

# Progress on the physics basis of the ITER DMS (and more)

PPPL Workshop on Theory and Simulation of Disruptions

Michael Lehnen

*for the ITER DMS Task Force & Design Team*

ITER Organization, Route de Vinon-sur-Verdon – CS 90 046,  
13067 St Paul Lez Durance Cedex – France

ITER is the Nuclear Facility INB no. 174. This presentation explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

The JET SPI experiments have been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.



# Contributors

## JET SPI team

S. Jachmich, U. Sheikh, C. Reux, O. Ficker, L.R. Baylor, G. Bodner, D. Bonfiglio, D. Craven, N. Eidietis, S. Gerasimov, Z. Huang, J.H. Kim, M. Kong, D. Kos, E. Matveeva, E. Nardon, C. Paz-Soldan, A. Peacock, L. Piron, D. Shiraki, S. Silburn, J. Wilson, and JET contributors

*JET SPI experiments are performed in collaboration between EUROfusion and the ITER Organization*



## DMS Task Force

E. Nardon, A. Matsuyama, J. Artola, V. Bandaru, H. Bergström, T. Fülöp, P. Heinrich, J. Herfindal, M. Hoelzl, D. Hu, C. Kim, A. Lvovskiy, S.J. Lee, B. Lyons, Y.S. Na, G. Papp, I. Pusztai, K. Särkimäki, W. Tang, O. Vallhagen

## DMS Design Team & TF technology group

U. Kruezi, M. Dibon, M. Kochergin, L.R. Baylor, D. Dunai, T.E. Gebhart, A. Horvat, F. Millet, M. Roveta, I.V. Vinyar, S. Zoletnik

## ITER

Y. Gribov, L. Chen, A. Loarte, R. Pitts

# Artificial Intelligence

Present pellet size is 28.5 mm, there may be reasons to reduce their size

Q: What are the optimum pellet sizes for shattered pellet injection in ITER for injections before the thermal quench, after the thermal quench, and into runaway electron beams? What is the justification for the choice of these optimum pellet sizes?

ChatGPT:

As of my knowledge cutoff in September 2021, I don't have specific information on the optimum pellet sizes for shattered pellet injection in ITER for different scenarios [...]

The optimum pellet size for shattered pellet injection depends on several factors, including plasma parameters, magnetic field strength, plasma density, and the desired effect on the plasma. Researchers and scientists perform extensive studies, simulations, and experiments to determine the most effective pellet sizes for different scenarios.

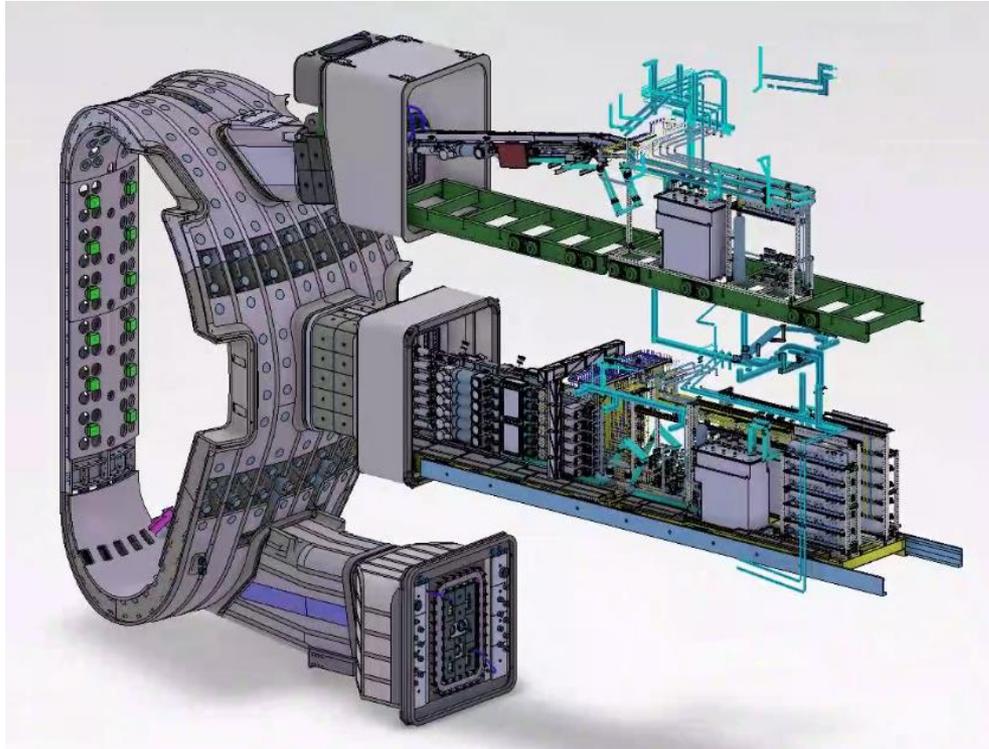
To obtain the most up-to-date and accurate information regarding optimum pellet sizes for shattered pellet injection in ITER, I recommend referring to scientific publications, research papers, and the latest experimental data from the ITER project. Additionally, contacting experts or organizations involved in the ITER project, such as the ITER Organization or associated research institutions, would provide the most current information on this specific topic.

# Outline

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**Impact of ITER re-baselining on the strategy for disruptions**  
**Present DMS design & technology development**  
**Experiment & Modelling efforts of the DMS Task Force**

# DMS design status



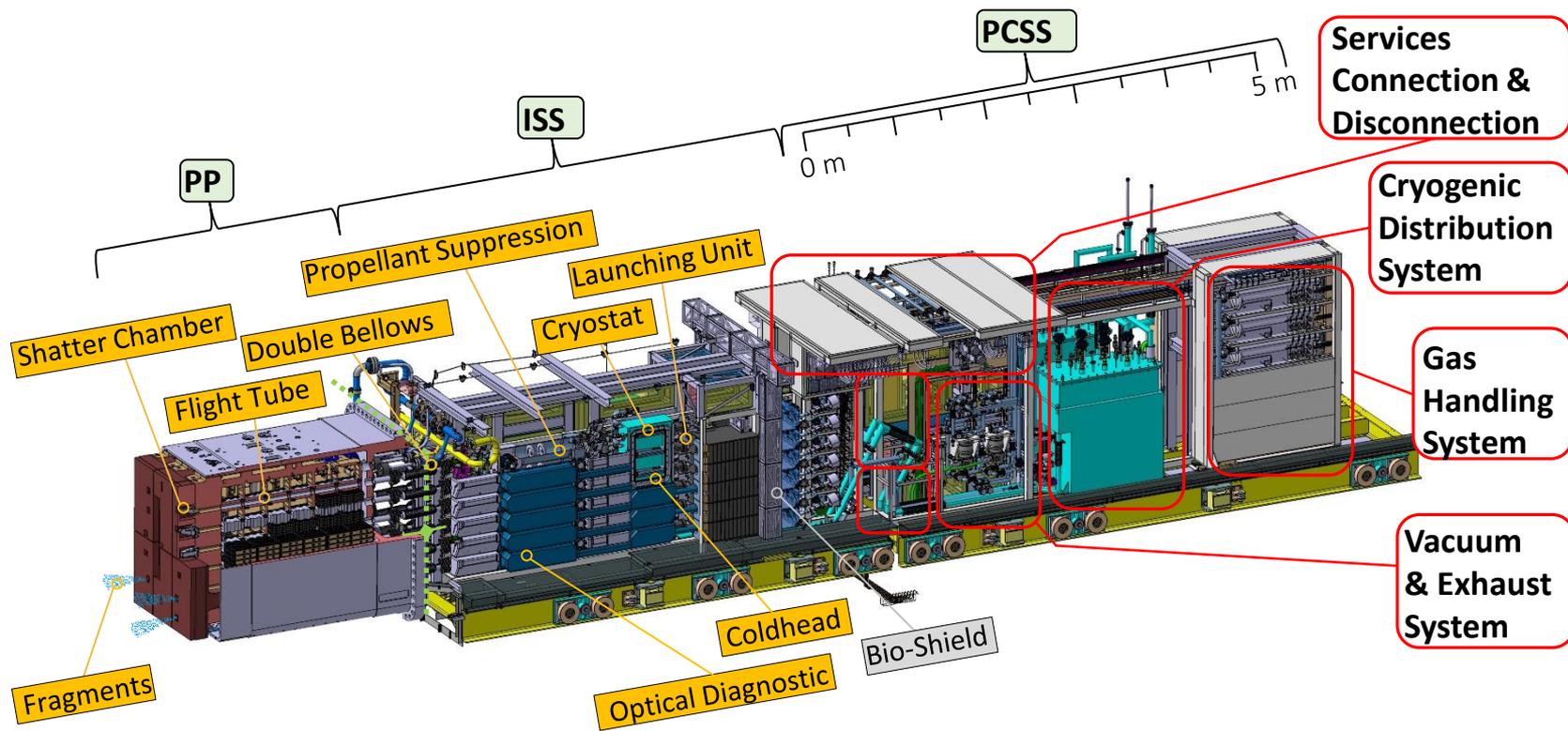
DMS Final Design Review  
Meeting rescheduled to  
**March 2024**

