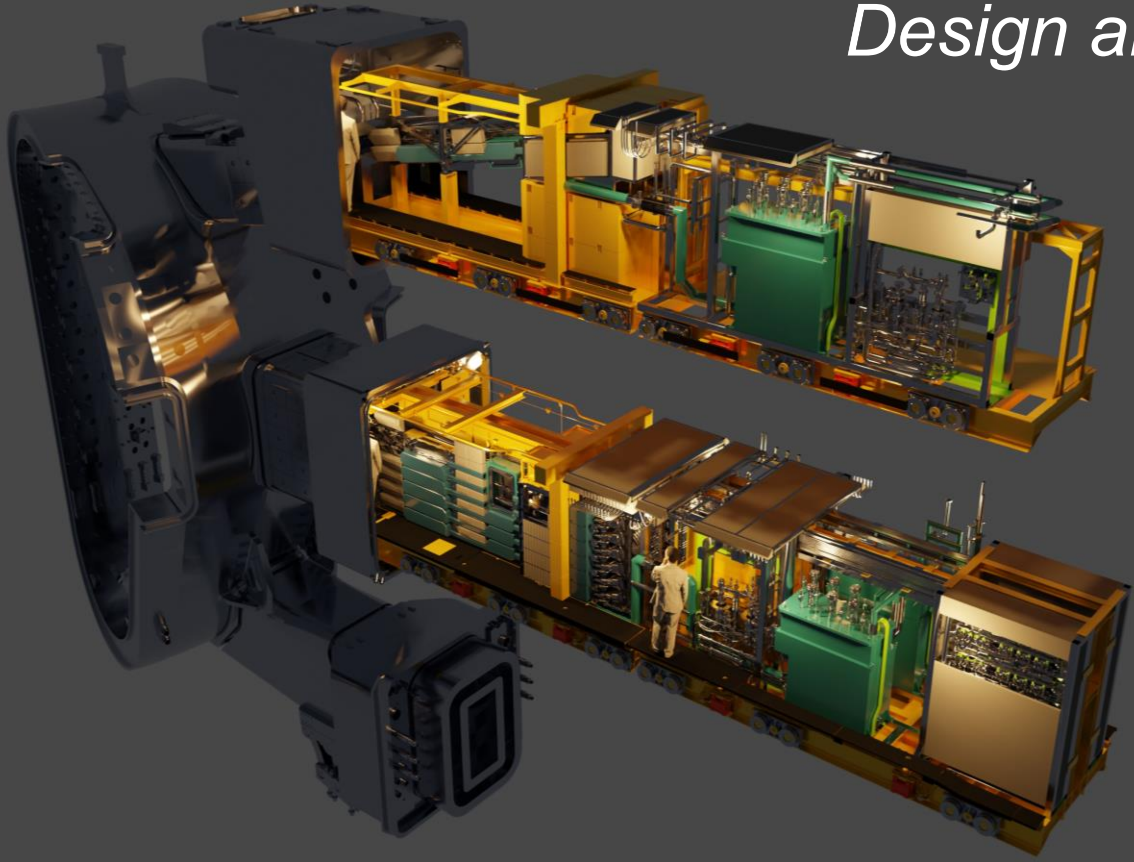
ITER Disruption Mitigation System:

Design and application strategy



Stefan Jachmich
ITER Organization

30th IAEA-FEC, Oct 2025
Chengdu, China

Acknowledgement

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Outline

- Introduction
- Design of the ITER Disruption Mitigation System
- DMS optimisation for ITER operation
- Summary and Outlook

Motivation

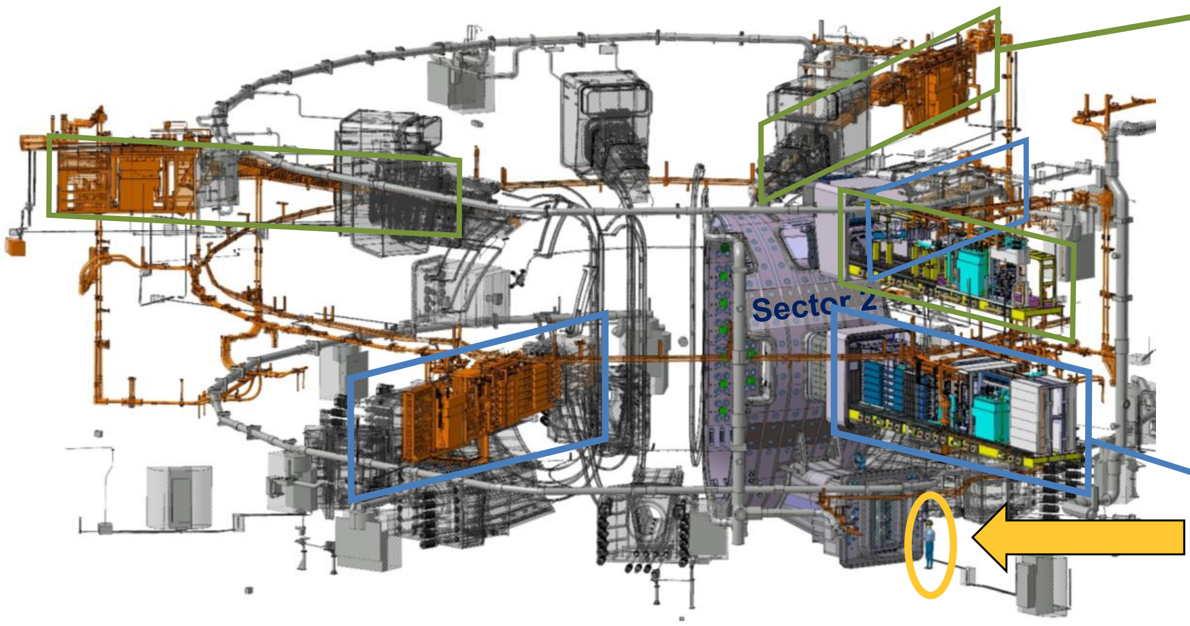
- ITER requires disruption mitigation system from early operation onwards
- ITER DMS design based on Shattered Pellet Injection: pellets of H, H/Ne mixtures and Ne

