Disruption Physics Studies at JET

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with thanks to: P. de Vries, A. Huber, M. Lehnen, C. Reux

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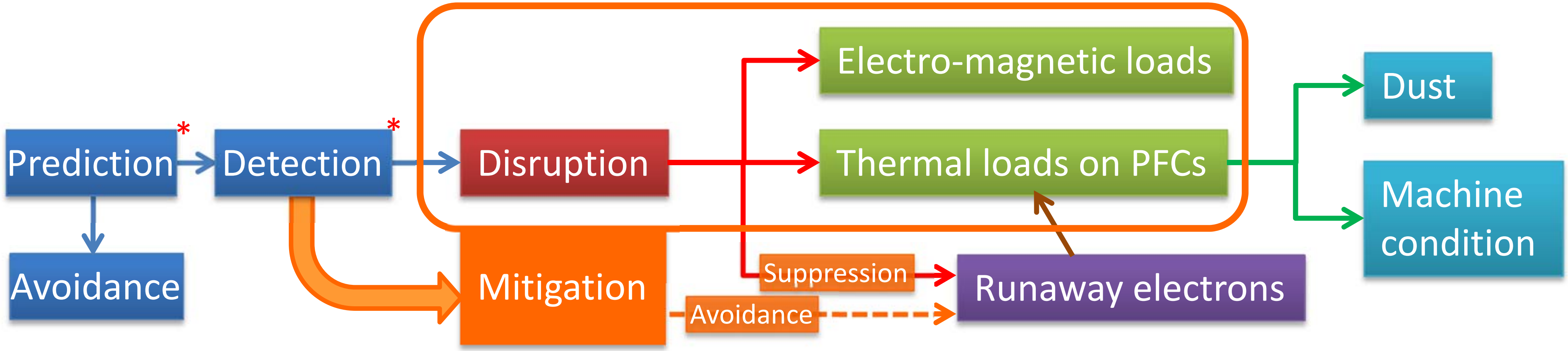
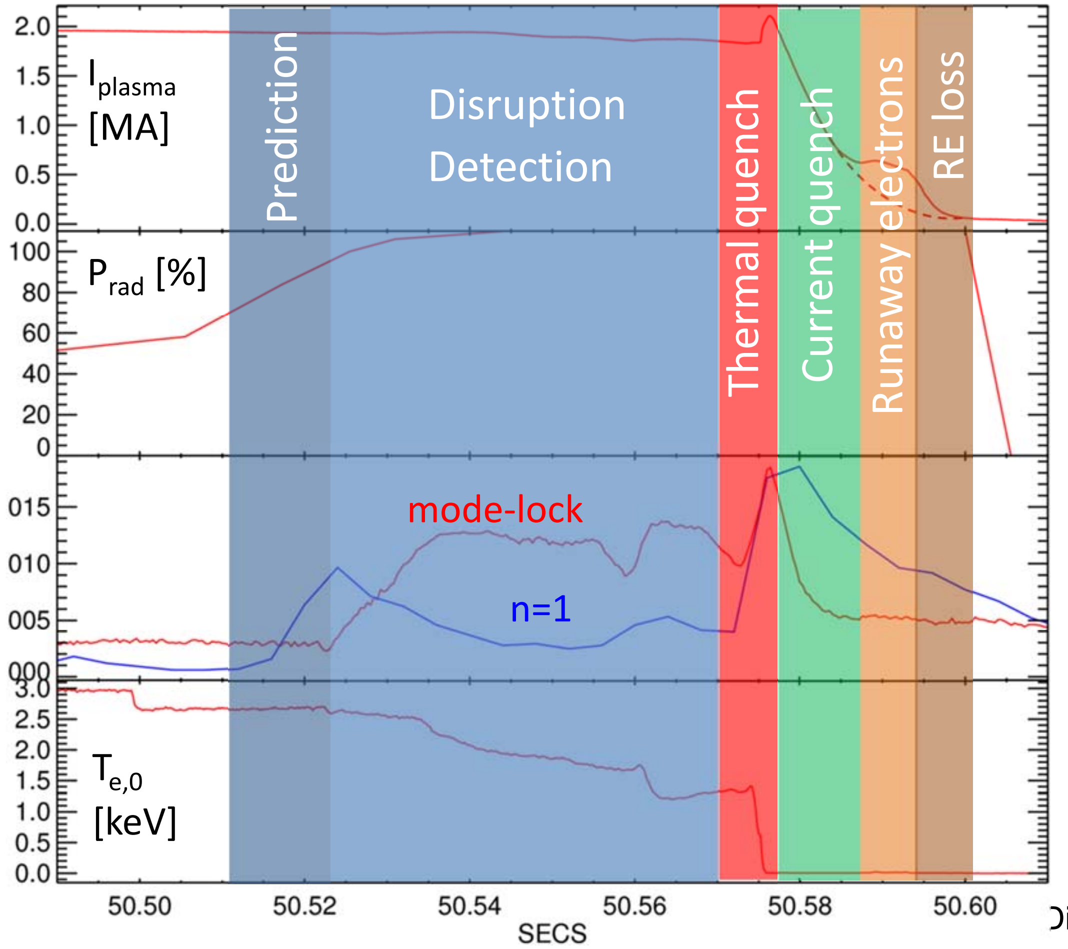
Disruption – time sequence



Impurity driven radiation limit disruption



* See talks by J. Vega and F. Volpe

JET

Outline

1) JET and its disruption mitigation system

2) Disruption characteristics in an all-metal wall

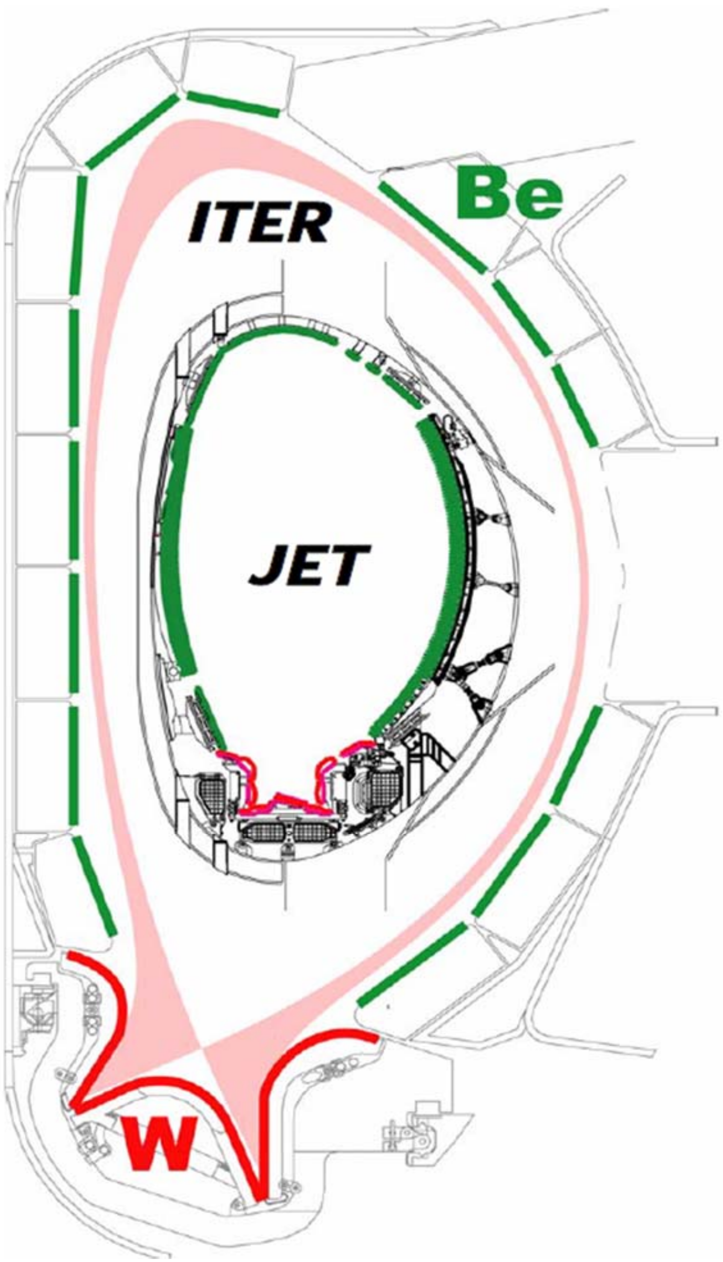
3) Mitigation of
- electro-magnetic loads
- thermal loads
- toroidal radiation asymmetries

4) Runaway electrons:
- production
- avoidance
- suppression

5) Summary

1) JET and its Disruption Mitigation System

JET - parameters

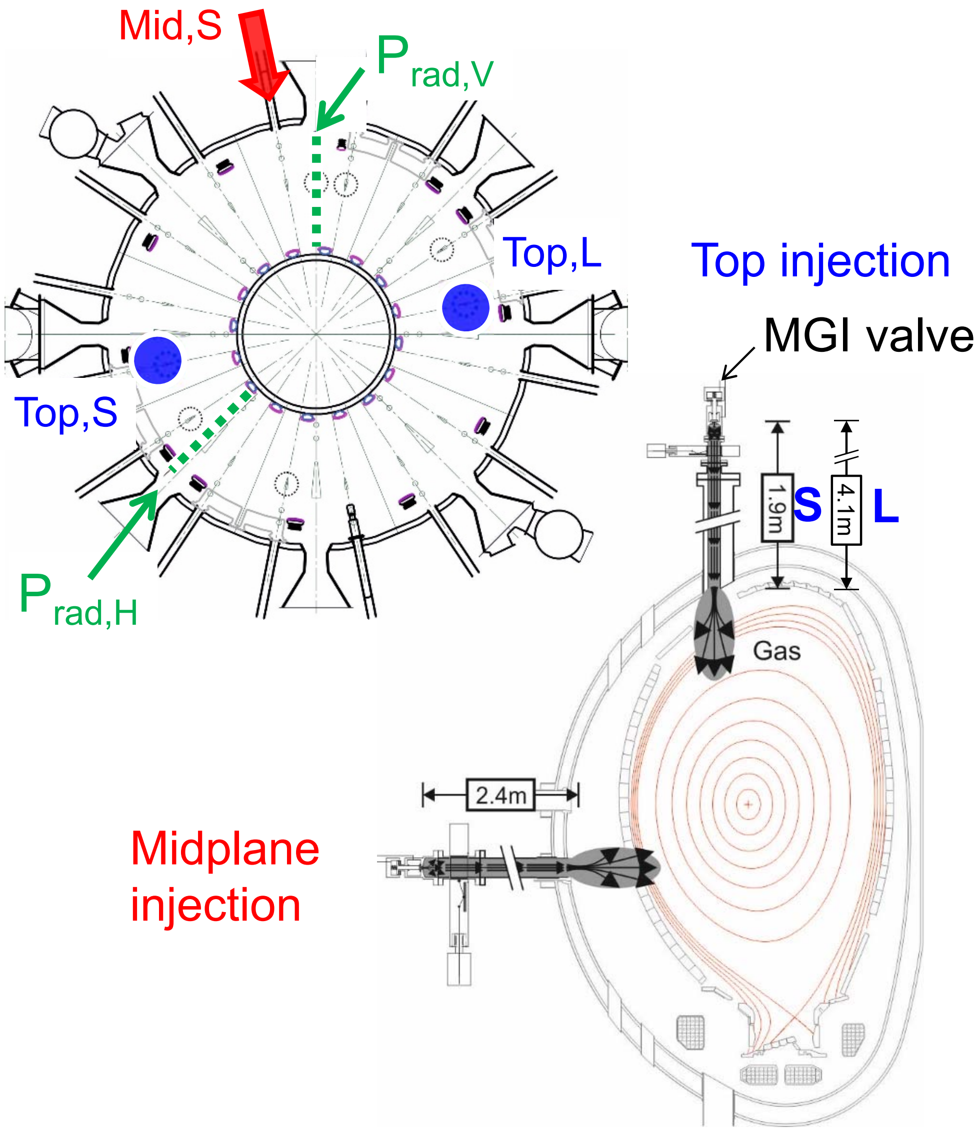


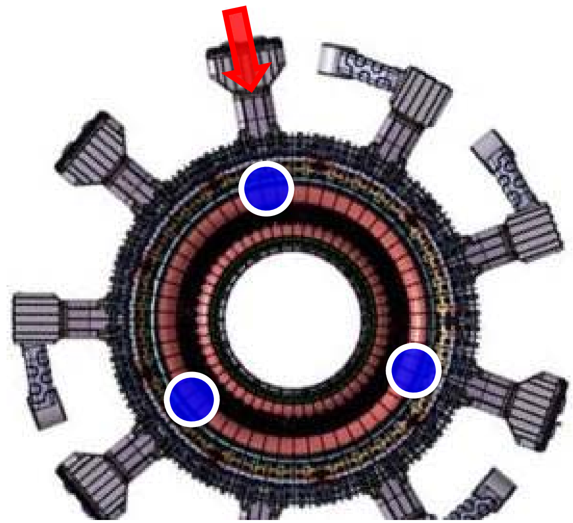
- JET operates since 2011 with an all-metal wall = ITER-like Wall (ILW)
- Due to melting of PFCs and large vessel forces, use of Massive Gas Injection (MGI) is mandatory

	JET	ITER	
R/a [m/m]	2.89/0.94	6.2/2.0	x2
A_{div} [m^2]	~1	~3-4	x3
I_{plasma} [MA]	4-4.5	15	x3.3
B_T [T]	3.7	5.2	x1.4
Forces [t]	~700 (unmitigated)	??	x10?
W_{th} [MJ]	~10	~350	x35
W_{mag} [MJ]	~40	~400	x10

ITER-like disruption mitigation system at JET

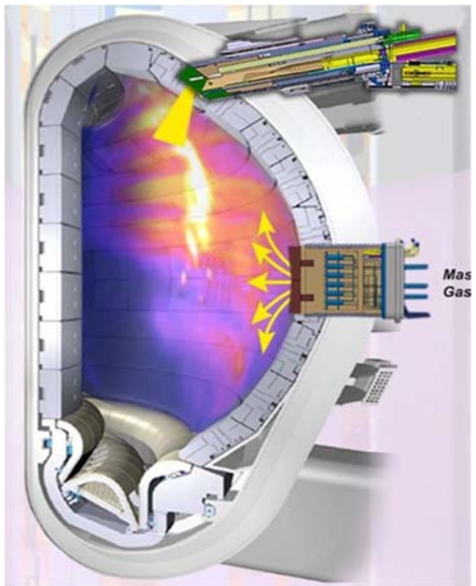
JET





Location of injectors

S. Maruyama, IEEE 2015



Upper Port

Equatorial Port

Injectors with (MGI) + SPI

2) Disruption characteristics in an all-metal wall

Effect of wall materials on disruptions

Carbon Wall ➔ Beryllium/Tungsten PFC:

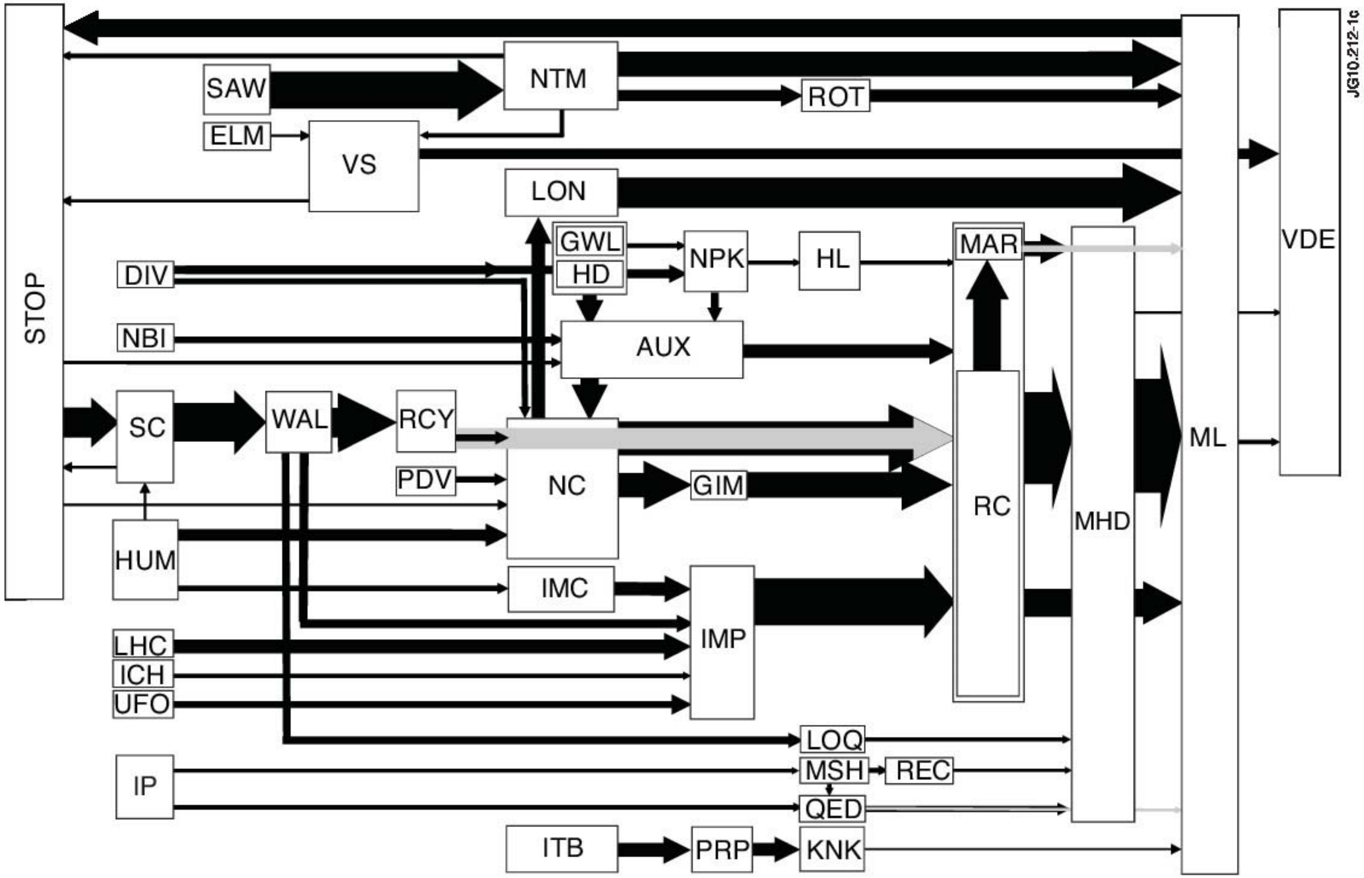
- less intrinsic impurities and higher plasma temperatures
  - ☹ lower radiated energy during disruption
  - ☹ slower current decay
  - ☹ larger halo currents and disruption forces
  - ☹ plasma energy less mitigated and melting of PFC more likely
  - ☹ “hot” VDEs more likely
  - ☺ runaway electrons less likely
- lower wall recycling
  - ☺ higher density limit
  - ☹ seeding of error field modes more possible
  - ☺ Non-Sustained Breakdowns after disruption less likely
- disruption cause has changed
  - ☹ higher disruptivity due to smaller operational H-mode window

Disruption causes – Carbon wall

Main causes:

- NTM and low density error field modes
- Greenwald limit disruptions
- Switch-off of auxiliary power at high density (HD->AUX)
- Most disruptions end with a clearly detectable mode lock. But this is not the original cause!
- End stage statistics: edge radiation instabilities=52%, error field modes=10%, NTMs=7%, VDEs=4%, low q=2.5%

NC = Density Control problem
IMC = Impurity Control problem
IMP = Influx of Impurities
RC = Radiative Collapse
ML = Mode Lock
VDE = Vertical Displ. Event



P. de Vries, NF 2011

Disruption causes – ITER-like wall

Changes to causes of unintentional disruptions:

- ☺ VS issues nearly absent due to improved VS-control (after upgrade)
- ☺ No disruptions caused by ITB or reversed shear: no such experiments
- ☺ Less disruptions follow SC⇨WAL⇨RCY due to better density control when close to wall
- ☹ IMP or impurity related disruptions have increased (W-divertor): new RPK
- ☹ Impurity control more difficult
- ☹ More disruptions due to UFOs (Be-melting and W-coating)
- ☹ More disruptions due to low density error field modes

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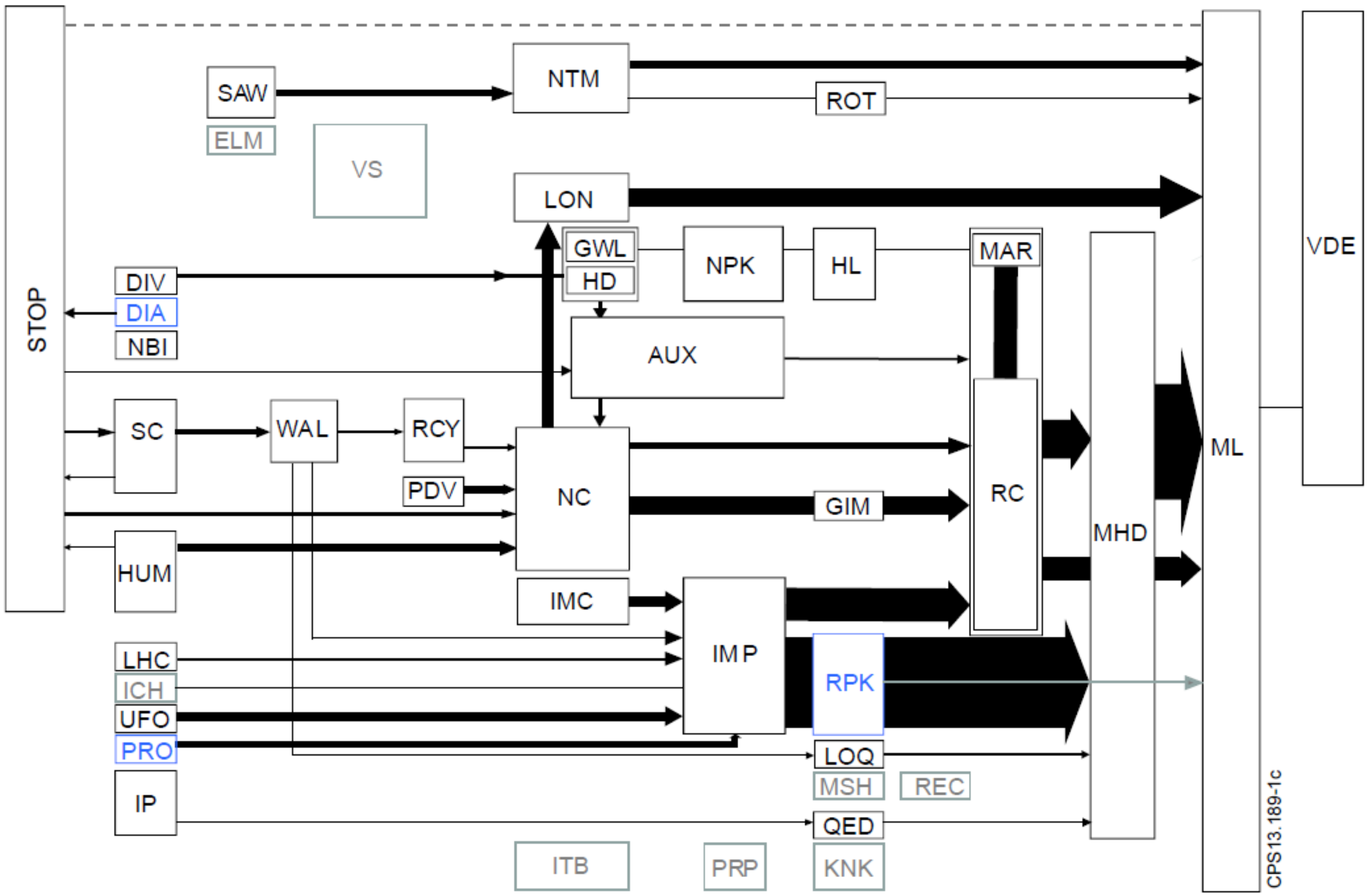


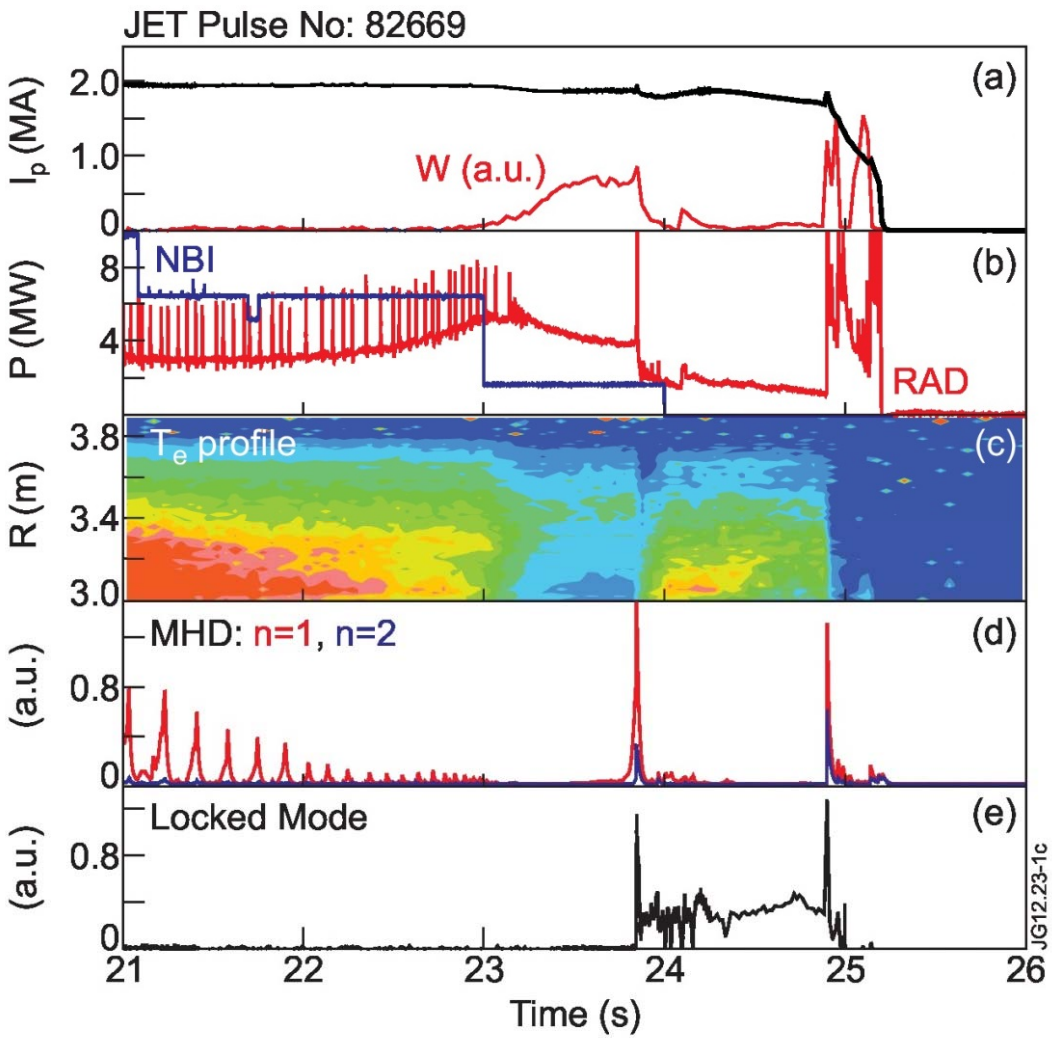
P. de Vries, PoP 2014

Disruption cause in ILW - example

Radiation increase (RPK):