UP #02, #08, #14  
(post-TQ for CQ mitigation):  
each 1 injector

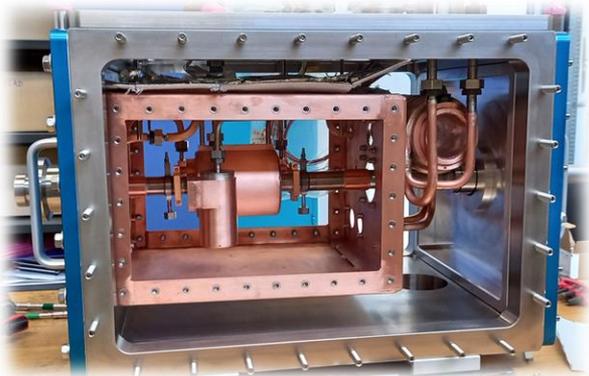
EP #02, #08, #17  
(pre-TQ & RE mitigation):  
total of 24 injectors

# DMS design status

## Present design for port plug EP#02

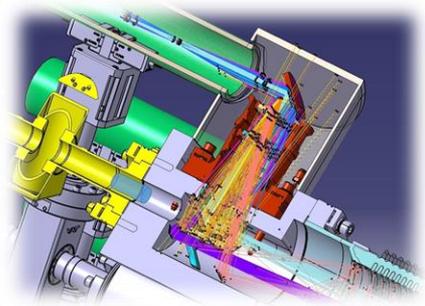
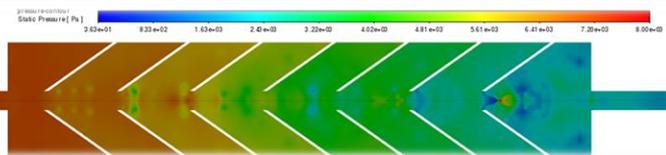


# DMS Technology Task Force - Activities



Cryostat and cold head to perform fundamental studies  
(CEA-Grenoble, France)

gas flow modelling for  
propellant suppressor  
(CASPU, UK)

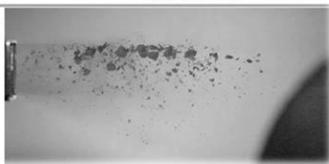


OPD front end optics  
(Fusion Instruments, Hungary)

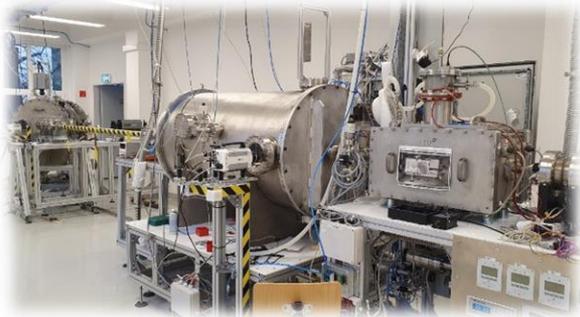
Simulation



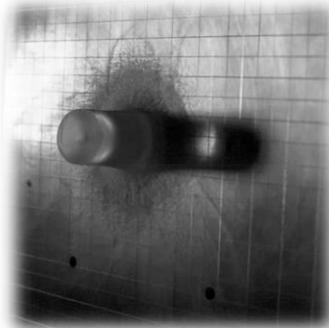
Experiment



Support Laboratory for  
component testing  
(EK-CER, Hungary)



pellet impacting target for  
trajectory measurements  
(ORNL, US)



Simulation of pellet fragmentation validated  
against experiments (EMI-Fraunhofer, Germany)

# DMS technology development

- ITER DMS technology meeting held 8-9 February 2023 at IO
  - Pellet Formation & Launching
  - Propellant Gas Suppression
  - Optical Pellet Diagnostic
  - Pellet flight accuracy
  - Shattering
  - Alignment diagnostic
  - Alternative Techniques

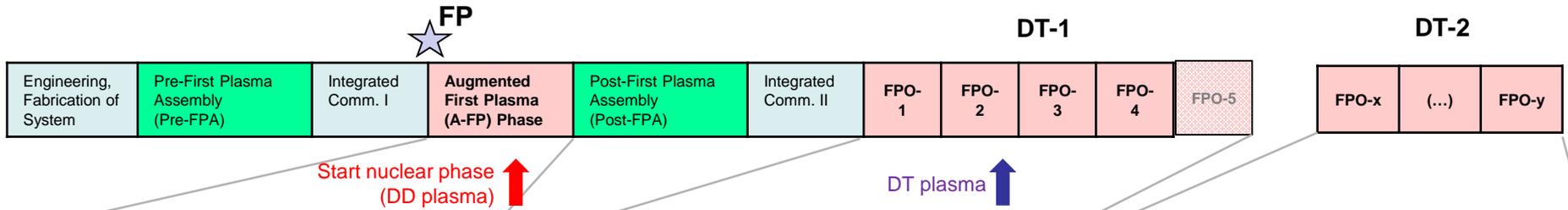


*Contact S. Jachmich for further information*

# New ITER Baseline

- Three scenarios were explored of which one was selected by IO and proposed to the ITER Council
- This new scenario will be further elaborated and presented to the September STAC and at the November Council meeting
- Main features of the new scenario:
  - Augmented First Plasma Phase with inertially cooled first wall and plasma operation up to 15 MA
  - Two main DT phases with multiple campaigns
  - Change of first wall material from beryllium to tungsten

# New ITER Baseline



- Operation up to 15 MA / 5.3T
- 40 MW EC heating
- 5 MW IC Wall Conditioning (upgradable to 20 MW for DT)
- PCS and DMS commissioning

- DT operation with limited neutron fluence (nuclear licence I)
- 67 MW EC heating
- 33 MW NBI

- DT operation with full neutron fluence (nuclear licence II)
- Possible NBI upgrade to 50 MW

## Opportunities

- Avoid Be handling and assembly difficulties
- FW more resilient to transient heat loads (PCS, DMS and ELM-control commissioning in AFP)
- Reactor relevant FW (change to W anticipated)
- Merge of FP with first experimental campaigns

## Challenges

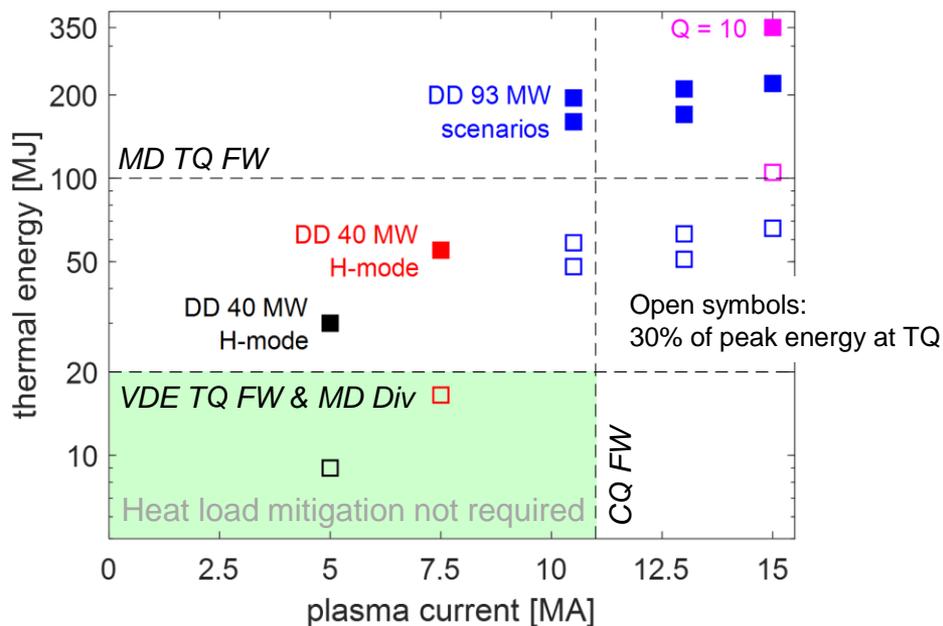
- Plasma start up difficult with W
- Boronization is mandatory and needs to be implemented in ITER
- B layers retain T → fuel removal scheme required
- Risk for Q=10 due to enhanced radiation losses

