Impact and mitigation of disruptions with the ITER-like wall in JET

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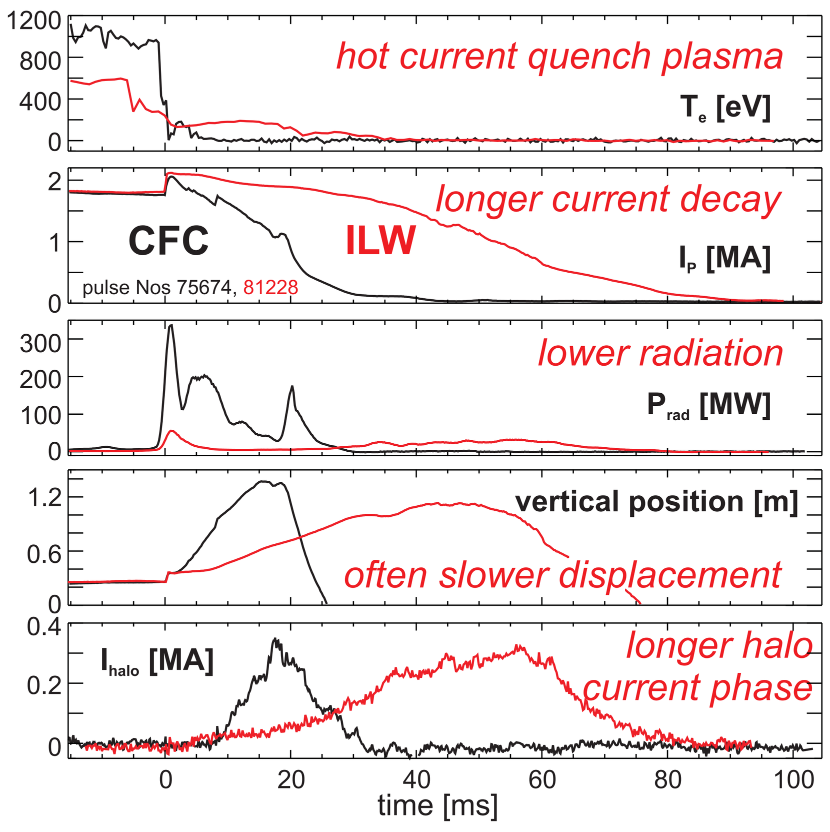
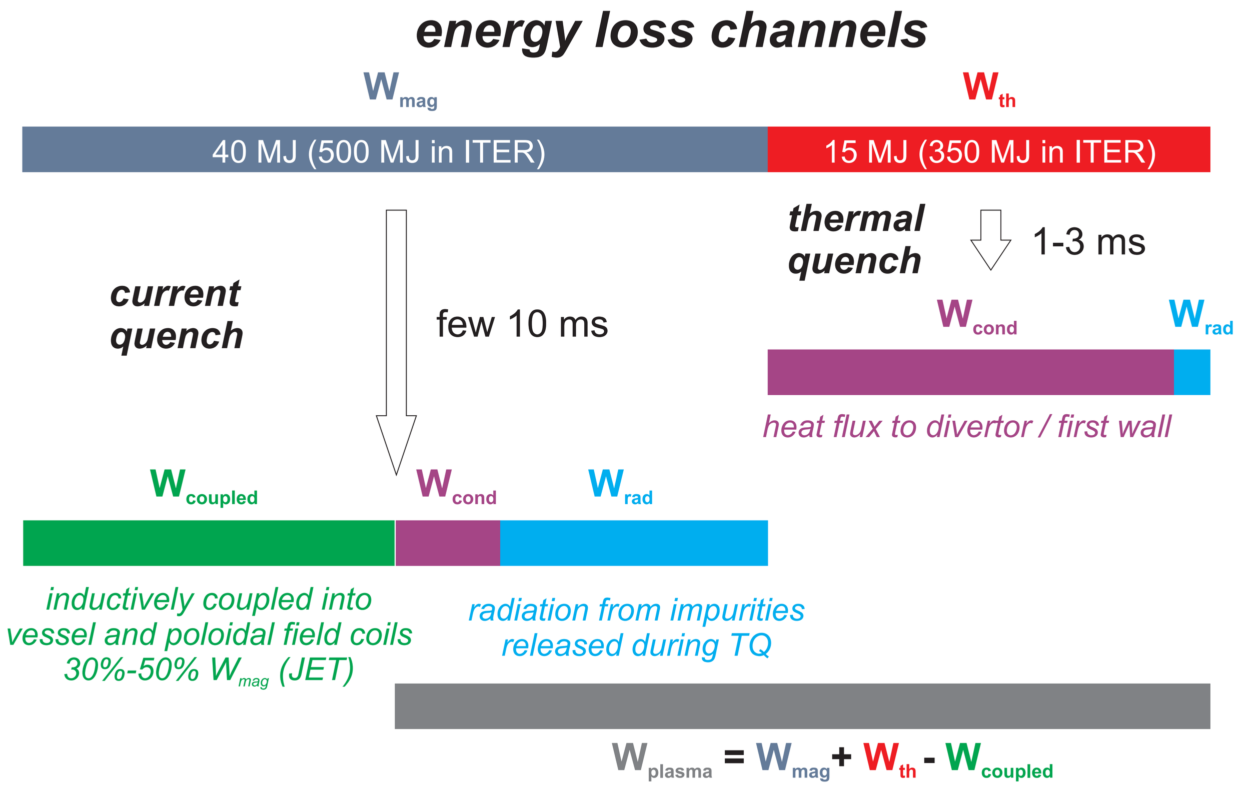
*see the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US

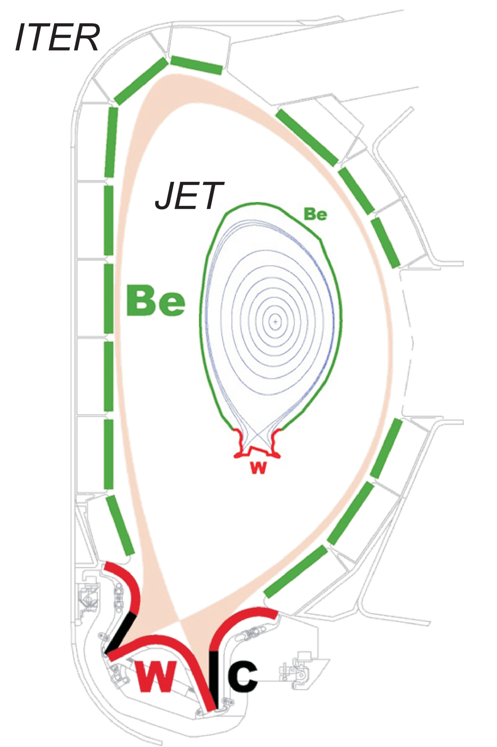
Introduction / Summary

Disruptions are a critical issue for ITER because of the high thermal and magnetic energies that are released on short time scales, which results in extreme forces and heat loads [1]. The choice of material of the plasma facing components (PFCs) has impact on heat load capabilities but also on the disruption properties themselves. Main change with the implementation of the **ITER-like wall (ILW)** in JET (main chamber: beryllium, divertor: tungsten) is a **low fraction of radiation during disruptions**. This has significant implications: a) a **hot current quench plasma**, b) **long current decay times** (often limited by vertical displacement), c) **high heat loads** caused by conduction of magnetic energy, d) **higher halo current and sideways impact**.
Massive gas injection mitigates the loads and is essential to protect the ILW from high heat loads and mechanical stresses.



