EUROfusion

Run-away studies in JET

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JET · iter (china eu india japan korea russia) · Oak Ridge National Laboratory · cea · CCFE Culham Centre for Fusion Energy

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

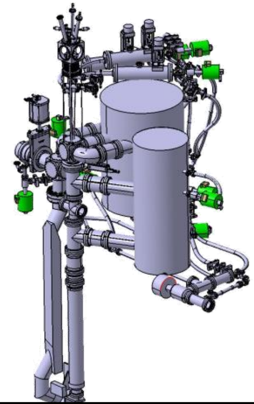
Outline

- JET disruption mitigation system (DMS) overview
- Summary of JET results on run-away mitigation
- SPI overview design
- JET run-away programme objectives in 2018

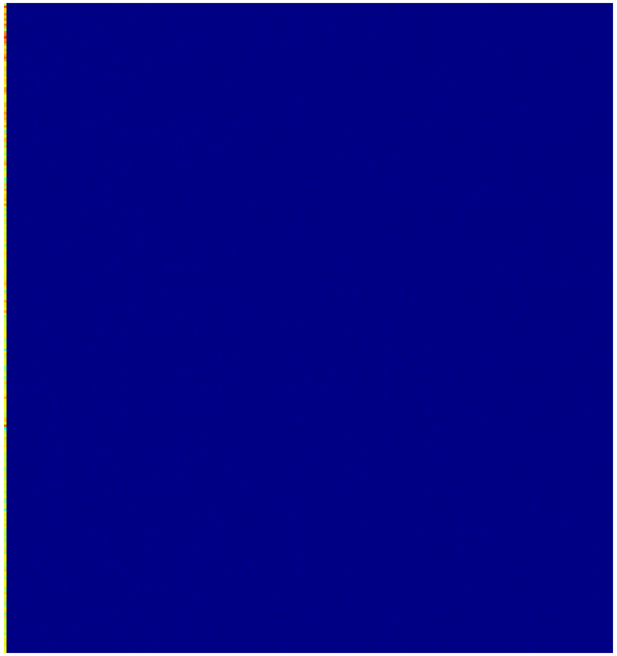
JET

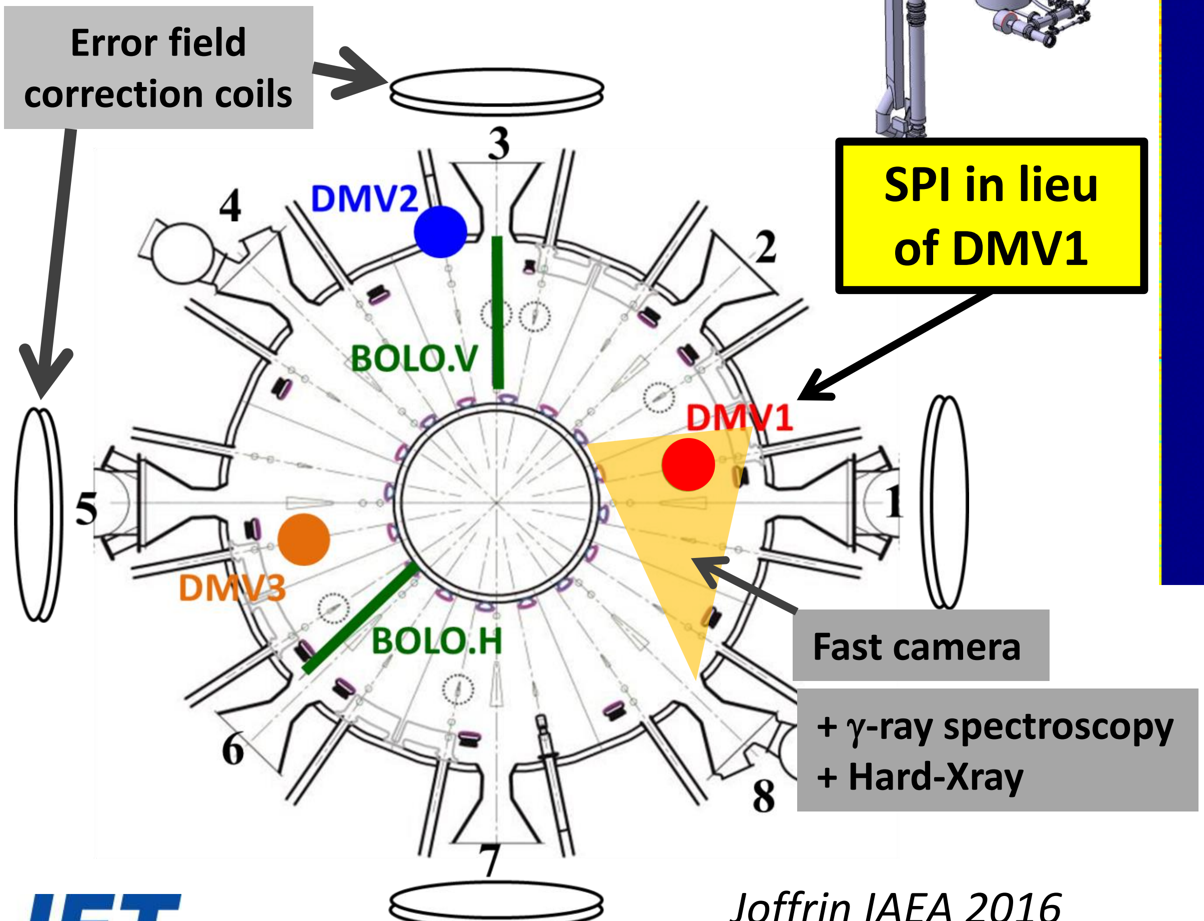
JET is equipped with a comprehensive disruption mitigation system (DMS)

DMV1	Upper port	4.6m to LCFS
DMV2	Horiz. port	2.8m to LCFS
DMV3	Upper port	2.4m to LCFS



The fast camera can be equipped with an Argon filter to measure its penetration into the plasma





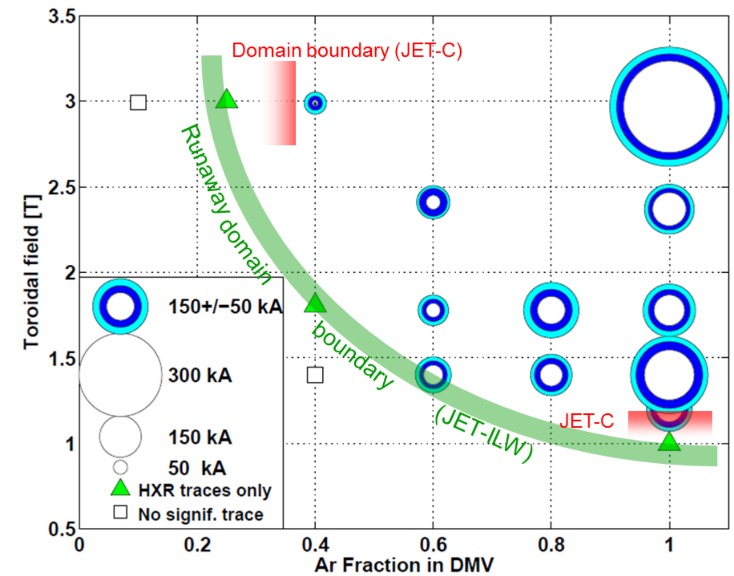
Massive gas injection mandatory in JET for:
- ❑ Ip > 2MA OR
- ❑ $W_{TH}+W_{MAG}$ > 5MJ

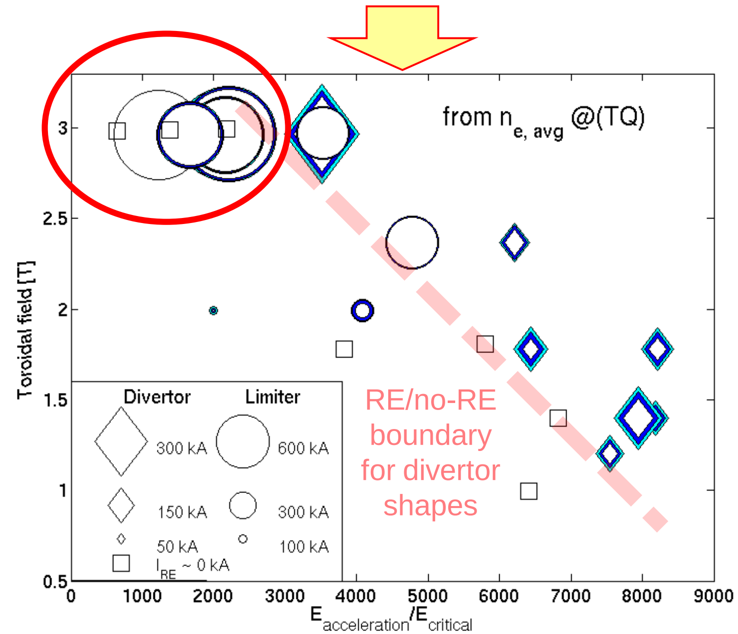
Joffrin IAEA 2016

Run-away existence domain in JET.