- Either *slow*, i.e. on transport time scales => accumulation of tungsten (W)
- Or *fast* (~30% of all cases) => likely fast influx of material
- Not a problem during main heating phase. But radiation remains high in the termination/ H-mode exit phase

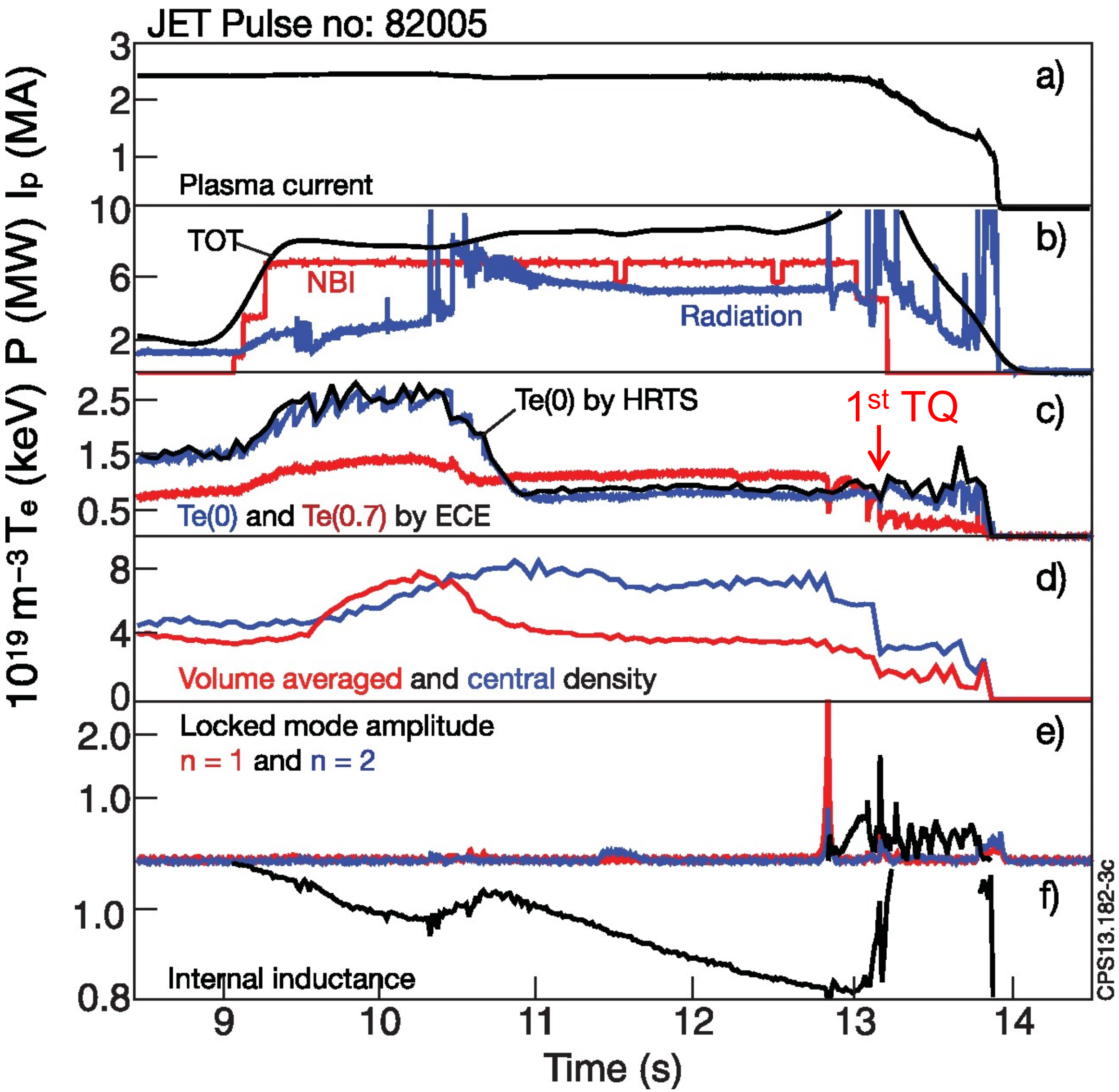
Example of slow increase:



P. de Vries, PoP 2014

Disruption cause in ILW – example of fast imp.

Fast increase of radiation (due to sudden strong impurity influx?):



Sudden jump of radiation @10.5sec, but Prad remains below Ptot!

Te-profile becomes hollow and Sawteeth disappear.

Strong density peaking, but well below Greenwald density

Strong loss of thermal energy

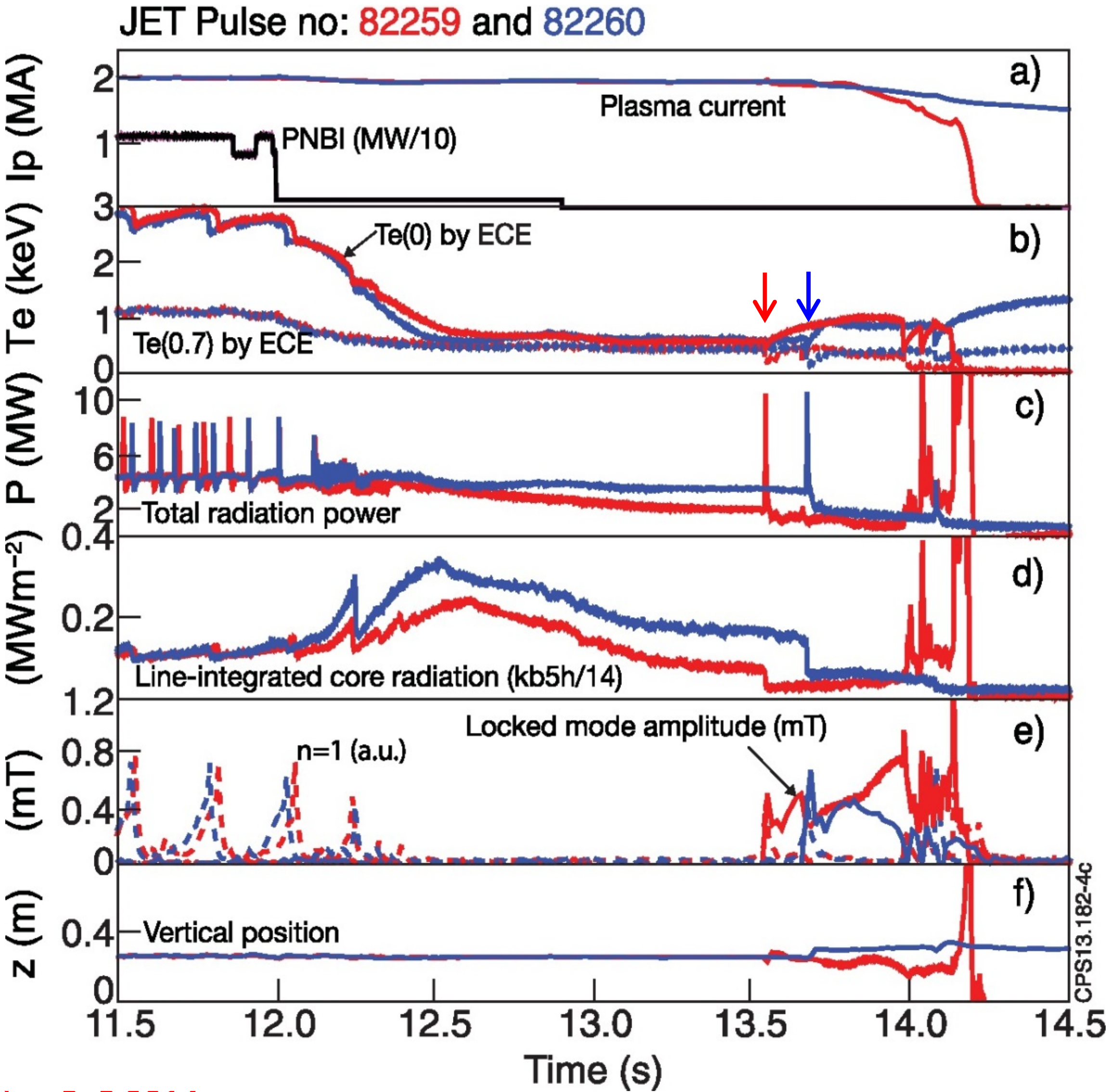
MHD-activity result in mode locking

n_e and T_e settle, but l_i and q(r) keep changing

P. de Vries, PoP 2014

Recovery after minor disruptions

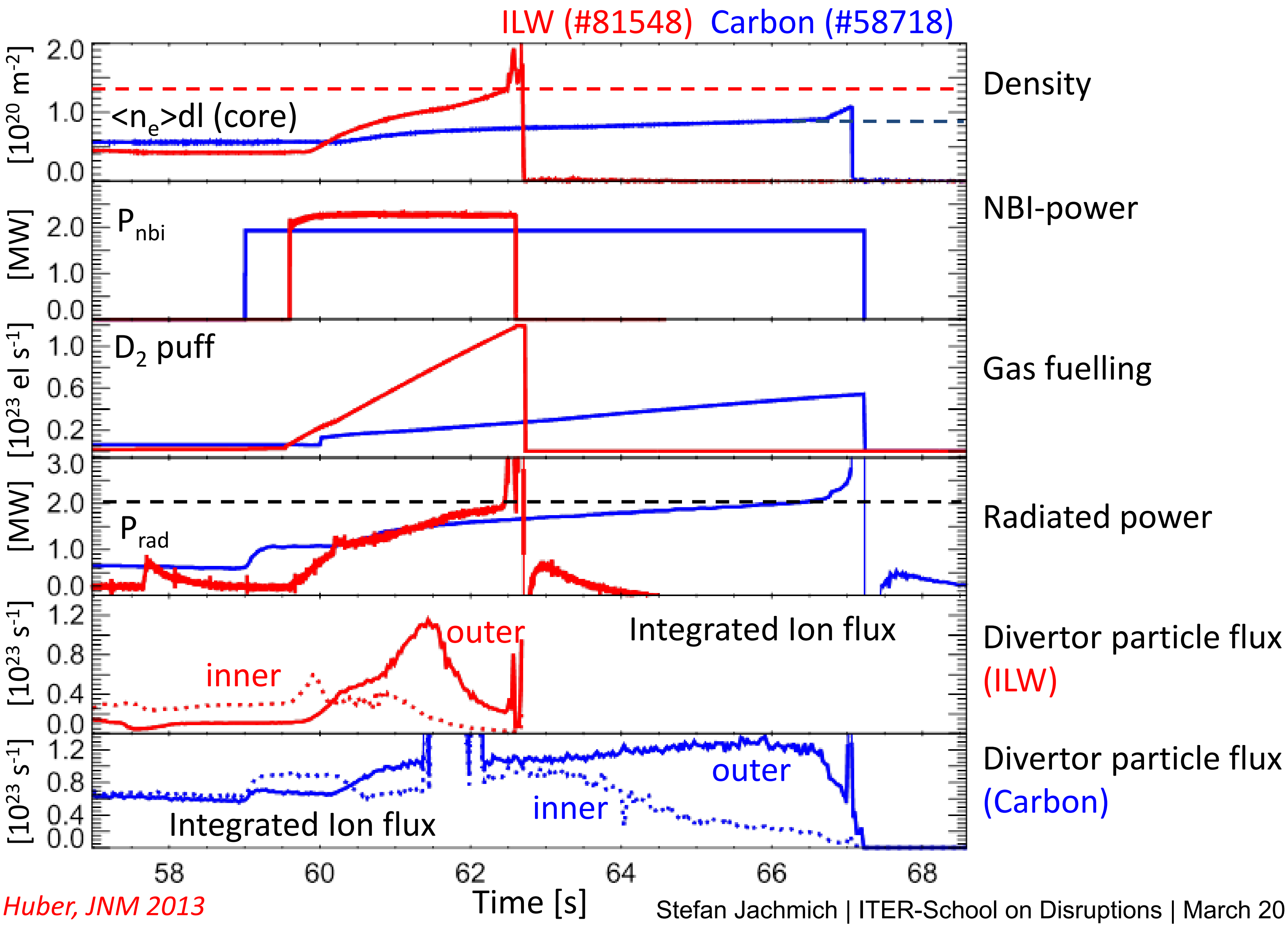
- Similar problems do not always result in a real disruption despite a thermal quench takes place
  - Radiation decreases ➔W ejected from core by quench ➔ T_e increases
  - Disruptivity is determined by the post thermal quench stability



P. de Vries, PoP 2014

Operational space: density limit

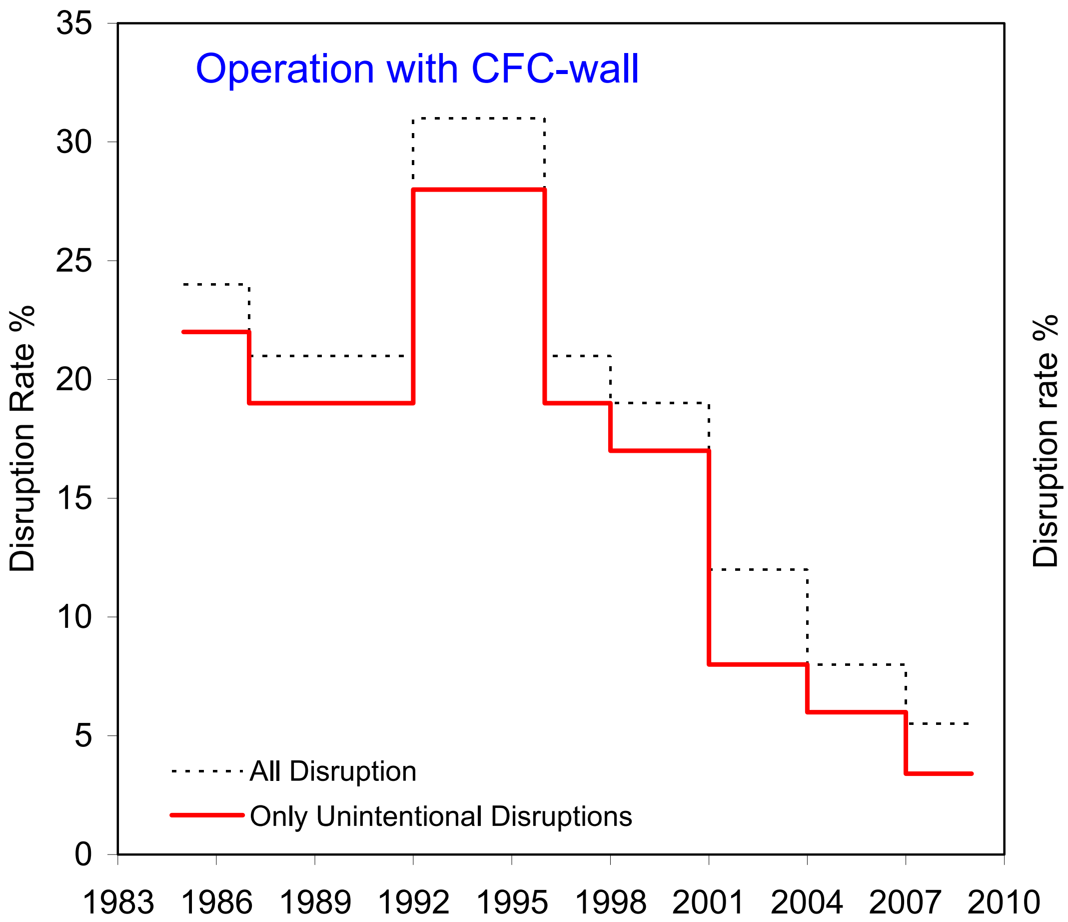
- Density limit is higher (~400%) in ILW than in Carbon-wall
- Increased gas consumption in ILW
- At same density, more radiation losses in C than in ILW.

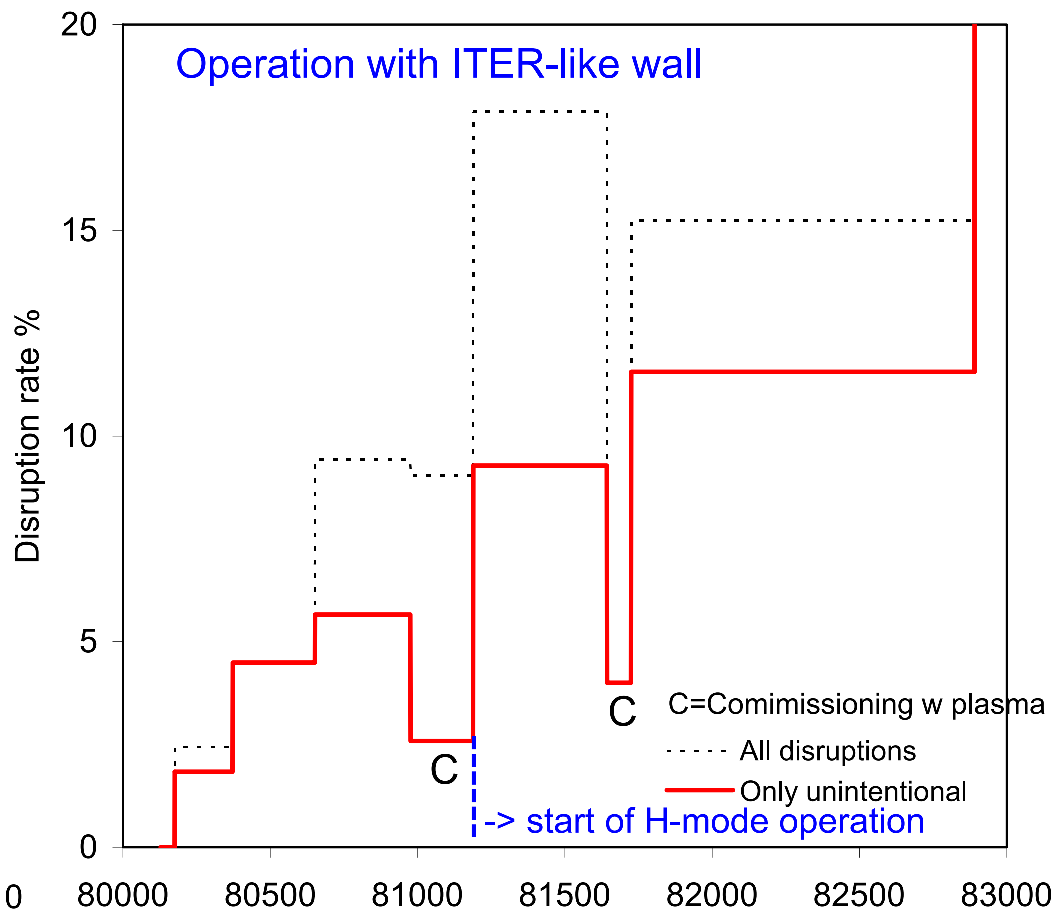


JET *A. Huber, JNM 2013*

Disruptivity

- JET disruption rate has decreased over the last decade prior ILW-installation
- ILW affected density and impurity control leading to new disruption causes
- Presently disruption rate ~20%, but can reach 50-60% in high performance pulses

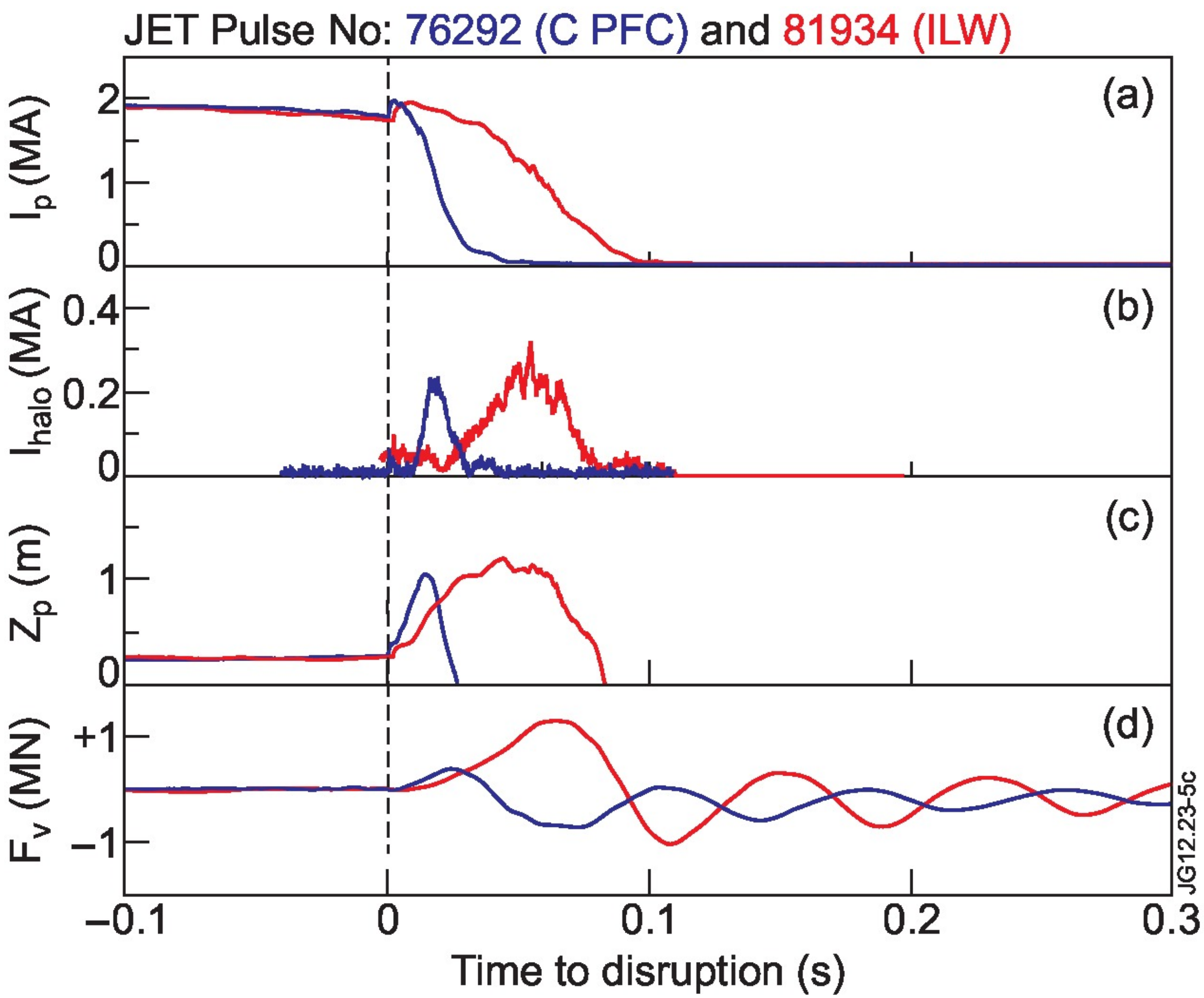




P. de Vries, PoP 2014

Disruption forces: Carbon vs ILW

- Longer current quench results in larger halo currents and increase of swing and reaction force of the vessel.



Longer current quench duration

Slightly higher halo current and longer duration of impulse

Larger and longer plasma excursion (=> melting)

Much larger swing (F_V)

P. de Vries, PPCF 2012
M. Lehnen, NF 2013

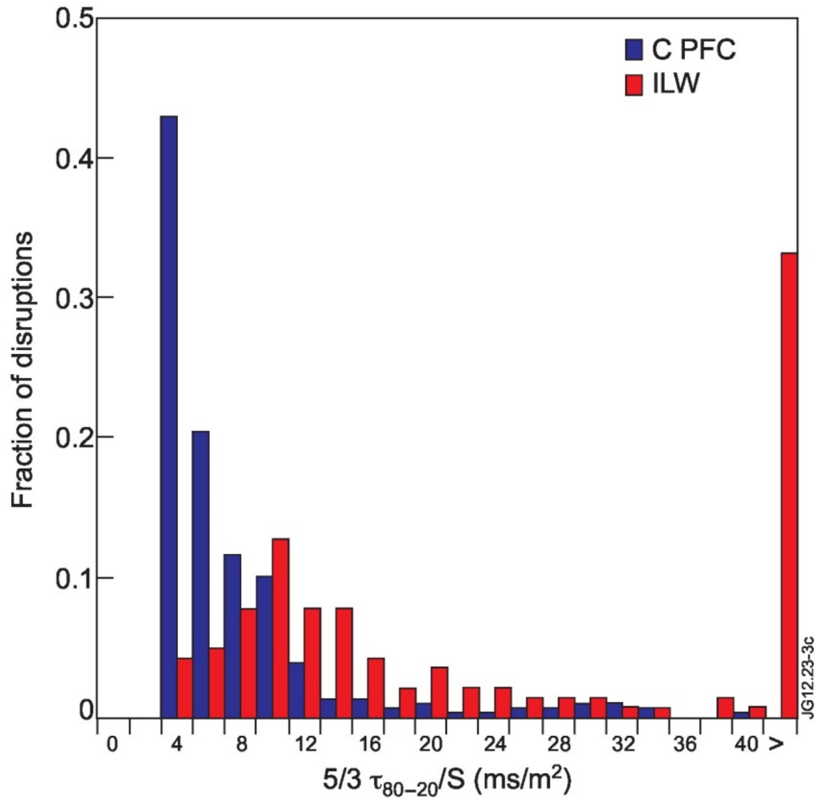
Current quench times

- ➢ Higher post-thermal quench temperatures with ILW thus longer current quench times (L/R time $\propto Z_{eff}^{-1} \langle T_e \rangle^{3/2}$)

☹ Large fraction of total energy can be conducted to PFCs

☹ Higher vessel reaction forces.

