Shattered Pellet Injection experiments at JET in support of the ITER Disruption Mitigation System

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ITER Organization

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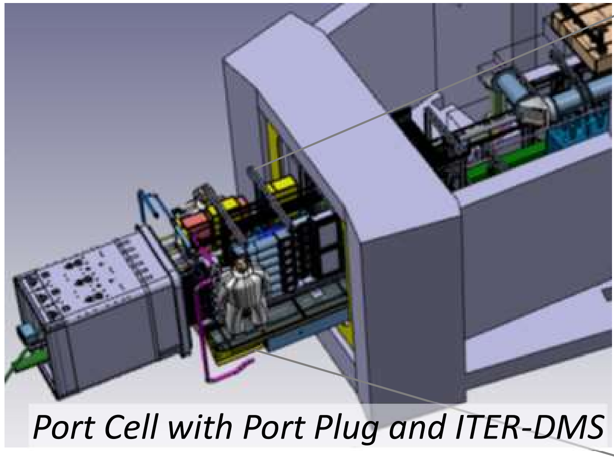
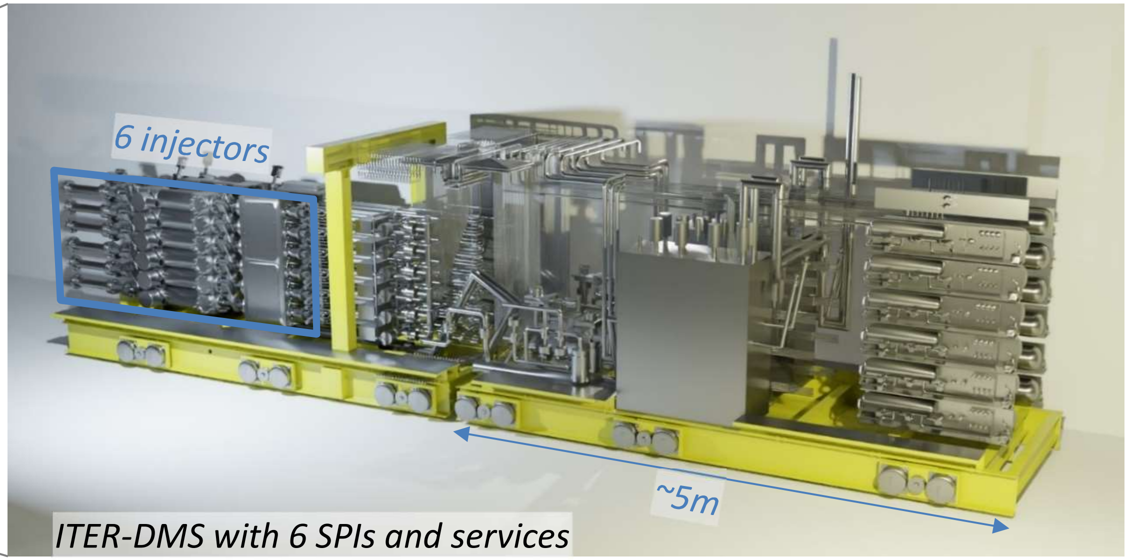
Key questions for the ITER-DMS studied at JET



Port Cell with Port Plug and ITER-DMS

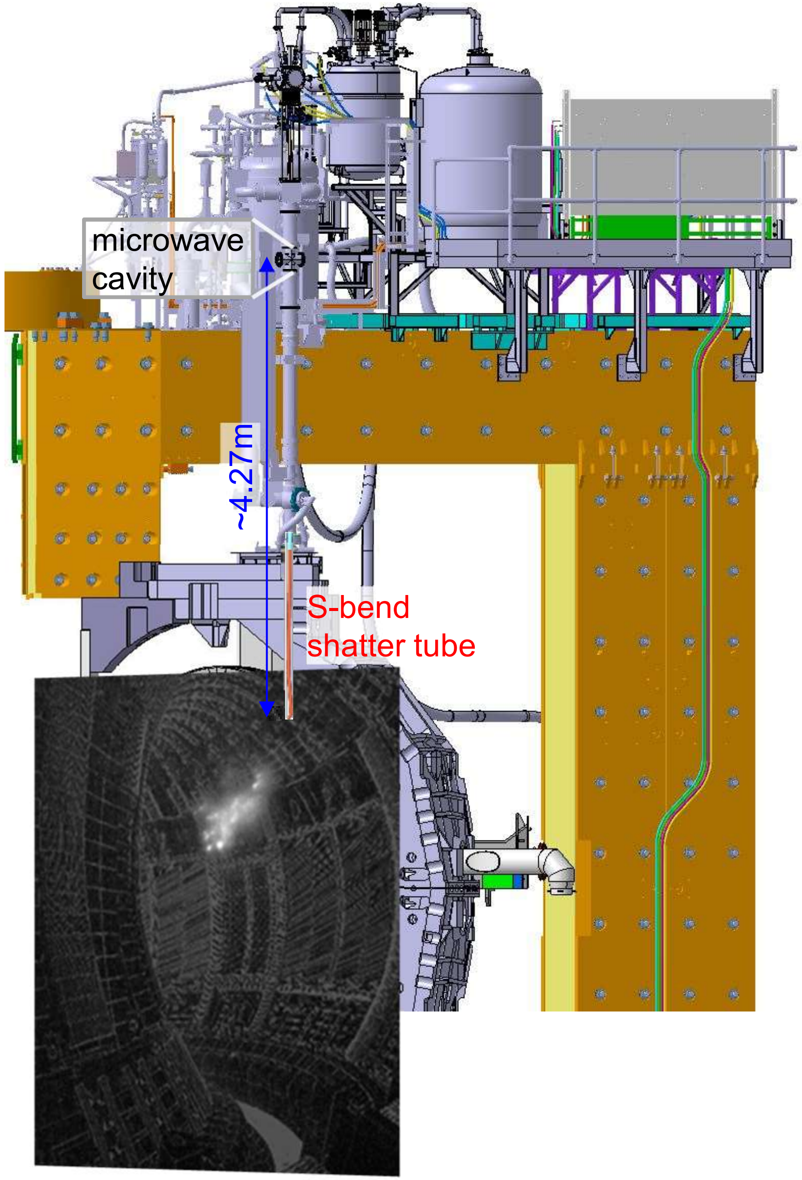


ITER-DMS with 6 SPIs and services

ITER DMS needs	JET-SPI contribution
Thermal load mitigation: keep conducted heat loads to divertor <20MJ through Ne/H-injection	• Provide data at high thermal energies (~8MJ) to project required Ne-quantity for ITER using 3D-MHD codes
Runaway electron avoidance: find viable scheme	• Test dilution cooling through D_2-injection
Radiation induced heat flux peaking needs to be limited <4	• Assess toroidal peaking factors
Current quench mitigation: control CQ-rate to be $50<t_{CQ}<150$ ms and radiate magnetic energy	• CQ-acceleration of disruption with low intrinsic radiation • Study post-TQ assimilation
Runaway electron impact mitigation	• Low-Z (D_2) and High-Z (Ne, Ar) injections into RE-beam