- 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 position

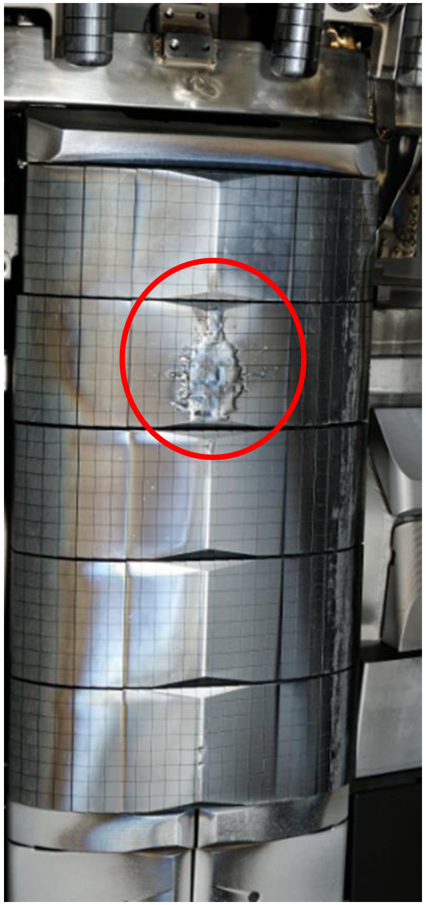


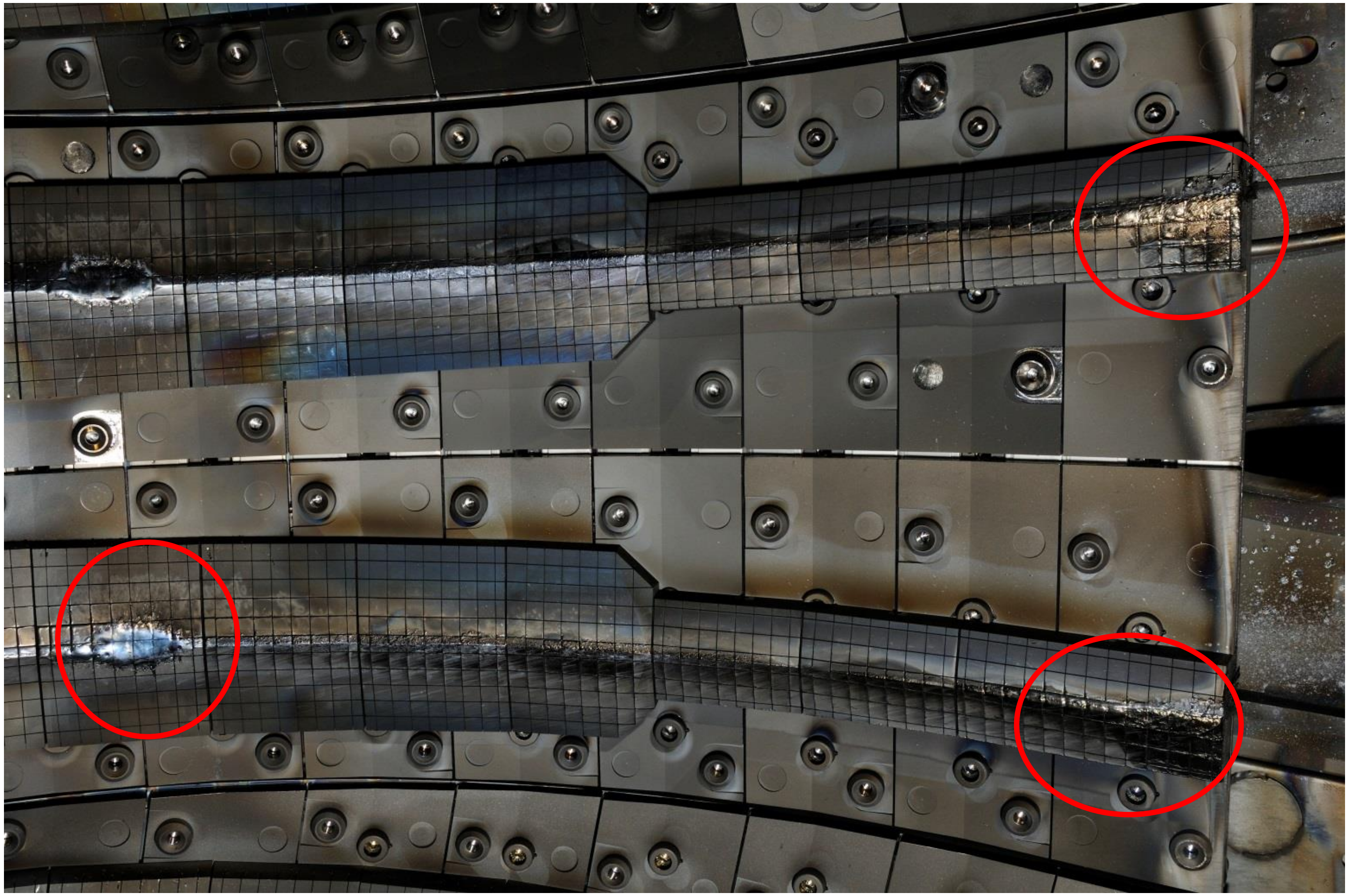


JET

Reux Nuc Fus 2015

Example of JET on Be component damages in JET





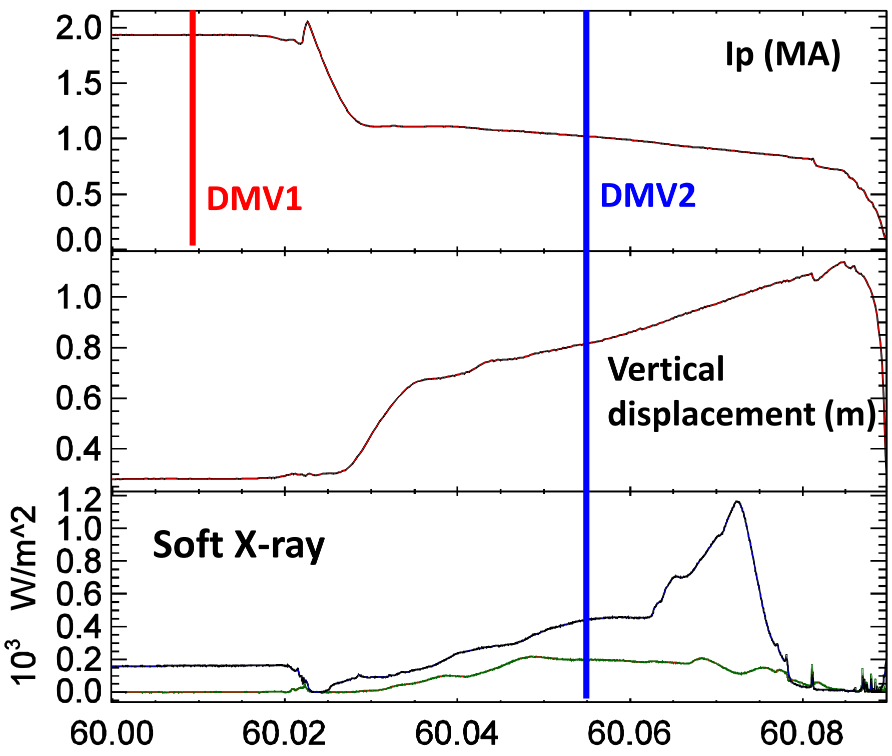
spray of droplets stuck on wall

Bubble-like damage to the upper dump and Inner Guard limiter place from run-aways localized toroidally