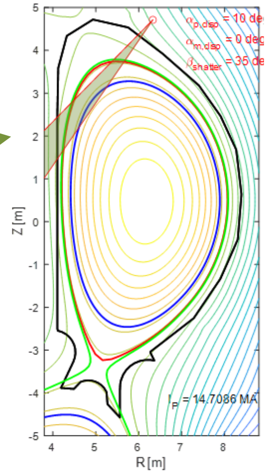
Material injection for mitigation:

Disruption phase:	pre-TQ	post-TQ	RE-beam
Thermal load of W_{th}	Ne (+H)	-	-
Thermal load of W_{mag}	Ne (+H)	Ne (+H)	-
Electromagnetic loads	Ne	Ne	-
RE avoidance	H	(H)	-
RE impact	-	-	H or Ne

ITER DMS design

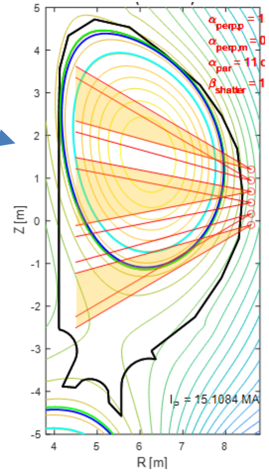
ITER DMS





3 Upper port injectors

for post-TQ injection



24 Equatorial port injectors

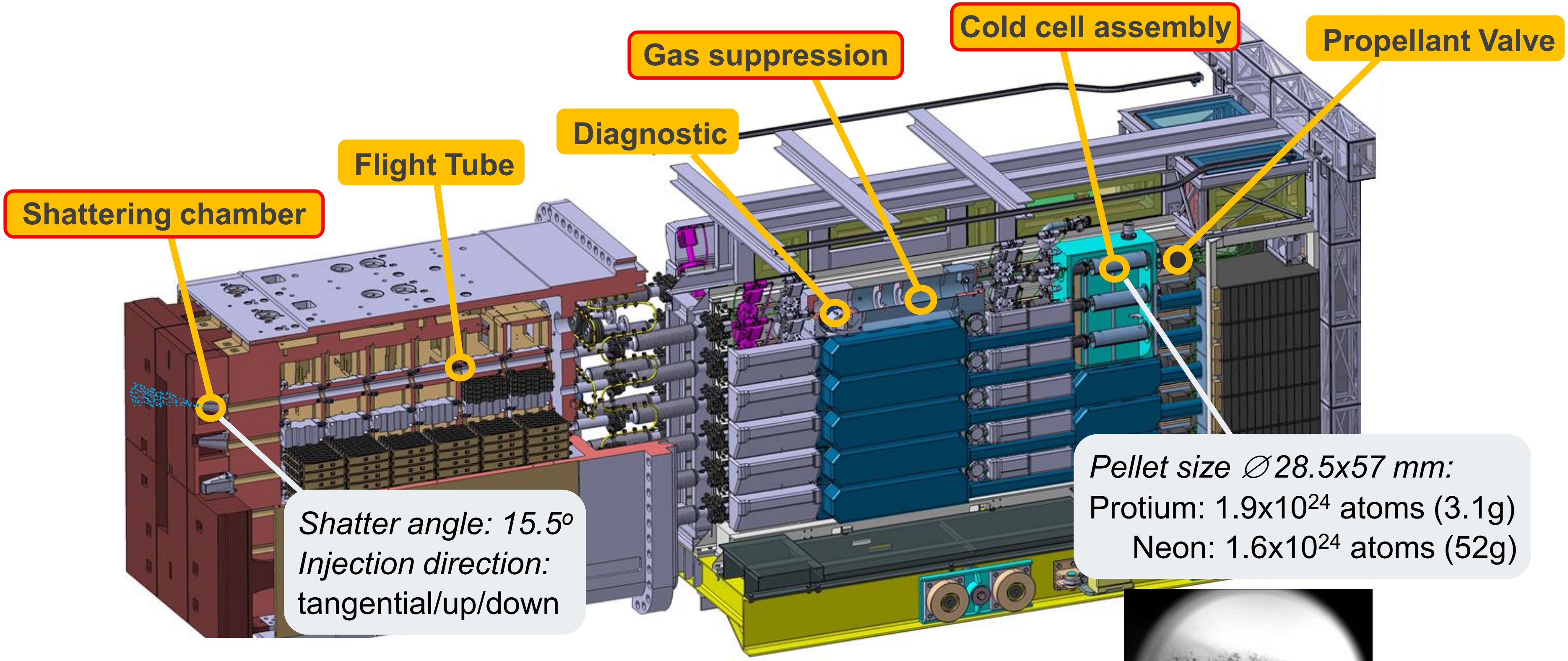
- pre-TQ injection
- post-TQ injection
- RE impact mitigation