☺ Lower induced electric fields reduce risks of runaway electron generation



M. Lehnen, JNM 2013

Electro-magnetic loads

Vertical force:

- Combination of electro-magnetic loads arising from halo currents and eddy currents.
- Halo currents $\propto \tau_{CQ}$: due to VDE, flow through conducting structures and plasmas.
- Eddy currents $\propto 1/\tau_{CQ}$: induced in structures due to fast change of I_{plasma}.

$$F_v = F_{halo} + F_{eddy} \propto f\, I_p^2$$

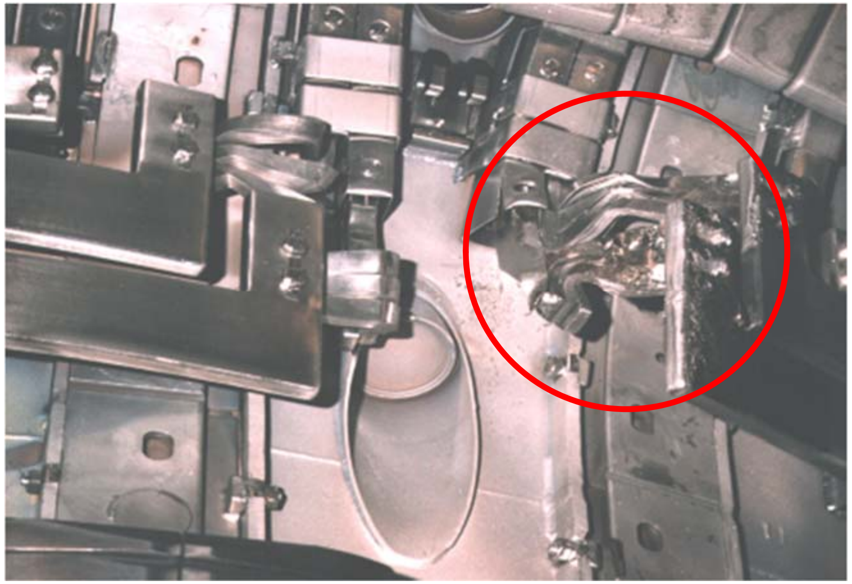
(f depends mainly on plasma shape (elongation) and minor radius)

- Control current quench time to minimise electro-magnetic loads on first wall and vessel.

Sideway forces:

- Due to halo current asymmetries $\propto I_p\, B_T$

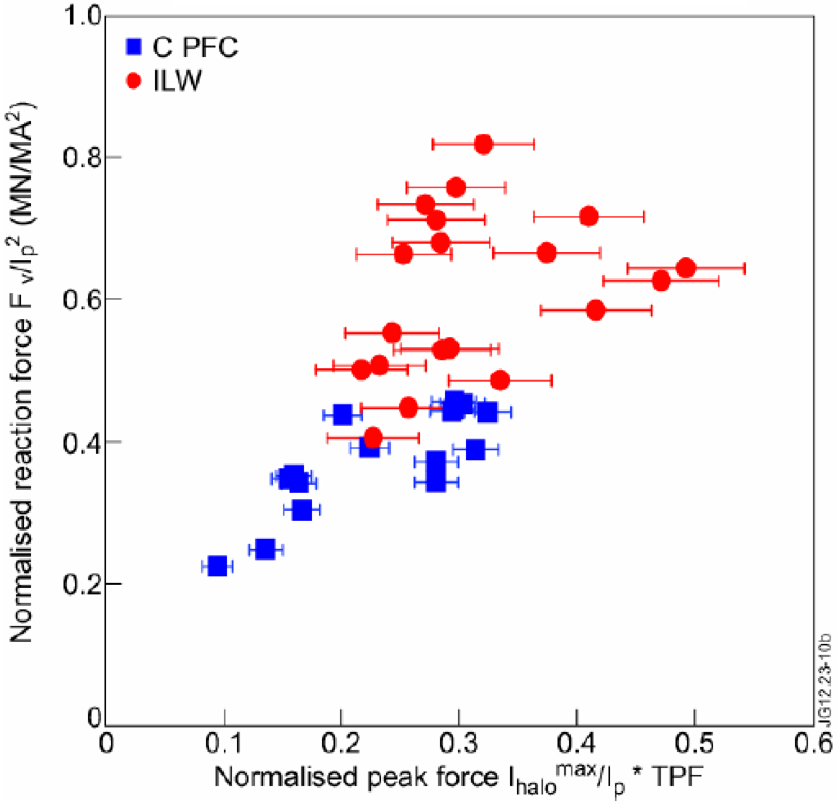
Damage due to halo currents:



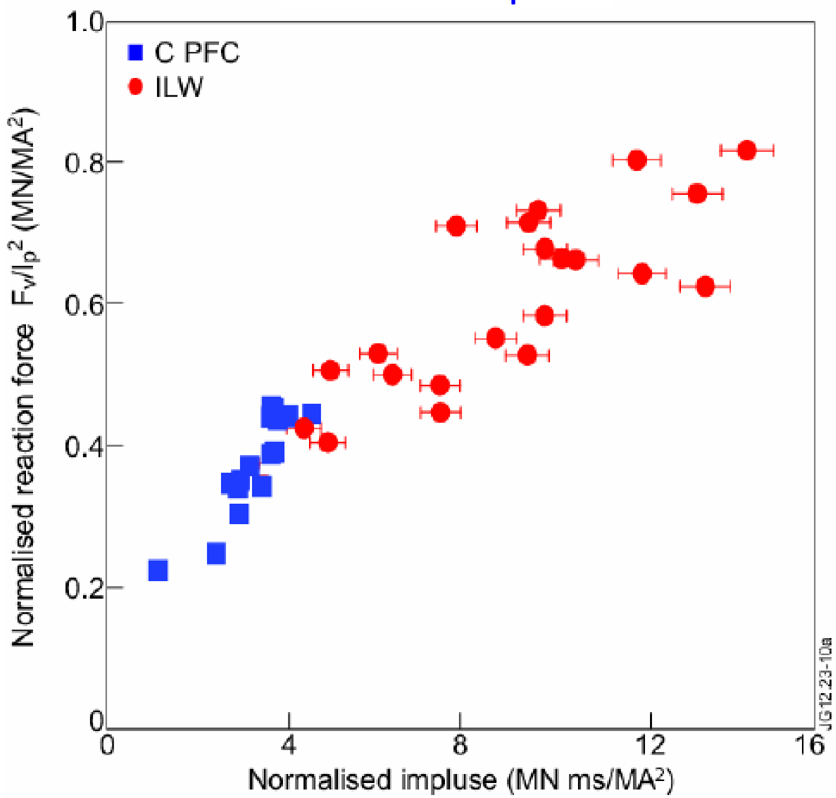
Scaling of reaction force

- For same halo current fractions: large range of F_v
- F_v scales with time integrated halo force (impulse)

Force vs. halo current fraction



Force vs. Impulse



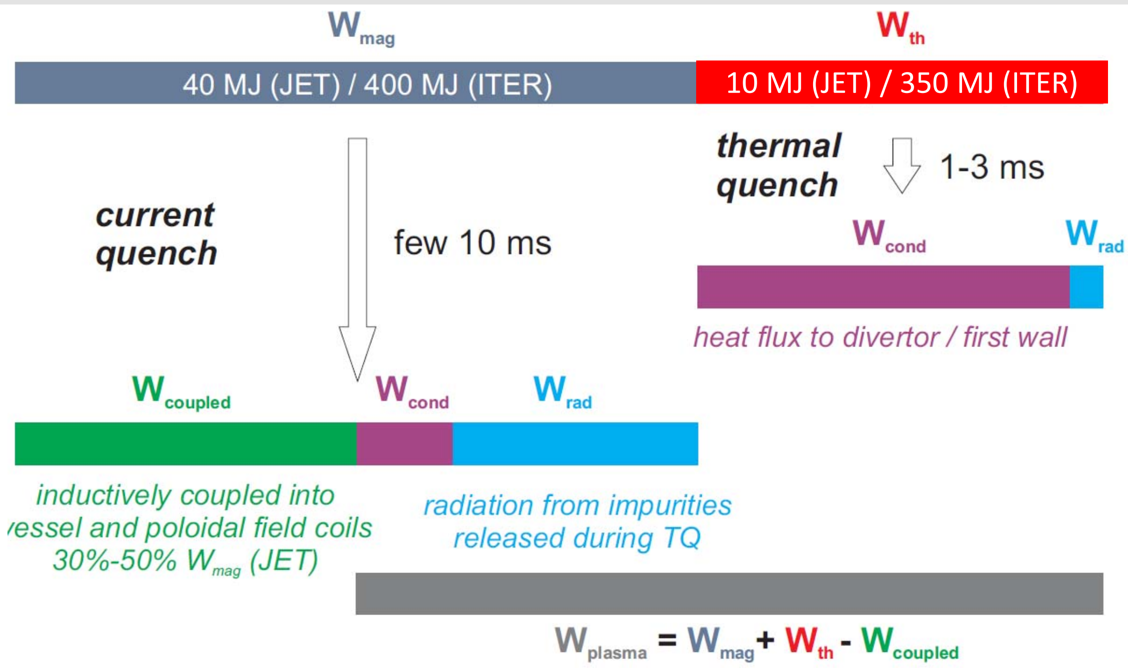
P. de Vries, PoP 2014

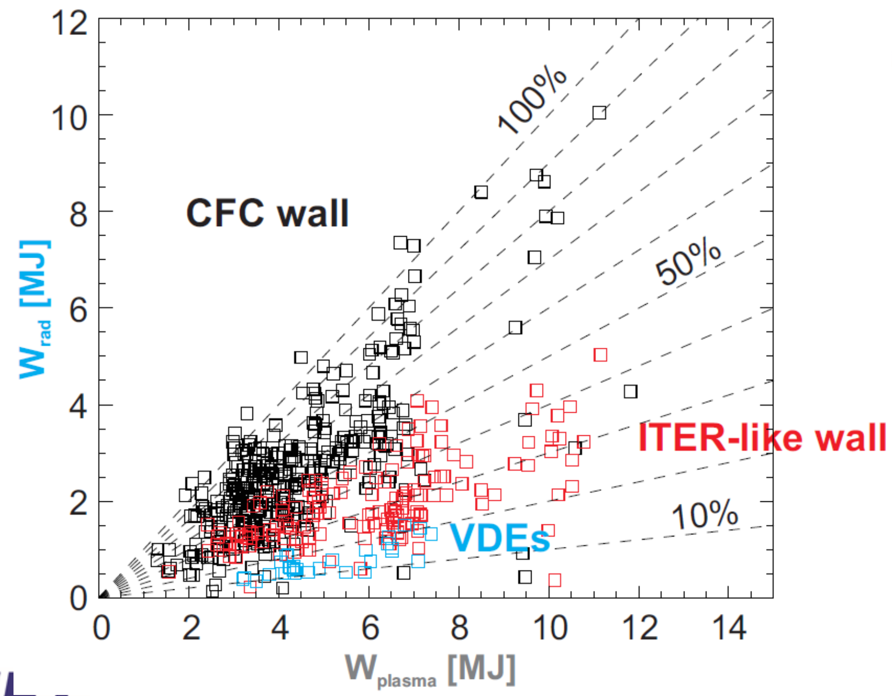
Thermal loads: energy balance

During a disruption,

magnetic and thermal energy

need to be dissipated



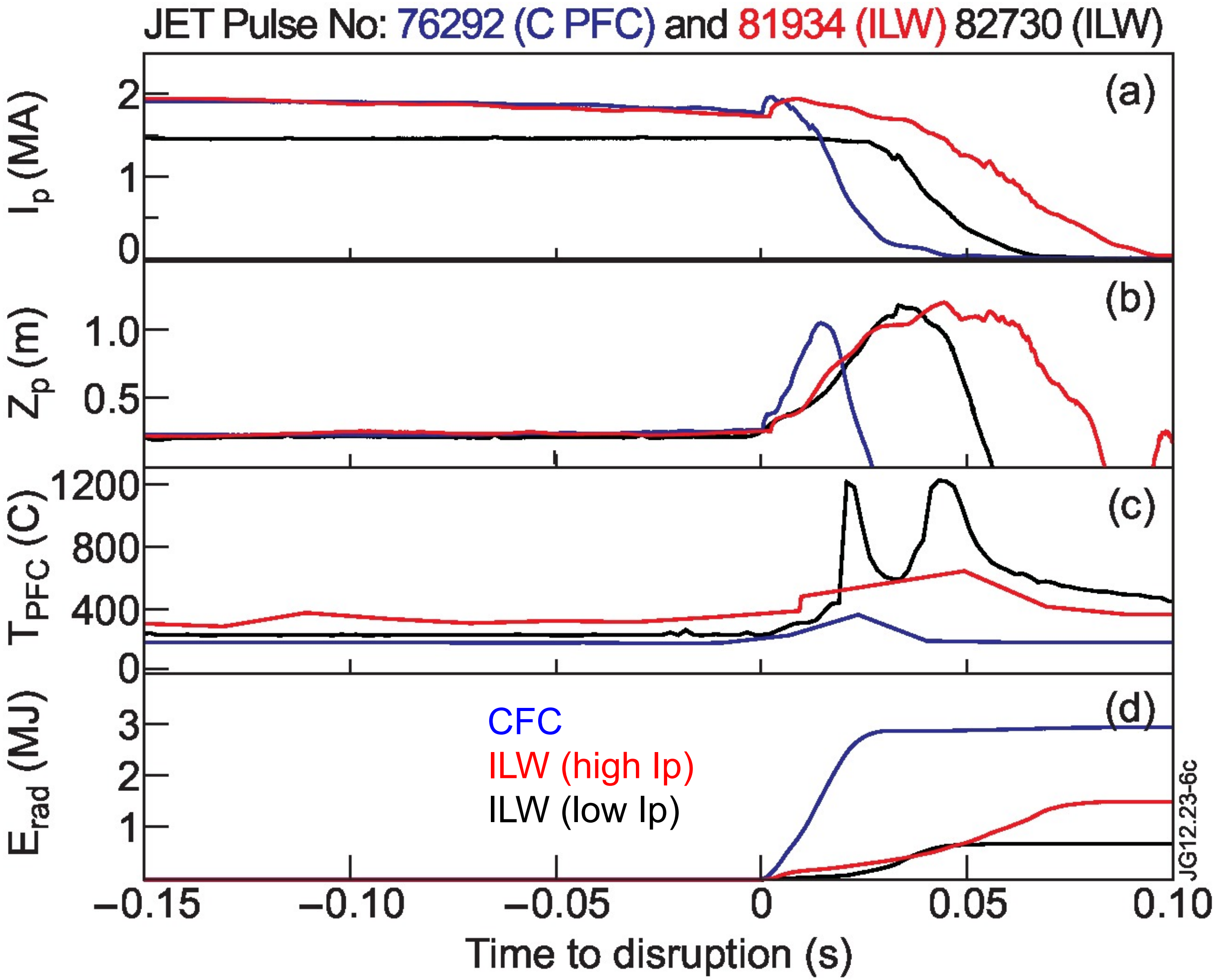


In ILW only maximum 50% of plasma energy is radiated

M. Lehnen, JNM 2013

Thermal loads

- Slower current quench in ILW: reduces power load
- Radiated energy much less: more energy conducted to PFCs!



Longer current quench

Higher temperature rise

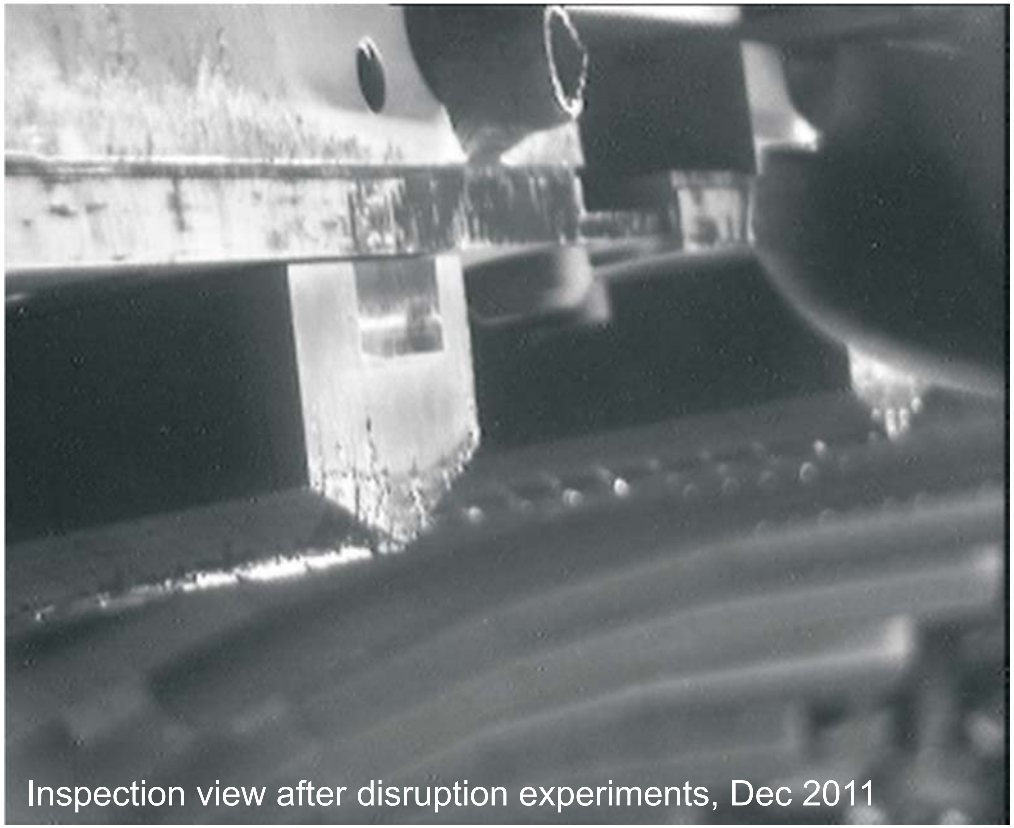
Less energy radiated

P. de Vries, PoP 2014

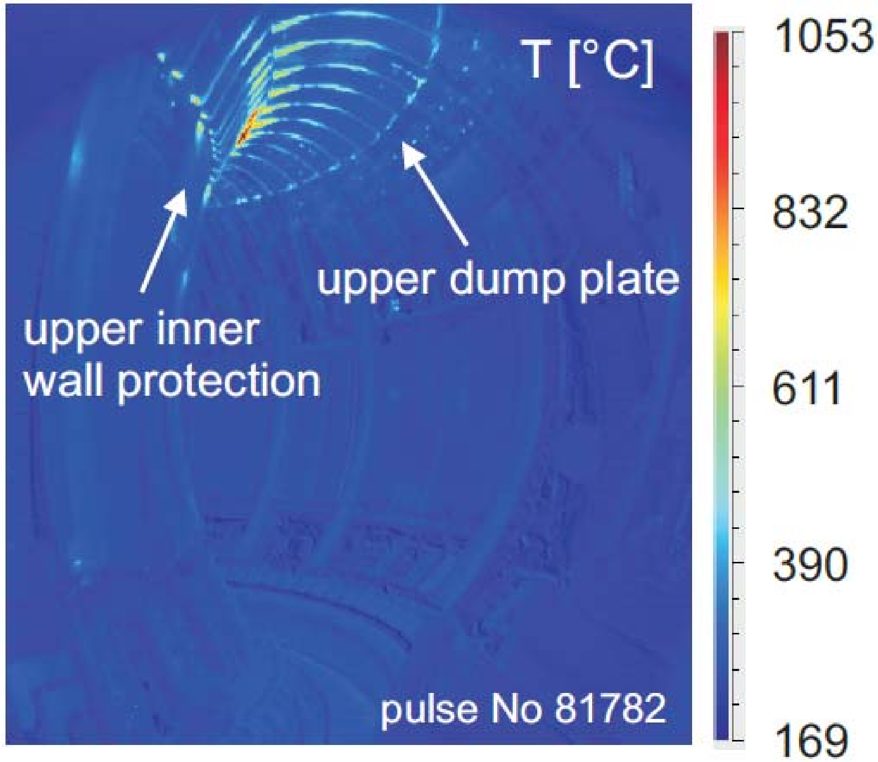
Thermal loads

- Large fraction of total energy is conducted to first wall
- Melting of Beryllium already after pure VDE at low I_p (E_{mag}=6MJ)

Melting at Upper dump plate:



IR-camera picture:



Consequences of ILW on disruptions and operation

- H-mode operation more restrictive (minimum fuelling, RF to avoid W-accumulation)
- Certain scenarios more difficult to achieve (e.g. ITBs)
- Disruption root cause has changed => mitigation strategy revised
- Disruption forces and thermal loads increased

=> need for routine disruption mitigation

3) Disruption Mitigation

Disruption mitigation strategies

At JET disruption mitigation strategy has changed:

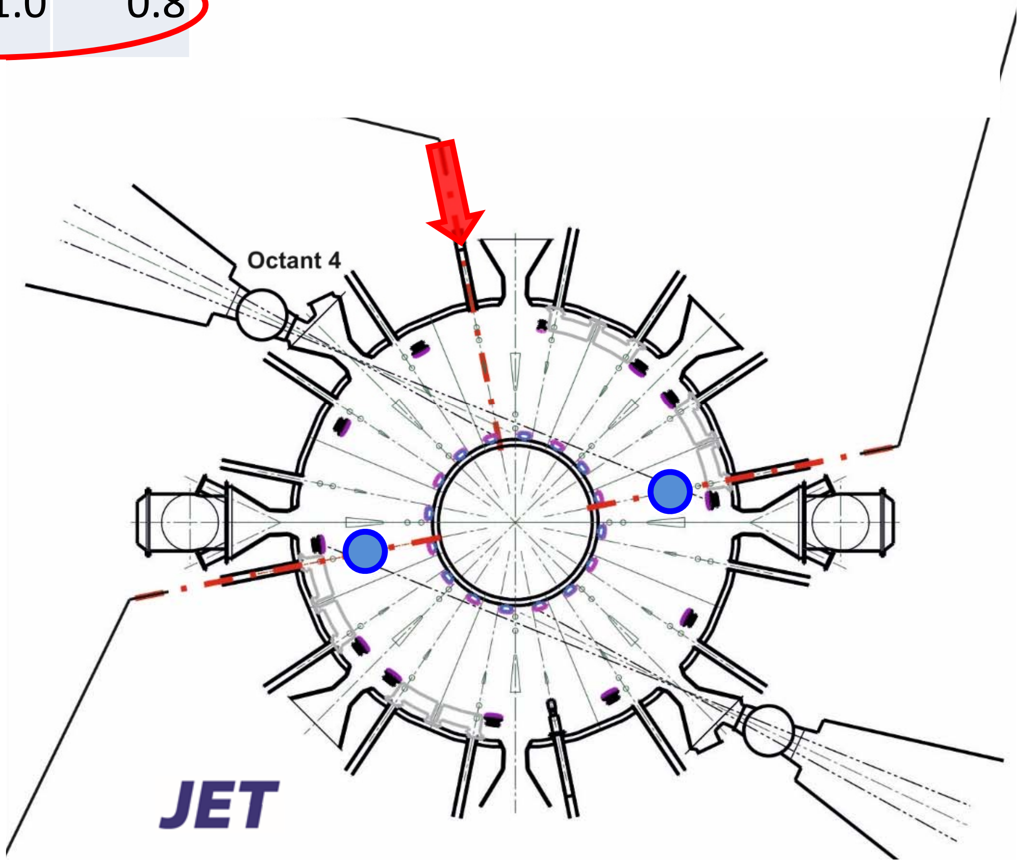
- Carbon:
  - Mode lock detected: fast ramp down of plasma current, switch off aux. heating
  - reduce vessel forces by reducing elongation
  - minimise deconditioning by stopping gas

- ILW:
  - Prevent plasma from touching wall (=> keep elongation?)
  - Avoid radiation limit (=> keep ICRF-heating on?)
  - Keep plasma spinning (=> neutral beam on?)
  - Inject massive gas to increase radiation during TQ and to lower CQ time

ITER-like disruption mitigation system at JET

- 2 Vertical and 1 Equatorial MGI

	TOP,L	MID	TOP,S
Vol [ltr]	0.65	0.975	0.35
p_{inj} [MPa]	3.6	5.0	5.0
Gas (D_2) [barL]	~10	~45	~17
Tube length [m]	4.1	2.4	1.9
Orifice [mm]	10	30	30
ToF [ms] (D2+10%Ar)	~1.8	~1.0	0.8



Characteristics of valves

- Onset of TQ occurs, when cold MGI-gas pulse reaches q=2 [1,2]
- Longer tube causes delayed start of TQ and slower rise of radiation
- No signifcant difference in vessel force F_v and radiated energy fraction f_{rad}

	DMV1 Top,L	DMV2 Mid,S	DMV3 Top,S
dt(pre) [ms]	5.3	4.0	3.7
dt(TQ) [ms]	2.0	1.0	1.2
dt(CQ) [ms]	19	20	17
Fv/Ip2 [t/MA^2]	27	23	26
frad,tot [%]	74	76	71
frad [%] (preVDE)	47	52	62