Outer ends beryllium protection tiles all damaged in a similar way toroidally

JET

In JET Massive gas injection is also inefficient in mitigating run-aways



C. Reux, Nuc. Fus 2015

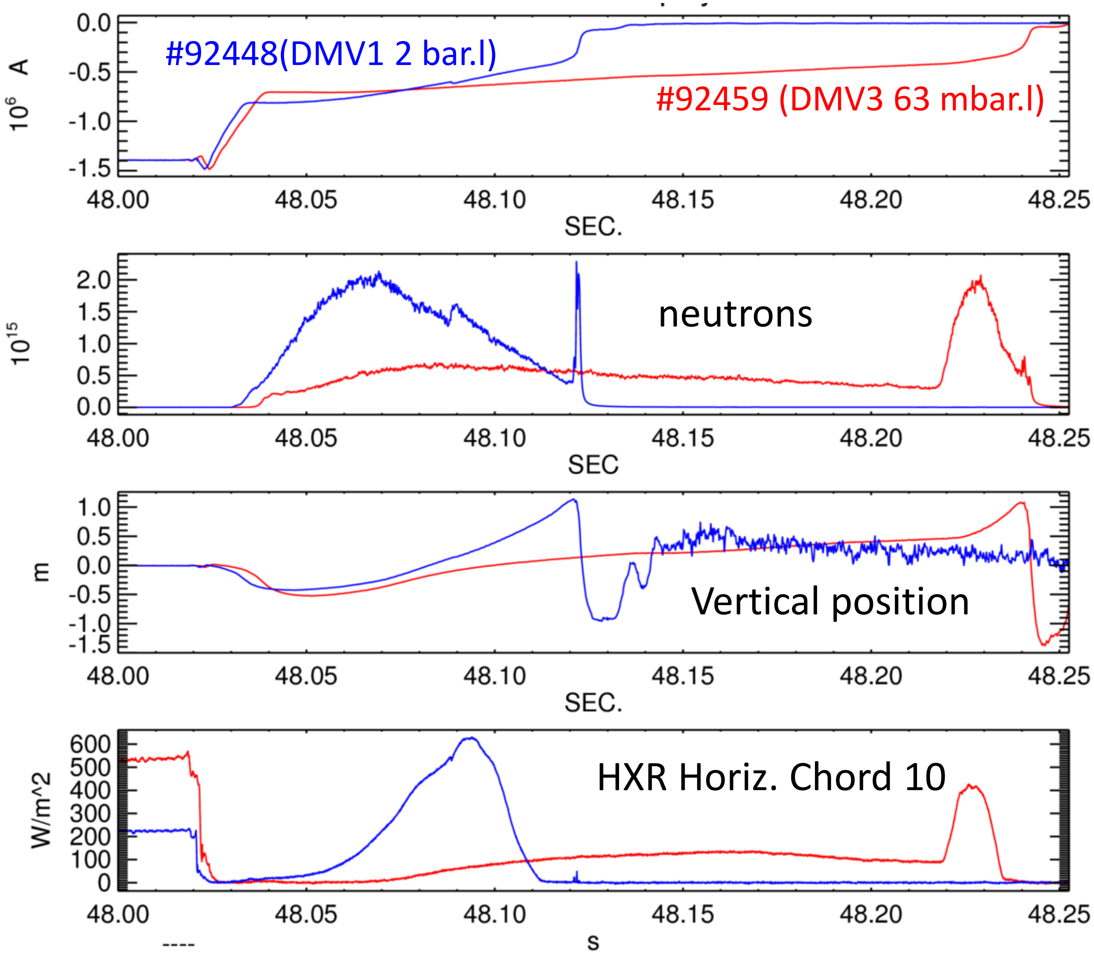
- ❑ **Massive gas injection inefficient at JET for mitigating RE for different gas (Ar, Kr, Xe,…) and pressures.**
- ❑ **Run-away beam can be mitigated by MGI in DIII-D, Tore Supra and ASDEX Upgrade.**
- ❑ **Hypotheses: the machine size or the surrounding plasma has a screening effect.**

➔ This hypothesis has been tested on JET in November 2016: analysis on-going

JET

In JET Massive gas injection is also inefficient in mitigating run-aways

- DMV1 was previously used to trigger runaway beams at JET (limiter configuration), DMV1 low pressure argon
- Recent experiments has proved that it is also possible with DMV3 (mid-plane)



- ❑ Longest post-disruptive runaway beam at JET-ILW with DMV3 (190 ms!)
- ❑ Much less gas injected to trigger the beam: possibly different generation conditions or runaway energies?
- ❑ To be confirmed with more statistics.
- ❑ Possible signs of enhanced mitigation with a second puff (DMV2 later in the beam phase)
- ❑ Role of the background plasma? Or RE energy ?

JET

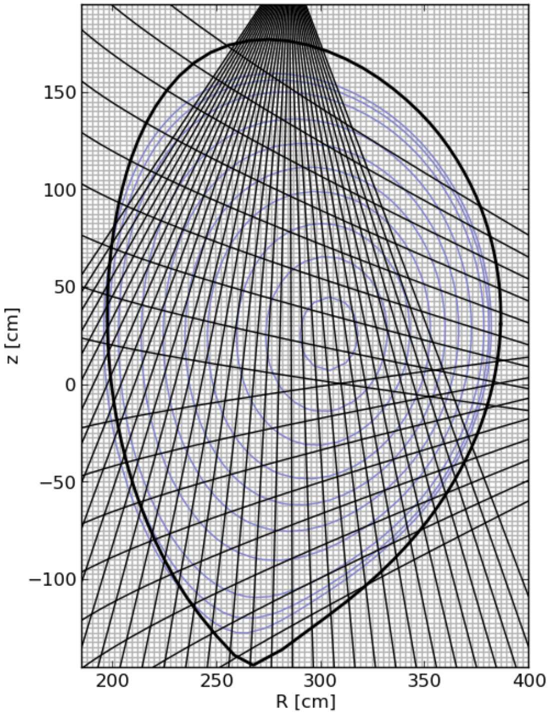
➔ **Analysis still on-going** *Reux, 2016*

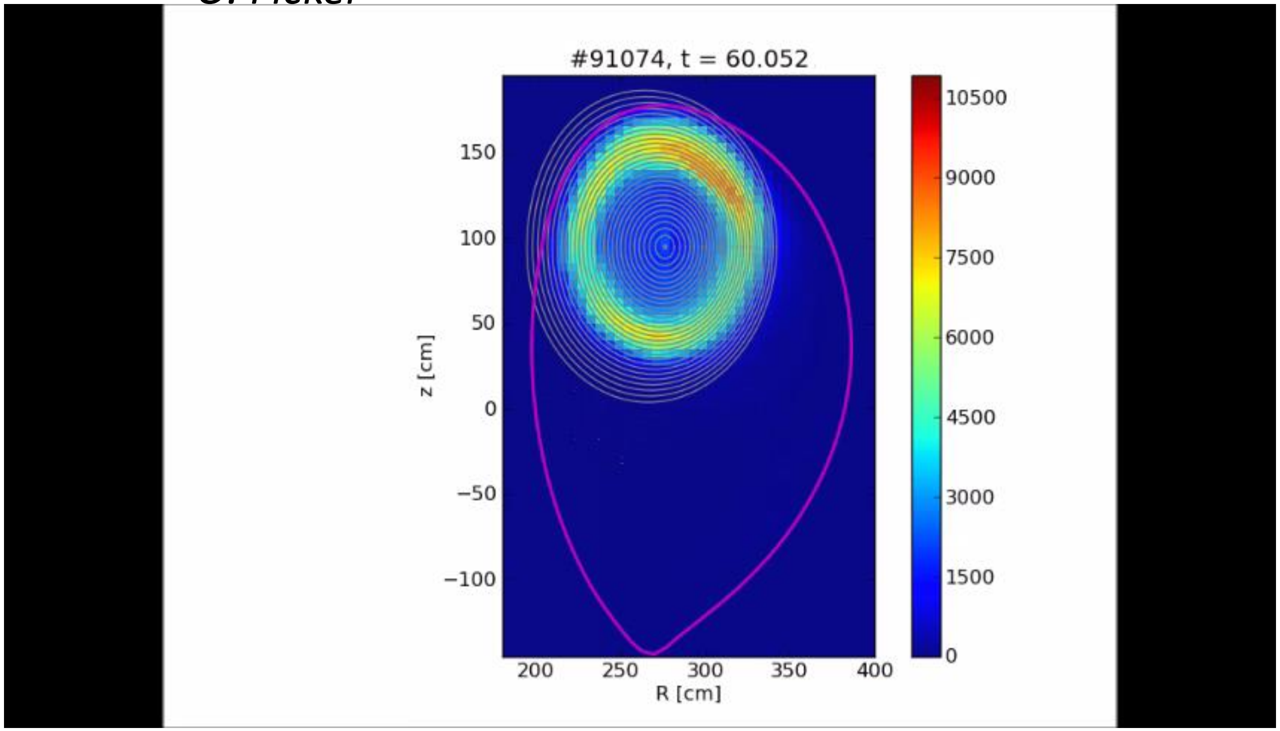
JET – SXR tomography of 2nd DMV

Soft X-ray
- 1-20 keV, braking radiation of electrons, line radiation
- RE beam – gas interaction

Tomography
- MFR - Tikhonov regularization
- 2 cameras used
- Hollow profile – gas cannot get into the beam??