# ITER New Baseline – strategy for disruptions

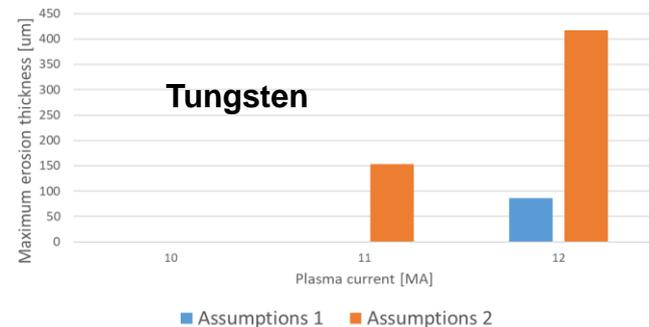
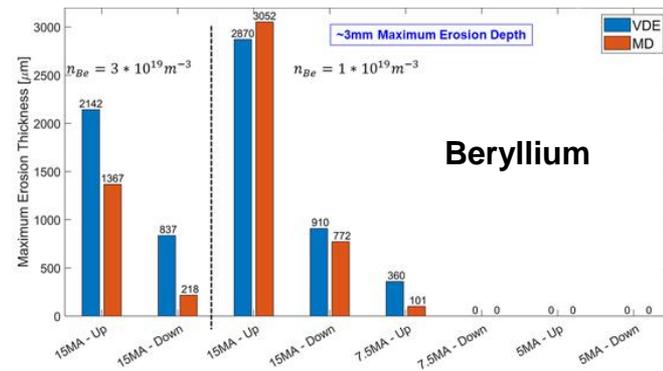
- AFP will allow to commission the DMS and extensively test all mitigation schemes before machine activation and implementation of water cooled FW components
- W first wall will be more resilient with respect to thermal loads during the CQ
- RE impact is not mitigated by changing to W if 8 mm thickness is kept  
→ *larger thickness appears possible and would allow testing the RE mitigation scheme (H SPI into RE beams)*
- Trace T in H plasmas of FPO-1 will allow validating strategies for RE avoidance with beta decay seeds

# New Baseline – consequences for disruptions

- CQ melting avoidance up to 11-12 MA with W wall
- TQ melt limits ~2 times higher
- DMS radiation flash load no issue for W, but still relevant for SS diagnostic FW and diagnostics/heating components



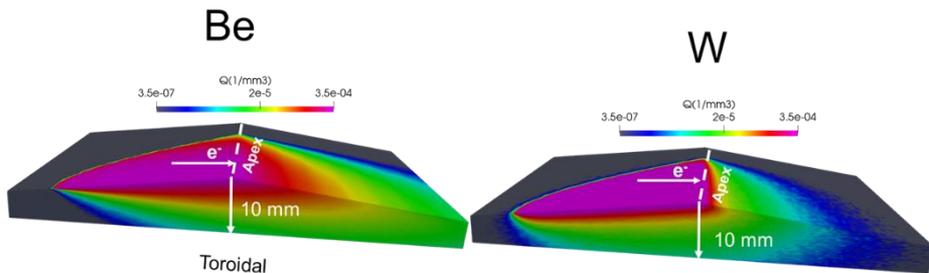
## MEMOS-U simulations



# New Baseline – consequences for disruptions

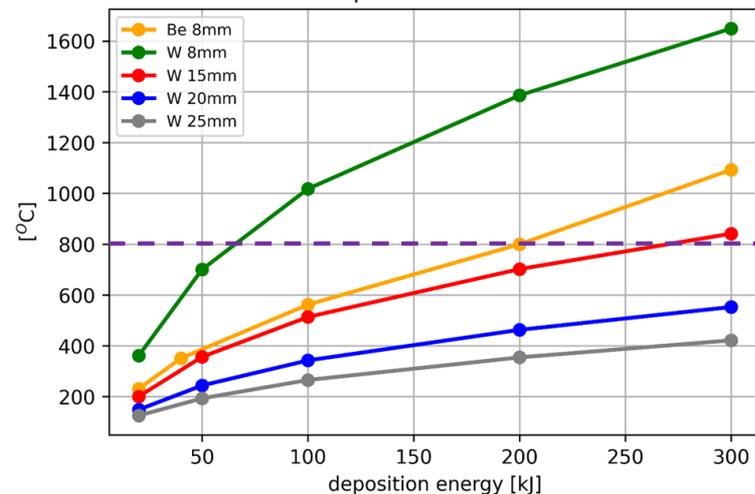
- W has higher stopping power → more localised loads
- Higher heating at cooling interface for W → RE mitigation should be developed with inertially cooled W PFCs (AFP)

SMITER-GEANT-MEMOS-U workflow



L. Chen, R. Pitts

Max. temp. at W/Be-Cu interface



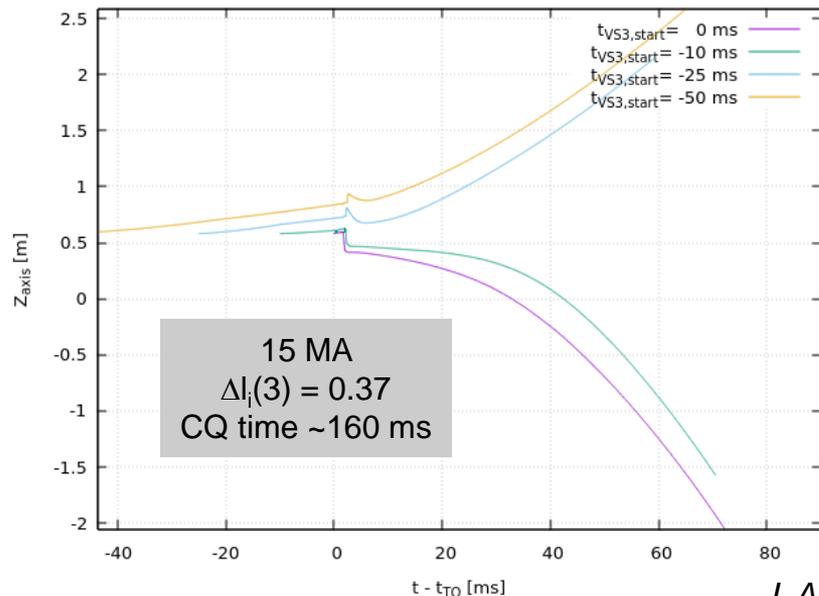
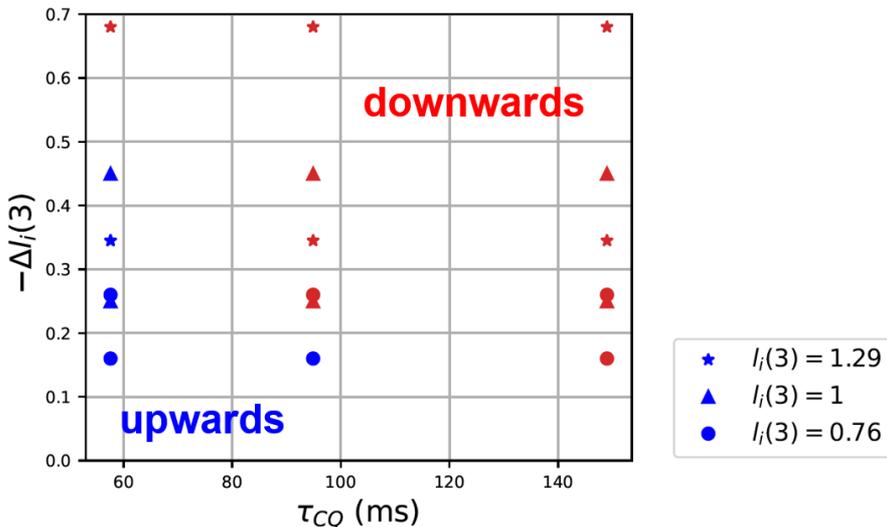
Threshold for cooling channel integrity with 8 mm W ( $T \approx 800^\circ\text{C}$ ):

