Disruption mitigation experiments at JET in support of ITER

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Outline

1) Disruption mitigation system at JET

2) Mitgation of electromagnetic loads

3) Heat load mitigation

4) Toroidal radiation asymmetries

5) Mitigation of runaway electrons

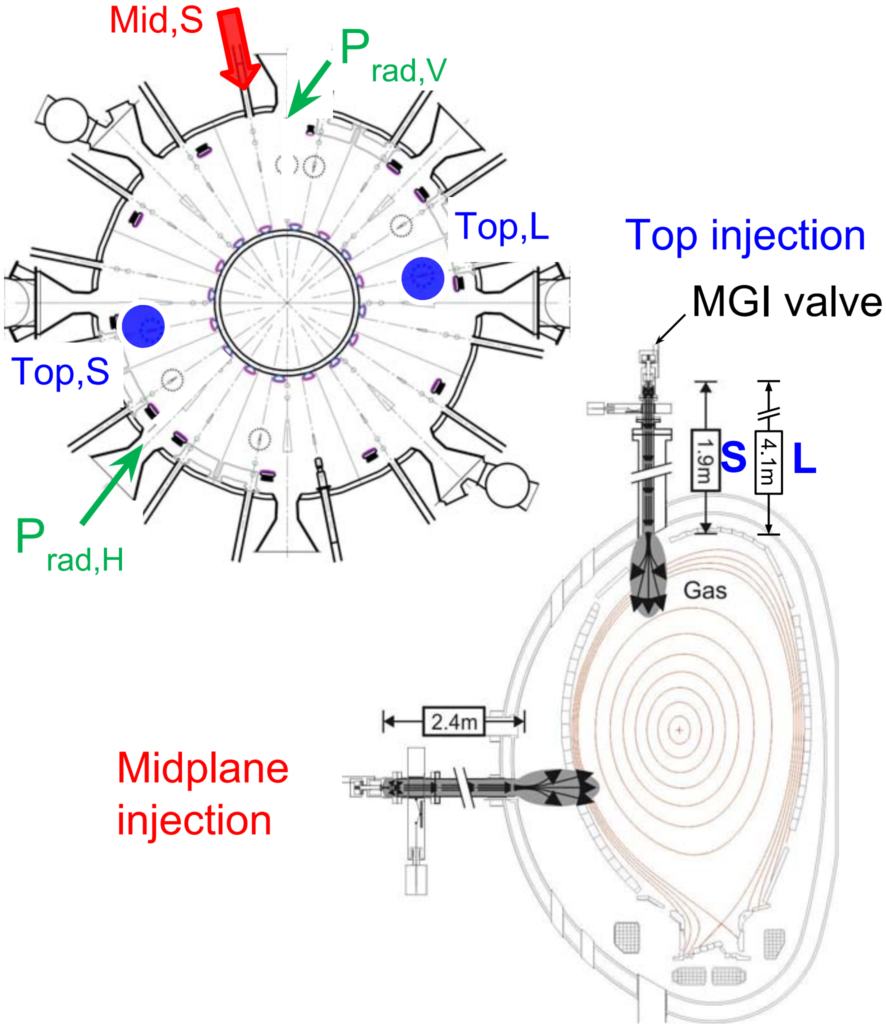
6) Summary

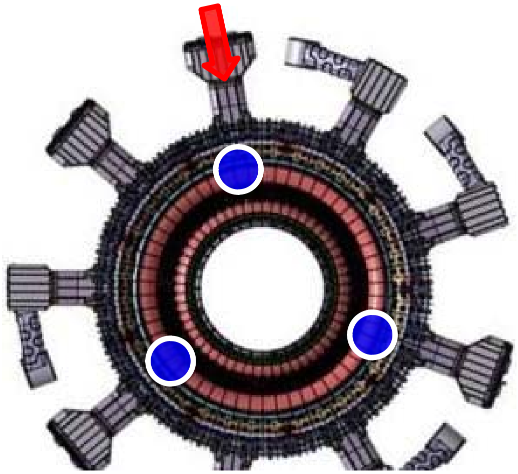
Disruption mitigation system at JET

JET

ITER-like disruption mitigation system at JET

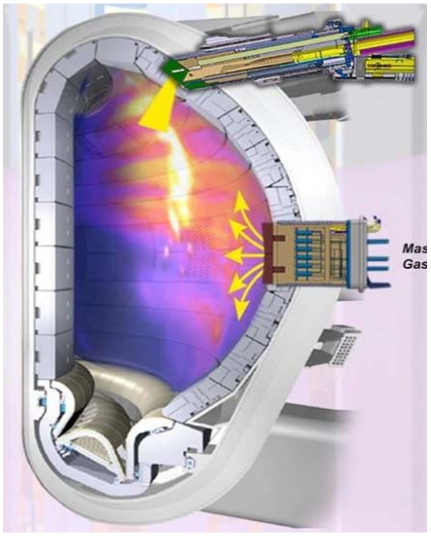
JET





Location of injectors

Maruyama, IEEE 2015



Upper Port ●

Equatorial Port ⬅

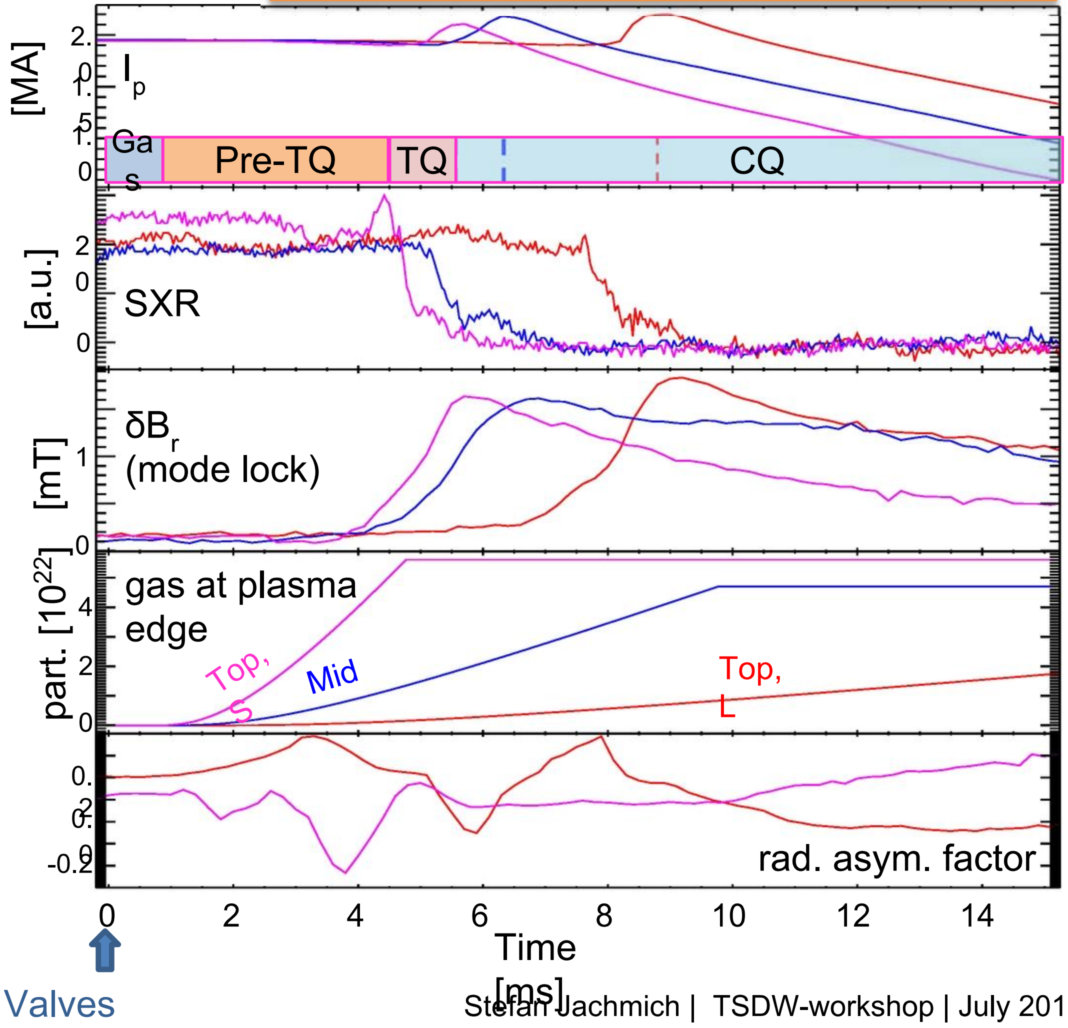
Injectors with MGI + SPI

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 Fv and frad

	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

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



TQ: thermal quench

CQ: current quench

Radiation asymmetry:

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

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[1] E. Hollmann, NF'05

[2] S. Bozhenkov, PPCF'08

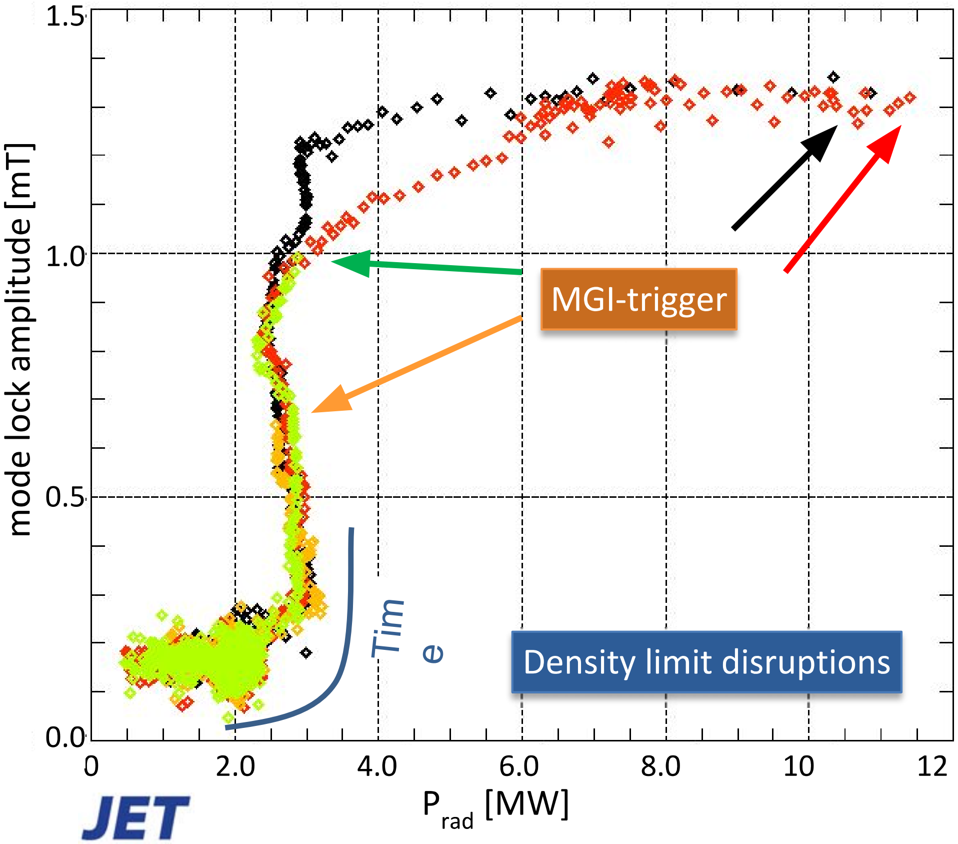
MGI-experiments a mimic for real disruptions?

