 5 - 23% E_{FW}/E_{th}



Yu. Gasparyan, D. Kovalenko, to be published

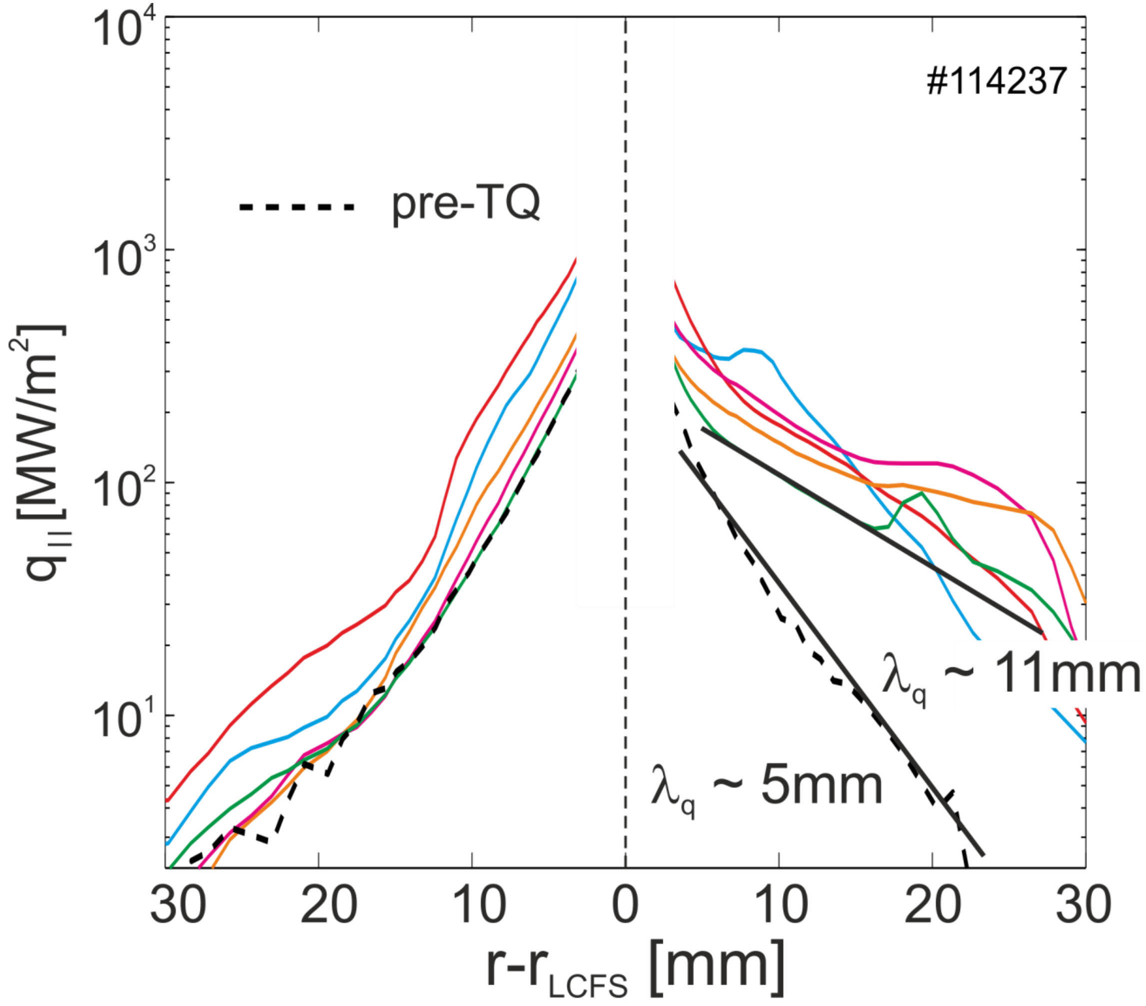
ASDEX Upgrade: broad heat flux distribution

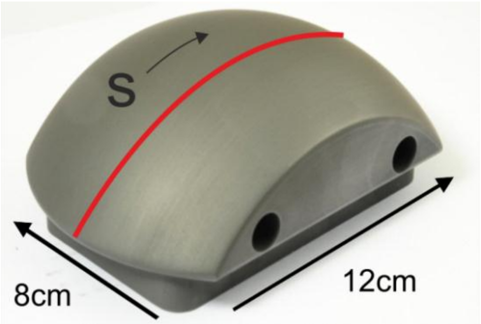




G. Pautasso et al., EPS 2003

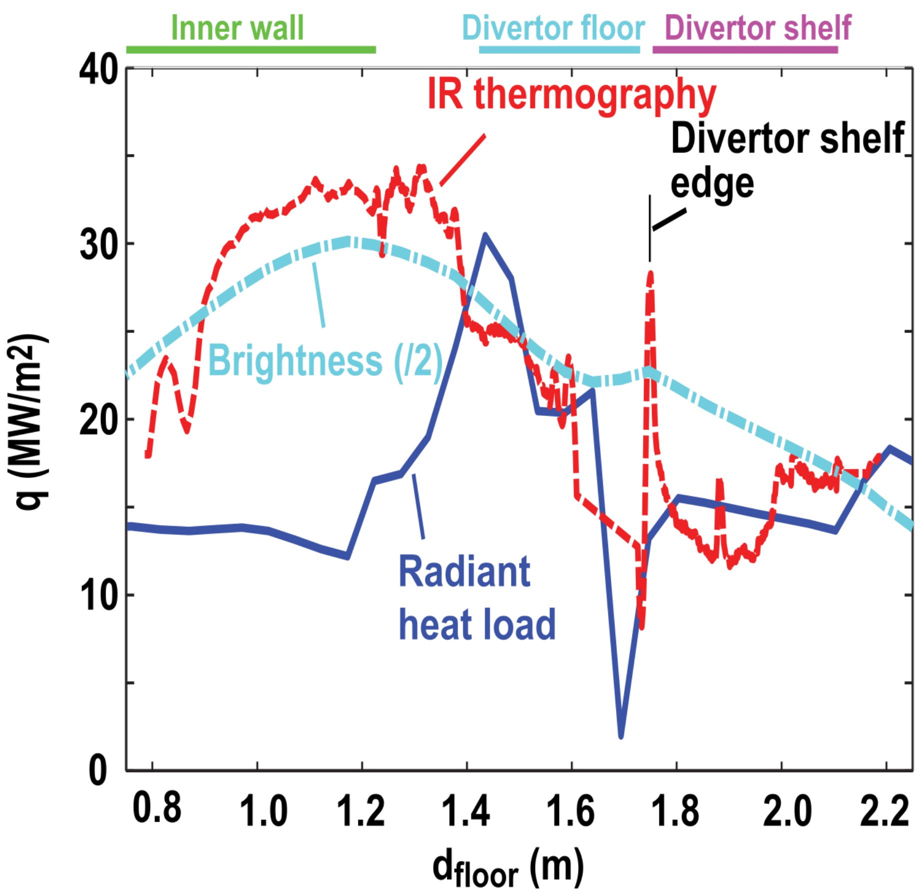
TEXTOR limiter: broadening reduced and asymmetric





N. Hartmann, PhD thesis in progress

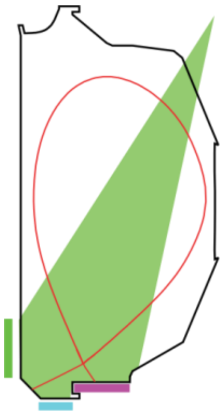
DIII-D: Divertor heat flux during VDE TQ



Broad heat flux profile

Conduction <u>and</u> Radiation

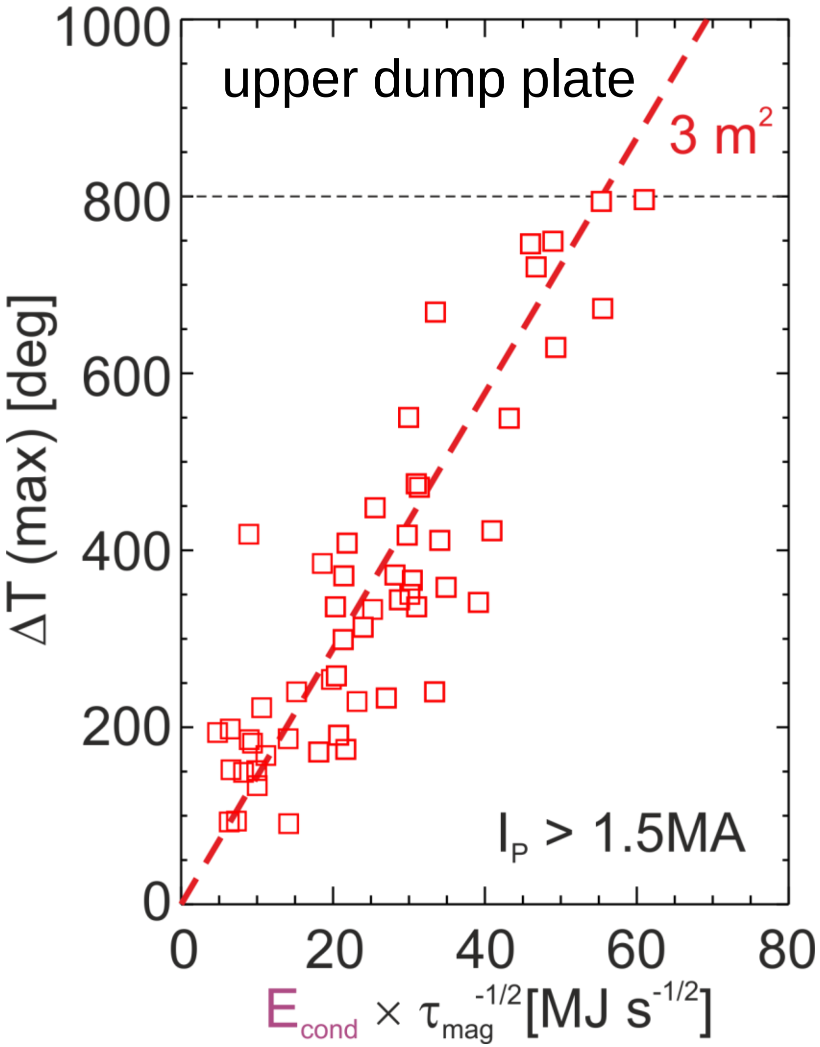
Plasma radiation in IR

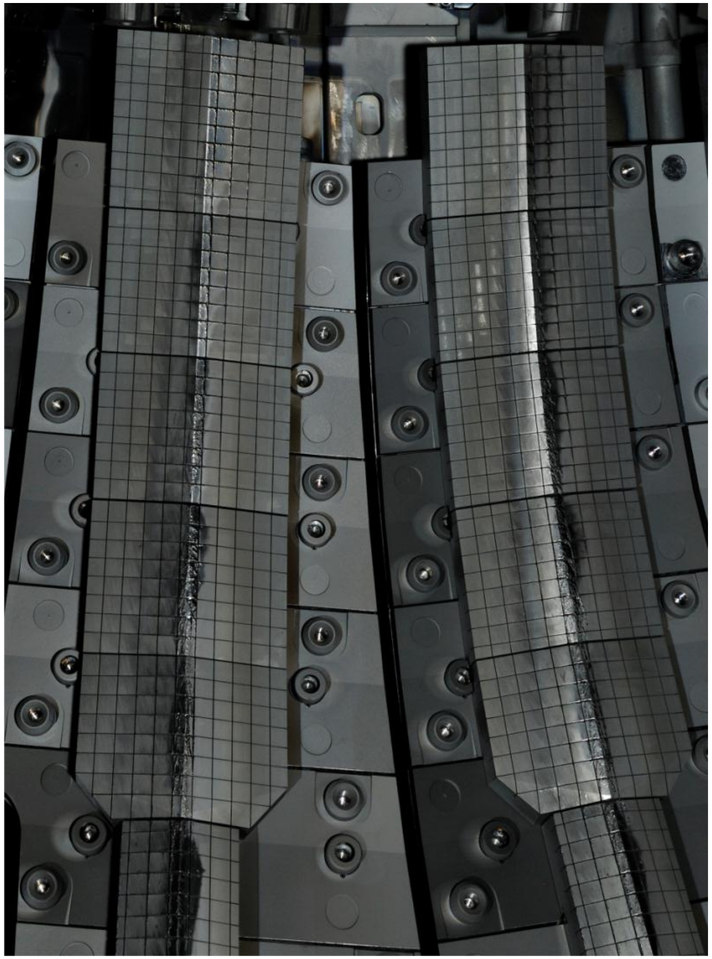


E.M. Hollmann et al., PoP 2013

Energy deposition during Thermal and Current Quench

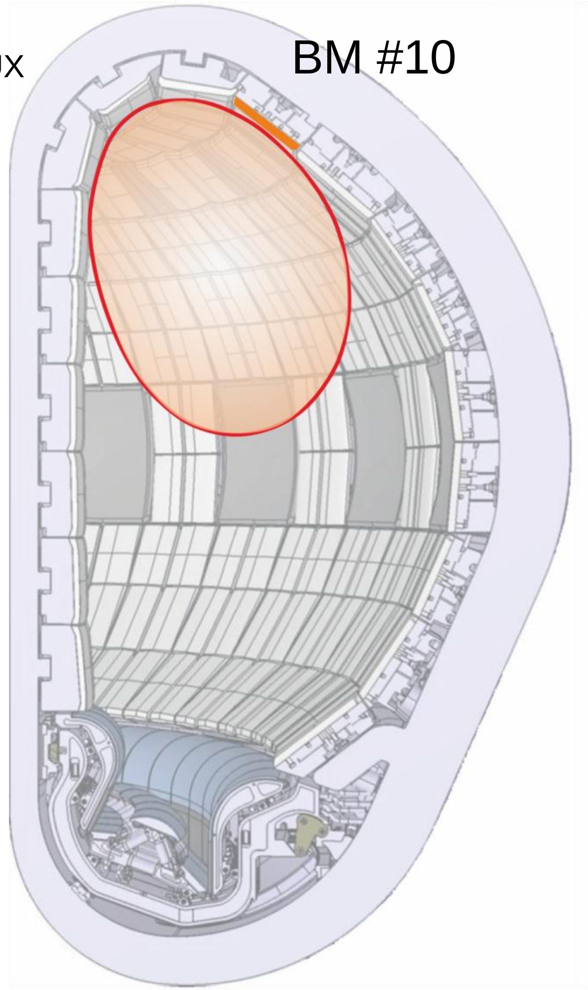
JET ITER-like wall: low radiation levels ➡ high conductive losses