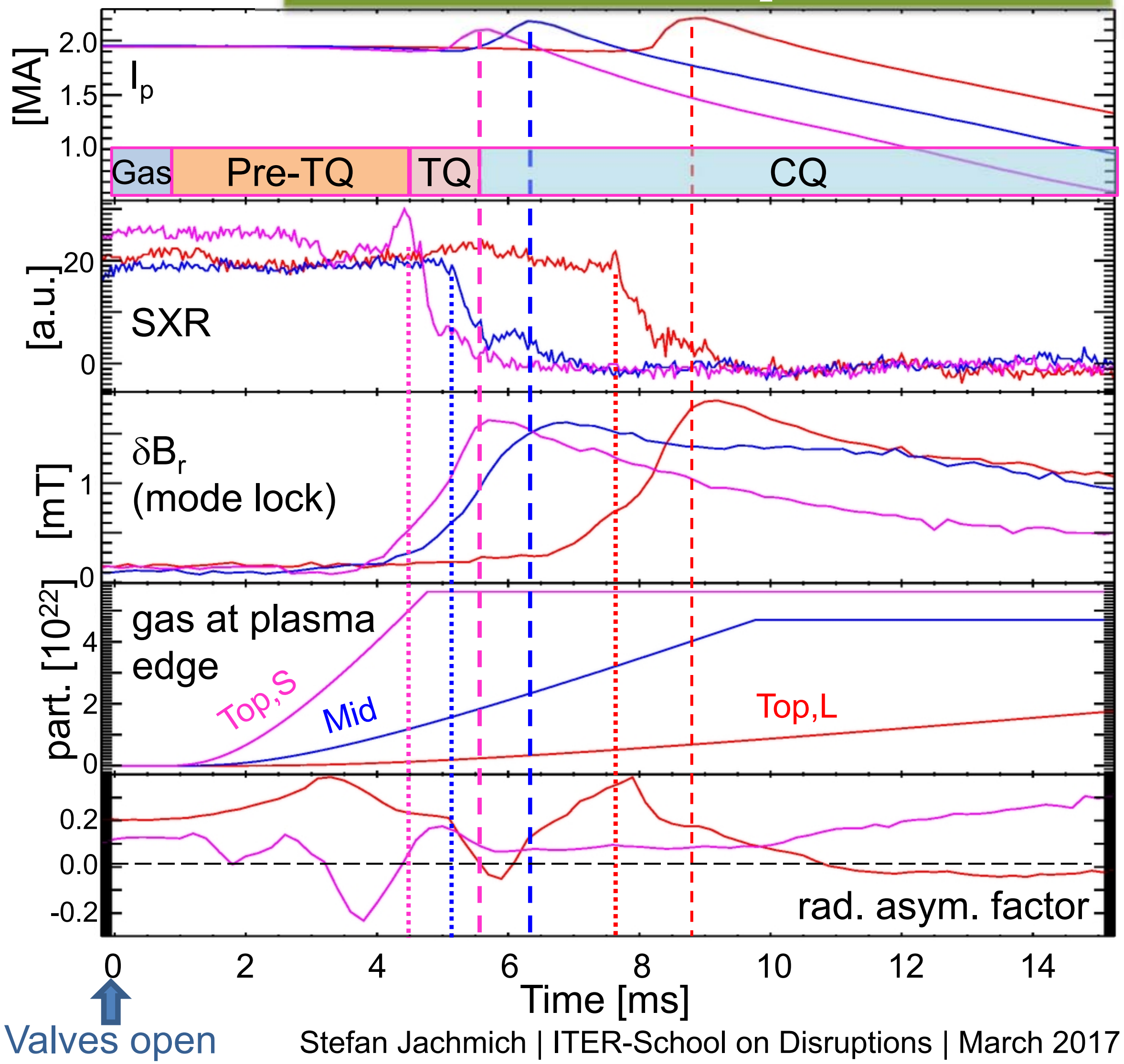
TQ: thermal quench

CQ: current quench

Radiation asymmetry:

$$\xi = \frac{P_{rad,V} - P_{rad,H}}{P_{rad,V} + P_{rad,H}}$$

MGIs into ohmic plasma, D_2+10%Ar, ~2.4barL



[1] E. Hollmann, NF'05

[2] S. Bozhenkov, PPCF'08

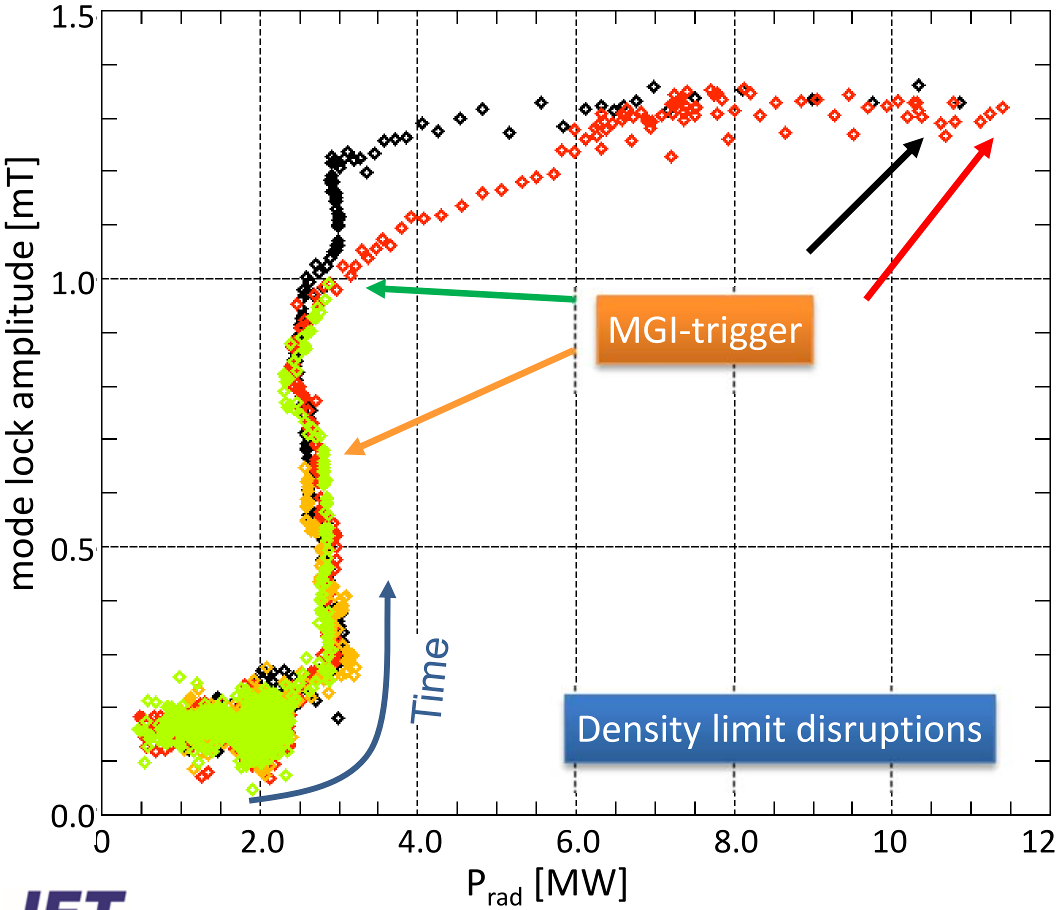
MGI-experiments a mimic for real disruptions?

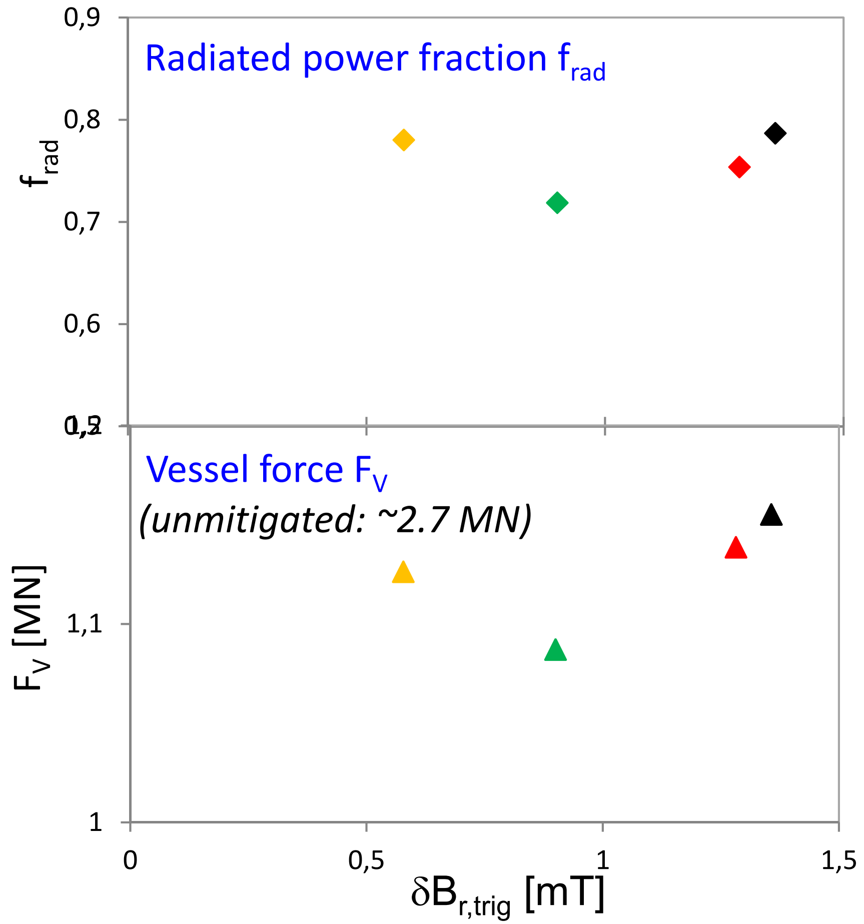
MGI-experiments:

- ➢ Injection into stable plasma, where no mode exists, to test various injection settings in reproducible plasma conditions

Density limit disruptions:

- ➢ DMV-gas was injected during different phases of ongoing disruption
- ➢ Presence of n=1 mode has little effect on assimilation of impurities
- ➢ Small variation of f_{rad} and F_V. MGI-disruptions can be used to study mitigation efficiency





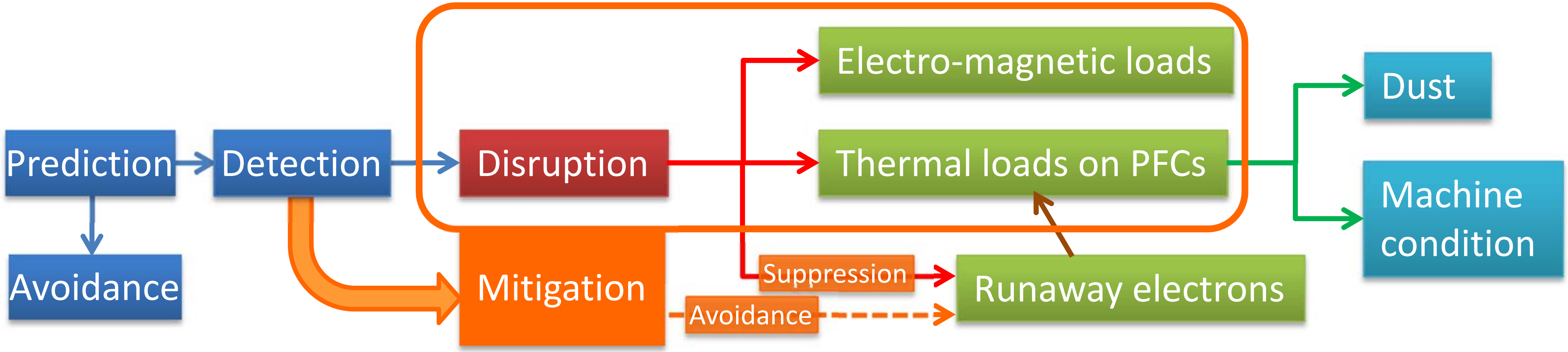
ITER-issues on disruption mitigation (excerpts)[1]

Assessment of thermal and EM load mitigation scenarios:

- Heat load mitigation requires E_{rad}/E_{th}>90%: How much gas?
- Control current quench time to minimise electro-magn. loads on first wall and vessel.
- Avoid generation of runaway electrons.
- Compare efficiency of massive gas injection from top with midplane injection.
- Dual injection with 2 top massive gas injectors and with add. midplane MGI.

Investigation and mitigation of toroidal asymmetries:

- Radiation asymmetries due to presence of MHD can lead to unacceptable heat loads.
- Determine radiation asymmetries.
- Reduce radiation asymmetries by optimising timing and amount of multiple MGIs.



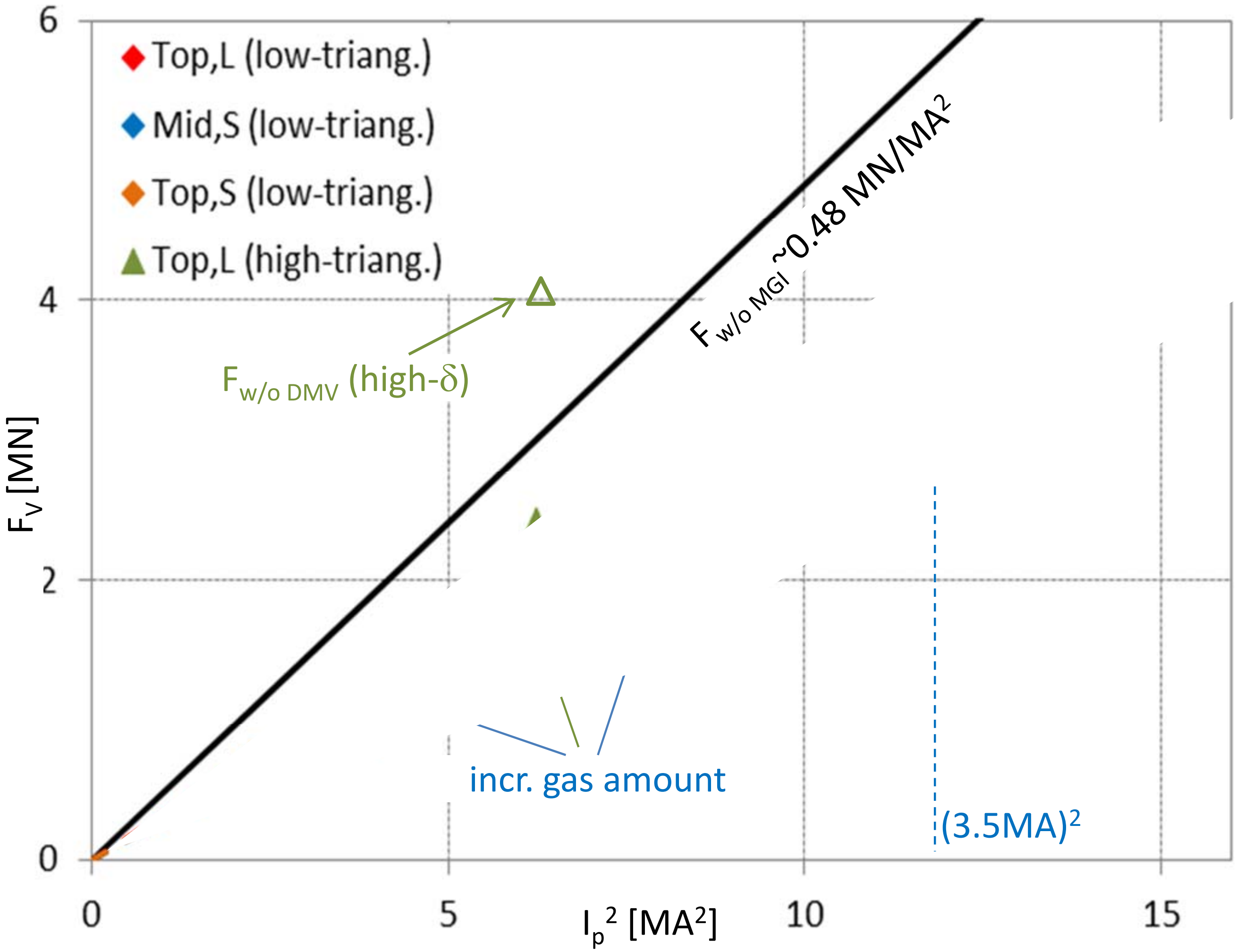
[1] M. Lehnen et al, JNM'15

3a) Mitigation of electromagnetic loads

Vessel force mitigation

- Same gas amount injected from a given valve at different plasma currents.
- $F_{w/o\ MGI}$: expected vessel force determined from unmitigated VDEs.
- Dynamic vessel forces are reduced by about 33% (MGI-topL) and 40% (MGI-mid).
- Injection location has no influence on force mitigation.
- No reduction in mitigation efficiency has been observed at high plasma current.

MGI (Top,L): 1.7 10^{22} Ar
MGI (Mid,S): 5.9 10^{22} Ar
MGI (Top,S): 3.5 10^{20} Ar
Scaling based on constant MGI-gas amount.



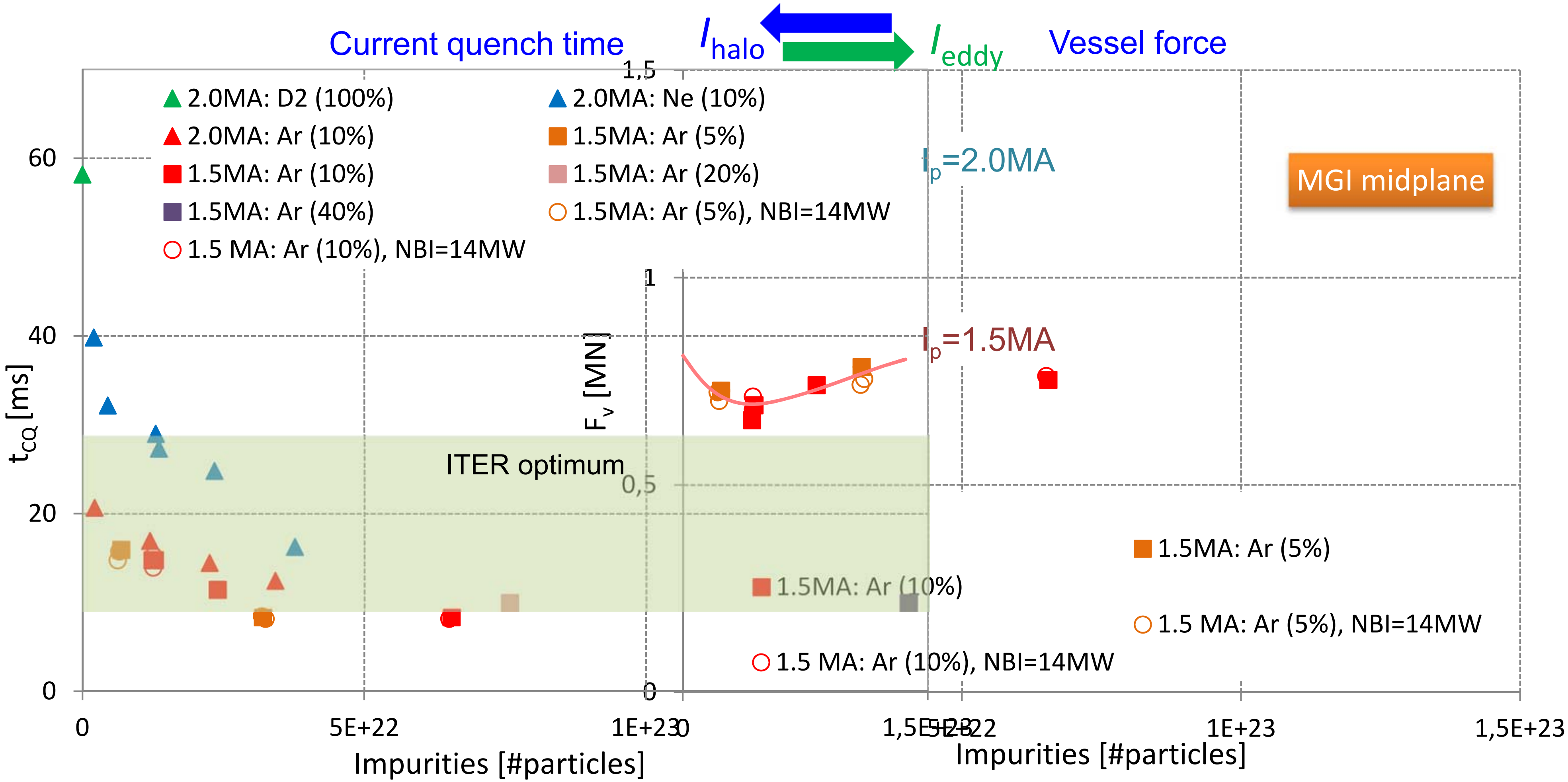
Note: no signs of runaway electrons up to explored plasma current of 3.5 MA.

JET

S. Jachmich, PSI2016

Optimising electromagnetic load reduction

- Scan of impurity injection at 1.5MA/1.5T and 2.0MA/2.0T
- Higher Ar-injection does not lead to further reduction of vessel forces.
- Data suggest minimum of vessel force at low gas amount (balanced impulse from halo and eddy currents?).



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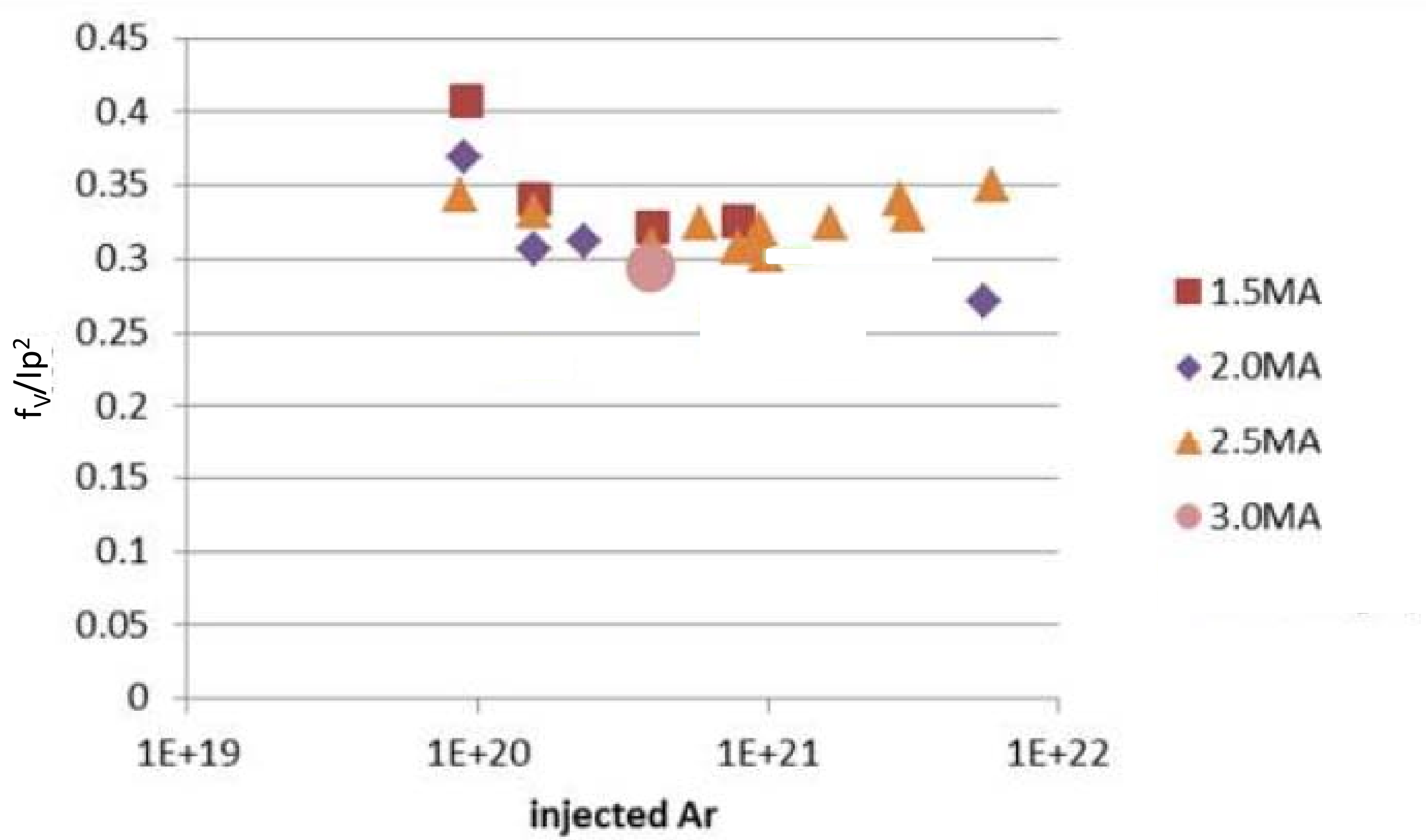
S. Jachmich, PSI2016

Electromagnetic load reduction: Top,S inj.