SPI system at JET

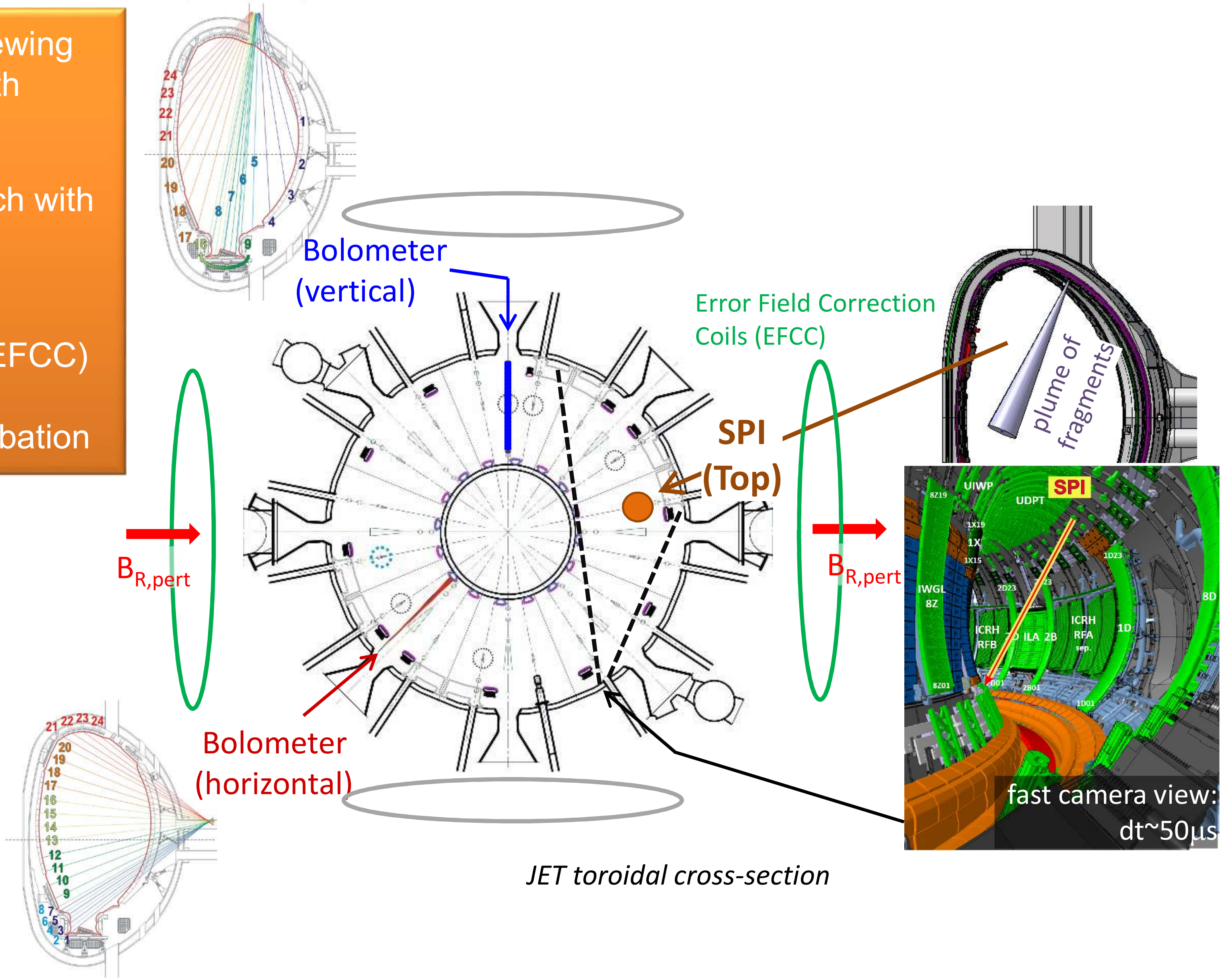
- 3-barrel gun system with diameters A=12.5mm, B=8mm, C=4.5 mm and L/D~1.5
- Gas species: H_2, D_2, Ne and Ar
- Microwave cavity diagnostic to determine pellet mass, integrity and velocity
- Punches can be fitted on two largest barrels to reduce velocity and to dislodge Ar-pellets.
- Shattering through S-bend with 20^o angle



see also L. Baylor et al, this conference

SPI and Diagnostics

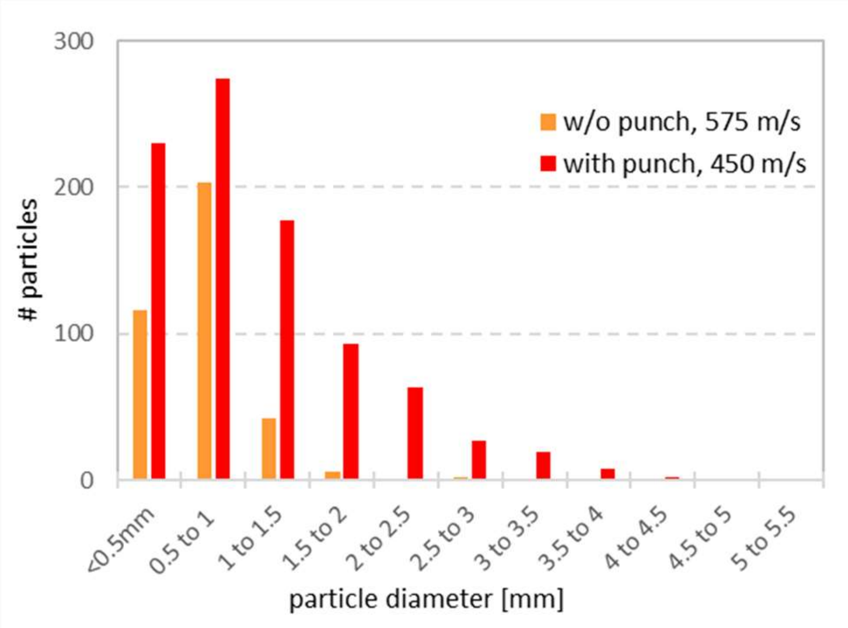
- Fast camera viewing SPI injection with various filters
- 2 bolometer each with 24 channels ($\rightarrow P_{rad,v}$, $P_{rad,H}$)
- External coils (EFCC) to provide n=1 magnetic perturbation



JET toroidal cross-section

Fragment size distribution

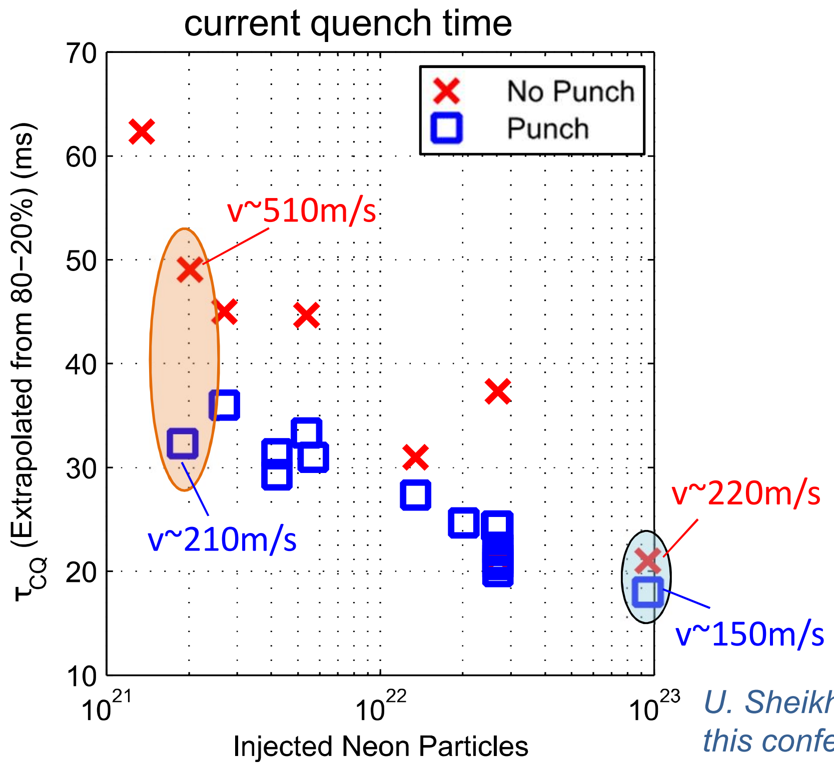
- Fragment plume analysis with 12.5mm pellet ($5\%Ne+D_2$-shell)
- mass detected in plume:
  - with punch = 74% for v~450m/s
  - w/o punch = 5.4% for v~575m/s



> *High fraction of gas and micro-fragments produced for high pellet velocities.*

T. Gebhart et al, IAEA-TM "Disruptions", 2020

- Scenario: injection into healthy H-mode plasma (I_p~2.5MA, W_{mag}~5.4MJ, W_{th}~3-4 MJ)