~70 kJ / roof → toroidal wetting 30% →  $I_{RE} = 0.4 - 1.6$  MA (1 & 100 ms impact)

# New Baseline – consequences for disruptions

- Disruptive plasmas (or plasmas for DMS commissioning) in AFP must deposit energy (and REs) on inertially cooled wall to avoid W divertor damage
- Passive schemes not viable ( $\Delta I_i$  moves plasmas down) → use of VS3 to trigger upwards movement (needs warning time  $> 10$  ms)

## JOREK simulations from DINA scenarios



J. Artola

# DMS Physics Basis - Experiments

- JET SPI experiments to be completed in July/August  
35 (!) sessions in 2023  
*(talks by C. Reux and U. Sheikh and next slides for non-RE exp's)*
- DIII-D: 1.5 run days completed in 2023  
*(talk by A. Lvovskiy, but on earlier experiments)*
- ASDEX Upgrade: ITER experiments completed in 2022  
SPI hardware remains on AUG for next campaign *(talk by P. Heinrich)*
- KSTAR: ITER experiments completed in 2022  
SPI will be tested offline during shutdown  
*(initial results presented at APS 2021 by J-H. Kim)*

# JET SPI experiments 2023

## Tasks

- 1) *SPI assimilation physics*
- 2) *Multiple SPI scenarios*
- 3) *Effect of q-profile and edge stochastization*
- 4) *Influence of intrinsic impurities*
- 5) *Impact of plasma instabilities*
- 6) *Radiation asymmetries*
- 7) *Benign RE termination*
- 8) *RE generation*

Loads of data, here just a very limited selection.

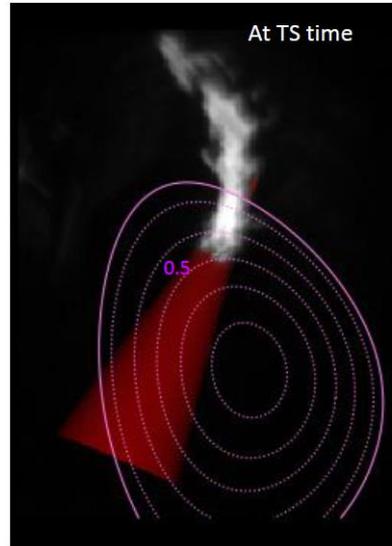
All data shown is preliminary!

# JET SPI experiments 2023

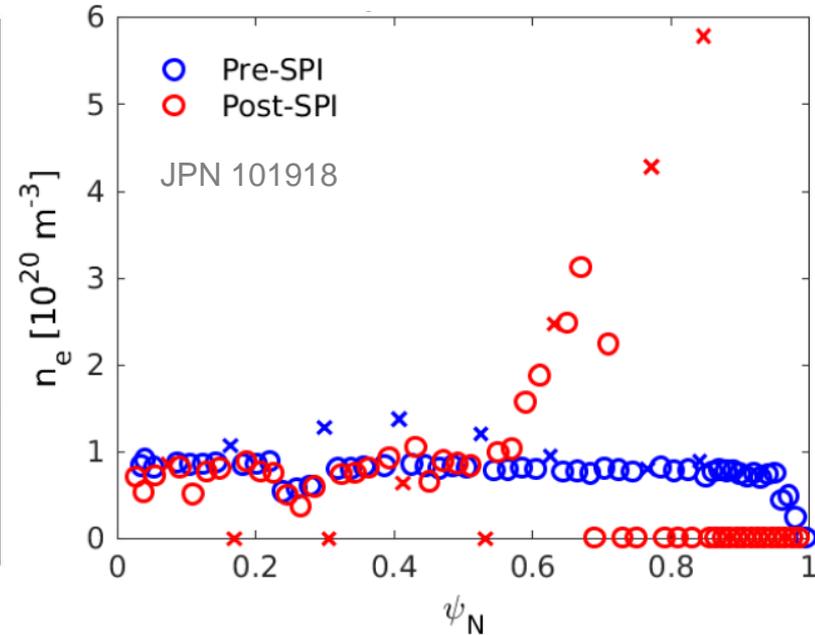
## Tasks

- 1) *SPI assimilation physics*
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Fast camera  
→ particle source



Thomson Scattering  
→ edge density rise



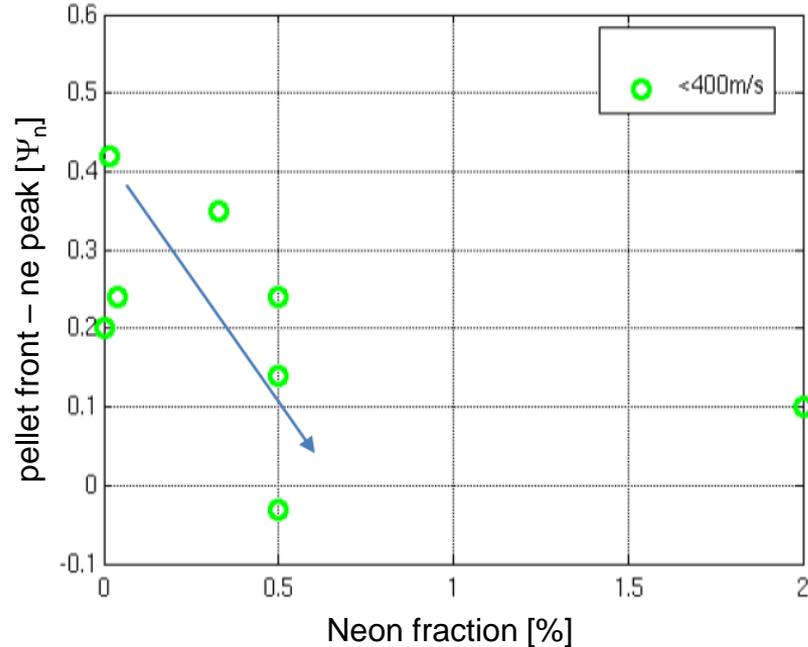
Note: SPI in JET from top to the HFS → plasmoid drift carries mass towards the core

# JET SPI experiments 2023

## Tasks

- 1) *SPI assimilation physics*
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Ne admixture reduces difference between ablation location and density peak  $\rightarrow$  plasmoid drift mitigation

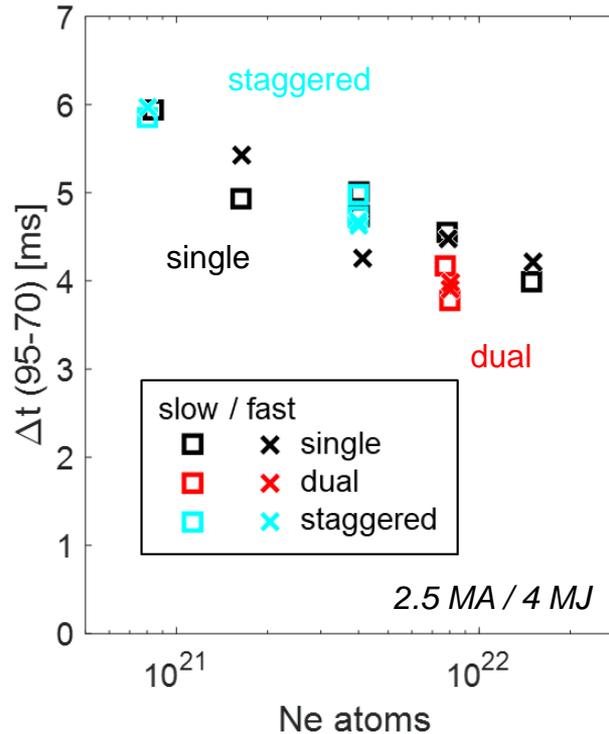


# JET SPI experiments 2023

## Tasks

- 1) SPI assimilation physics
- 2) Multiple SPI scenarios
- 3) Effect of  $q$ -profile and edge stochastization
- 4) Influence of intrinsic impurities
- 5) Impact of plasma instabilities
- 6) Radiation asymmetries
- 7) Benign RE termination
- 8) RE generation