O. Ficker





Low assimilation reported using DMV

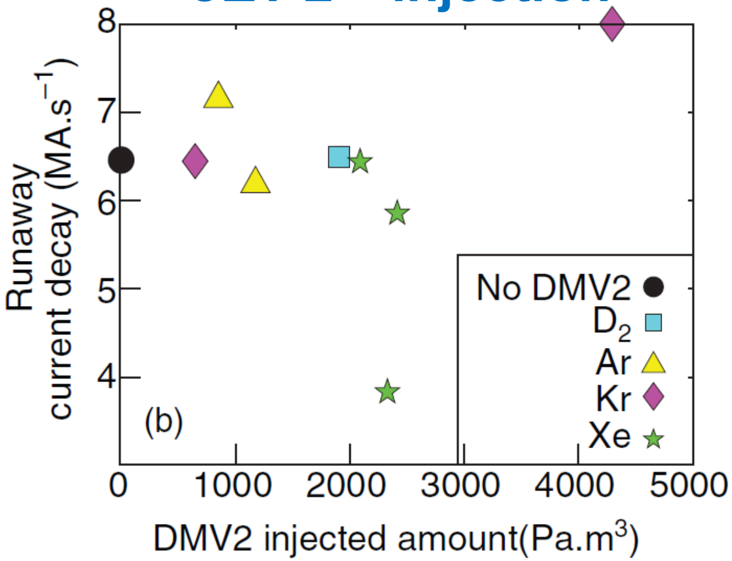
Penetration of impurities is likely to depend on

- Injection parameters (especially injection geometry)
- CQ / RE plasma parameters

Low assimilation reported from experiments

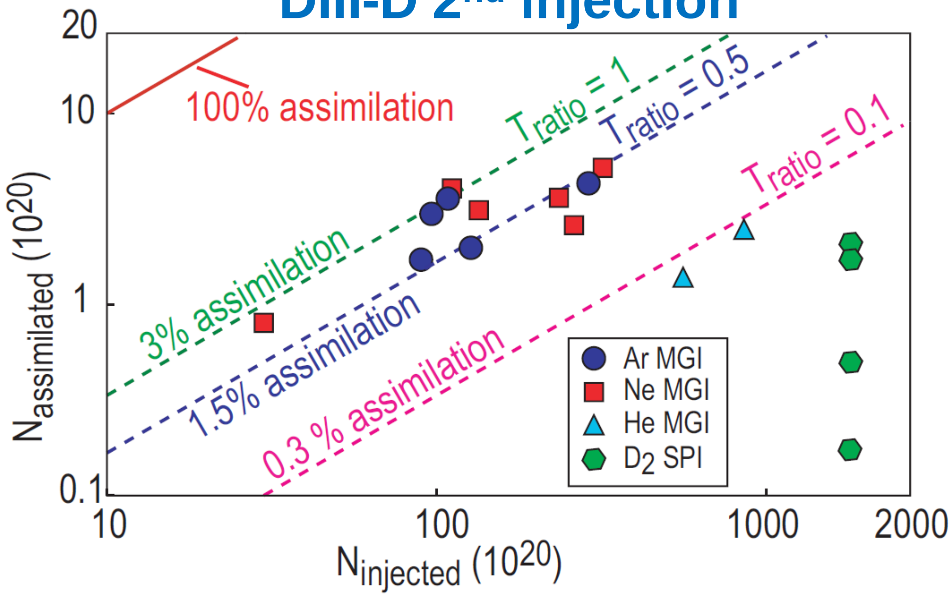
- JET: f_{assim} = 0 (from current decay and n_e)
- DIII-D: f_{assim} = 1 % range (from pressure balance)

JET 2nd injection



C. Reux et al., Nucl. Fusion 2015

DIII-D 2nd injection

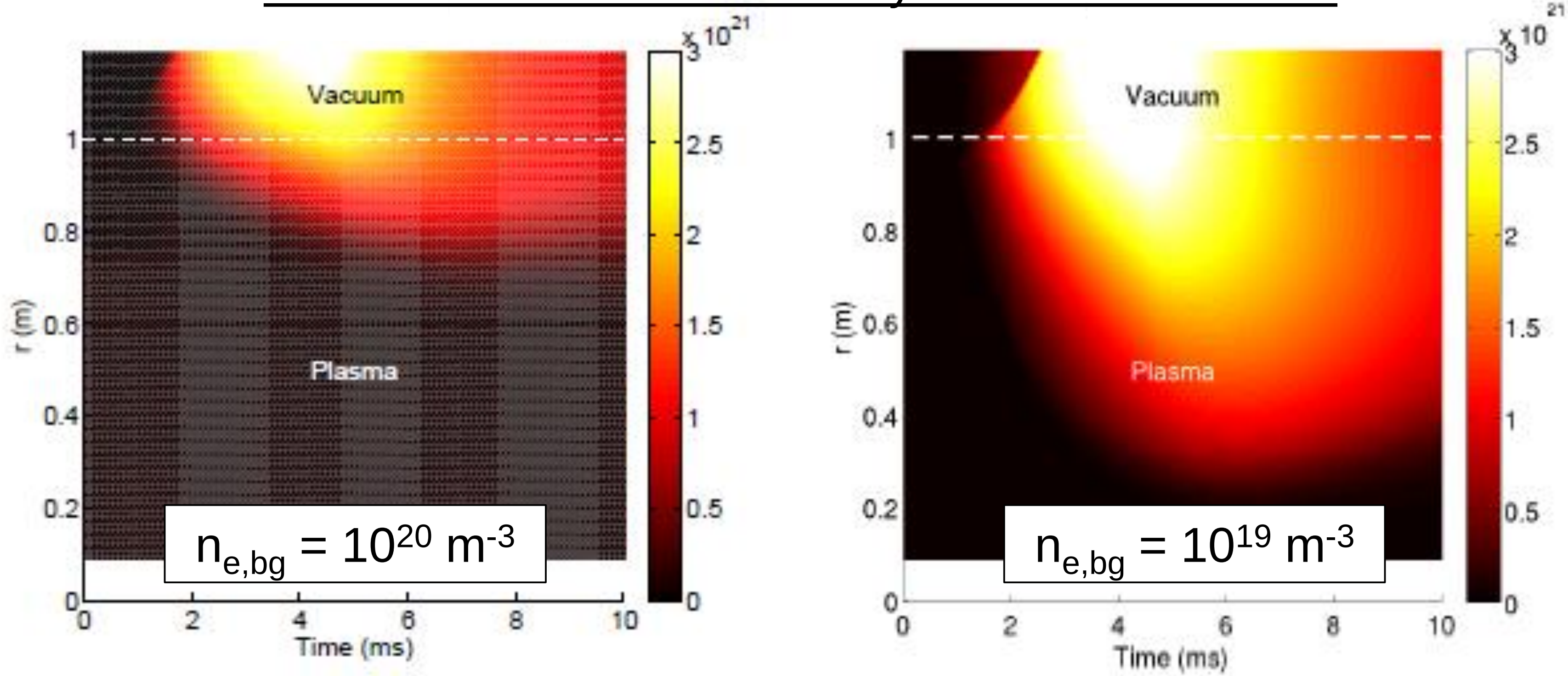


E.M. Hollmann et al., Nucl. Fusion 2013

Simulation are suggesting a role of the background plasma

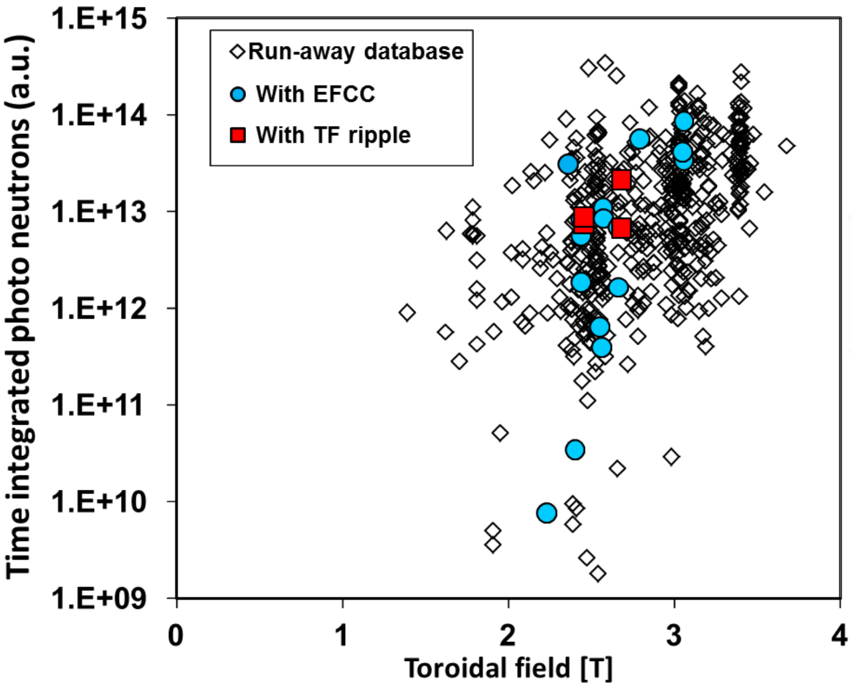
- Works on Tore Supra [Saint-Laurent FST 2012], DIII-D [Hollmann NF 2013] and ASDEX Upgrade [Pautasso EPS 2015] but no effect on JET! [Reux et al., NF 2015]
- A possible explanation supported by simulations: gas cannot reach RE beam because it is **"shielded" by the high density ($n_{e,bg}$ ~ 10^{20} m^{-3}) background plasma**