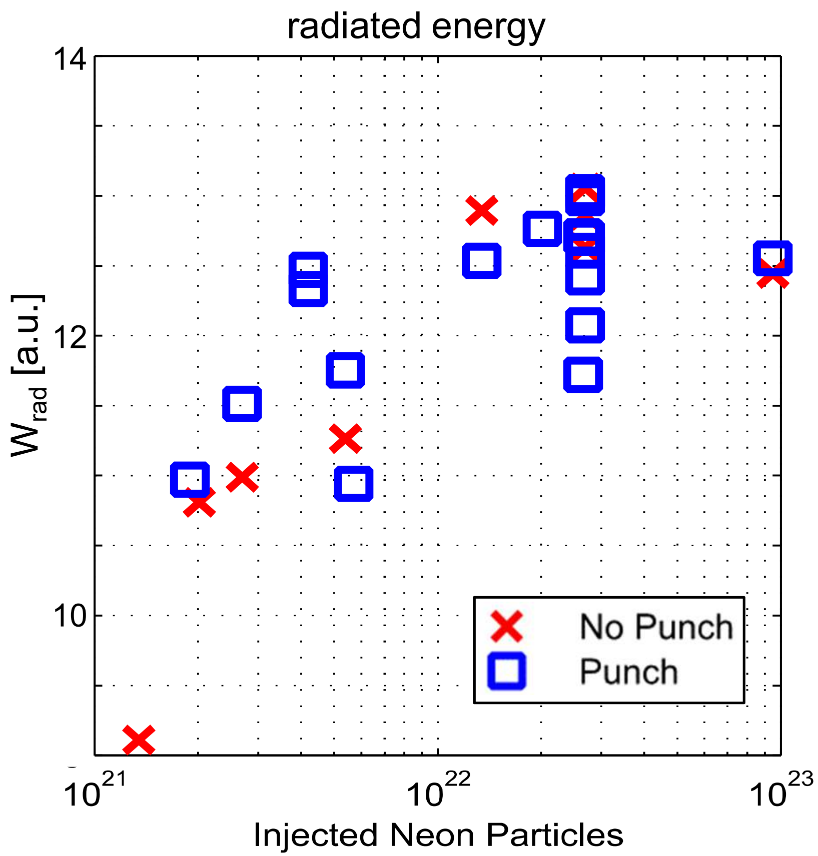
U. Sheikh et al, this conference

> *Shorter CQ times with punch:*
> - *More resistive plasma → better assimilation of injected impurities*
> - *Assimilation better due to larger amount of solid material or different fragment velocities?*

Thermal load mitigation with D_2/Ne mixtures

Impact of neon quantity on radiation

- Scenario: injection into healthy H-mode plasma (I_p~2.5MA, W_{mag}~5.4MJ, W_{th}~3-4 MJ)

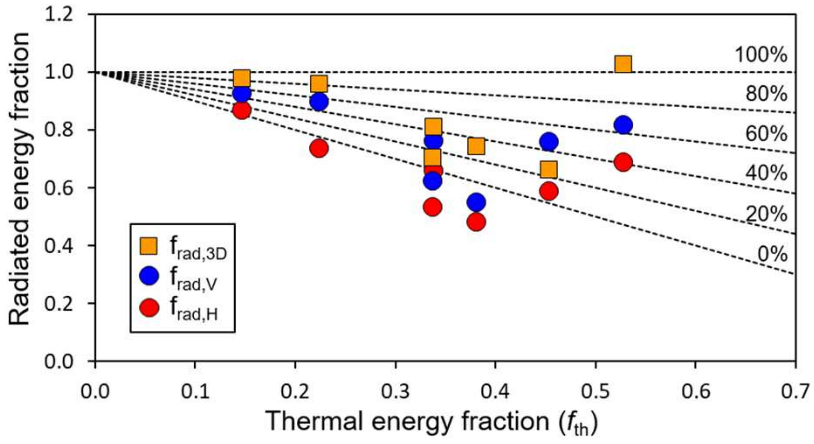


U. Sheikh et al, this conference

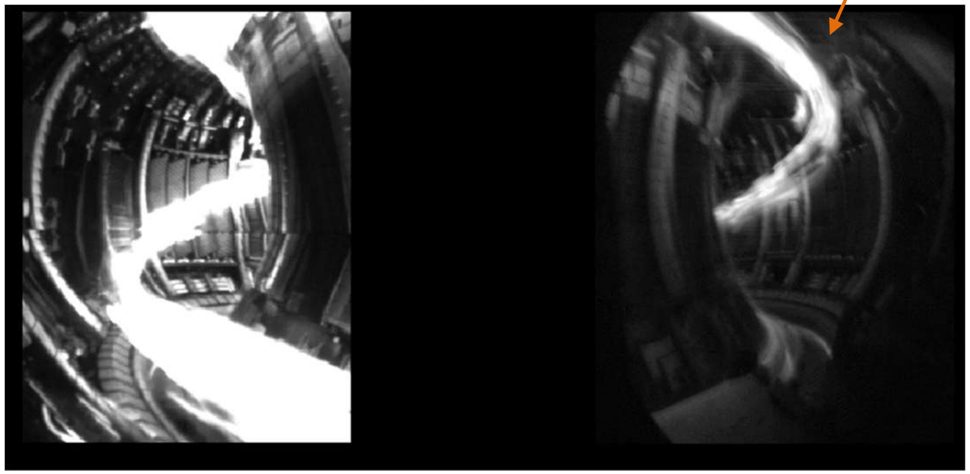
> ➢ *Indication of saturation of radiated energy with increasing amount of Ne-atoms*
>
> ➢ *Modelling required because of unknown assimilation efficiency and radiation distribution*

Radiation efficiency

- Vary P_{NBI} to scan f_{th} (W_{th}=0.3-1.5MJ for W_{mag}~3 MJ)
  - Pellet: 80% Ne (Ne=2.4x10^{22} atoms + D-shell)
- Axisymmetric weighted is significant lower than 100%



- Fast cameras show large helical structure: SPI-location



> ➢ *Difference in W_{rad} measured by 2 bolometers → radiation asymmetries*

- Emis3D code to determine helical structure fitting best the LOSs of the bolometers
- Assumes Gaussian toroidal distribution using $P_{rad,V}$ and $P_{rad,H}$ as boundaries

