The ITER Disruption Mitigation System – Design progress and design validation

Michael Lehnen

for the ITER Disruption Mitigation Task Force

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.

Outline

- ❑ Present DMS design and design challenges
- ❑ Mitigation requirements
- ❑ Needs for injection quantity, species and location
- ❑ Injection scenarios
- ❑ Physics and technology activities within the DMS Task Force

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DMS design – key dates

2-3 June 2021	System Design Review meeting
June 2021	Freezing of interfaces with Diagnostic First Wall and Diagnostic Shielding Modules
Feb 2022	Preliminary Design Review
May 2022	Report to STAC
Q1/Q2 2023	Final Design Review
Q1 2024	Start manufacture and assembly of DMS equipment on port plugs
Q1 2025	Start of port plug testing

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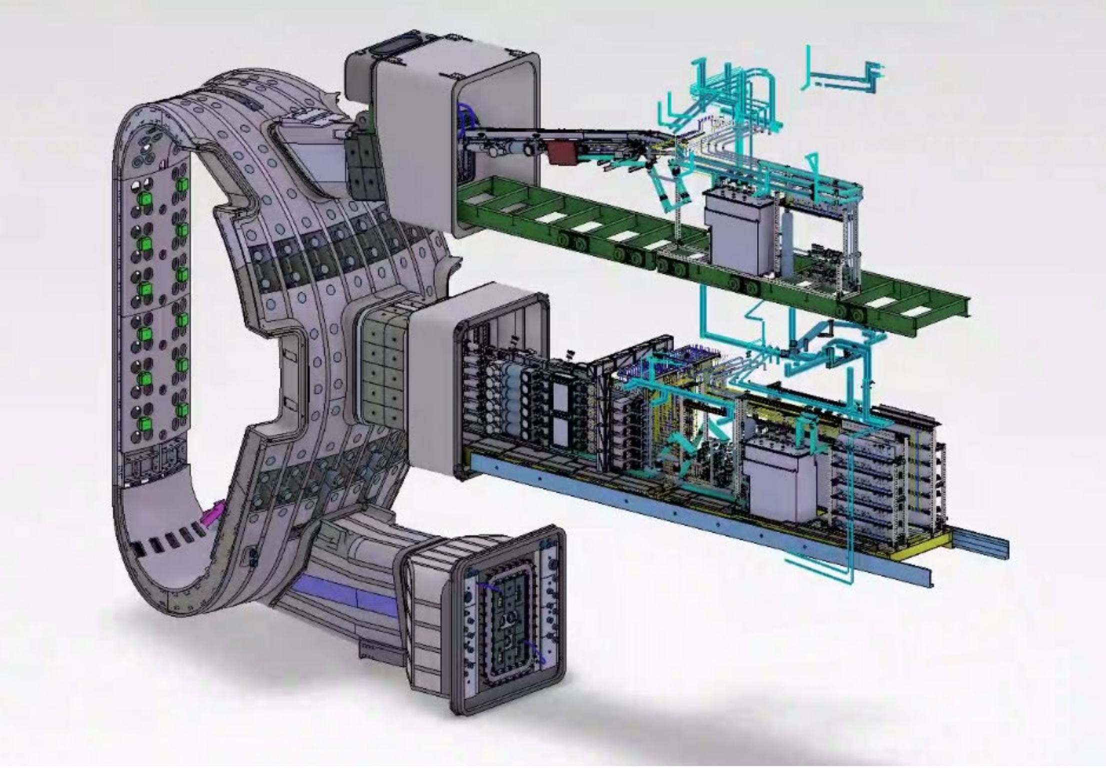
DMS design status



UP #02, #08, #14:
each 1 injector

EP #02:
12 injectors

EP #08, #17:
each 6 injectors

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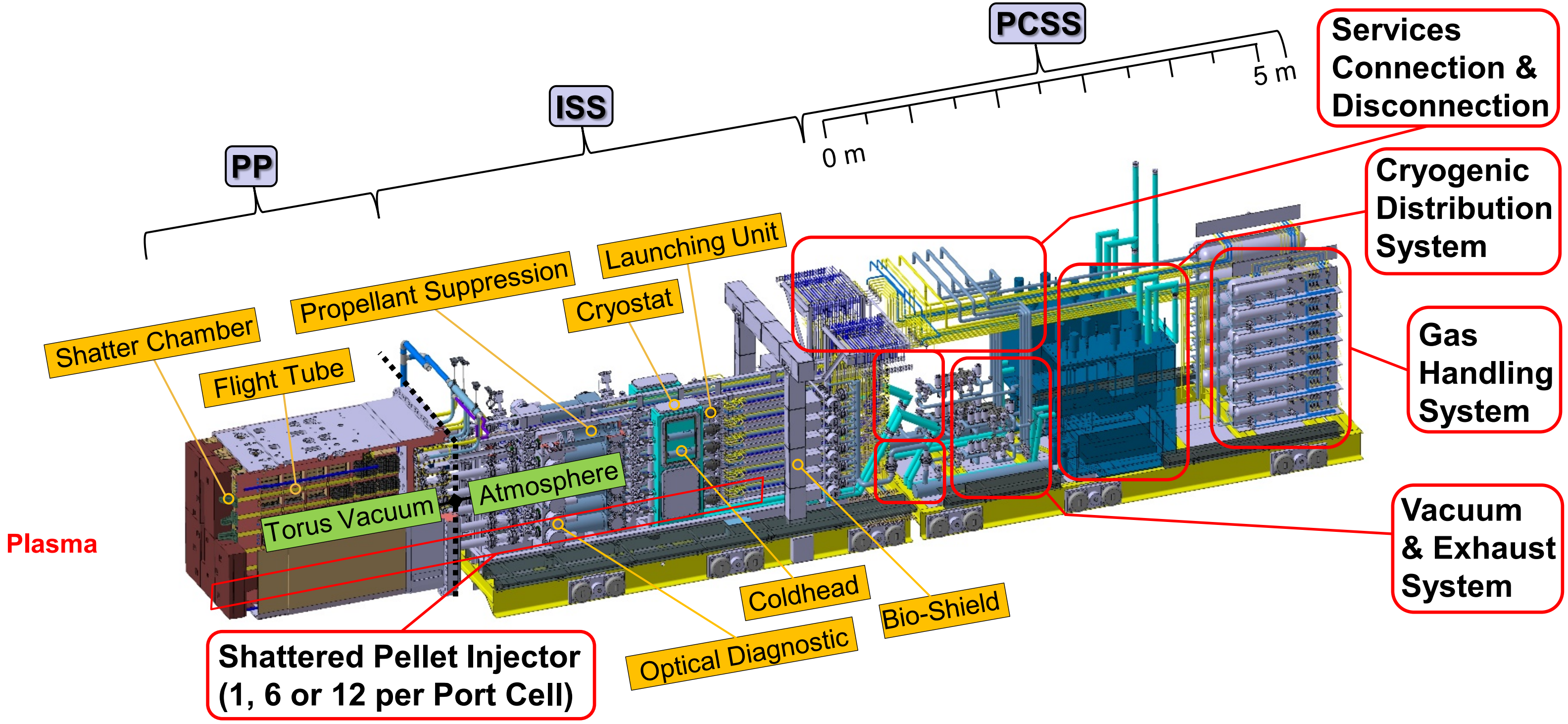
DMS design status



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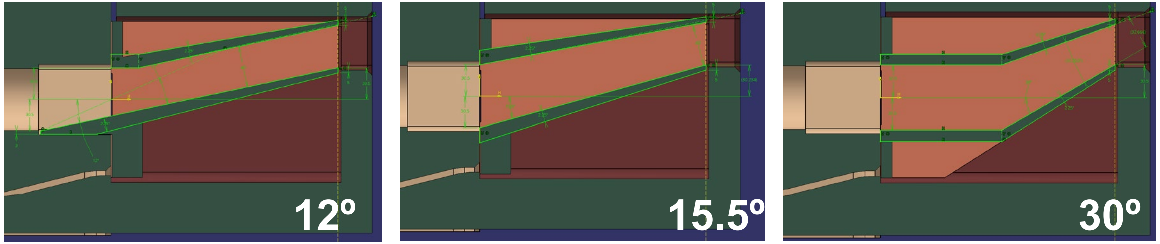
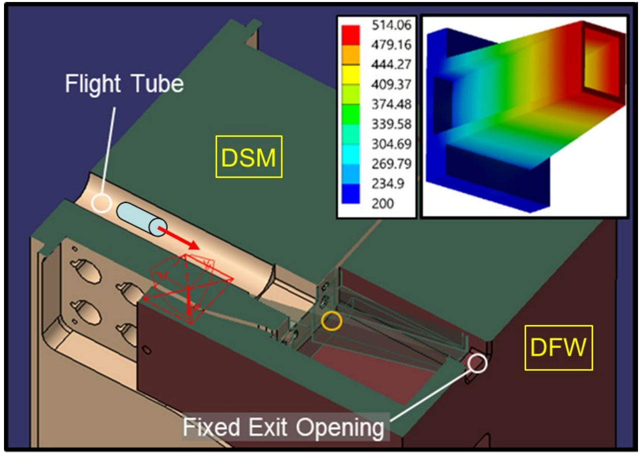
DMS design: shattering unit