S. Jachmich, PSI2016

3b) Thermal load mitigation

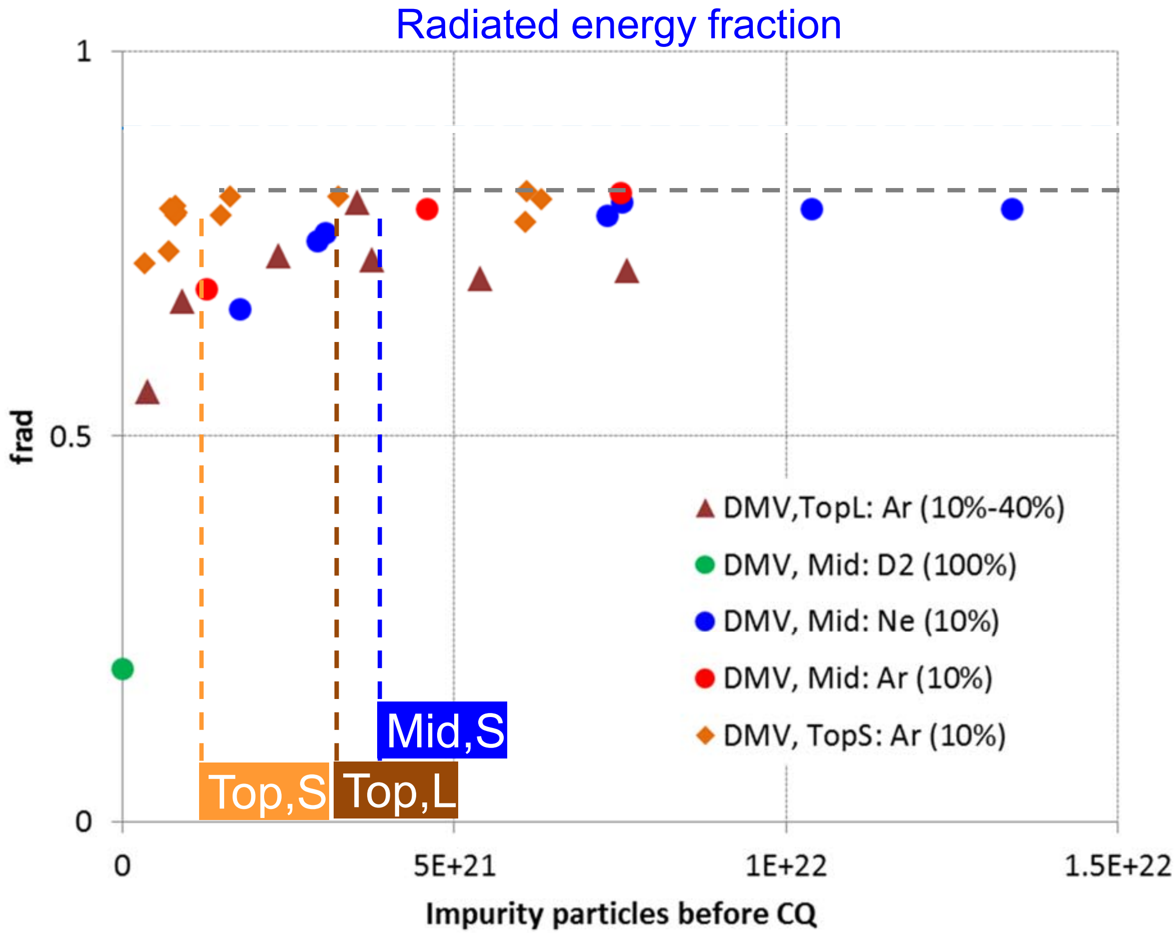
Efficiency of energy radiation

- Radiated energy fraction f_{rad} does not further increase with increasing MGI-impurities.
- Similar maximum f_{rad} for Top,S- and Mid-MGI.
- Top,S reaches saturation with less impurities (->more efficient?)
- However, required minimum injection might depend on thermal energy.
- Caveat: uncertainty in radiated energy due to toroidal asymmetries and potential diagnostic limitations

Radiated energy fraction:

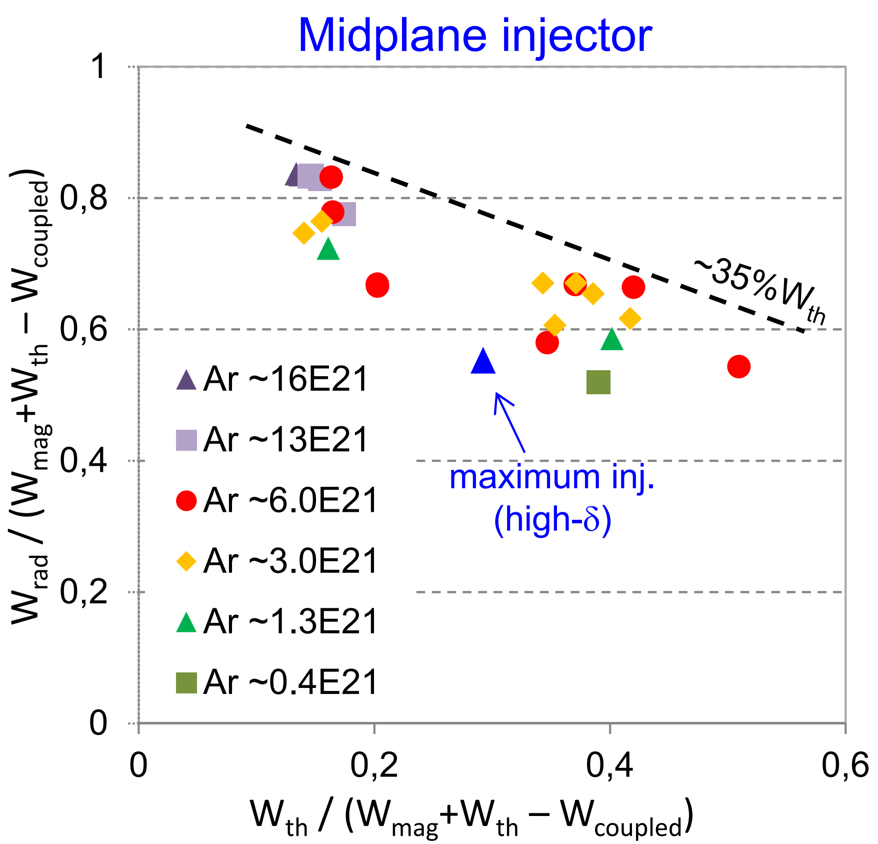
$$f_{rad} = \frac{W_{rad}}{W_{mag}+W_{thermal}-W_{coupled}}$$

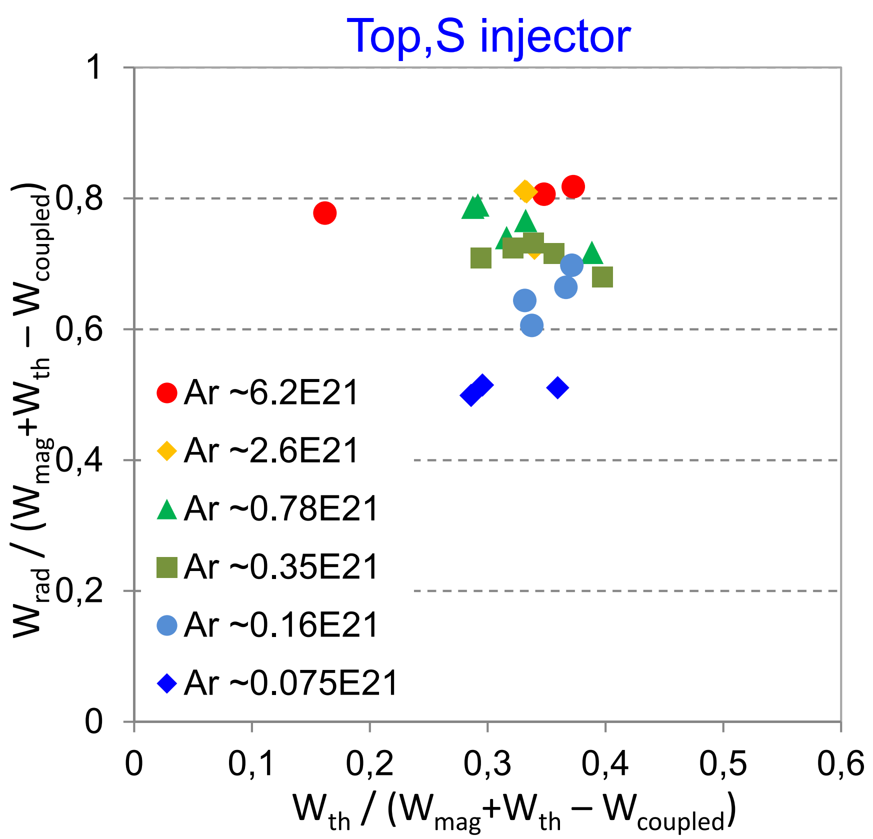
W_{rad}: radiated energy during disr.
W_{mag}: magnetic energy
$W_{thermal}$: thermal plasma energy
$W_{coupled}$: energy dissipated into vessel and PF-coils



Mitigation efficiency for high thermal energy

- Initial experiments with MGI (Top,L) showed degradation of efficiency towards higher thermal energy
- At <u>high thermal fraction:</u> higher radiated fraction achieved with MGI from top (short tube)
- Influence of injector location on f_{rad} at high f_{th} cannot be excluded





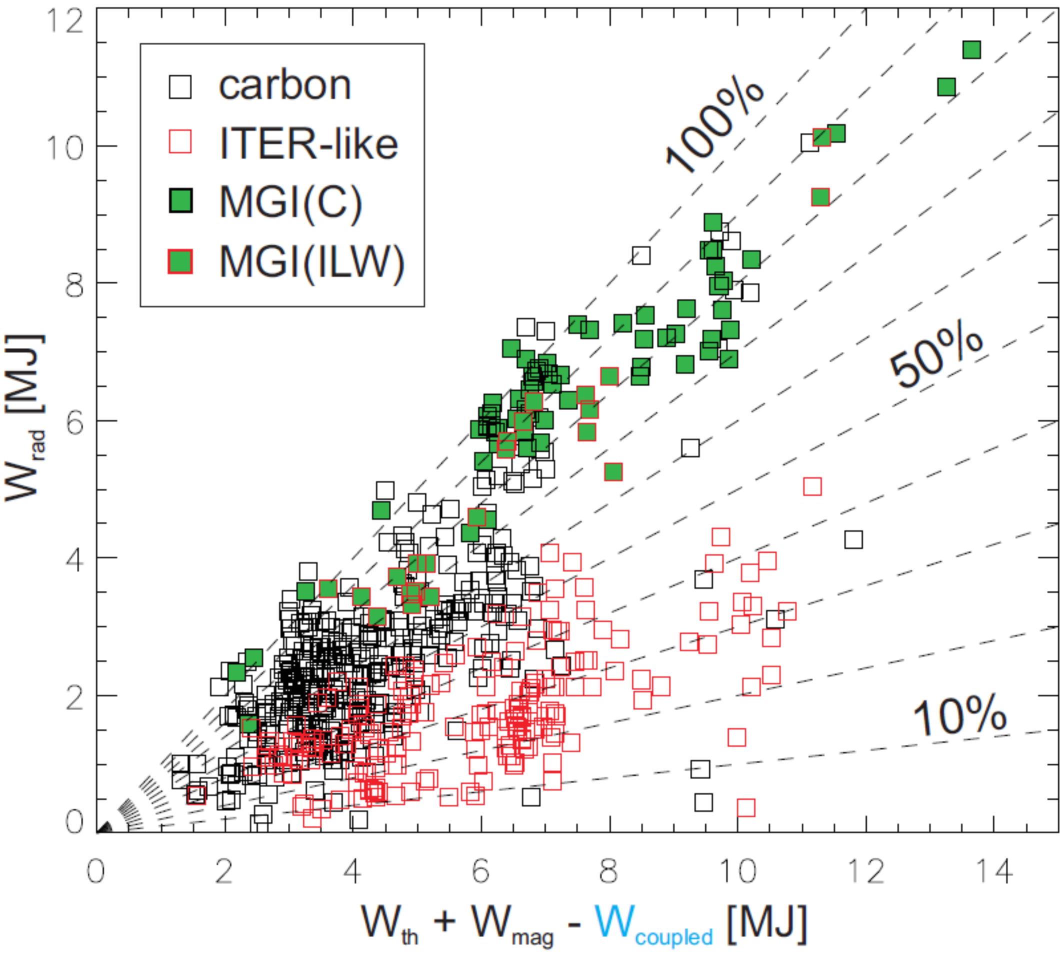
S. Jachmich, PSI2016

Note: Plasma energy is corrected for energy dissipated into coils.

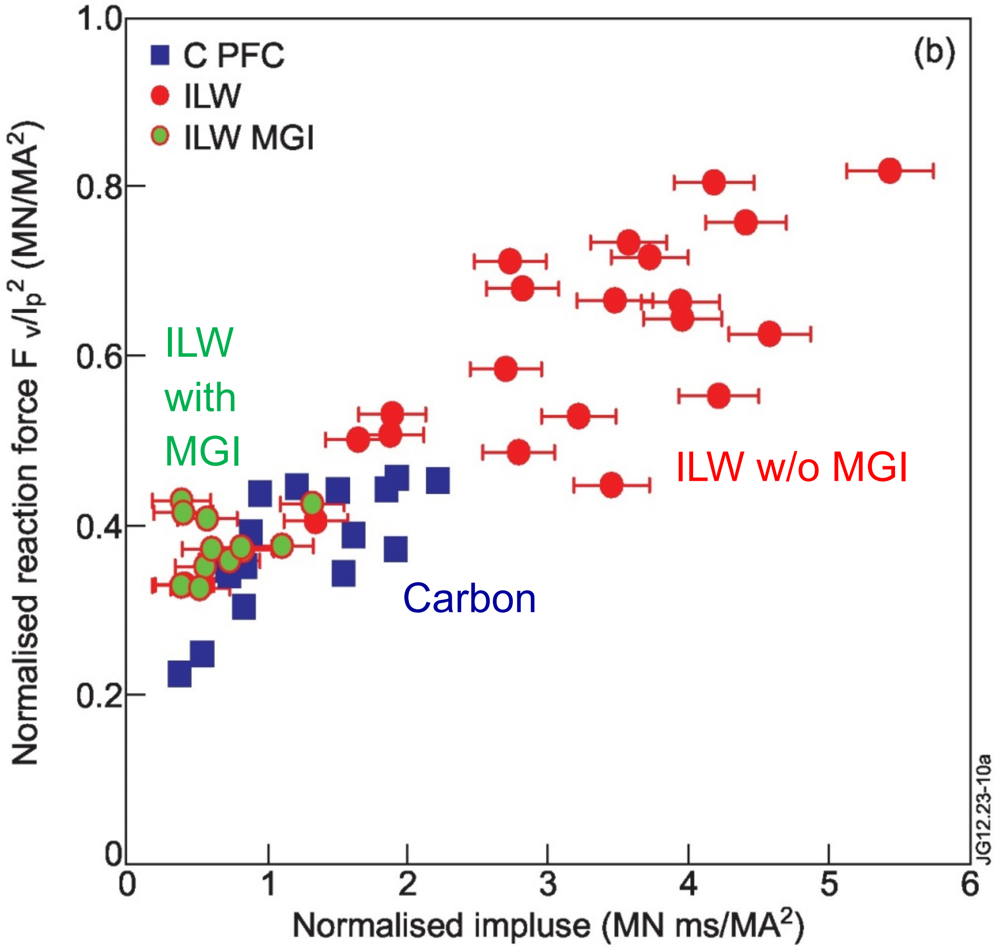
Disruption mitigation in routine operation

- Massive gas injection (MGI) in ILW recovers radiation fraction back to 70-100%
- Shortening of current quench time reduces and hence reaction force

Radiated energy



Vessel force



M. Lehnen, JNM 2013

3c) Toroidal radiation asymmetries

Toroidal radiation asymmetries

- ITER: about 80% of stored energy might be lost in TQ
- Localised injection into n=1 mode during TQ cause large radiation asymmetry
- High toroidal peaking factor in radiation might lead to local heat load beyond melt limit

$$TPF = \max\left(P_{rad}(\phi)\right) / \langle P_{rad}(\phi)\rangle$$

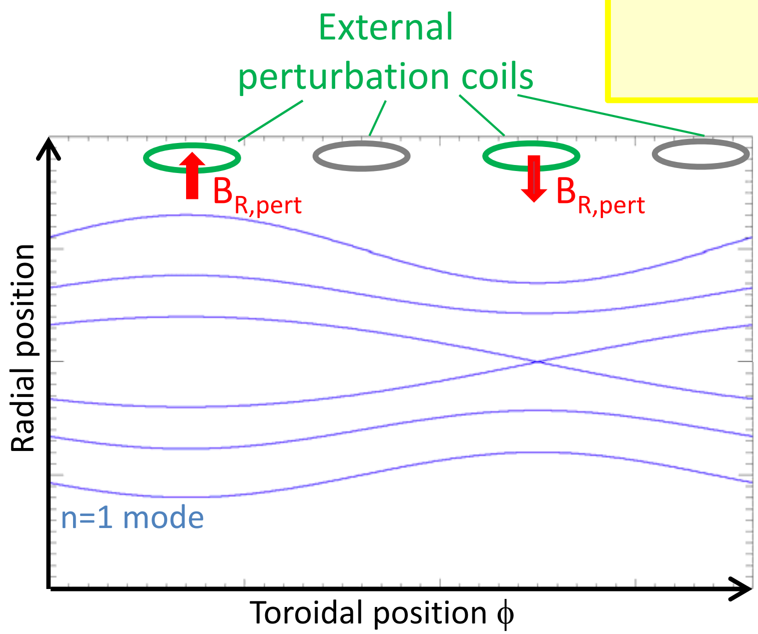
- External magnetic field perturbations were applied to seed n=1 modes
- Phase of n=1 mode can be varied by changing coil polarities
- MGI fired into existing n=1 mode

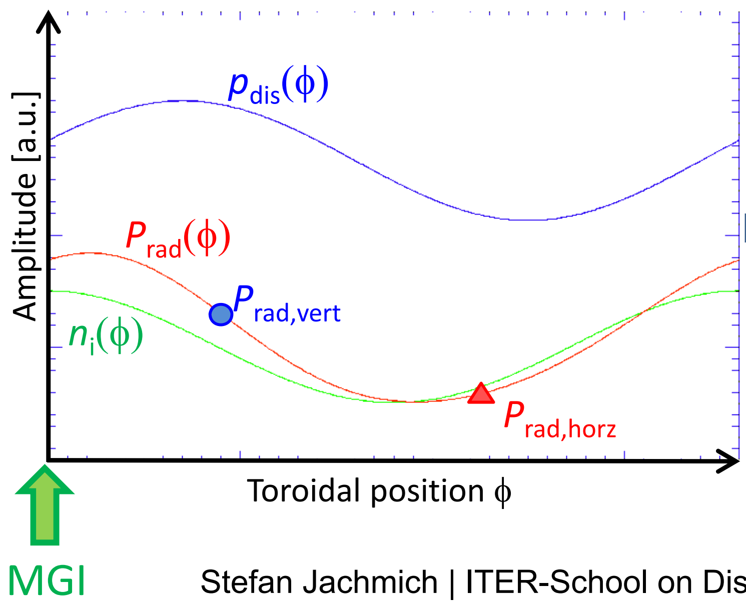
Interpretative model: Impurity density: $n_i(\phi) = n_{i,0} \exp(-(\phi - \phi_{inj})^2/\lambda_n^2)$

Radiation distribution: $p_{dis}(\phi) = 1 + \Delta p \cos(\phi_{n=1} - \Delta\phi_{n=1} - \phi)$

Radiated power: $P_{rad}(\phi) = \langle P_{rad}\rangle\, p(\phi)\, n_i(\phi)$

– = free fit parameter



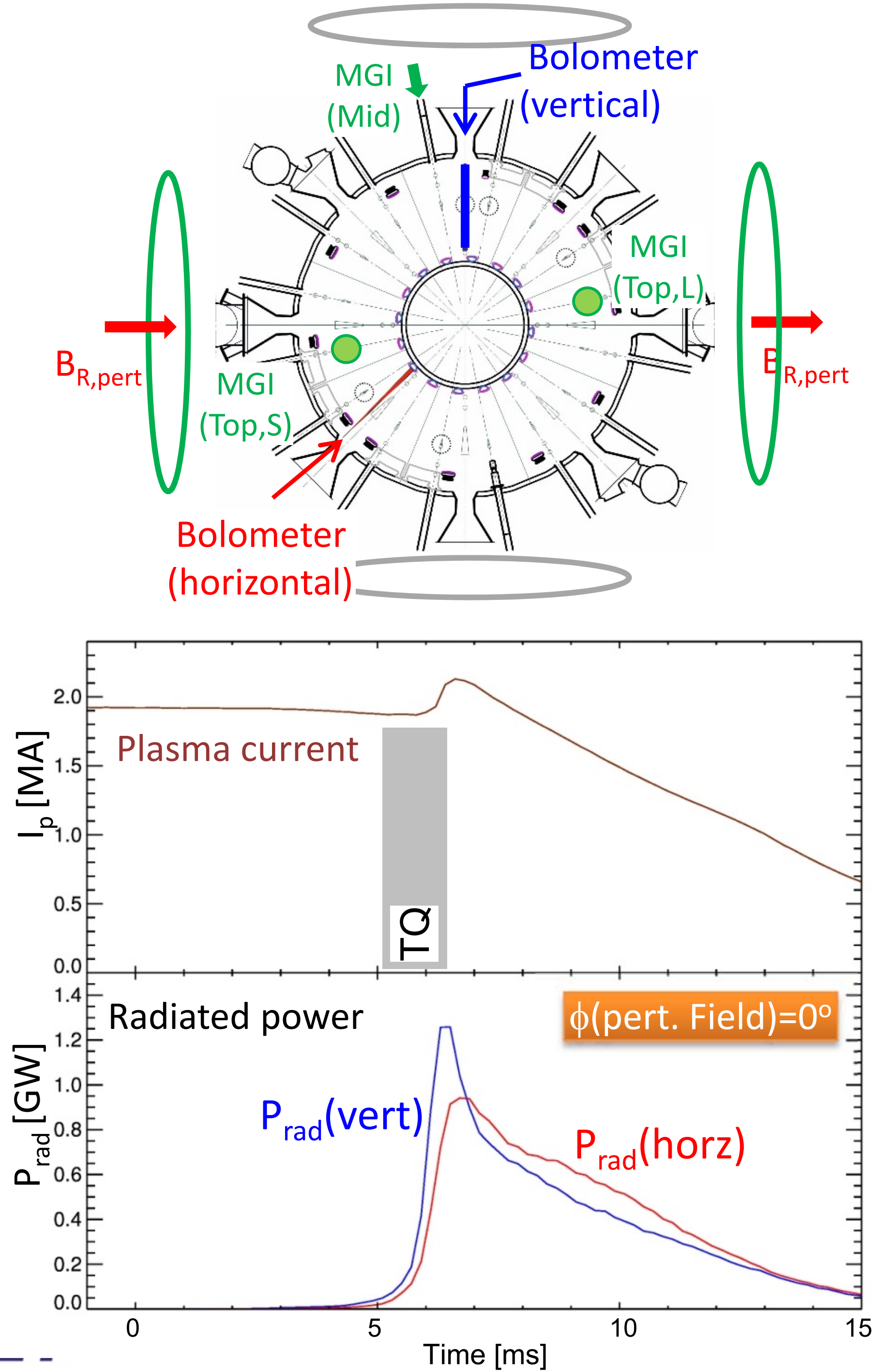


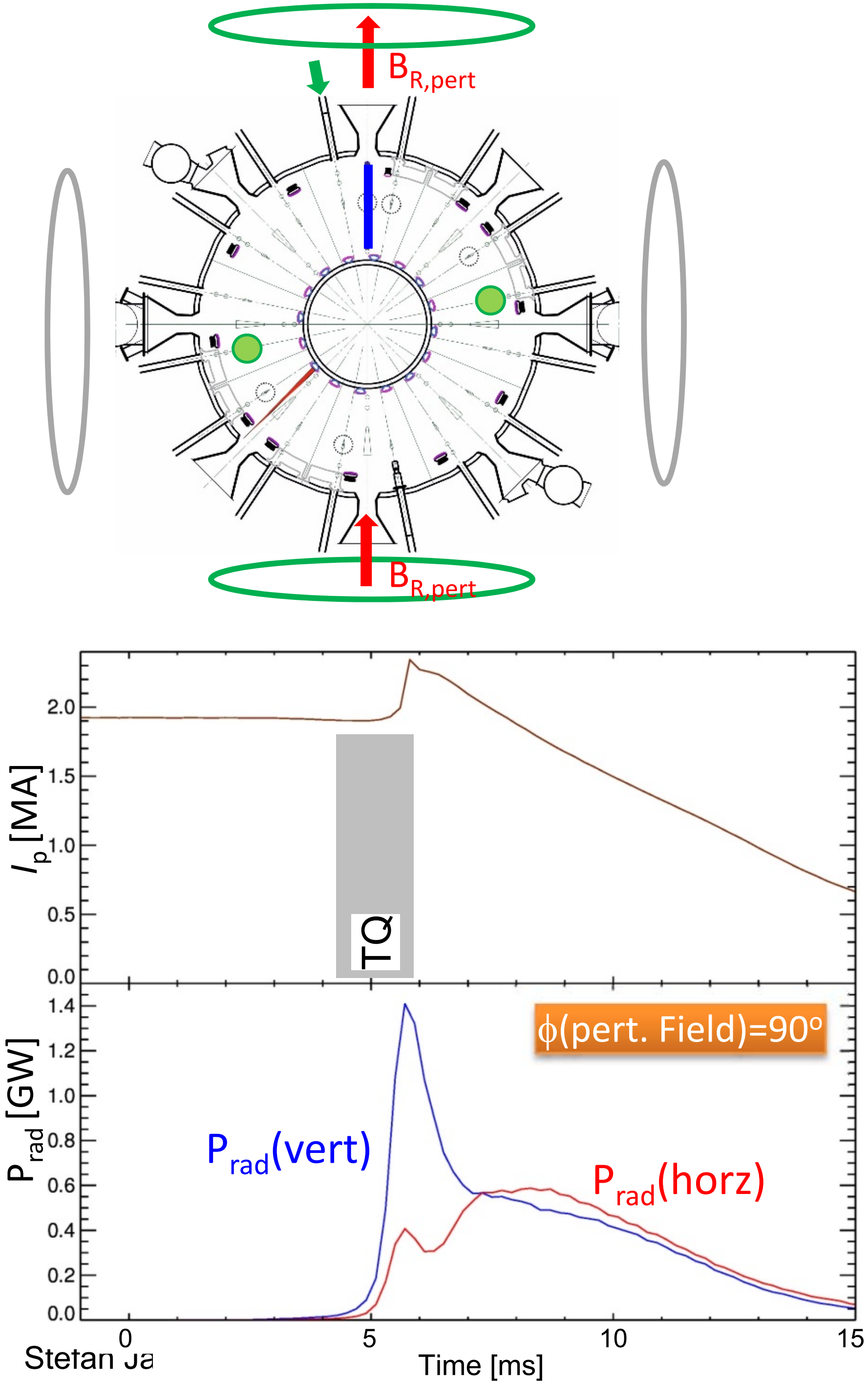
$$\xi = \frac{P_{rad,vert} - P_{rad,horz}}{P_{rad,vert} + P_{rad,horz}}$$

$TPF(\phi_{n=1})$

M. Lehnen et al, NF2015

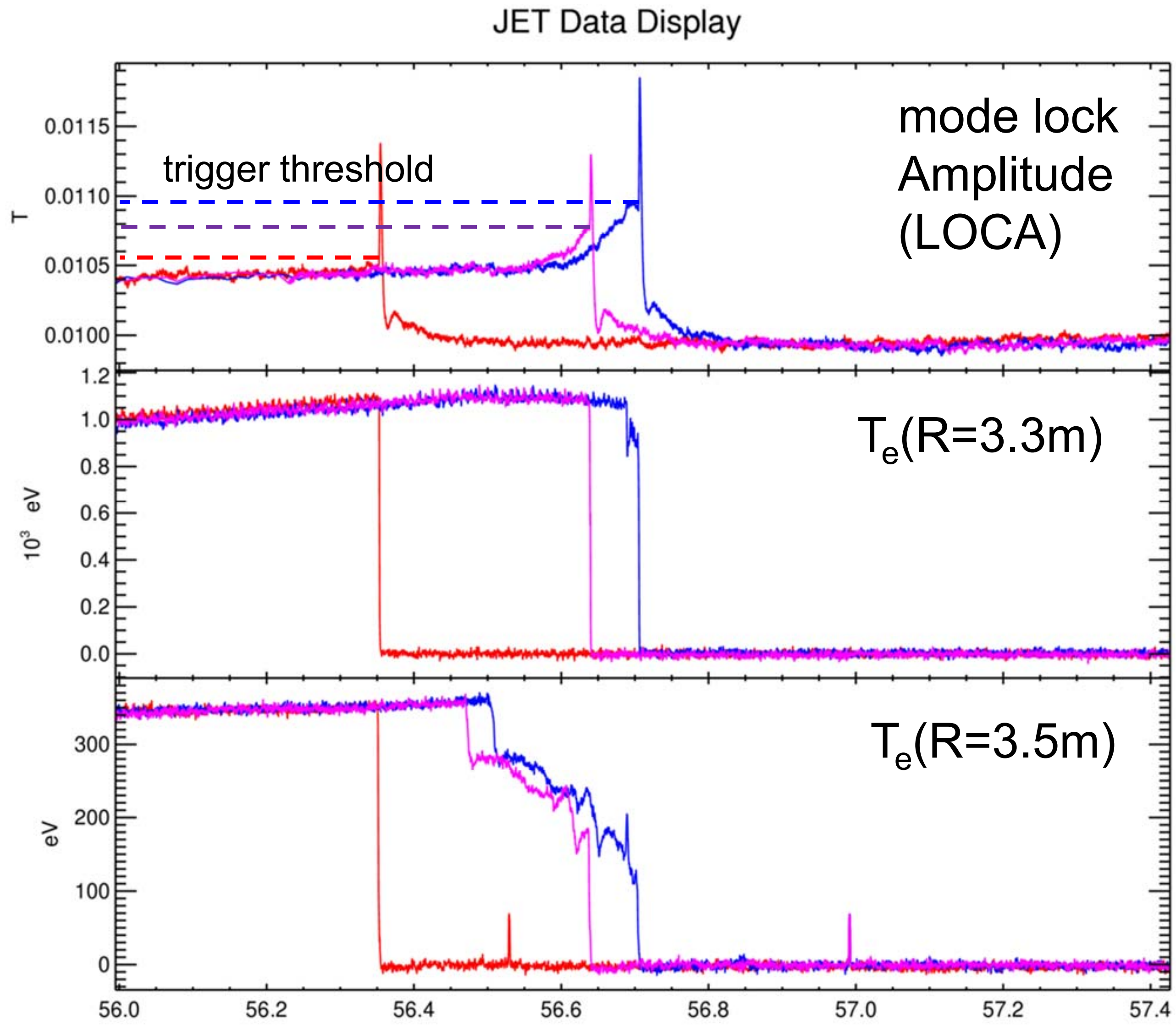
n=1 phase variation





MGI triggering

- trigger on real time mode-lock signal (LOCA)
- **optimal** MGI timing is:
  - not too early (no fixed n=1 mode phase)
  - not too late (core confinement degradation)