> ➢ *Toroidal peaking ~2.2*

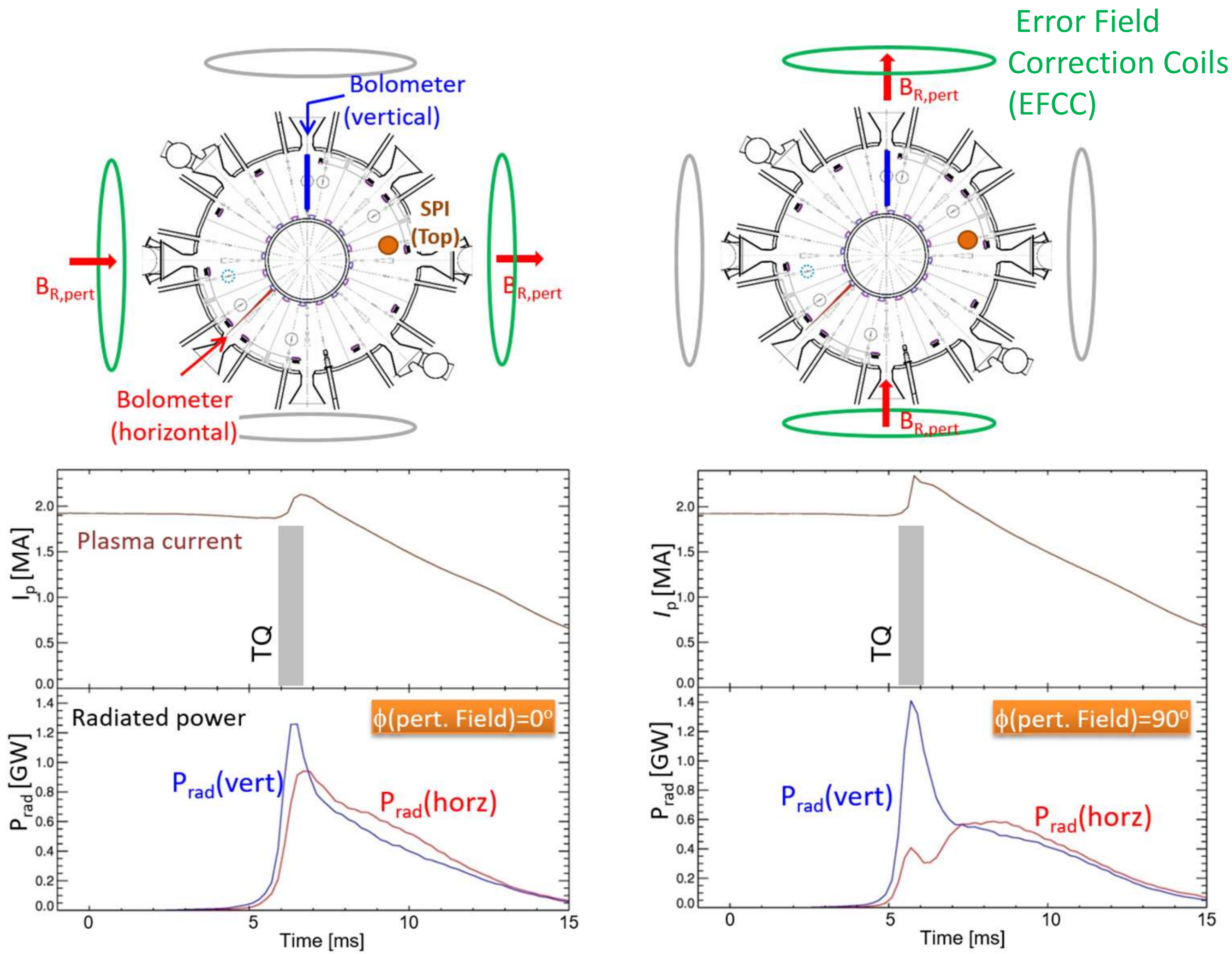
Radiated energy fraction: $\langle f_{rad}\rangle = W_{rad,H} / (W_{mag}+W_{th}-W_{coupled})$
Thermal energy fraction: $f_{th} = W_{th} / (W_{mag}+W_{th}-W_{coupled})$

R. Sweeney et al, 62nd APS DPP meeting, 2020

Radiation asymmetries for SPI into plasmas with pre-existing n=1 mode

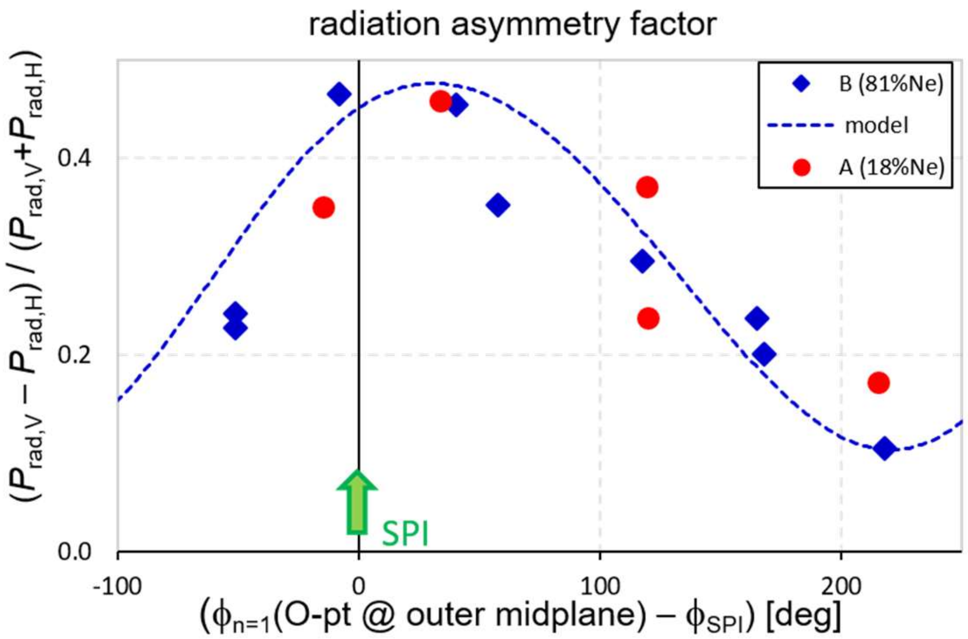
Strategy to determine radiation asymmetries

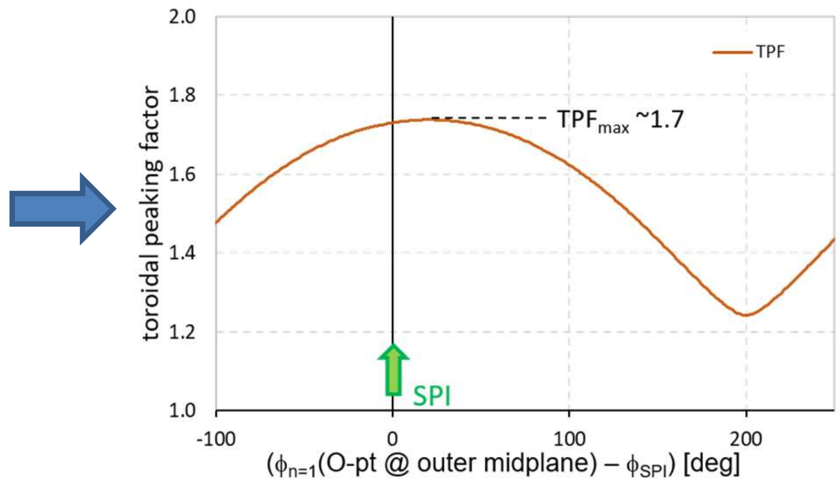
- Bolometer coverage insufficient to determine TPF (and PPF) directly
- Vary O-point location of n=1 mode with respect to injection location to determine "toroidal" dependence of radiation
- Assumes relative weights of LOS of bolometer channels correctly add to total radiated power at toroidal location of diagnostic
- Poloidal peaking factor not assessable.



Radiation asymmetries – H-mode

- H-mode (I_p=2.0MA, P_{NBI}=12MW, W_{th}~2 MJ, f_{th}~0.4)
  – Pellets used: B (81% Ne) and A (18%Ne), i.e. amount of injected neon is kept constant
- Model assumes Gaussian-like impurity density and cosine-dependence for n=1 mode effect





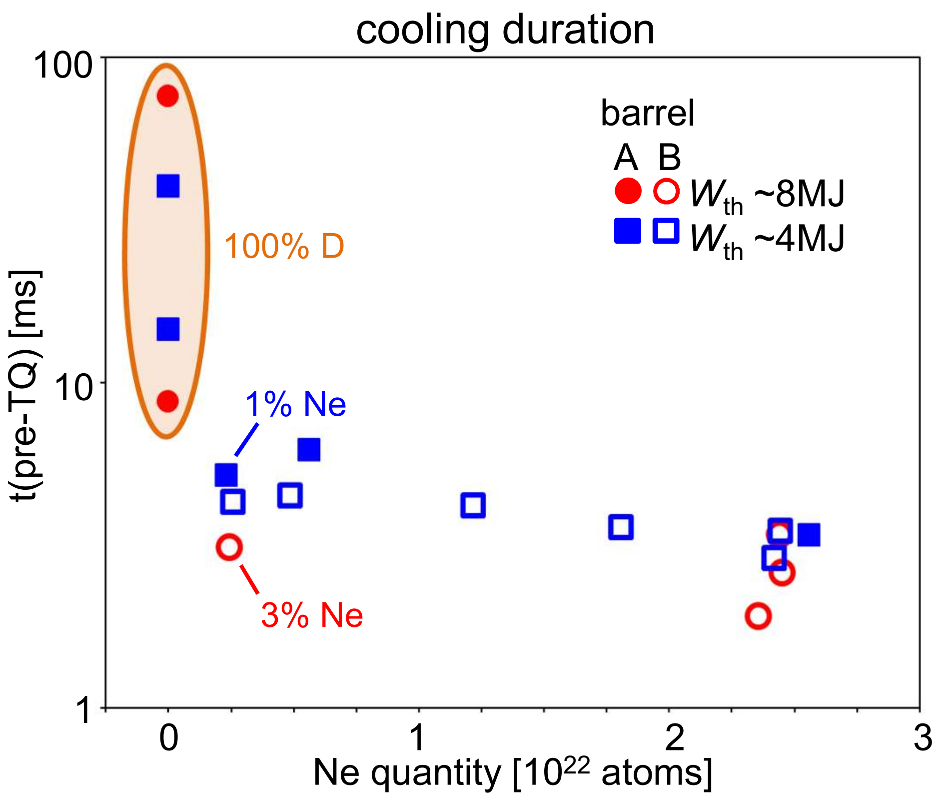
- *TPF varies from 1.2 to 1.7 and is maximum for injections into the n=1 O-point.*
- *Current quench time does not depend on n=1 mode → similar particle assimilation.*

Model based on M. Lehnen et al., Nucl. Fus. 2015.

