ITER Needs for Disruption Modelling

M Lehnen

ITER Organization

Preamble

- Design of plasma facing components, VV, PF, TF close to finalisation/finalised
- Design of Disruption Mitigation System is ongoing and needs physics input
- Further understanding of disruption physics is needed to operate ITER in a regime with controlled and tolerable disruption loads
- The ITER disruption strategy is a progressive approach towards higher loads
  - understanding of disruption physics is needed to extrapolate to each next step (lack of statistics)
  - the coupling between plasma parameters and the resulting stresses on components has to be understood and quantified
- Besides loads and their mitigation: plasma control includes developing disruption prevention and detection strategy

Outline

This talk will give an overview on the most urgent ITER disruption issues to provide input to discuss theory and modelling needs.
It is not intended to list specific modelling needs.

Disruption Loads

- Asymmetric (rotating) VDEs
- Heat Loads
- Runaway electrons

Disruption Mitigation

- Refining system requirements
- Understanding of mitigation process and predicting efficiency
- Runaway electron control / mitigation

Disruption detection

Disruption Loads *asymmetric VDEs - electro-mechanical loads*

symmetric VDE: vertical forces on VV

asymmetric VDE: vertical and sideways forces on VV

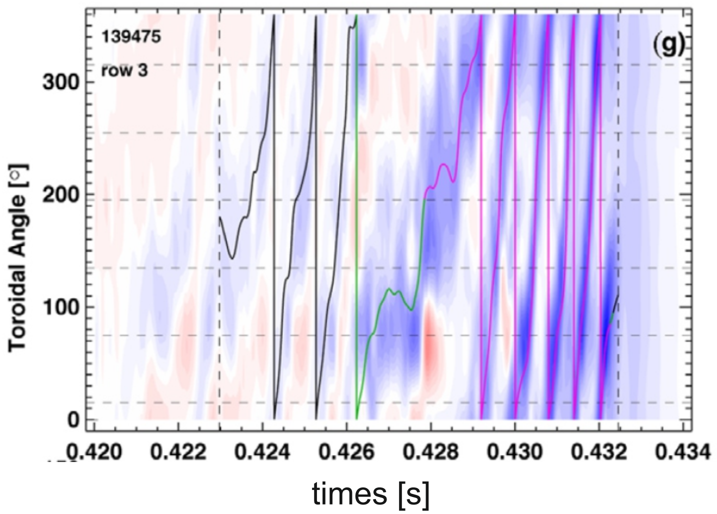
rotating asymmetric VDE: resonant amplification

presently any raVDE considered as Cat. IV event*!

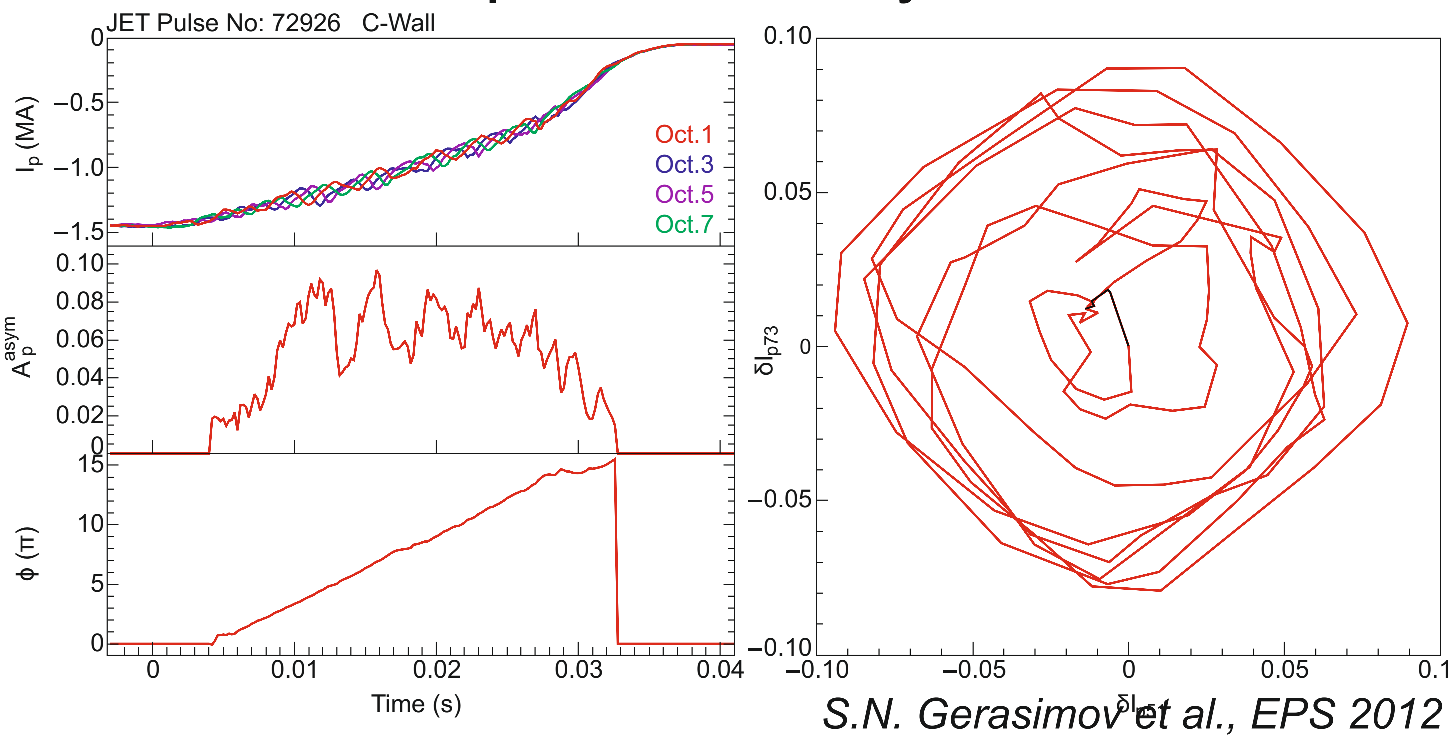
physics input urgently needed to refine load spec's

toroidal current asymmetries as seen on JET are linked to halo current peaking as seen in DIII-D, AUG, NSTX.

NSTX, S. Gerhardt, NF 2013



JET: plasma current asymmetries



S.N. Gerasimov et al., EPS 2012

*for load specifications see [ITER_D_222QGL v6.0]

Disruption Loads *asymmetric VDEs - electro-mechanical loads*

halo current distribution (DINA)

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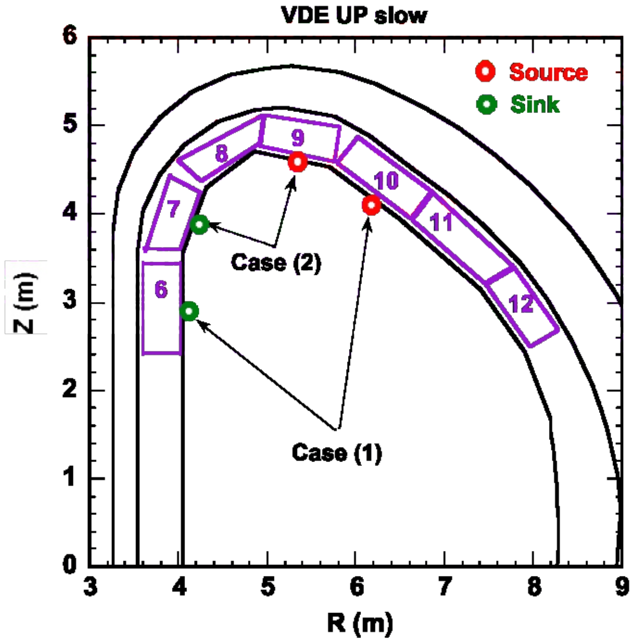
(rotating) sink+source

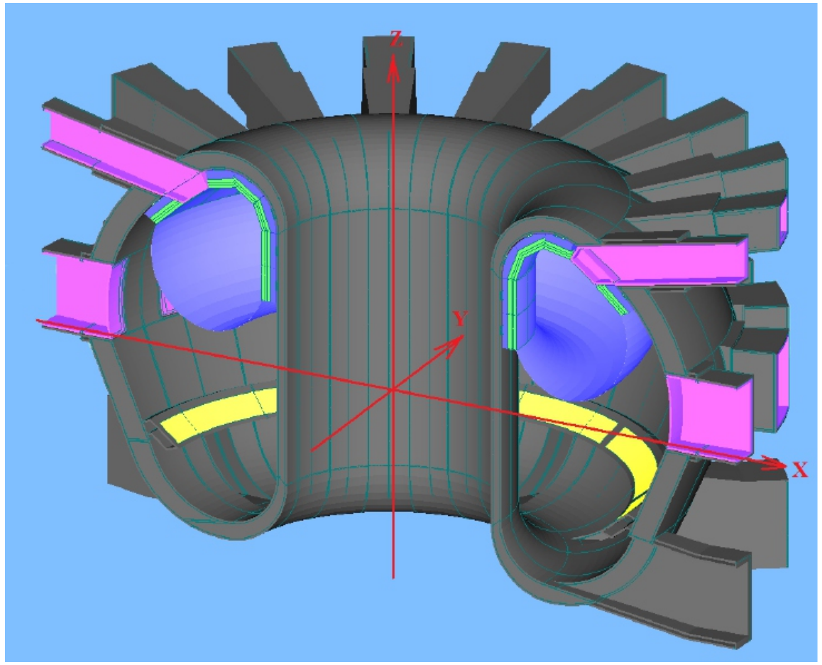
⇩

electro-mechanical loads

⇩

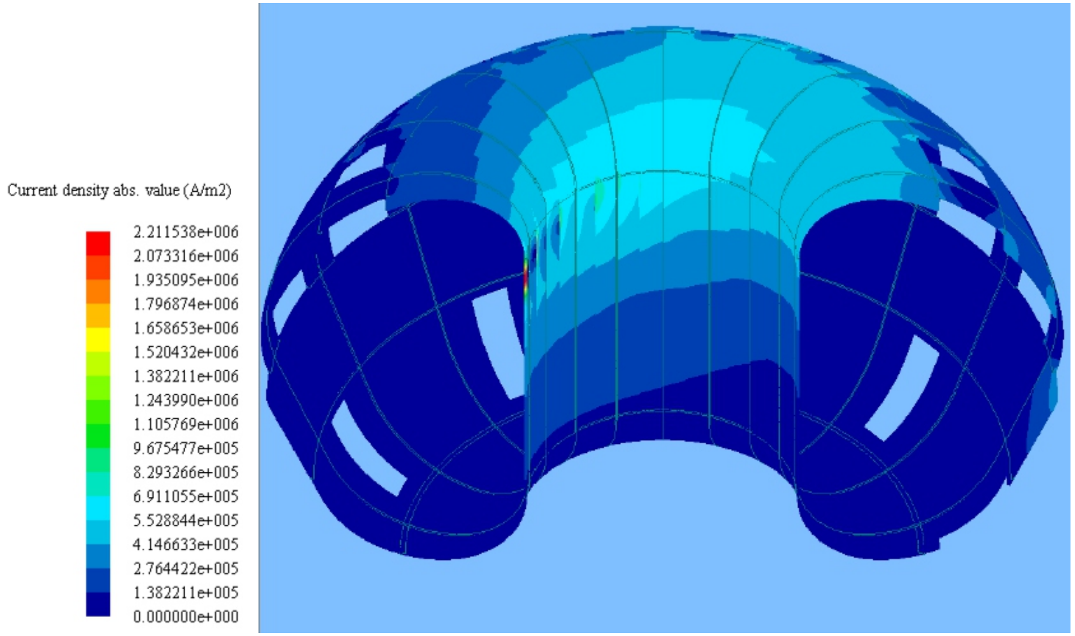
structural analysis





DINA+FE model:

sideways forces and tilting moments associated to toroidally asymmetric halo current distribution (here n=1)



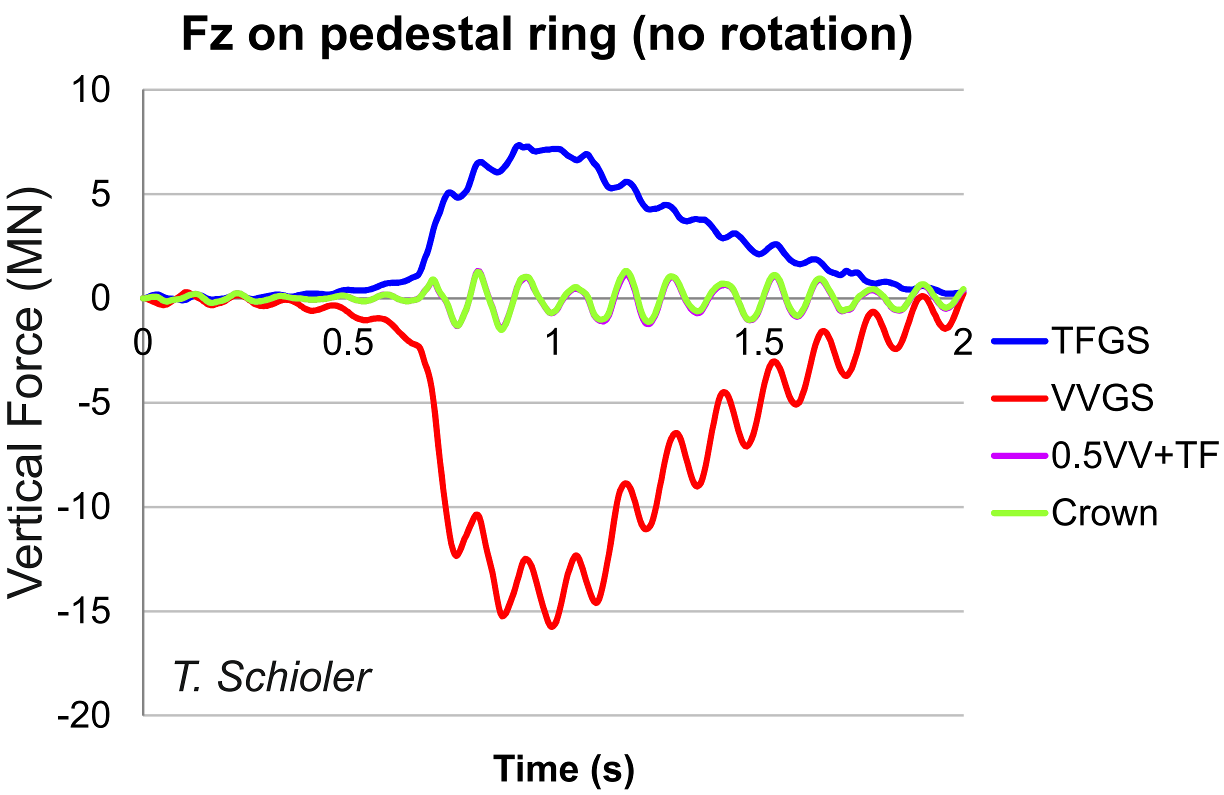
Disruption Loads *asymmetric VDEs - electro-mechanical loads*