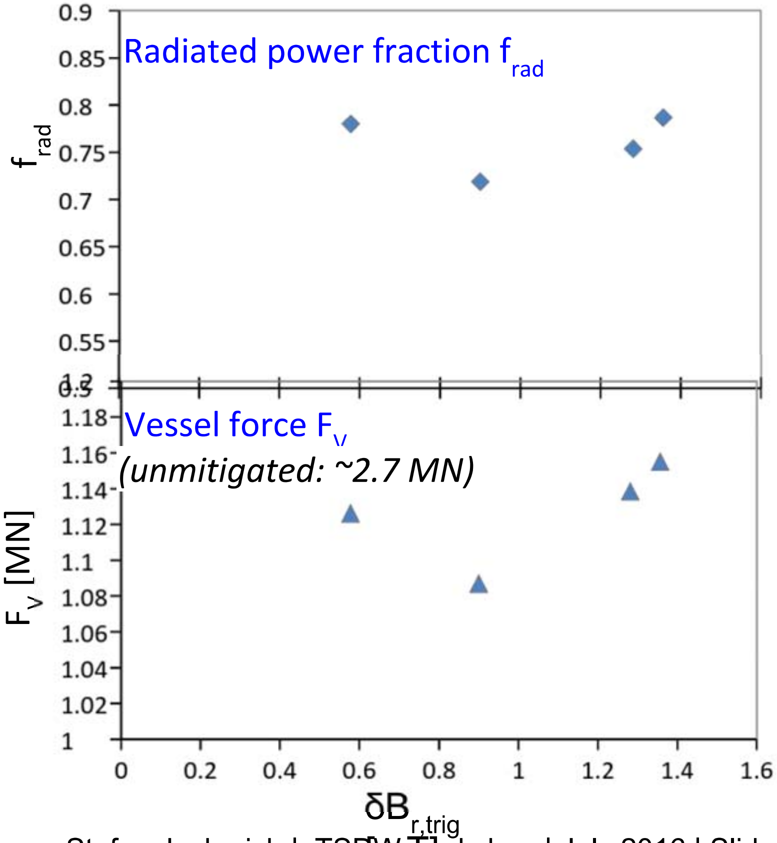
MGI-experiments:

- 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





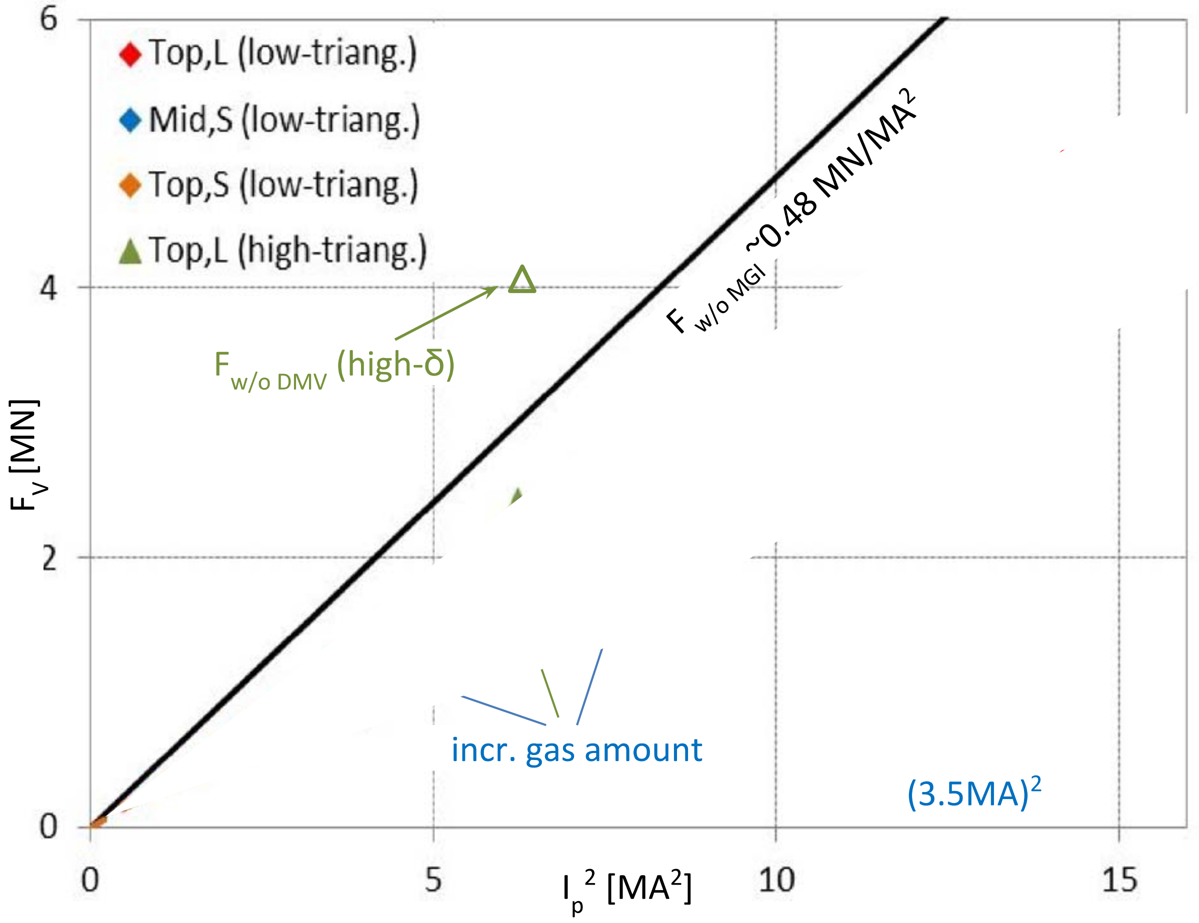
Mitigation of electromagnetic loads

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.

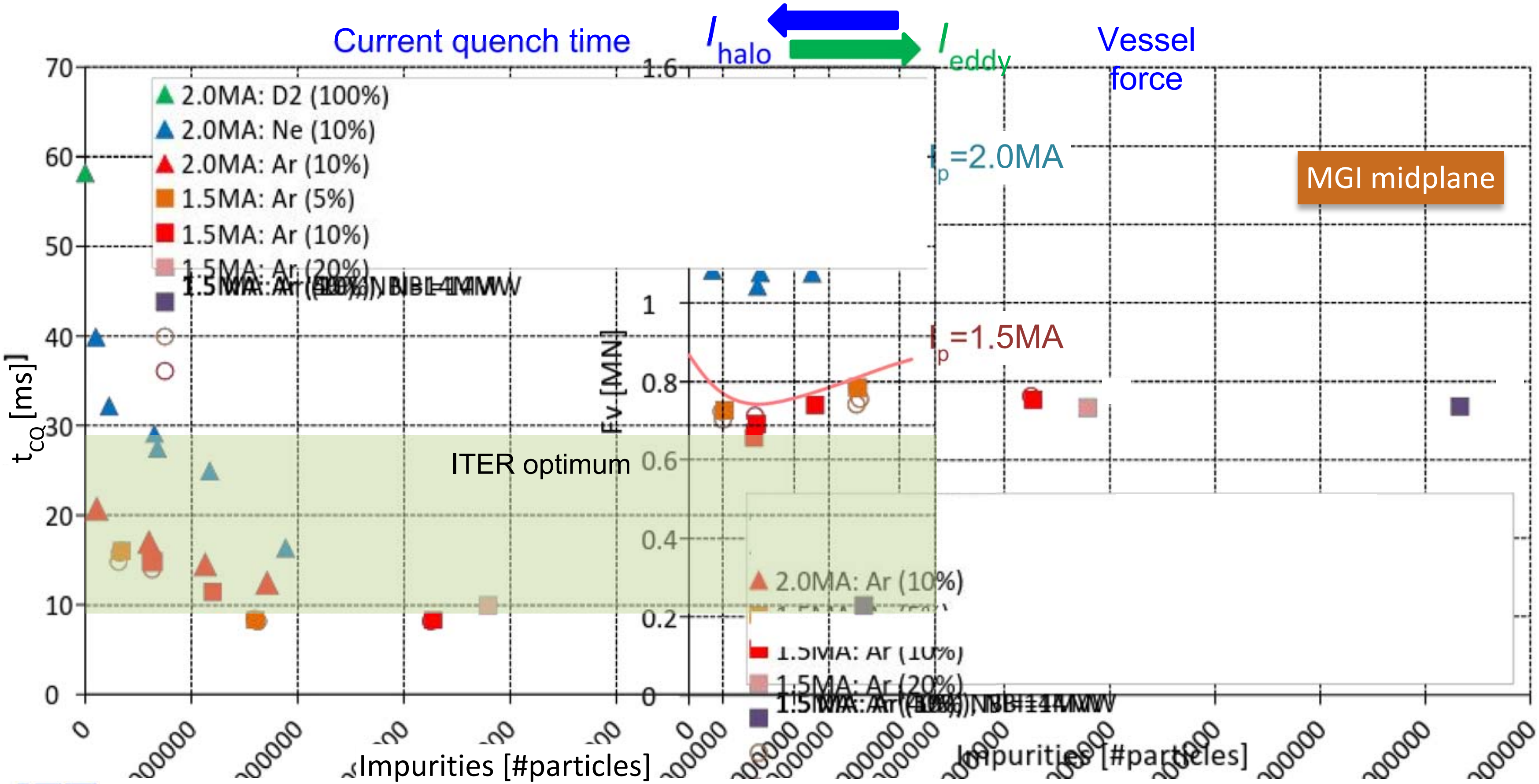
Note: no signs of runaway electrons up to explored plasma current of 3.5 MA.



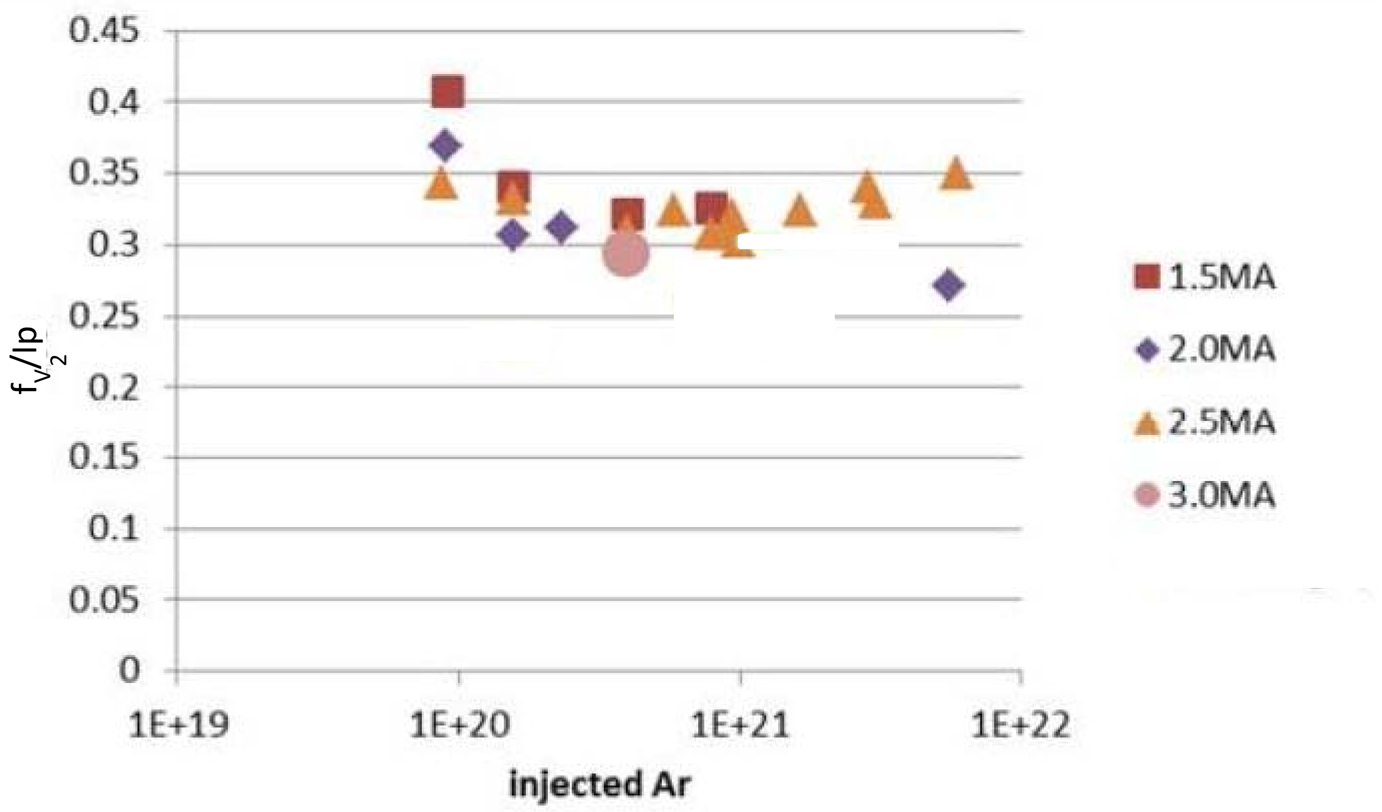
JET

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?).



Electromagnetic load reduction: Top,S inj.