Runaway electron avoidance scheme
“Dilution cooling”

Cooling duration

- Long pre-TQ cooling duration could be beneficial for
  - increasing plasma density for runaway electron avoidance
  - reducing the required amount of neon to achieve sufficient TQ radiation while staying within electromagnetic load limits
- Pure deuterium injection needs to be followed by Neon injection prior TQ and CQ (→ timing?)



> - *Already small injection of neon shortens cooling duration to a few millisecond*
> - *Pure D_2 injection results in much longer delays of TQ (several 10ms)*
> - *Scatter due to fragment injection properties?*

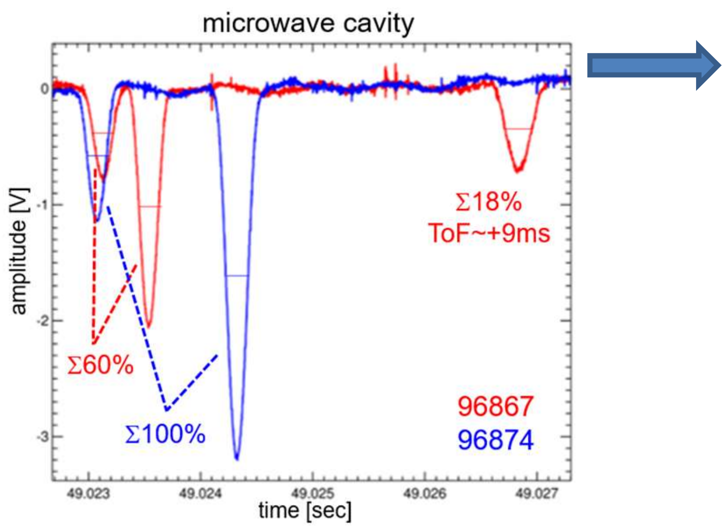
M. Lehnen et al, 4th Asia-Pac. Conf. Plas. Phys., 2020

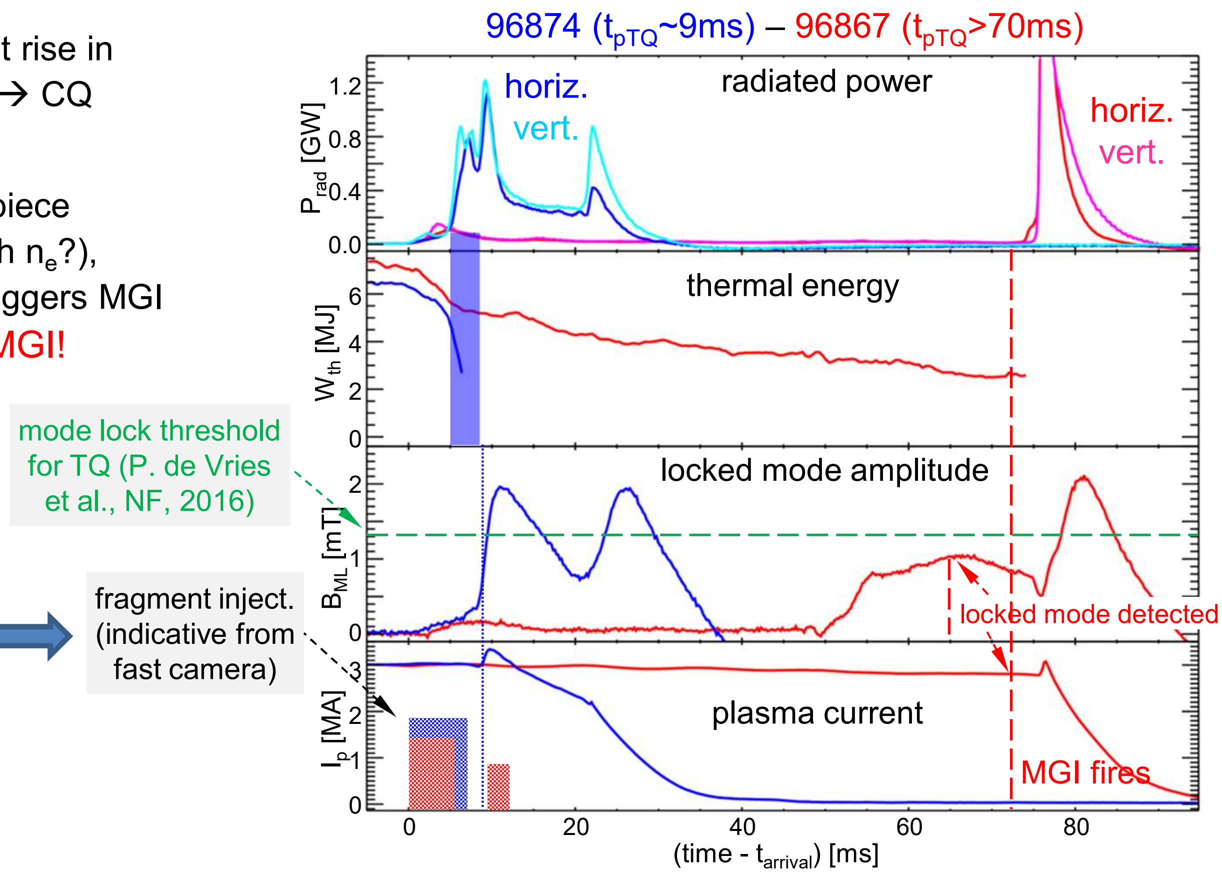
Multiple pure-D_2 injection

- Different sequence of events:
  96874: prompt material deposition → fast rise in radiation → n=1-mode triggered → TQ → CQ
  - ➢ W_{th} mainly radiated at TQ.

  96867: radiation remains small → @3rd piece interferometer laser refracts (due to high n_e?), MARFE and n=1-mode → mode lock triggers MGI
  - ➢ W_{th} reduced by ~65% at time of MGI!

- TQ trigger consistent with predicted mode lock threshold *(D. Shiraki et al, this conference)*