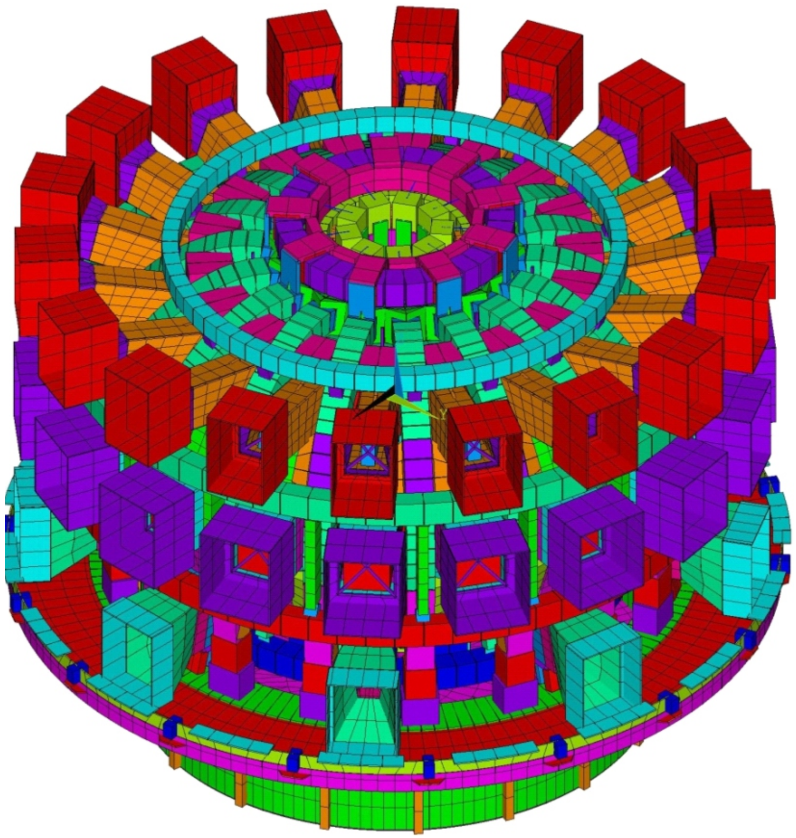
initial modelling with simplistic current distribution - work in progress

Resonance frequencies: VV 8Hz, TF 12Hz

VDE III, down, TPF = 1.39, 0 Hz

Loads applied (source/sink model)
- vertical force
- sideways or horizontal force
- tilting moment due to TPF
- tilting moment due to δI_p



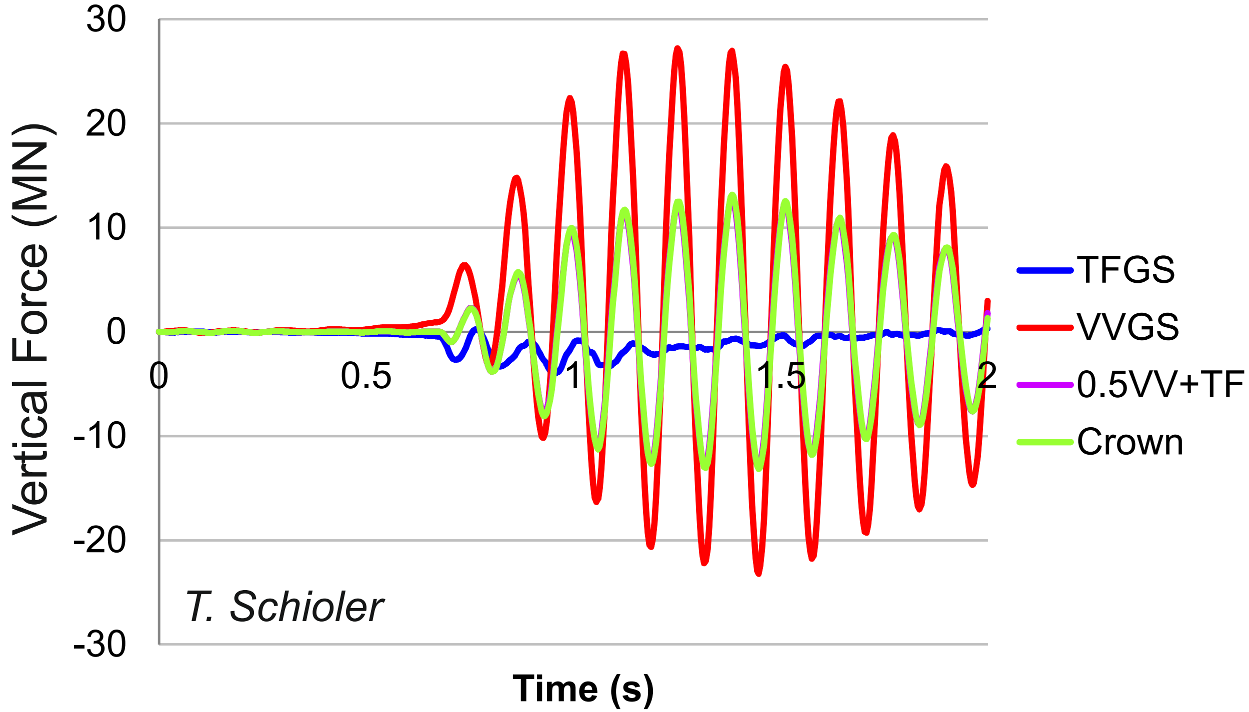


initial modelling with simplistic current distribution - work in progress

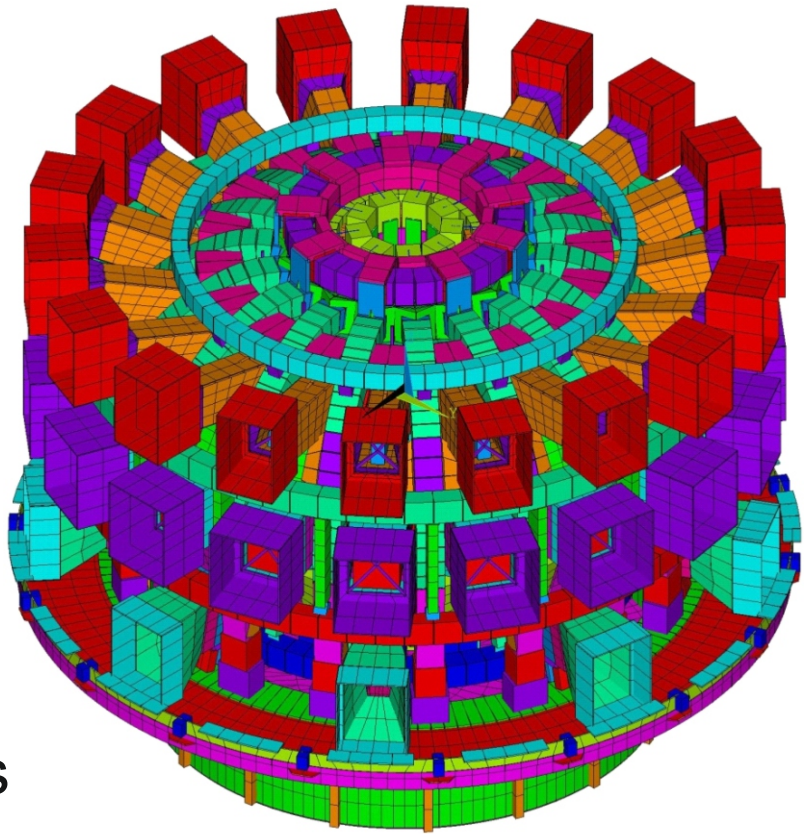
Resonance frequencies: VV 8Hz, TF 12Hz

VDE IV, up, TPF = 2.78, **7.7 Hz**

Fz on pedestal ring (rotation)



Loads applied (source/sink model)
- vertical force
- sideways or horizontal force
- tilting moment due to TPF
- tilting moment due to δI_p



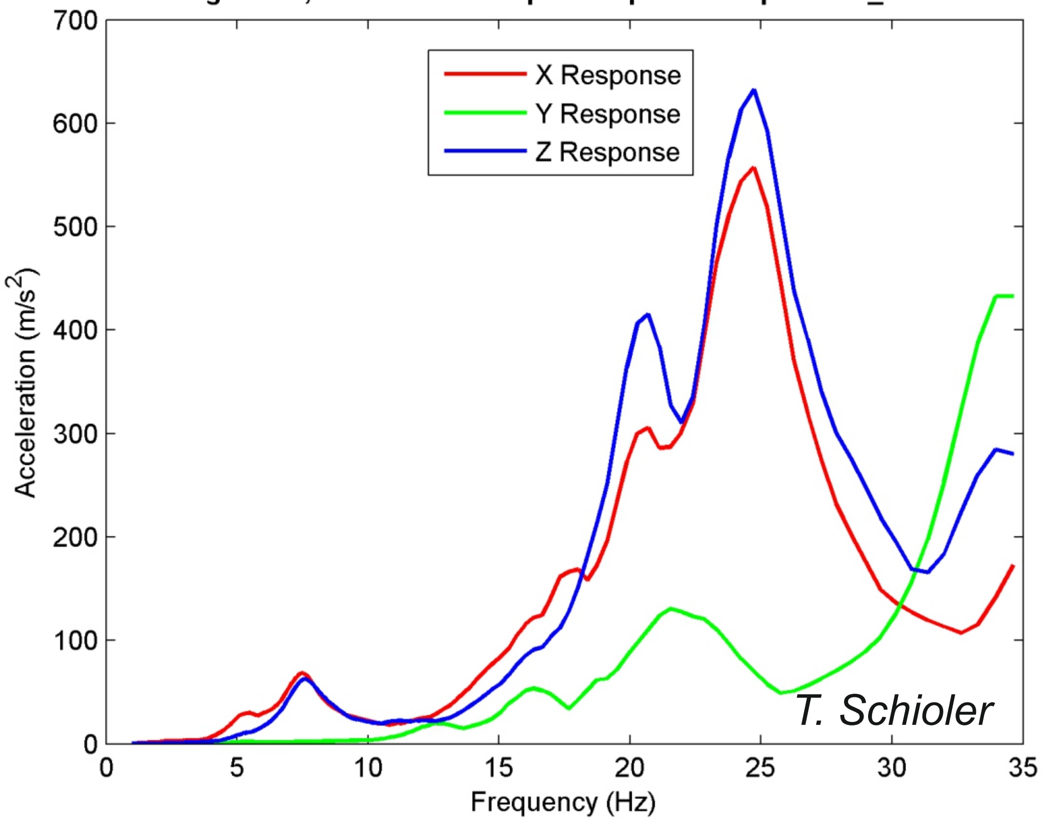
low damping ⇨ max amplitude after 4 turns

Disruption Loads *asymmetric VDEs - electro-mechanical loads*

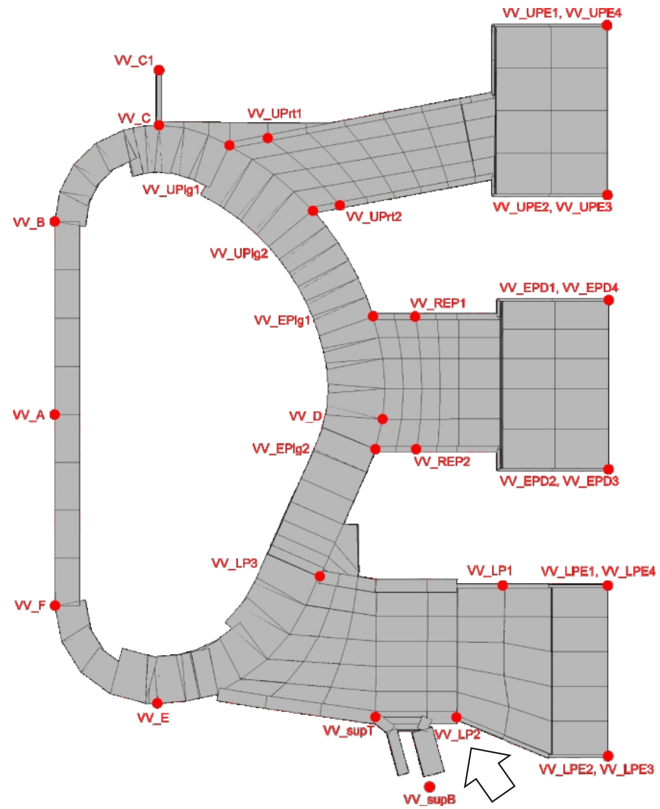
initial modelling with simplistic current distribution - work in progress

acceleration response spectrum

Figure A3, Acceleration response spectra for point VV_LP2



VV



Uncertainties increase with higher frequencies
Model to be validated / cross-checked

Disruption Loads *asymmetric VDEs - electro-mechanical loads*

Initial modelling with simplistic current distribution shows that rotating VDEs could cause significant mechanical loads - needs special attention from both sides, analysis of the experimental database and modelling

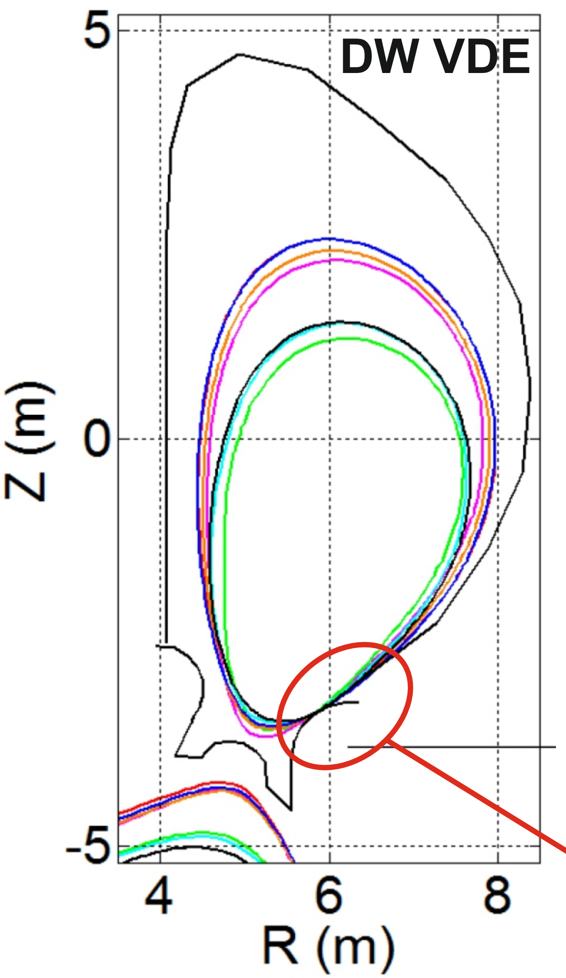
- What determines the VV current distribution?
  - Relation between toroidal asymmetry in poloidal halo current and toroidal plasma current?
  - Mode number / safety factor
  - Impact of rotation on the distribution
  - VV structure / resistivity
- What determines the rotation of the kink mode?
  - Rotation frequency shows quite a variety in the experiments
  - Torque due to interaction with VV currents?
  - CQ duration short compared to $1/\nu$?
  - How to extrapolate to ITER?