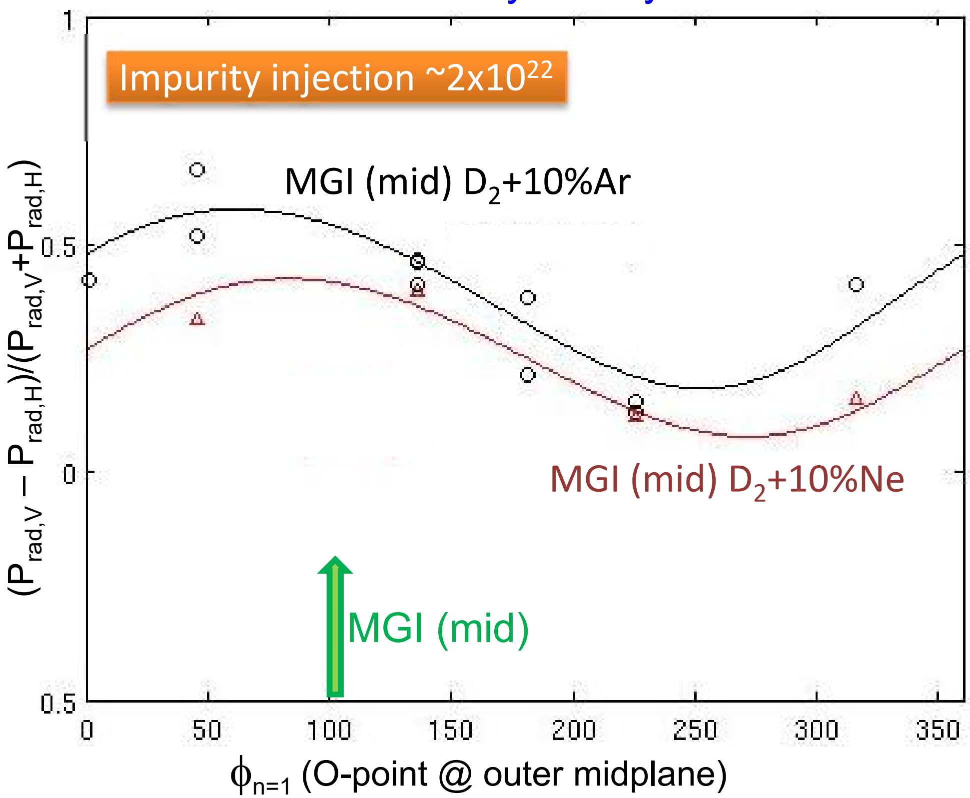


P. Drewelow et al

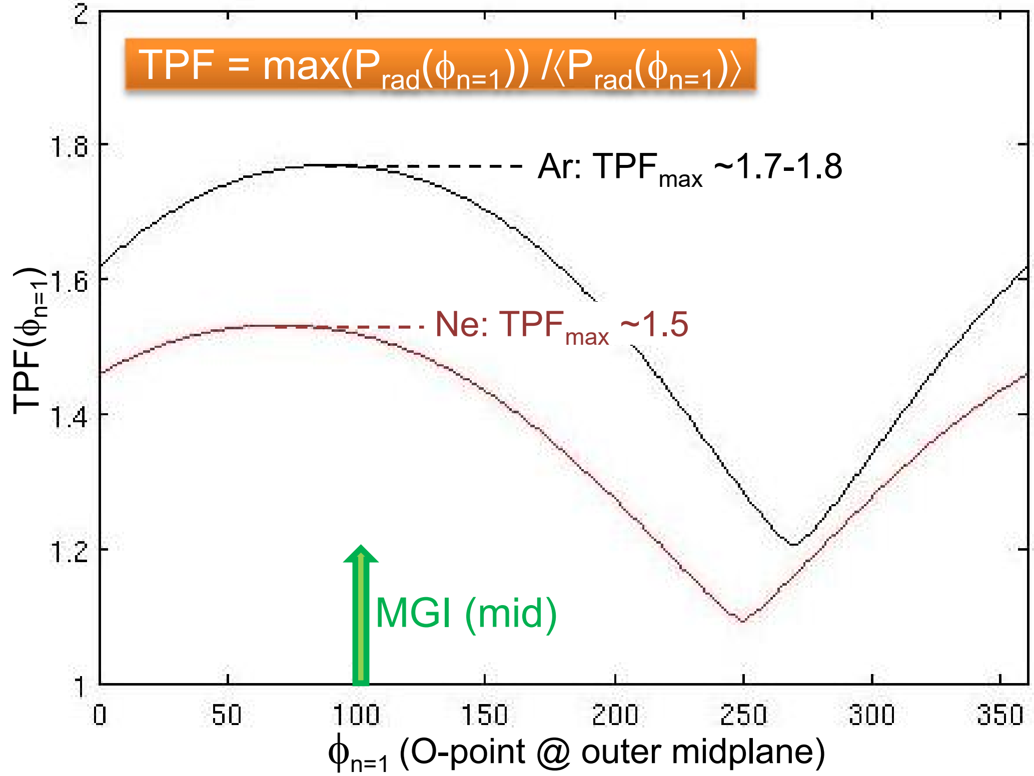
Toroidal peaking factor

- Radiation asymmetry factor smaller for Ne
- Data of phase variation are fitted with model asumming cos(ϕ)-dependence for radiation and toroidal Gaussian impurity distribution
- TPF is higher for injections into the O-point.
- TPF for Argon higher, probably due to smaller toroidal distribution of impurities

Radiation asymmetry factor



Toroidal peaking factor

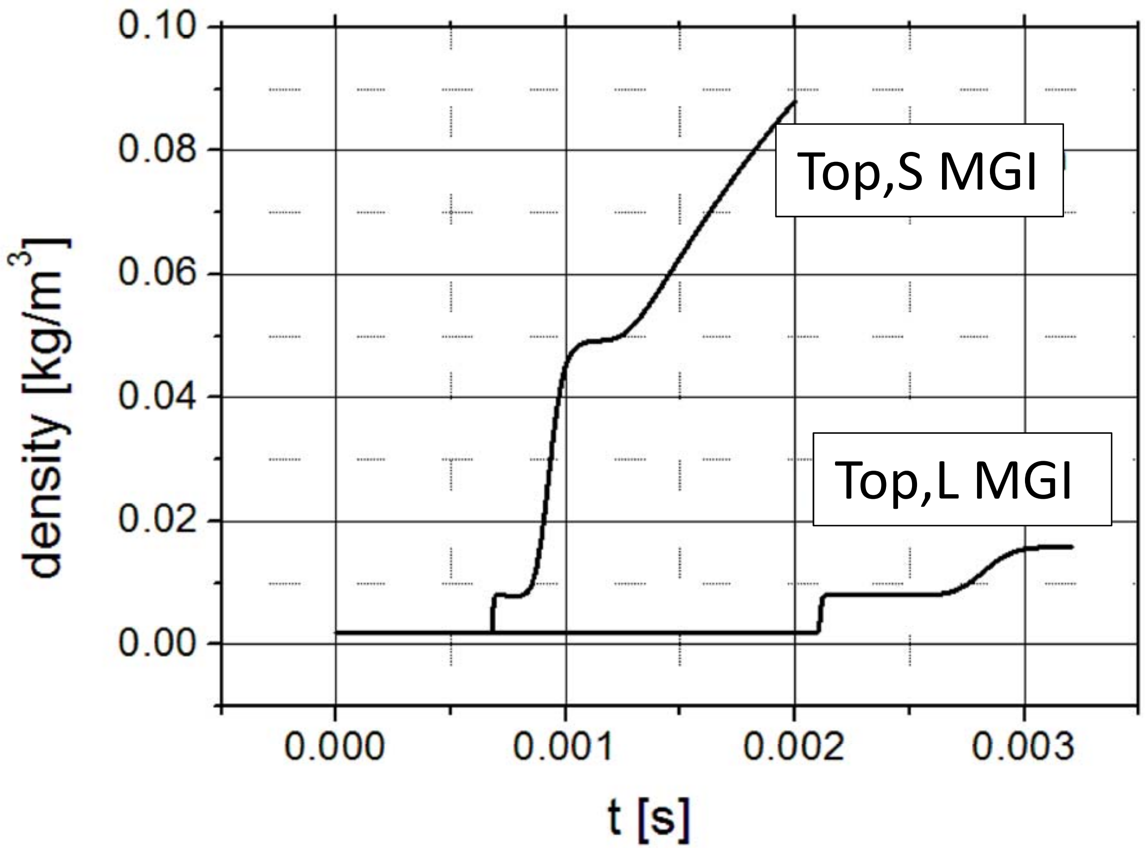


Synchronous MGI injections

- use mode-lock signal to trigger MGI
- BUT: gas delivery differs for Mid,S, Top,S and Top,L MGI

- use time delay based on individual time from injection to CQ for each MGI
- modify gas pressure in MGI for equal injected amount of impurities at CQ

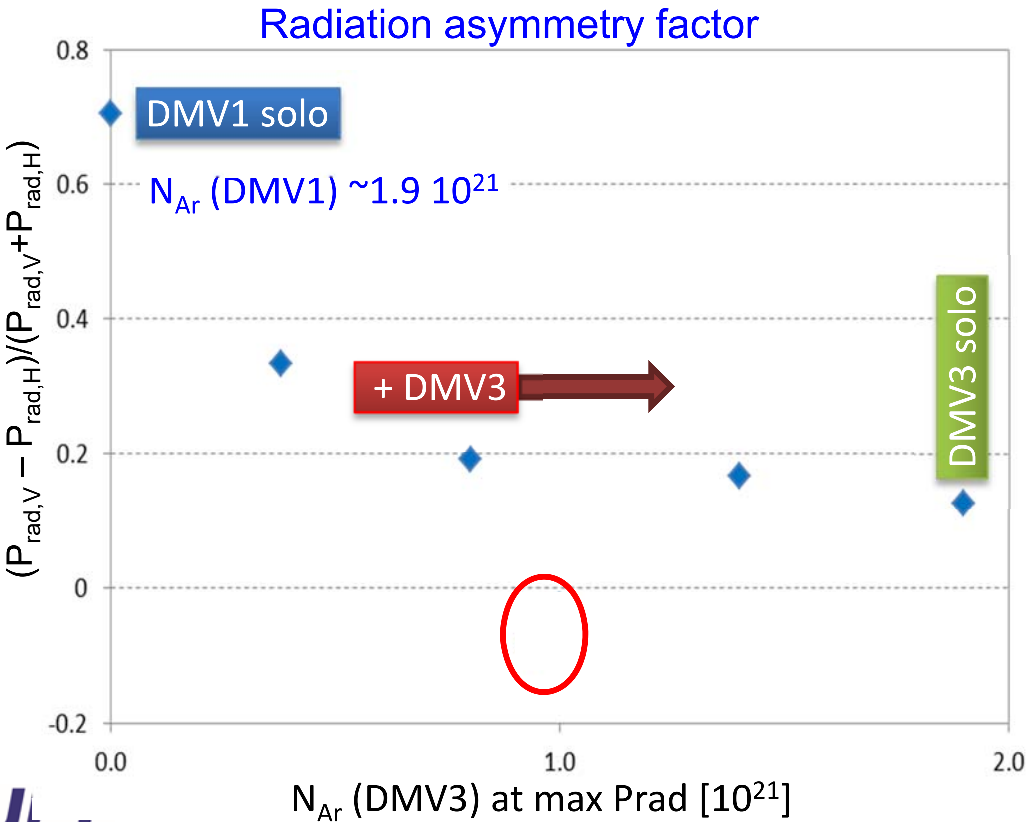
→ symmetric injection?

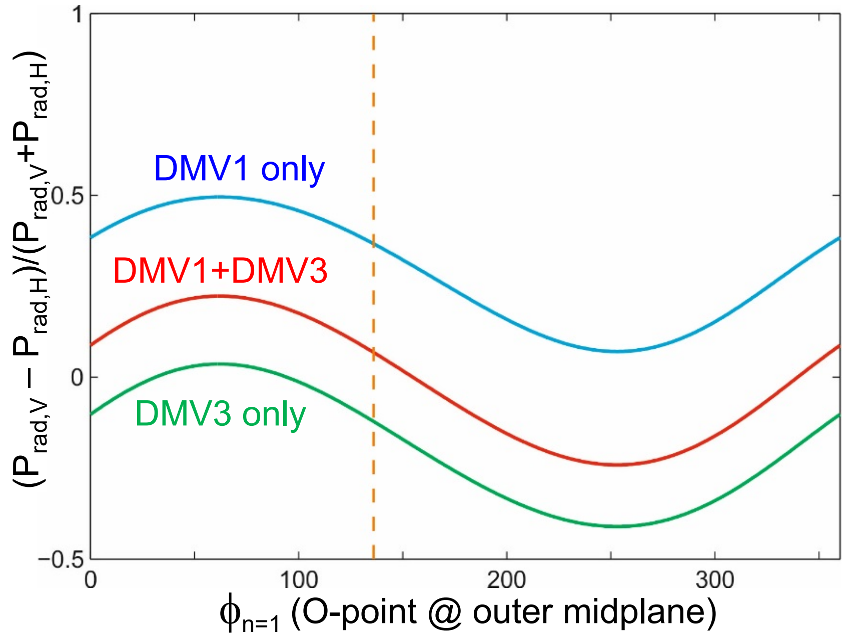


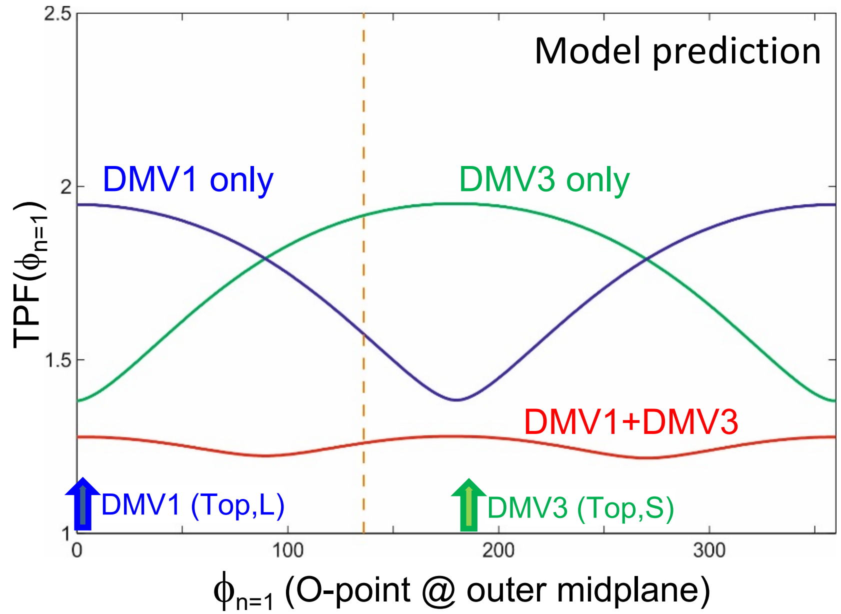
U. Kruezi et al

Radiation asymmetry in dual injections

- Gas amount and timing of DMV1 and DMV3 (Top-injectors) has been varied to control total amount of particles at time of radiation peak.
- Injecting additional gas from opposite site reduces asymmetry factor down to 10%.
- Asymmetry factor reverses when $N_{rad,peak}$(DMV3) ~10^{21}.



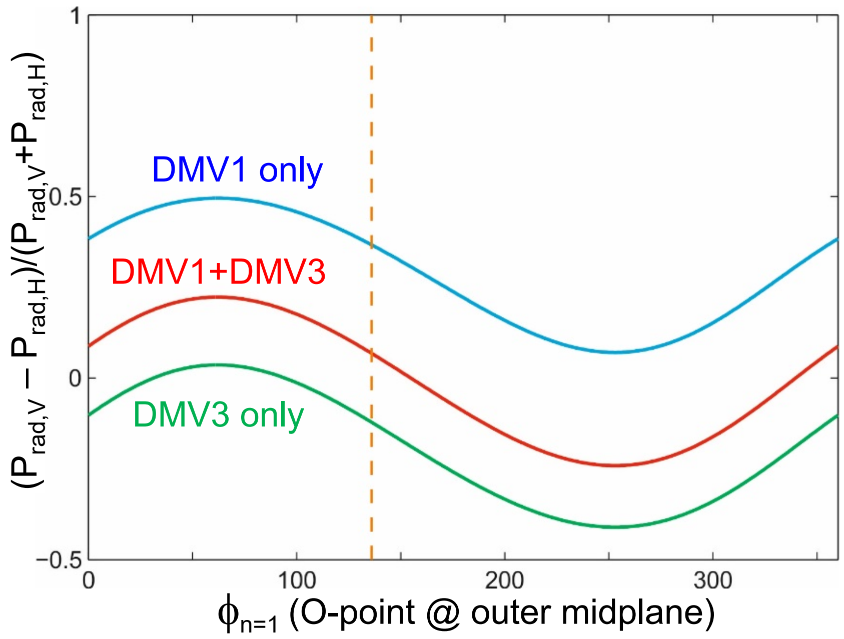


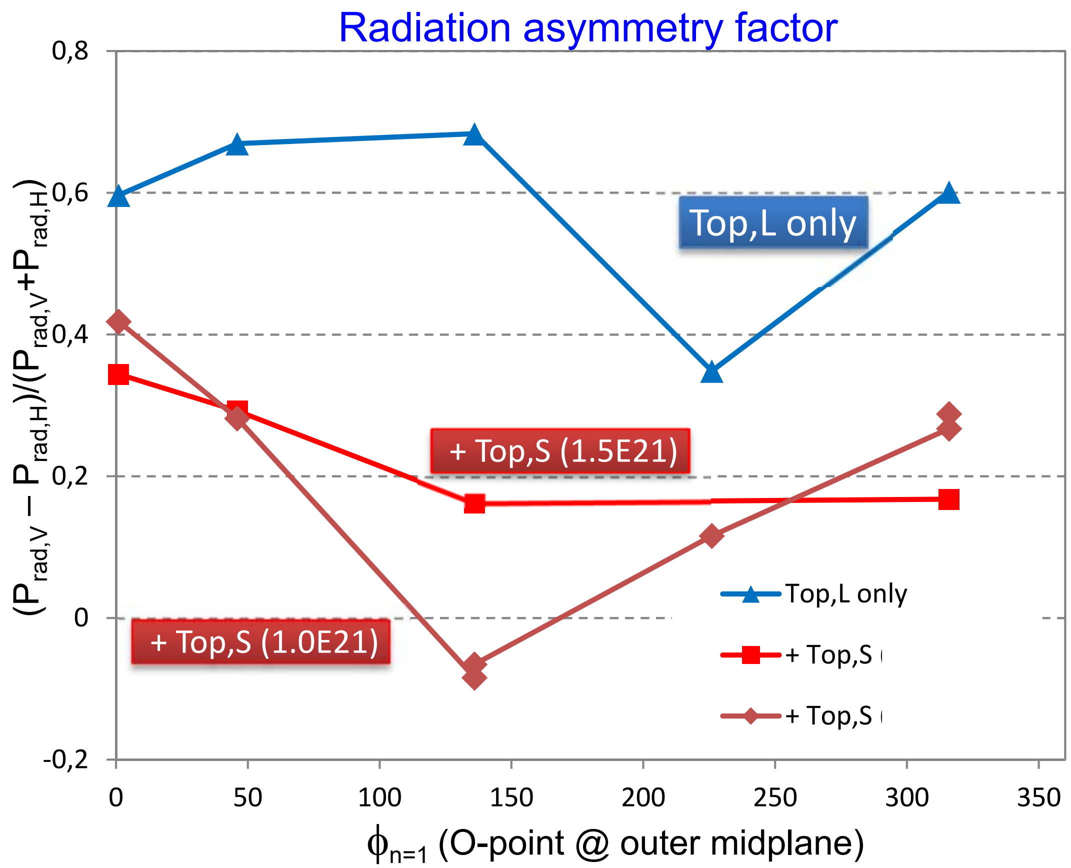


S. Jachmich, PSI2016

Radiation asymmetry for dual injection

- Toroidal profile of rad. asym. fact. for dual injection smaller than for single inj.
- Reduction very sensitive to gas amount from second MGI





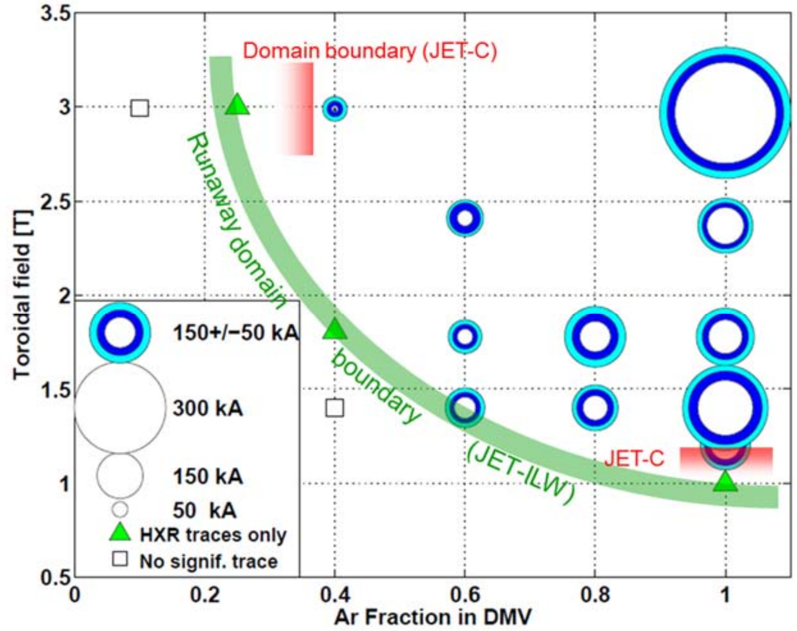
S. Jachmich, EPS2016

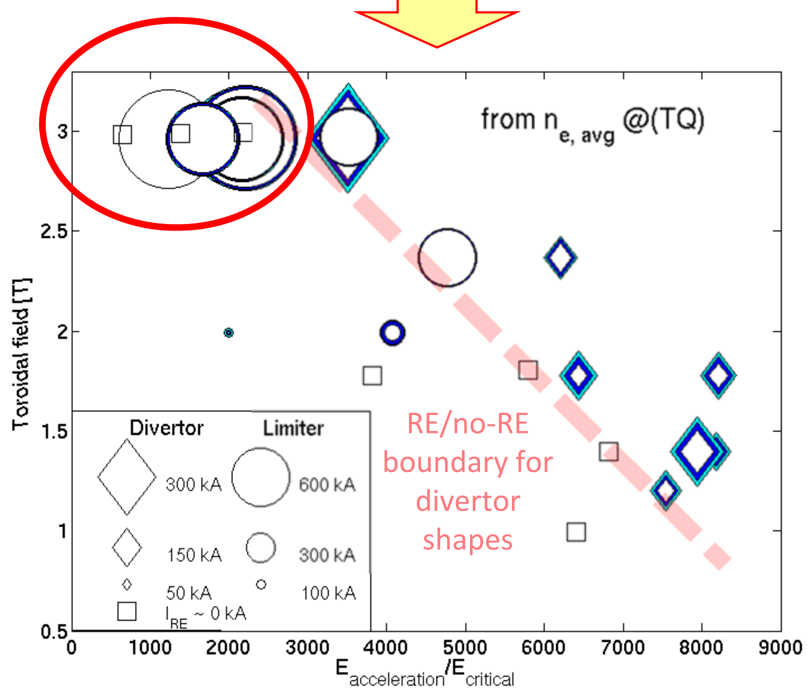
4) Runaway electrons:

Production, Avoidance, Suppression

Runaway existence domain

- RE generation using D_2+Ar MGI to determine the operational domain
- Domain boundary (entry points) similar between JET-C and JET-ILW
- Known runaway generation dependencies:
  - Accelerating electric field E_a
  - Critical electric field (Dreicer and avalanche mechanisms) $E_c = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon^2 m_e c^2}$
  - Toroidal field B_t
- With divertor pulses: clear domain in (E_a/E_c, B_t) space
- At equal E_a/E_c, limiter pulses generate higher runaway currents