- Interface with the Diagnostic First Wall has been frozen
- Cut-outs and injection directions were defined
- Design is constrained by the challenging environment (heat loads)
- Shattering units still have some design flexibility

Shattering angles from 12° to 30° can be accommodated





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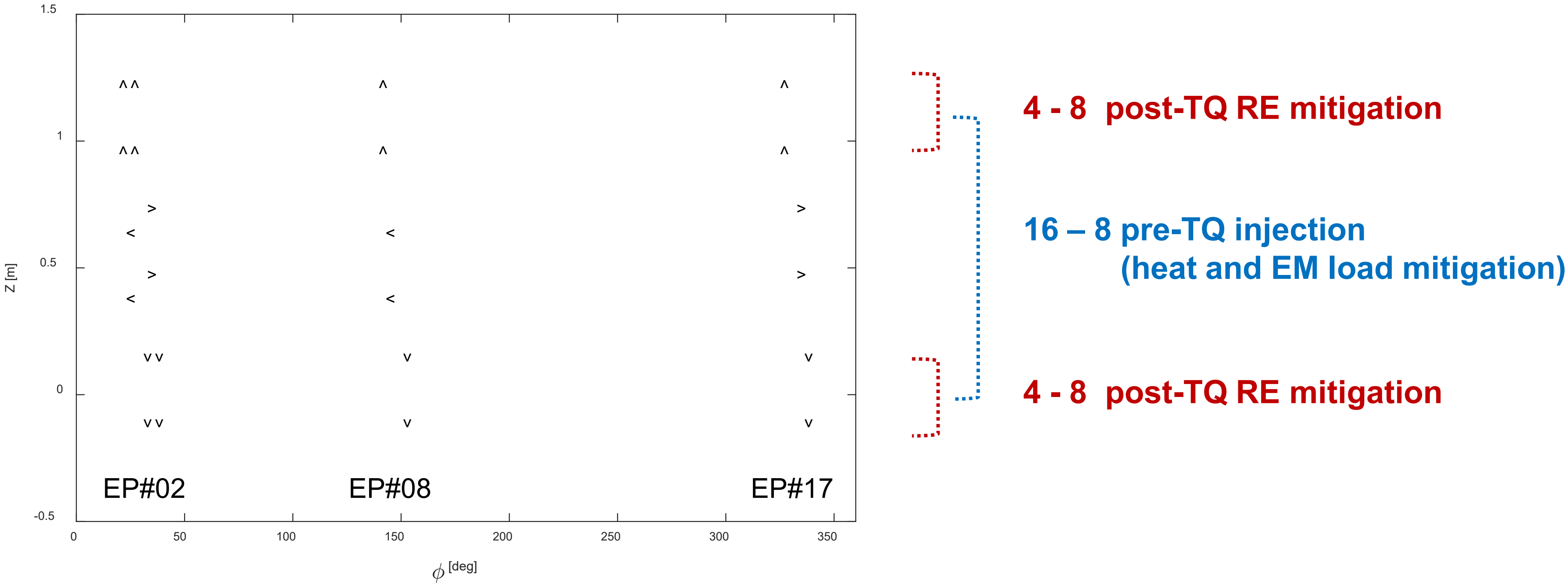
DMS design: injection configuration

- Configuration choice takes into account the requirements for the different mitigation scenarios, need for redundancy, and technical constraints



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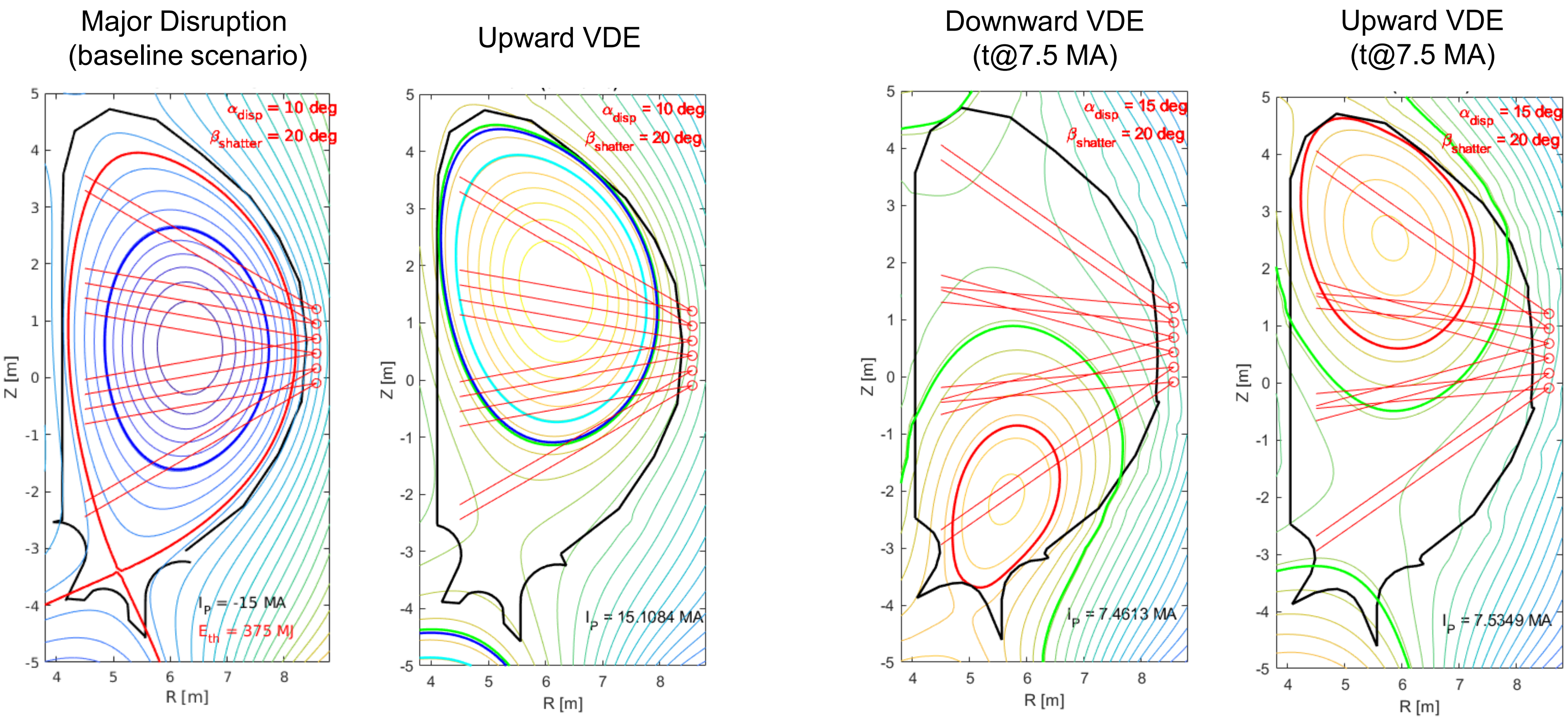
DMS design: injection configuration