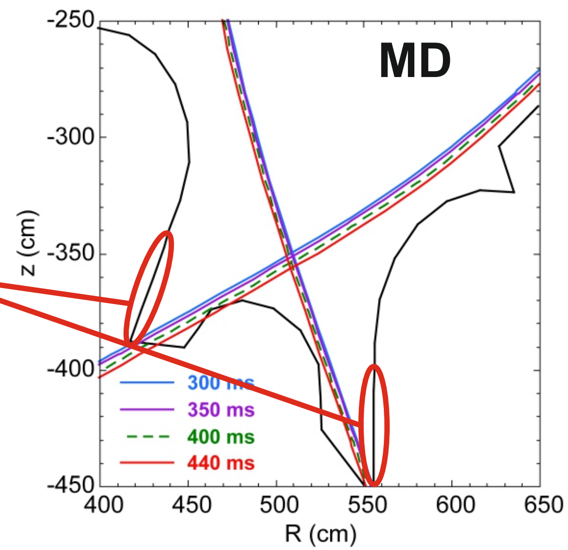
Disruption Loads *heat loads*

Heat loads can be very asymmetric and MHD can play a significant role in distributing them.

ITER heat load assumptions:

- broadening of heat flux footprint: 3 – 10$\lambda_{q||}$
- Maximum in/out divertor asymmetry = 2
- TQ duration 1-3ms
- MD: all energy into the divertor
- DW VDE: all energy to outer baffle
- UP VDE: all energy to blanket





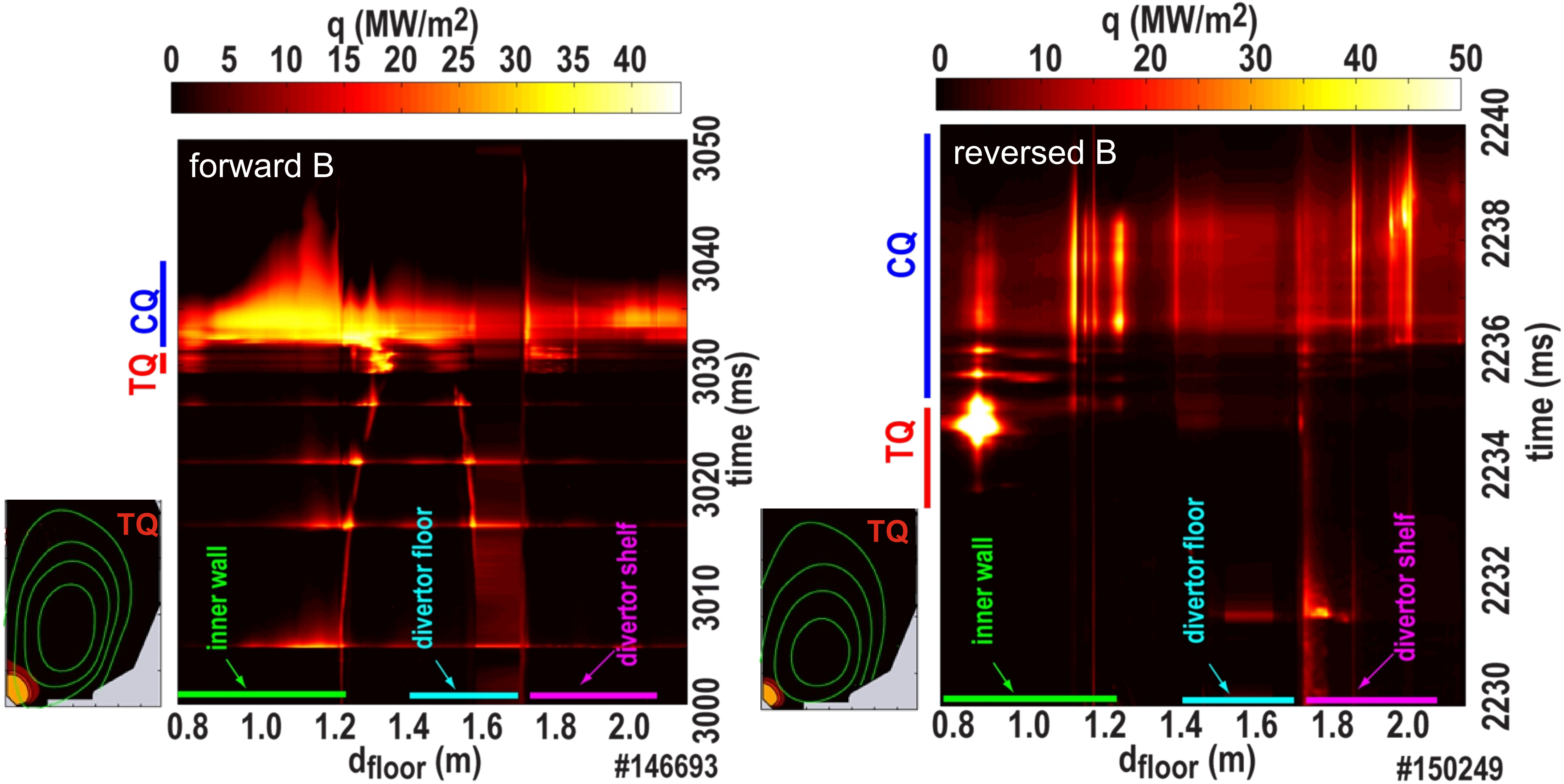
Impact on divertor target plates

Impact on outer baffle or BM

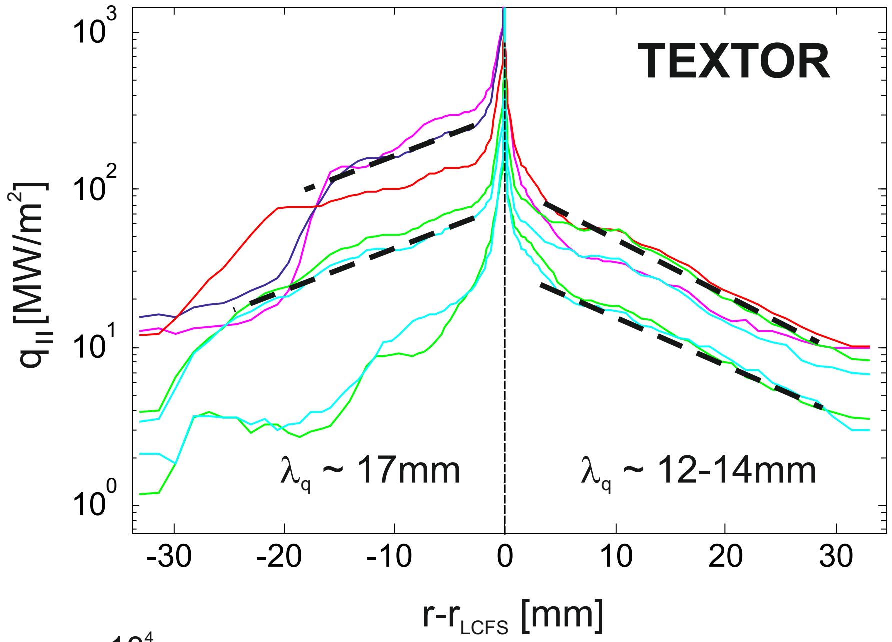
Disruption Loads *heat loads*

Poloidal asymmetries are observed during VDEs

DIII-D, E. Hollmann et al., EPS 2013



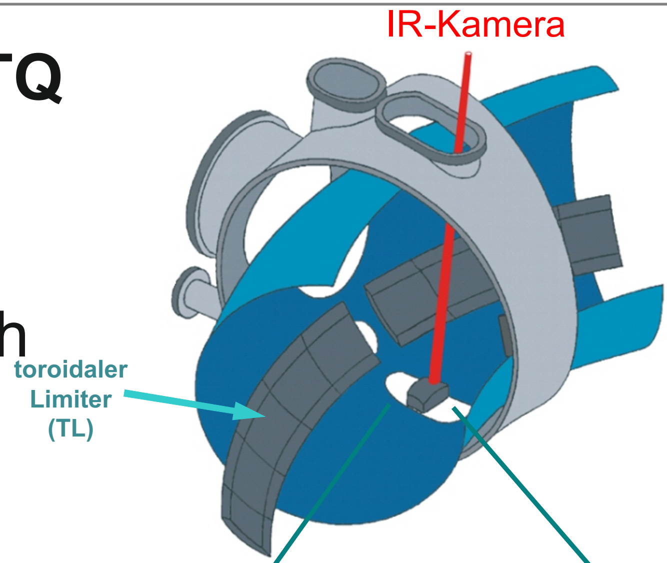
Disruption Loads *heat loads*

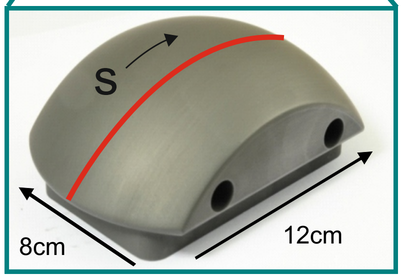


heat flux during TQ

density limit

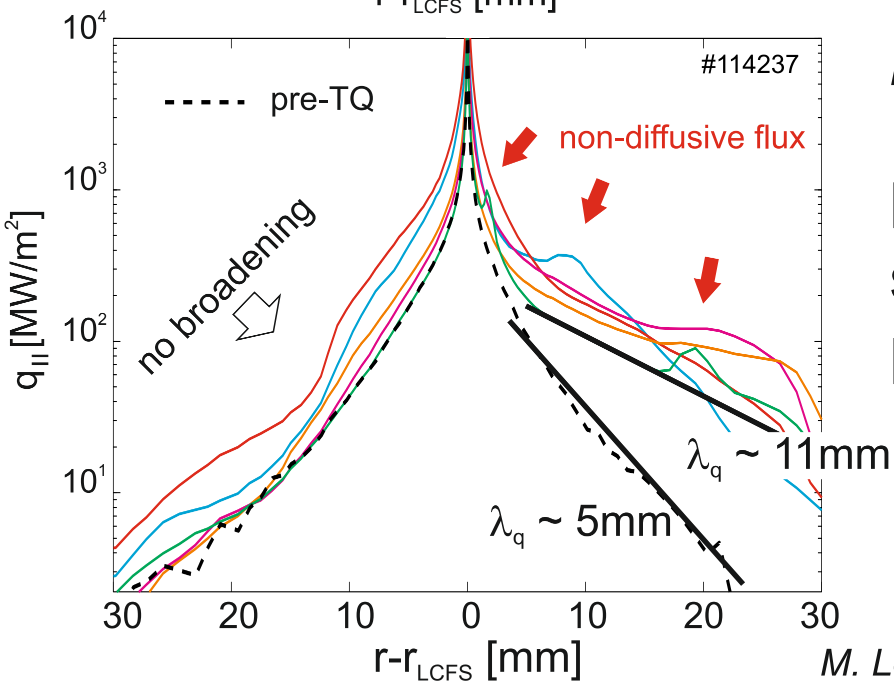
broadening on both limiter sides: factor 2-3

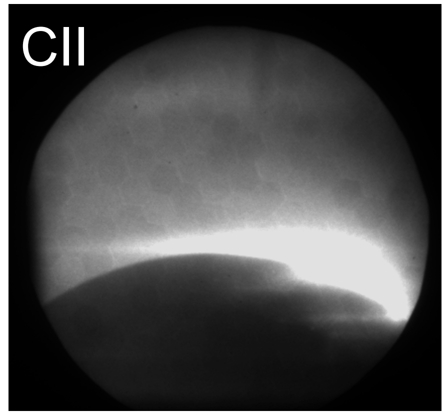




low q

broadening on one side only, spikes on profiles





M. Lehnen et al., ITPA DivSOL, January 2012

Disruption Loads *runaway electrons*

Runaway electrons can cause severe damage to first wall components.

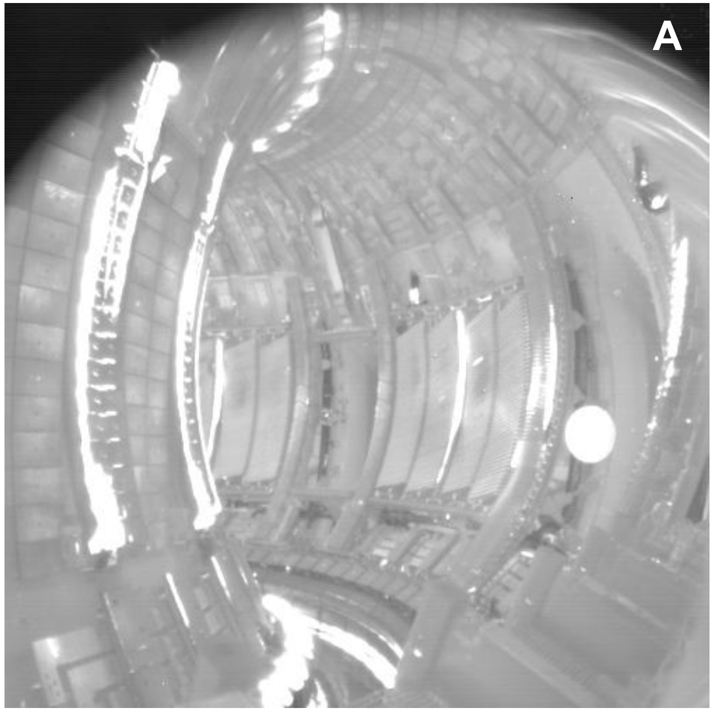
RE avoidance is mainly investment protection. They may become a safety issue if they cause large water leaks.