ITER DMS status

- Final design review approved Dec 2024 → **design phase of DMS project concluded**

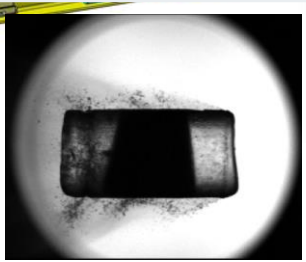
- **Next:** manufacturing phase of DMS:
  - → Detailed design and construction of onsite SPI laboratory (alignment test facility) started
  - → Prototyping of cryo system, propellant valve, CCA launched
  - → Manufacturing: 2027-2029
  - → Assembly and offline testing: until 2030
  - → Port-plug integration: starting 2029
  - → Port-plug installation: 2032/2033
  - → First DMS injection into plasma: 2034

ITER DMS – Injector



Shatter angle: 15.5º
Injection direction:
tangential/up/down

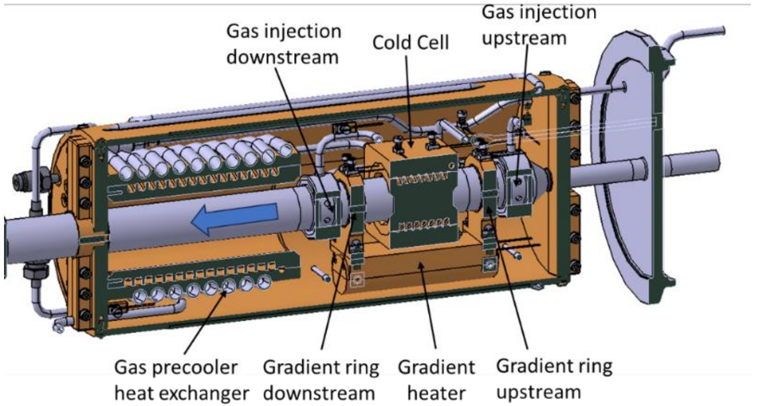
Pellet size ∅28.5x57 mm:
Protium: 1.9×10^{24} atoms (3.1g)
Neon: 1.6×10^{24} atoms (52g)



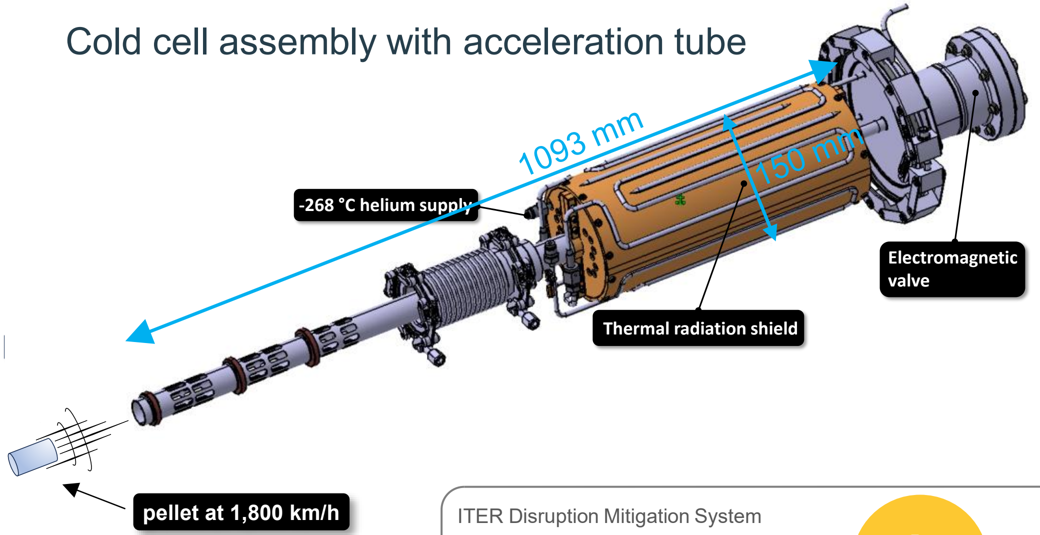
Cold cell assembly (CCA) – pellet formation