pre-TQ injection

post-TQ RE mitigation



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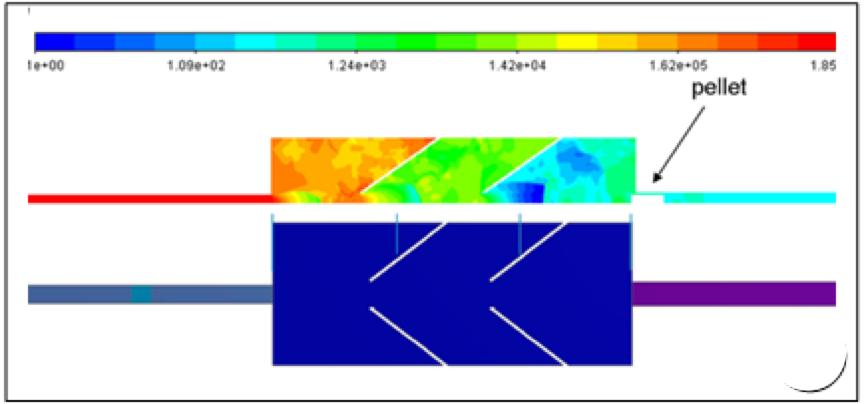
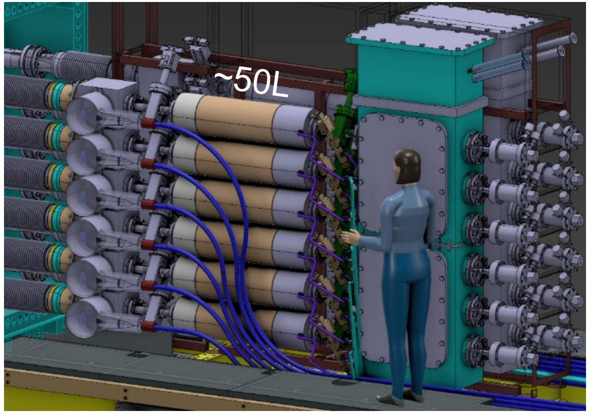
DMS design: propellant gas

- Propellant gas entering the plasma before the fragments must be minimised
- Space restrictions → expansion volume ~50 l (JET 1000 l, AUG 300 l)
- Structures inside the expansion volume can delay the gas flow
- SOLPS and ASTRA simulations have been performed showing that about 0.5% of the propellant gas could be acceptable
- Possible development of a fast shutter or propellant methods without gas





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Mitigation requirements

The DMS mitigation action must target to result in disruptions of

- Category I (EM loads)

  I_P decay $\geq$ 15 MA / 50 ms
  I_H(peak) < 2.25 MA (DINA simulations: I_P decay < 15 MA / 150 ms)

- Category HL-I (thermal loads)

  Melt limit of plasma facing components *(see following slides)*

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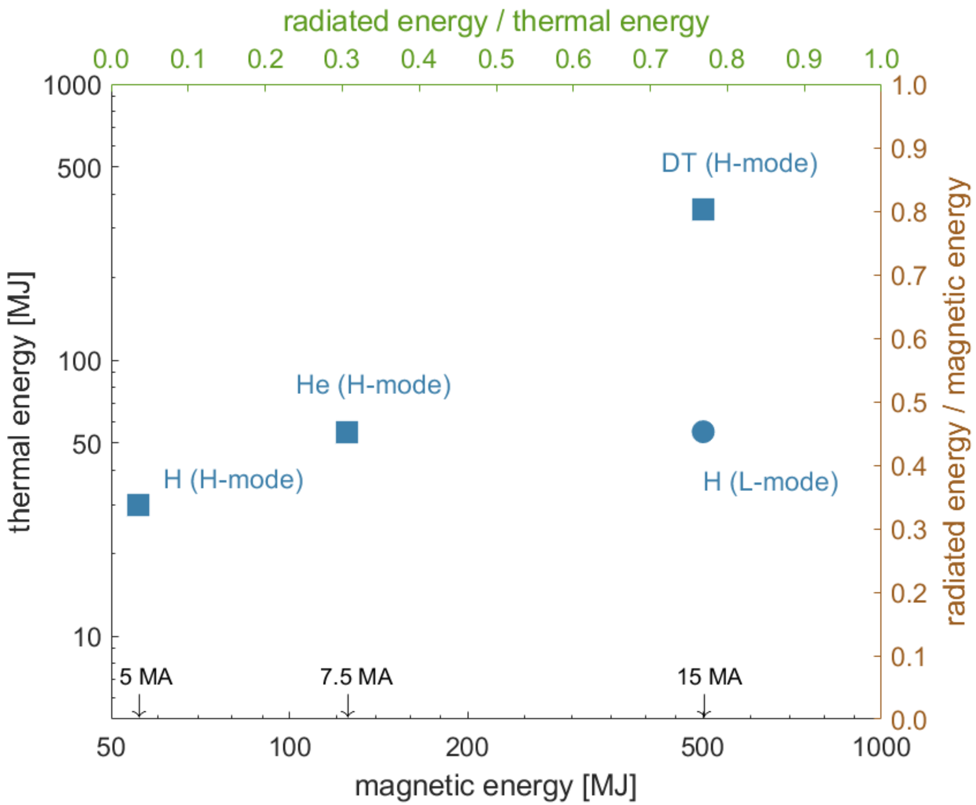
Mitigation requirements – Thermal loads



- Current and energy will be successively increased during the execution of the ITER Research Plan
- Thermal loads arise from thermal <u>and</u> magnetic energy
- Limits depend on wetted area and PFC material
- Thermal load mitigation relies on energy dissipation through radiation

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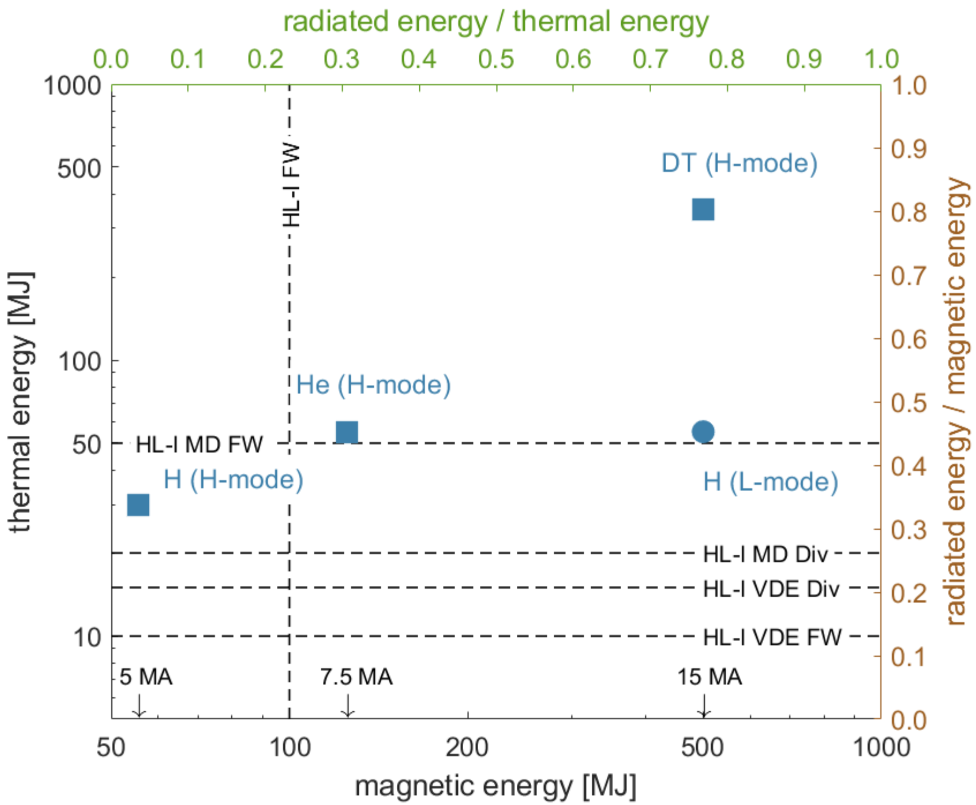
Mitigation requirements – Thermal loads