M. Lehnen et al., NF 2013

Energy deposition during Thermal and Current Quench



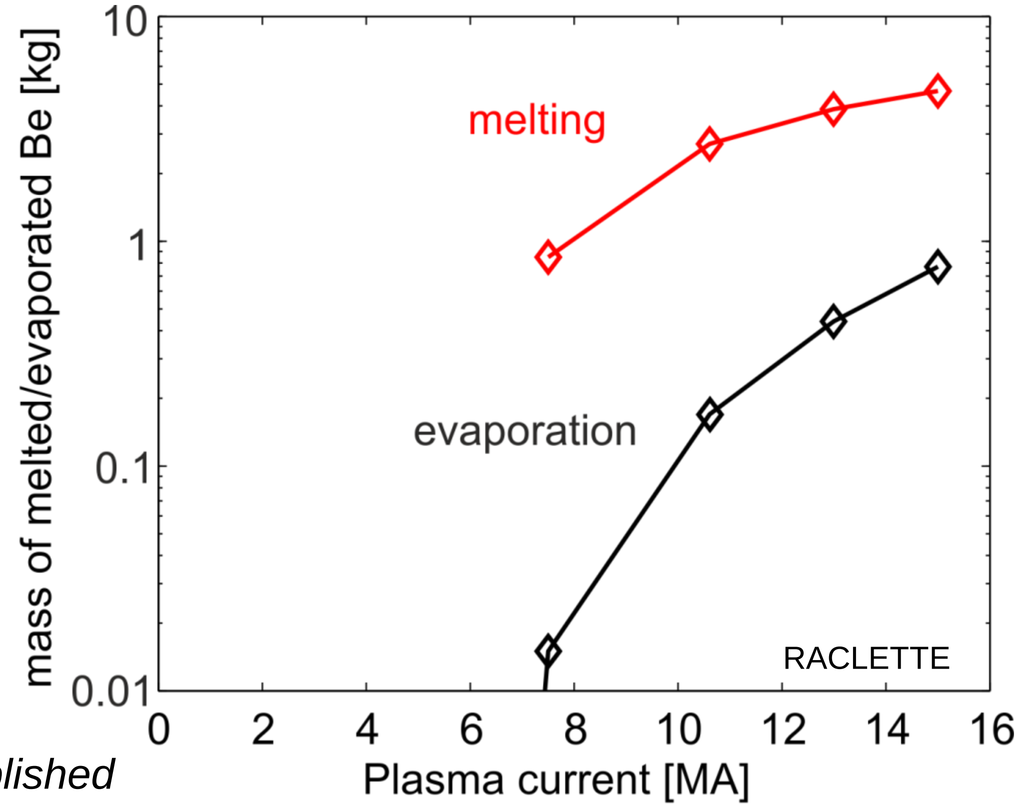
Current quench heat loads

Conductive loss of magnetic energy

E_{mag} = 400 MJ (15 MA, inside VV)

60 MJ on BM #10 in 70 ms

λ_E = 10mm (no broadening)

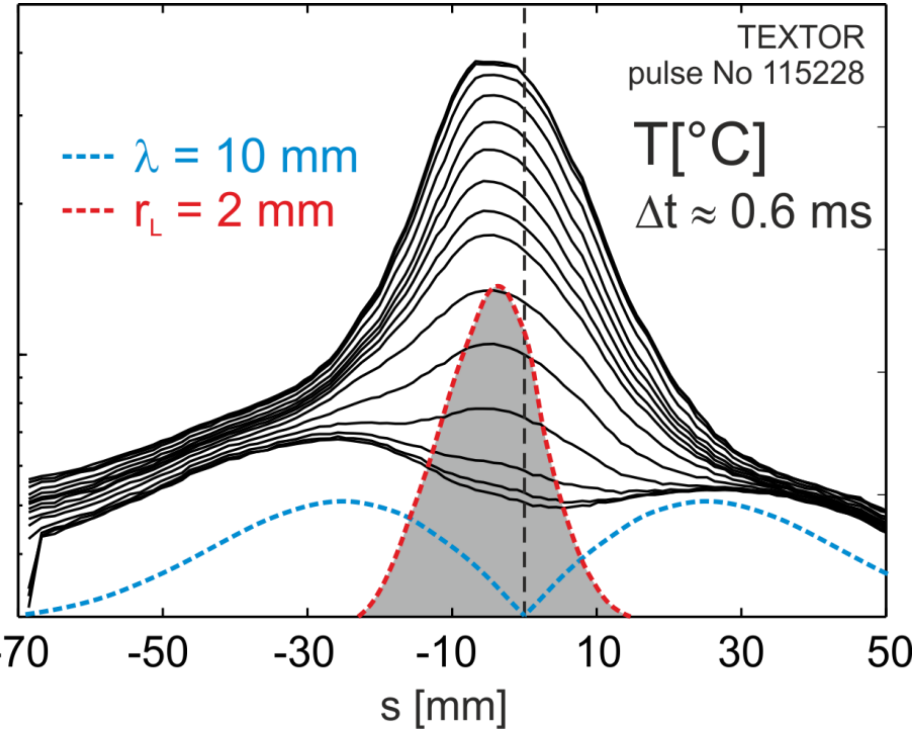


Yu. Gasparyan, D. Kovalenko, to be published

Energy deposition during Thermal and Current Quench

- Field line tracing with effective broadening is a simplified approach to assess heat loads / melt damage
- Validation or improvement by MHD codes and by experiments is needed
- Characterisation of current quench transport/radiation in unmitigated disruptions is needed

TEXTOR: Runaway impact on limiter



Radial deposition length

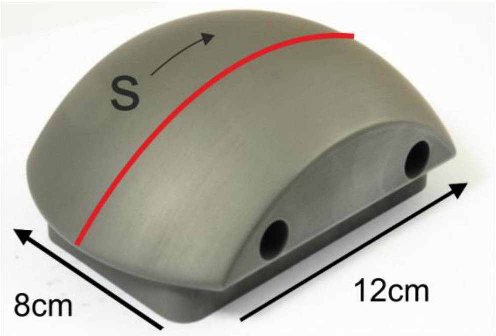
~ r_L

Poloidal extent (JET/ITER)