Free + bound electron density vs. time and radius

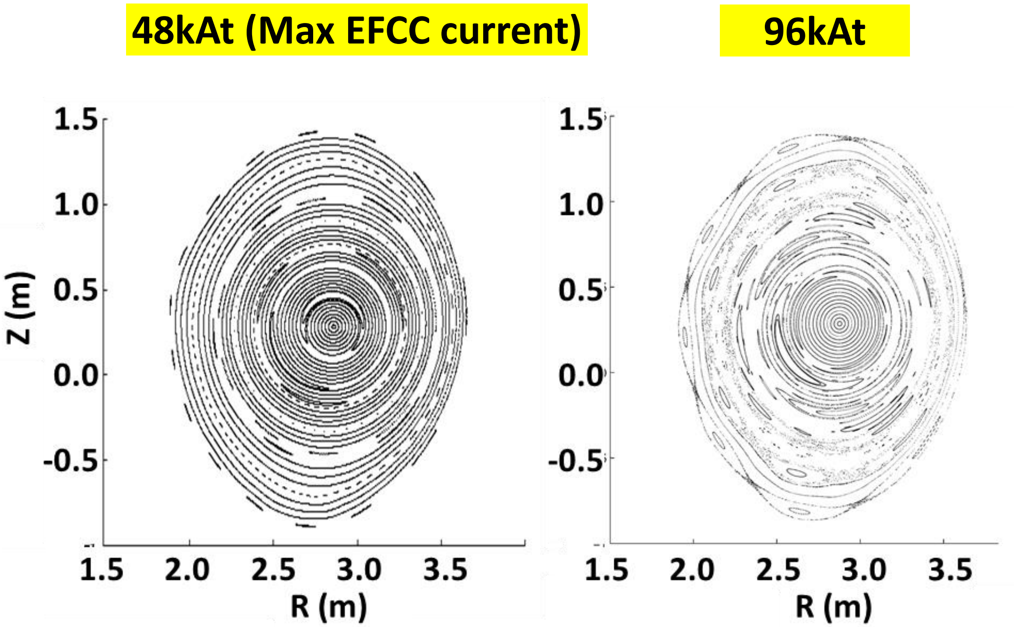


Nardon EPS 2017

In JET magnetic perturbations are inefficient in mitigating run-aways



V. Riccardo, PPCF 2009



R. Paprok, PPCF 2016

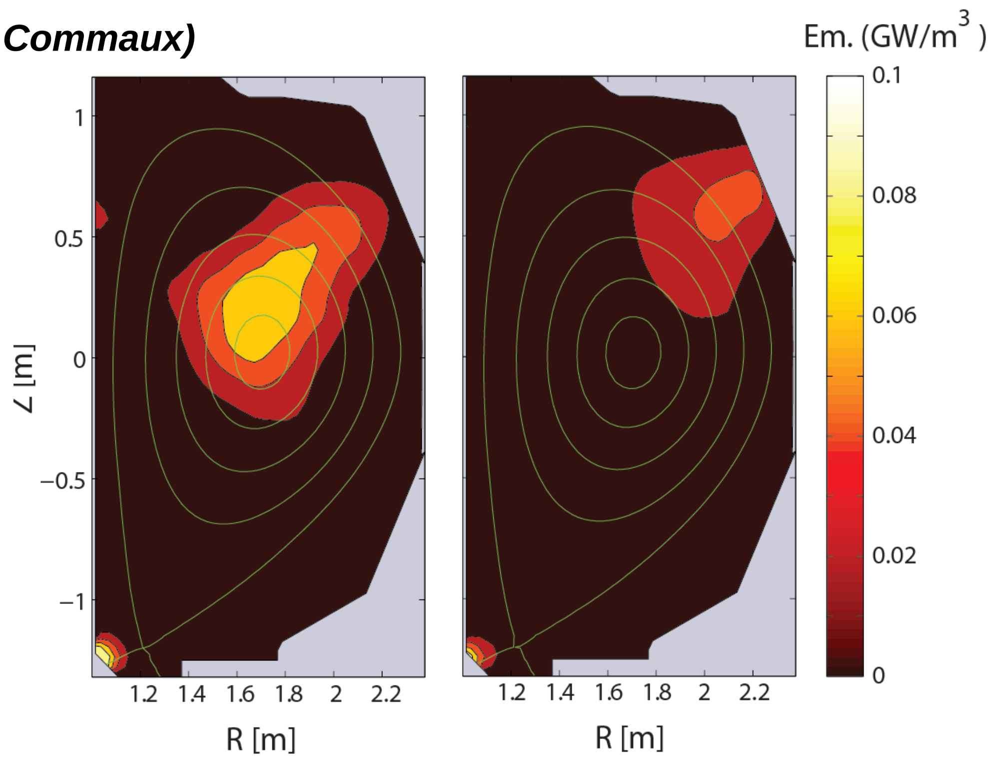
- **EFCC and TF–ripple do not lead to a reduction of RE population in JET**
- **Relativistic (5-20MeV) electron particle motion modelling predicts no stochastization of trajectories at maximum EFCC coil currents.**

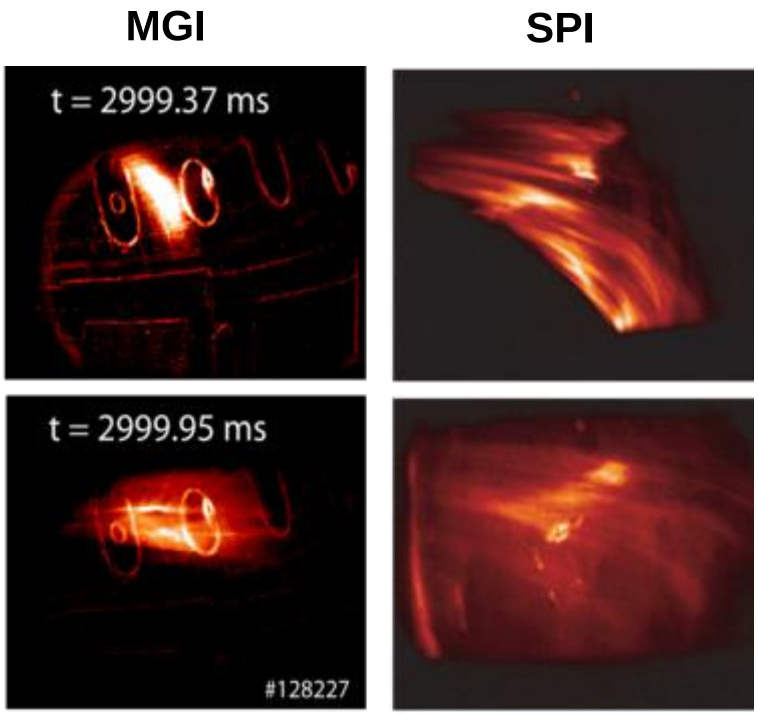
JET

Shattered pellet injected tested on DIII-D

- ❑ Pellet injection (SPI) yields a faster and more efficient particle delivery than massive gas injection (MGI)
- ❑ SPI tested on DIII-D:

(N. Commaux)





Shattered pellet injection has been tested on DIII-D and leads to deeper penetration and higher density assimilation than massive gas injection.