energy loss channels





Disruption Properties - Radiation

CFC

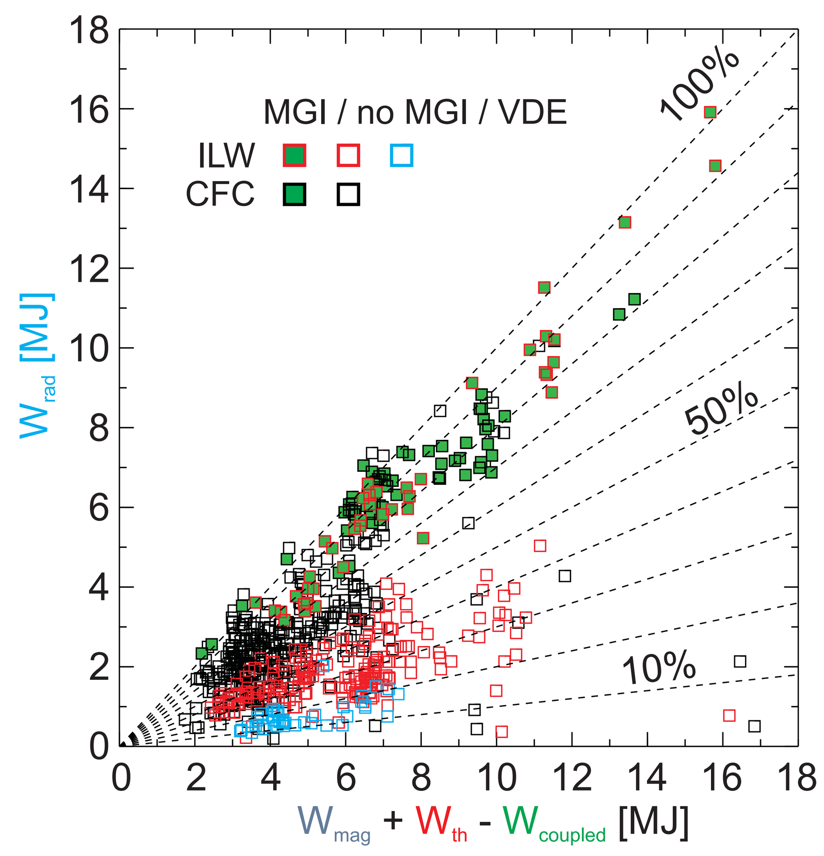
High fraction of radiated energy from 50% up to 100% of the available energy in the plasma.

ILW

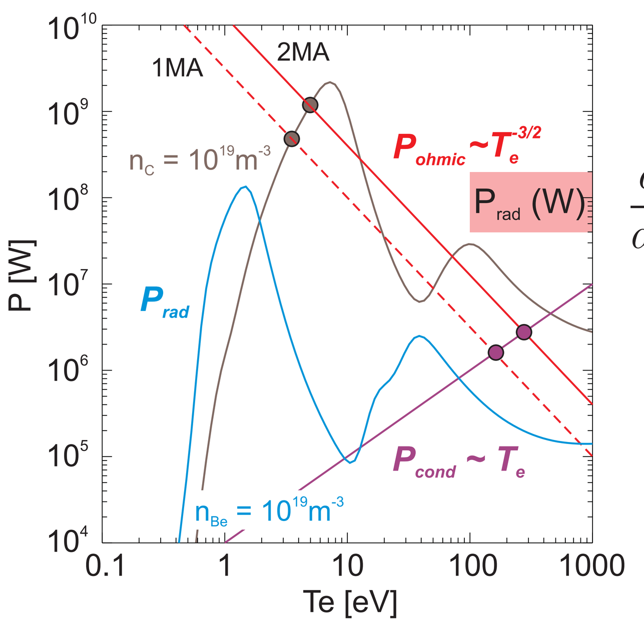
Low fraction of radiated energy at maximum around 50%. Lowest fraction for VDEs with only 10% of W_{plasma}.

MGI

High level of radiation between 70% and 100%. Scatter results from different injected species, valve pressure or timing.



Power balance during the current quench



$$\frac{d}{dt}W_{mag} = -P_{coupled} - P_{ohmic}$$

$$\frac{d}{dt}W_{th} = P_{ohmic} - P_{rad} - \underbrace{P_{cond}}_{W_{th}/\tau_{th}}$$

ITER-like wall (Be)

$P_{ohmic} \gg P_{rad}$

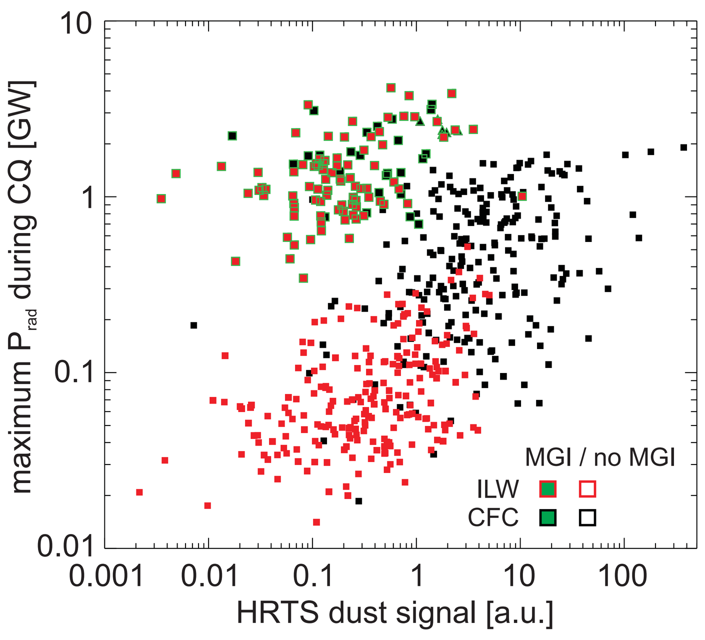
⇨ high temperature
⇨ slow current decay
⇨ significant P_{cond}