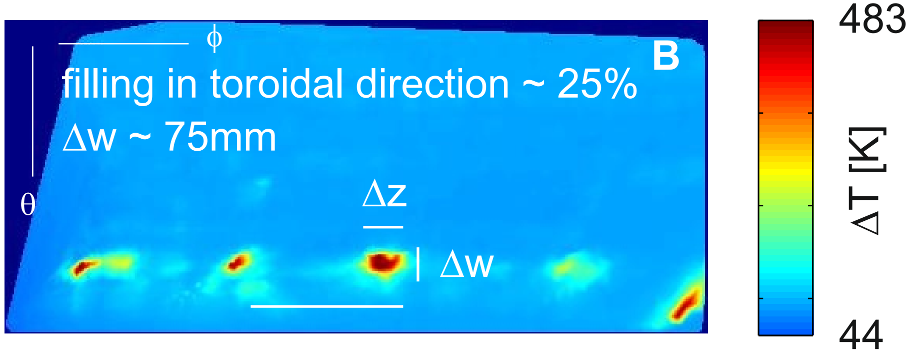
Operating scenarios have to ensure

- that one stays away from the parameter range generating MAs of RE current
- that potential RE generation and impact does not cause major damage

Disruption Loads *runaway heat loads - wetted area/volume*

JET RE impact*



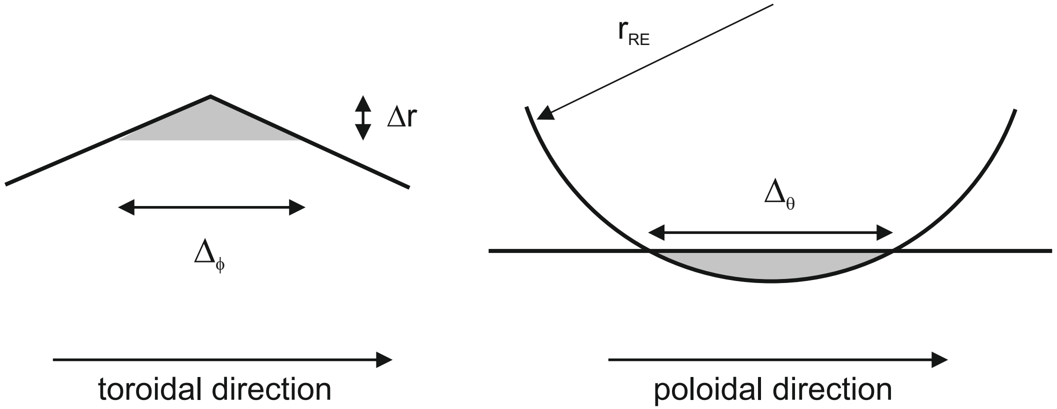


$$\Delta\theta = 2\sqrt{(r_{RE} + r_L)^2 - r_{RE}^2} \approx 75 - 113 \text{ mm}$$

$$r_L^{max} \approx \frac{E(\text{eV})}{cB_t} \approx 0.01\text{m (15MeV)}$$

α = 0.08[1] - 0.2[2]

$$r_L = r_L^{max}\left(1 + \frac{1}{\sin\alpha}\right)^{-1} \approx 0.7 - 1.6 \text{ mm}$$

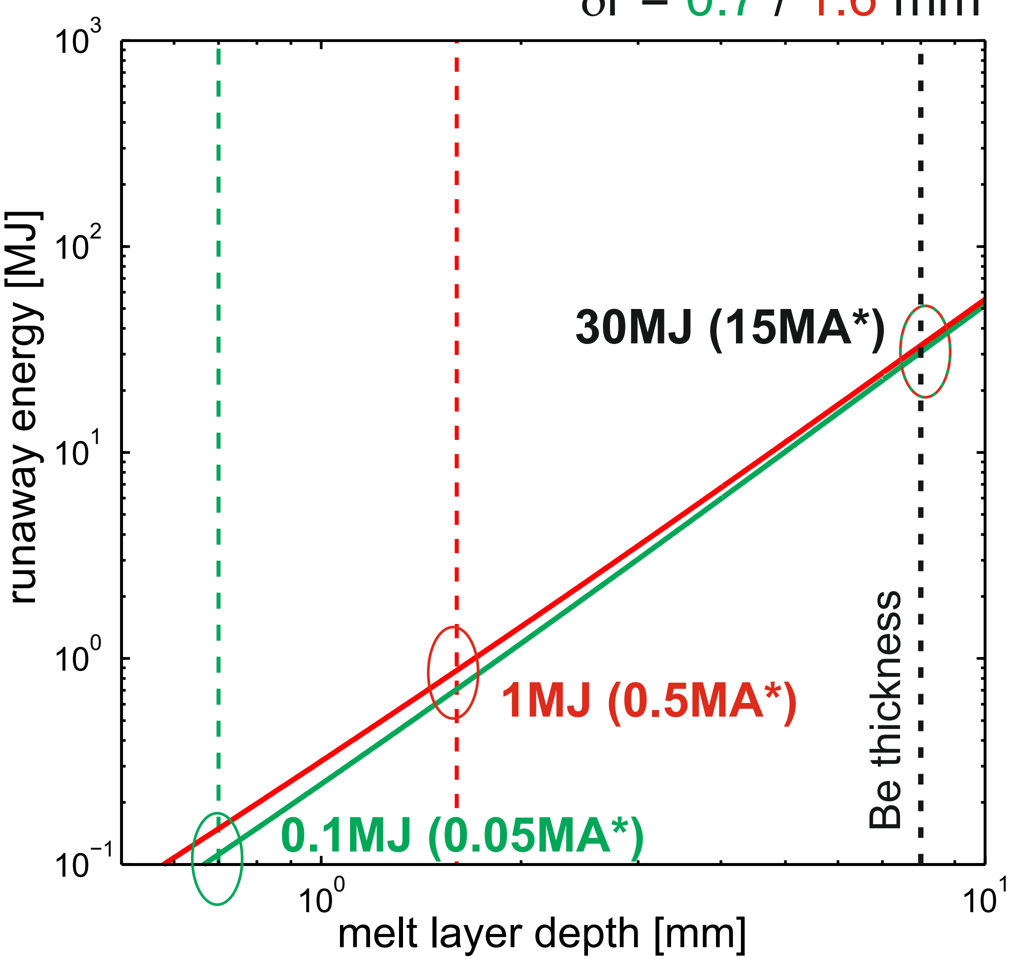


[1]K.H. Finken et al., Nucl./ Fusion 30 (1990) 859.
[2]E. Hollmann et al., FEC IAEA 2012 San Diego

**M. Lehnen et al., JNM 2009*

Disruption Loads *runaway heat loads - melting limit*

1MJ has the potential to melt **330 g** beryllium (heat capacity + heat of fusion)



assume energy is deposited on timescale short compared to heat transport

assume homogenous energy distribution in volume

r_L = 0.7-1.6 mm, r_{RE} = 1.0m

$$\Delta_\phi = \lambda_q^{design}(1 - exp(-\Delta r/\lambda_q^{design})/C$$

volume of melting: $V = N \times \int \Delta_\phi \Delta_\theta dr$

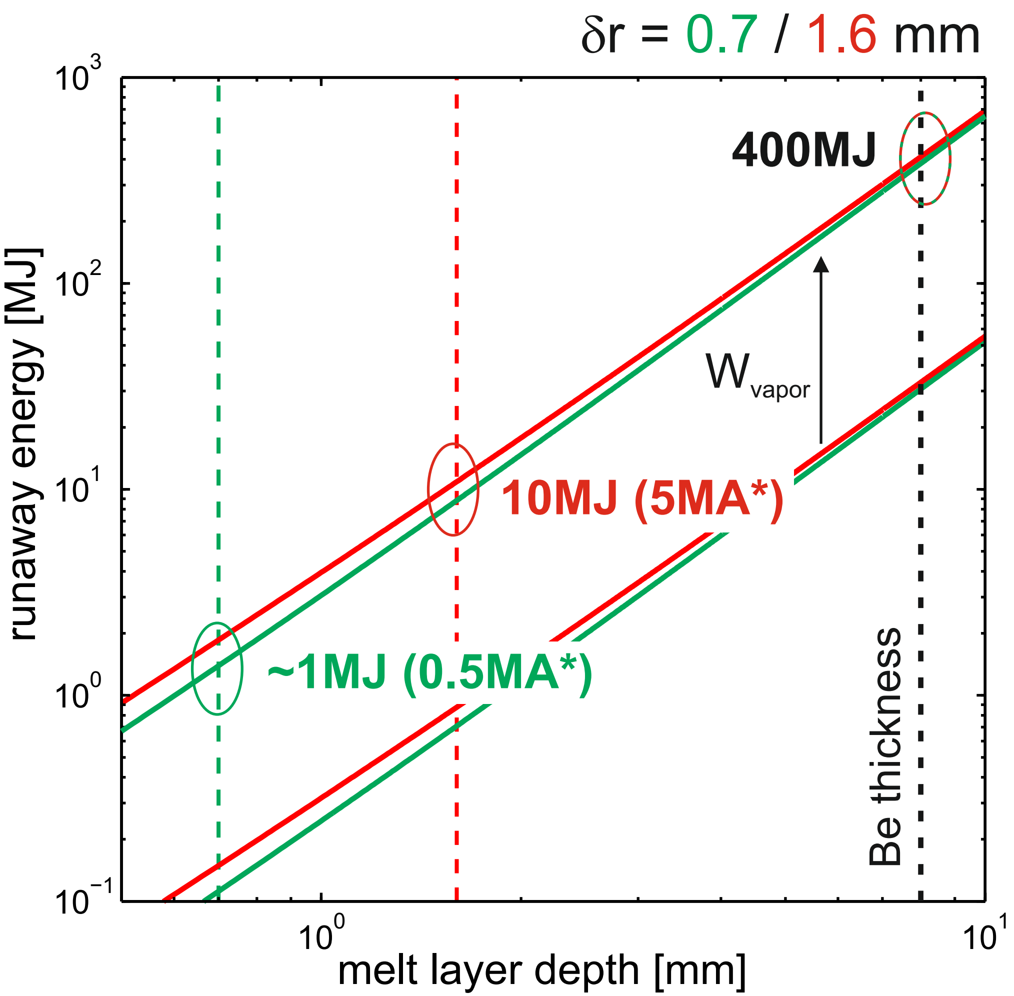
(MA*) for 15 MeV, no magnetic energy conversion

λ_q^{design}, C: BM shaping parameters

N = 36 × 2 (#BM × #roofs)

Disruption Loads *runaway heat loads - melting limit*

up to 1MJ can be dissipated by **~25 g** of beryllium if vaporisation is included
shown here: maximum possible energy dissipation - needs detailed analysis!



How efficient is “vapor shielding”?

assume energy is deposited on timescale short compared to heat transport

assume homogenous energy distribution in volume

r_L = 0.7-1.6 mm, r_{RE} = 1.0m

$$\Delta_\phi = \lambda_q^{design}(1 - exp(-\Delta r/\lambda_q^{design})/C$$

volume of melting: $V = N \times \int \Delta_\phi \Delta_\theta dr$

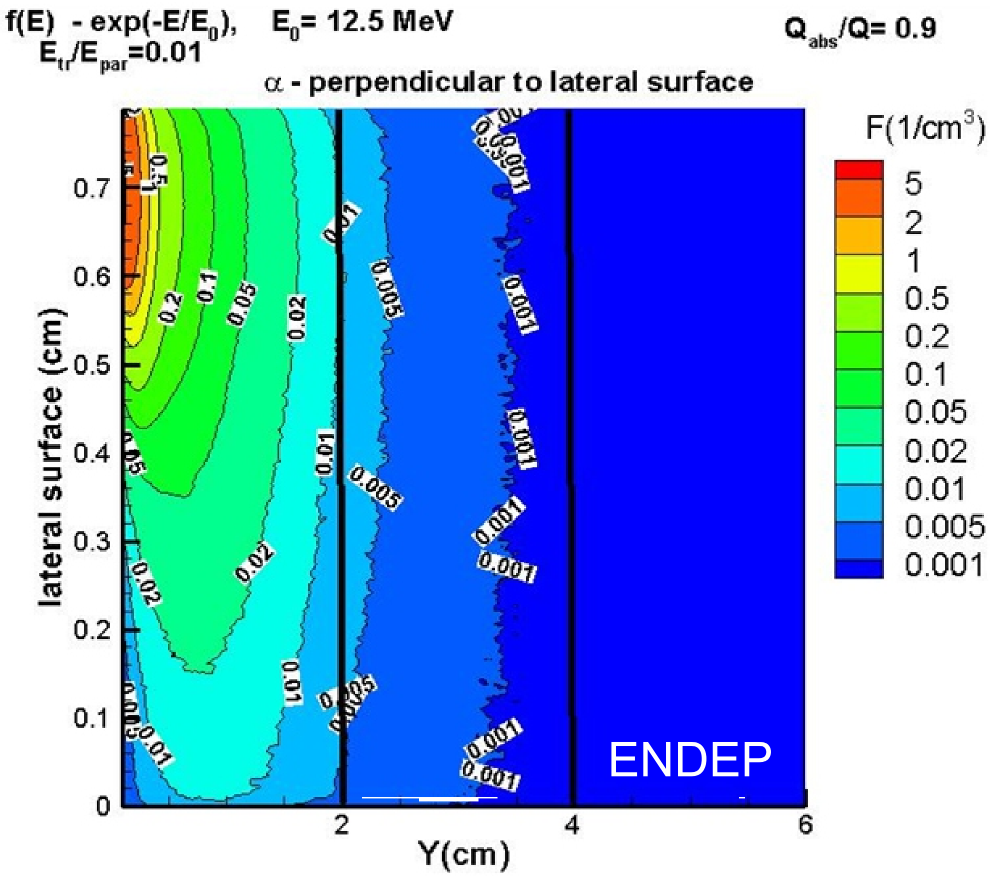
(MA*) for 15 MeV, no magnetic energy conversion

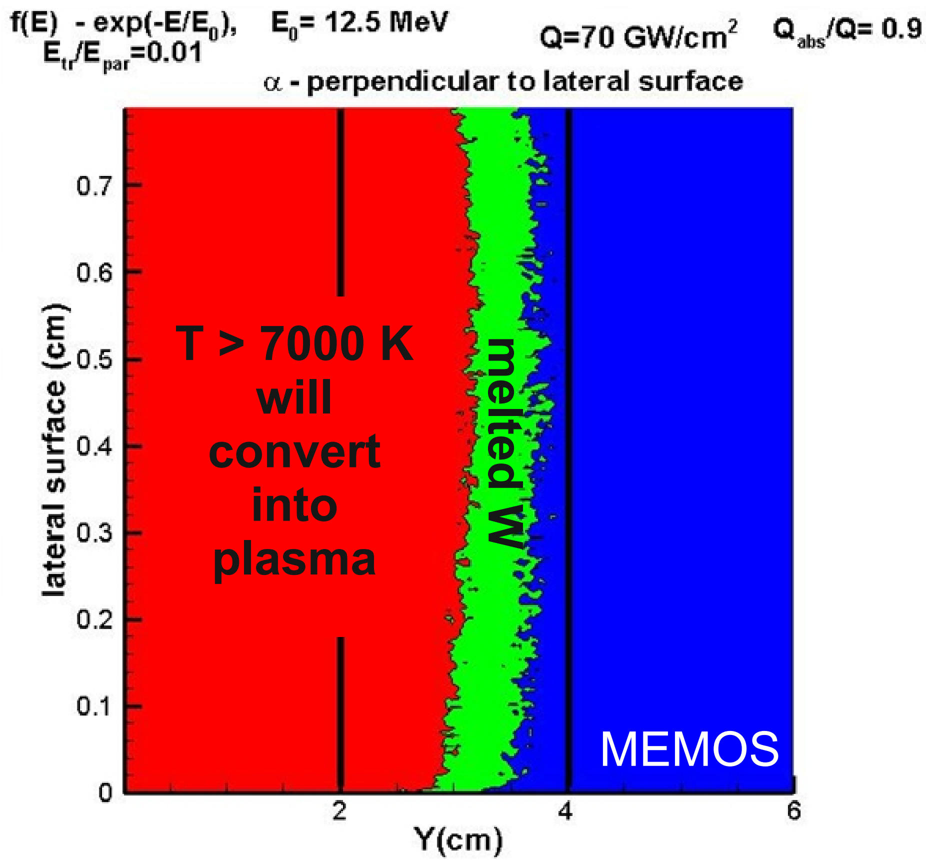
λ_q^{design}, C: BM shaping parameters

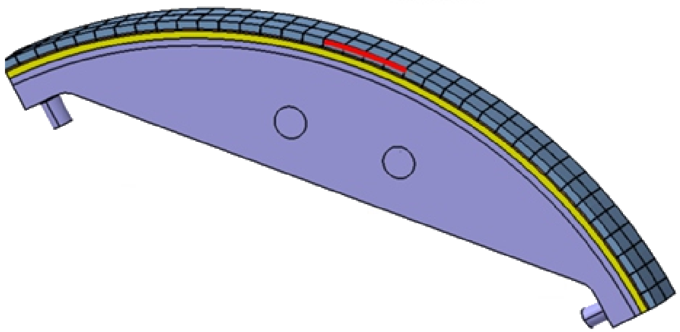
N = 36 × 2 (#BM × #roofs)