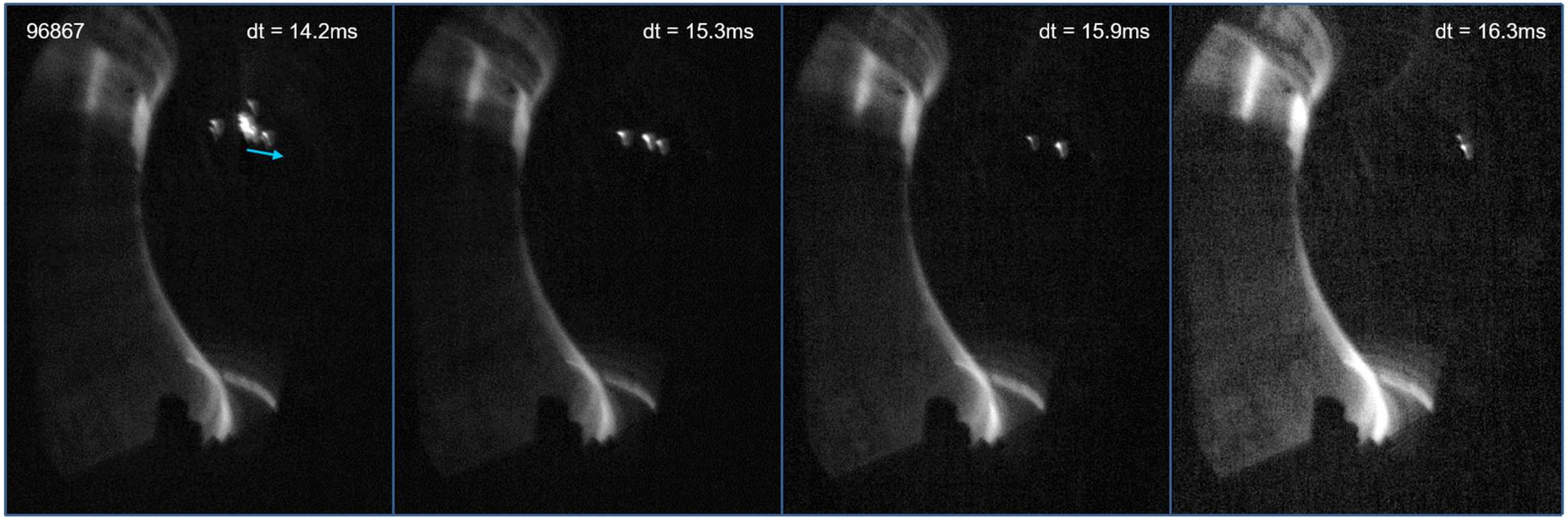


- ➢ *Does it help to inject train of "smallish" pellets rather one big one?*
- ➢ *Unclear correlation between n=1 growth rate and pre-TQ duration*

Assimilation limitation of multiple injections

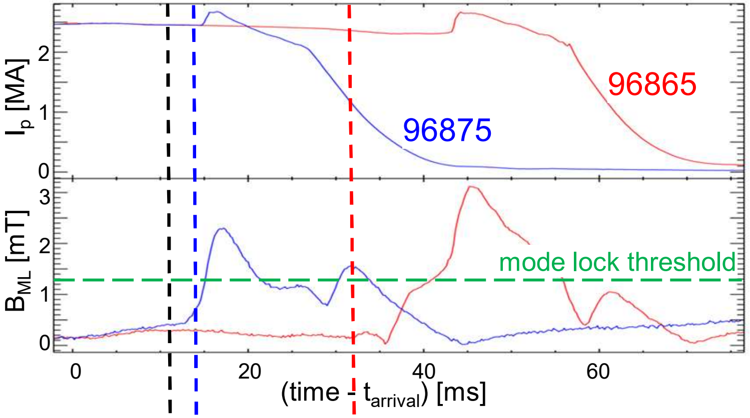
- Last fragments from 3rd piece are being deflected and are not assimilated anymore
  → friction or rocket effect?

➢ *First injection reaches maximum possible amount of material assimilation*

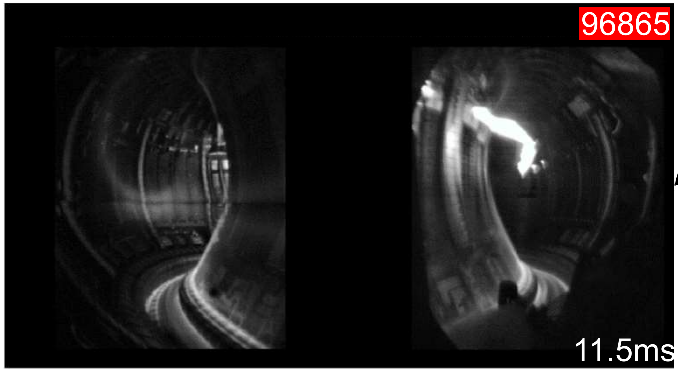


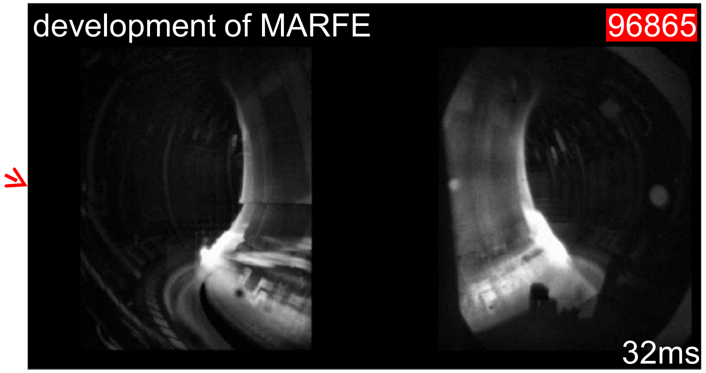
Termination of pre-TQ phase

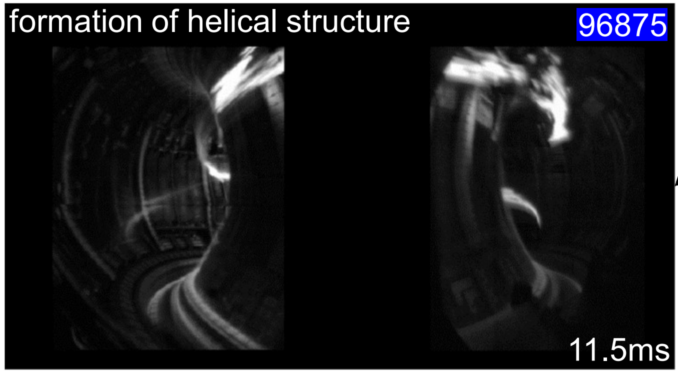
- pure-D_2 pellets (broken)
- 96865: 2 injections of fragm. over ~10ms
- 96875: fragments as one injection over ~5ms

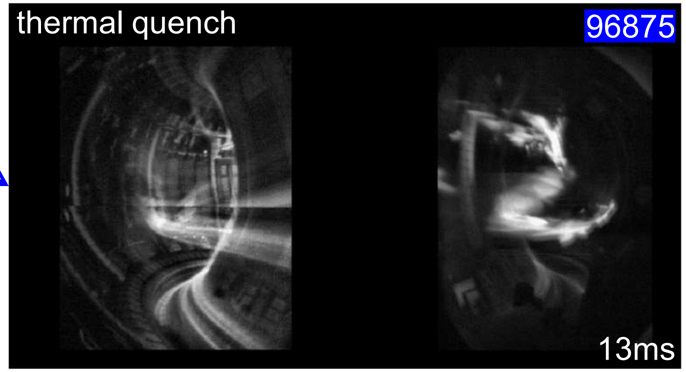


> ➢ *Formation of helical structures linked to short pre-TQ phases*
>
> ➢ *Scheme requires careful tailoring of injections*