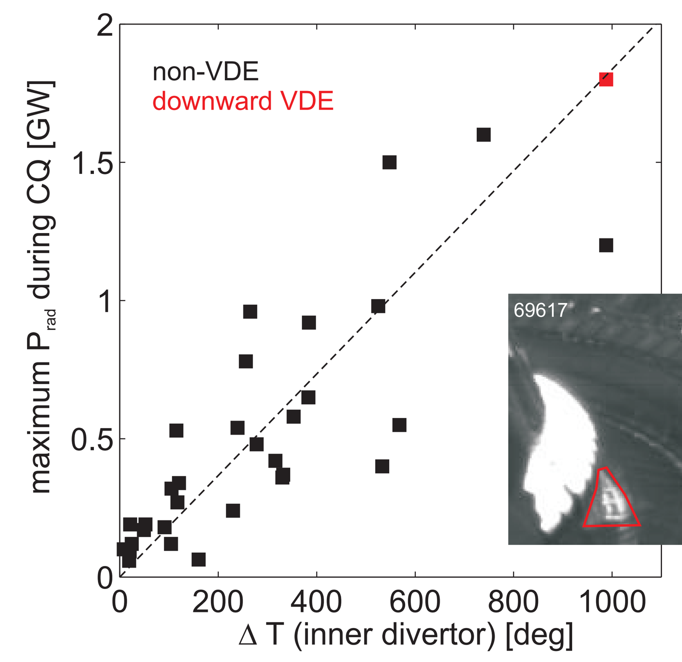
CFC wall

$P_{ohmic} \approx P_{rad}$

⇨ low temperature
⇨ fast current decay
⇨ negligible P_{cond}

Impurity source / dust





reduction of dust with ILW by factor 10-100
peak radiated power during CQ is related to dust mobilisation or production

peak radiated power as indicator for impurity density
temperature rise in the inner divertor related to thermal decomposition of C layer

Disruption Properties - Timescales

CFC

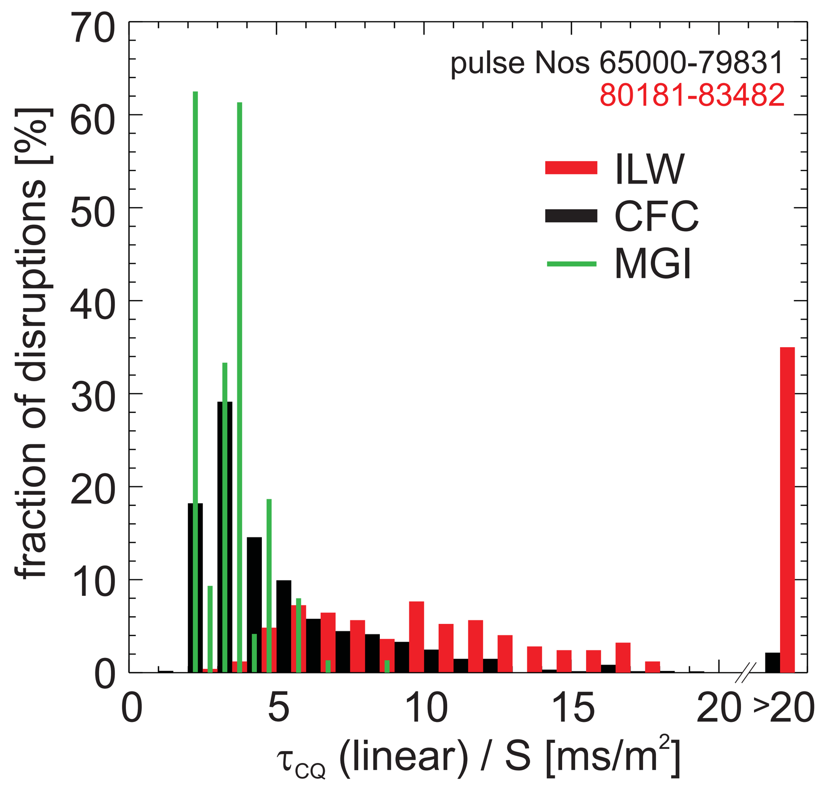
High radiation fraction causes fast current quenches. Distribution peaks around 3ms/m².

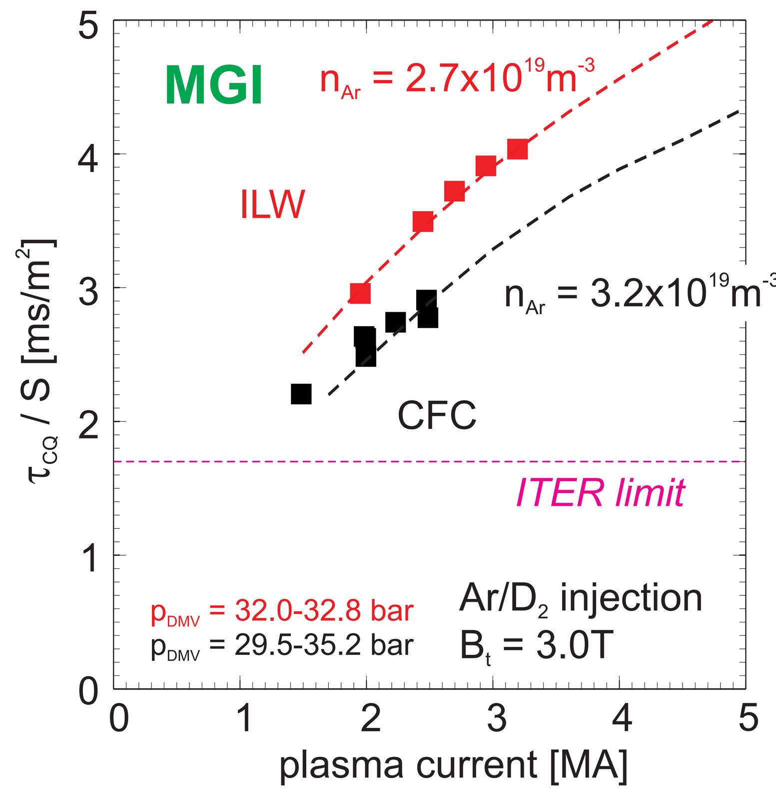
ILW

Slower current quenches with broad distribution. More than 30% of all disruptions have current quench times longer than 20ms/m².

MGI

Fast current quenches recovered. Tendency towards slightly slower current quench with ILW.





Disruption Properties - Electro-magnetic loads

Symmetric halo and **eddy** currents: **vertical force causing rolling motion** of the vessel
Asymmetric halo currents: radial vessel displacement
Displacement increases with **impulse** (time integrated force)

CFC

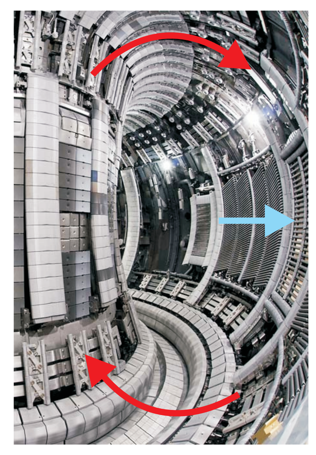
A maximum I_H/I_P of around 0.2 is reached for non-VDE at t_{CQ}= 20-30ms. This limits the impulse and the vessel stresses.