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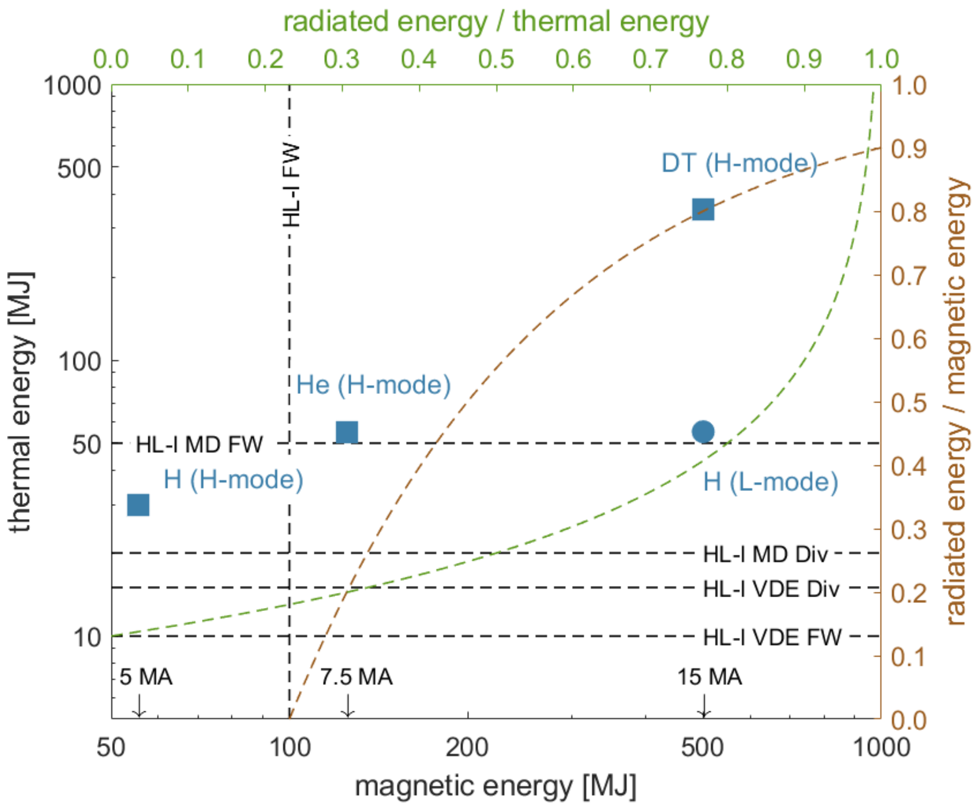
Mitigation requirements – Heat loads



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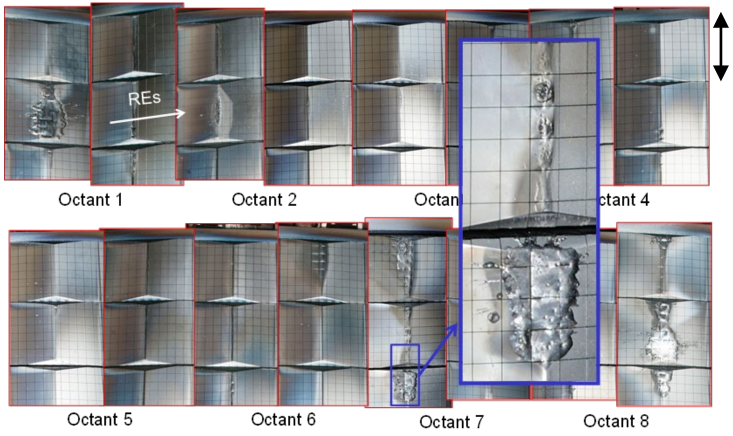
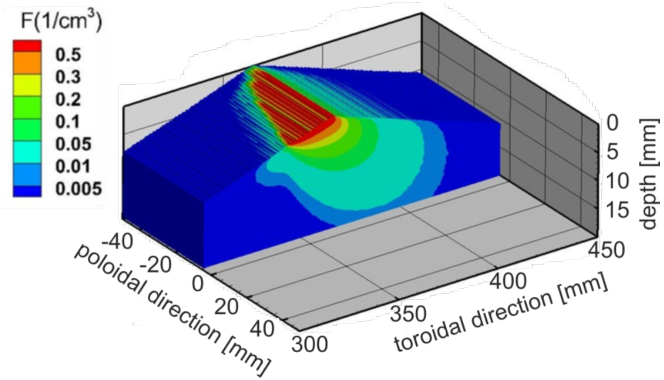
Mitigation requirements – Runaway Electrons



Melting caused by RE impact in JET

G. F. Matthews et al., PFMC 2015



Energy deposition on ITER FW panels (ENDEP)

Category I

I_{RE} < 100 kA (FWP)

I_{RE} < 150 kA (Divertor)

or

E / divertor cassette < 0.15 MJ

E / FWP < 0.3 MJ

Presently re-assessed with the DINA-SMITER-GEANT4-MEMOS-U workflow *(L. Chen, AAPPS-DPP 2021)*

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Injection quantities & species

Purpose	Species	Quantity [atoms]*	Injection Time	Reference
Thermal load mitigation *Thermal Quench*	Ne	$>8\text{x}10^{21}$ (pure Ne) $>1\text{x}10^{21}$ (with H)	pre-TQ	3D fluid simulations
RE avoidance (mixed pellets)	H	$\sim 1.5\text{-}3\text{x}10^{24}$	pre-TQ	1D simulations
RE avoidance (staggered injection)	H	$\sim 1\text{x}10^{24}$	pre-TQ	Dilution cooling to $T_e \sim 1$keV
Thermal load mitigation *Current Quench*	Ne	$> 2\text{x}10^{21}$ (pure Ne)	pre-TQ or post-TQ	DINA
EM load mitigation *Current Quench*	Ne	$> 4\text{x}10^{21}$ (pure Ne) $< 5\text{x}10^{22}$ (pure Ne)	pre-TQ / post-TQ	DINA
RE impact mitigation (high-Z)	Ne	$\sim 1\text{x}10^{25}$	post-TQ	DINA
RE impact mitigation (low-Z)	H	$\sim 2.5\text{x}10^{24}$	post-TQ	JET data

*for the 15 MA baseline scenario

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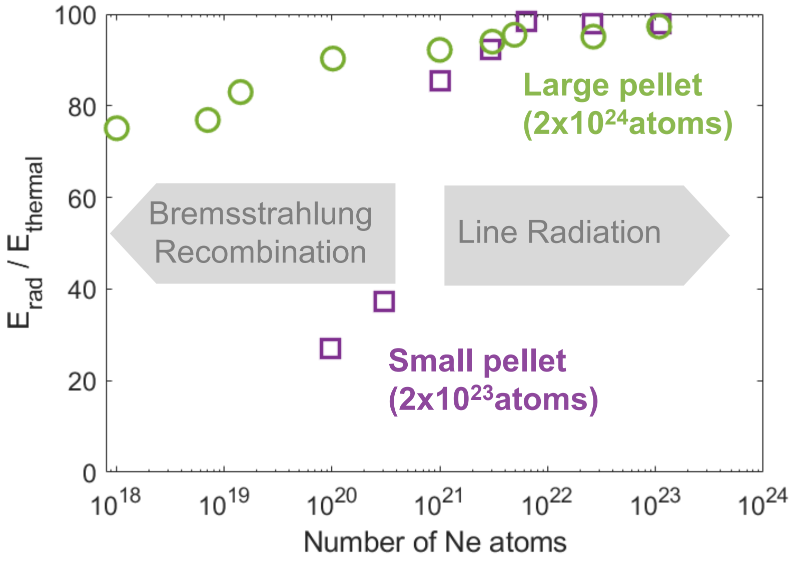
Injection quantities & species

TOKES simulations



S. Pestchanyi et al., FED 2020

Thermal Energy Impact Mitigation

- Pre-TQ injection of Neon to increase E_{rad}
- Addition of H for RE avoidance decreases required Ne quantity
- 3D MHD simulations ongoing
- Experiments at KSTAR and AUG with enhanced radiation measurements

>10^{21} Ne atoms

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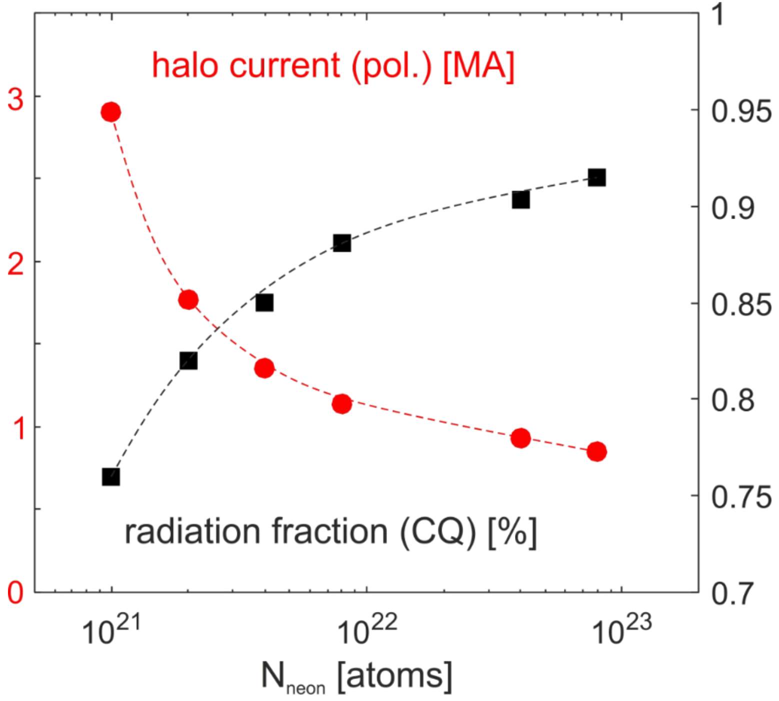
Injection quantities & species