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Heat load mitigation

Efficiency of energy radiation

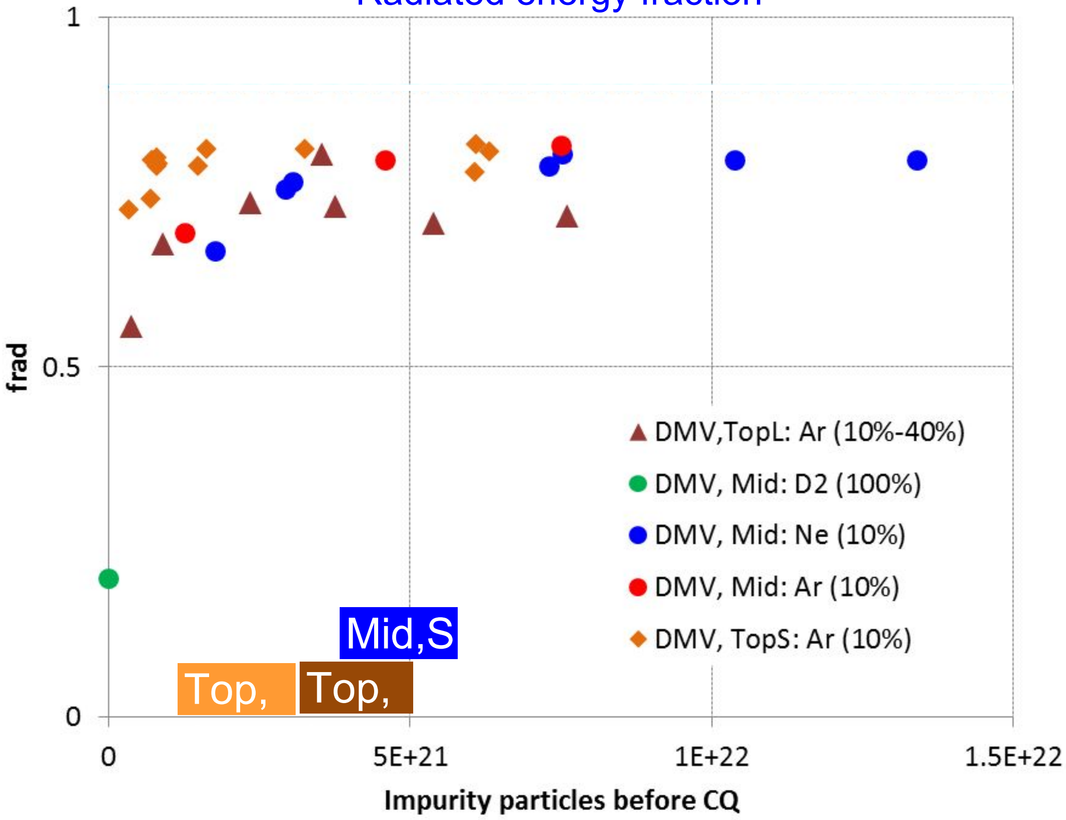
- Radiated energy fraction f_{rad} does not further increase with increasing MGI-impurities.
- Similar maximum f_{rad} for Top,S- and Mid-MGI.
- Top,S reaches saturation with less impurities (->more efficient?)
- However, required minimum injection might depend on thermal energy.
- Caveat: uncertainty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

Radiated energy fraction:

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

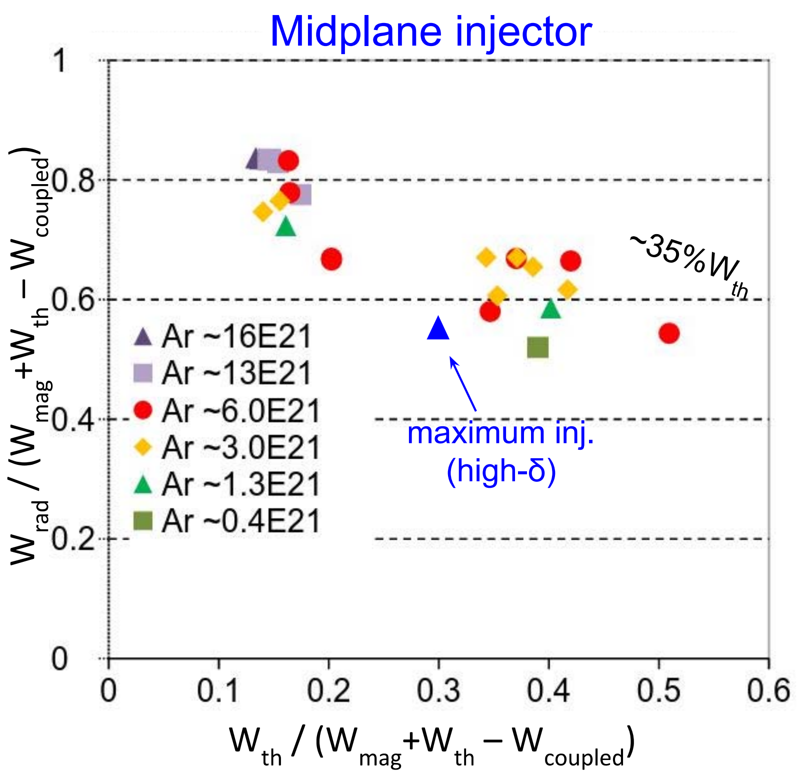
W_{rad}: radiated energy during disr.
W_{mag}: magnetic energy
$W_{thermal}$: thermal plasma energy
$W_{coupled}$: energy dissipated into vessel and PF-coils

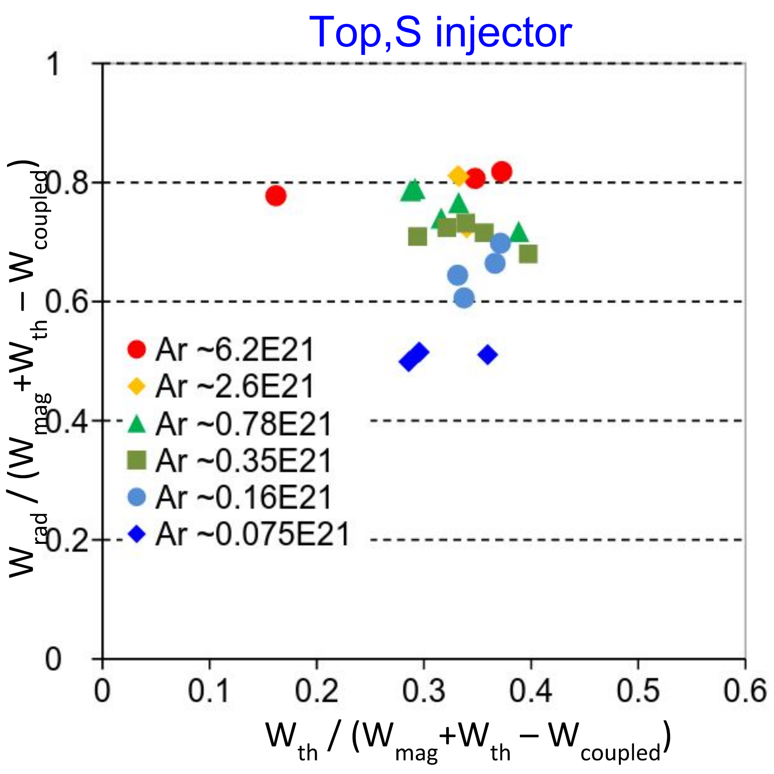
Radiated energy fraction



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





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

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

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

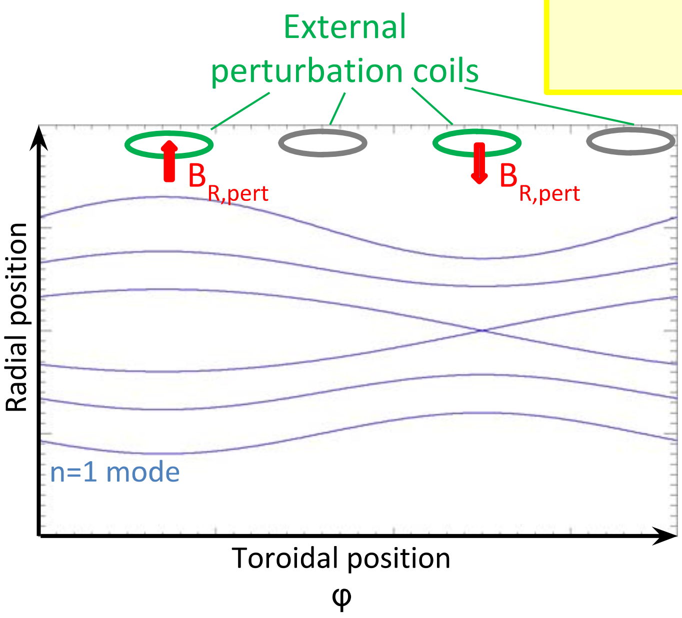
- External magnetic field perturbations were applied to seed n=1 modes
- Phase of n=1 mode can be varied by changing coil polarities
- DMV fired into existing n=1 mode

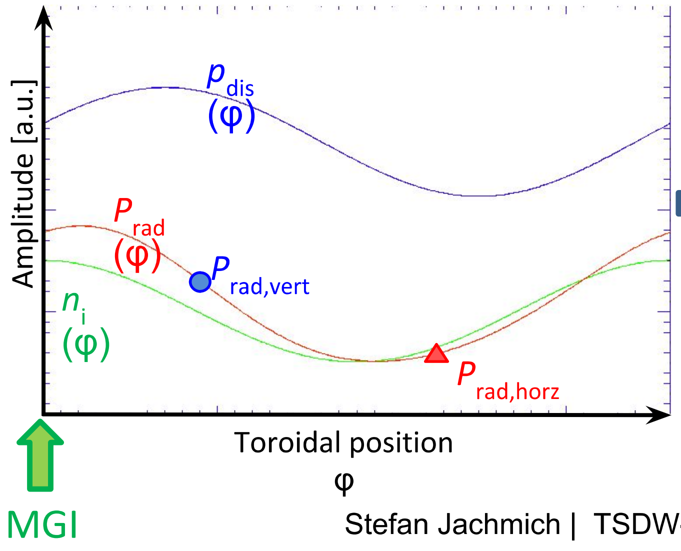
Interpretative model: Impurity density: $n_i(\varphi) = n_{i,0} \exp(-(\varphi - \varphi_{inj})^2/\lambda^2)$

Radiation distribution: $p_{dis}(\varphi) = 1 + \square p \cos(\varphi_{n=1} - \square\varphi_{n=1} - \varphi)$

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

– = free fit parameter





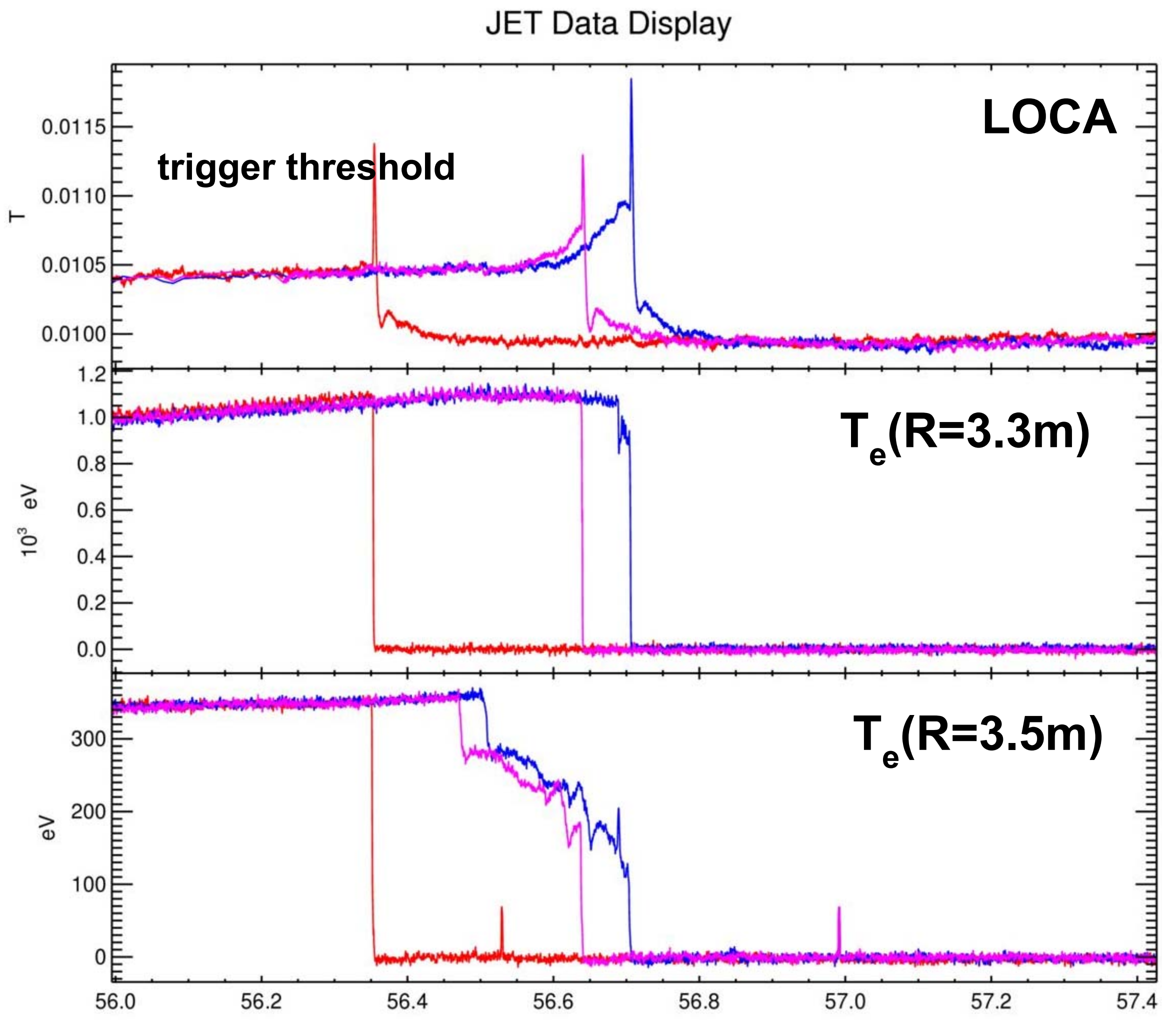
$$\xi = \frac{P_{rad,vert} - P_{rad,horz}}{P_{rad,vert} + P_{rad,horz}}$$