- ITER duty cycle has a target of 30 min → gas pre-cooling required
- SHe feed to 6 CCAs in parallel → risk of unbalance for simultaneous H and Ne pellet formation
- Tight prismatic cryostat and flexibility for pellet size required
  → cartridge design including electroformed cold cell on acceleration tube

Electroformed cold cell and T_{grad} control



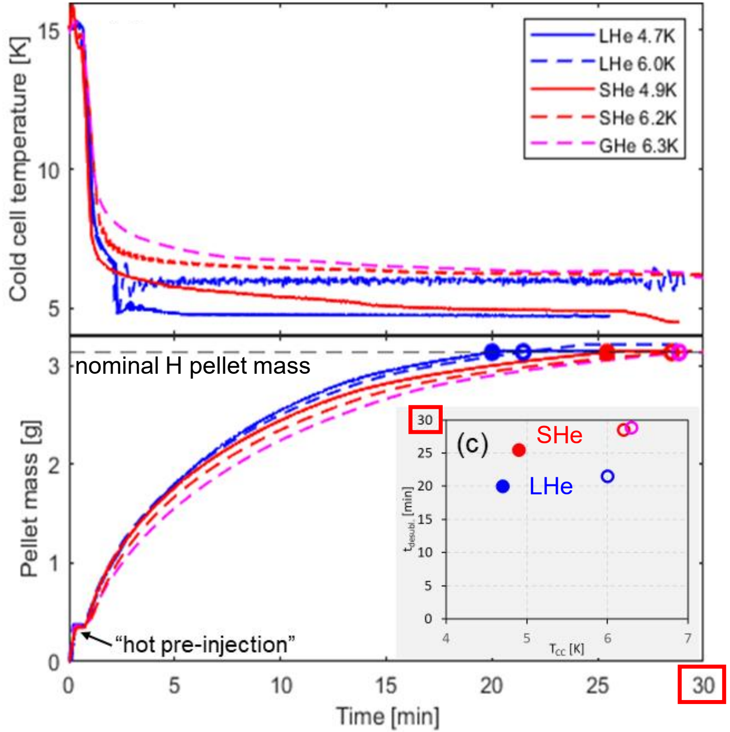
Cold cell assembly with acceleration tube



Cold cell assembly – pellet formation

- CALYPSO cryostat: set of heat exchanger for SHe production
- Cold cell assembly prototype manufactured for use with GHe and SHe

Pellet formation tests



- Formation tests with "hot pre-injection" recipe
- Better control of desublimation pressure resulting in improved pellet crystal structure

➡ Longer formation times with SHe due to slower cooldown but still within duty cycle requirement

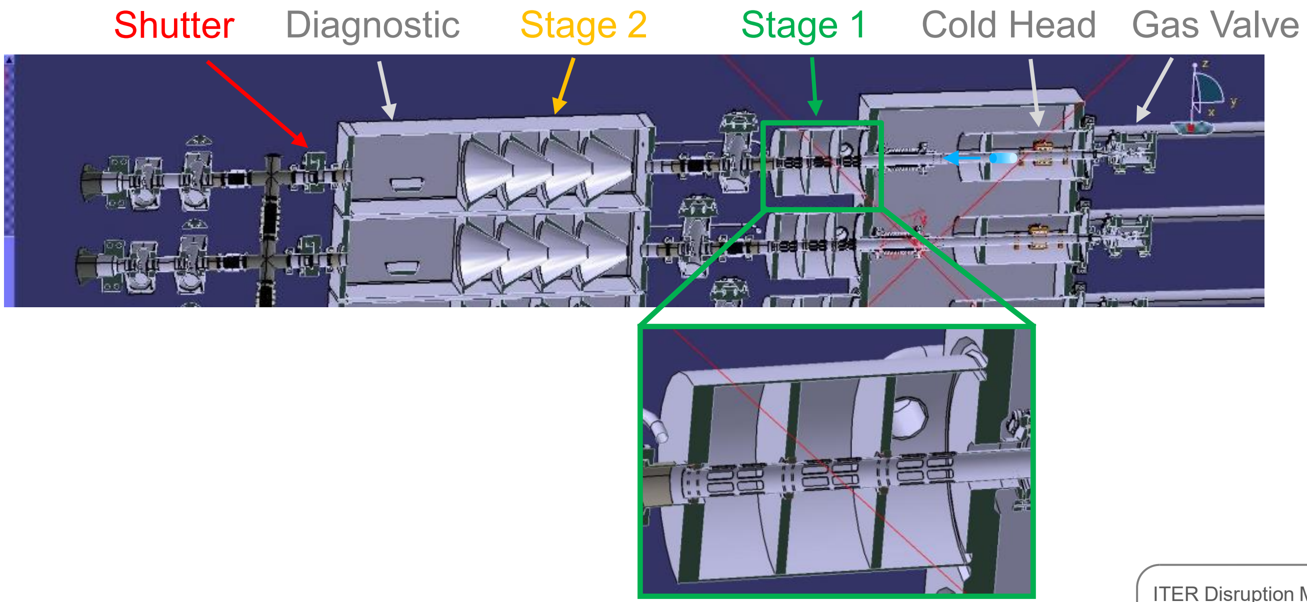
Note: T_{CC}< 6K required to limit pellet sublimation (loss of mass) prior DMS trigger (~ hours) and to minimise impact on breakdown