ILW

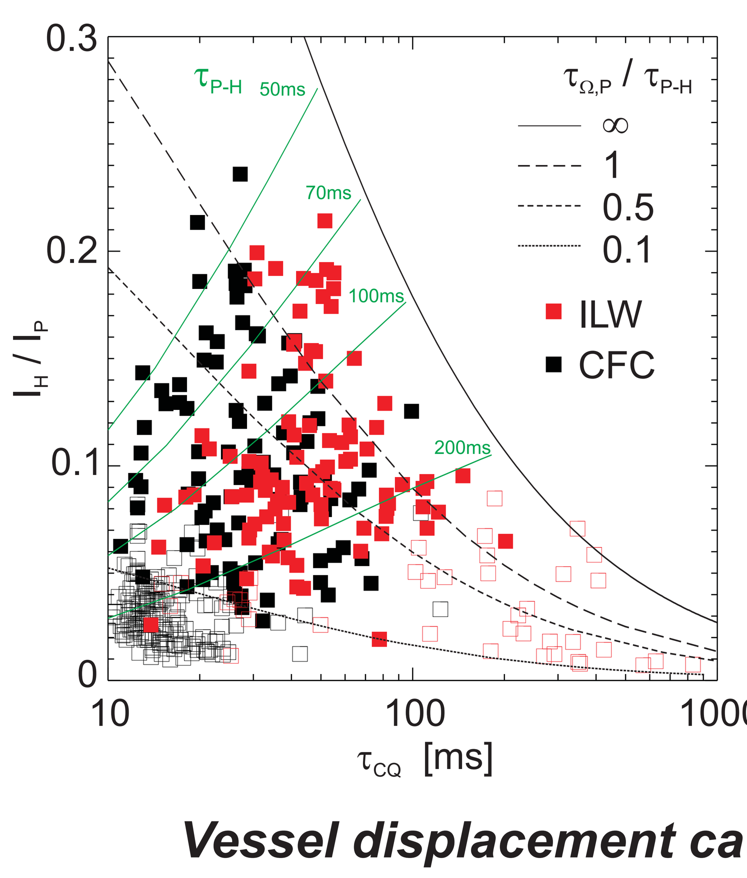
The same peak values of I_H/I_P as with CFC but at longer CQ times: higher halo current impact and also higher sideways impact. Very long CQ with low I_H/I_P found for vertically stable plasma (long τ_{CQ} allows for shape control).

MGI

Accelerates the CQ and by this reduces halo and sideways impact. Higher eddy current forces.



Halo current fraction and current quench time



$\tau_{\Omega,H}$ = 30ms

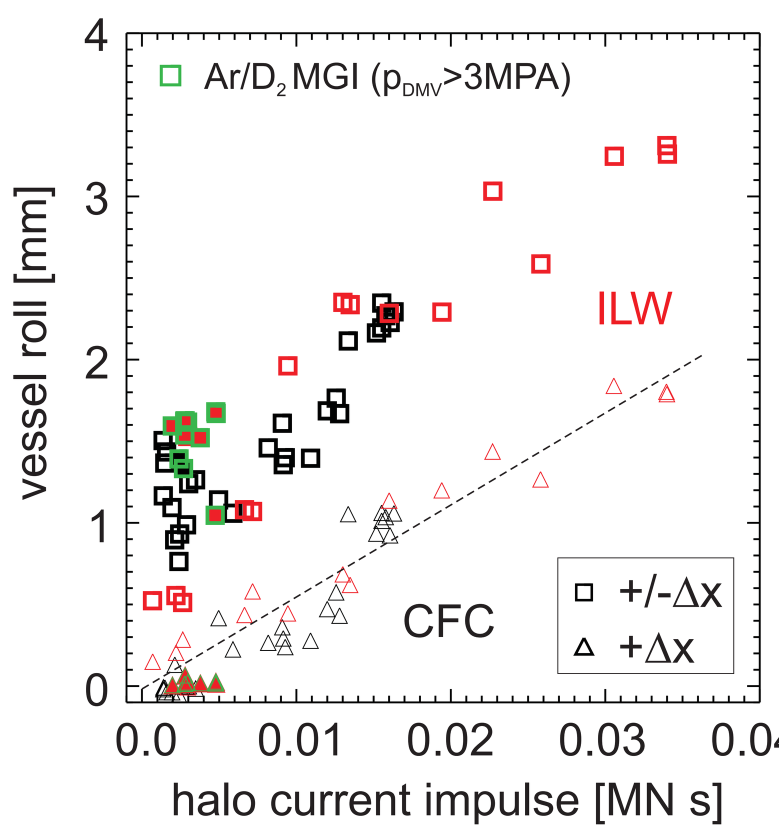
closed symbols:
Δz > 0.4m at 70%I_P(0)
open symbols:
Δz < 0.4m at 70%I_P(0)

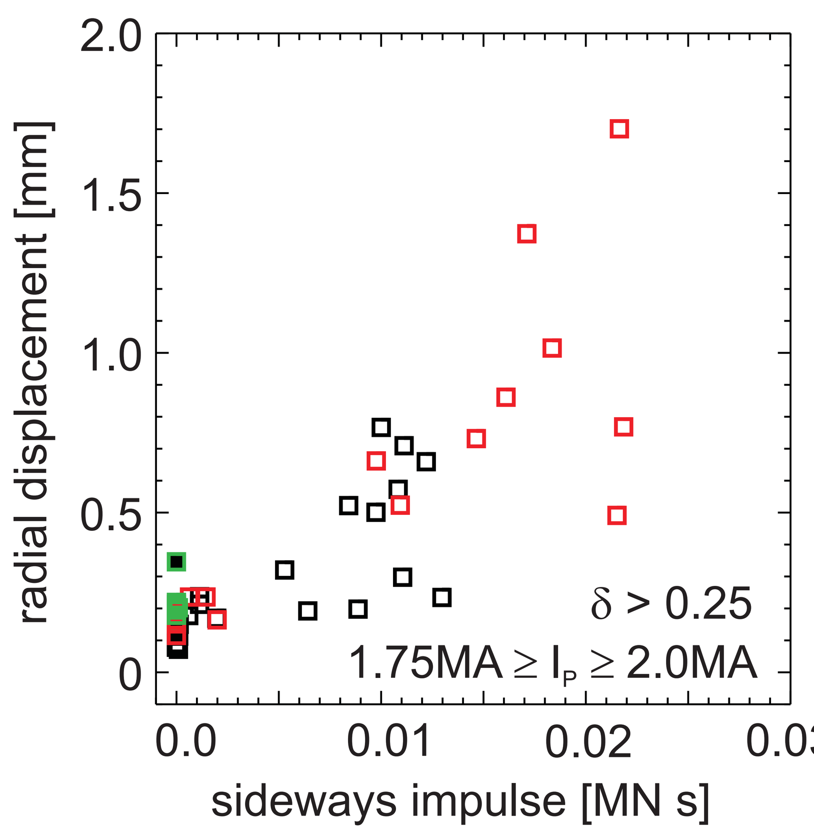
***simple picture:** maximum I_H/I_P determined by resistive time of the plasma $\tau_{\Omega,P}$ and the halo current $\tau_{\Omega,H}$ and the transfer time τ_{P-H} (vertical displacement)*

$$\frac{dI_H}{dt} = -\frac{I_H}{\tau_{\Omega,H}} + \frac{I_P}{\tau_{P-H}}\,, \quad \frac{dI_P}{dt} = -\frac{I_P}{\tau_{\Omega,P}} - \frac{I_P}{\tau_{P-H}}$$

with current quench time $\tau_{CQ}^{-1} = \tau_{\Omega,P}^{-1} + \tau_{P-H}^{-1}$