TPF

M. Lehnen et al, NF2015

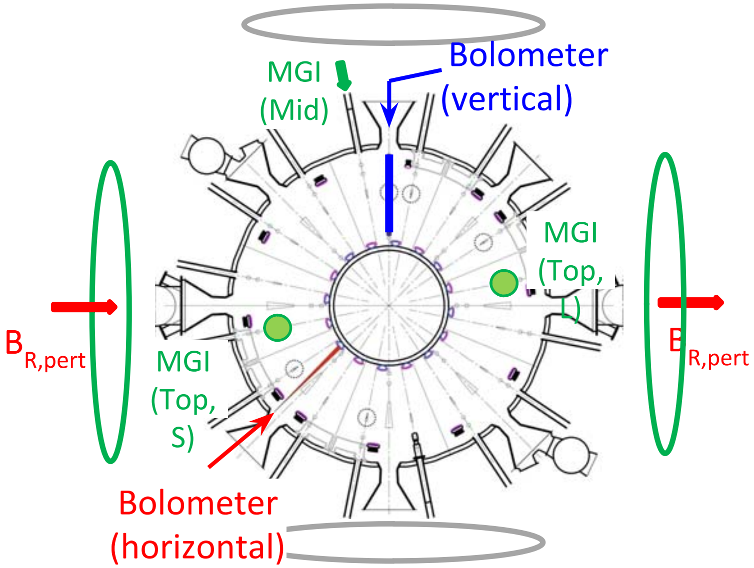
MGI triggering

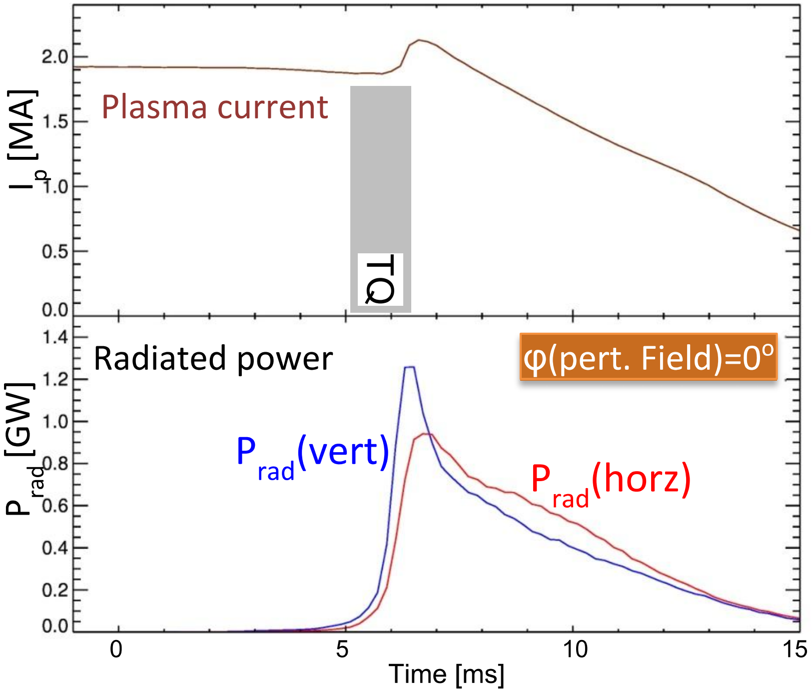
- trigger on real time mode-lock signal (LOCA)
- **optimimal** MGI timing is:
  - not **too early** (no fixed n=1 mode phase)
  - not **too late** (core confinement degradation)