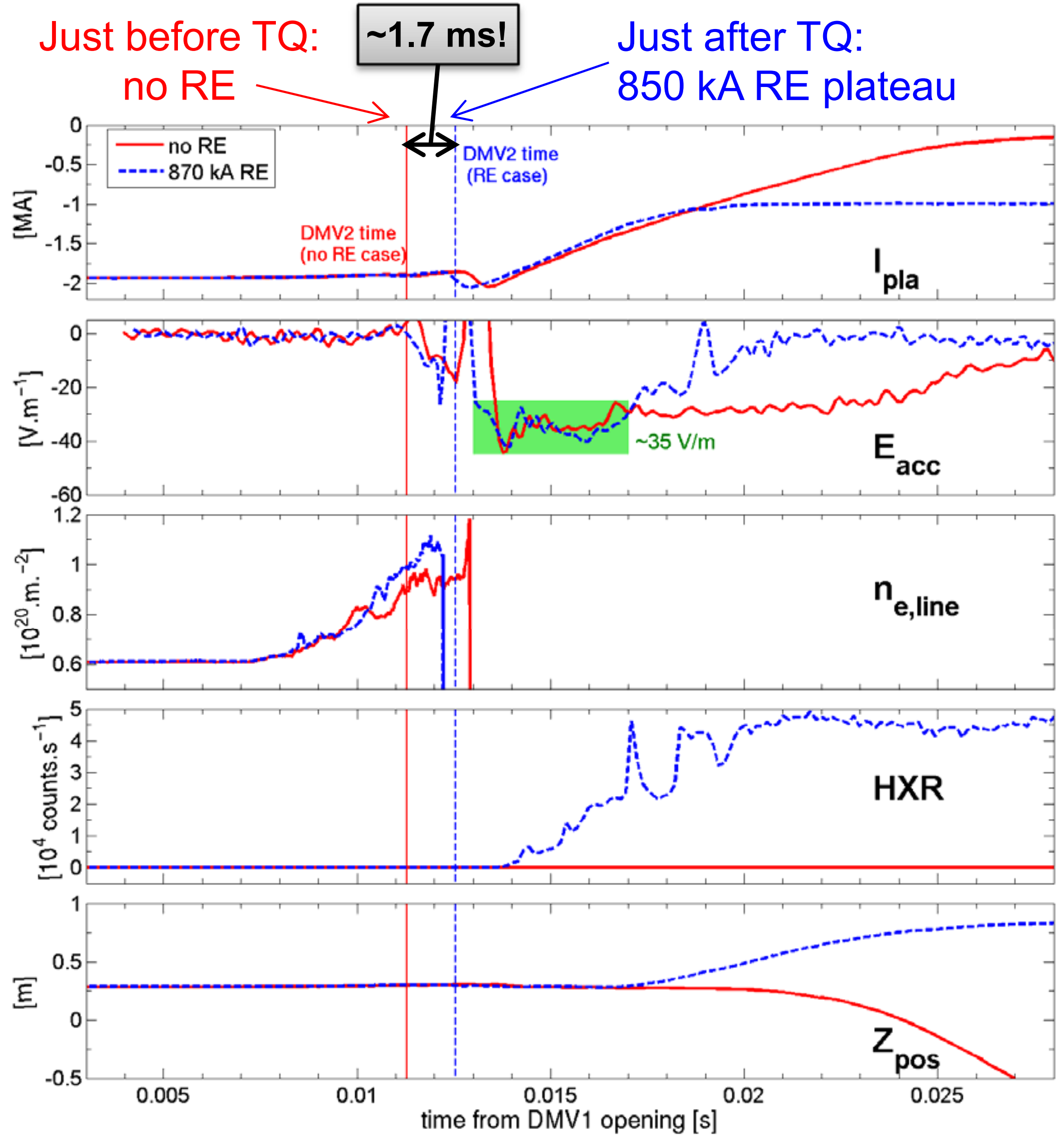
Strong dependence of RE generation on vertical stability

C. Reux et al, NF15

Runaway suppression before TQ

- Scenario: trigger runaway beam with DMV1 low pressure (1.7 bar.l) 100% Argon ➔ ~0.7 MA 50 ms
- Mitigation attempts: fire DMV2 high pressure D_2 at different times Result:
  - No runaways when DMV2 gas arrives before the thermal quench
  - Fully unmitigated runaway beam when DMV2 gas arrives after thermal quench
- dI_p/dt, accelerating electric field E_a almost identical during early CQ
- Density rise before TQ very similar

➔ DMV2 gas mixing regime very different if the D_2 front arrives before or after TQ

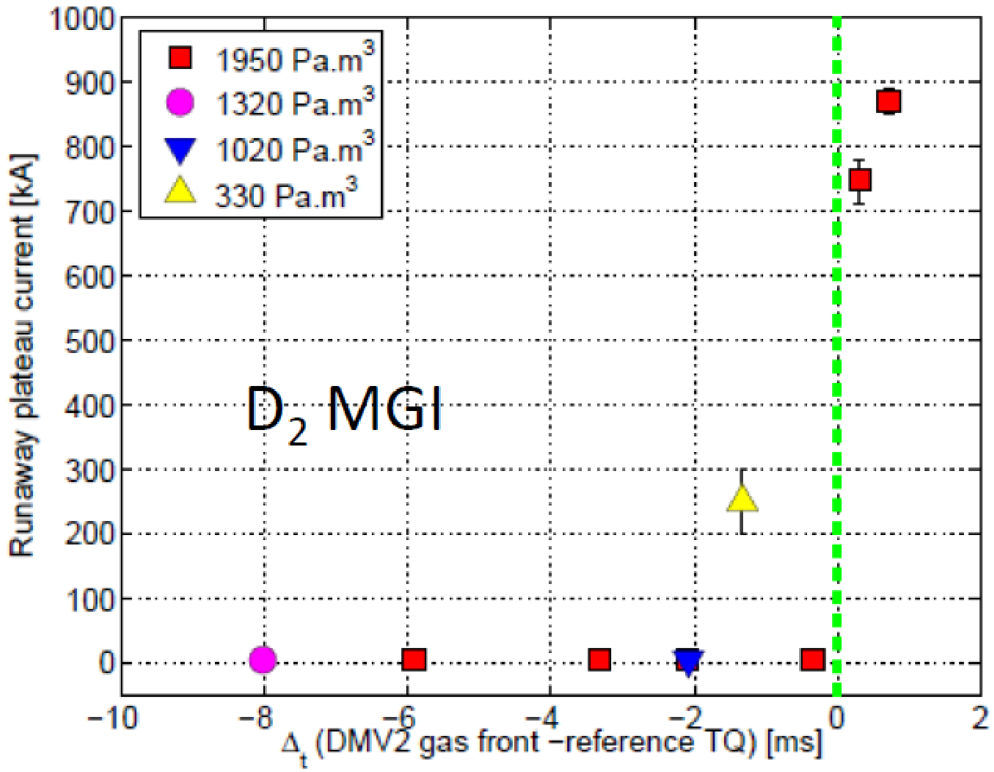


Suppression of an incoming runaway beam feasible if done before TQ

C. Reux et al, NF15

Runaway suppression during TQ

- DMV2 timing varied with respect to DMV1-initialised disruption
- Minimum amount of gas required to achieve avoidance

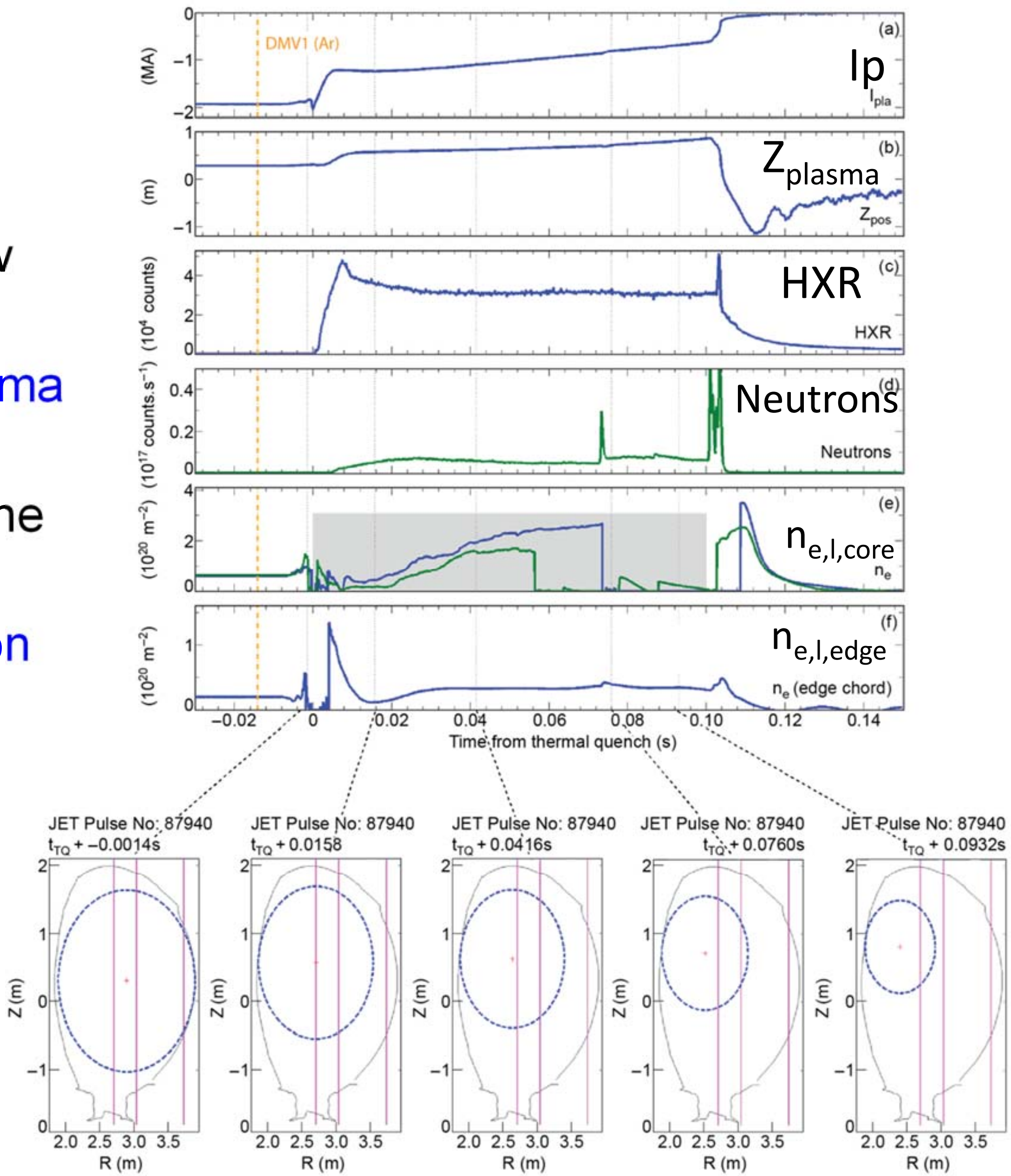


Sharp transition from complete prevention of RE-generation to full developed runaway beam

C. Reux et al, NF15

Runaway beam studies

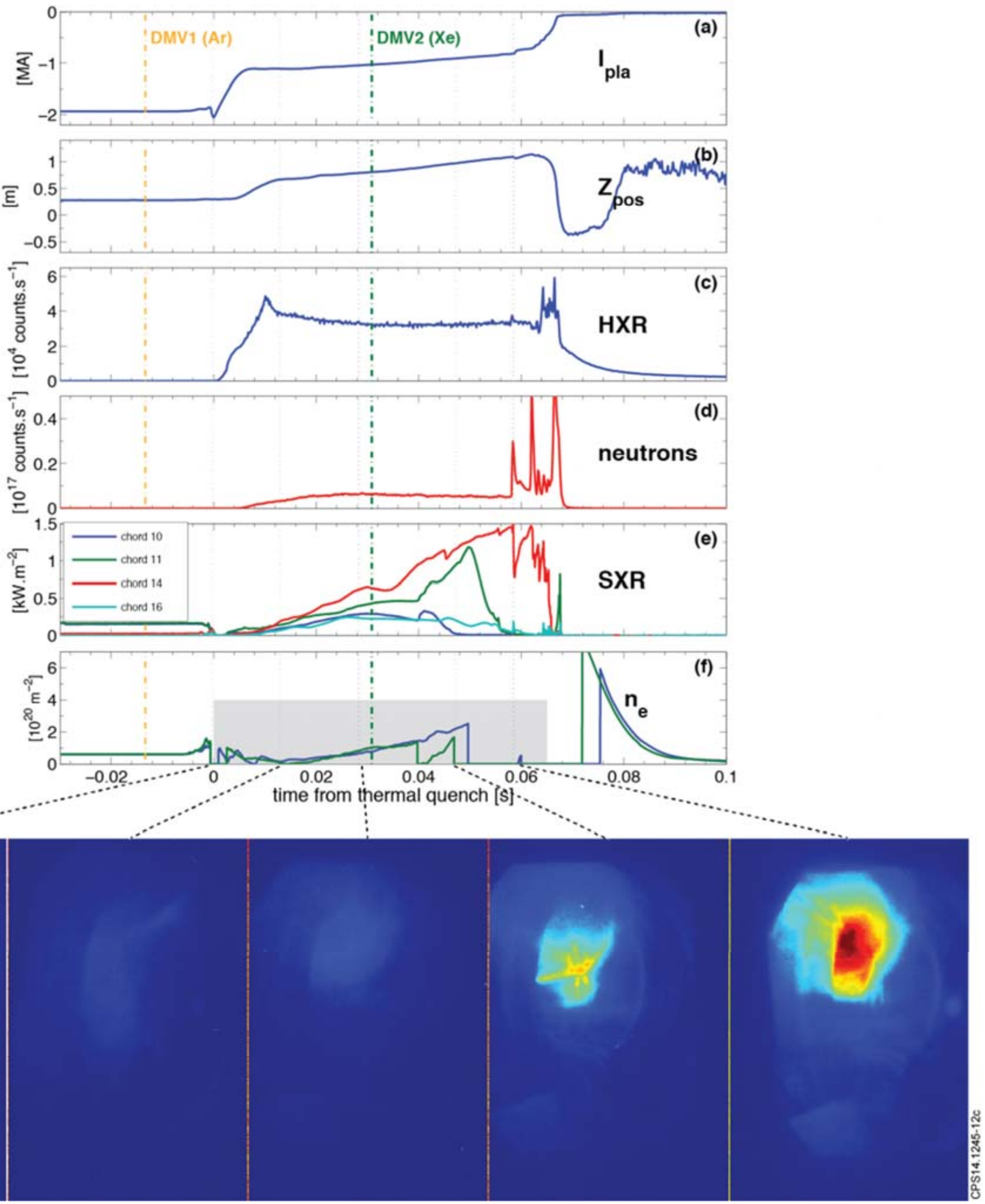
- Runaway beam created using pure argon massive gas injection at low pressure in Top,L-MGI.
    - Up to 100 ms duration with slow current decay.
- Main feature: cold background plasma in and around the beam volume
- Steadily increasing density during the beam phase until final collapse
- Not only in the confined beam region



C. Reux et al, NF15

Runaway beam suppression after TQ

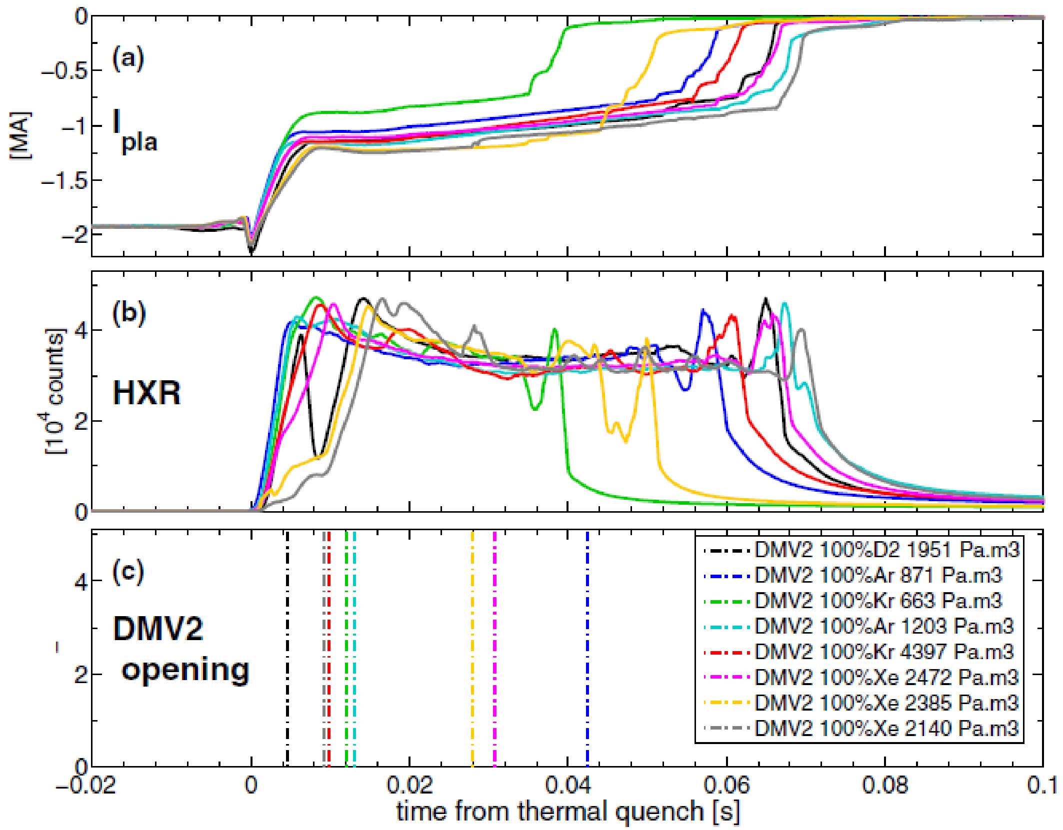
- RE beam recipe:
  - Triggered by pure Ar injection
  - Second injection (killer) during the beam phase
  - From ~ 870 $Pa.m^3$ Argon to 2500 $Pa.m^3$ Xe and 4400 $Pa.m^3$ Kr.
- No effect on runaway current, HXR, neutrons, SXR, background density
- Only indication that something happened: visible camera

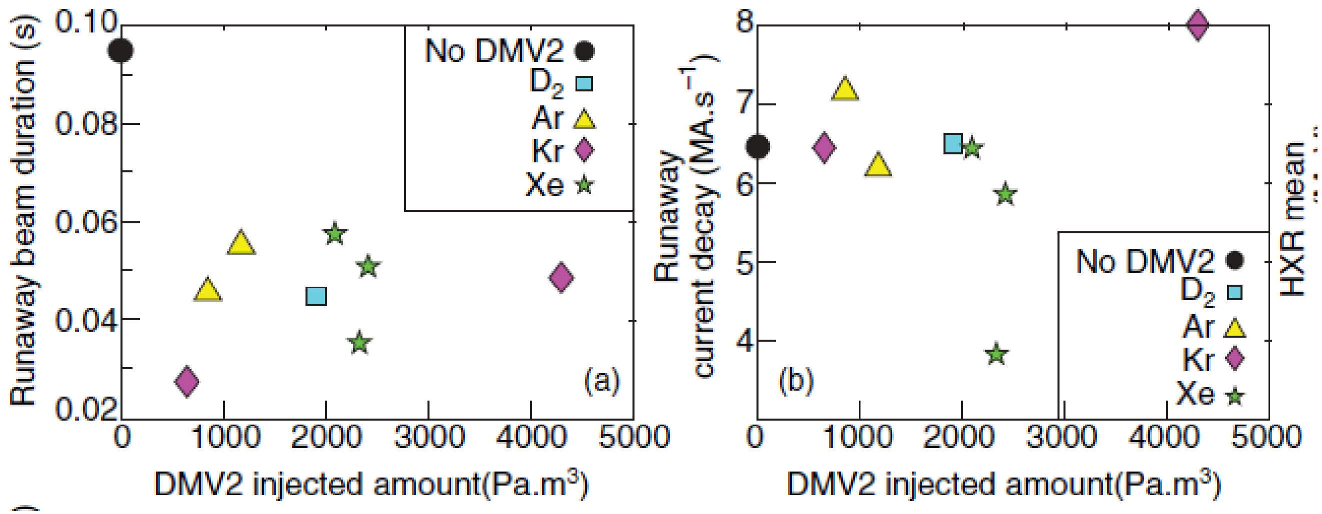


C. Reux et al, NF15

Runaway beam suppression after TQ - results

- **Aim:** mitigate fully accelerated RE beam
- Trigger RE-beam as before with Ar-MGI
- Fire DMV2 (mid-MGI) with Ar, Kr or Xe at maximum pressure at various times during RE-beam
- **Result: no mitigation observed!**

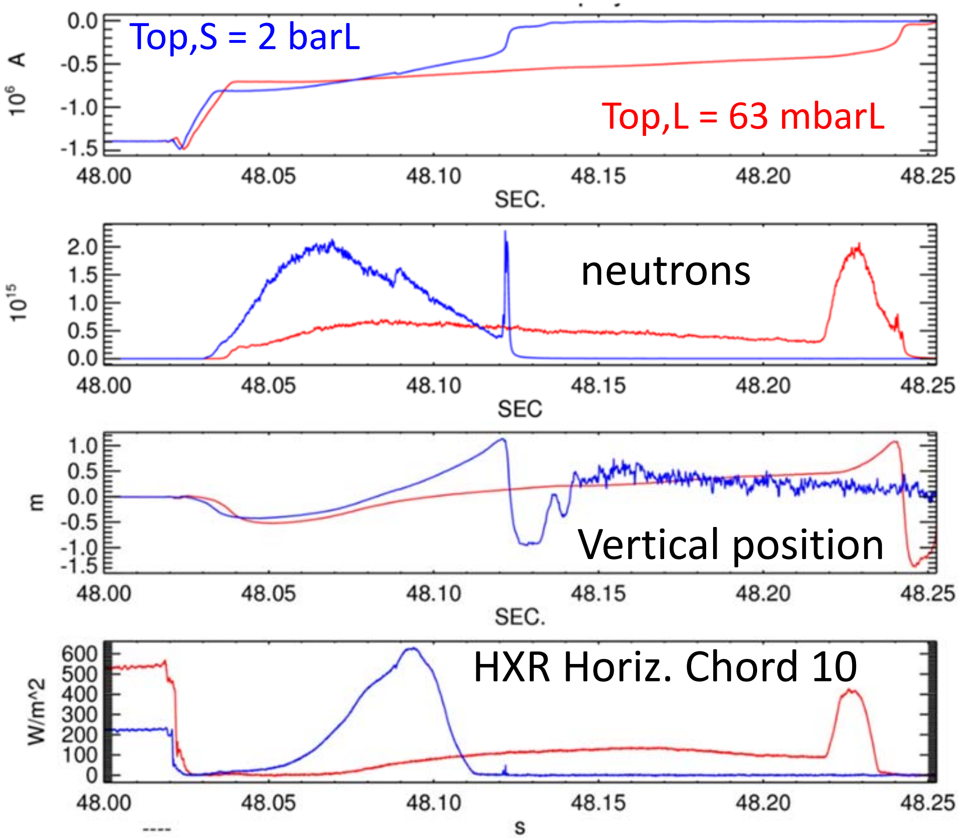




RE-beam suppr. after TQ: Outlook

Possible explanations for failed mitigation:

- Geometry effect (RE-beam drifts upwards away from midplane-MGI):
  - still didn't work with Top-MGI!
- DMV1 gas pressure and cold background plasma impeding DMV2 gas mixing:
  - triggered beam with very low Ar-injection:

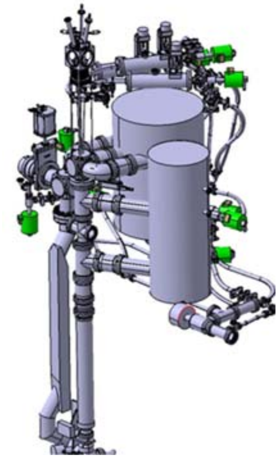


C. Reux et al, to be published

Preliminary Results!

- Longest post-disruptive runaway beam at JET-ILW with Top,S MGI (190 ms!)
- Much less gas injected to trigger the beam: possibly different generation conditions or runaway energies?
- Possible signs of enhanced mitigation with a second puff (DMV2 later in the beam phase)
- Role of the background plasma? Or RE energy ?

SPI at JET:



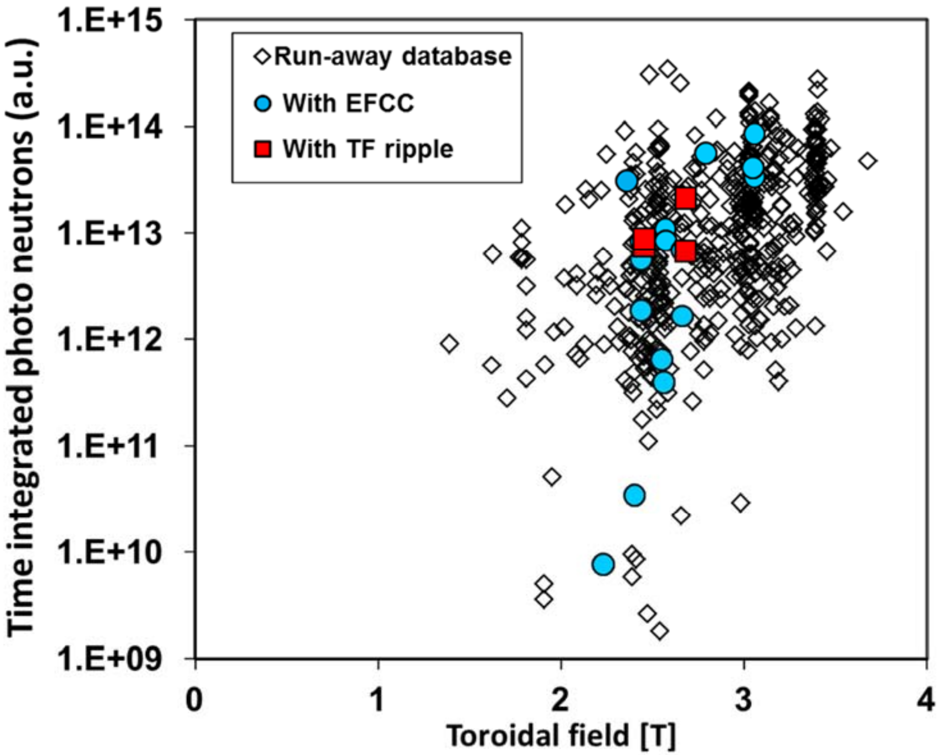
Other techniques:

- Improved beam control: "Let them die"
- Shattered pellet injection system (SPI): to be operating in JET 2018 (IO/ORNL/EF)

Effect of magnetic perturbations on REs

➢ In JET magnetic perturbations are inefficient in mitigating run-aways:

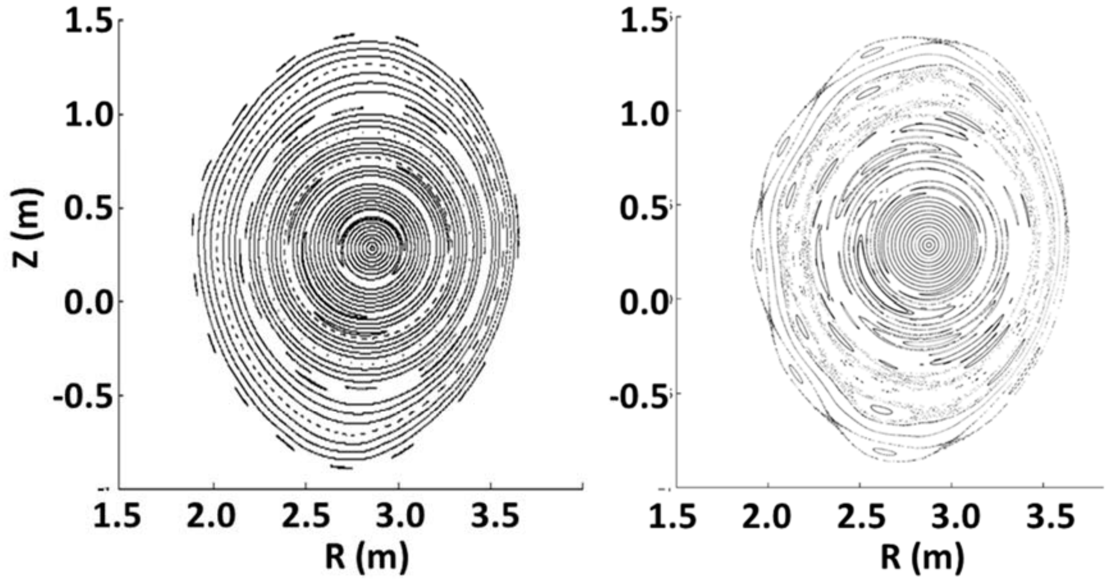
- EFCC and TF-ripple do not lead to a reduction of RE population in JET



V. Riccardo, PPCF 2009

- Modelling of relativistic (5-20MeV) electron particle motion predicts no stochastization of trajectories at maximum EFCC-currents.