Disruption Loads *runaway heat loads - modelling energy deposition*

t_{loss} = 0.1 ms, W_{RE} = 20 MJ, E_{RE} = 12.5 MeV





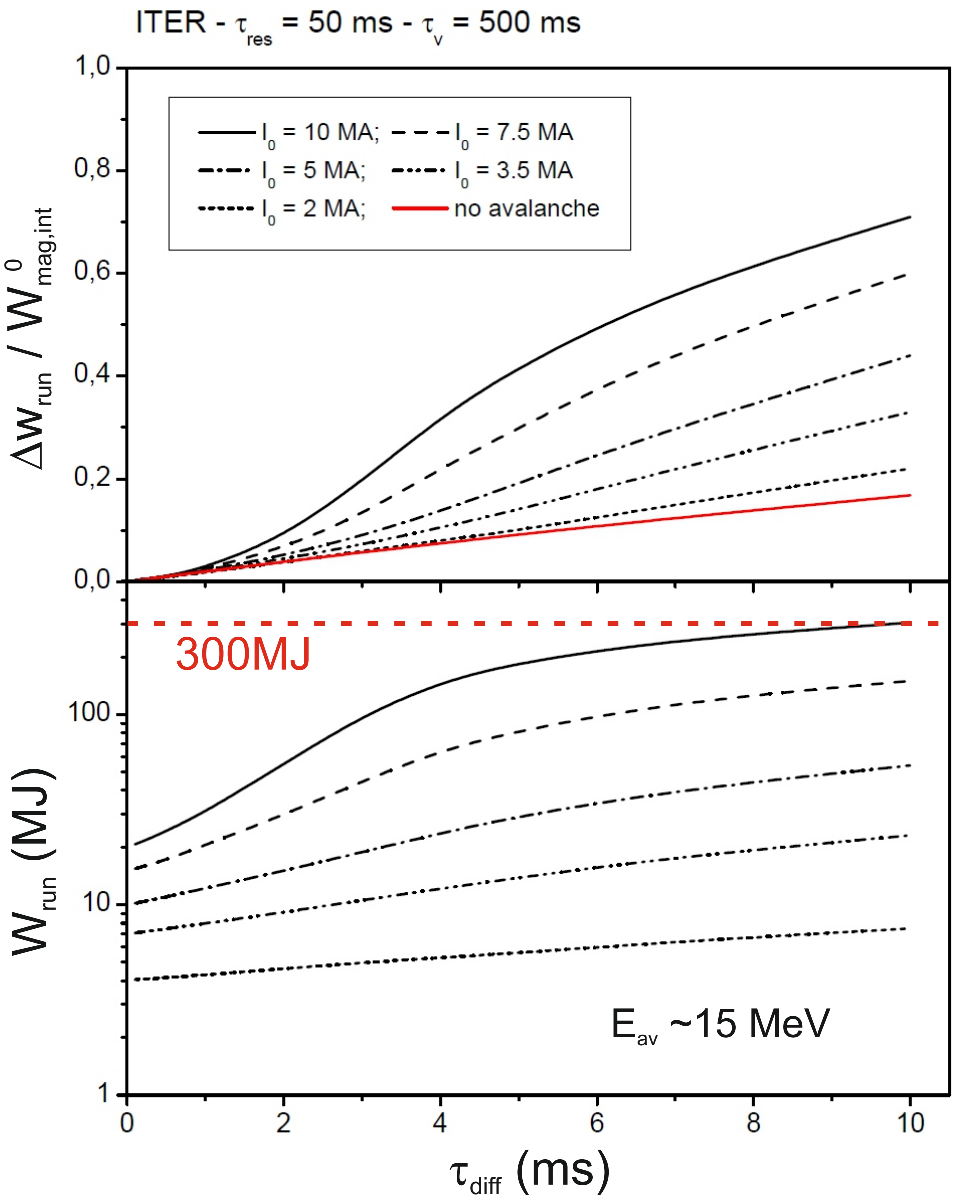


Very serious damage to be expected on first W flat tiles intercepting the RE beam. Cooling interface almost certainly at risk

B. Bazylev, KIT, presented by R. Pitts, FDR W-divertor June 2013

Disruption Loads *runaway electrons - maximum energy*

magnetic energy conversion during the RE loss phase



high energy conversion for high τ_{diff}/τ_{res}

τ_{diff} = effective diffusion time of RE

τ_{res} = L/R time of thermal plasma

up to 300MJ for I_{RE}=10MA and τ_{diff} = 10ms

open questions:

profile shape development

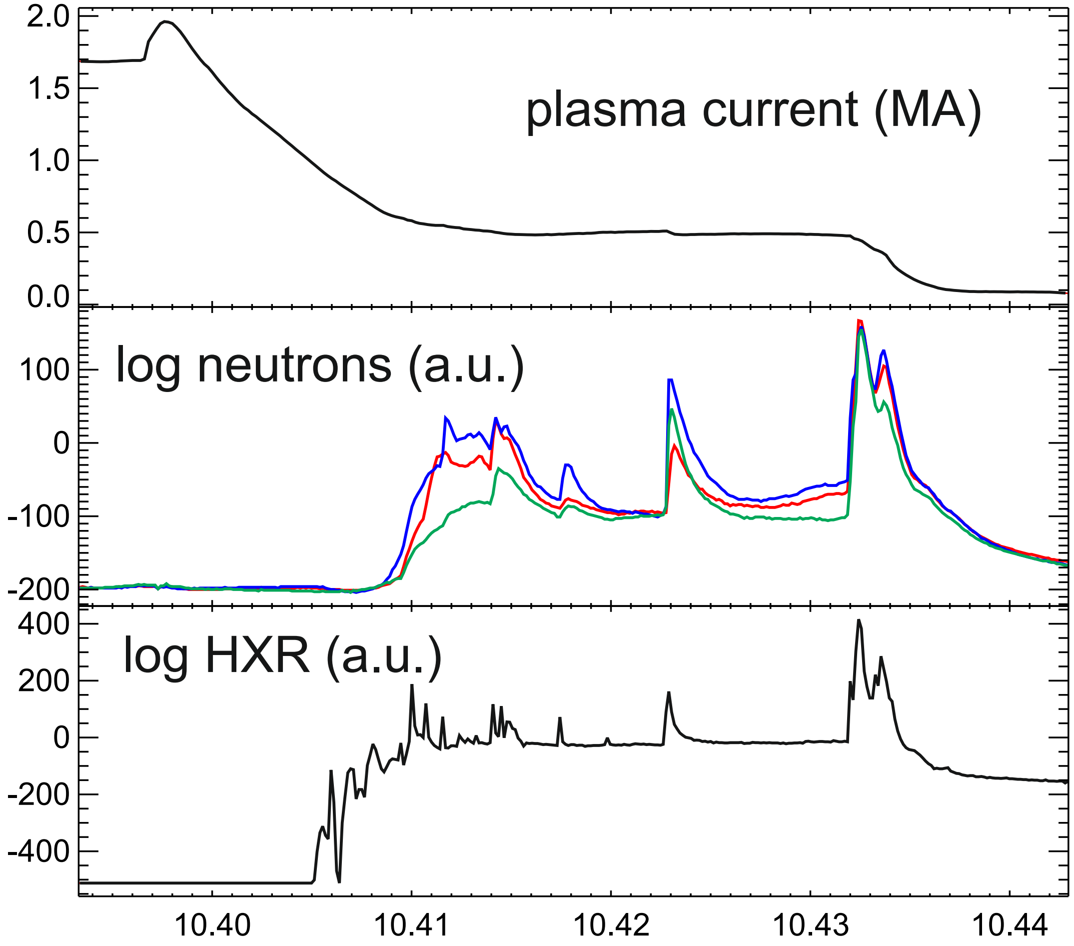
impact of vertical movement

stability boundary for RE beam

J.R. Martín-Solís, submitted to NF 2013
Inter-machine comparison on runaway magnetic energy conversion (FTU,DIII-D,JET).

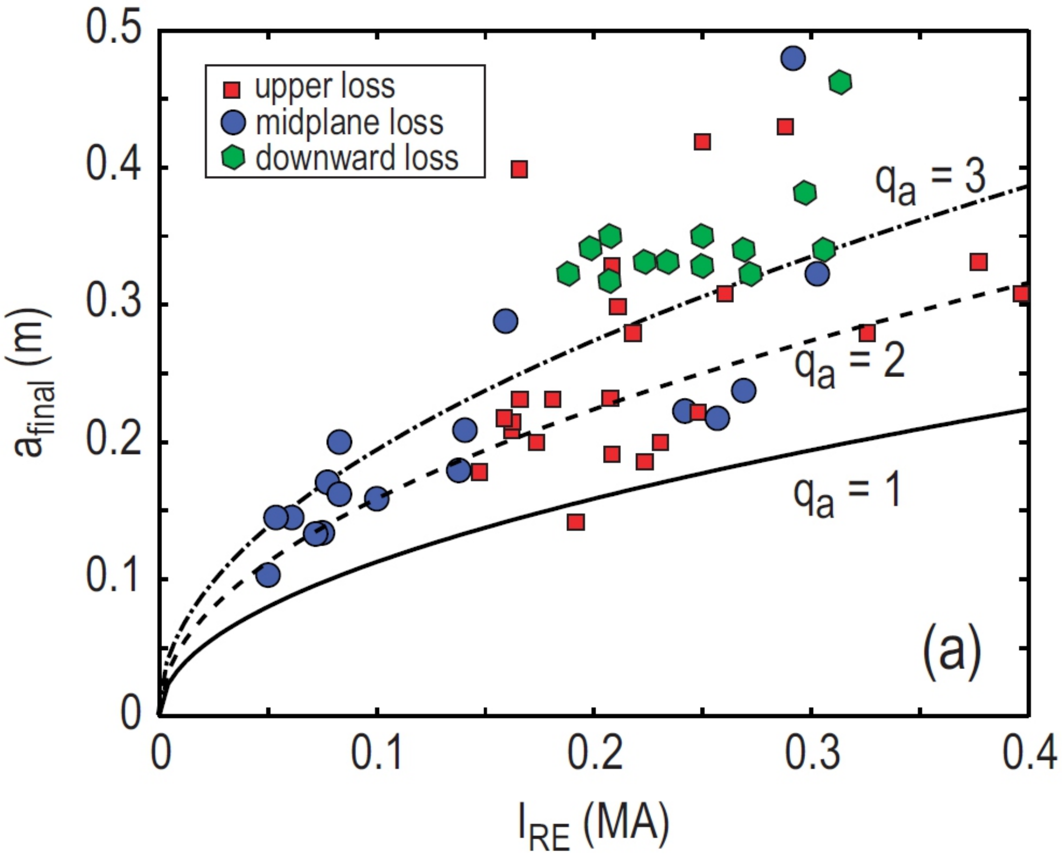
Disruption Loads *runaway electrons - loss mechanism*

JET: RE loss can occur with significant separation in time



MHD causing final loss?!

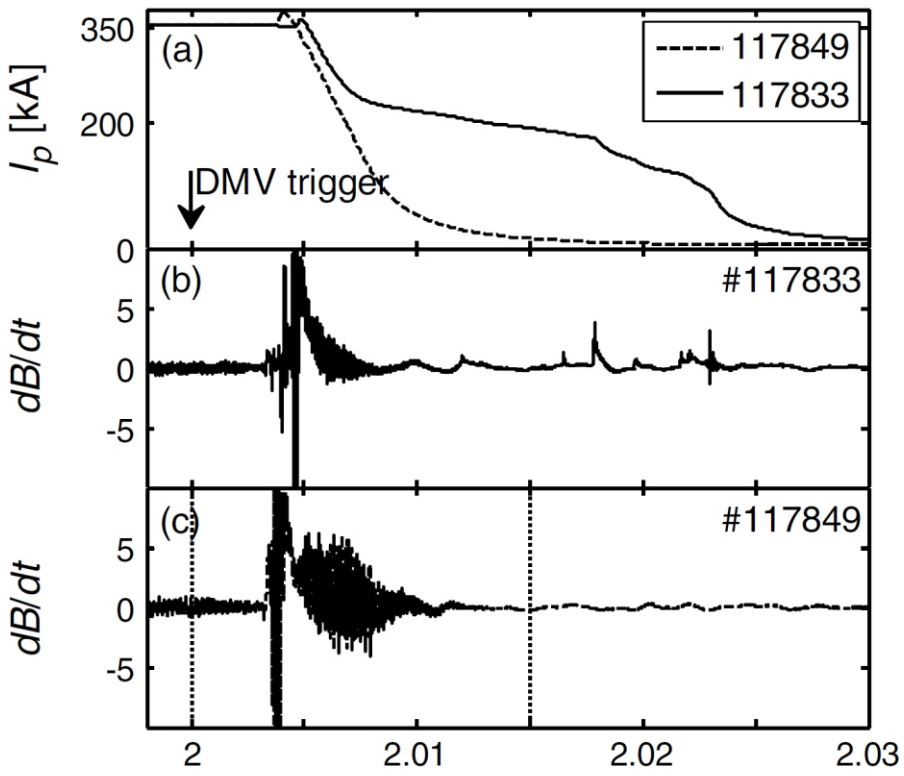
DIII-D: suggesting kink instability but large scatter