~ 100 mm

ITER melt depth*

30 MJ ➡ 8 mm

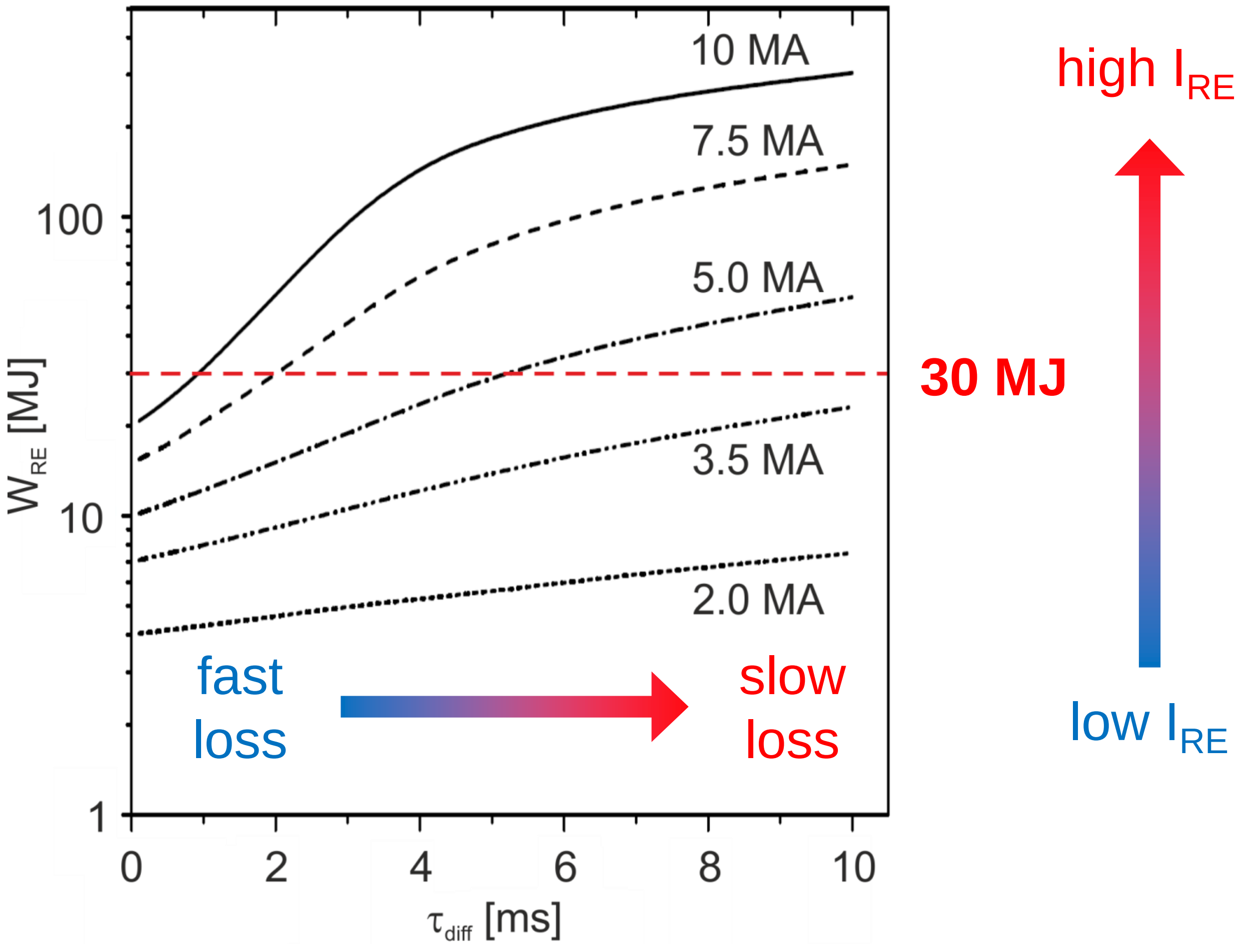


*purely geometry

M. Lehnen, N. Hartmann, ITPA MHD meeting March, 2011

Energy deposition during Runaway impact

Total impact energy of runaway electrons

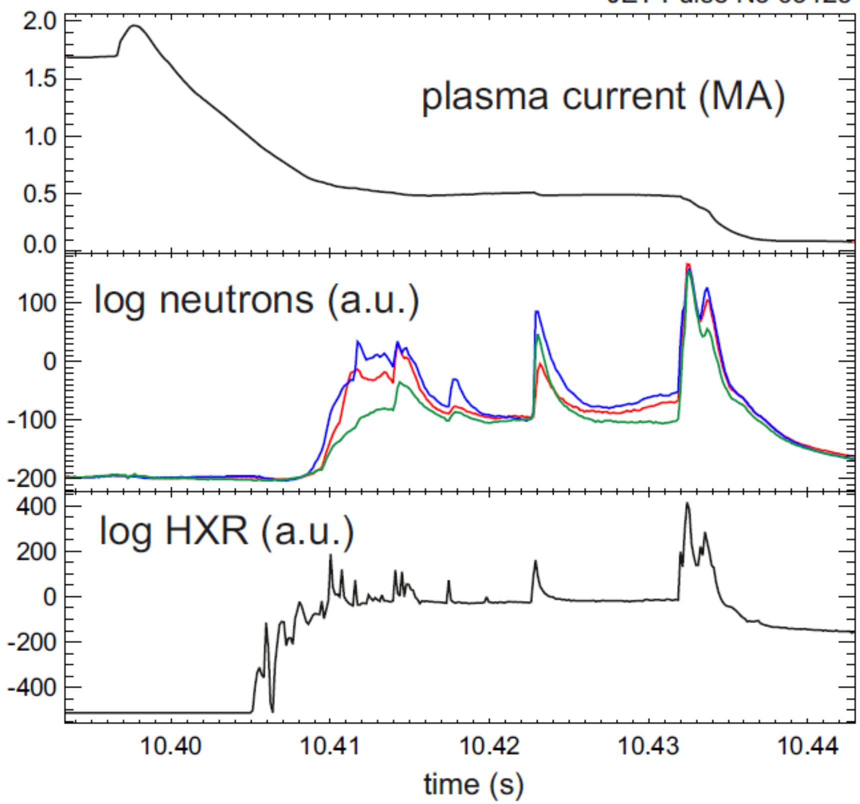


J.R. Martín-Solís, accepted for publication in NF 2014; A. Loarte, NF 2011

Energy deposition during Runaway impact

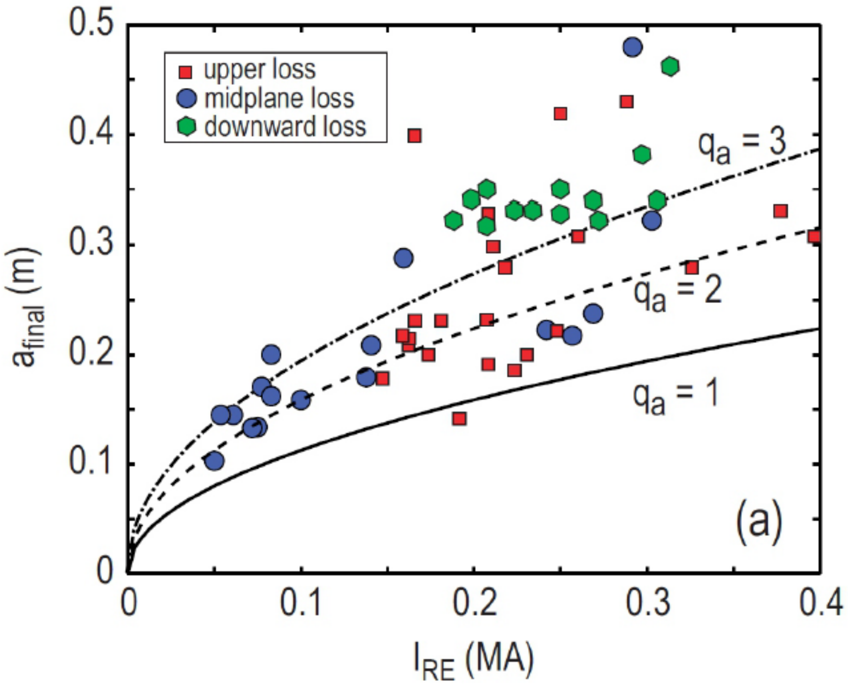
The causes and dynamical processes of runaway loss are not fully understood yet

JET: RE loss can occur with significant separation in time



MHD causing final loss?!

DIII-D: suggesting kink instability but large scatter



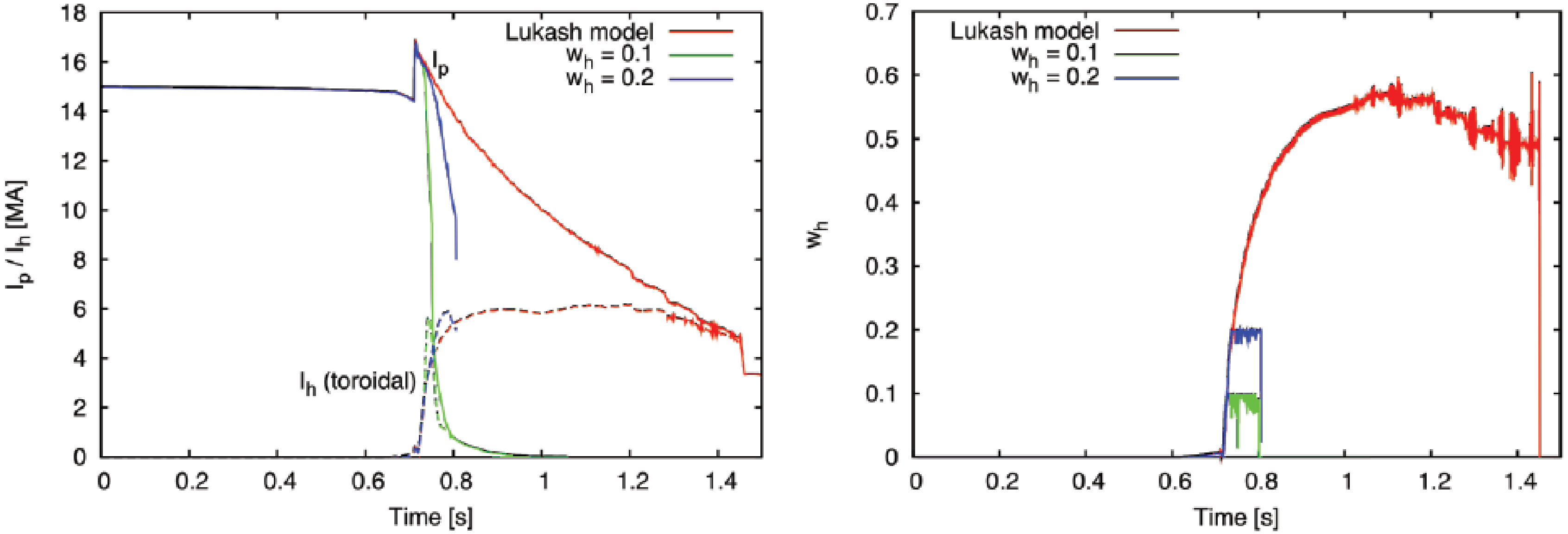
E. Hollmann et al., NF 2013

Energy deposition during Runaway impact

- Further understanding of runaway loss instabilities
  - Timescales?
  - Asymmetries?
- Quantitative description of energy deposition and material melting/loss
  - Impact energy?
  - Footprint?
- Simulations including RE and equilibrium solver

Halo currents, Asymmetries, Rotation

DINA simulations



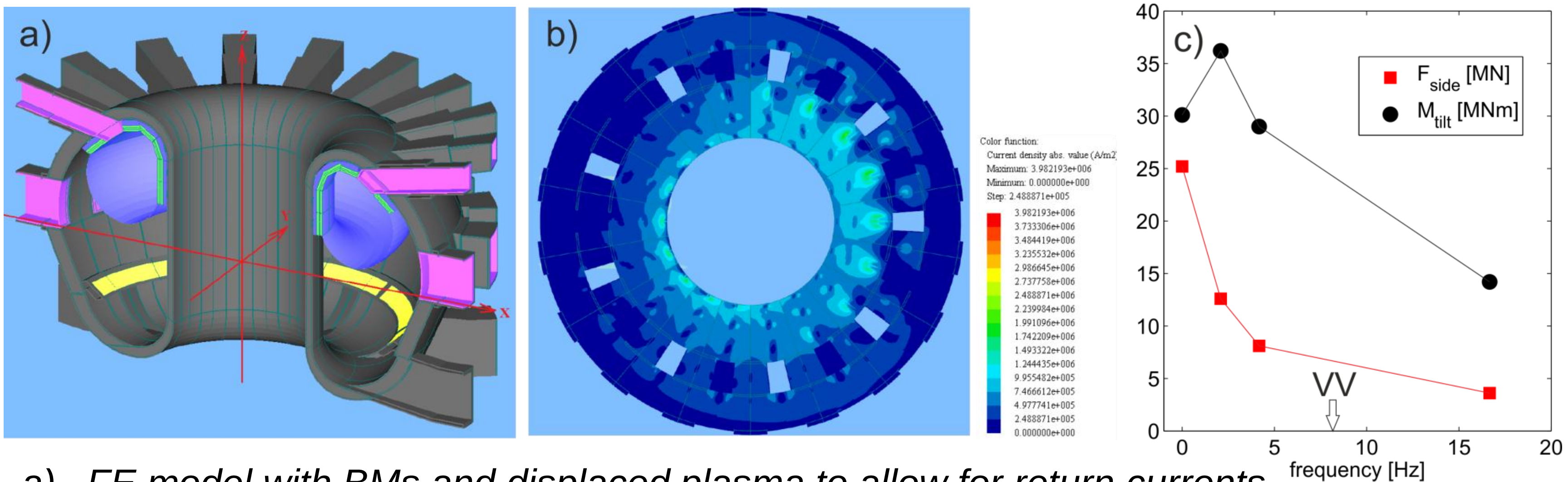
I. Bandyopadhyay, ITPA MHD meeting, October 2013

- Choosing different halo widths has significant impact on the results of current quench simulations
- Self-consistent description of the halo parameters is needed

➡ *ITPA MHD task launched 2013*

Sink & source model to assess VV forces caused by current asymmetries on VV forces

Halo current distribution and waveform is prescribed using DINA 2D output, no self-consistent description

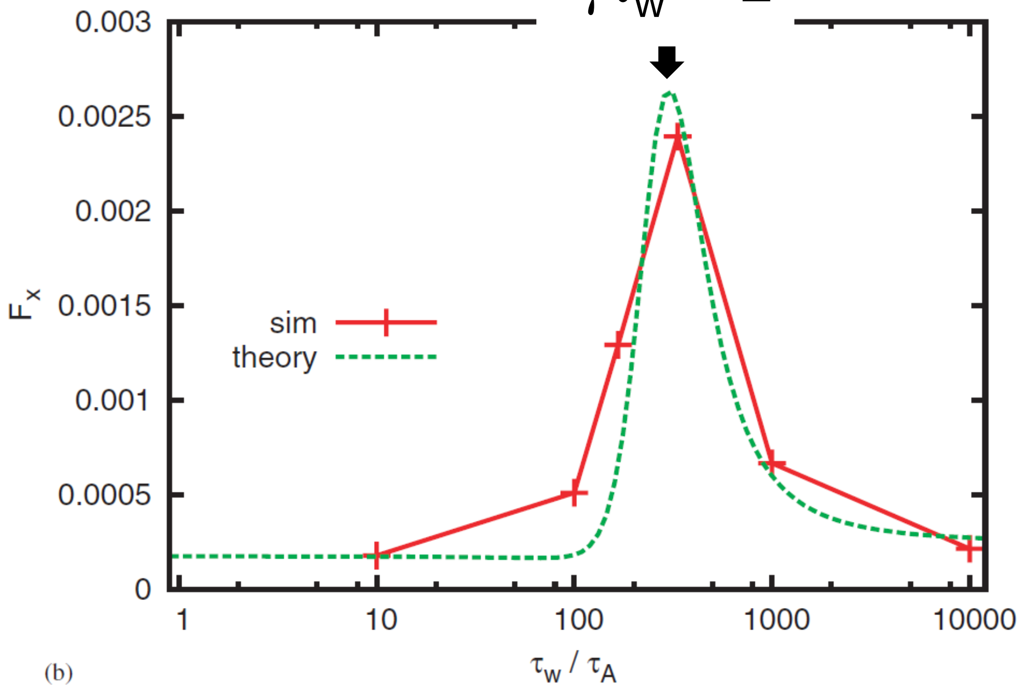


a) *FE model with BMs and displaced plasma to allow for return currents*
b) *Current distribution on the inner VV shell at 2Hz*
c) *Sideways force and tilting moment on VV+BM versus frequency*

Variable current distribution ⇨ talk by Riccardo Roccella

Impact of τ_w on asymmetries?

$\gamma\tau_w = 1$



JET: $\gamma\tau_w \approx O(10)$
ITER: $\gamma\tau_w \approx O(1000)$

H. Strauss et al., NF 2013

Halo currents, Asymmetries, Rotation

- ❑ Self-consistent description of the halo region
- ❑ What drives rotation?
- ❑ What is the mode structure (existence of zonal flows?) and what is the link between poloidal and toroidal halo currents?
- ❑ What determines the amplitude and is there a correlation between amplitude and frequency?
- ❑ Impact of plasma-wall coupling?

Qualitative understanding: *3D MHD simulations*
Experimental validation: *ITPA task led by Stefan Gerhardt*

Disruption Prediction

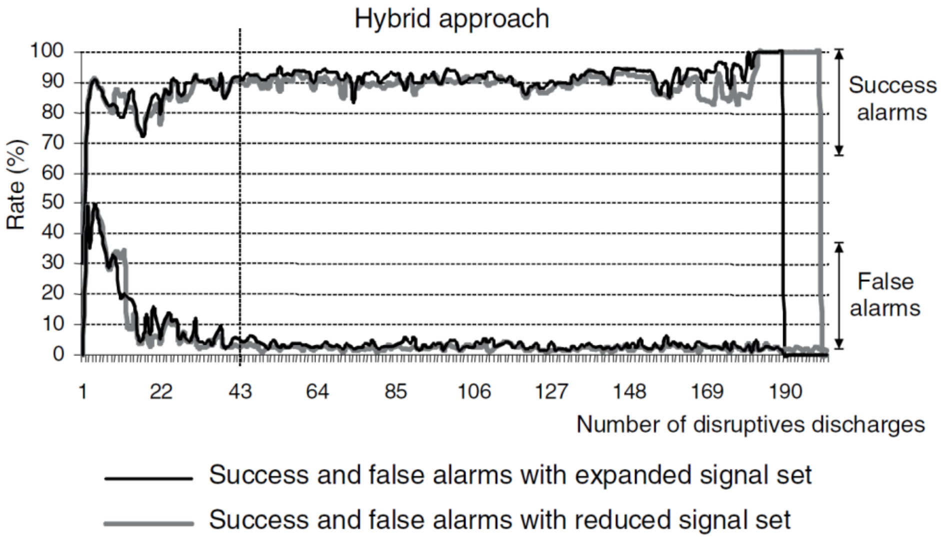
Neural networks and derivatives

- needs disruptions for training
- gives warning times, disruption classification to be developed
- extrapolation to new parameter range can lead to performance degradation