Early CQ as proxy for assimilation



## Single Ne/D SPI

- No impact of velocity on CQ duration  $\rightarrow$  similar assimilation

## Staggered SPI

- CQ unchanged despite Ne is injected into dilution cooled target ( $T_e$  a few 100 eV)  $\rightarrow$  lower Ne assimilation may be compensated by higher density

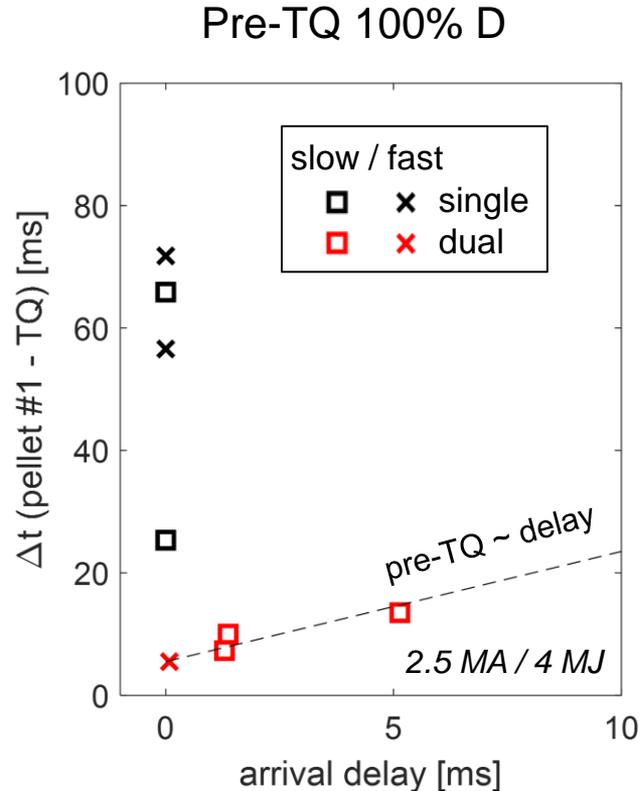
## Dual Ne/D SPI

- Faster CQ  $\rightarrow$  higher assimilation

# JET SPI experiments 2023

## Tasks

- 1) SPI assimilation physics
- 2) *Multiple SPI scenarios*
- 3) *Effect of q-profile and edge stochastization*
- 4) *Influence of intrinsic impurities*
- 5) *Impact of plasma instabilities*
- 6) *Radiation asymmetries*
- 7) *Benign RE termination*
- 8) *RE generation*



## Single D SPI

- Long pre-TQ, but large spread

## Dual D SPI

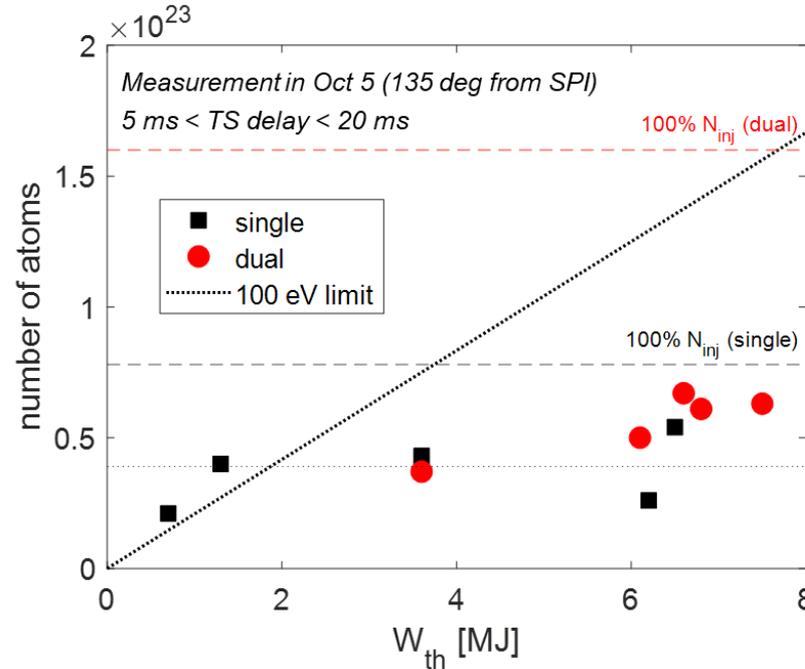
- Short pre-TQ  
→ Implications for timing of Ne/D in staggered SPI

# JET SPI experiments 2023

## Tasks

- 1) SPI assimilation physics
- 2) Multiple SPI scenarios
- 3) Effect of q-profile and edge stochastization
- 4) Influence of intrinsic impurities
- 5) Impact of plasma instabilities
- 6) Radiation asymmetries
- 7) Benign RE termination
- 8) RE generation

## D SPI assimilation from TS



**Single:** ~50 % assimilation  
**Dual:** slightly more assimilation compared to single, but < 50 %

Caution: 3D effects not taken into account!

Dotted line:

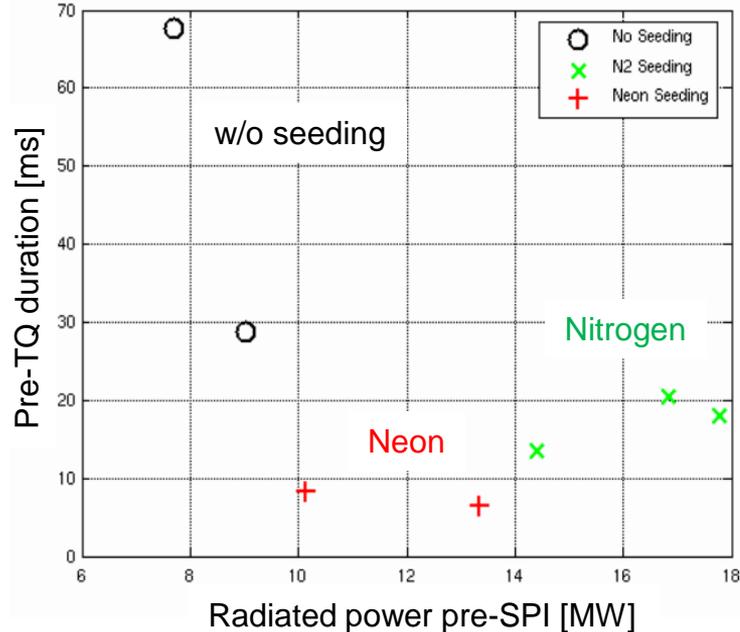
$$\Delta N \approx \frac{E_{th}}{3kT_{lim}}$$

# JET SPI experiments 2023

## Tasks

- 1) SPI assimilation physics
- 2) Multiple SPI scenarios
- 3) Effect of q-profile and edge stochastization
- 4) Influence of intrinsic impurities
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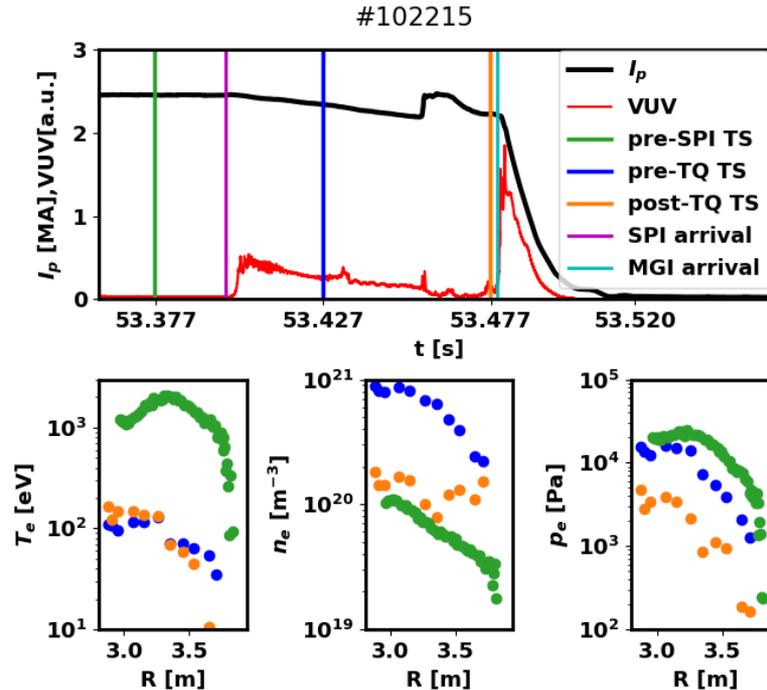
Pre-TQ significantly shortened for D SPI into seeded scenarios  
→ Consequences for multiple SPI scenarios