F. Millet, J. Manzagol *et al*, 2025

Propellant gas suppression

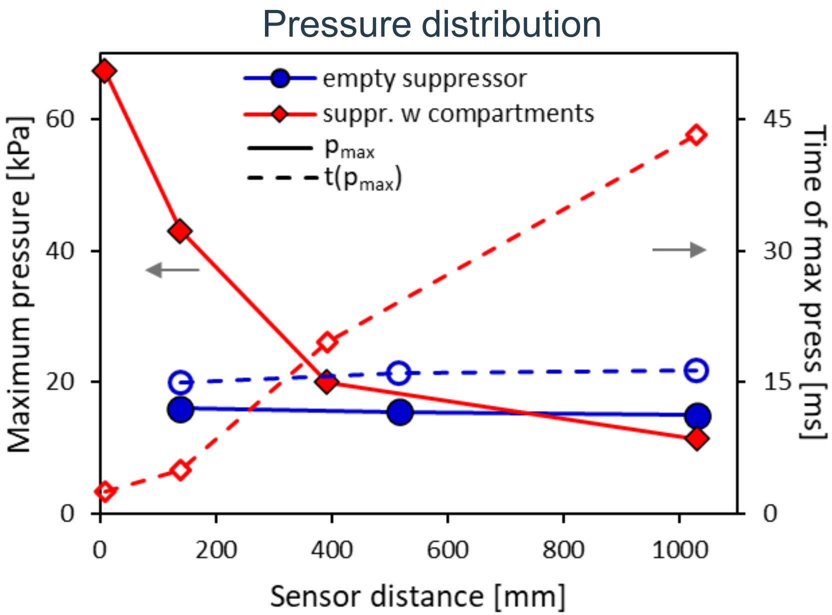
Needed for

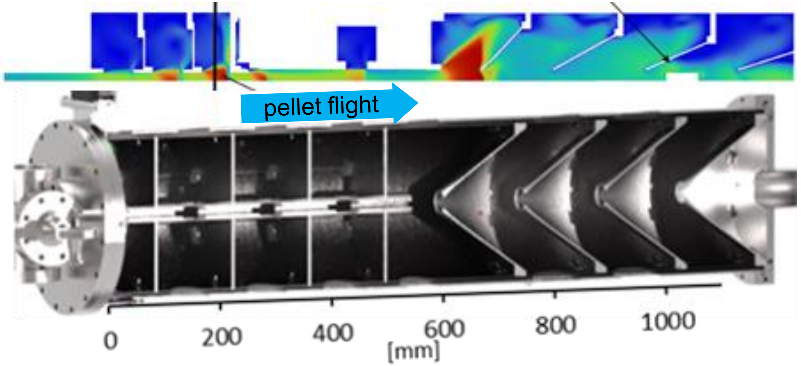
- Propellant gas retention to avoid premature trigger of TQ ($\Gamma_{gas} < 5x10^{24}$ H_2/s)
- Pressure reduction behind pellet to ensure precise pellet trajectory (stage 1)
- Deflection of debris produced during pellet launch (stage 2)

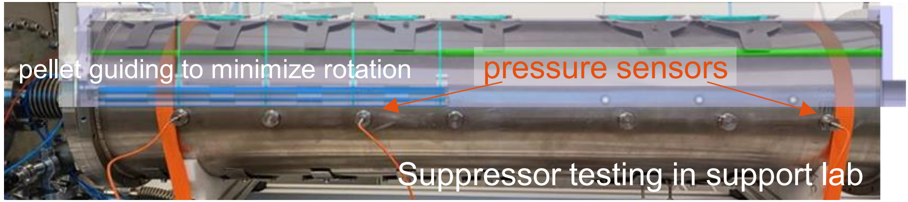


Propellant gas suppression

- CFD modelling to guide design (similar to acoustic delay)
- Setup mimicking ITER design tested in DMS Support Laboratory