Single/Multi threshold detection

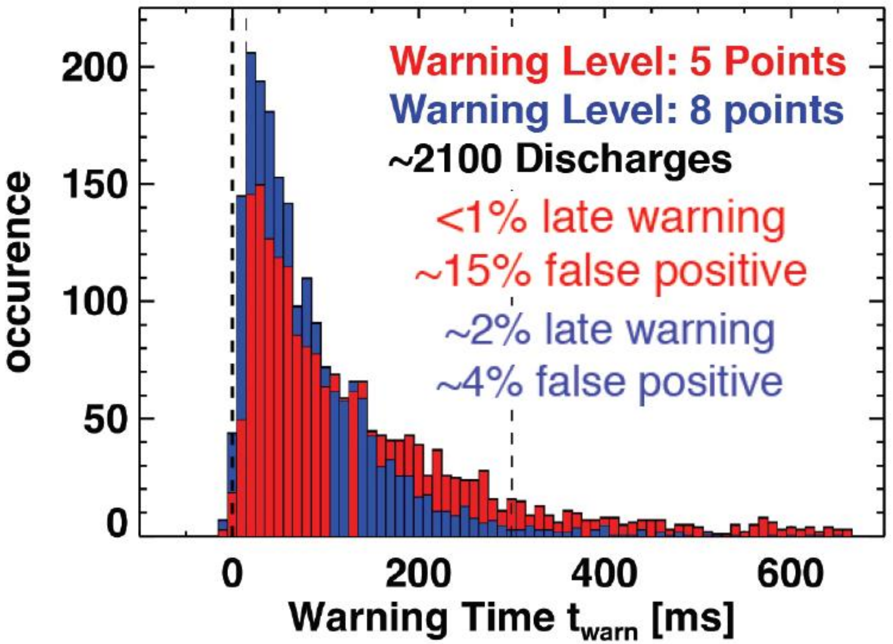
- "Manual" thresholds and logical combinations based on extrapolation and modelling
- JET: successful with mode lock detection
- NSTX: compound threshold tests needed

JET: SVM trained from scratch



*S. Dormido-Canto, NF **53** (2013) 113001*

NSTX: compound threshold tests

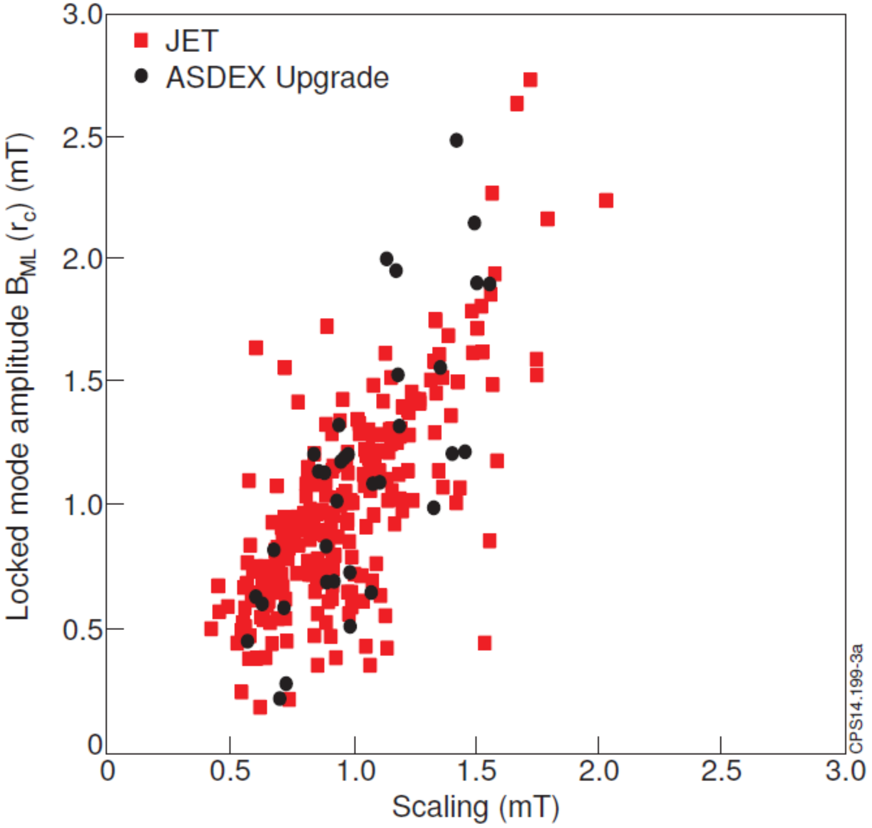


S. Gerhardt, IAEA 2012, San Diego

Parameters for threshold test

Threshold amplitude for TQ onset

P. De Vries, EPS 2014



- Scaling points to critical island size for TQ onset
- What drives the TQ onset?
- What is the growth time and therefore the reaction time?

$$B_{ML}(r_c) = 7.35\ I_p^{1.10\pm0.06} \cdot q_{95}^{-0.97\pm0.07} \cdot li(3)^{+1.35\pm0.06} \cdot \rho_c^{-3.00\pm0.14}$$

Disruption Prediction

- Transparent and physics based approach providing warning time and disruption classification to allow appropriate action (prevention/mitigation)
- Identify disruption root causes and the evolution towards the quench
- Identify suitable parameters and establish a quantitative understanding in order to scale to ITER

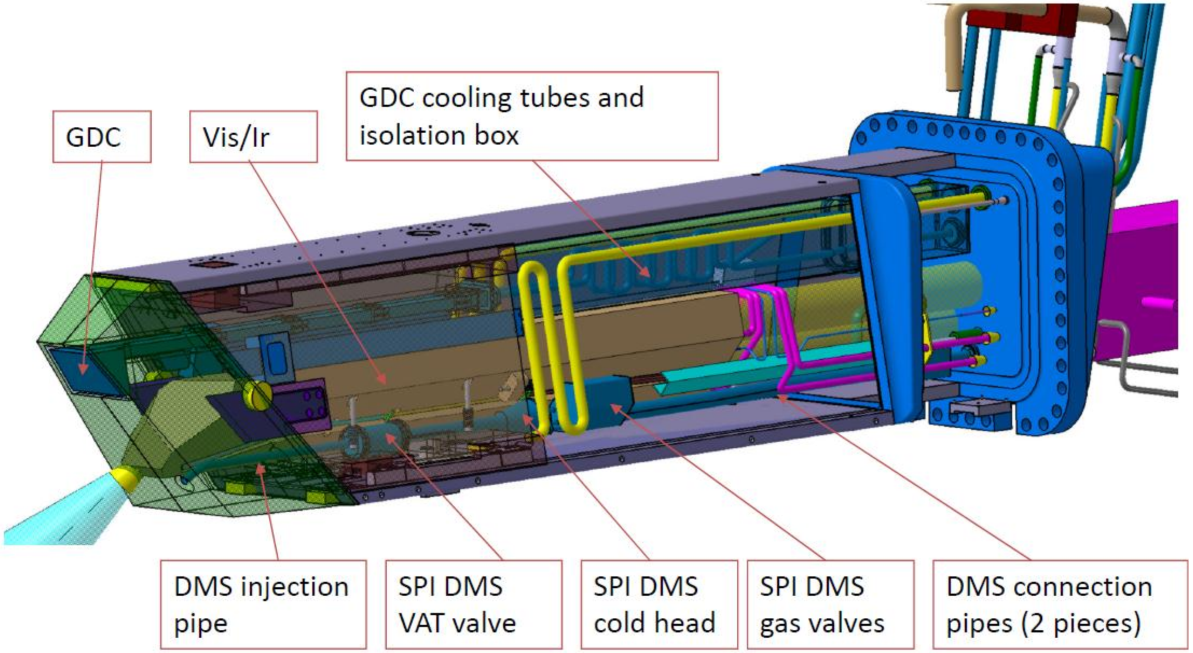
ITPA MHD task led by Gabriella Pautasso

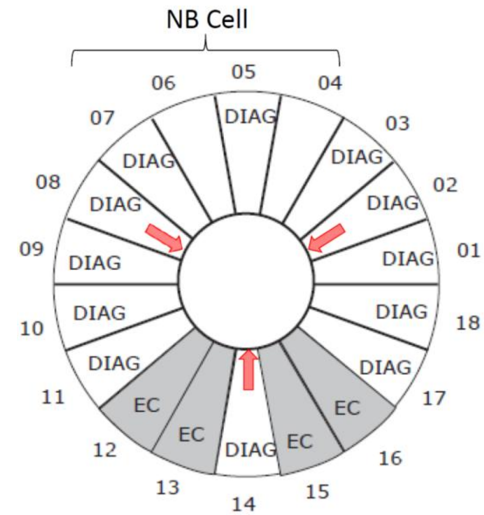
Thermal Load mitigation

Thermal Load Mitigation *(UP&EP)*
He, Ne, Ar, H_2/D_2
up to 8kPam^3 (1.8x10^{24} particles)

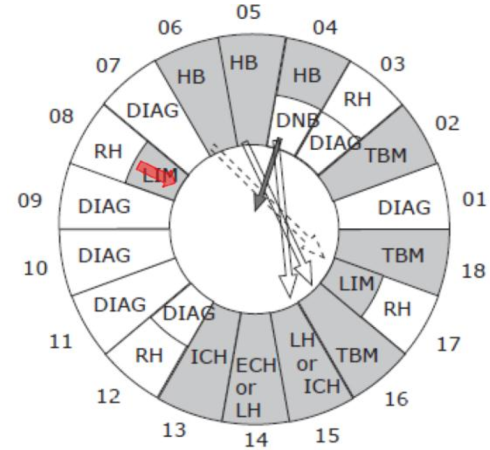
Runaway Mitigation *(EP)*
up to 100kPam^3 (2.2x10^{25} particles)

Candidate systems:
Shattered Pellet Injection / Massive Gas Injection



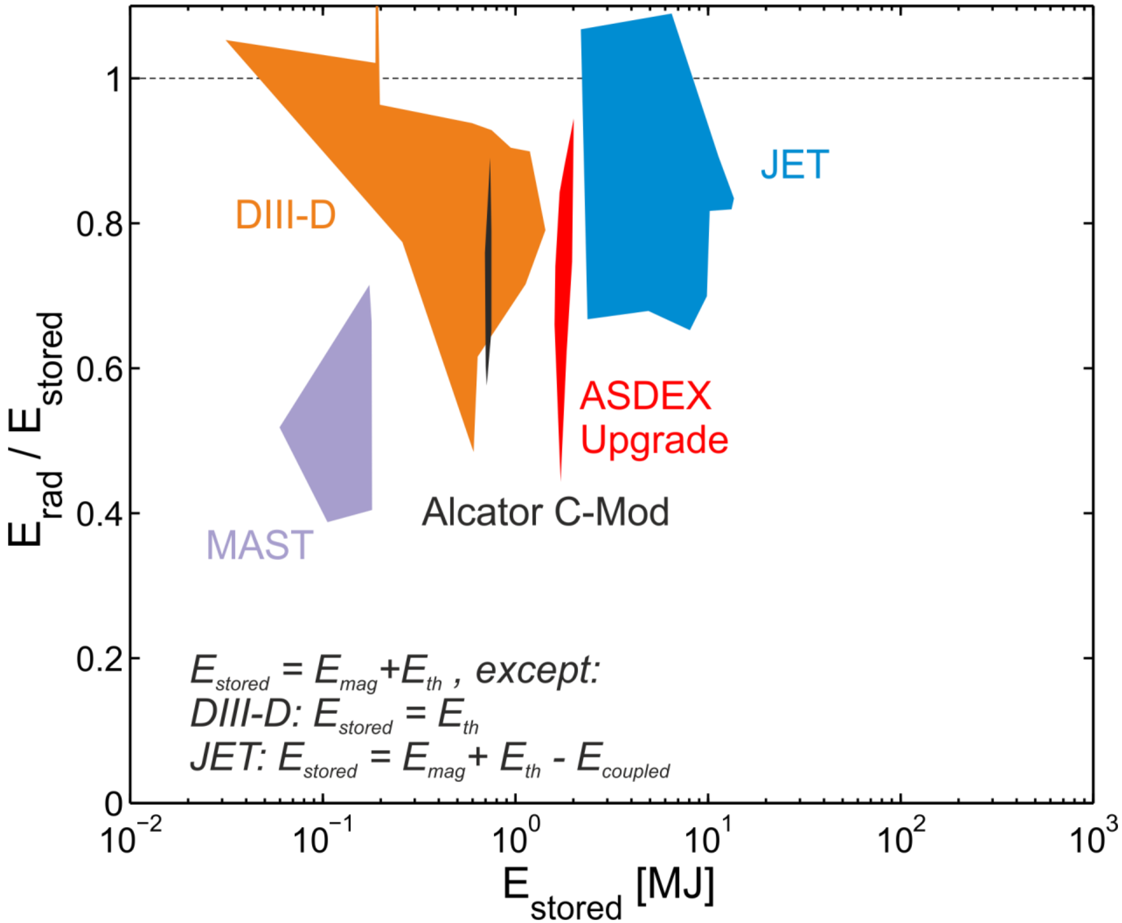


Upper port
#02, 08 and 14



Equatorial port
#08

Radiated energy / stored energy
(data envelopes*)