# JET SPI experiments 2023

## Tasks

- 1) SPI assimilation physics
- 2) Multiple SPI scenarios
- 3) Effect of  $q$ -profile and edge stochastization
- 4) Influence of intrinsic impurities
- 5) *Impact of plasma instabilities*
- 6) Radiation asymmetries
- 7) Benign RE termination
- 8) RE generation



Pre-TQ duration and density rise similar w/ and w/o tungsten accumulation

Can be explained by flat response on  $T_e$  of W radiation

# DMS Physics Basis - Modelling activities

## IO collaborations

- SPI assimilation (INDEX, QST) *completed*
- SPI scenarios (M3D-C1, NIMROD, General Atomics) *ongoing*
- SPI scenarios (JOEKK, Beihang University) *ongoing*
- RE avoidance (DREAM, Chalmers University) *completed* ➔ talk by T. Fülöp
- RE mitigation (JOEKK + RE fluid, IPP Garching) *completed*
- AUG SPI (JOEKK, IPP Garching) *ongoing*
- KSTAR SPI (JOEKK, Seoul National University) *ongoing*

*Additionally liaison with modelling activities in domestic programmes through regular meetings coordinated by E. Nardon and A. Matsuyama*

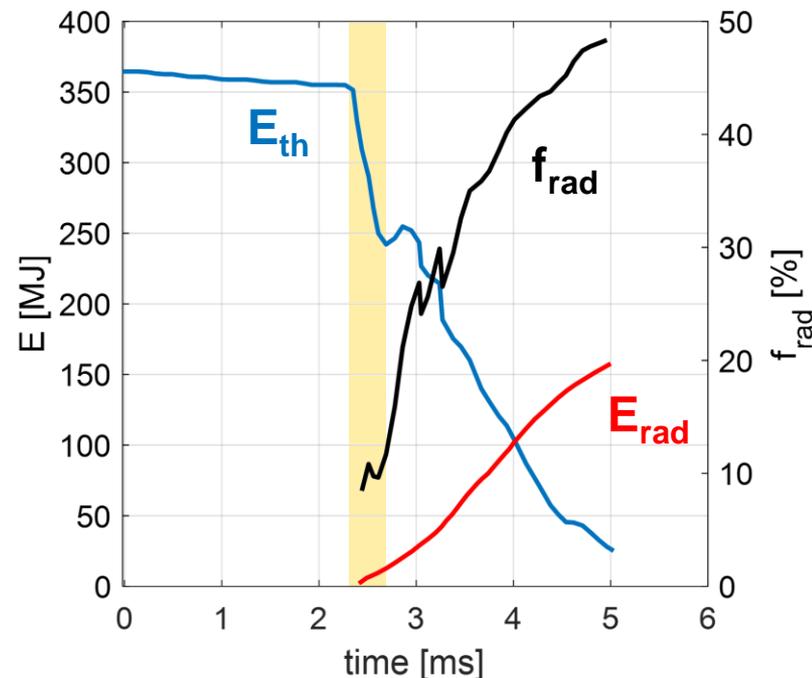
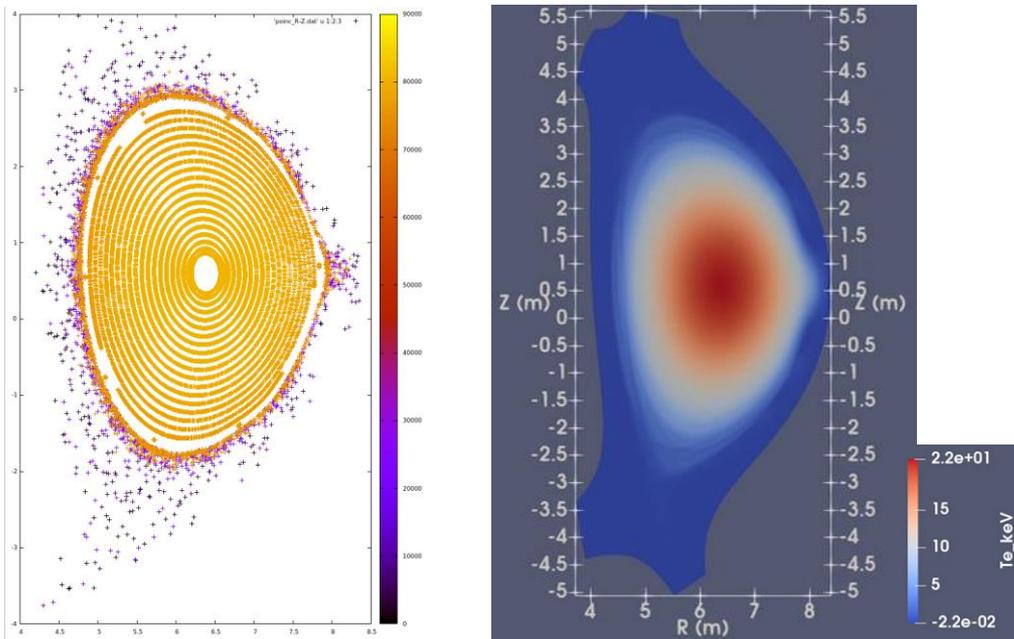
# DMS Physics Basis – JOEUK ITER SPI

D. Hu

## 3D H-mode simulation of dual SPI with $5 \times 10^{22}$ Ne atoms

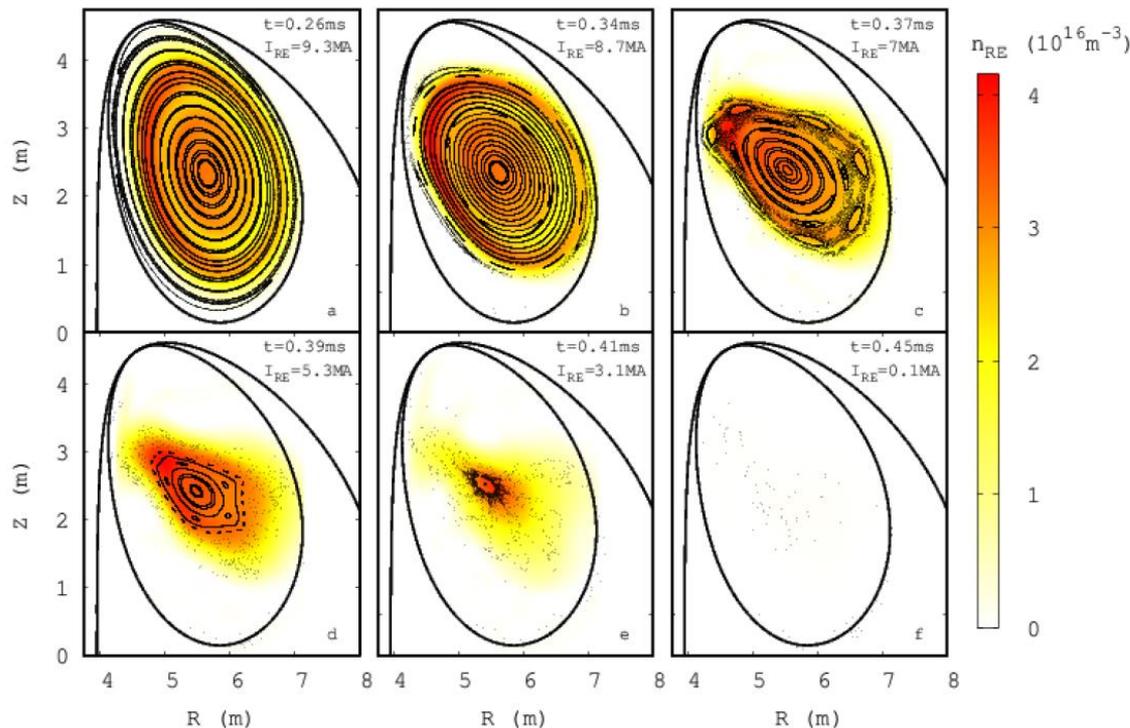
Plasmoid drift observed when the fragments from the first pellet reaches the pedestal