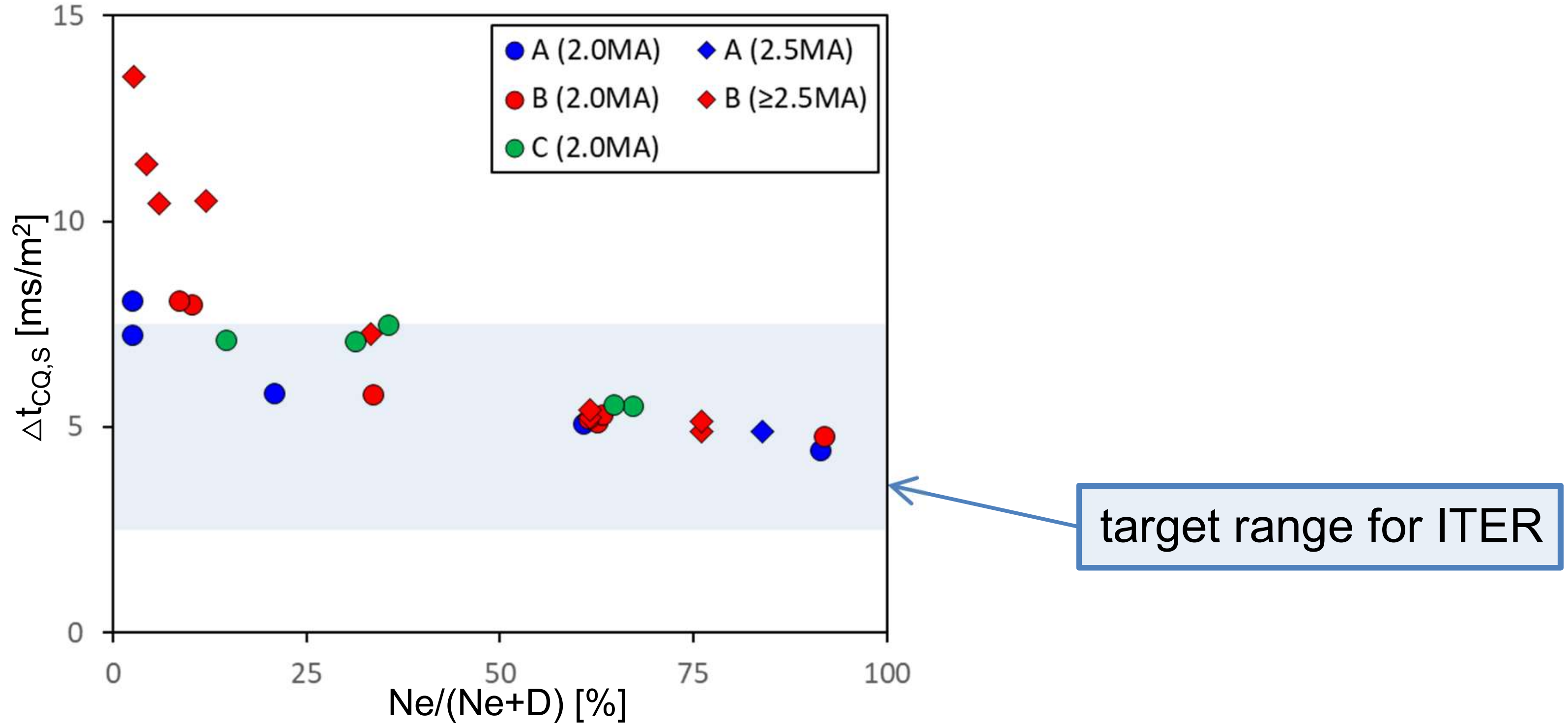




Current quench mitigation

Current quench control

- Neon fraction in deuterium pellets and pellet size was varied
  - target I_p=2.0MA (for diamonds $I_p \geq 2.5$MA)

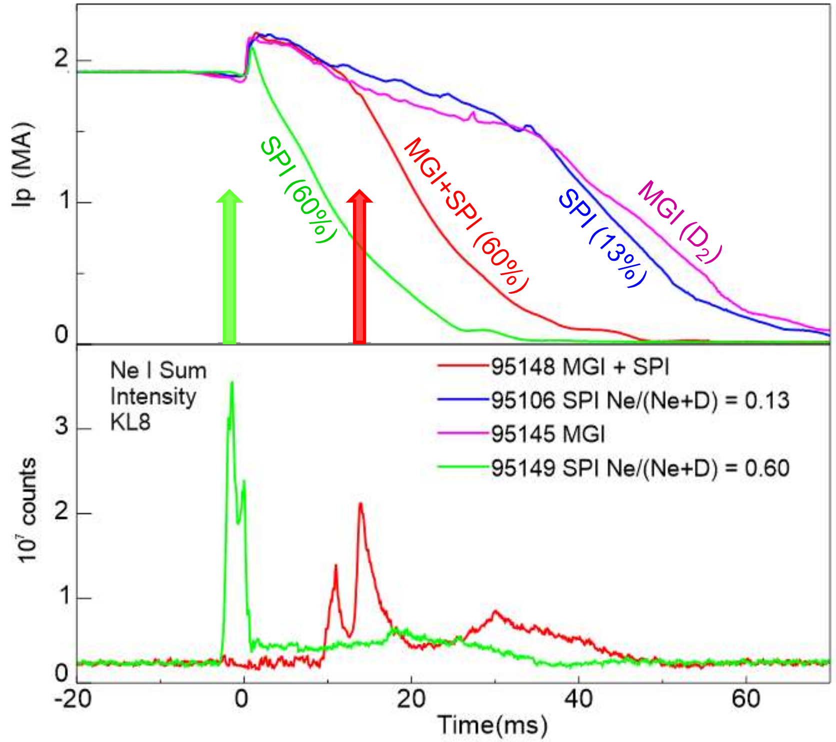


- *Current quench duration does not depend on the total injected quantity but on the Ne fraction.*
- *TQ triggered before pellets are fully assimilated, i.e. at the same ablated Ne/D quantity.*

S. Gerasimov et al, IAEA-TM "Disruptions", 2020

Effectiveness of SPI on post-disruptive plasma

- CQ mitigation in ITER must be ~100% reliable: mitigation upon TQ detection must be effective.
- Induced disruptions by MGI ($2x10^{21}D_2$) or SPI (13% and 60% Ne/D mixtures) and mitigated with SPI (60% Ne/D mixtures)



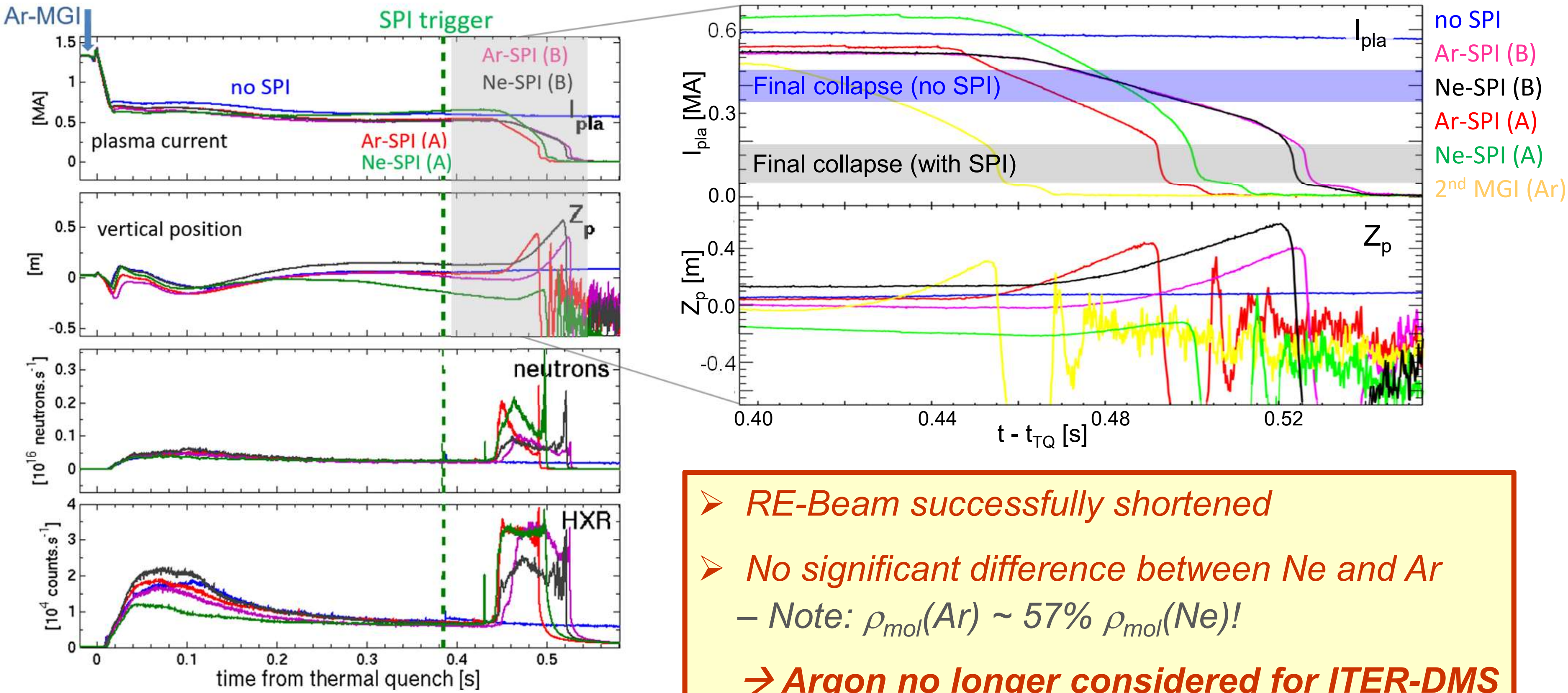
S. Gerasimov et al, IAEA-TM "Disruptions", 2020