Vessel displacement caused by halo and sideways impact





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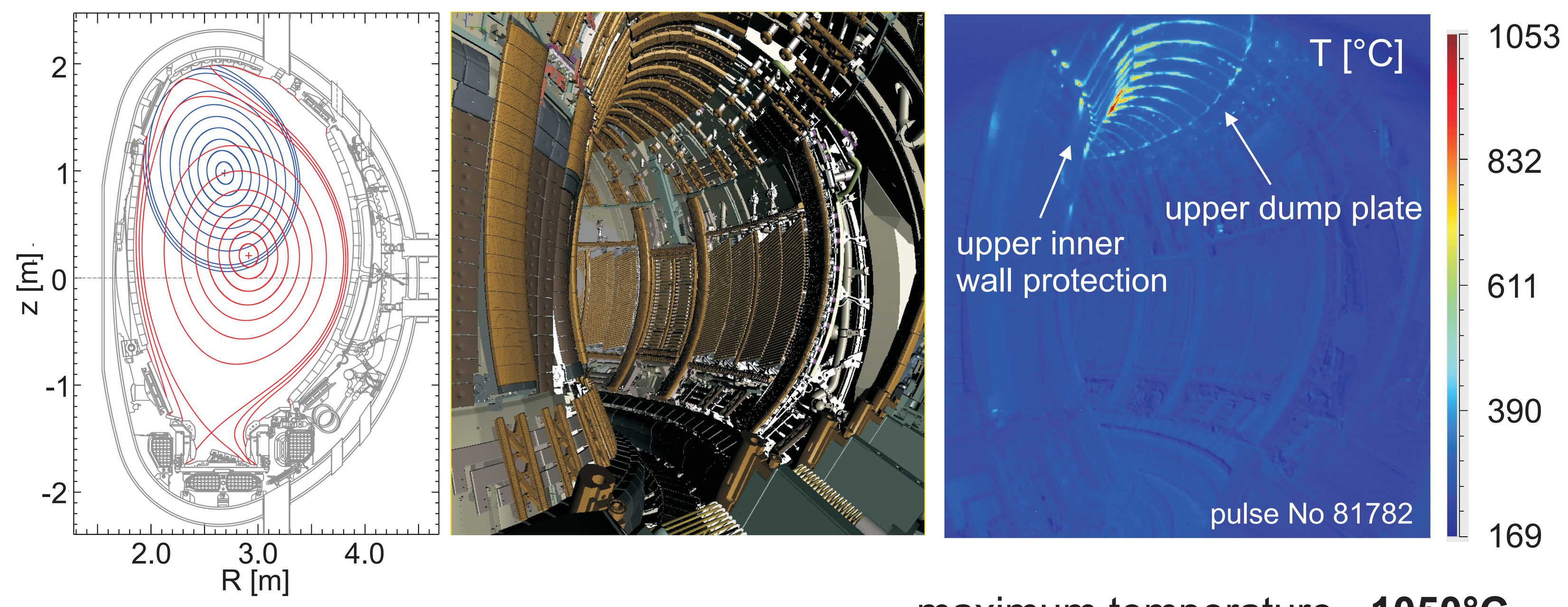
Disruption Properties - Thermal Loads

CQ-VDE deposits high fraction of W_{mag} on upper PFCs



modest magnetic energy: W_{mag} = 14.3MJ (2.2MA)
low thermal energy: W_{th} = 1.5MJ

maximum temperature **~1050°C**
slow time resolution of 20ms
⇨ actual maximum temperature can be higher

CFC

Thermal loads arise mainly during the thermal quench. Main loss channel for magnetic energy is radiation.

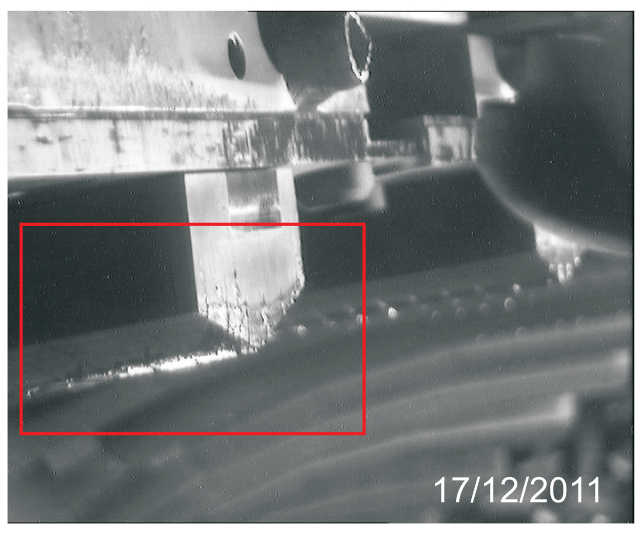
ILW

Increased heat loads due to conduction of magnetic energy. Localised melting occurred.