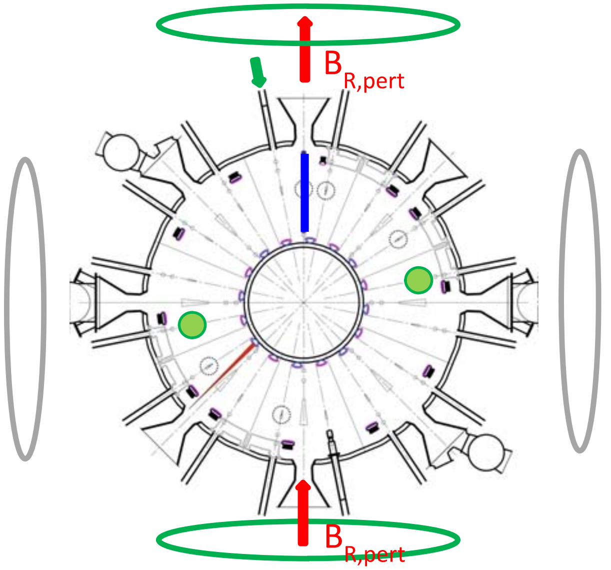


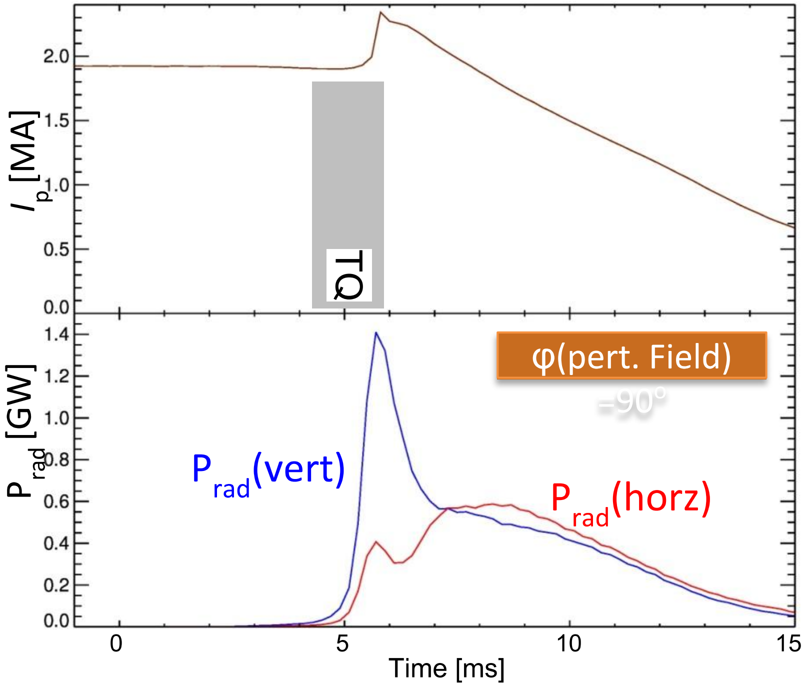
P. Drewelow et al

n=1 phase variation





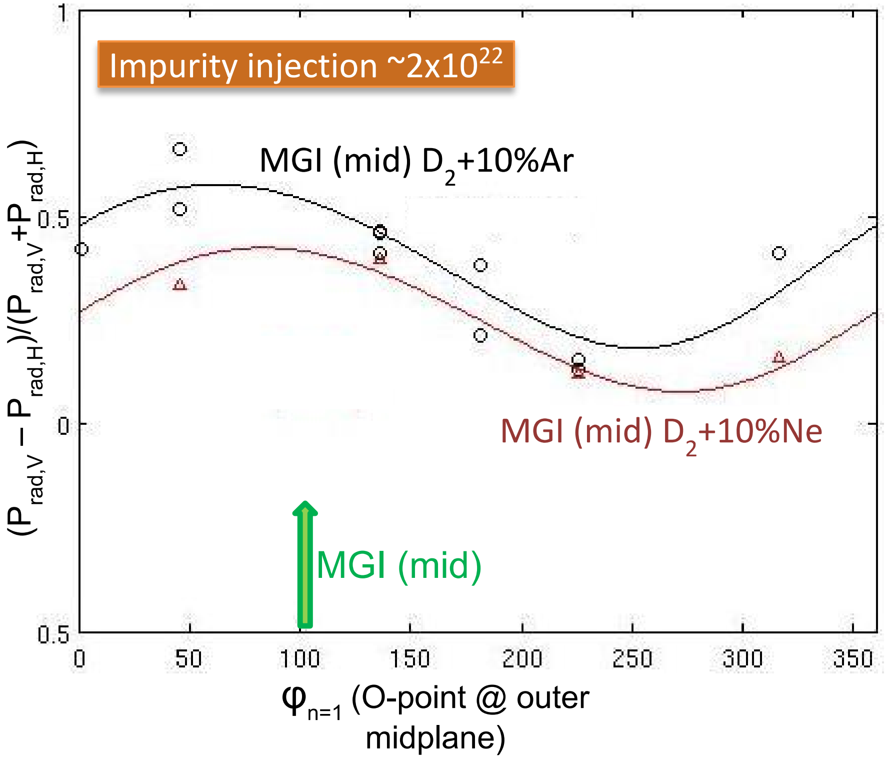




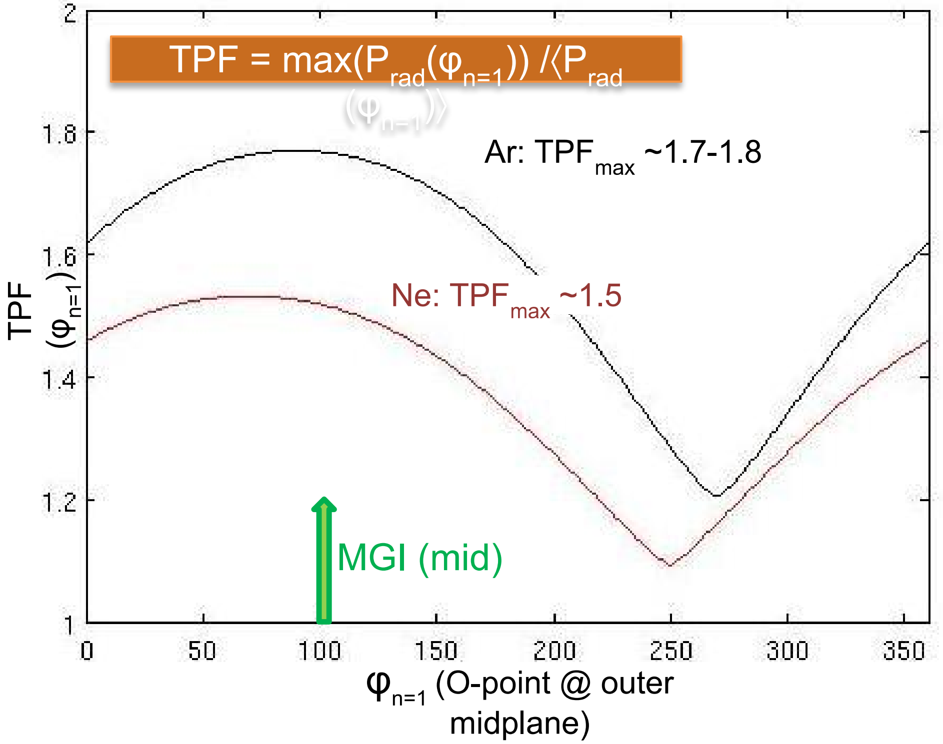
Toroidal peaking factor

- ➢ 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



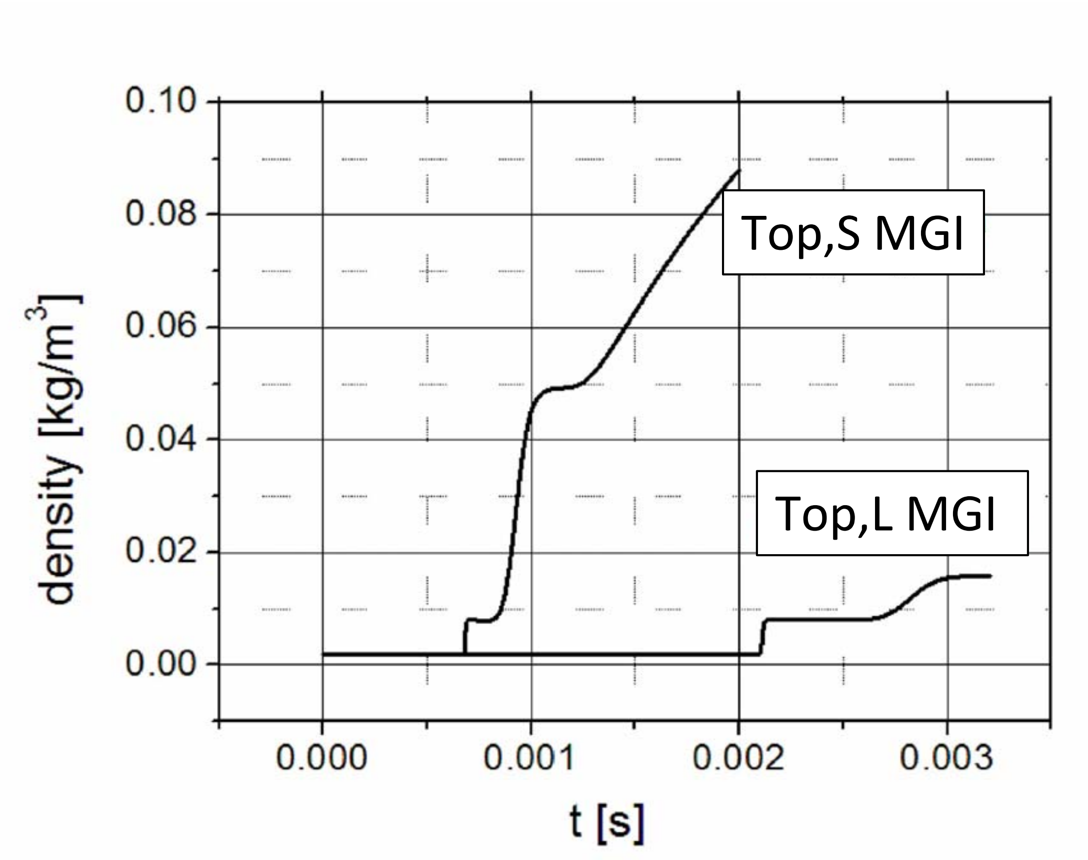
Toroidal peaking factor



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?

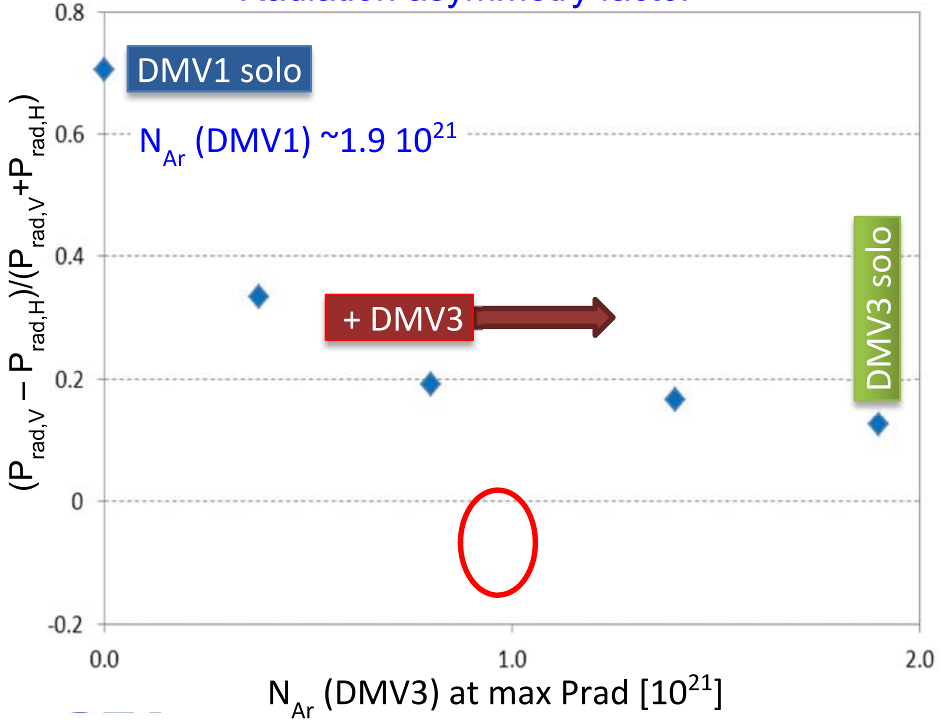


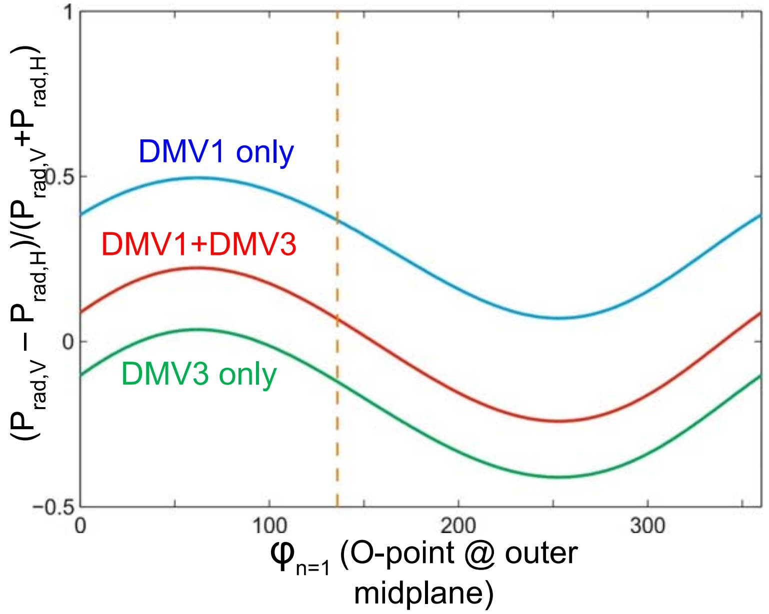
U. Kruezi et al

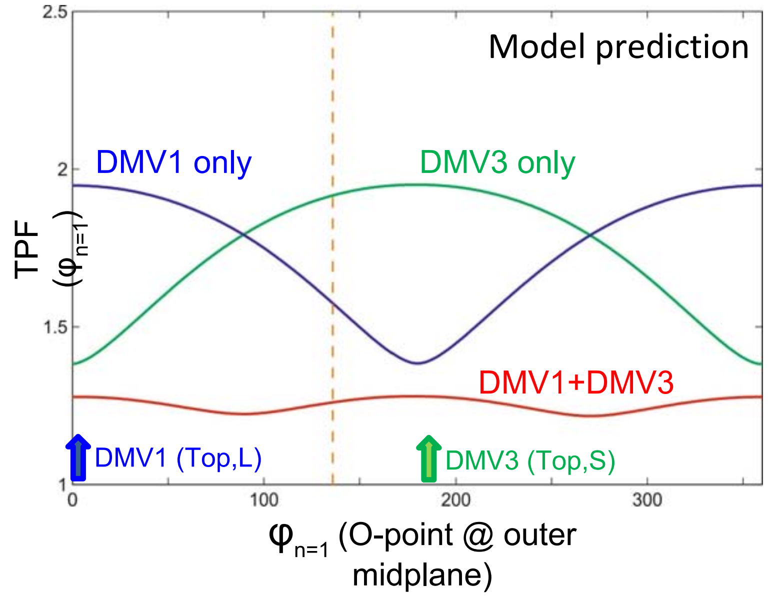
Radiation asymmetry in dual injections

- 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) $\sim 10^{21}$.