Commaux, et al., Nucl. Fus. 2011

ITER DMS design overview

Baseline System: Shattered Pellet Injection

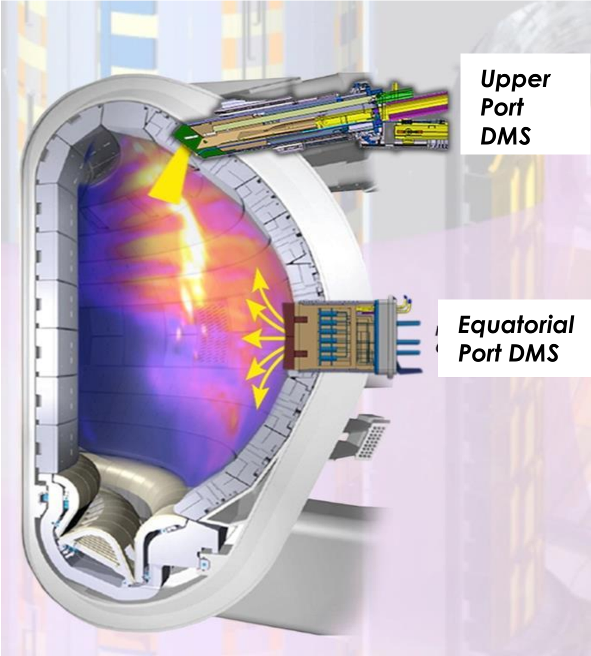
Thermal and electromagnetic load mitigation (TLM):

Ne < 8 $kPam^3$, pre-TQ injection (back-up: early CQ)

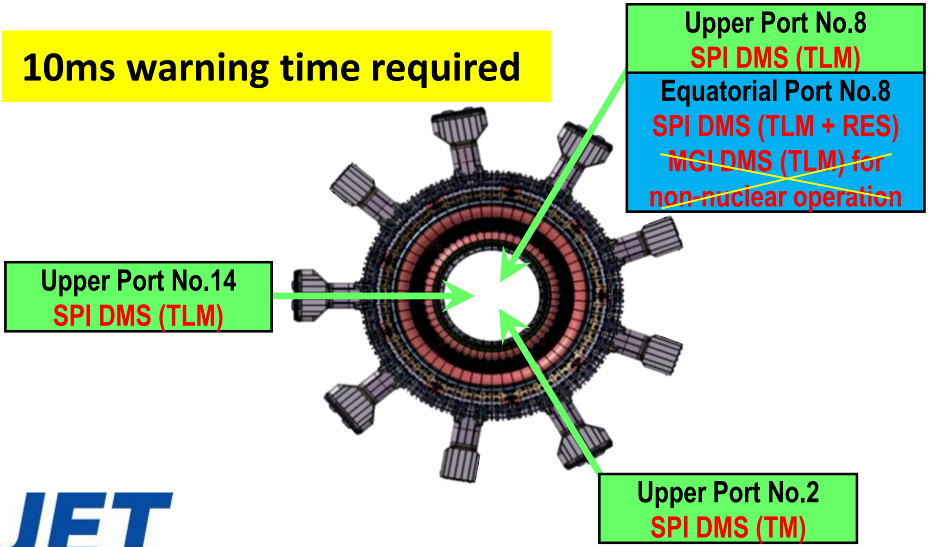
Runaway electron suppression (RES):

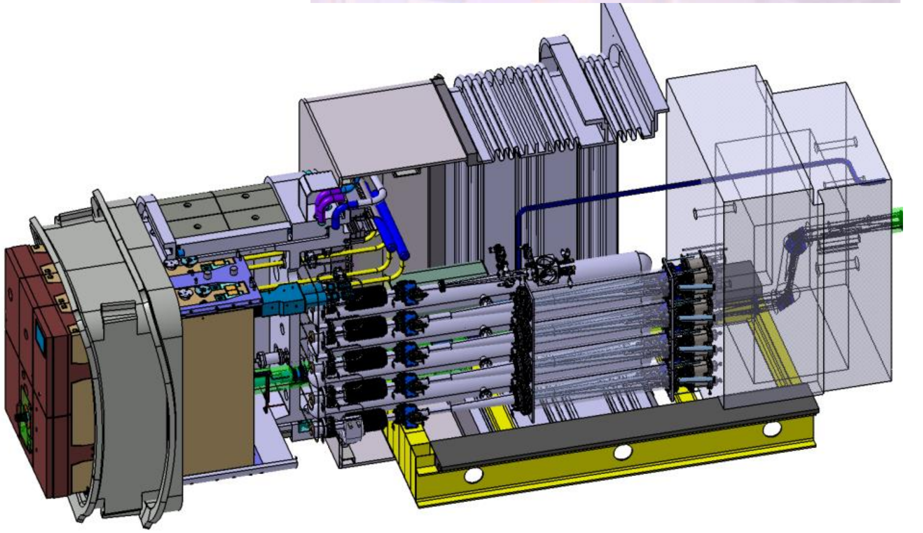
Ar, Ne < 100 $kPam^3$, D_2 < 50 $kPam^3$, pre-TQ for RE suppression, post-TQ for runaway energy dissipation

Significant gaps in physics basis especially on RE mitigation and urgent need for R&D has been identified at the IO Workshop March 2017, report available.



10ms warning time required





Recent ITER STAC statement

- STAC endorses the IO strategy to have shattered pellet injection (SPI) as the primary baseline Disruption Mitigation System (DMS). However, there are concerns that the planned SPI systems may not be able to mitigate runaway electrons, which may cause serious damage to first wall components.

- Since the DMS is of utmost importance for ITER, it should receive the necessary priority over other sub-systems as needed to achieve its technical requirements. The DMS design should not be frozen prematurely and design flexibility should be retained including alternate port allocation, depending on the outcome of the forthcoming DIII-D and JET experiments.

- The STAC recommends that the IO work with the DAs and the ITPA to define an efficient framework for the coordination of the DMS R&D.

SPI installation on JET

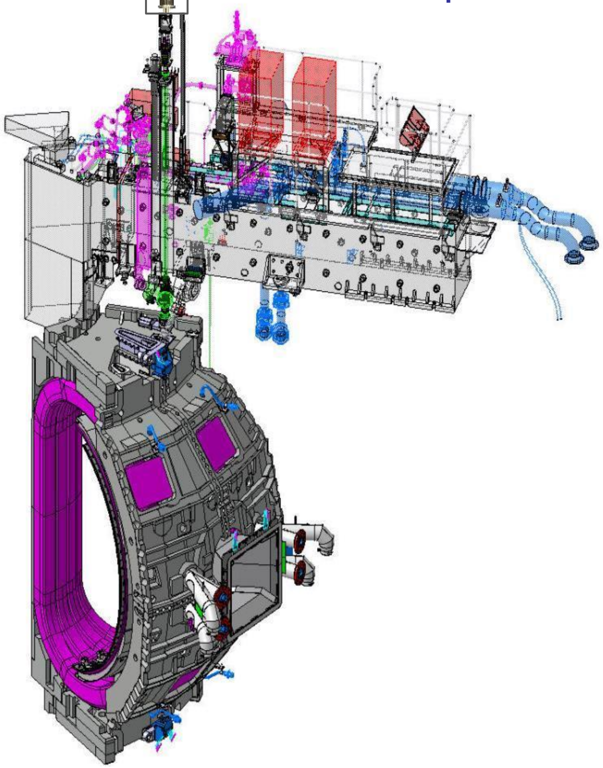
Contractual framework: installation + research programme (17/01/2017)

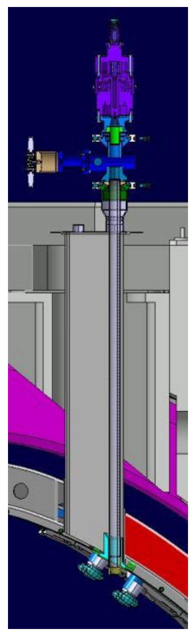
1- European Atomic Energy Community (EURATOM): EUROfusion + CCFE