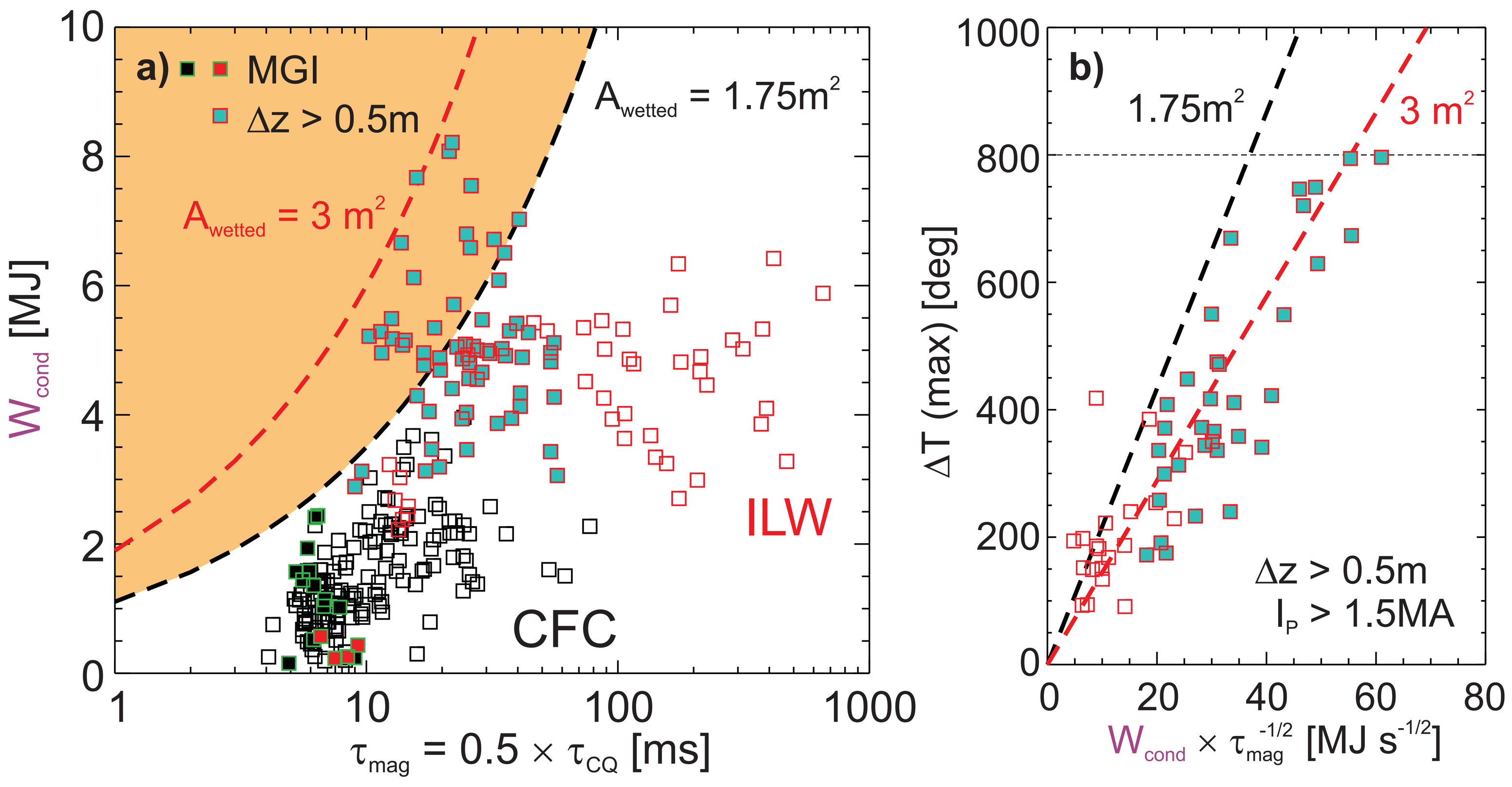
MGI

Mitigates both, heat loads from thermal and magnetic energy (see MGI section for efficiency).

melting on upper dump plate tiles

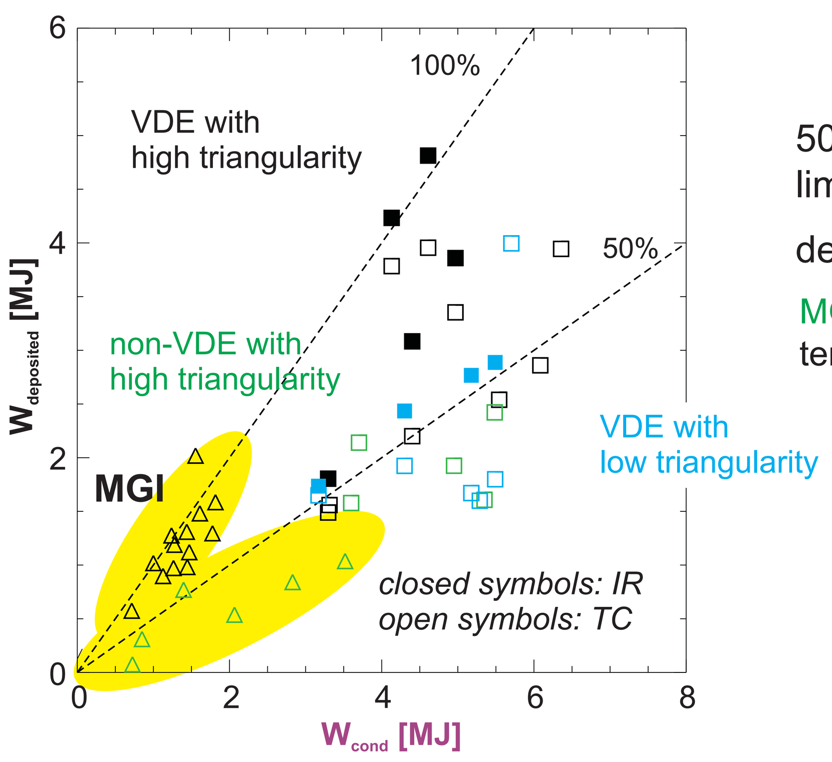


Energy impact



a) Heat loads increase with the energy conducted to PFCs, $W_{cond} = W_{mag} + W_{th} - W_{coupled} - W_{rad}$, and decreasing deposition time (upper limit is the loss time of W_{mag})
b) Peak temperature rise during disruption (maximum if several peaks)

Deposited energy with ILW measured by TC and IR



50% to 100% of W_{cond} is found on upper protection limiter and dump plate

deposition on outer divertor is about 5% to 10% of W_{cond}

MGI keeps energies below 2MJ for W_{mag}+W_{th} up to 20MJ and temperatures below 400°C

Disruption Properties - Runaways

CFC

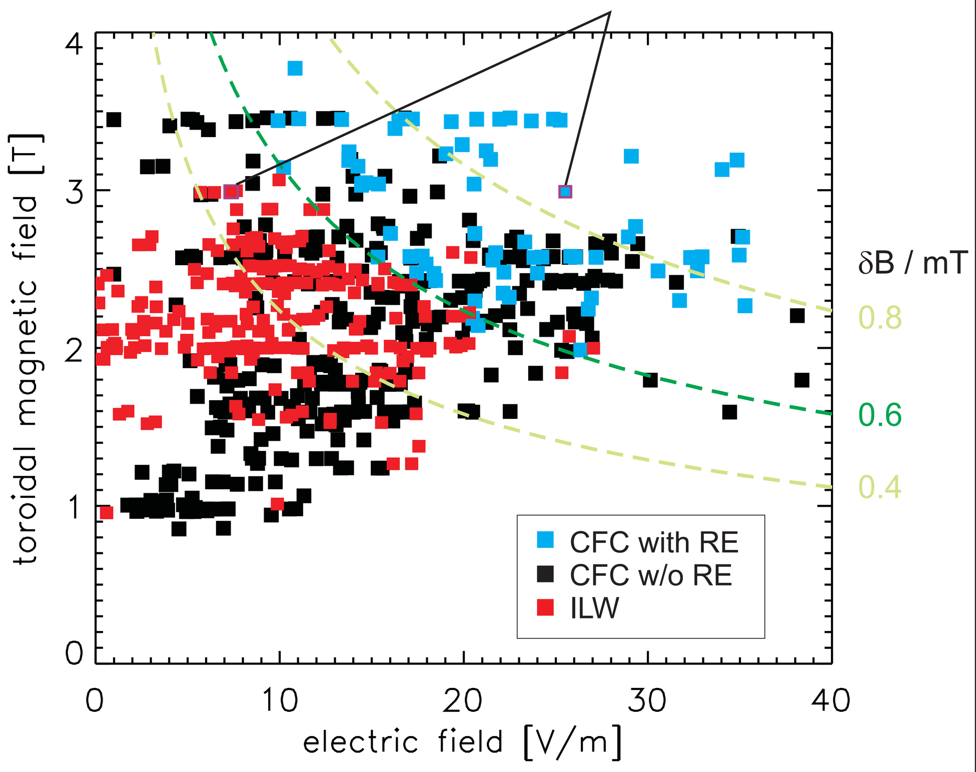
Runaways are observed in ~ 15% of all unintentional disruptions. Toroidal magnetic and electric field defines boundary for RE generation. Ar injection into limiter configuration is a receipe to generate RE.