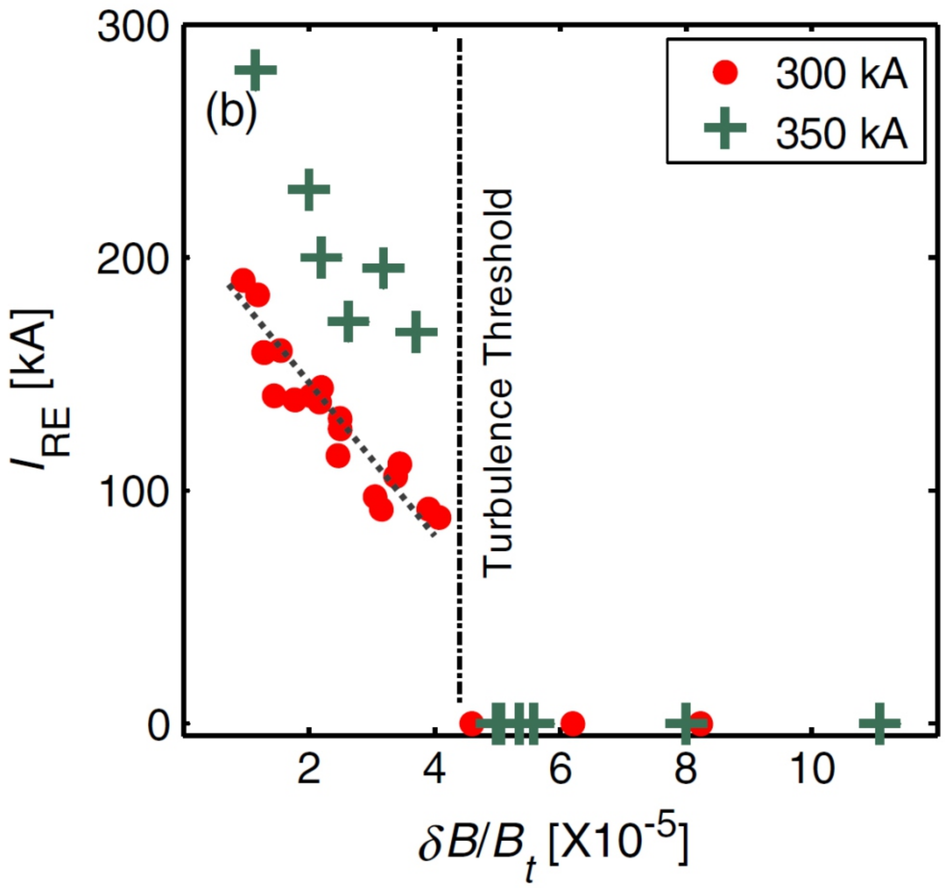


E. Hollmann et al., NF 2013

Magnetic turbulence plays an important role in the RE beam built-up

TEXTOR: threshold in $\delta B/B$





L. Zeng et al., PRL 2013

Disruption Loads - Runaway Electrons

- Energy deposition
  - What is the wetted area/volume?
  - What determines the timescale of energy deposition?
  - What type of instabilities lead to the loss of RE?
  - Total energy and energy distribution?
- Runaway generation
  - How do loss mechanisms influence the RE current?
  - Role of pitch angle scattering (whistler waves, impurities)?
- Runaway position control
  - *with pre-adjusted* Δz*:* I_{RE} > 10 MA, dI_P/dt < 0.5MA/s (initial I_P=15MA)*
  - *without:* I_{RE} > 14.3 MA (limited by VS coil current)*

** V. Lukash, EPS 2013*

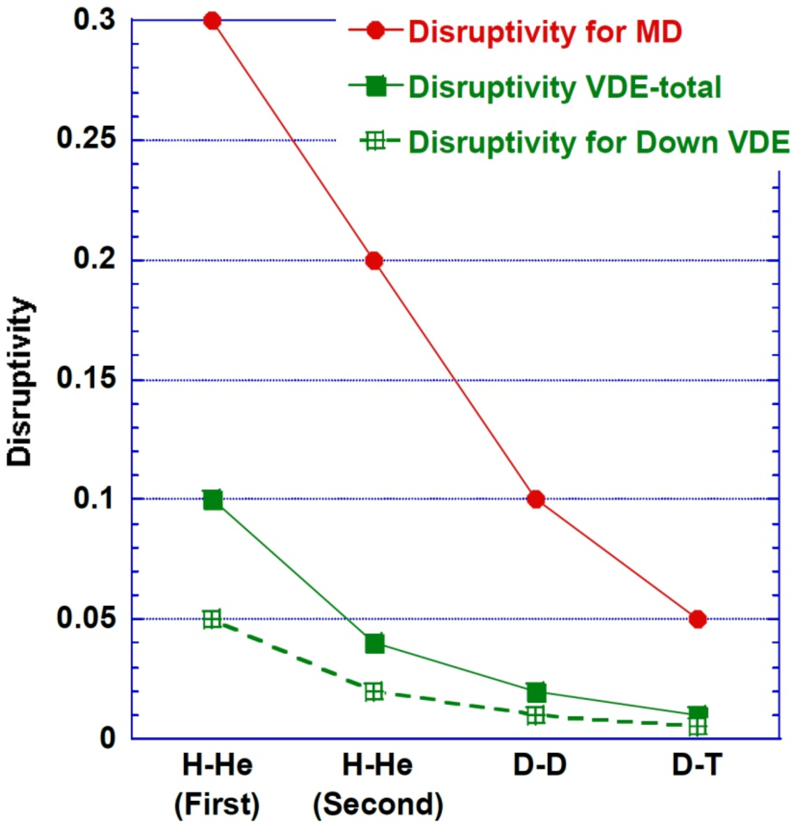
Disruption Mitigation

- Extremely challenging because of the high energies and short time scales
- A lot of work is done, but still the physics basis is limited
- Three systems were reviewed at the CDR in December 2012
  - The necessary response times for the various DMS subsystems, TM, RE suppression, RE dissipation need to be more clearly defined. This is related to latency periods of diagnostics and disruption prediction (warning times).
  - The runaway mitigation goal needs to be validated in experiments.
  - What is the impact of the port location on mitigation efficiency?
  - Physics basis for Be injection is missing.
  - Impact of separation of thermal load mitigation and RE suppression: experimental assessment needed
  - Flexibility of the different concepts to adapt to plasma parameters / disruption situation?
  - RE beam control: DINA calculations to be validated.
- Decision on design has to be taken soon: PDR Aug 2014, FDR Jan 2017

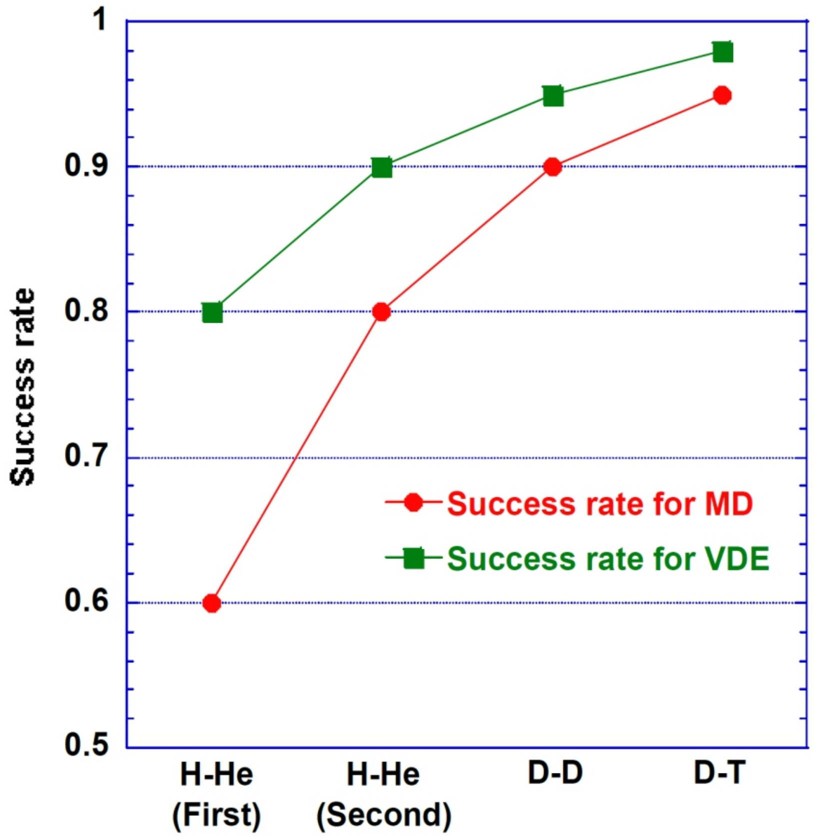
Disruption Mitigation *requirements*

Main driver for mitigation requirements are heat loads to PFCs
(material loss per disruption / material thickness)

Disruptivity
(disruptions/total pulses)



Prediction Success
(mitigated disruptions/total disruptions)



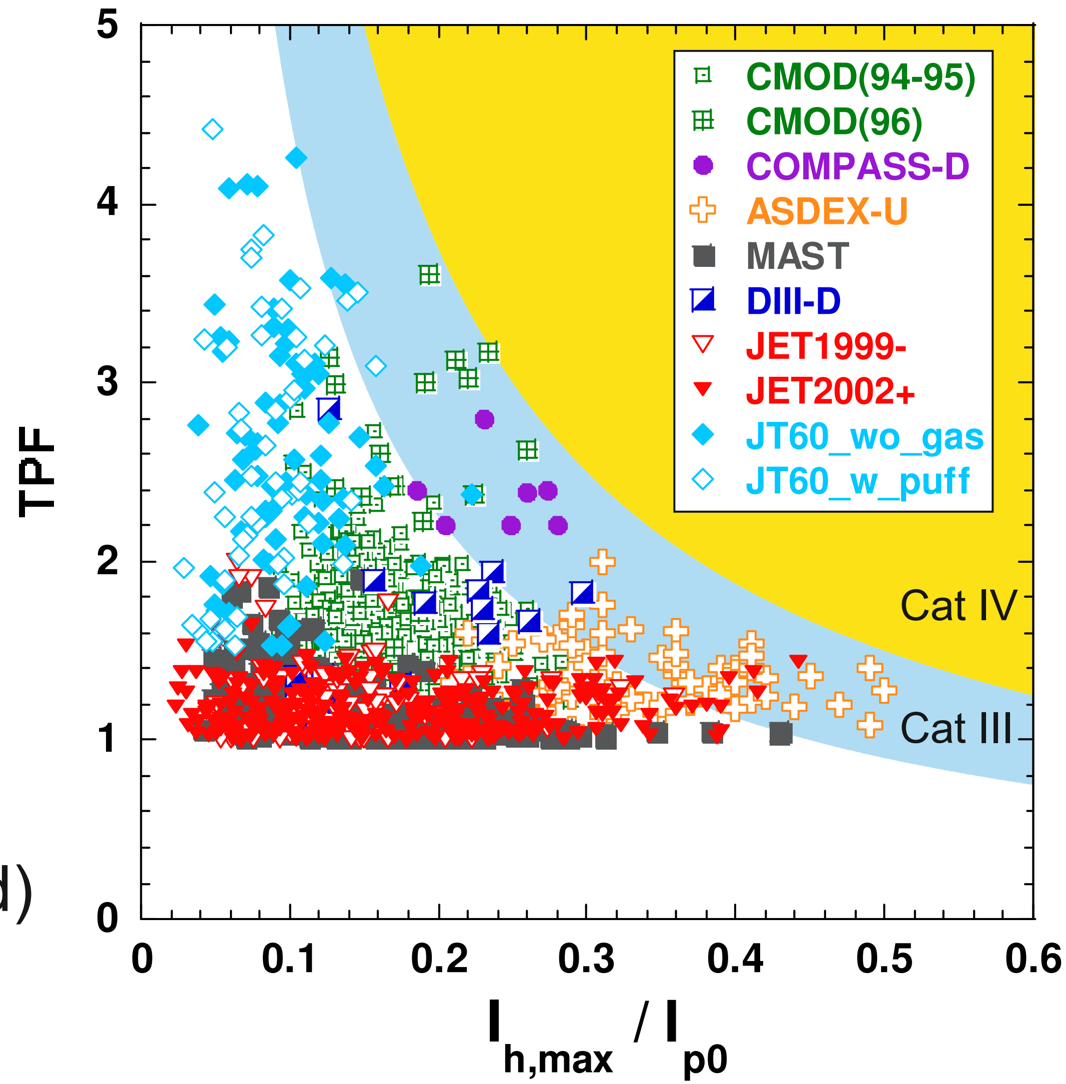
Disruption Mitigation *requirements*

Cat III event: “unlikely”
needs to be converted to Cat I/II
Cat IV event: once in a lifetime, inspection needed, severe impact on further operation

reduce halo currents by factor 2 (corresponds to CQ time < 150ms)

CQ rate to stay above 50ms

limited number of CQ with 36ms allowed (expected to be non-mitigated)



Disruption Mitigation *systems presently under consideration*

Three systems considered for thermal load mitigation (TLM) and runaway suppression (RES):

Massive Gas Injection (MGI) Ne, Ar, He, D2
TLM: <$2x10^{24}$ particles
RES: <$2x10^{25}$ particles

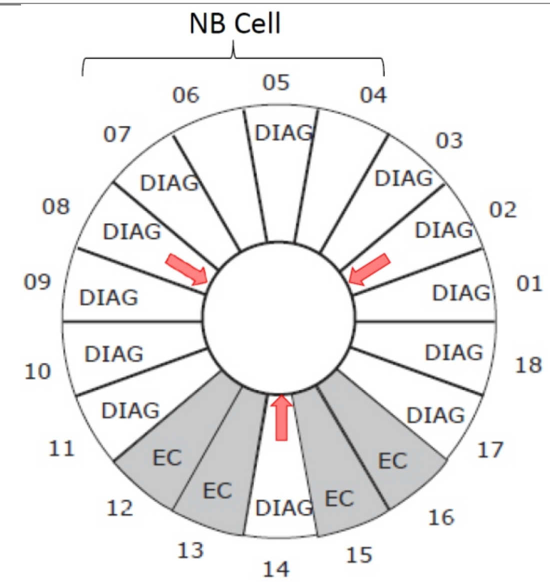
Shattered Pellet Injection (SPI) Ne, Ar, D2
TLM: <$2x10^{24}$ particles
RES: <$2x10^{25}$ particles

Be injection (BEI) order of 100g Be

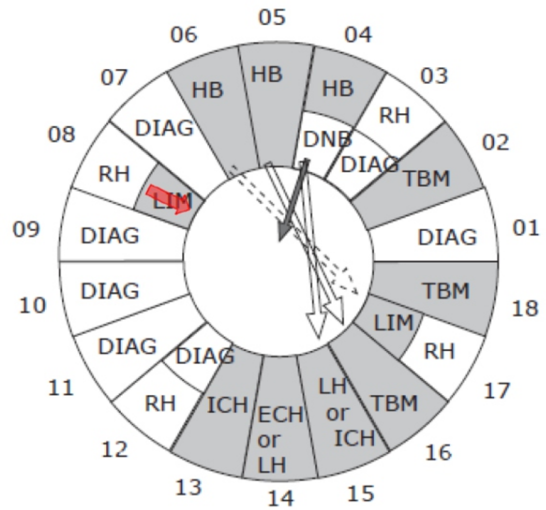
TLM: 4 injection locations (3 upper , 1 mid-plane)
RES: 1 injection location (mid-plane)

TLM and RES independent systems (time delay possible)

all system are presently considered to be inside the port plug as close as possible to the plasma to reduce reaction times and to ensure sufficient material being delivered before the TQ