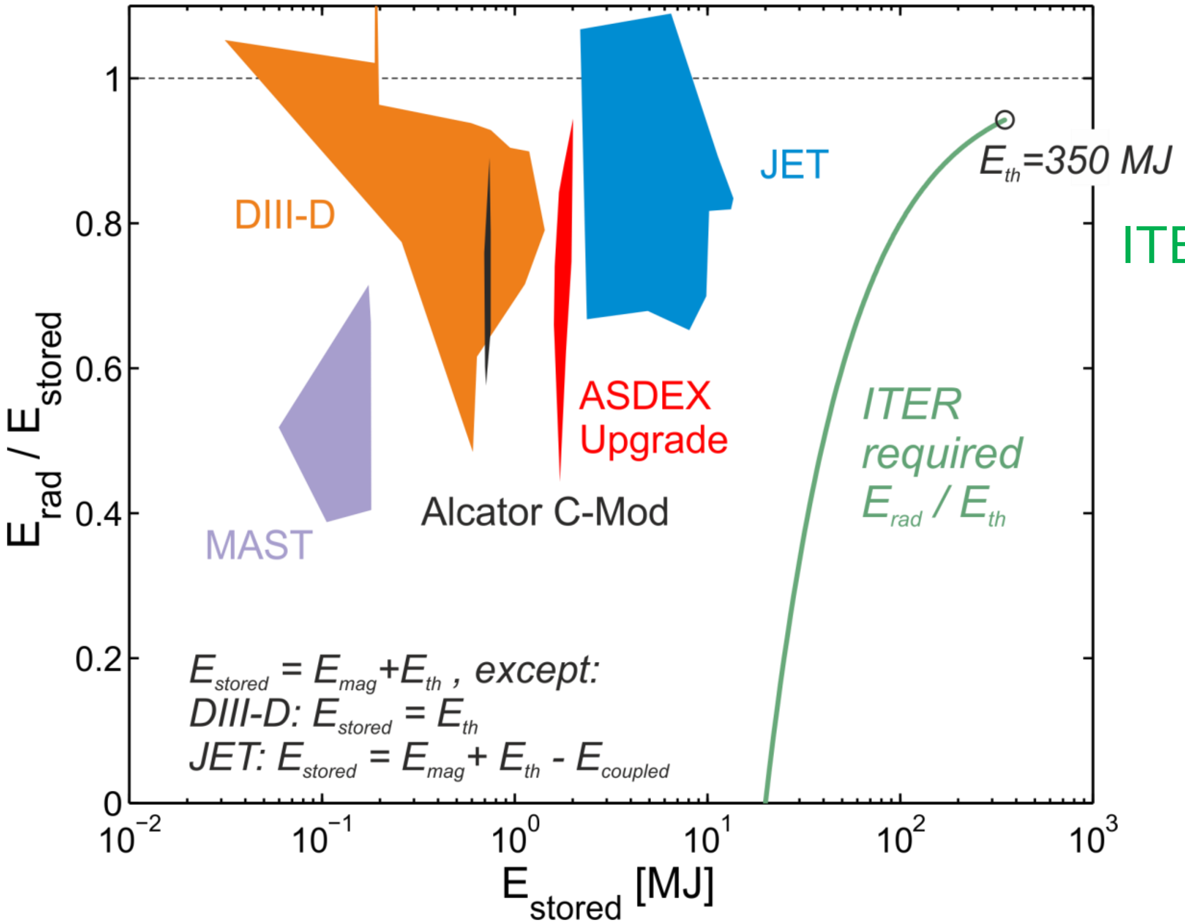
Data spread:

- Different gases and quantities
- Energy dissipated in structure
- Radiation Asymmetries
- Time resolution

Role of macroscopic MHD?

** See PSI paper for references*

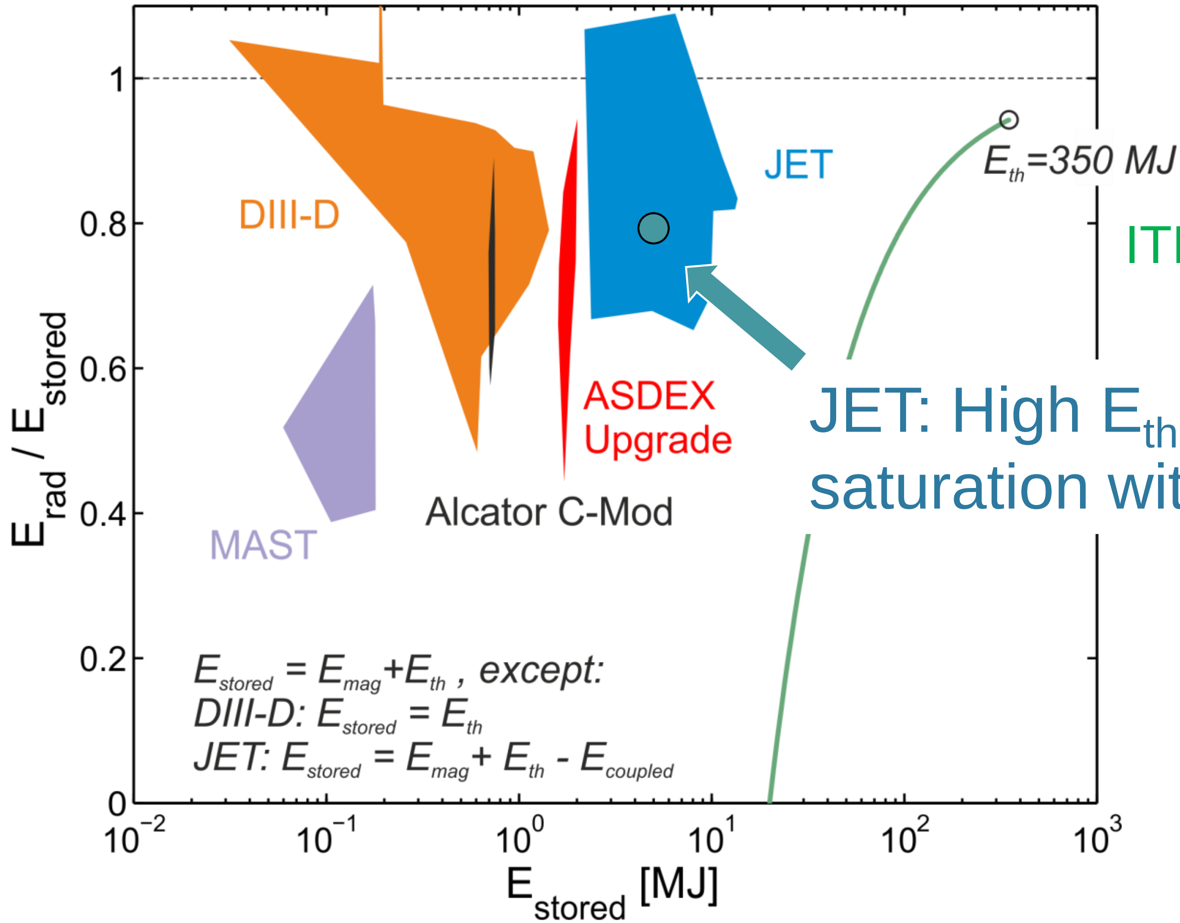
Radiated energy / stored energy
(data envelopes*)



ITER ultimately requires > 90%

** See PSI paper for references*

Radiated energy / stored energy
(data envelopes*)



JET: High E_{th} shows saturation with N_{inj} (Ar)

ITER ultimately requires > 90%

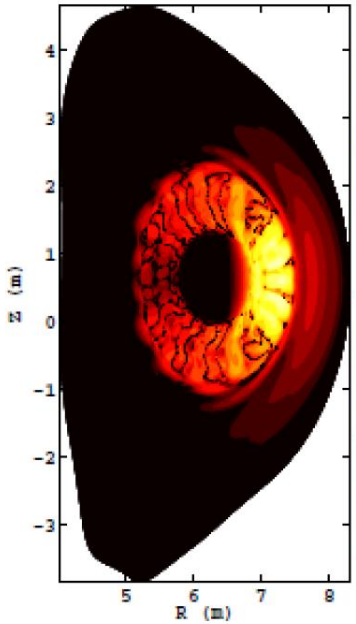
** See PSI paper for references*

Thermal Load mitigation

NIMROD simulations (preliminary results)

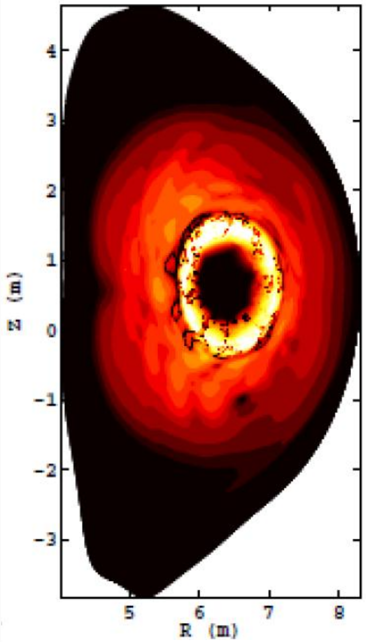
V. Izzo et al., ITER TA C19TD48FU

1 midplane jet, 0.5 $kPam^3$



- dominant n=1
- TPF ≈ 2
- high poloidal peaking
- $E_{rad}/E_{th} \approx 25\%$

1 midplane jet, 2.0 $kPam^3$



- dominant high n
- TPF ≈ 1.3
- low poloidal peaking
- $E_{rad}/E_{th} > 90\%$

Thermal Load mitigation

Radiation peaking is caused by

Localised injection

⬍ **TQ**

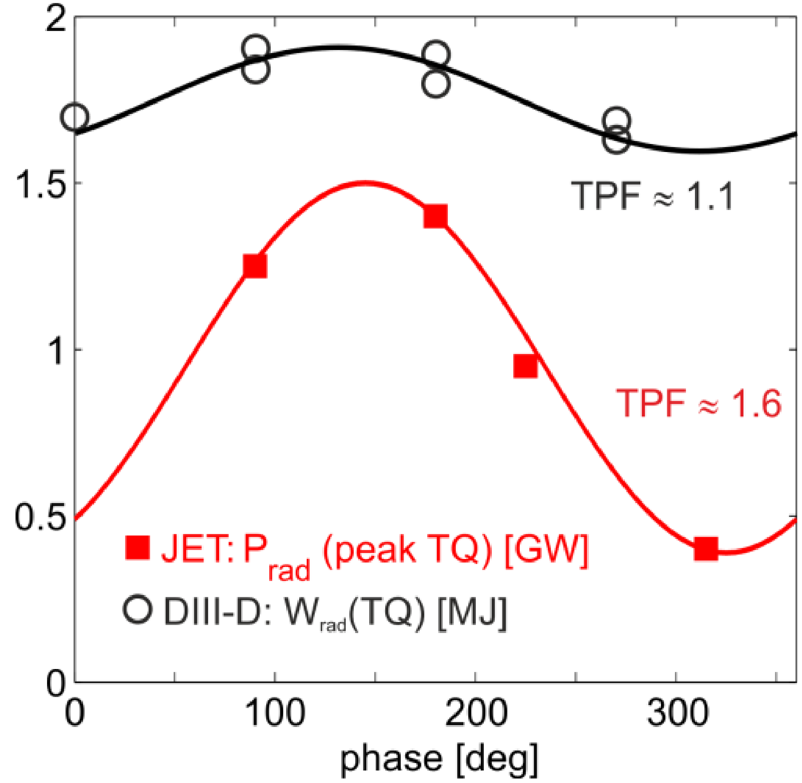
MHD activity

Critical heat flux peaking:

$\langle TPF \rangle \times \langle PPF \rangle \leq 360 MJ/E_{th}$ (SS)
$720 MJ/E_{th}$ (Be)

MHD Dynamics can reduce peaking / radiation heat load

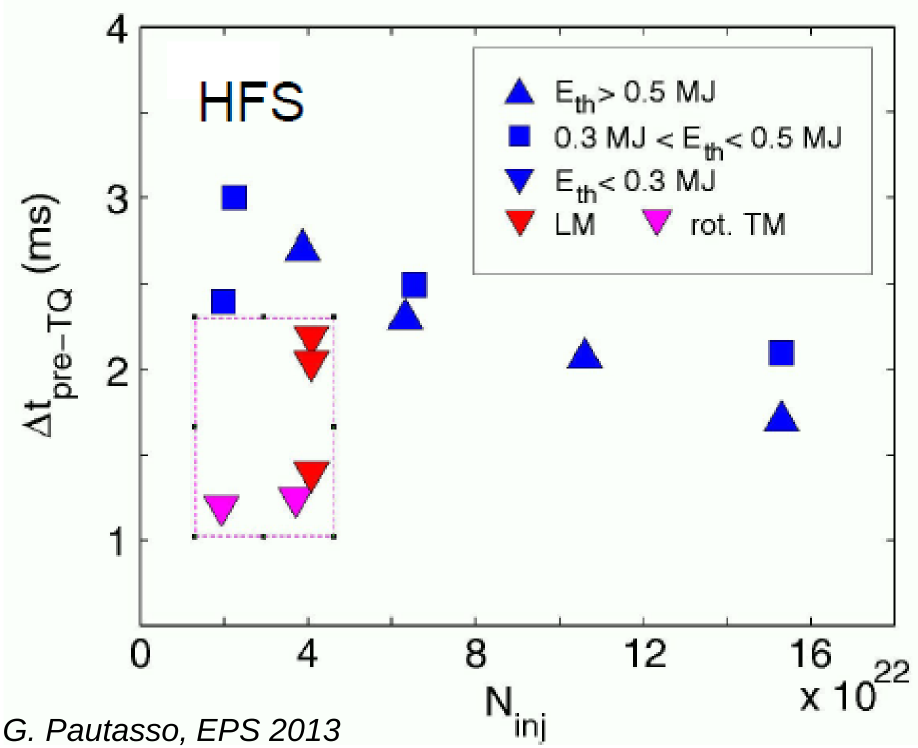
JET / DIII-D: toroidal radiation distribution with locked phase



DIII-D: N. Commaux and N. Eidietis, APS 2013
JET: H.R. Koslowski, to be published

Thermal Load mitigation

- Mitigation is the last resort when a plasma becomes unstable
- Most MGI experiments have been done with well-defined, healthy plasmas
- The database has to be extended to “unhealthy” plasmas as their properties can significantly impact on the mitigation efficiency
- Modelling of the impact on thermal/EM/RE load mitigation is required



G. Pautasso, EPS 2013

ASDEX-Upgrade
- pre-existing TMs tend to decrease pre-TQ duration
- this can reduce fuelling and mitigation efficiency

Thermal Load mitigation

- Further understanding of TQ processes needed to predict mitigation efficiency and radiation loads

- Comparison SPI/MGI:
  penetration/assimilation, MHD, mitigation efficiency
  (combination of MGI and solid pellets an option?)