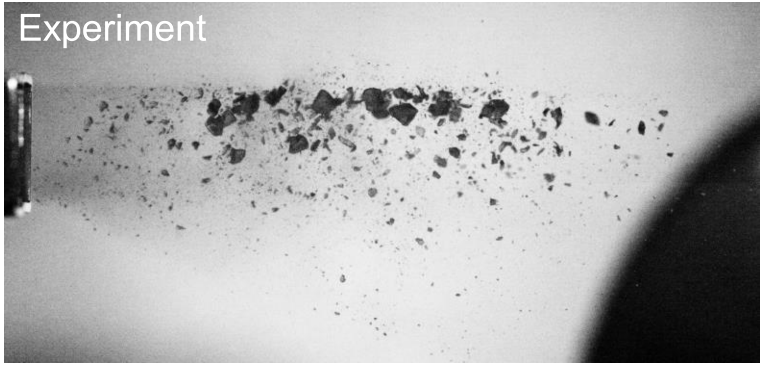


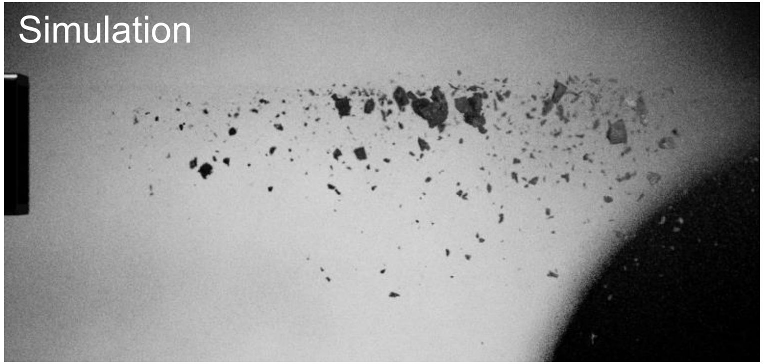
➡ Muzzle break concept feasible

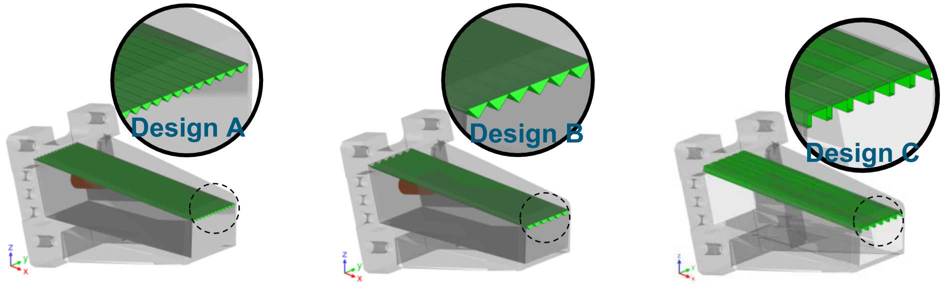
- Note: gap pellet-wall deteriorates gas retention

Pellet fragmentation

- Fragmentation simulated with MD-cube (discrete element code)
- Material parameters calibrated against lab shattering experiments using synthetic diagnostics







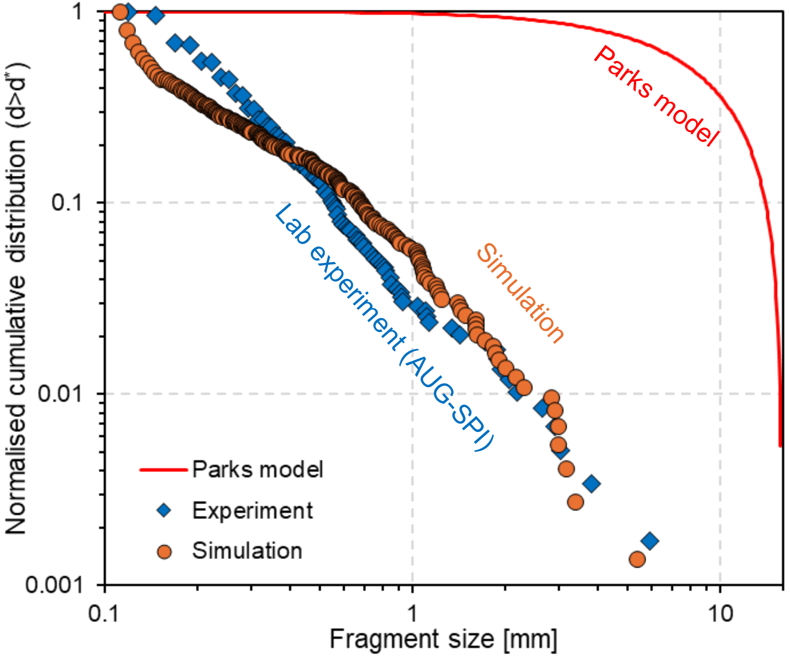
➡ Tool to assess advanced shattering geometries

P. Mature, S. Signetti *et al*, HVIS 2025

Pellet fragmentation

- Fragment size distribution on log-log scale expected to be linear
- Statistical fragmentation model developed by Parks and refined by Gebhart et al.