Radiation asymmetry factor

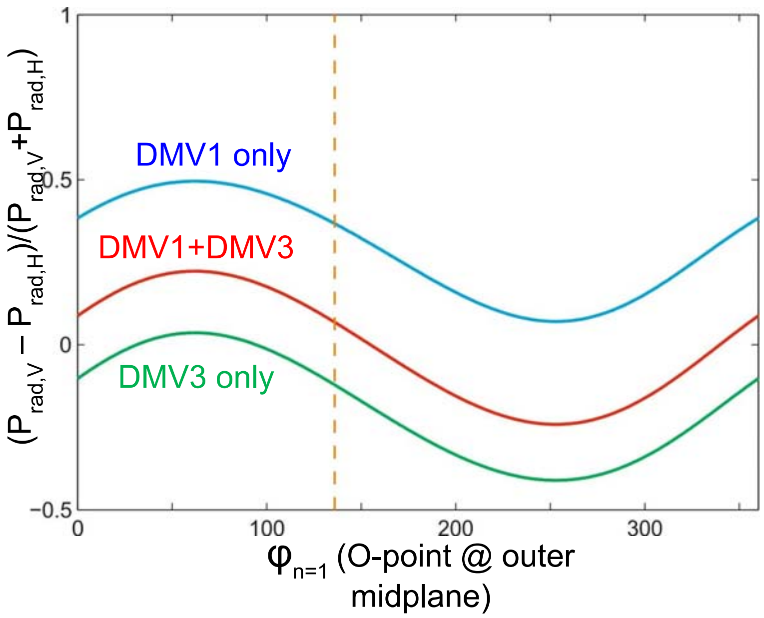


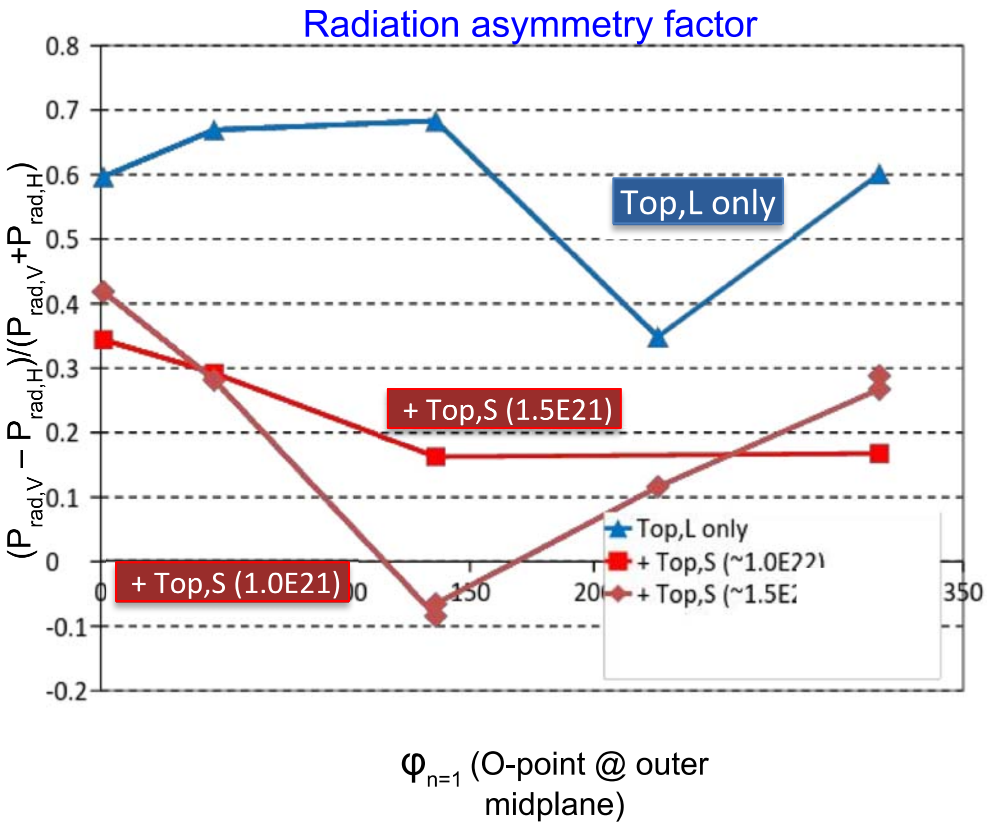




Radiation asymmetry for dual injection

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





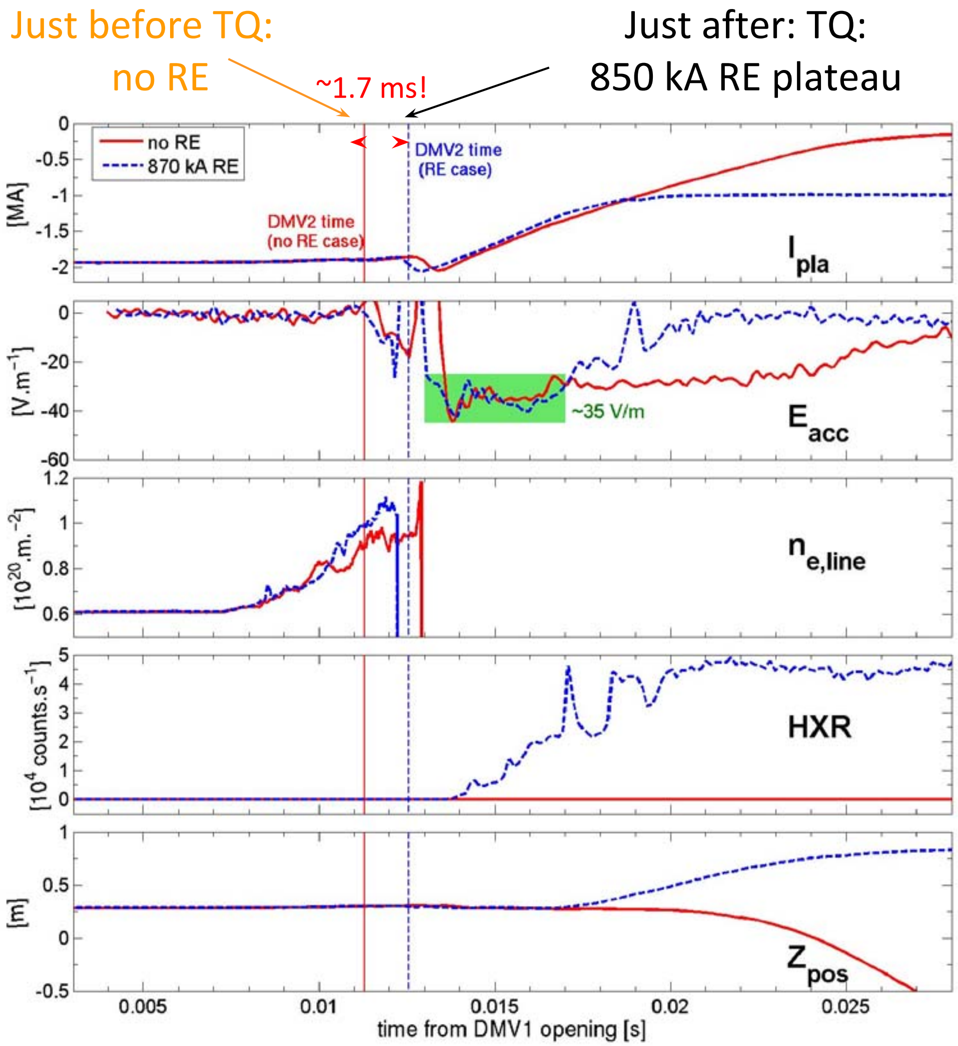
N_{Ar} (DMV3) at max Prad [10^{22}]

Mitigation of runaway electrons

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



Just before TQ: no RE

~1.7 ms!

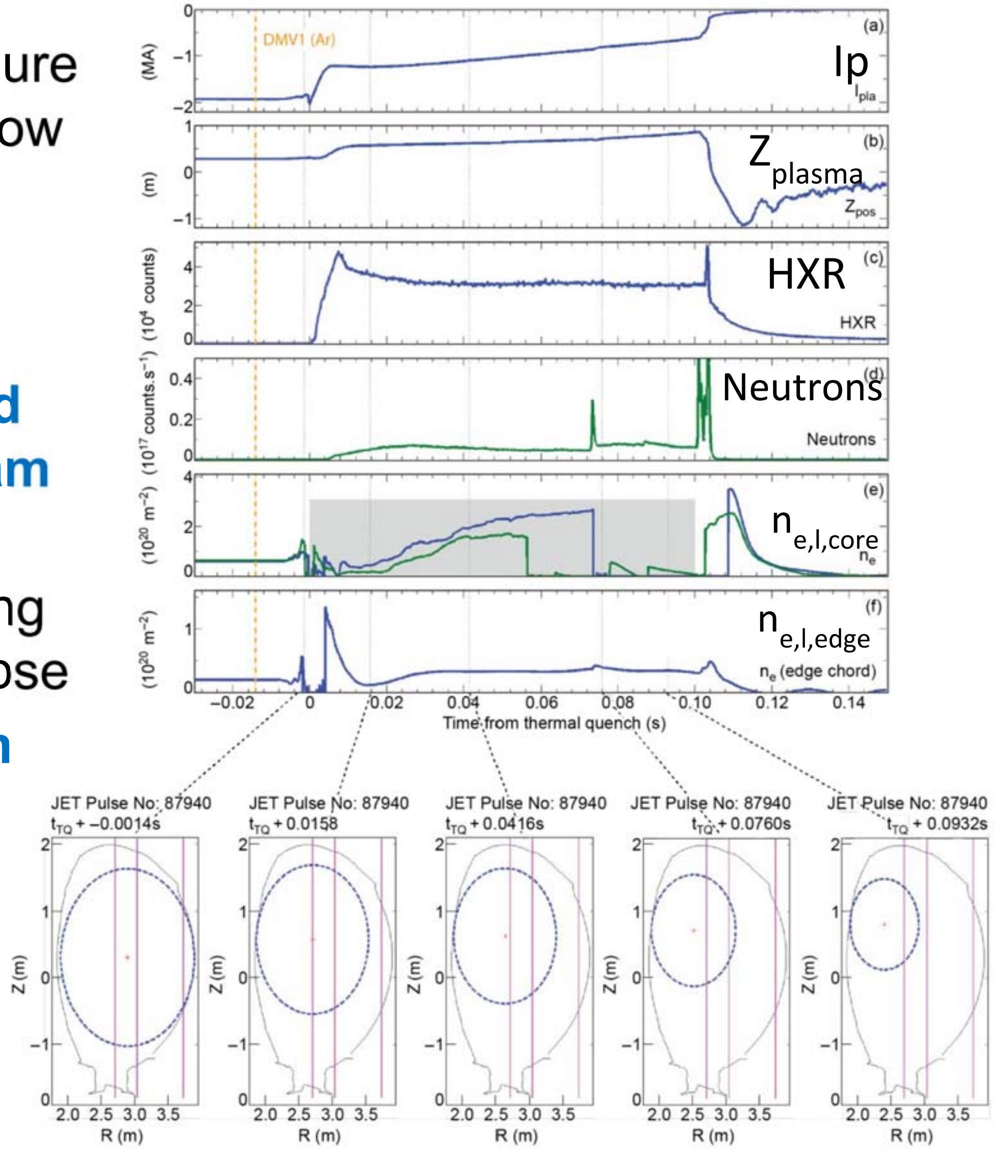
Just after: TQ: 850 kA RE plateau

Suppression of an incoming runaway beam feasible if done before TQ

C. Reux et al, NF15

Runaway beam studies

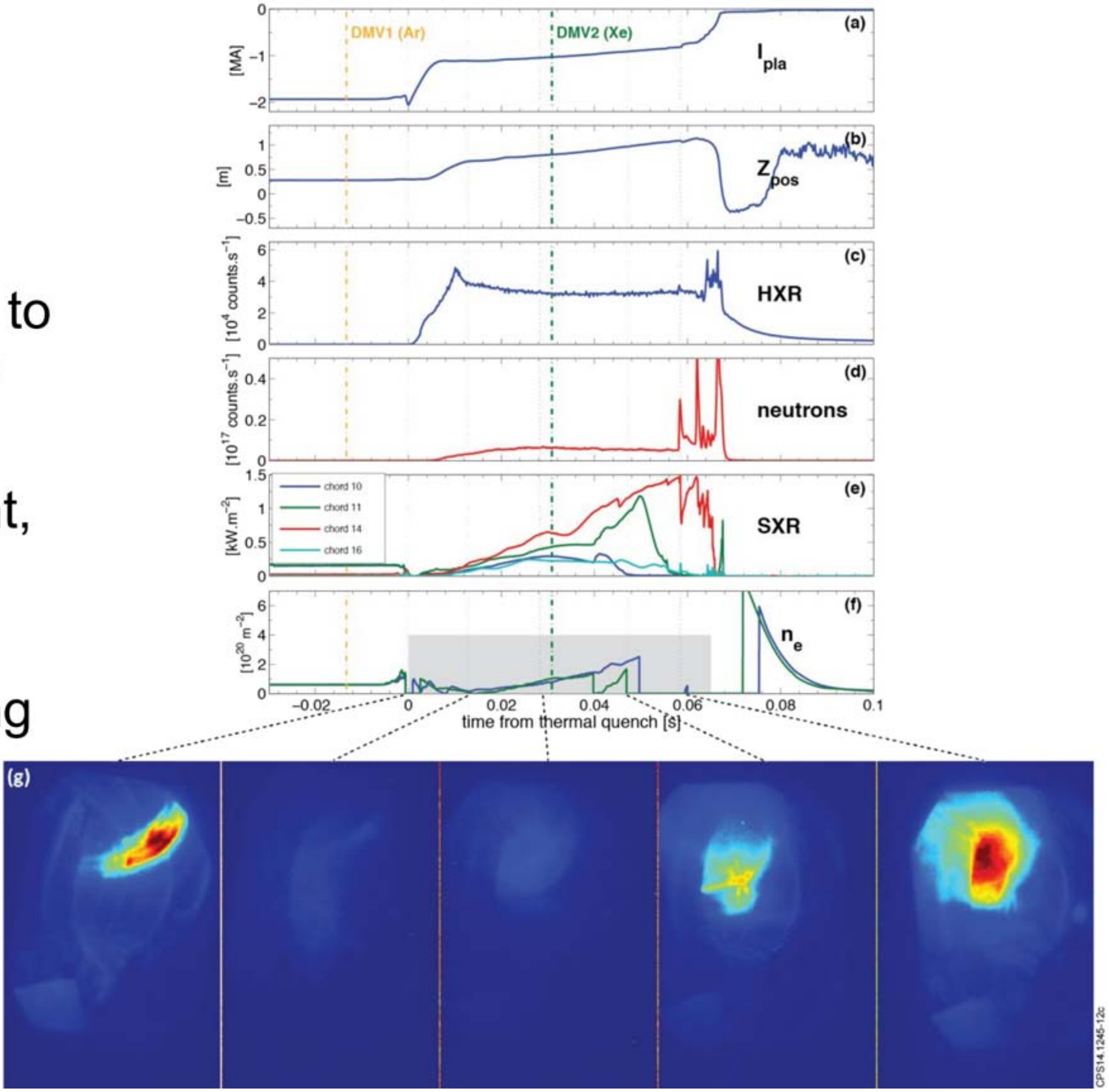
- Runaway beam created using pure argon massive gas injection at low pressure in DMV1.
  - Up to 100 ms duration with slow current decay.
- Main feature : **cold background plasma in and around the beam volume**
- Steadily increasing density during the beam phase until final collapse
- **Not only in the confined beam region**



C. Reux et al, NF15

Runaway beam suppression after TQ

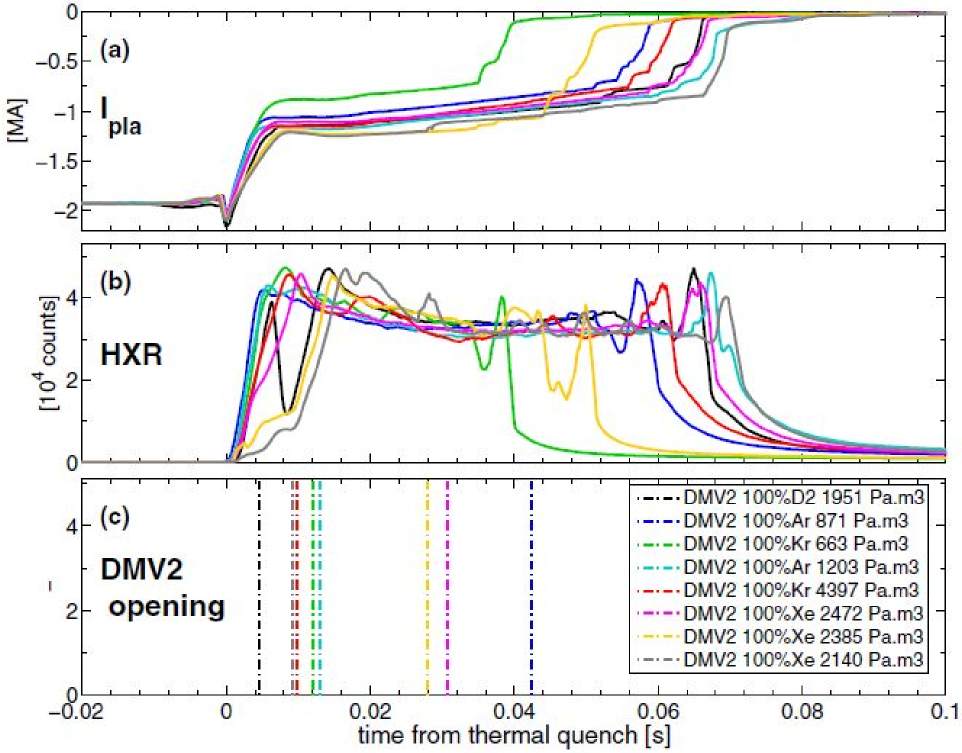
- RE beam recipe:
  - Triggered by pure Ar injection
  - Second injection (killer) during the beam phase
  - From ~ 870 Pa.m^3 Argon to 2500 Pa.m^3 Xe and 4400 Pa.m^3 Kr.
- **No effect** on runaway current, HXR, neutrons, SXR, background density
- Only indication that something happened: visible camera



C. Reux et al, NF15

Runaway beam suppression after TQ - results

- Summary of all the mitigation attempts: no suppression.