- Mitigation efficiency in “unhealthy” plasmas?

RE suppression / mitigation

Runaway generation unlikely during unmitigated disruptions

JET ITER-like wall ➡ slow current quench / low electric fields

Load mitigation has to avoid runaway electron formation

➡ *sufficient suppression of primary RE generation*
confirmed feasible in existing devices, but very strong avalanche in ITER!

Activated phase: additional sources for primary runaways
➡ *suppression of avalanche essential*

Critical density

original avalanche model: $n_c \sim 10^{22}\ m^{-3}$

Ar, Ne with assimilation > 20% ↯ eddy current limit!

- Recent flat-top experiments (ITPA) observe drop in HXR for $E < E_c$ / 3-5

RE suppression / mitigation

Critical density

Position control

would allow techniques with longer timescale

feasible with in-vessel coil for I_{RE} > 2/3 $I_{P,0}$ only (15 MA)

RE suppression / mitigation

Critical density

Position control

Magnetic perturbations

- field from ELM in-vessel coils not sufficient
- destabilisation of MHD during CQ were unsuccessfully tested in ToreSupra, ASDEX Upgrade

RE suppression / mitigation

Critical density

Position control

Magnetic perturbations

Wave excitation

Magnetised waves led to instabilities in experiments with low density or high RE current density

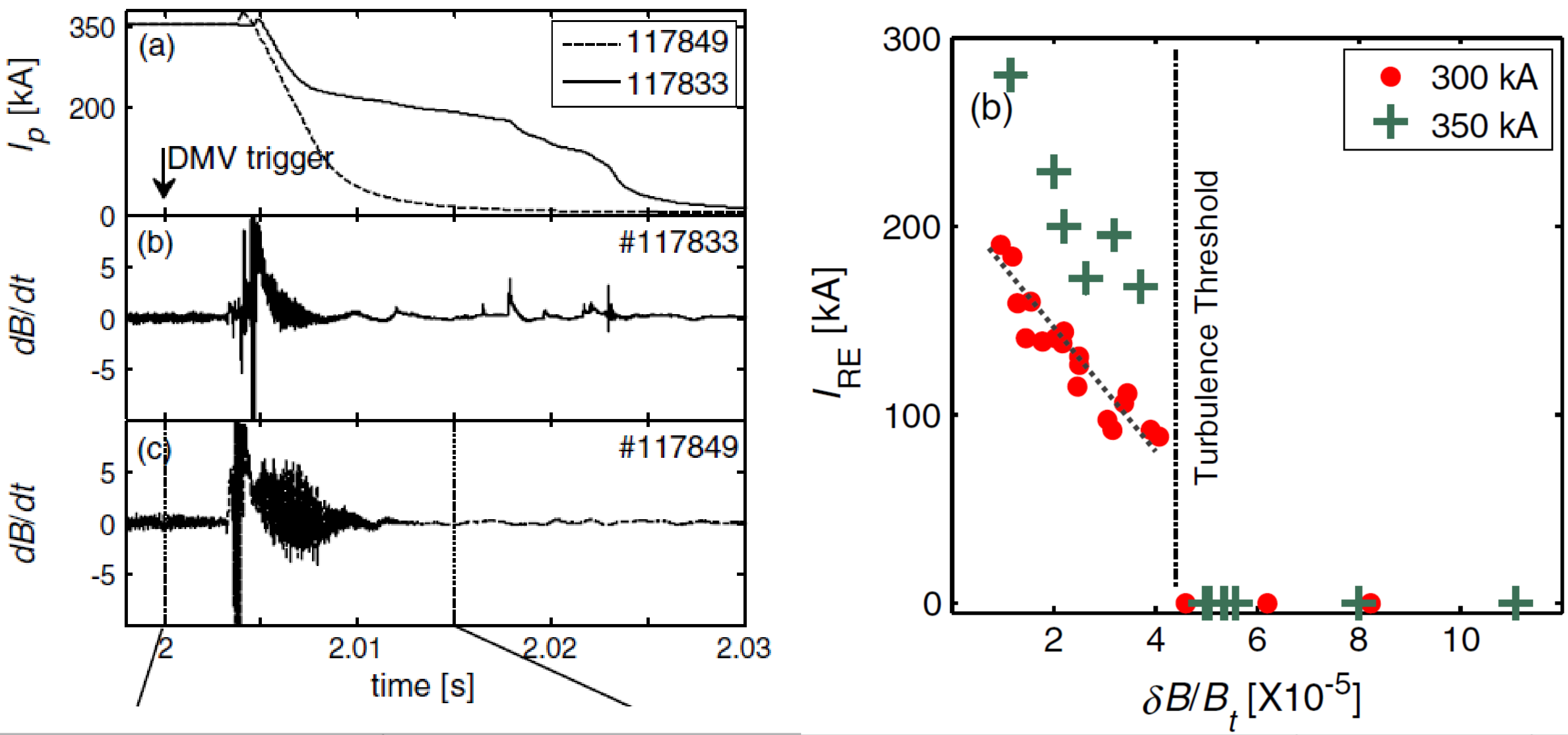
ITER: T_e > 20 eV at 1MA/m^2 and $n_e \approx 1x10^{20}m^{-3}$

Breizman/Aleynikov

RE suppression / mitigation

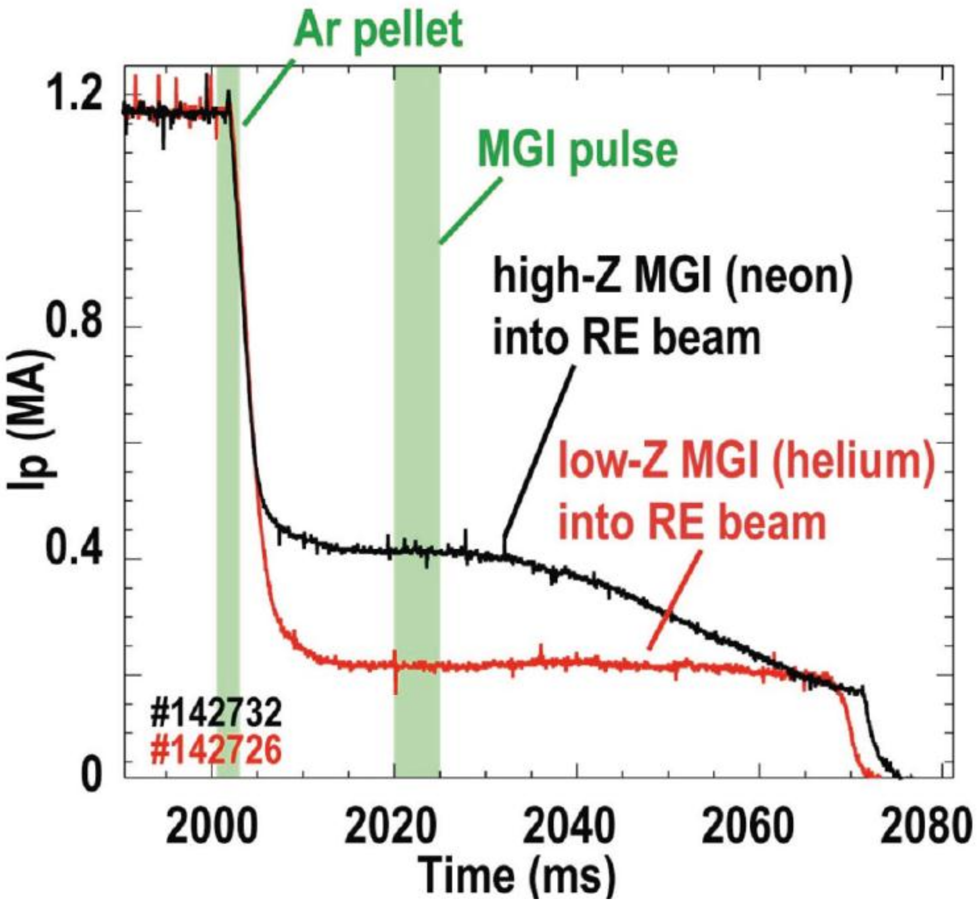
- Strong magnetic fluctuations in the current quench can prevent from RE beam formation
- R&D needed to understand the drive *(S.Newton, G.Papp, EPS 2014: TAE)* and to assess implications for RE formation in ITER

Runaway formation in TEXTOR after Ar injection (L. Zeng, PRL 2013)



Runaway electron mitigation by collisions

DIII-D: high-Z impurities increases runaway current decay



Similar observation in Tore Supra

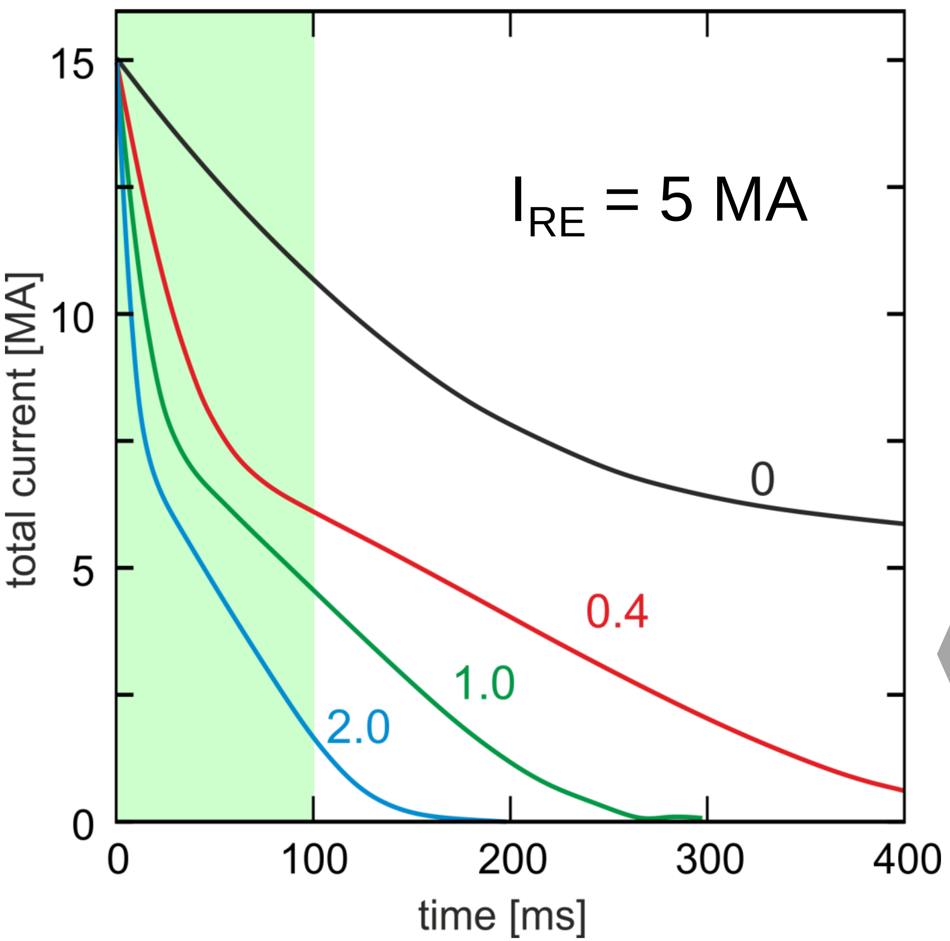
JET, TEXTOR: steady decay of RE current

E. Hollmann, Nuclear Fusion 2013

Note: DIII-D experiments with current control

RE suppression / mitigation

Kinetic simulations: E_{RE} dissipation by high-Z impurities
*increased pitch angle and synchrotron radiation**



ITER critical timescale ~ 100ms (vertical movement)

only 10% of n_c required!