ILW

Slow current quenches cause low electric fields and MHD instabilities. Deliberate Ar injection in limiter configuration shows no signs of RE.

MGI

Argon and neon injection with CFC wall caused in most cases RE generation. Deuterium mixtures prevent from RE generation.



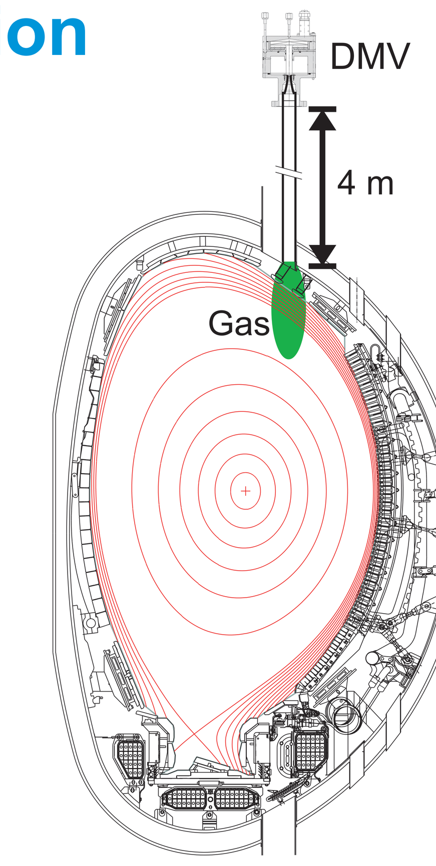
Mitigation - Massive Gas Injection

Massive gas injection is done by a disruption mitigation valve (DMV)

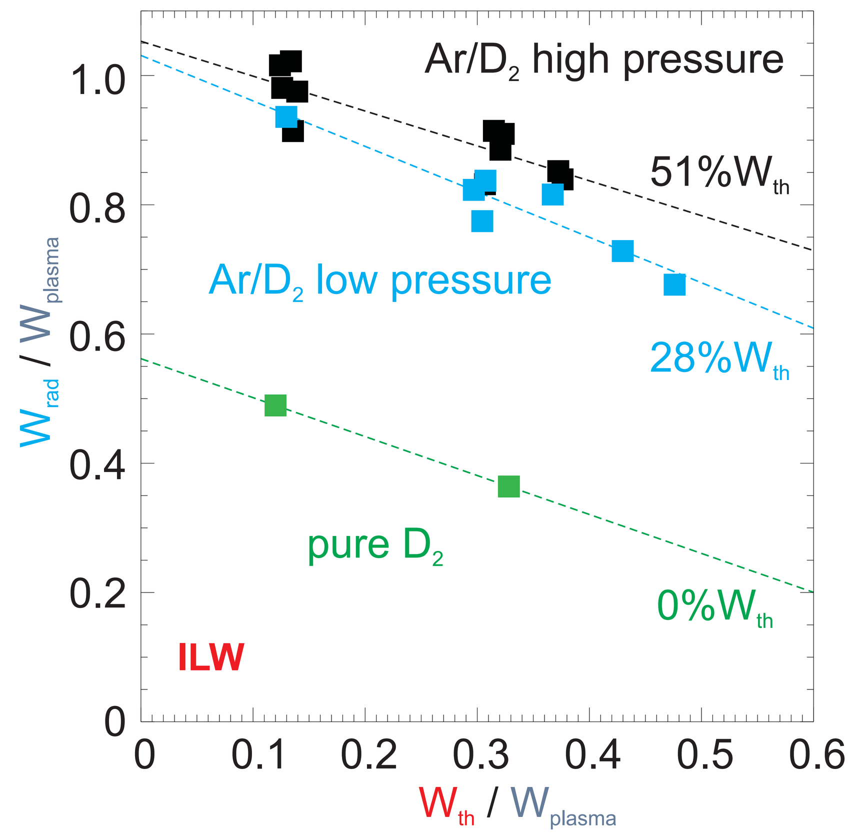
DMV parameter

injection volume:	**650ml**
maximum pressure:	**3.6 MPa**
orifice diameter:	**10mm**
distance to separatrix:	**~4.5m**
time to full open:	**1-2ms**

injected species:
Ar, Ne, D_2, He, 10%Ar or Ne in D_2 (CFC)
D_2, 10%Ar or Ne in D_2 (ILW)



Mitigation - Radiation efficiency



High radiation fraction up to 100% achieved with Ar+D_2 mixtures

pure D_2 shows much lower radiation fraction (with ILW much less impact from released C)

Radiation fraction decreases with increasing thermal energy

Linear fit gives <u>low radiation efficiency during the thermal quench ≤ 50%</u>!

Decay in W_{rad}/W_{plasma} found for both bolometer locations (see „asymmetries“)

Mitigation - Radiation asymmetries

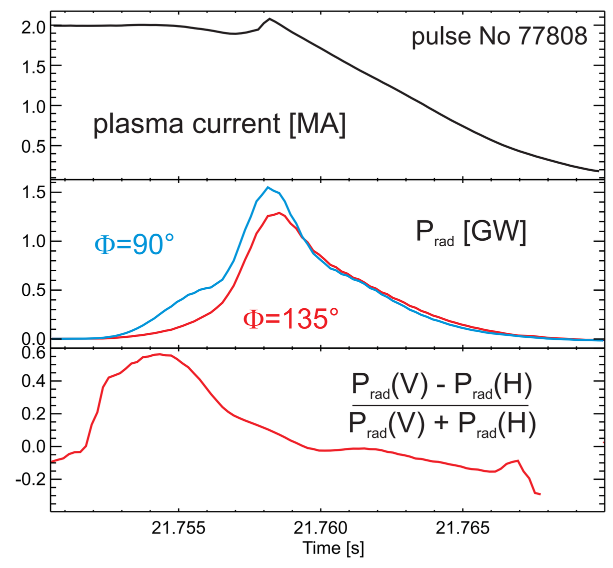
Massive gas injection is prone to radiation asymmetries because of localised gas injection at Φ = 0°.