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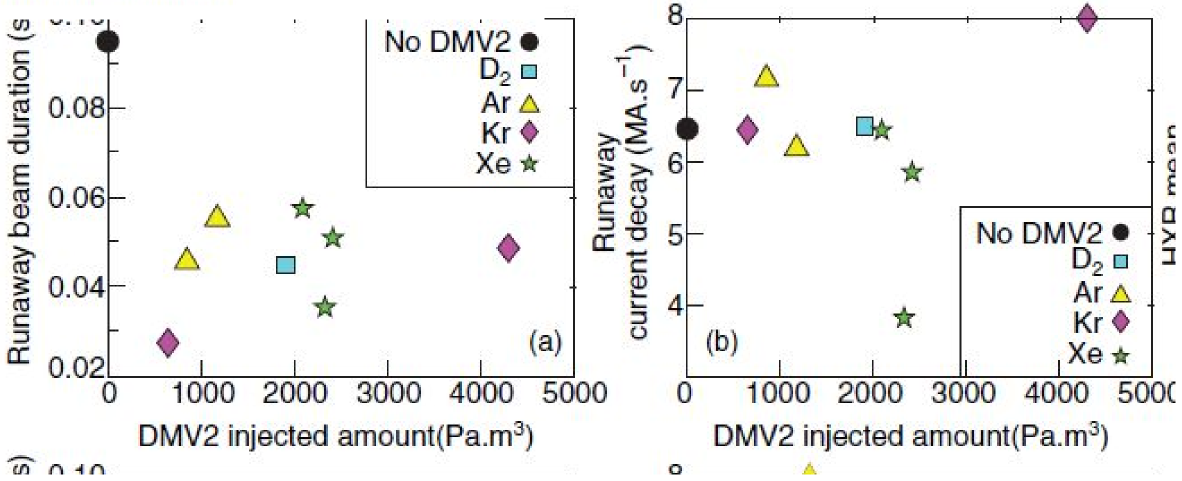
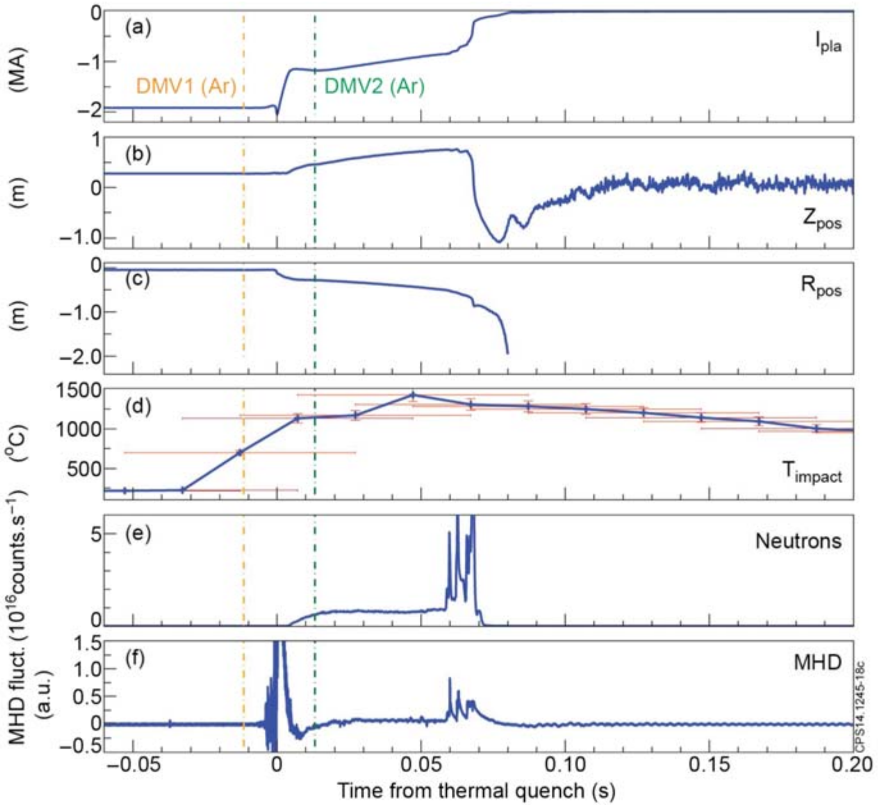
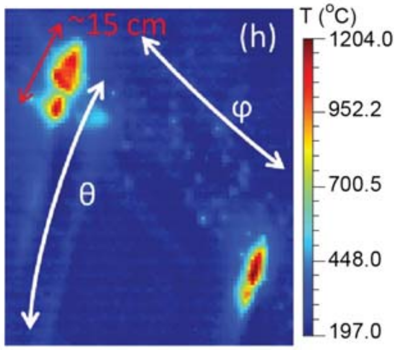
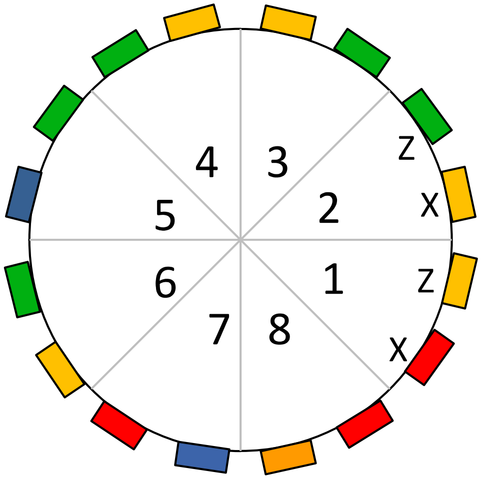


Runaway impacts

- Most of impacts: upper part of inner wall (>melting temperature)
- Important features:
  - Tile heating starts before the final collapse
  - **Asymmetrical impacts** (>mounting tolerances)







🟥	Significant melting
🟨	Traces of melting
🟩	Surface alteration only
🟦	No damage

C. Reux et al, NF15

Summary

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

- 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

Thank you

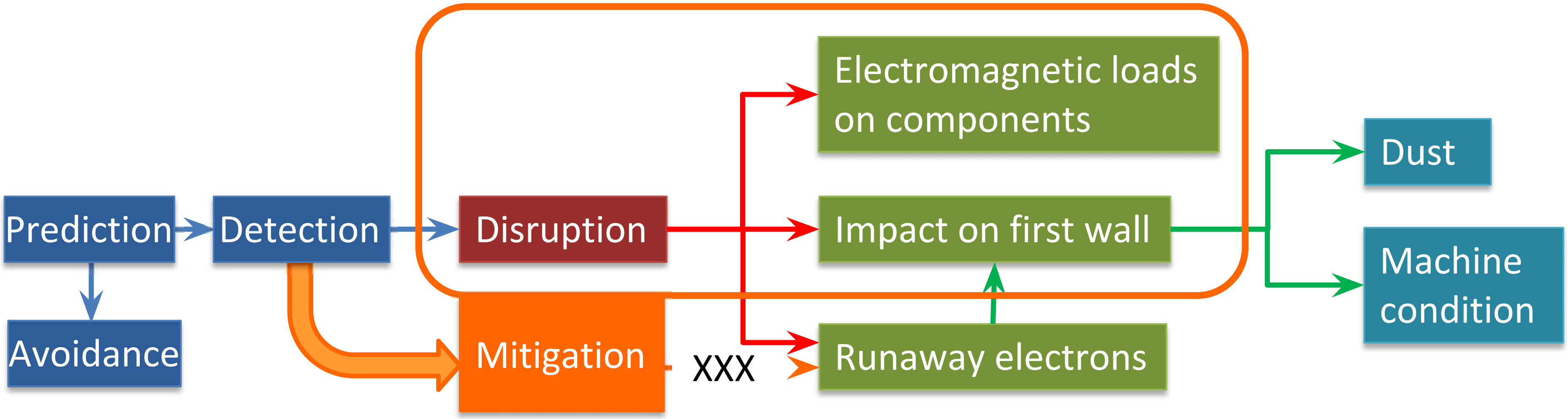
ITER-issues on disruptions (excerpts)[1]

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.



JET

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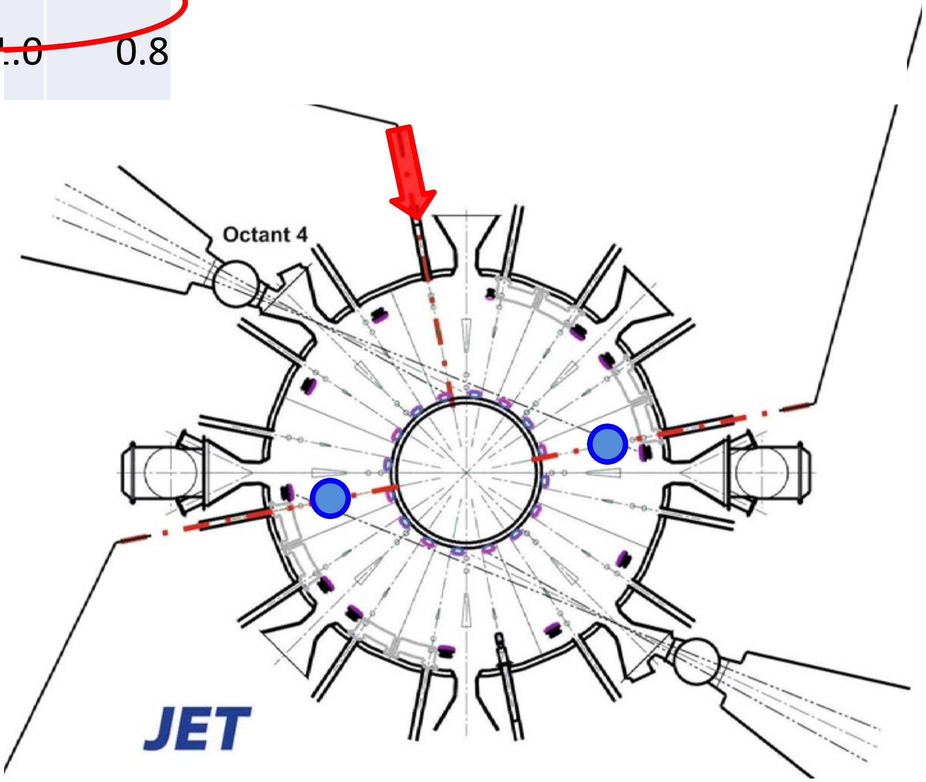
[1] M. Lehnen et al, JNM'15