2- US DOE: ORNL + US ITER Project Office

3- ITER Organisation

SPI to be located on top of machine in place of DMV1



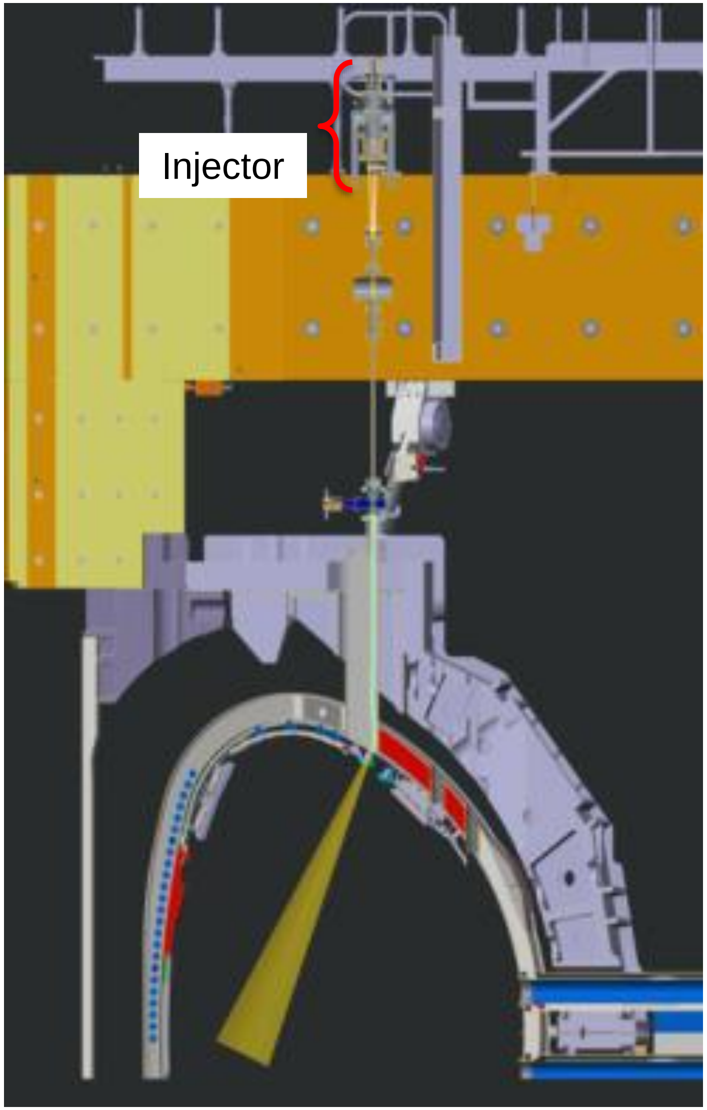


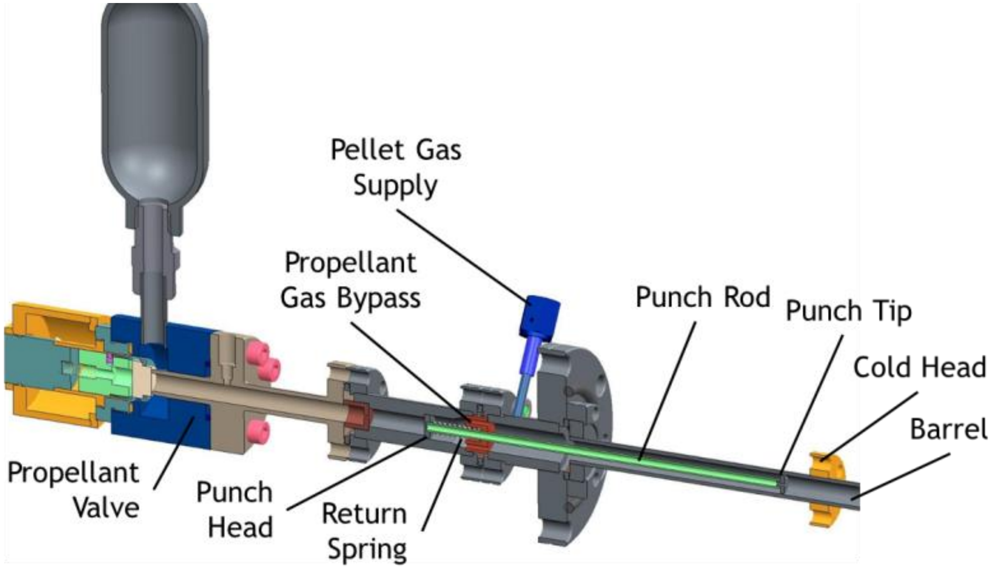
SPI shatter tube fits inside vertical injection line with bend just before entering the plasma.

Must be inserted from above which means a 40mm opening.