> - *Injection into post-TQ plasma induced by density limit leads to similar CQ-duration as injections into pre-TQ plasma.*
>
> *Note: ITER needs to inject into the CQ for heat load mitigation and electromagnetic-load already for plasma currents 7.0-8.0MA.*

Runaway electron impact mitigation

High-Z injection for RE energy dissipation

- RE-beam generated by Ar-MGI into ohmic limiter plasma
- After ~350ms SPI-injection of pure neon or argon

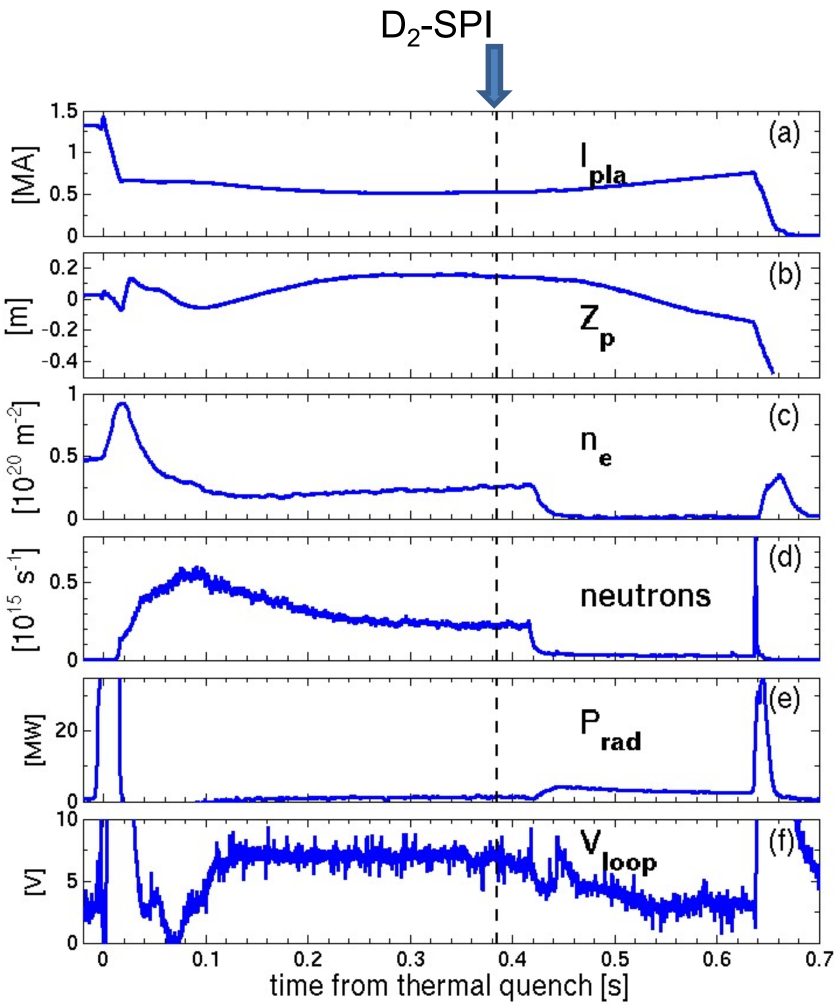


> ➢ *RE-Beam successfully shortened*
>
> ➢ *No significant difference between Ne and Ar*
> – *Note:* $\rho_{mol}(Ar) \sim 57\% \ \rho_{mol}(Ne)$*!*
>
> → ***Argon no longer considered for ITER-DMS***
>
> ➢ *At final loss: still significant energy → impact?*

C. Reux et al, IAEA TM, ITER, 2020

Low-Z injection for RE impact mitigation

- RE-beam generated by Ar-MGI into ohmic limiter plasma
- After t~380ms deuterium SPI into existing RE-beam
- Current increases and neutrons drop
- Electron density drops to <10^{18}m^{-2}
  → plasma recombines
- Loop voltage decreases
  → indicates purging of impurities?
- IR cameras indicate disappearance of RE synchrotron emission within 3ms after final neutron spike

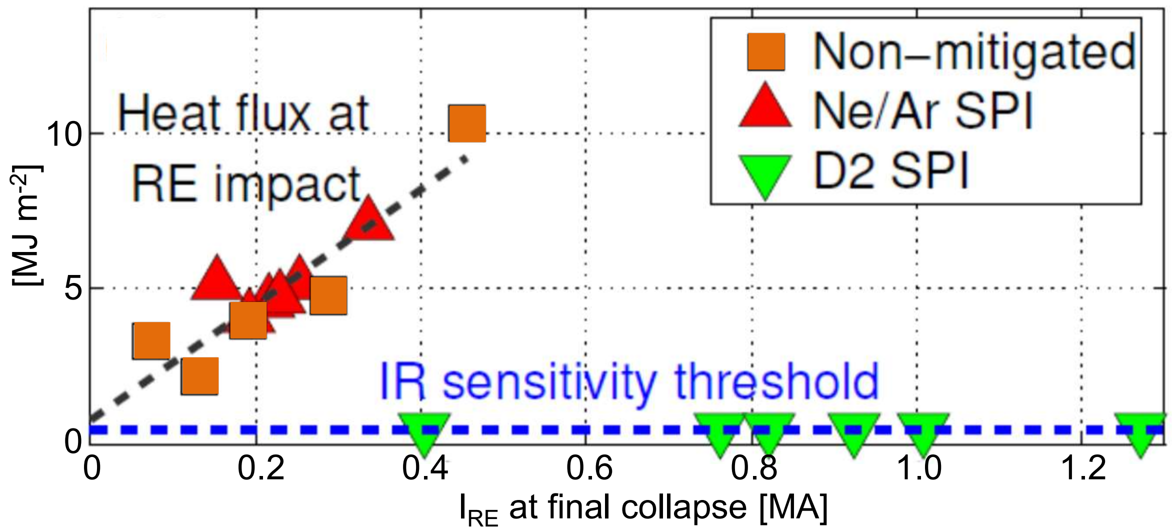


> ➢ *Final current decay similar to ohmic CQ with*
> *– absence of re-avalanche of REs*
> *– strong MHD (→ leading to larger wetted areas?)*
> *→ benign termination*

C. Reux et al, Phys. Rev. Letter 2021
C. Paz-Soldan et al, this conference

Assessment of RE impact

- Heat flux of RE beam impact on inner wall measured by IR-camera



> *High-Z SPI: heat loads up to ~7 MJ/m²*
> *Low-Z SPI: no relevant energy deposition during final MHD event!*

C. Reux et al, Phys. Rev. Letter 2021

Summary and Conclusions

Summary and conclusions

1) Quantification of radiation asymmetries are essential to conclude on achievable radiation levels for thermal quench mitigation → requires modelling.

2) Assessment of radiation asymmetries has revealed TPF ~2.2 (w/o n=1) and max 1.7 (with imposed n=1) (→ ITER: total peaking must be <4!).

3) Long pre-TQ times (>>10ms) have been achieved with D_2-SPI
   → Alternative ITER-DMS injection scheme for TQ-mitigation and RE-avoidance.
   → But sensitivity to fragment delivery and required Ne-amount for dissipating the remaining W_{th} needs to be assessed.

4) CQ-rate can be controlled over corresponding required ITER-range and even post-TQ injection has been seen to be effective.

5) Injection of Ar into RE beam has shown no advantage compared to Ne for mitigation of the runaway electron impact → use of Ar is no longer part of ITER-DMS design.

6) Injection of D_2 into RE beam successfully demonstrated benign impacts at final loss → considered as alternative mitigation scheme for runaway electrons in ITER.

- *JET experiments with the SPI have made (and hopefully will make further in the future) an important contribution to the ITER-DMS design!*

Thanks for your attention!