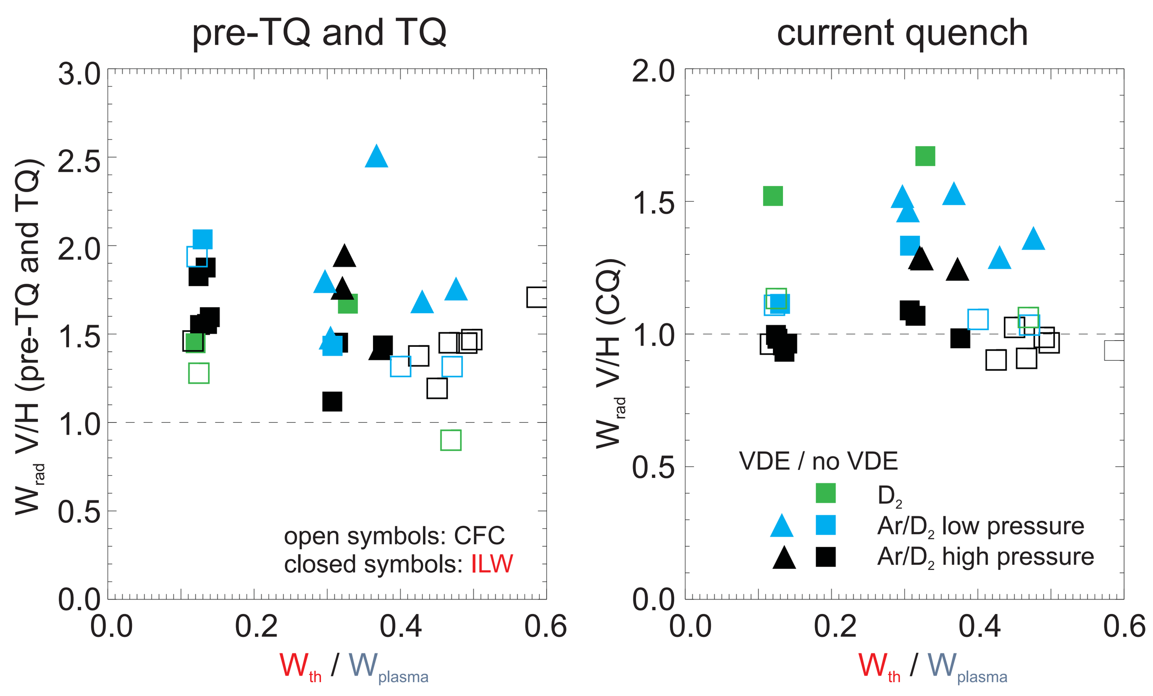
Bolometry at JET consists of two systems: horizontal view (Φ = 135°) and vertical view (Φ = 90°).

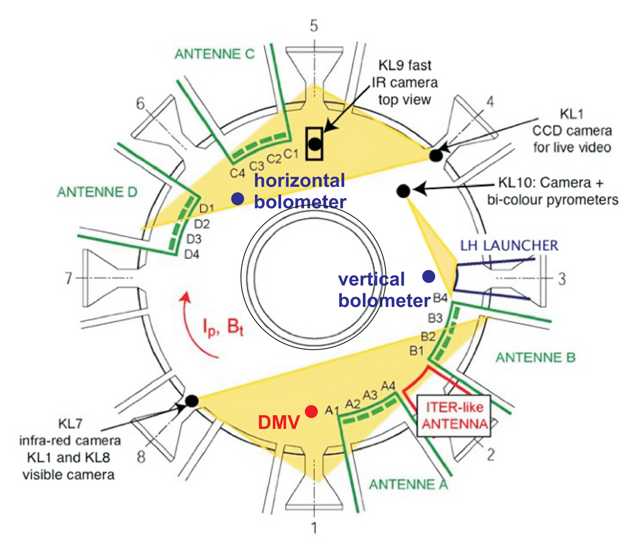
Strong asymmetries during pre-TQ and TQ

Asymmetries during CQ are decrease with increasing gas amount

ILW tends towards higher asymmetries







Mitigation - Closed-loop

Closed-loop operation is now mandatory in JET for $I_p \geq 2.5$MA

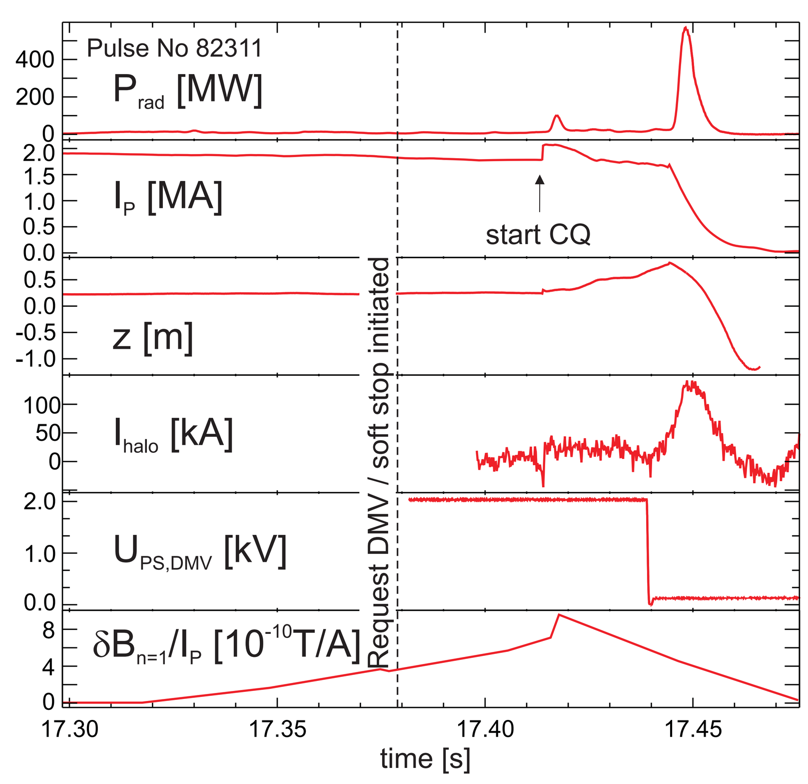
DMV triggered by n=1 mode lock or loop voltage

67 unintentional disruptions were mitigated by MGI during ILW campaigns 2011-2012

5 disruptions were missed due to inhibits in the commissioning phase

4 disruptions were missed due to incorrect timing (human error)

Gas injection after the first TQ for all closed-loop disruptions (sufficient for CQ mitigation, W_{th} low prior to TQ); interlock delay and trigger to be improved



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This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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