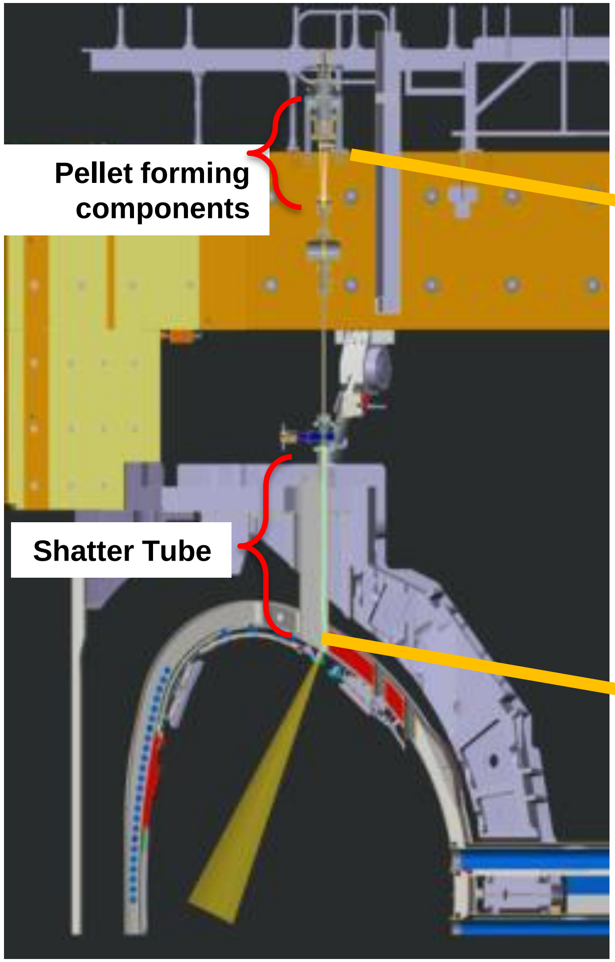
JET

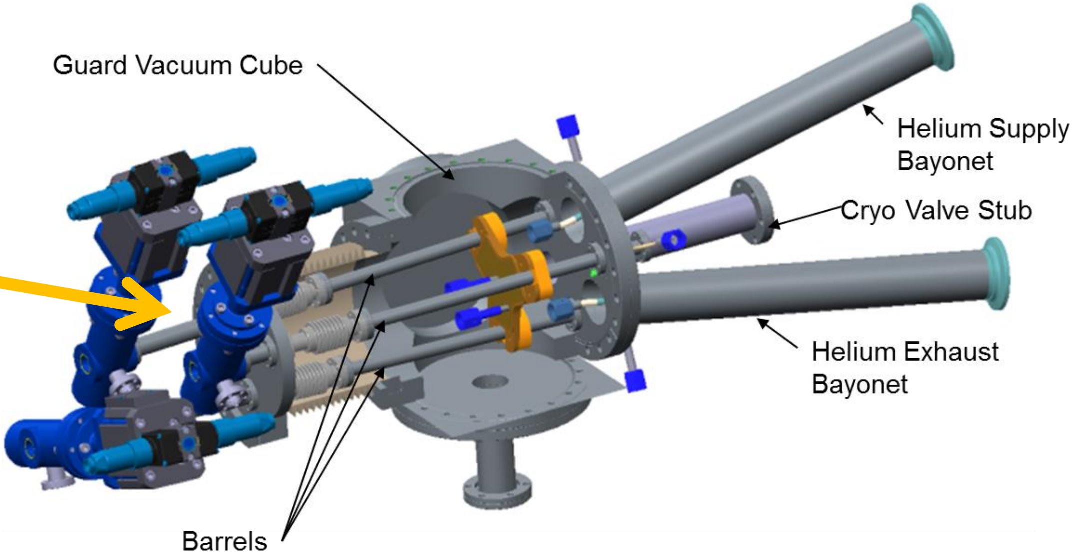
SPI main components (I): the injector

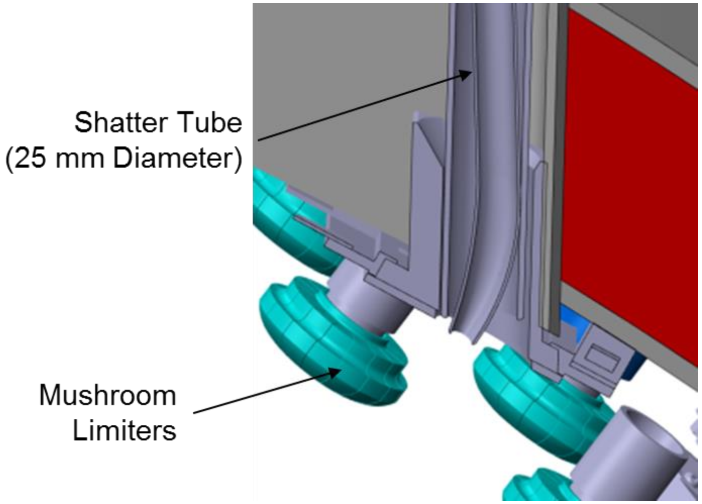




SPI main components (II): Pellets forming component and tube





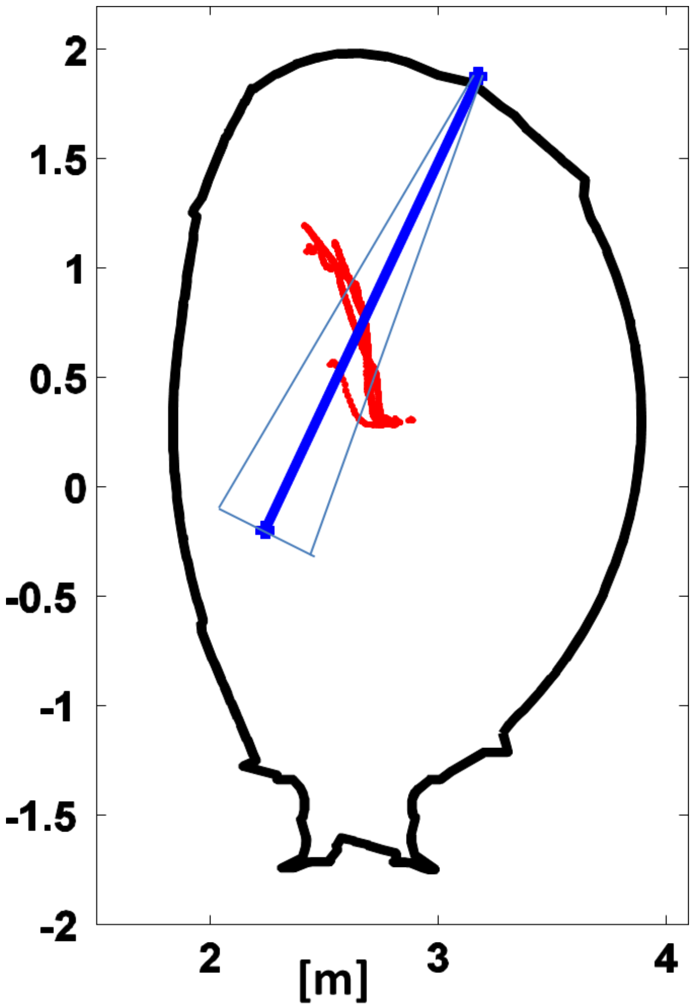


SPI: range of pellets / particle quantities

Barrel No	Diameter [mm]	Length [mm]	Expected range of pellet speed [m/s]	Ar quantity	Ne quantity	D2 quantity
1	12.5	31.25	150-200	9×10^{22}	1.6×10^{23}	2.3×10^{23}
2	8.0	12.0	150-200	1.5×10^{22}	2.6×10^{22}	3.6×10^{22}
3	4.5	5.8	250-500	-	4.0×10^{21}	5.6×10^{21}

- **Different pellet sizes for varying injection quantities to compare with MGI efficiency (~10^{21})**
- **Option to vary the impurity quantity in the pellet by adding deuterium with accuracy below 1%,**
- **Larger quantities of up to 10^{23} are required to perform the studies on runaway energy dissipation.**
- **The maximum argon quantities tested with MGI at JET were around 2×10^{23}.**
- **Note: the SPI is not DT compatible.**

Run-away beam trajectory in the vacuum vessel

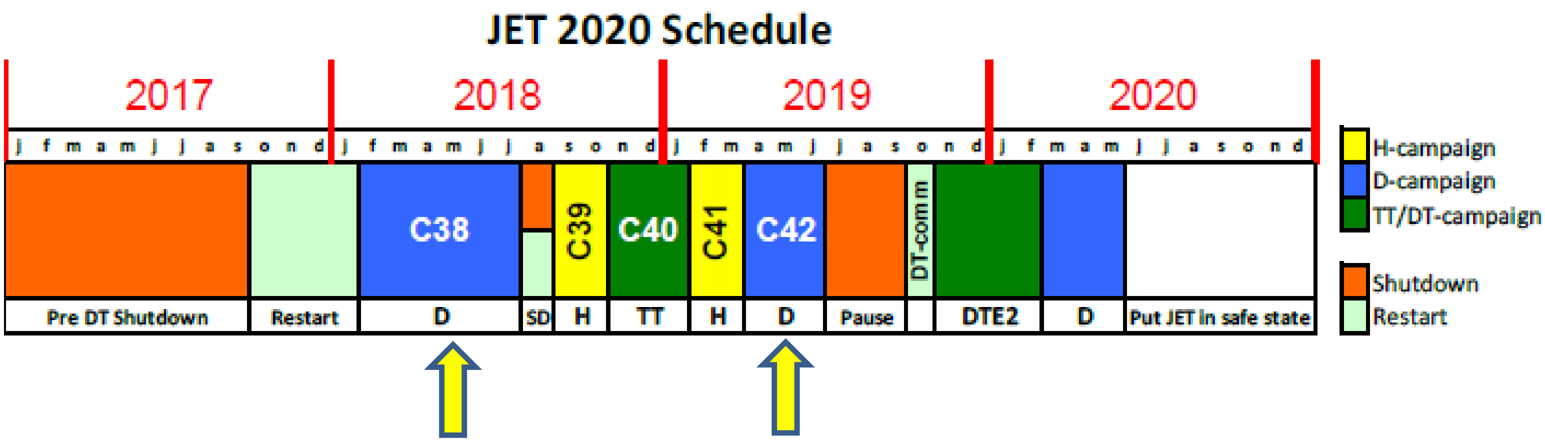


- Trajectory of the run-away beam current centroid measured by the magnetics.
- All data are taken from the current quench time until the end of the run-away beam.
- The beam moves towards the upper –inner board side (where the impacts are also observed)
- The planned cone for the SPI is crossed by the trajectory of the runaway
- All these examples have used DMV1 for generating the RE beam.

- **In November 2016 it has been demonstrated that DMV2 or DMV3 are able to generate a upward-moving beam.**
- **Action is presently on-going to improve the RE beam control in the chamber (2017 Task)**

SPI at JET: programme for 2018 campaigns

Disruption mitigation is one of the <u>top three priorities</u> in the present JET programme of EUROfusion. It will remain so whilst testing SPI on JET.



The objectives of the experimental studies are as follows (as per the contract)

1. **Assess the efficacy of SPI on runaway energy dissipation of a full blown runaway electron beam**
2. **Define the parameter domain for which pre-thermal quench injection with SPI fully prevents runaway electron generation; and**
3. **Assess the efficiency of SPI in preventing heat loads during the thermal and the current quench and in controlling the current quench rate.**

➔ The maximum number of experimental shifts allocated to testing SPI at JET is 16.

JET work organization and agenda

2 Task forces:

Integrated Operating scenario (IOS): J. Mailloux, M. Barruzo, M. Romanelli
Physics and Technology for ITER (PTI): E. Joffrin, D. Borodin, J. Hillesheim, H. Weisen

3 Top objectives:

1- Prepare scenarios for fusion performance and alpha particle physics.
2- Determine the isotopes dependence of H-mode physics, SOL conditions and fuel retention.
3- Quantify the efficacy of SPI versus MGI on runaway and disruption energy dissipation and extrapolate to ITER.

12/05/2017:	Call for proposal (including the SPI). Members of this PB also recipients
04/08/2017:	Deadline for receiving experiment proposals
04/09/2017:	General task force meeting: discussion of priorities of proposals.
End Oct 2017:	Plasma restart
Mid Nov 2017:	Selection of Scientific coordinator and staffing.
Mid Dec 2017:	Staffing finalised
12/02/2017:	Start of C38 deuterium campaign until 27/07/2017

http://users.euro-fusion.org/tfwiki/index.php/Proposals_C38_to_C42

JET

Conclusions / prospects

- For the next 2018-19 experiment campaigns, JET ITER like Wall will be equipped with a comprehensive DMS for studying disruptions and run-away for ITER.

➔ It is therefore essential that the EU and US community working on run-aways put together their efforts in this Programme for contributing to the safe operation of ITER.

➔ An on-going analysis task in the present JET programme is already preparing the analysis and modelling tools for these experiments: you are welcome to join (T17-13: SC: C. Reux).

➔ The JET programme is strongly encouraging your participation and ideas of experiments for 2018-19