Initial  $W_{th}$  drop not radiated  
Total  $f_{rad} \approx 50\%$



# DMS Physics Basis – JOEAK RE mitigation

## RE loss at 10 x Spitzer resistivity



3D simulations of the termination phase @  $q=2.2$  with  $n=1..5$

Tested impact of

- Increase in resistivity
- Decrease of ion density

Both lead to reduction in RE population at end of loss phase  
→ Supports H SPI induced recombination recipe

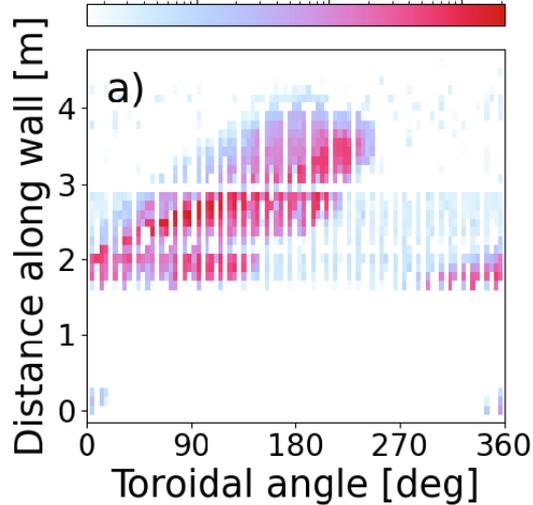
But: in all test cases RE loss is not complete and reformation occurs when flux surfaces heal

*V. Bandaru, M. Hoelzl, K. Särkimäki, H. Bergström, IO report*

# DMS Physics Basis – JOEKE RE mitigation

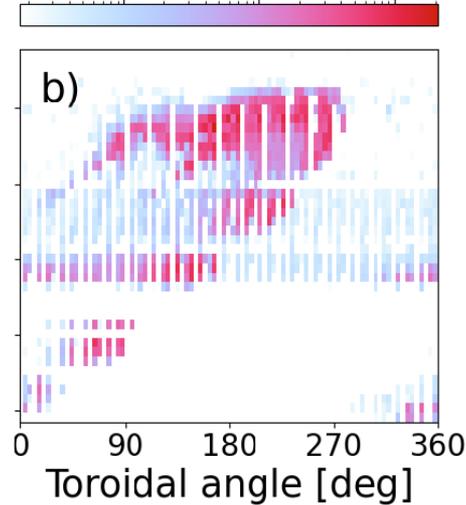
**3 x Spitzer**

Energy load  $\text{J/m}^2$   
 $10^5$   $10^6$   $10^7$



**10 x Spitzer**

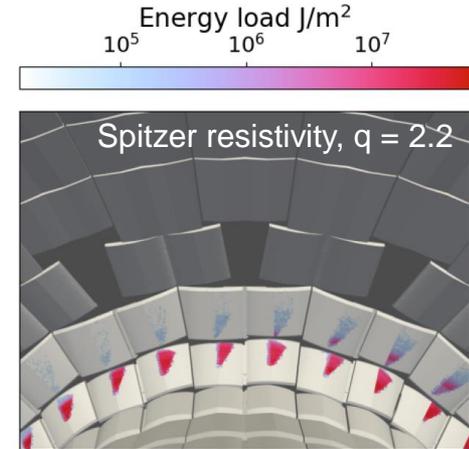
Energy load  $\text{J/m}^2$   
 $10^5$   $10^6$   $10^7$



Energy load more spread for higher resistivity

Peak energy densities are not reduced

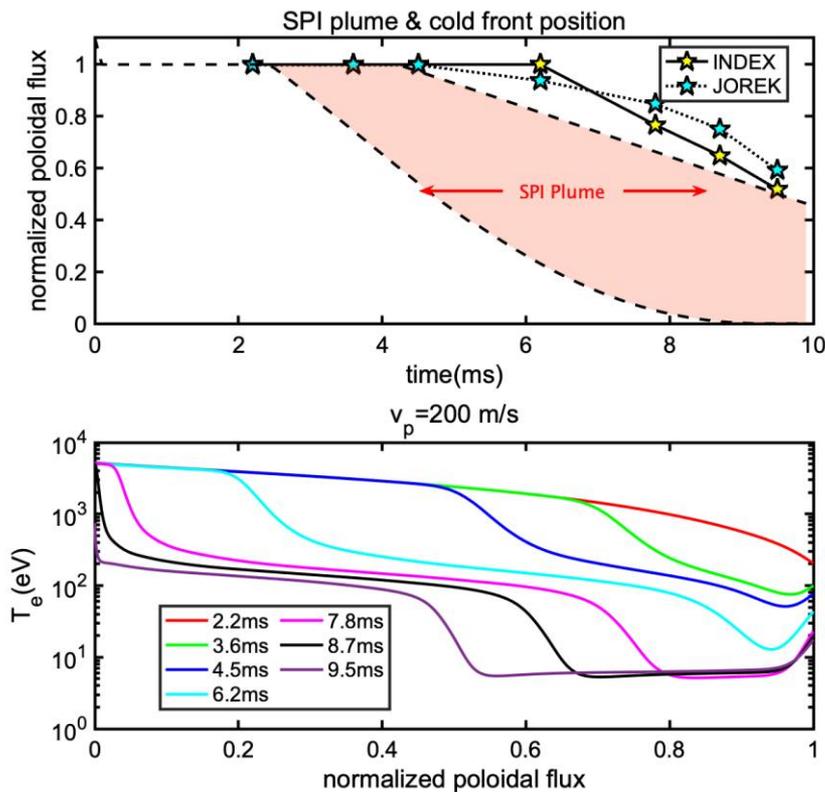
Similar, but weaker effect for lower D ion density



*V. Bandaru, M. Hoelzl, K. Särkimäki, H. Bergström, IO report*

# DMS Physics Basis – INDEX SPI assimilation

## ITER pre-TQ simulations



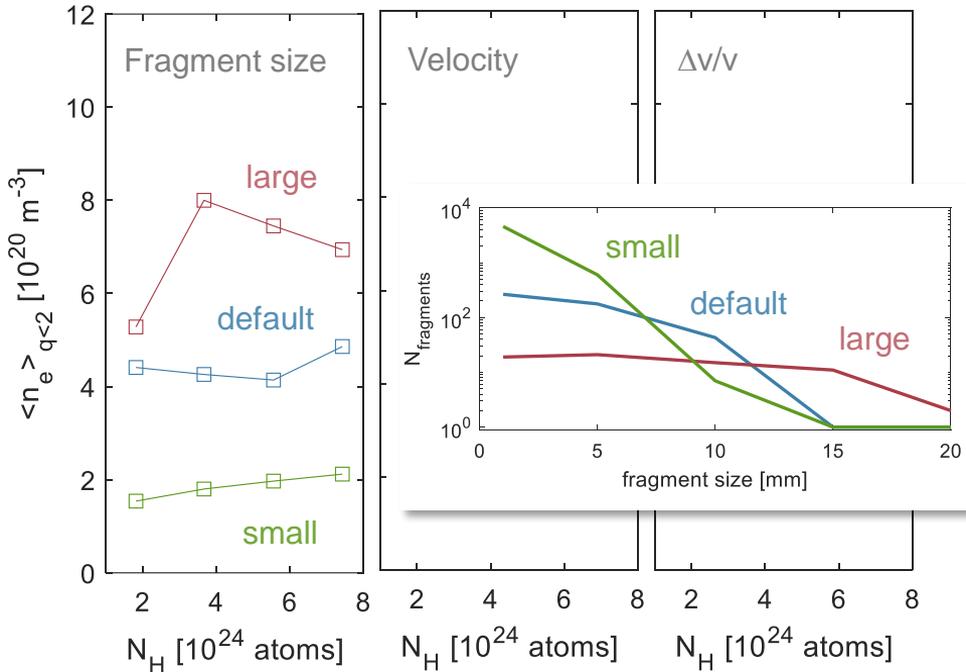
## Two stage plasma cooling

- Dilution cooling to  $\sim 100$  eV  
*ablation rate  $f(T_e) \rightarrow$  self-regulated*
- Cold front ( $\sim 10$  eV) through radiation