DINA simulations



CQ Thermal & EM load mitigation

- Pre-TQ or post-TQ injection of Neon to increase E_{rad}
- 100% reliability required at 15 MA
- Impact of H from RE avoidance to be assessed
- 3D effects not considered and uncertainties in the halo model

>4x10^{21} Ne atoms

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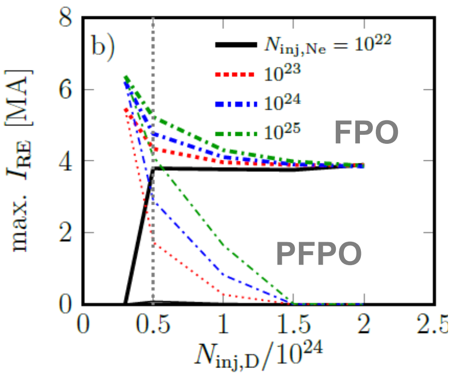
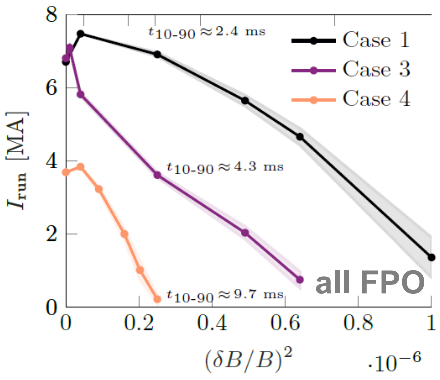
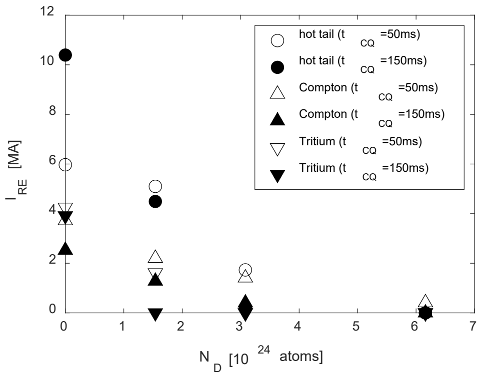
Injection quantities & species



O. Vallhagen, master thesis 2020



P. Svensson, arXiv:2010.07156



J.R. Martín-Solís, NF 2017

Runaway Electron Avoidance

- Density increase:
  - dilution cooling
    prevent RE formation from hot tail
  - reduce avalanche multiplication
    Compton scattering/ T decay
- Self-consistent kinetic simulations needed incl. MHD driven transport
- 3D MHD + seed formation?

~1.5 – 3 x 10^{24} H atoms

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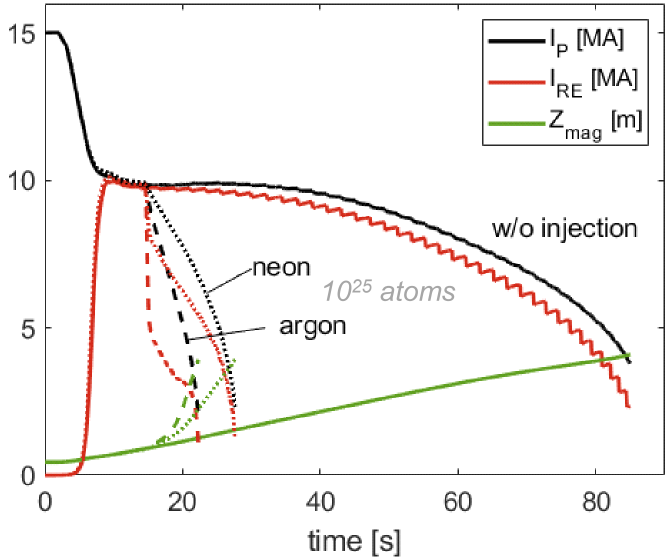
Injection quantities & species

Runaway Electron Impact Mitigation

DINA high-Z simulations



High-Z

- Dissipate energy through collisions and radiation
- Higher efficiency of argon is compensated by its lower pellet density

IMAS disruption database: 100206/2, 100203/2, 100184/2 (https://confluence.iter.org/display/IMP/Disruption+database)

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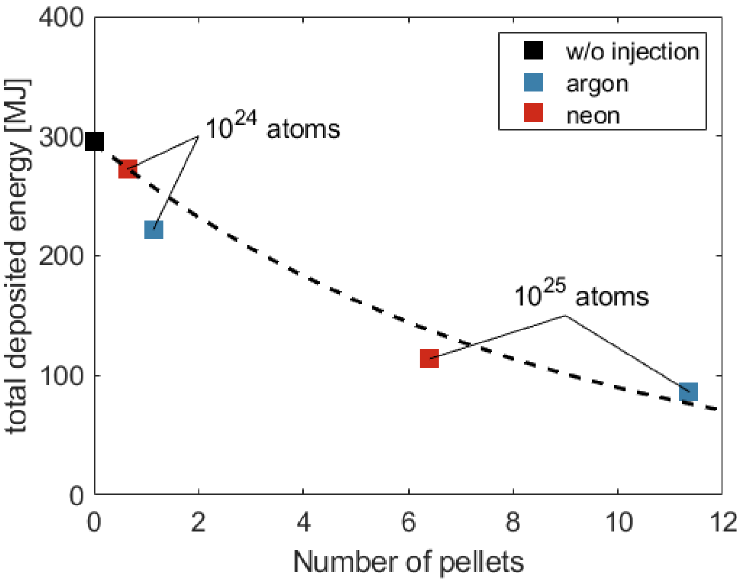
Injection quantities & species

DINA high-Z simulations



Runaway Electron Impact Mitigation

High-Z

- Dissipate energy through collisions and radiation
- Higher efficiency of argon is compensated by its lower pellet density
- Cannot fully mitigate impact
- MHD to be taken into account

~ 10^{25} Ne atoms

IMAS disruption database: 100204/2, 100194/2, 100203/2, 100184/2 (https://confluence.iter.org/display/IMP/Disruption+database)

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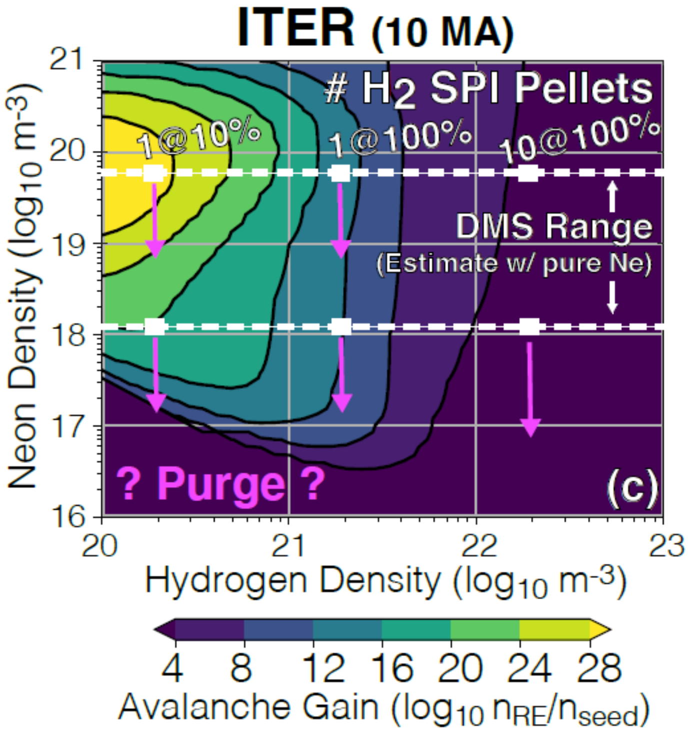
Injection quantities & species