Ar density scan [$10^{20}m^{-3}$]

K.O. Aleynikova, P.B. Aleynikov, EPS 2013

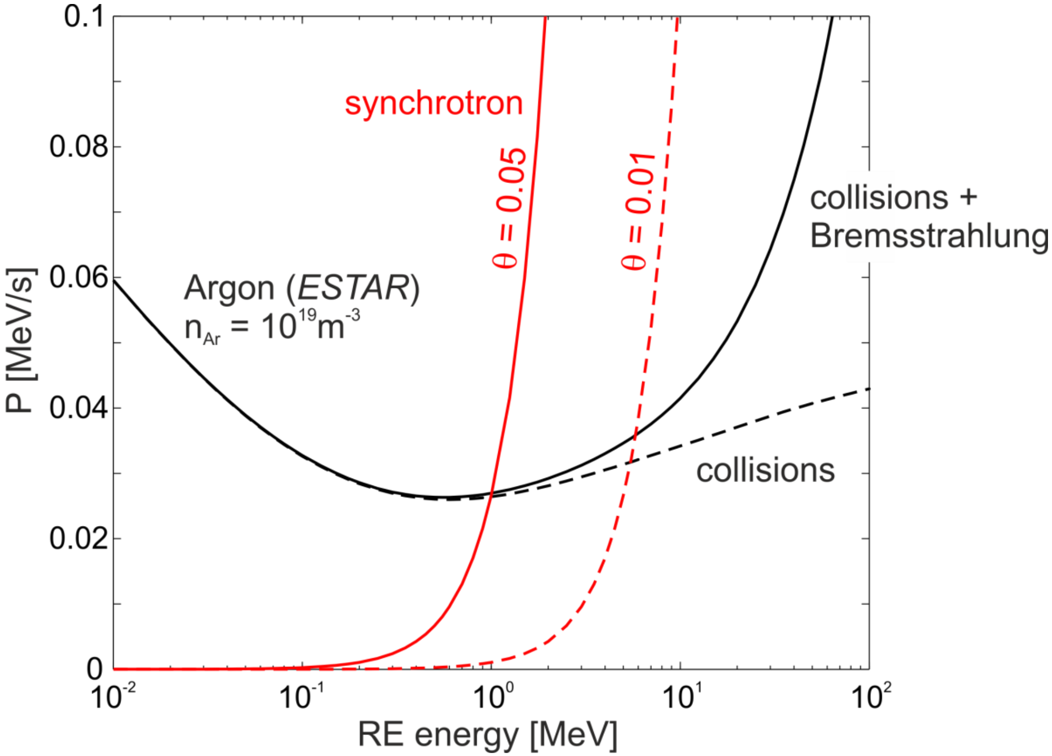
*Calculations based on avalanche energy spectrum; ohmic decay prescribed to fix I_{RE}

RE suppression / mitigation

Energy loss channel:

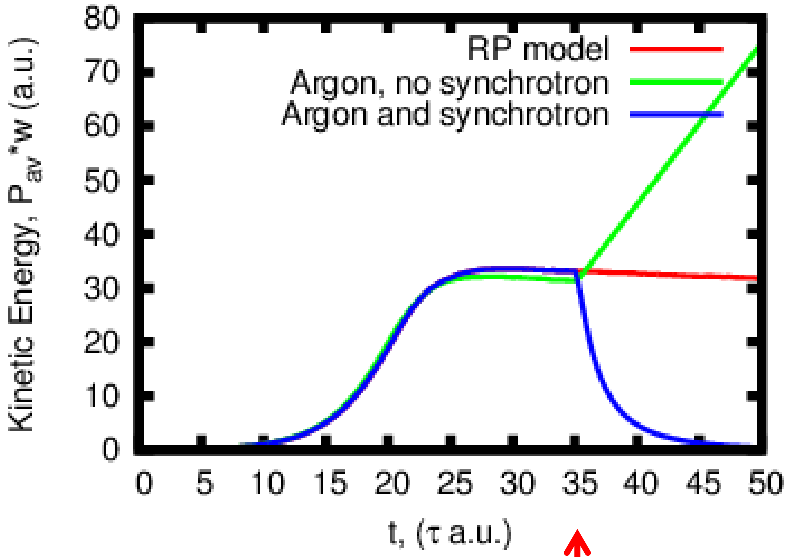
RE spectrum in ITER and in present experiments?

RE loss power



Kinetic Simulation

Aleynikov, RE workshop, Chalmers, June 2014

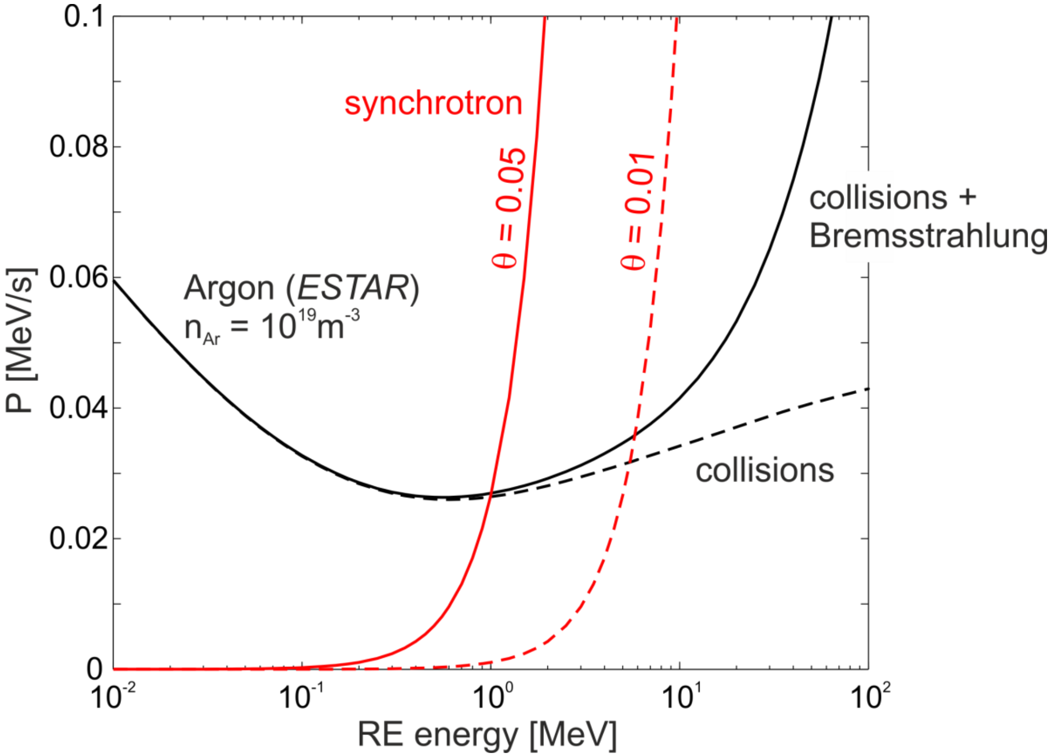


n_{Ar} raised

Energy loss channel:

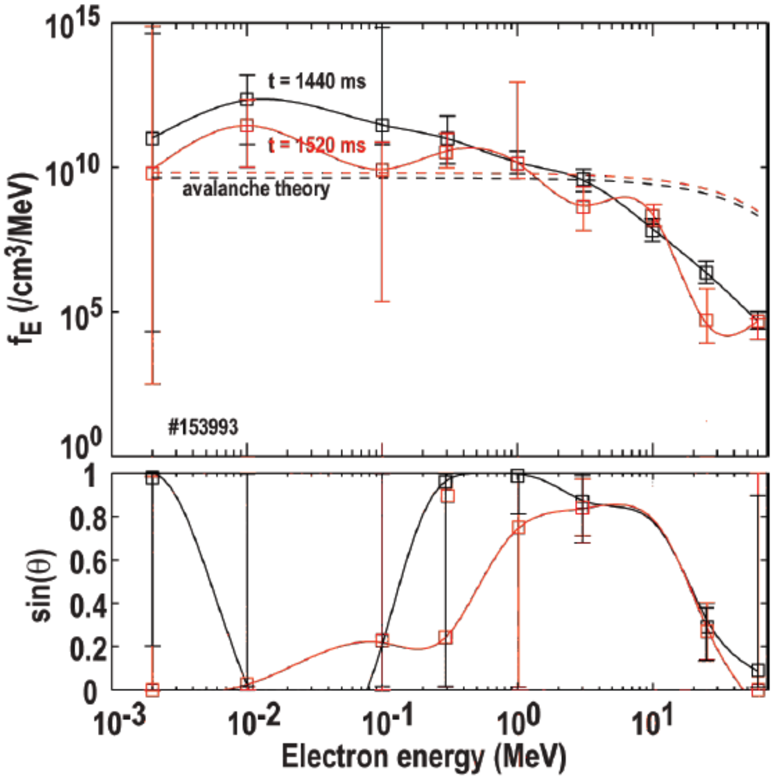
RE spectrum in ITER and in present experiments?

RE loss power



DIII-D RE energy spectra

Hollmann, RE workshop, Chalmers, June 2014

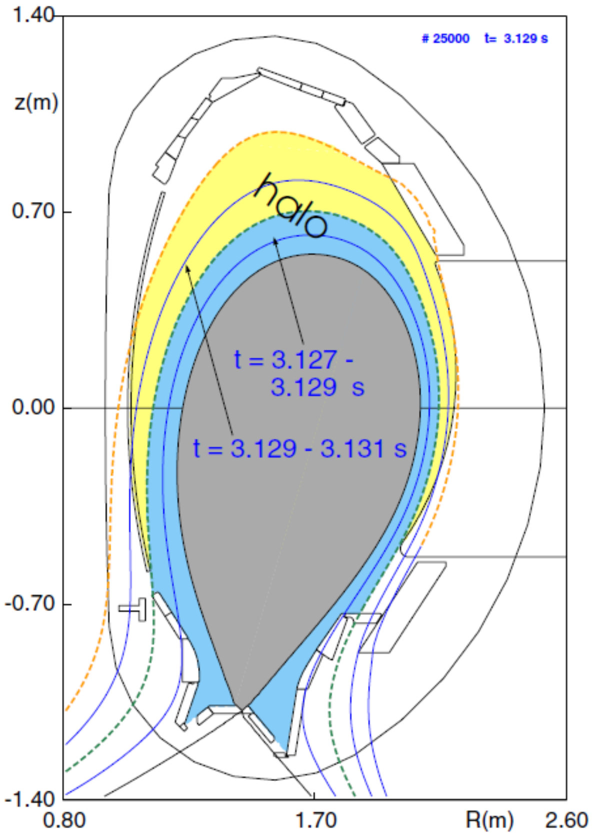


RE suppression / mitigation

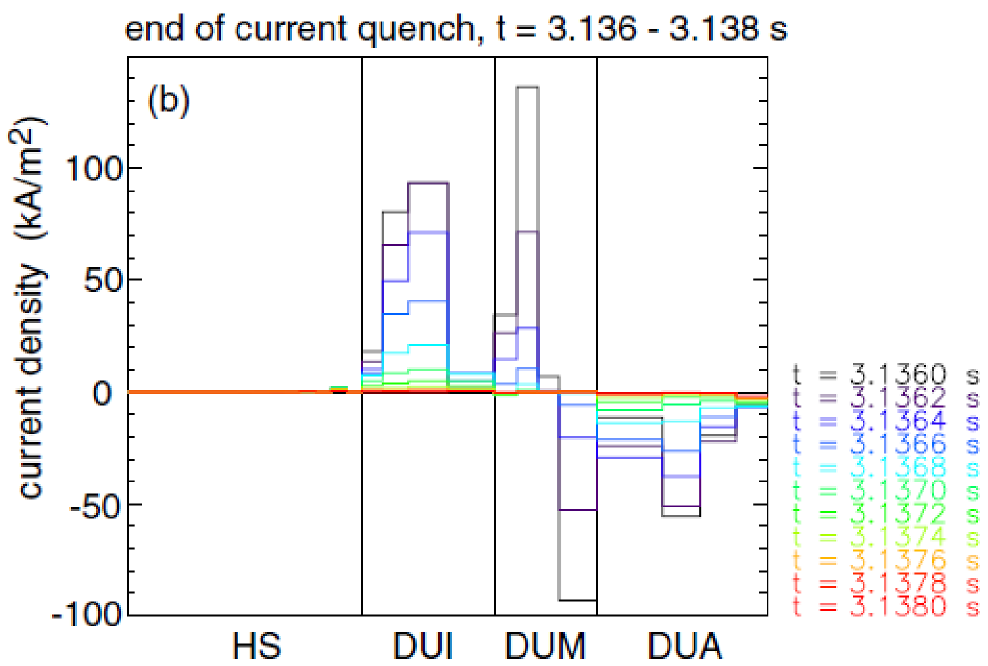
- Impact of pre-TQ plasma parameters on RE generation (hot tail, TQ dynamics, …)
- Sufficient suppression of primary RE compatible with thermal and EM load mitigation?
- Do we understand the low effective n_c in flat-top experiments and what do we expect during disruptions with $E \gg E_c$?
- RE energy dissipation by high-Z collisions:
  - RE spectra in current experiments "ITER-like"? Impact of impurities that are used to trigger RE generation?
  - confirmation of timescales (RE beam stability limits)
- Self-consistent simulation of primary and avalanche generation with equilibrium evolution and MGI/SPI possible?

Back-up Slides

What determines the halo width and temperature?