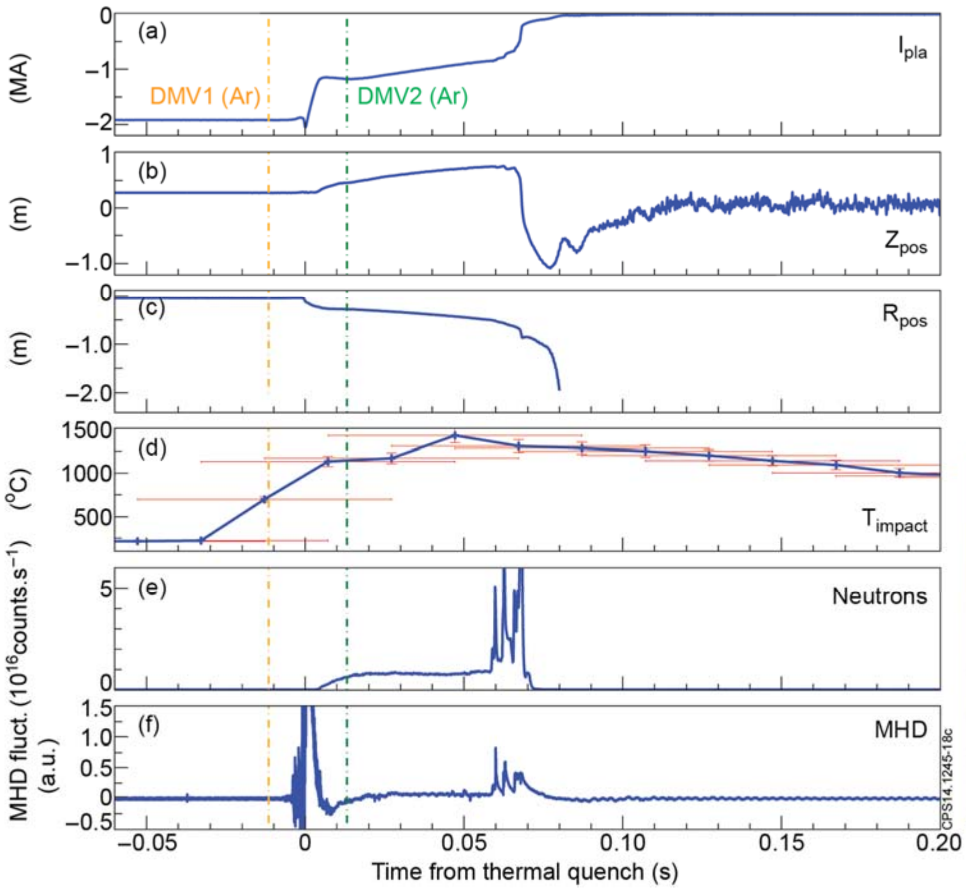
EFCC-current=48kAt: 96kAt:

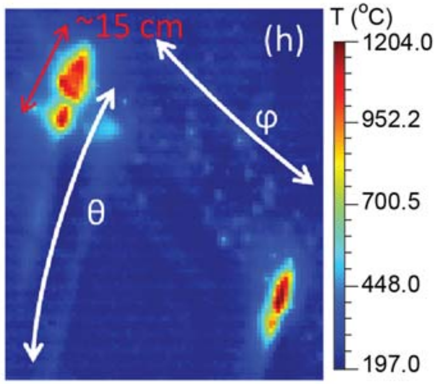


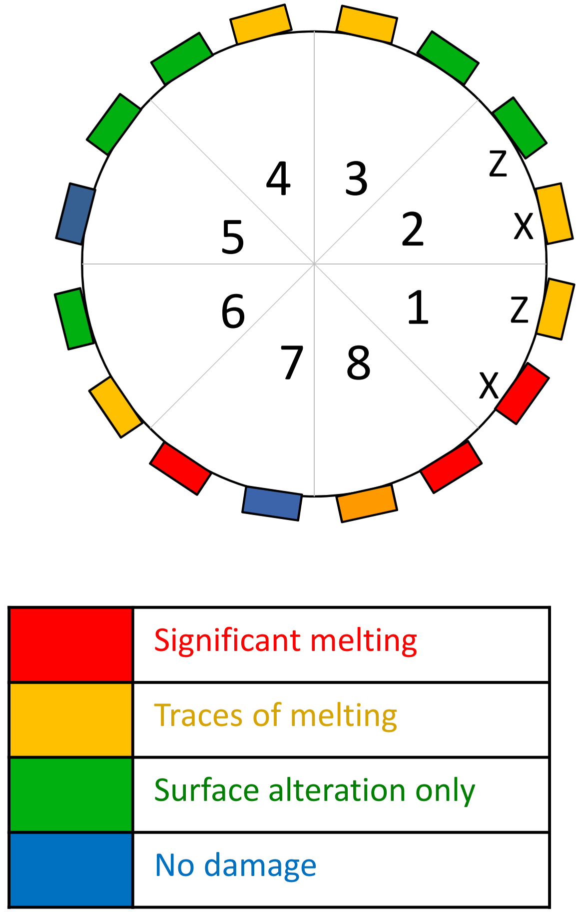
R. Paprok, PPCF 2016

Runaway electron impact on first wall

- Most of impacts: upper part of inner wall (>melting temperature)
- Important features:
  - Tile heating starts before the final collapse
  - Toroidal asymmetrical impacts: misalignment tolerances? or MHD instabilities?







C. Reux et al, NF15

5) Summary

Summary: disruption characteristics

- Enhanced impurity influx (tungsten) has effected root causes for disruptions and lead to higher disruption rate
- Lower wall recycling increased operational space (density limit)
- Absence of intrinsic radiator such as Carbon reduced radiated energy during disruption prolonged current quench times.
- This results in higher disruption forces and thermal loads, which could be mitigated by massive gas injection
- Less likely appearance of runaway electrons in unintentional disruptions

Summary: disruption mitigation

Assessment of thermal and EM load mitigation scenarios:

- **Electromagnetic load mitigation:**
  - No change in disruption mitigation efficiency of EM-loads has been observed for different poloidal injection location.
  - Optimum injection rate for disruption force mitigation at JET is ~1.5 10^{22} impurity particles.
  - No difference of mitigation efficiency between Argon and Neon.
- **Heat load mitigation:**
  - Radiated power fraction saturates a certain level. Our data indicate a level of around 85% (for Ar and Ne).
  - At JET minimum required impurity particles before CQ: ~10^{21}.

Investigation and mitigation of toroidal asymmetries:

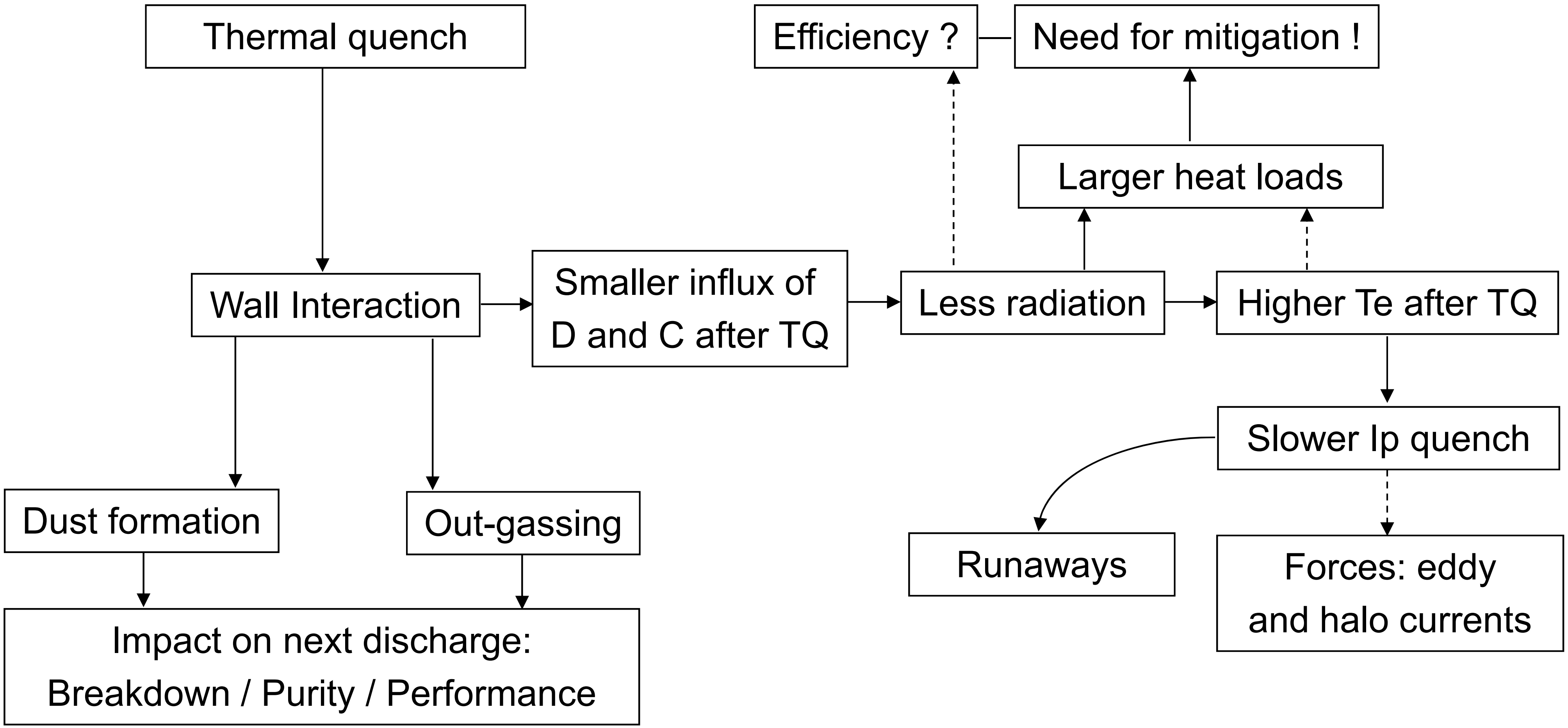
- Toroidal peaking factors up to 1.7 have been determined for single MGI.
- Optimised dual injection can reduced radiation asymmetry factor. This might result in toroidal peaking factors down to 1.2.

Summary: runaway mitigation

- Runaway generation depends on vertical stability
- Mitigation is possible if enough D2 is injected before TQ (primary suppression?, better mixing?)
- Mitigation was unsuccessful if done on the already developed RE beam (Kr, Xe up to 4.3kPa m^3)
  - Possible explanations: background plasma, gas plume geometry, neutral pressure
- Beam termination leads to toroidal asymmetrical impacts on wall and melting of Beryllium tiles

Thank you

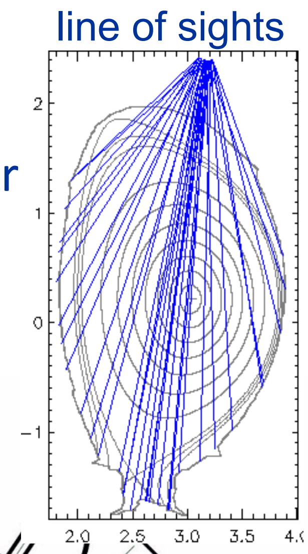
Disruptions with an all-metal wall

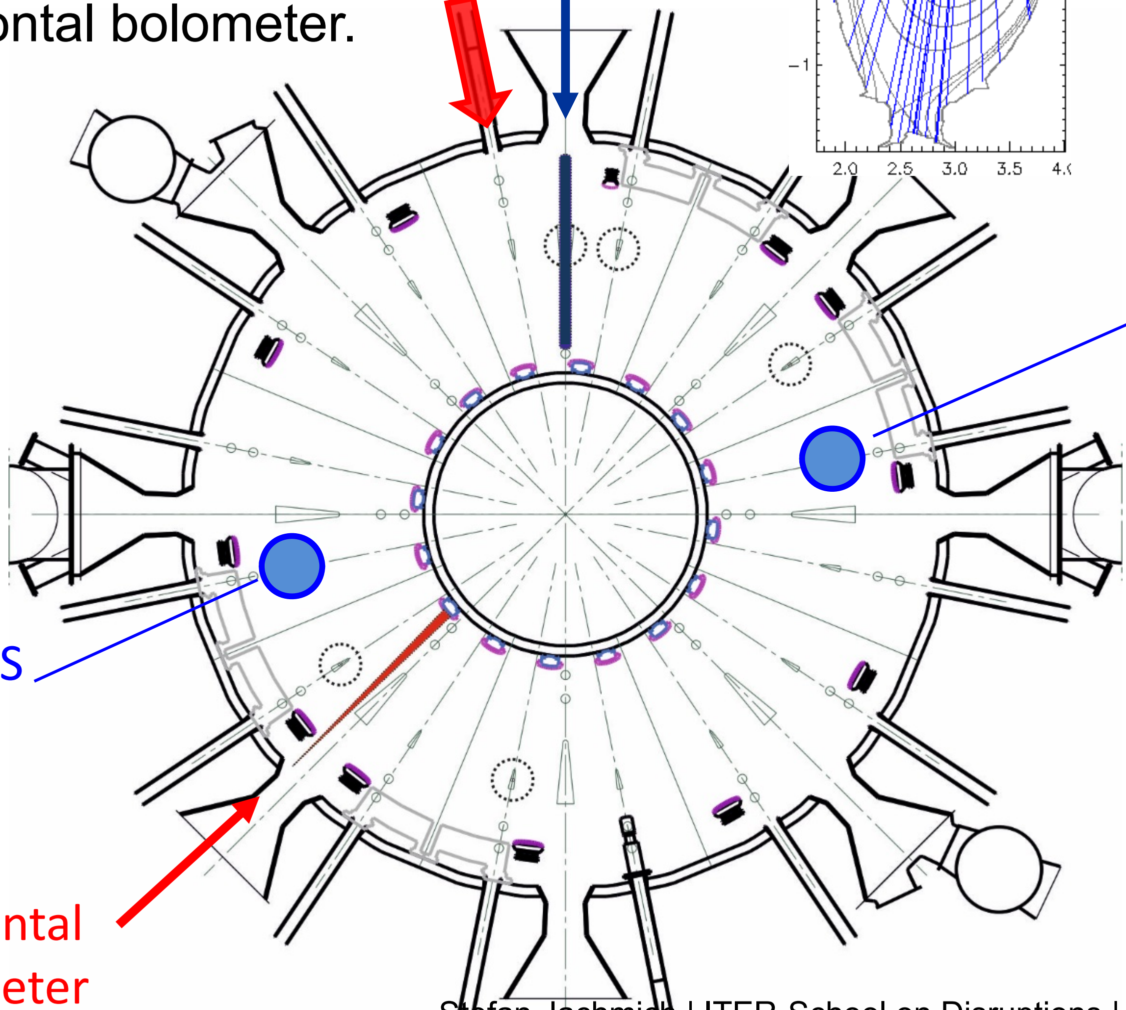


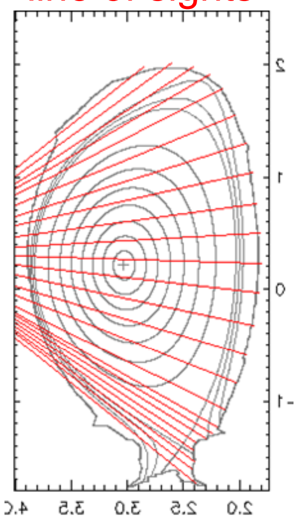
P. de Vries, JET Science Seminar 2012

Diagnostic setup

- Mid-MGI located near vertical bolometer. Measurements are affected in the initial phase due to the pressure rise caused by the gas injection.
- Comparison with Mid-MGI data are mainly based on horizontal bolometer.





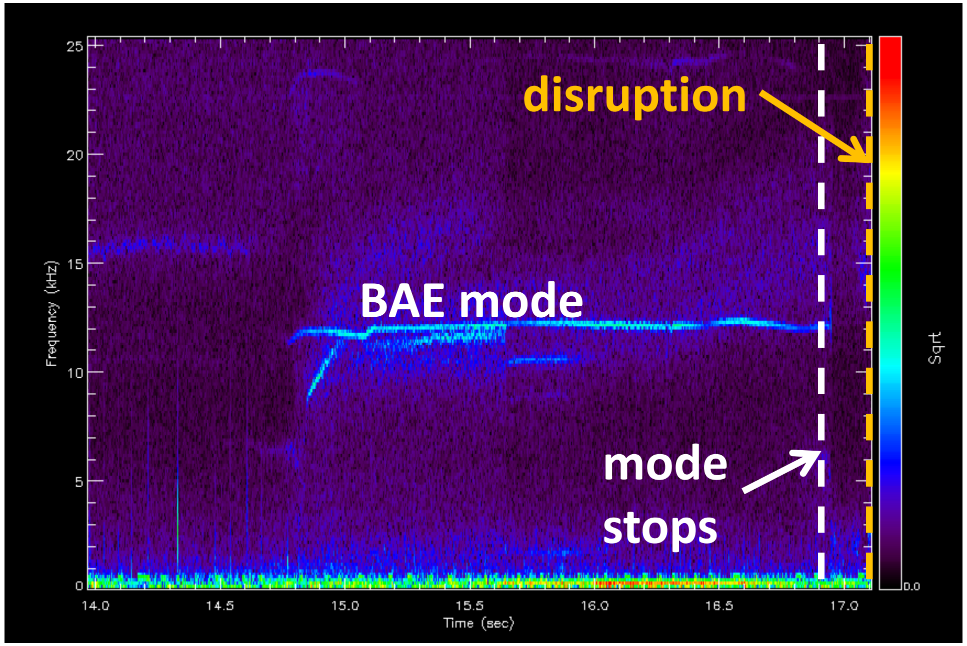


JET

Indicators for optimal MGI triggering

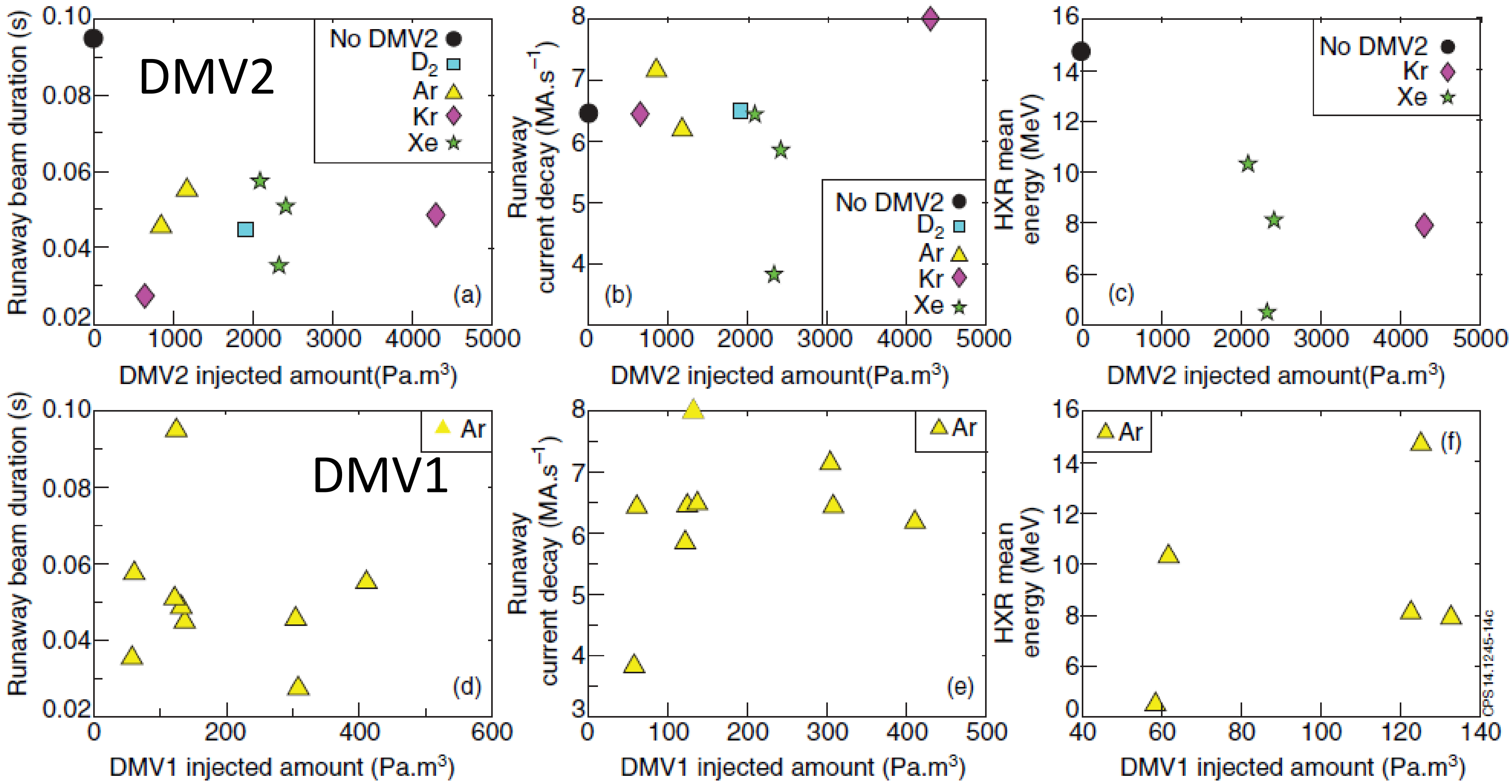
- external perturbation field fixes Beta-induced Alfven Eigenmode (BAE) at 12kHz
- n=1 mode lock causes T_e drop
  → BAE mode stops

→ $t_{\text{BAE mode stop}} < t_{\text{disruption}}$



- if n=1 island grows too much core plasma degrades from target condition
  → visible in ECE profile

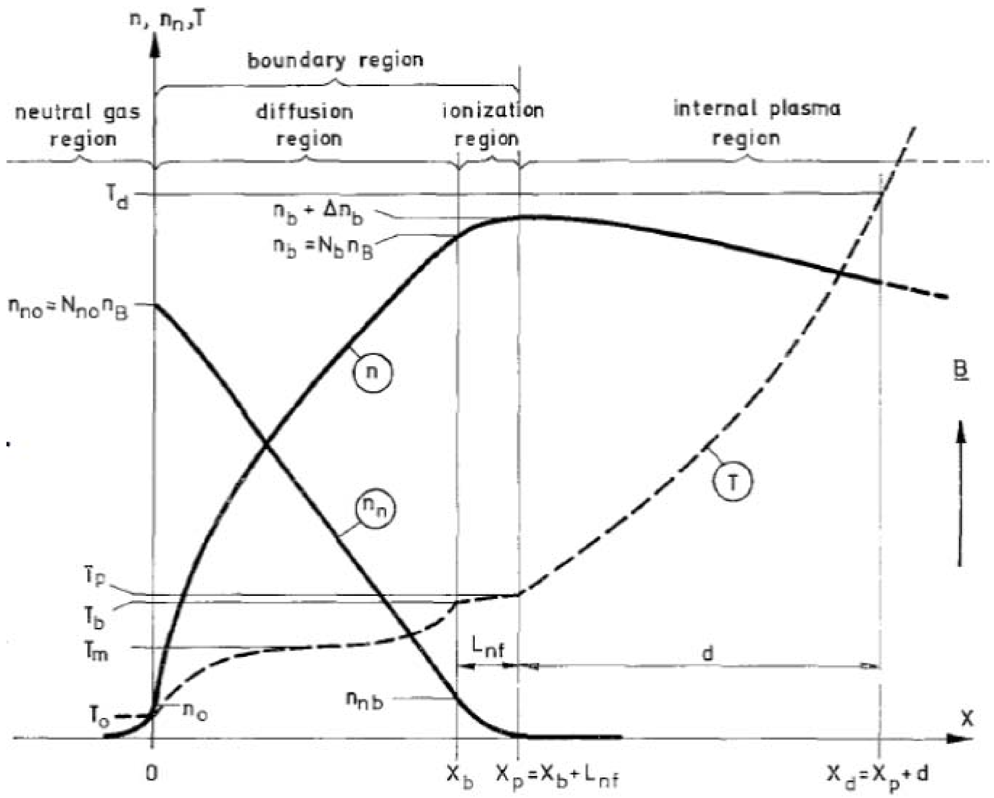
Runaway beam suppression after TQ



- No correlation between the DMV1/DMV2 injection scenario and the beam features (duration, slope, energy)

Background plasma: impermeable?

- Cold dense plasmas model from Lehnert *et al.* (Nucl. Instr. Meth. 75)
- Impermeable plasma regime (i.e. neutrals cannot get in):
  - happens if ionization layer is thinner than neutral diffusion layer
- JET case: happens if Ti>10 eV
- Argon lines for Ar I, II, III observed (min. 27 eV for Ar III needed) during beam:
  - sign that the background plasma is hot enough to be in this regime



C. Reux, 3rd RE mtg, 2015, Pertuis, France