Upper port
#02, 08 and 14



Equatorial port
#08

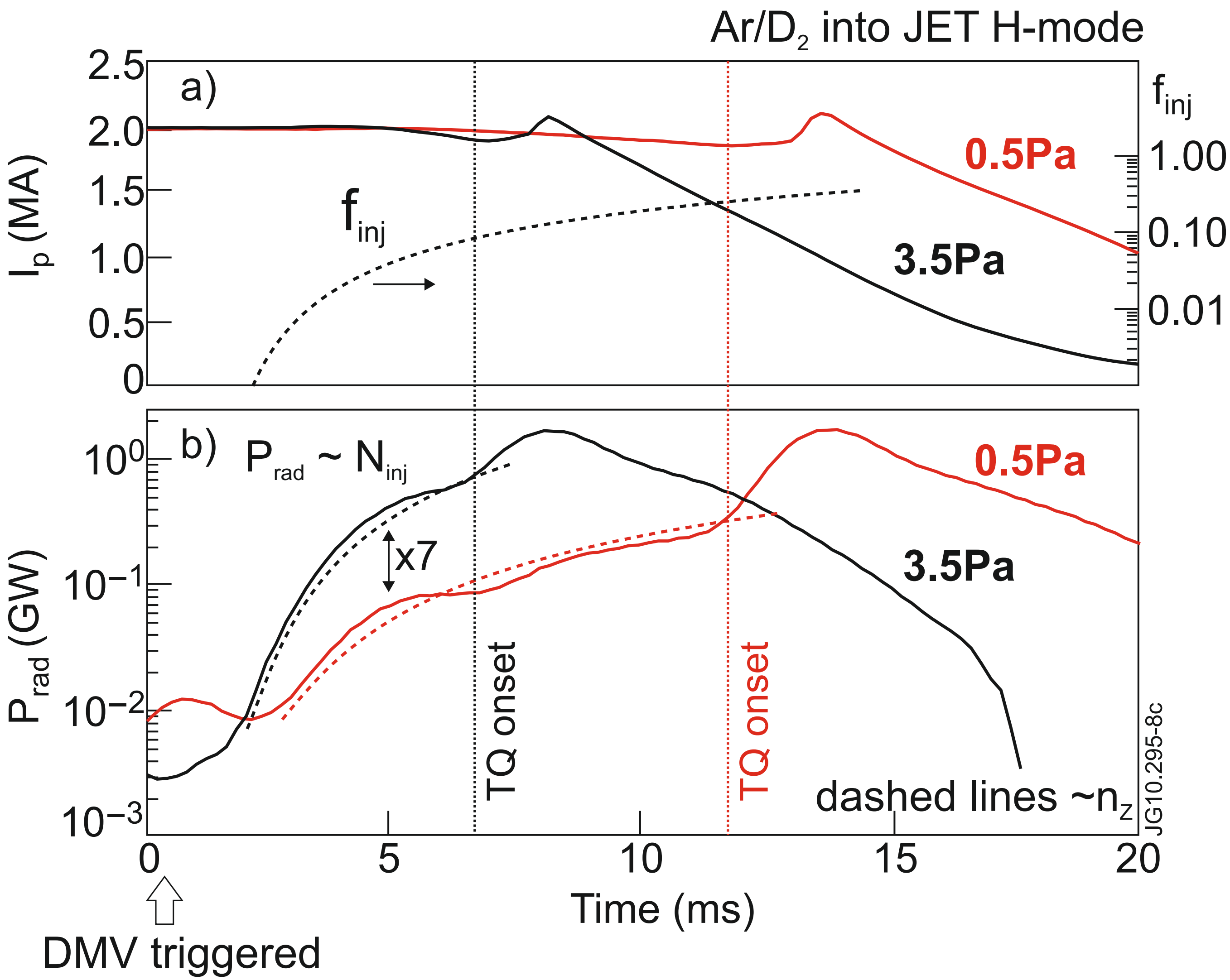
Disruption Mitigation *issues*

- radiation distribution — *pre-TQ: injector distribution*
  TQ: MHD dominated
- radiation efficiency — *> 90% is required for TQ duration 1-3ms*
  radiation in competition to MHD enhanced transport
  dependence on injector location?
- mass penetration — *MGI: impurity transport on timescale ~10ms*
  TQ onset in case of MGI or SPI?
  Ablation and assimilation of SPI?
  Efficiency of penetration into CQ plasma?
  Role of MHD for assimilation efficiency?
- runaway suppression — *densification to Rosenbluth density necessary?*
  runaway control possible?
  role of magnetic turbulence?

Disruption Mitigation System *timescales*

TQ onset after a certain fraction of thermal energy has been radiated

This determines the pre-TQ duration for MGI



higher flow rate

⇩

shorter pre-TQ

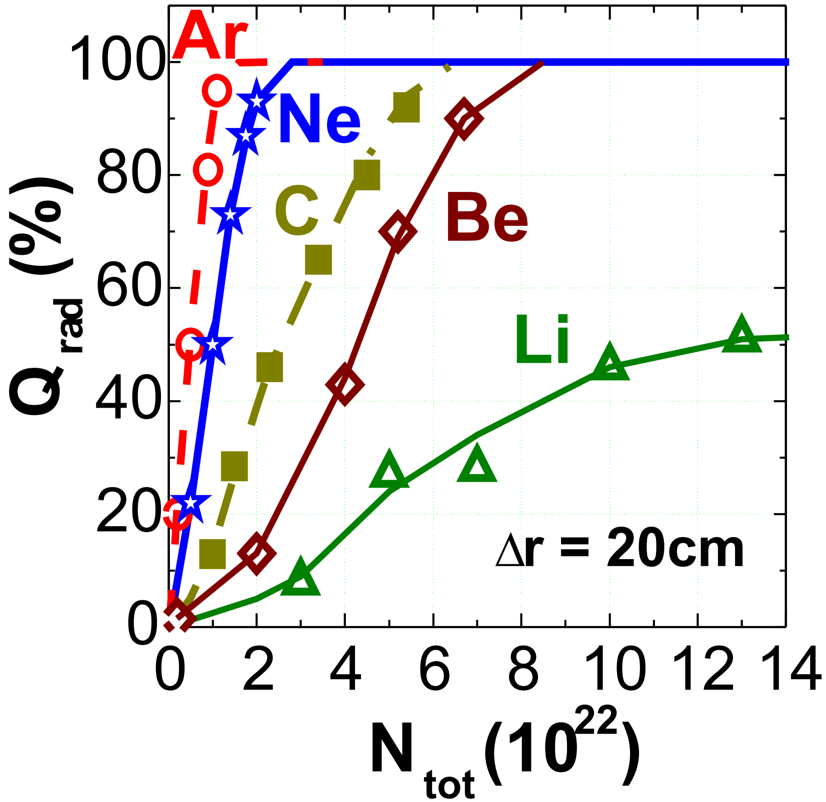
extrapolation to ITER?

determines distance of MGI valve to plasma

M. Lehnen et al., Nucl. Fusion 2011

Disruption Mitigation System *TQ mitigation coupled to CQ mitigation*

CQ speed is coupled to Thermal Load Mitigation - optimisation of TLM quantity and composition needed to avoid to fast a CQ and RE generation



Dependence of radiated power fraction on impurity content at radiating layer of 20 cm width

DINA/ASTRA simulations

	N_{tot}, 10^{22}	T_e eV	I_{RE}, MA	t_{CQ}, ms
Ar	1	4.9	7.0	16
Ne	2	6.6	6.8	33
C	5.4	3	6.6	12
Be	6.6	20	0.08	320
Li	14 (60%) too low	13	1.4	145

too short

too long

RE free without additional seed

S.V. Konovalov, Fusion Energy Conference, San Diego, USA, October 2012

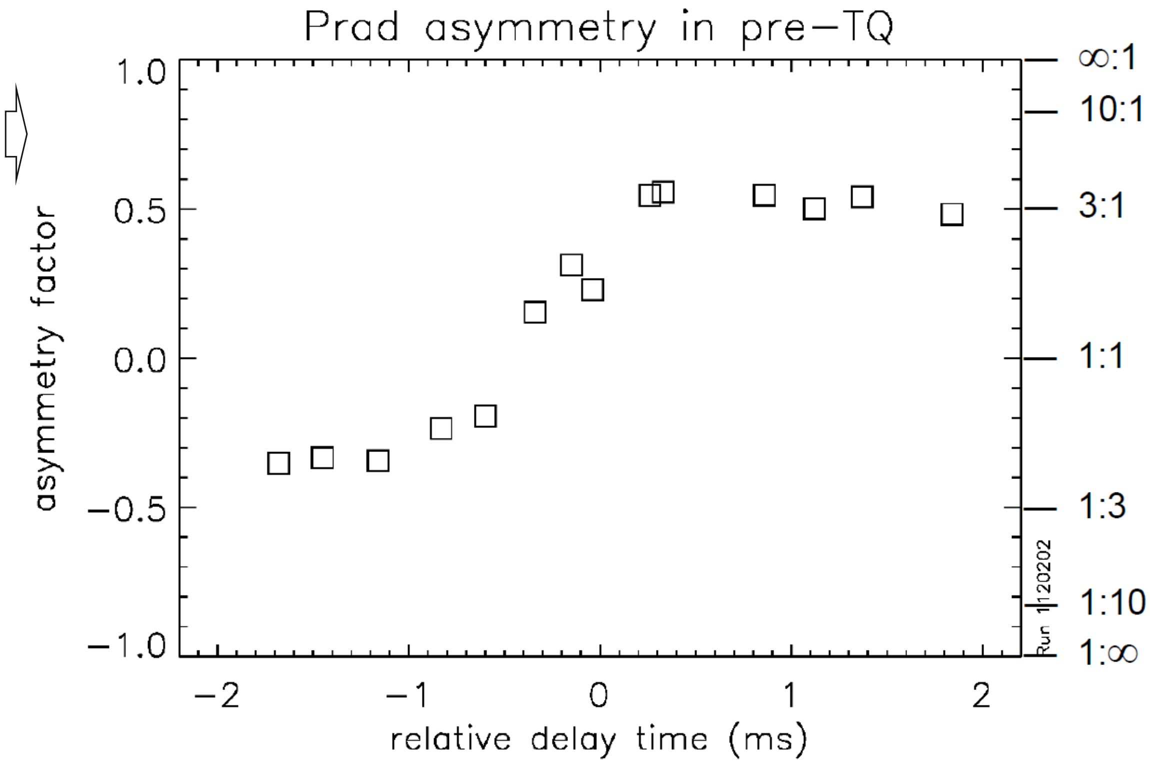
Disruption Mitigation *radiation asymmetry*

Radiation peaking can cause melting of Be or other components facing the plasma (incl. diagnostics)

$PPF \times TPF \times \Delta E_{th} \Delta t^{-1/2} S^{-1} \approx 17\text{-}58\ MJ\ s^{-1/2} m^{-2}$ (pre-TQ) / $17\text{-}51\ MJ\ s^{-1/2} m^{-2}$ (TQ)

pre-TQ and TQ: $33\text{-}105\ MJs^{-1/2}m^{-2}$ (1.5-4.0 × melt limit)*

C-mod: pre-TQ asymmetry can be controlled with multiple injectors



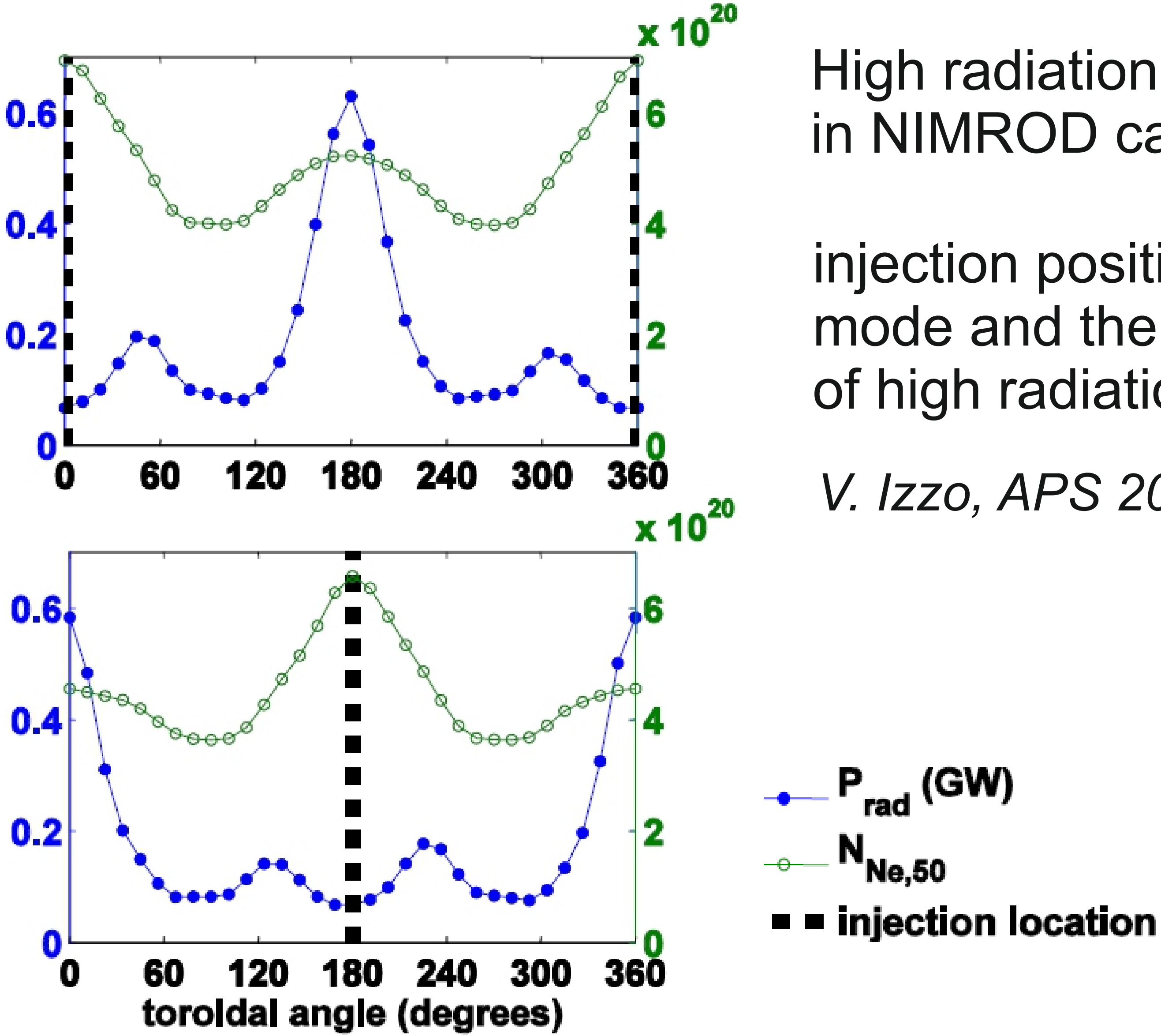
Asymmetry during TQ?

Radiation asymmetry during SPI?