C. Paz-Soldan et al.,
IAEA FEC / NF 2021

Runaway Electron Impact Mitigation

Low-Z

- Flush neon to prevent re-avalanching
- Initiate MHD driven loss without scraping-off
- 3D MHD modelling ongoing

> ~10^{23} H atoms (purge)
~8 x 10^{24} H atoms (no purge)

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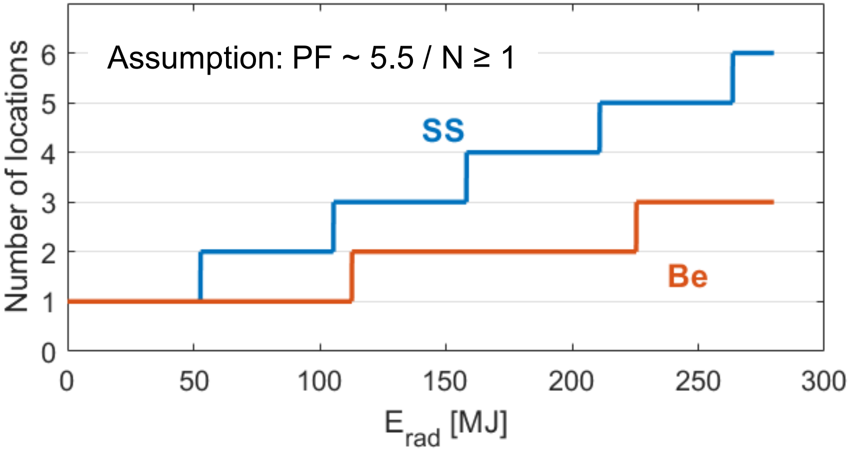
Injection locations

Number of required locations for HL-I



D. Shiraki et al., IAEA FEC 2021
N.W. Eidietis et al., PoP 2017
D. Hu et al., NF 2021
S. Pestchanyi et al., FED 2020

Multiple injection locations

- Decrease the radiation peaking
- Could be beneficial to increase assimilation

3D MHD simulations ongoing

KSTAR experiments

Single injection locations:

Initial simulations:
PF = 5.5-7.6

Initial experimental values:
TPF = 1.7-2.5 and PPF = 2.2

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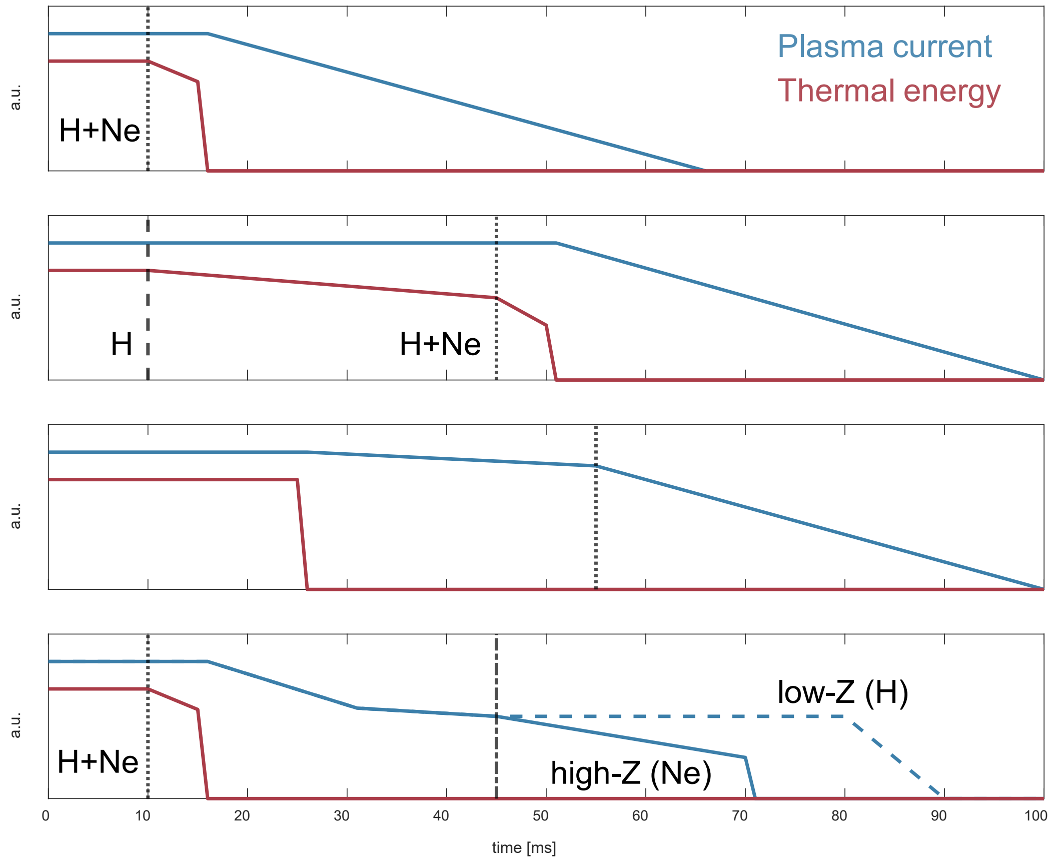
Mitigation Scenarios



Pre-TQ mixed injection

Pre-TQ staggered injection

Post-TQ mixed injection

Pre-TQ mixed injection (or other)
+ RE impact mitigation

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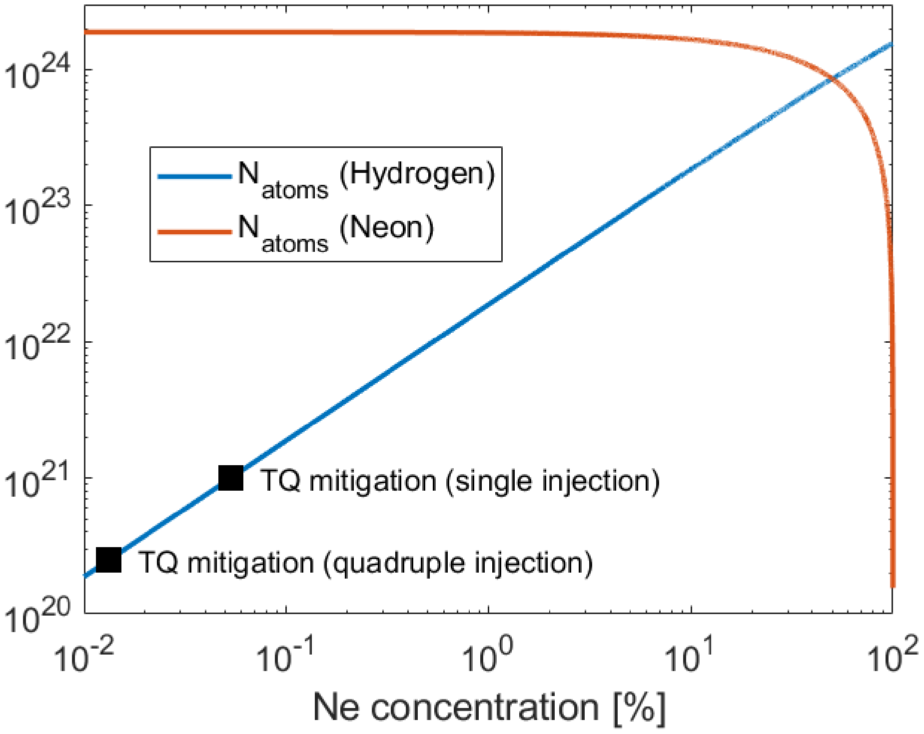
Quantities per pellet



Size of present ITER DMS pellets

D = 28.5 mm

L = 57.0 mm

$N_{atoms} = 1.9\text{x}10^{24}$ (H)

$N_{atoms} = 1.6\text{x}10^{24}$ (Ne)

H shell may be considered to to facilitate the pellet launching process

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Required number of pellets (15MA baseline)