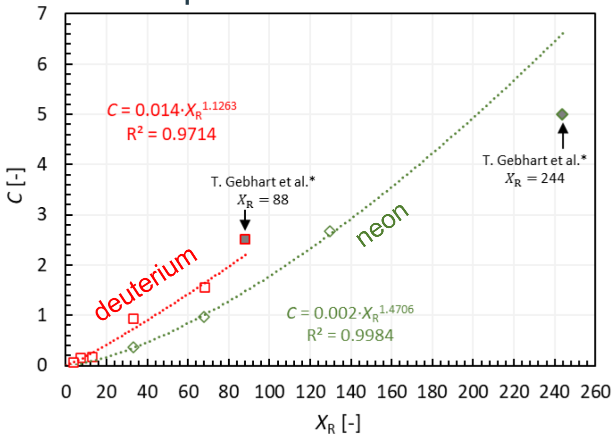
Cumulative fragment size distribution



➡ Parks model overestimates fraction of large fragments
=> prediction for material assimilation affected

Better predictability with amended parameterisation:

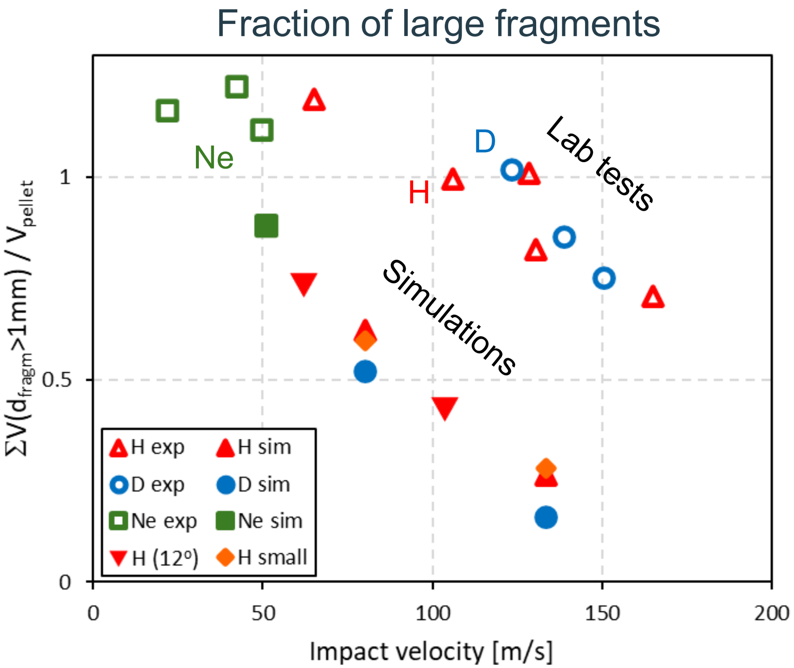
Adaptation of Parks model

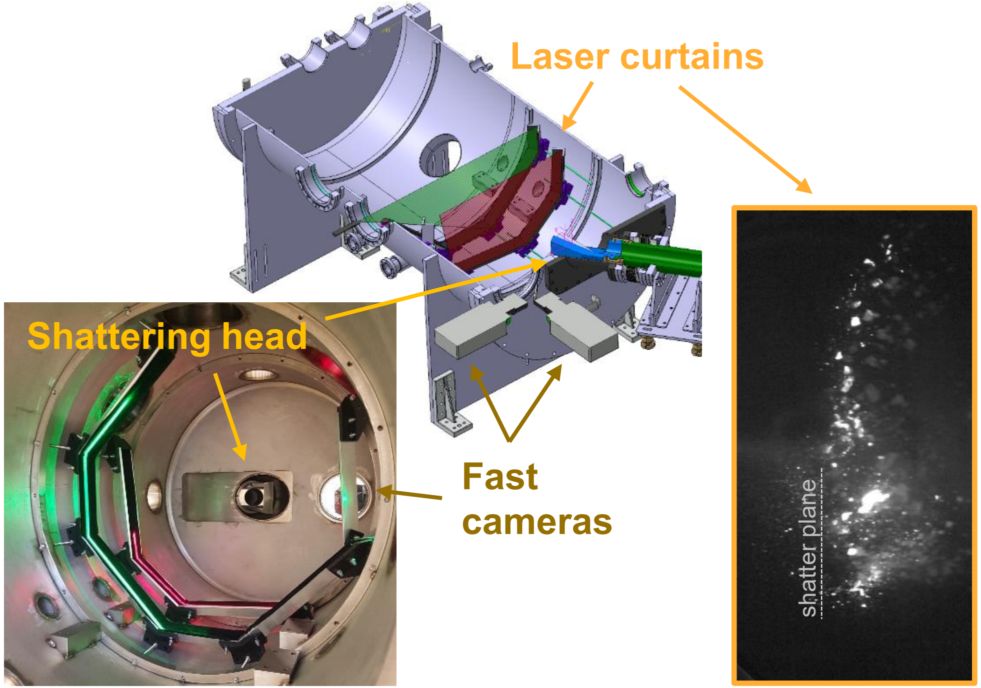


Pellet fragmentation

- Fragment plumes of ITER-DMS pellets characterised with laser curtains

➡ Simulations reproduce trend of for FSD dependence on impact velocity
Note: discrepancy of absolute volume fractions possibly due to 2D imposed volume estimates