*first report on radiation asymmetries of WG-8 / ITPA MHD

R. Granetz, ITPA-MHD Oct 2012

Disruption Mitigation *radiation asymmetry*



High radiation peaking observed in NIMROD calculations with TPF = 3.5

injection position determines phase of n=1 mode and therewith the position max P_{rad} of high radiation

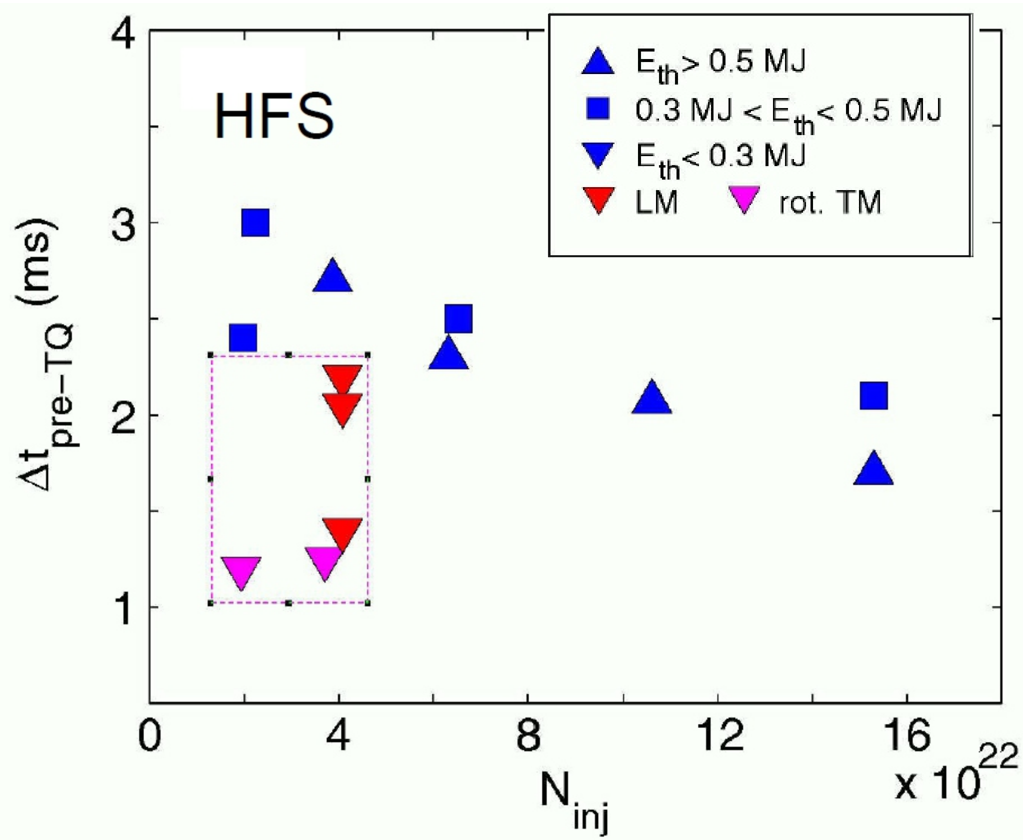
V. Izzo, APS 2012

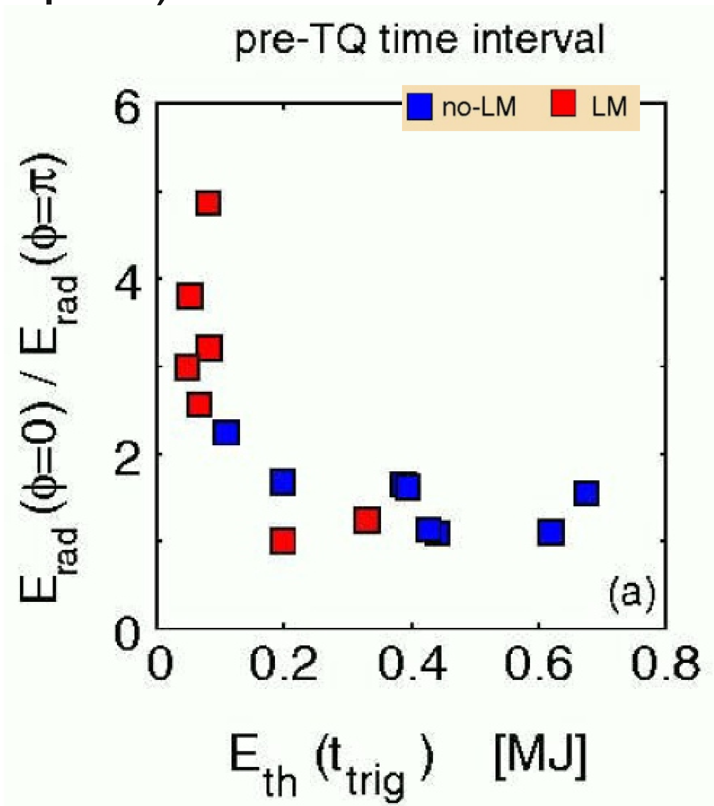
Disruption Mitigation *"unhealthy" plasmas*

Mitigation efficiency might be degraded in plasmas close to disruptions (displaced, modes, etc.) - these plasmas are actually the target for the DMS

Impact on injection/ablation efficiency, radiation distribution, mitigation efficiency

AUG: TQ onset much earlier ⇨ less time to inject gas
pre-TQ radiation asymmetry higher, but E_{th} lower
TQ: $E_{rad}(0) / E_{rad}(\pi) \sim 0.8\text{-}1.8$ (LM has no impact)





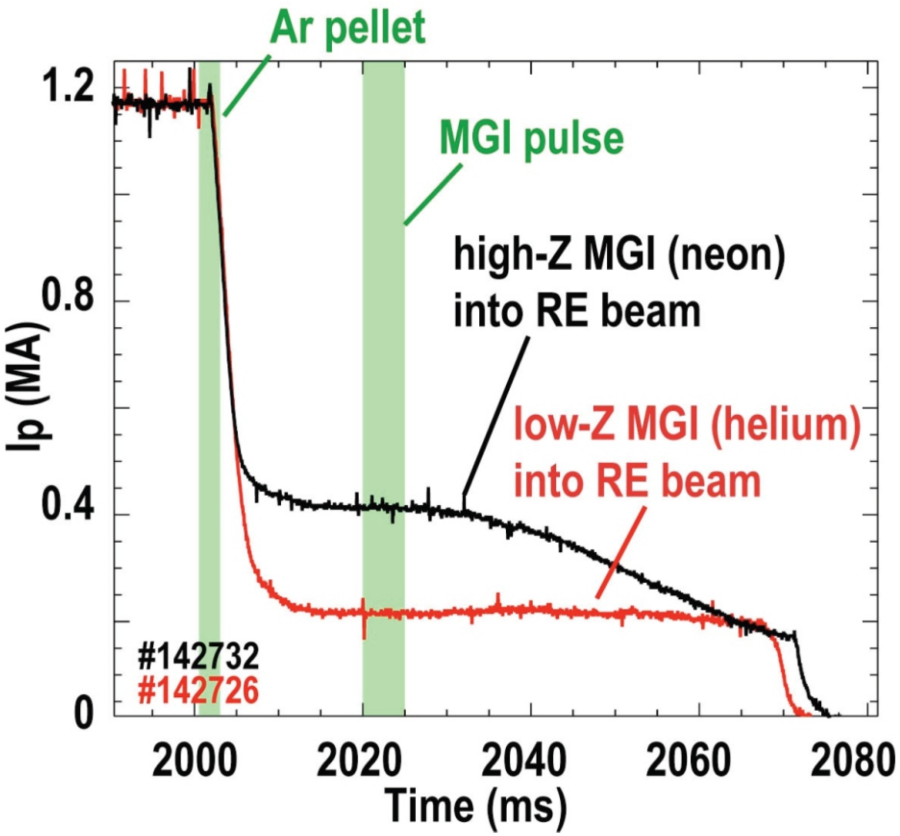
G. Pautasso et al., EPS 2013

Disruption Mitigation *RE scattering by impurities*

pitch angle scattering caused by impurities

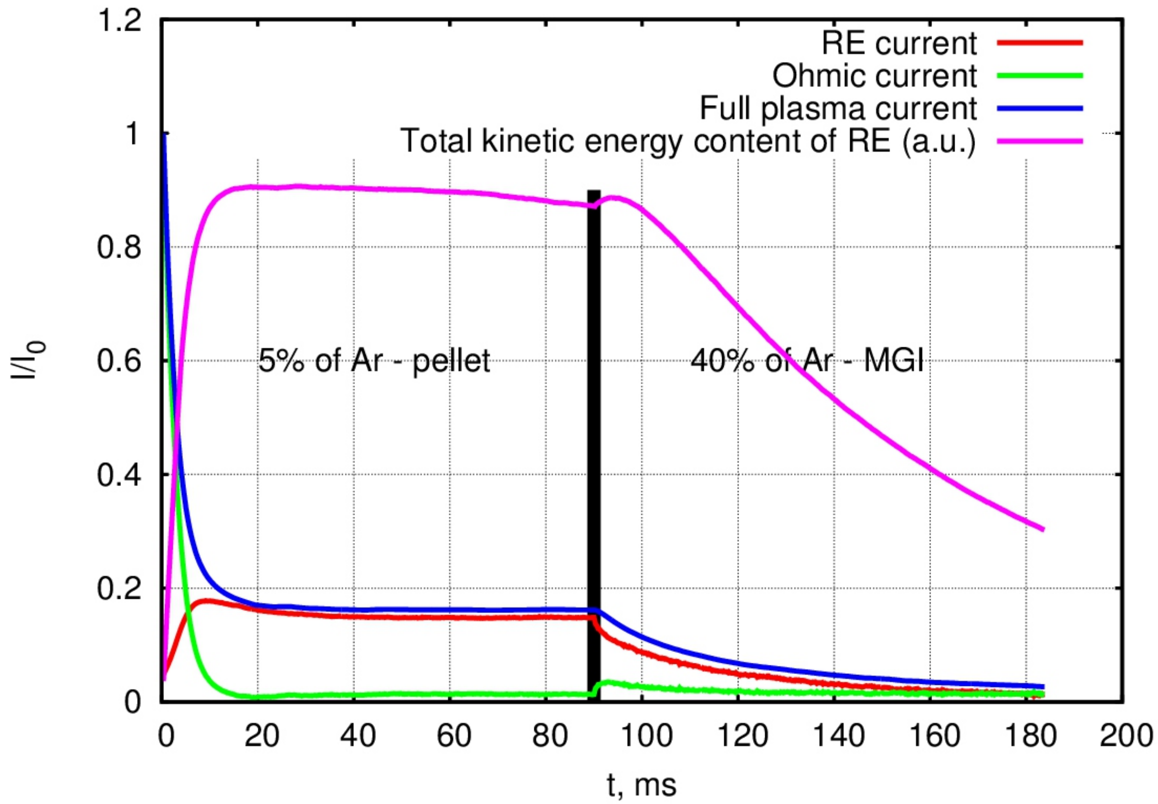
➡ energy dissipation by synchrotron radiation on fast timescale

DIII-D: Impurity injection in RE beam



E. Hollmann et al., IAEA 2012

Model: RE/impurity pitch angle scattering and synchrotron emission



K.O. Aleynikova, P.B. Aleynikov, et al., EPS2013

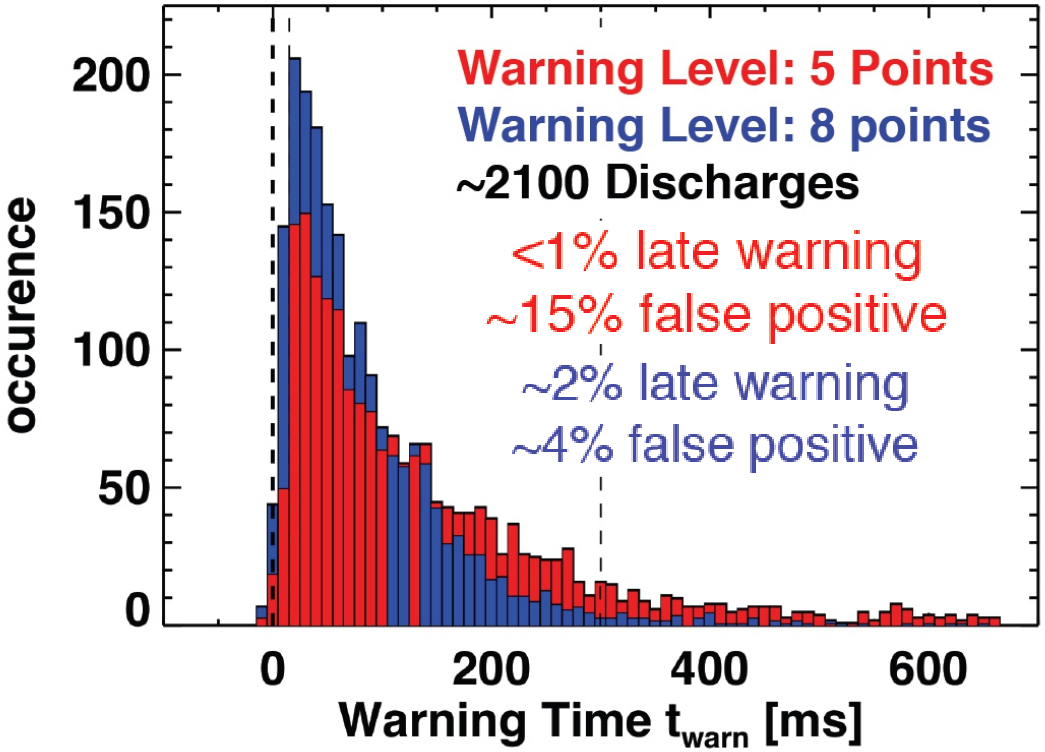
Disruption Mitigation *prediction and avoidance (plasma control/specific action)*

How to extrapolate
- *response times (growth times)*
- *corrective actions (heating/current shaping/etc)*
- *indicator (mode amplitudes, gradients, etc.)*

to ITER?

Neural networks and related tools are successful, but limited portability
- probably no option for ITER

Deeper understanding of chain of events leading to a disruption and identification of corrective actions to apply is needed



Disruption prediction in NSTX with compound threshold tests*

Both raw diagnostic data and comparisons to simple models can contribute to prediction.

Single diagnostic test not sufficient *(JET: simple locked mode detection very efficient)*

**S.P. Gerhardt, IAEA 2012 San Diego*

Summary

- Rotating aVDEs are very critical for ITER
  what drives the rotation, what is the expected rotation in ITER,
  what determines the current distribution?
- Heat fluxes in unmitigated disruptions are likely to cause melting of PFCs
  what are the thermal quench properties: timescales, heat flux distribution?
- Heat loads by runaways are critical with respect to investment protection, they may be a safety issue if they cause large water leaks
  what drives the RE loss and the related energy deposition on PFCs,
  what are potential suppression mechanisms?
- The requirements for disruption mitigation in ITER are challenging
  further physics understanding is necessary to chose the right strategy
- Disruption prediction has to be very reliable in ITER already in the early phase (W-divertor)
  not much room to teach predictors
  extrapolation from "training" range needs quantitative understanding