Scheme	Species and Quantities	Number of pellets *(for different assimilation)*			Injection port
		100%	*50%*	*30%*	
Pre-TQ staggered	$1x10^{24}$ H $5x10^{22}$ Ne (max)	3 3	3 3	3* 3**	EP
Pre-TQ mixed	$5x10^{22}$ Ne (max) + $6x10^{24}$ H	4	7	11	EP
RE high-Z	10^{25} Ne	7	13	22	EP
RE low-Z	10^{23} – $8x10^{24}$ H	1 – 4	1 – 8	1 – 14	EP
Post-TQ	$5x10^{22}$ Ne (max)	1	1	1	UP
Total (EP)	**Staggered + high-Z**	**13**	**19**	**29**	
	Mixed + high-Z	**11**	**20**	**33**	
	Staggered + low-Z	**7 – 10**	**7 – 14**	**7 – 20**	
	Mixed + low-Z	**5 – 8**	**8 – 15**	**12 - 25**	

* 3 injection locations to possibly avoid fast mode growth   ** 3 injection locations for radiation flash mitigation

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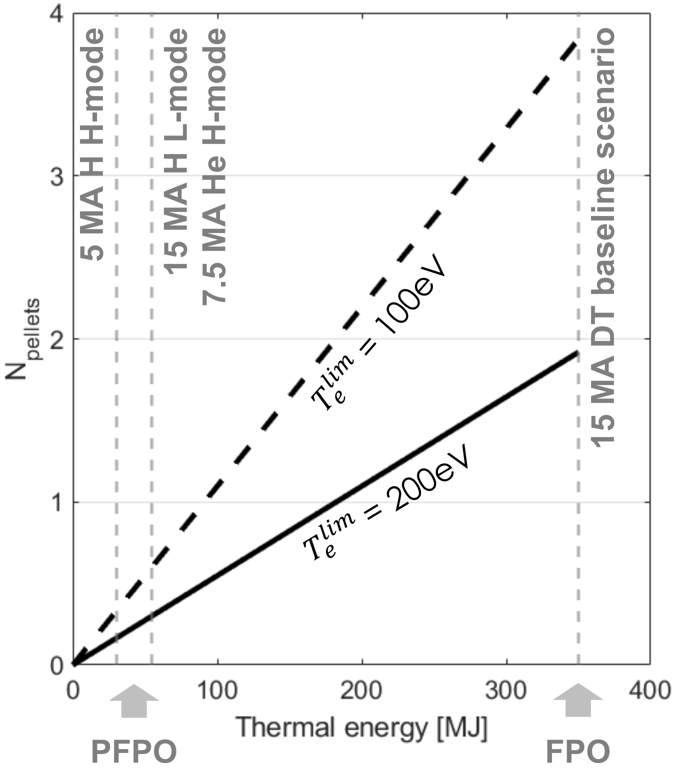
Required number of pellets



Theoretical maximum ablation
(by a thermal plasma)

Lower limit for relevant ablation rates:

$$\Delta N \approx \frac{E}{3kT_e^{lim}}$$

More pellets are likely needed:

- Injection from multiple locations
- Assimilation < 100%

SPI into high I_P but low E_{th} cannot provide required n_e for 'classical' RE avoidance

→ Dilution cooling by staggered injection to prevent hot tail RE formation

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ITER Disruption Mitigation Task Force

Scope

- Design Specification through experiments and modelling
- Engineering studies to develop SPI technology and adapt to the ITER requirements

Organized in three groups:

- Experiments
- Modelling
- Technology

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Task Force - Experiments and Modelling

- Adequacy of the injection locations
- Efficiency of multiple simultaneous injections
- Efficacy of runaway electron avoidance and mitigation schemes
- Optimum fragment sizes and velocities for highest assimilation
- Required quantities, pellet compositions, injection sequences

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KSTAR
2 triple injectors toroidally 180° separated

DIII-D
2 triple injectors toroidally 120° separated

JET
Single triple injector

ASDEX Upgrade
Triple injector with different shatter ends

J-TEXT
Single Ar / single Ne injector with different L/D

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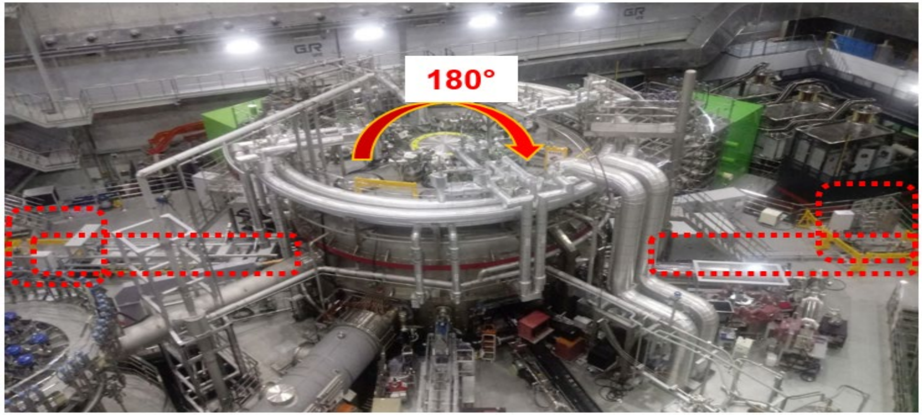
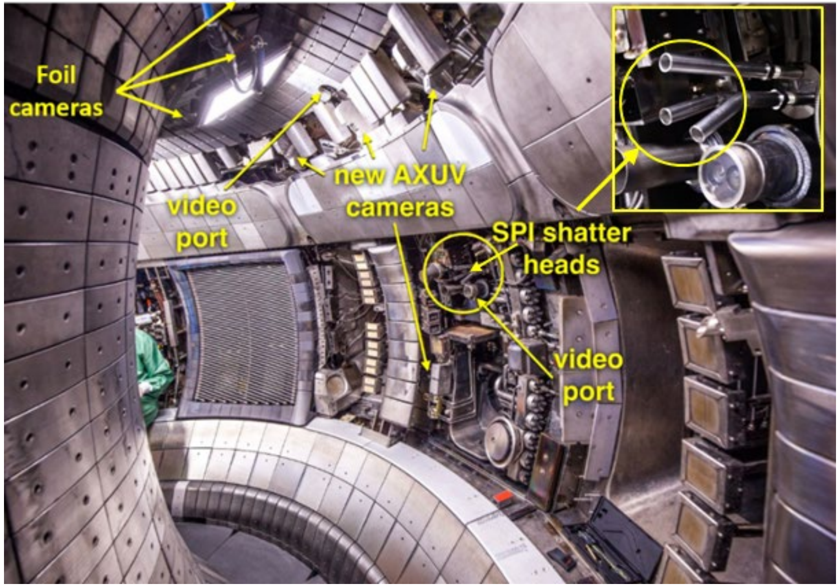
Task Force - Experiments

KSTAR with two SPI locations



ASDEX Upgrade with three shatter bends



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NIMROD/M3D-C1 (3D MHD)
Model optimisation, Benchmarking, Validation, ITER simulations

JOREK (3D MHD)
Model optimization, ITER simulations

JOREK (3D MHD)
KSTAR SPI simulations

DREAM (kinetic/fluid RE code)
RE avoidance simulations incl. MHD driven transport

JOREK (3D MHD + RE fluid model)
Code optimization, Benchmarking, post-TQ RE formation and RE termination phase

INDEX (1D transport solver)
Validation (JET, KSTAR, DIII-D), Benchmarking, ITER simulations for extensive parameter range

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NIMROD/M3D-C1 (3D MHD)
Model optimisation, Benchmarking, Validation, ITER simulations

JOREK (3D MHD)
Model optimization, ITER simulations

JOREK (3D MHD)
KSTAR SPI simulations

DREAM (kinetic/fluid RE code)
RE avoidance simulations incl. MHD driven transport

JOREK (3D MHD + RE fluid model)
Code optimization, Benchmarking, post-TQ RE formation and RE termination phase

INDEX (1D transport solver)
Validation (JET, KSTAR, DIII-D), Benchmarking, ITER simulations for extensive parameter range