Halo current density distribution in ASDEX-Upgrade

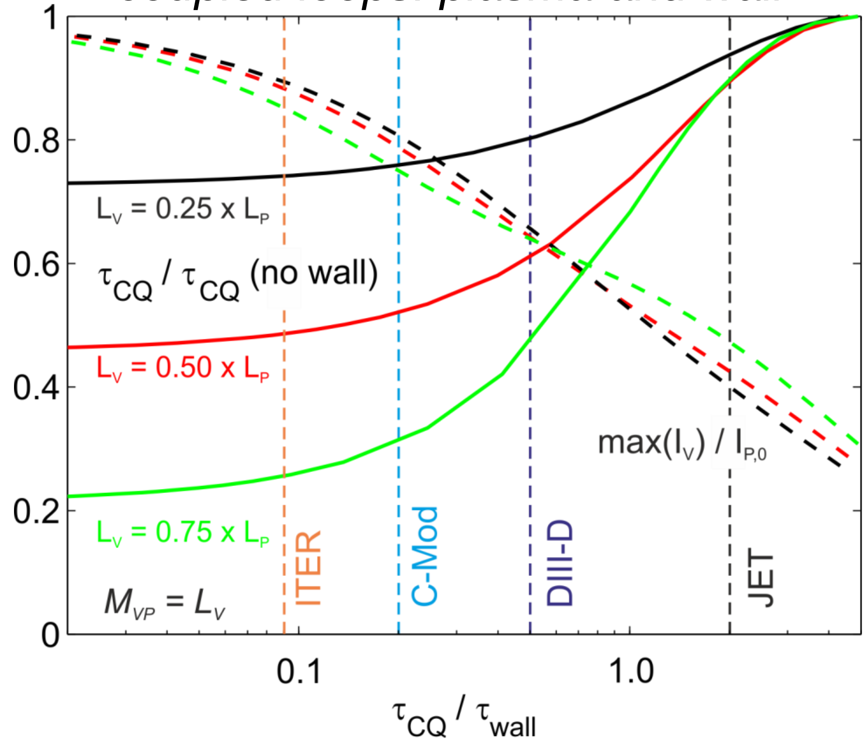


G. Pautasso, NF 2011

Halo currents, Asymmetries, Rotation

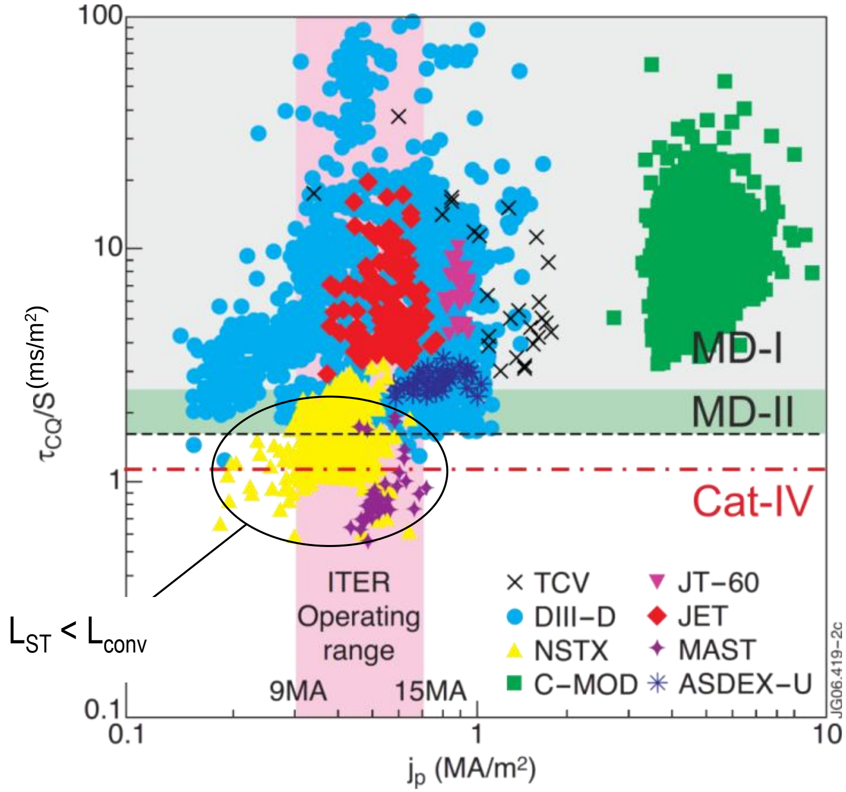
Impact of τ_{wall} on τ_{CQ}

coupled loops: plasma and wall



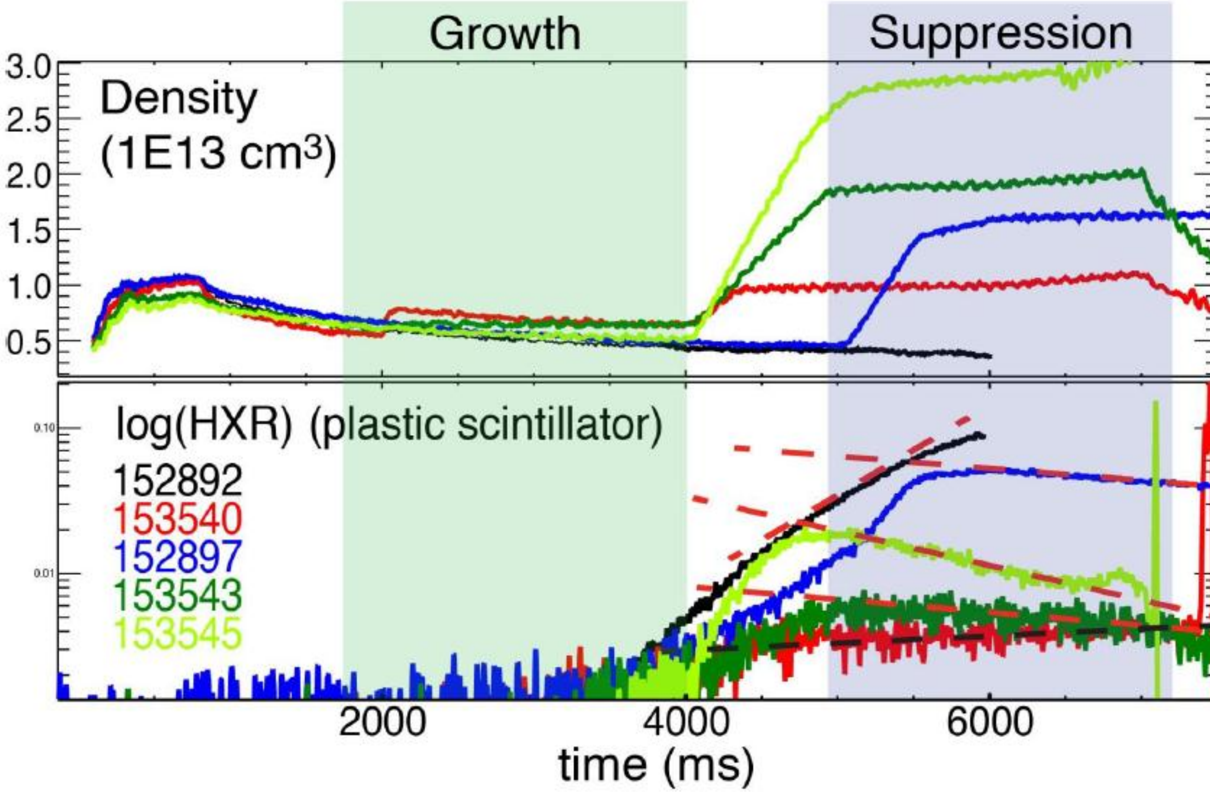
Vertical lines: fastest τ_{CQ} in IDDB and τ_{wall}:
C-Mod: 50 ms; DIII-D: 5 ms; JET: 3 ms;
ITER: 400 ms

Eddy current forces



Runaway electron mitigation: Densification

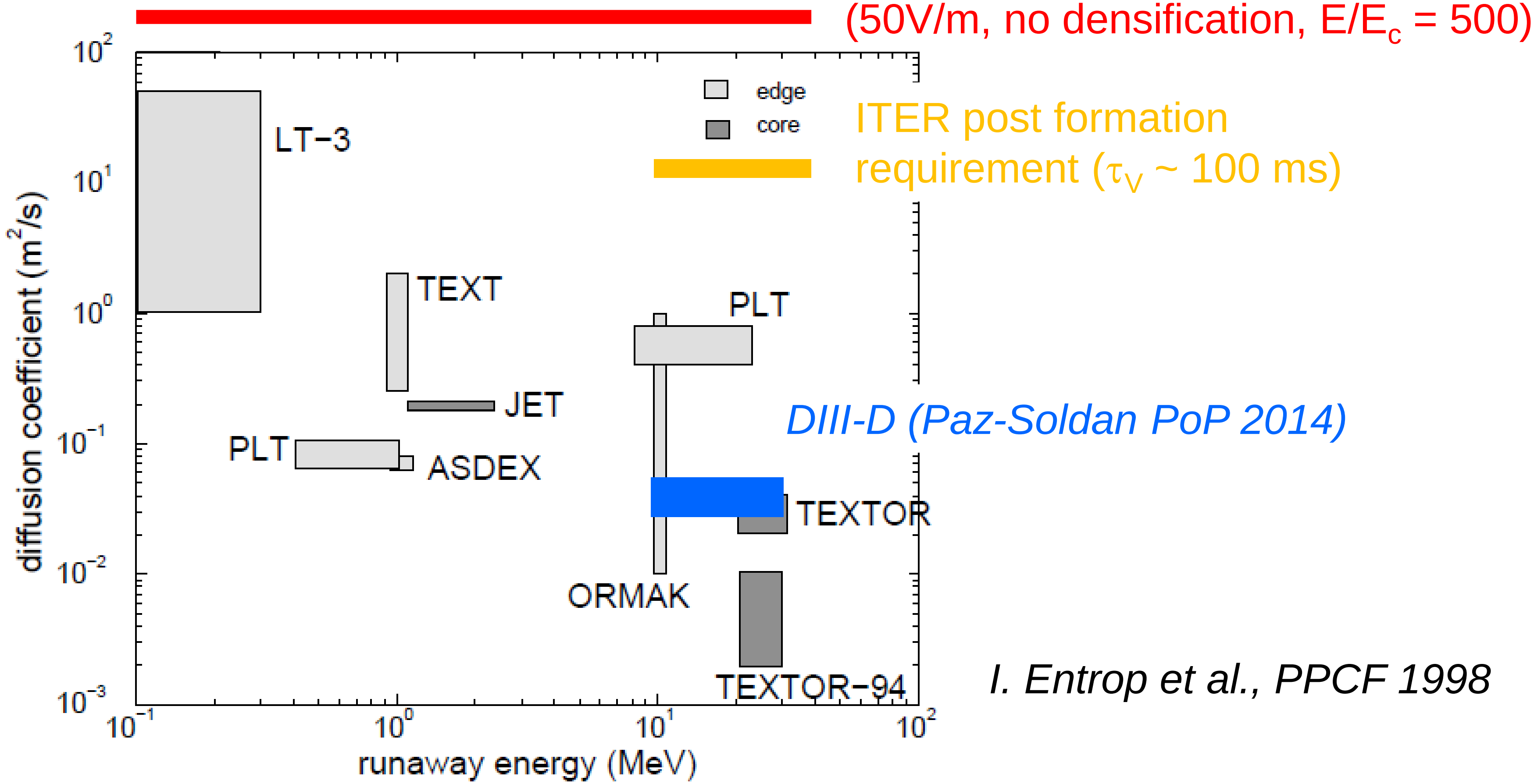
- MDC-16: joint experiment to address the critical electric field for runaway generation during flat-top low density runaway pulses (DIII-D, TEXTOR, FTU, Alcator C-Mod), R. Granetz
- net runaway electron generation above about $E/E_c \approx 5$



R. Granetz, APS 2013
C. Paz-Soldan, PoP2014

Runaway electron mitigation: Densification

Diffusion coefficients and approximate ITER requirements



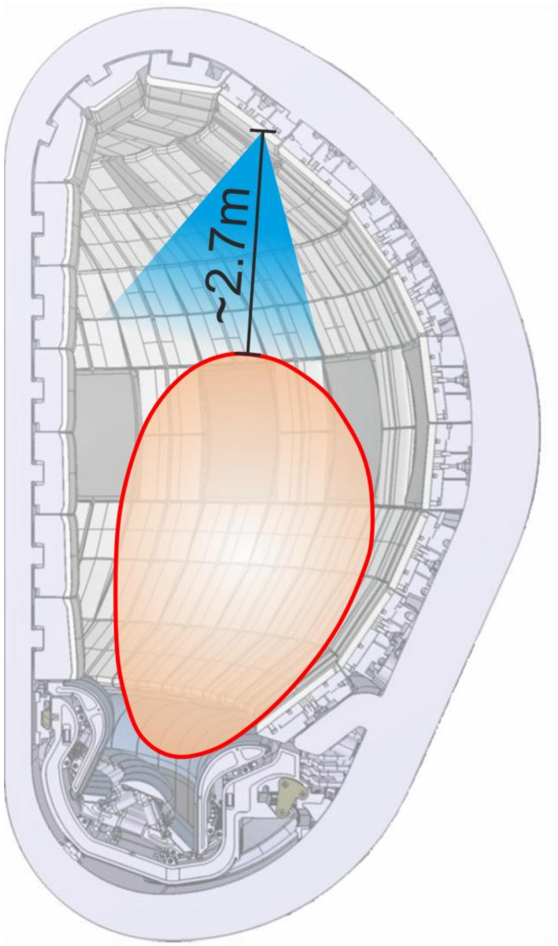
I. Entrop et al., PPCF 1998

Mitigation Issues: Impact of injection location

What is the impact of

- poloidal and toroidal injection position / distribution
- gap between plasma and first wall
- distance to q=2 or x-point
- multiple injection

on timescales, radiation loads, mixing efficiency and mitigation efficiency?



DINA: DW VDE ($t=t_{TQ}$)
(extreme case of very late injection,
$\Delta Z > 0.2$m can trigger already trigger the DMS)