ITER-like disruption mitigation system at JET

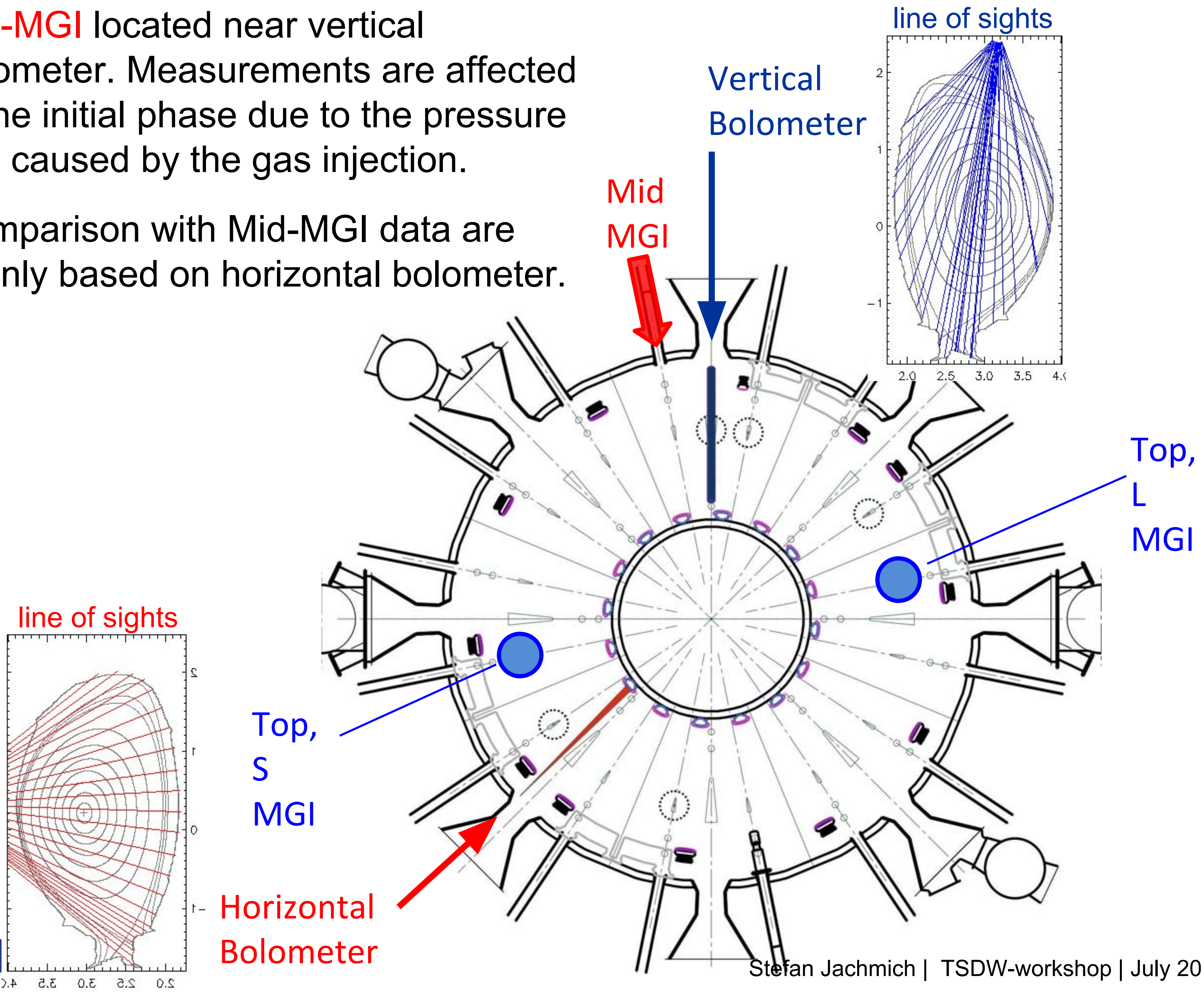
- 2 Vertical and 1 Equatorial MGI

	DMV1	DMV2	DMV3
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]	~1.8	~1.0	0.8



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.

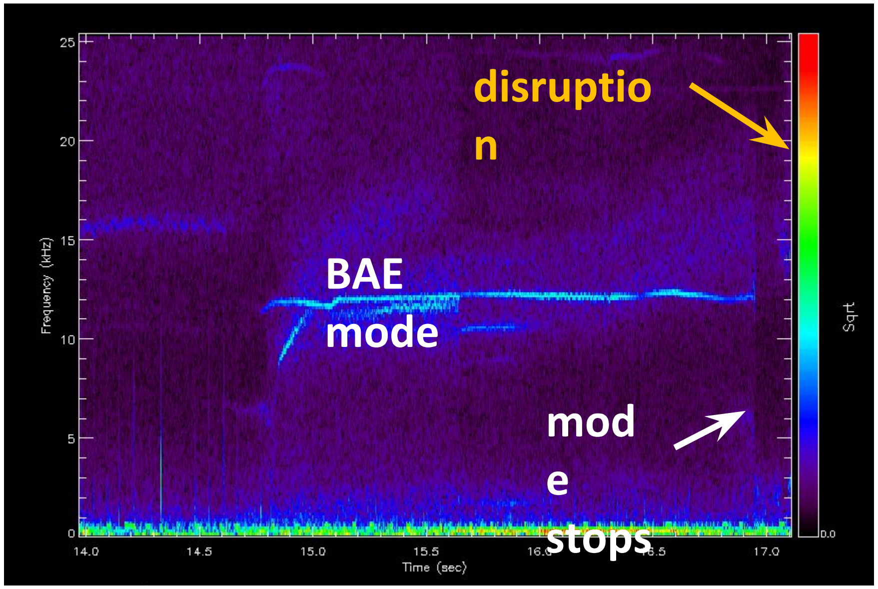


Indicators for optimal MGI triggering

- 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



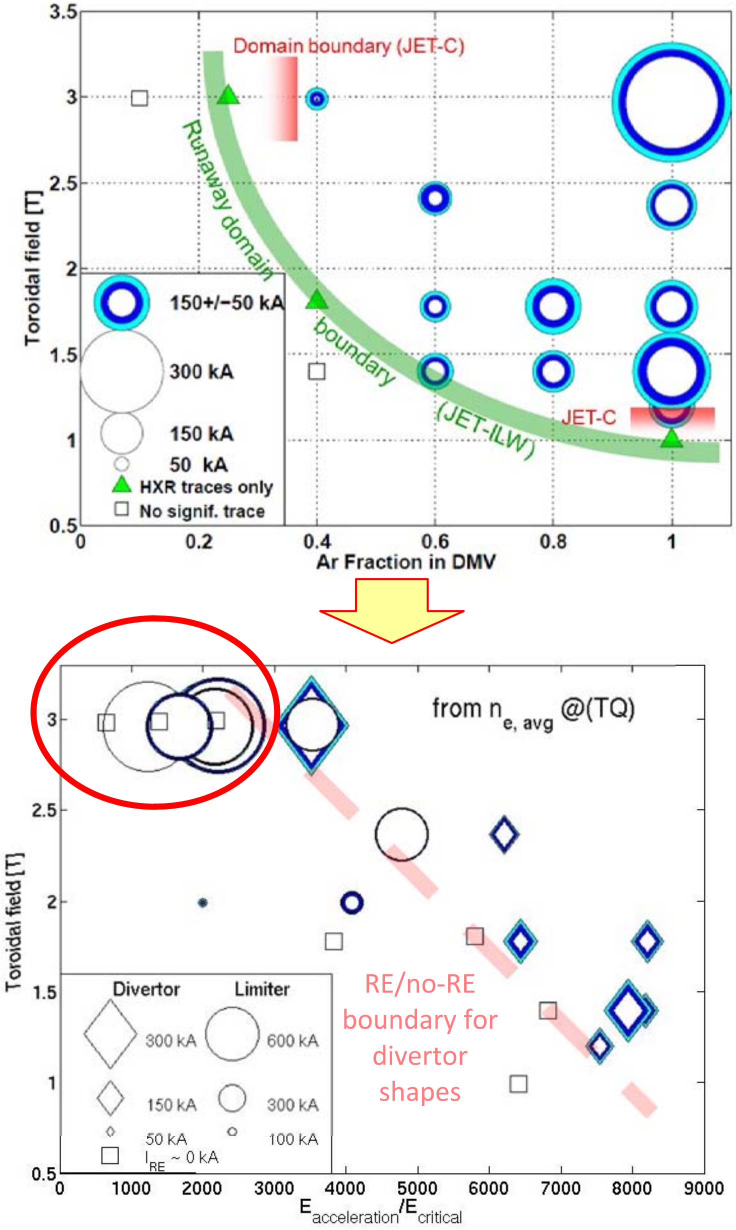
Runaway existence domain

- 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)

$$E_c = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon^2 m_e c^2}$$

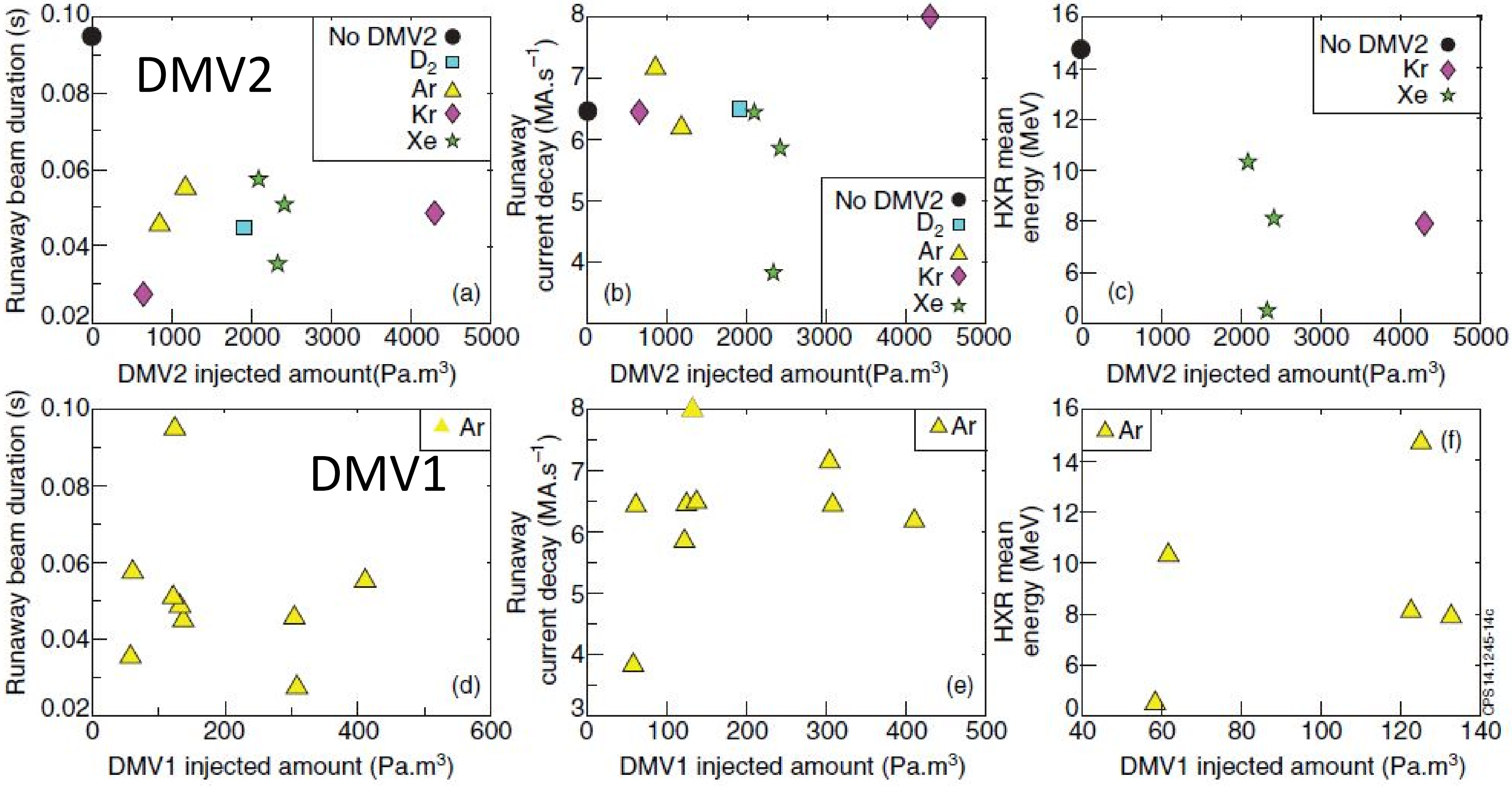
  - Toroidal field B_t
- With divertor pulses: clear domain in $(E_a/E_c, B_t)$ space
- At equal E /E limiter pulses

Strong dependence of RE generation on vertical position



JET

Runaway beam suppression after TQ



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