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Task Force - Modelling

- Adequacy of the injection locations
- Efficiency of multiple simultaneous injections
- Efficacy of runaway electron avoidance and mitigation schemes
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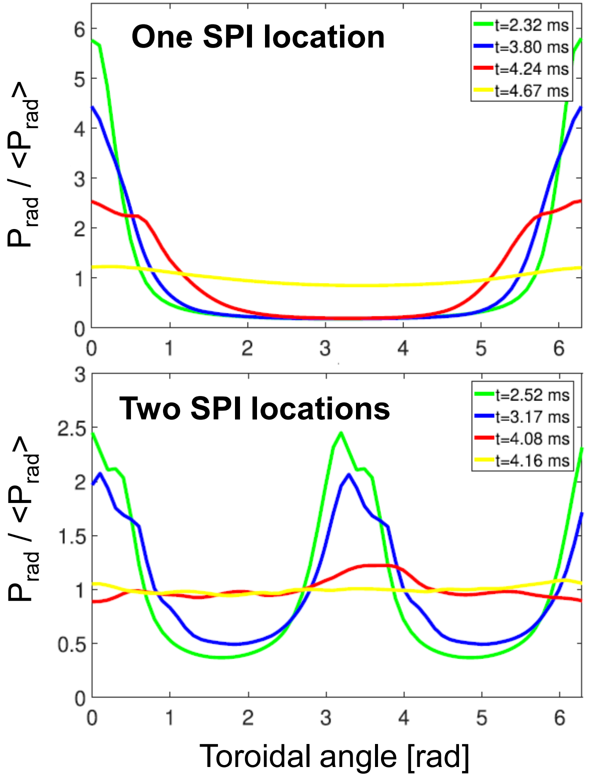
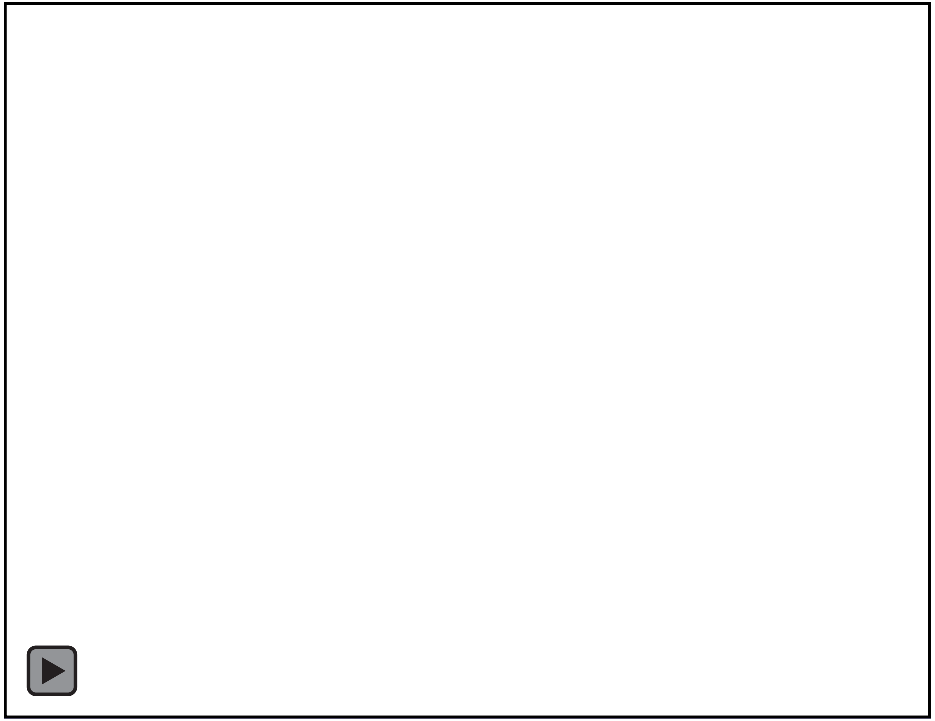
Task Force - Modelling

3D MHD simulations with JOREK





D. Hu et al., Nucl. Fusion 2021

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Task Force - Technology

- Ensure defined and reproducible pellet integrity and pellet acceleration
- Develop means to monitor the pellets
- Optimise the flight path
- Guarantee reproducible pellet shattering with defined fragment sizes and injection plume characteristics

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Support Laboratory

Test bench for ITER DMS components
Shattering tests with various geometries

Fundamental Studies

Systematic pellet formation and release studies for different pellet sizes

Optical Pellet Diagnostic

Design and testing of a pellet monitor for integrity, orientation, velocity for the ITER DMS

ORNL support

Shattering studies with 28.5 mm (D) and 23 mm (H)
Propellant valve development
Shear strength measurements (pellet release)
Pellet dispersion

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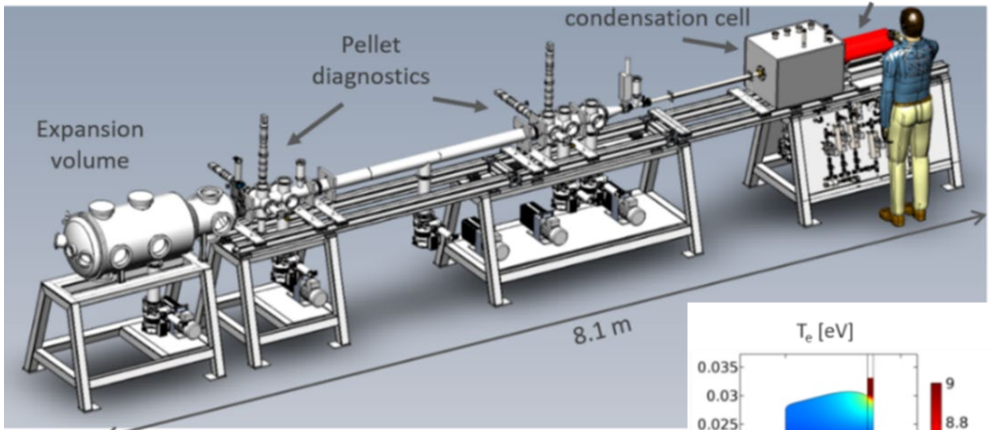
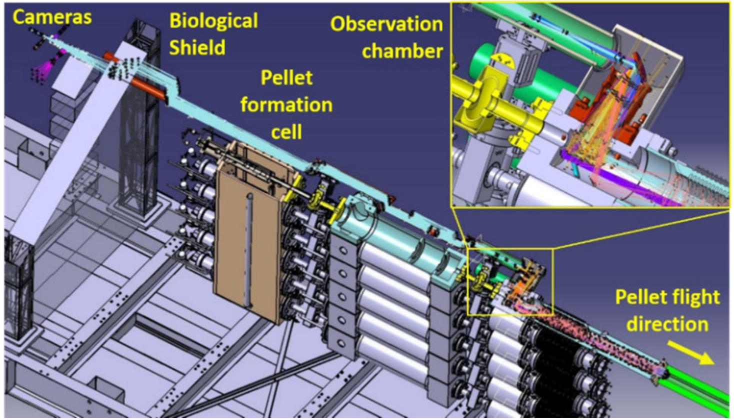
Task Force - Technology

CEA-Grenoble/DSBT

Test bench for the fundamental studies

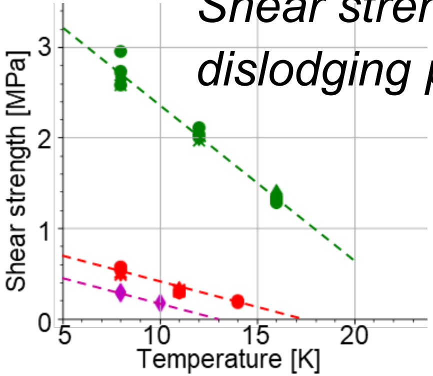


Optical Pellet Diagnostic integrated into the injector line

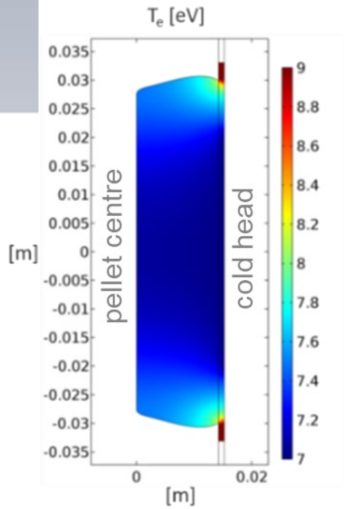


Fusion Instruments

T. Gebhart, IAEA FEC 2021



Shear strength for dislodging pellets



Pellet growth simulations

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Concluding Remarks

- The DMS design is progressing and interfaces with other tokamak components are successively frozen;
- The required quantities and injection locations have been assessed on the basis of present knowledge, confirming the present DMS layout;
- To address knowledge gaps and to develop the required technologies, the ITER Disruption Mitigation Task Force is running an extensive programme;
- The task force work is complemented by significant activities within domestic R&D programmes.

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