*Note: Current redistribution and TQ onset depend on cold front dynamics*

# DMS Physics Basis – Fragment parameters

## 1D INDEX ITER simulations (15 MA L-mode, Ne/H with $5 \times 10^{22}$ Ne atoms)



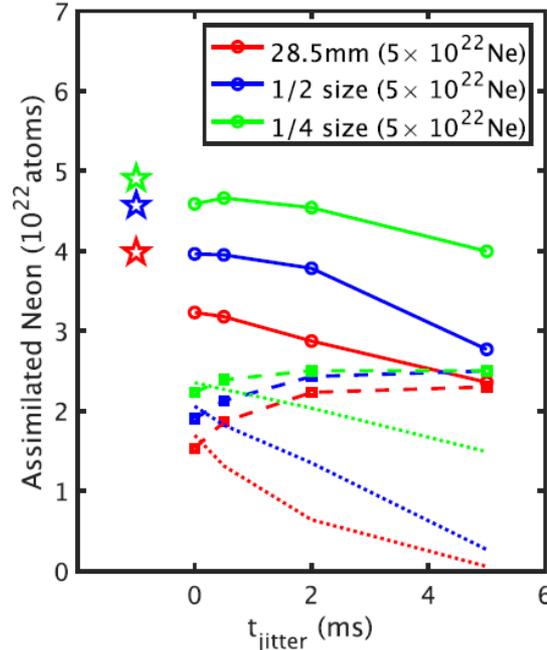
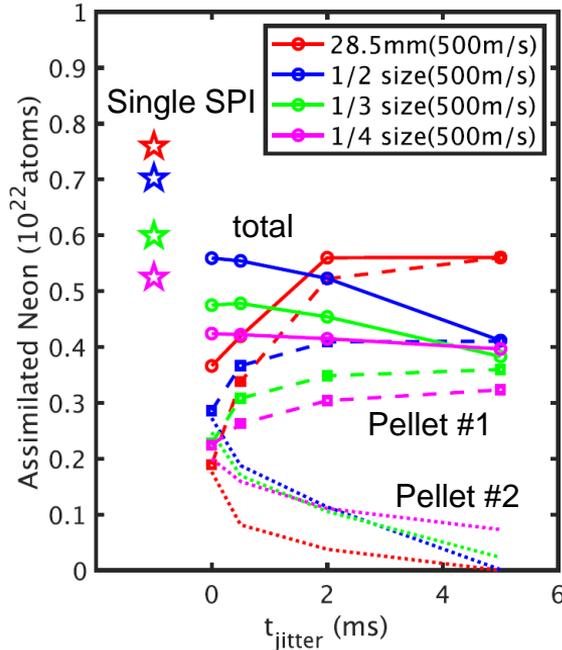
- Simulations suggest deeper penetration with
  - **larger** fragment size
  - **higher** velocity
  - **higher** velocity dispersion  $\Delta v/v$
- Recommended from simulations:  
 **$v = 500 \text{ m/s}$ ,  $\alpha = 15^\circ$**  (“large”)

A. Matsuyama, IO report

# DMS Physics Basis – Pellet Size

15 MA L-mode

15 MA H-mode



**Low assimilation driven plasma cooling and TQ onset**

Only 350 MJ (!) plasmas absorb almost an entire 28.5 mm pellet

Assimilation of 2<sup>nd</sup> pellet negligible in L-mode and still low in H-mode for realistic synchronisation within 2 ms

**Smaller pellets** would allow testing/using dual injection in pre-FPO

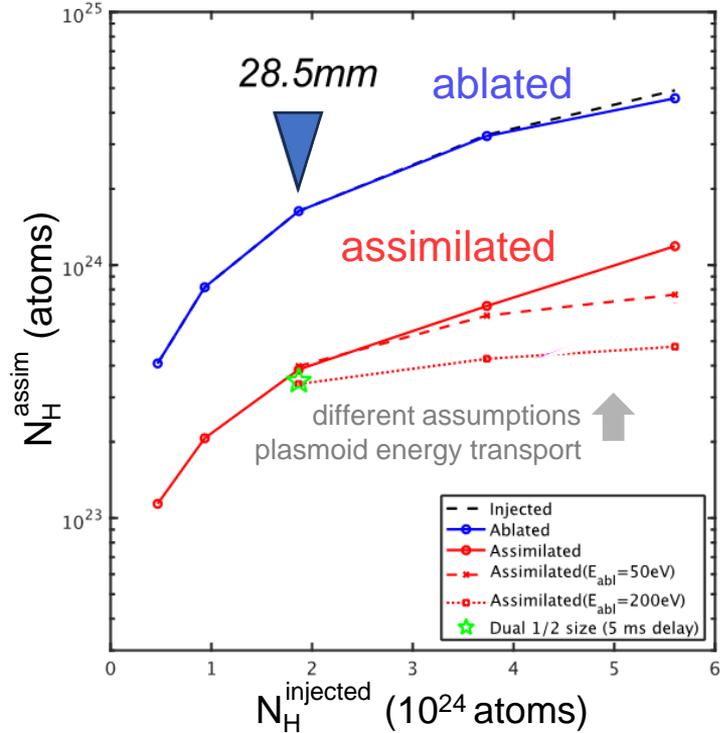
*INDEX, A. Matsuyama*

5e22 Ne and 1.8e24 H atoms in full size (single/dual)

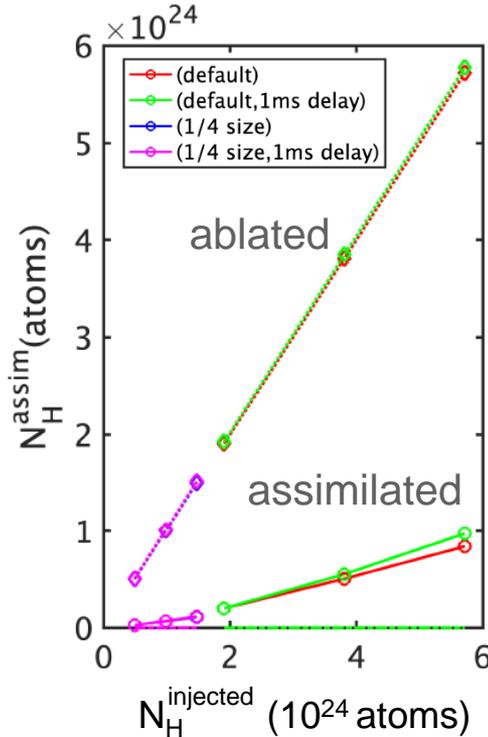
L-mode: Smaller pellets → Ne quantity reduced proportionally

# DMS Physics Basis – Pellet Size

## H SPI into ITER L-mode



## H SPI into ITER H-mode



Back-averaging used with parameter validated with DIII-D data

Assimilation ~ 25% (L-mode)  
~ 8-16% (H-mode)

**Low assimilation driven by plasmoid drift**

Plasmoid energy transport limits assimilation for large quantities

**Large pellets needed** because of poor assimilation (assimilation not limited by TQ onset as for Ne/H)

INDEX, A. Matsuyama

# Main remaining R&D needs

- Impact of plasmoid drift on mass assimilation (back-averaging/teleportation model used in most cases, though JOREK sees plasmoid drift in H-mode)
- Refinement of TQ onset criteria in 1D transport simulations for better estimates of assimilated mass
- Validate required pellet sizes, fragment sizes and speed
- Impact of seeded ITER plasma scenarios on mitigation schemes
- Quantification of required H for benign RE termination: self-consistent description of atomic, RE and MHD physics
- Assess RE avoidance schemes with more complete and self-consistent models (impact of vertical displacement, TQ and CQ radial transport losses, etc.)
- Simulations/Estimates to quantify required T to carefully assess impact of beta decay seeds in FPO-1 with H plasmas