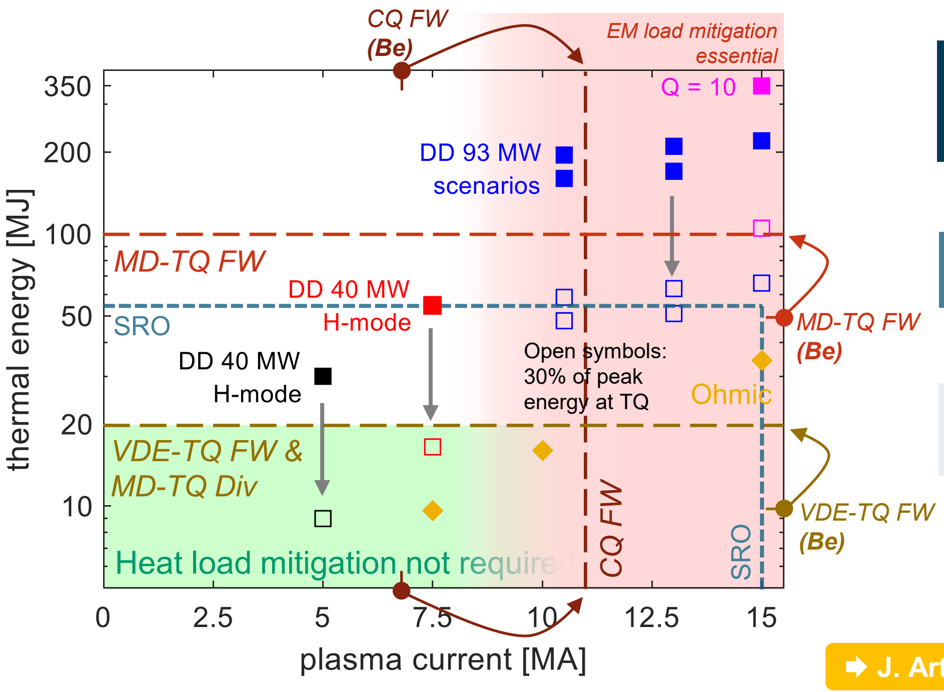




DMS Optimisation for ITER Operation

Load limits

- CQ melting avoidance up to 11-12 MA with W wall
- TQ melt limits for FW ~2x higher
- DMS radiation flash load no issue for W and remains acceptable for SS diagnostic FW
- Electromagnetic load mitigation required for $I_p \geq$ 8-9 MA



➡ Requirement to fully radiate W_{th} and W_{mag} before TQ and CQ onset is relaxed

➡ SRO covers full range of I_p and W_{th} up to ~60MJ

- 1st phase (SRO): W FW (w/o active cooling) + W actively cooled div.
- Later phases (FPO-x): actively cooled W first wall (FW) and divertor

➡ J. Artola, Poster #2762

DMS Optimisation in ITER Research Plan

SRO: FP, lim., div. ≤ 3.5 MA Protium → ≤ 7.5MA & 2.65/5.3 T Protium → ≤ 7.5 MA & 2.65 T Deuterium H-mode → ≤ 15MA & 5.3 T Protium

FPO-1: Protium → ≤ 15MA & 5.3 T Protium + Tritium → ≤ 7.5 MA & 2.65 T Deuterium H-mode → FPO-2, …

A. Loarte, PPCF 2025

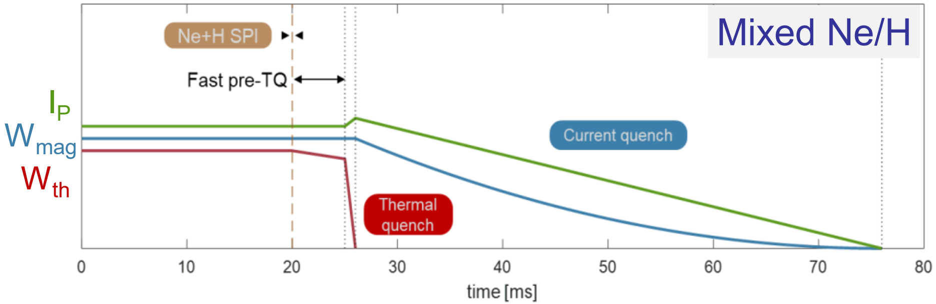
S. Yoon, TEC/1-1

Targets for DMS Optimisation:

Mitigation:	W_{th}	W_{mag}	Electromagn.	RE Hot tail	RE β decay (T)	RE Compton	RE Avalanch.	Impact of RE
Demonstr. in SRO	60 MJ	400 MJ ✓	15 MA ✓	10-20 keV ✓	Y ✓ (in FPO-1)	N	15 MA (✓) (if w/o risks)	Up to (✓) low risk I_{RE}
Needs for DT-1	350 MJ	400 MJ	15 MA	10-20 keV	Y	Y	-	-

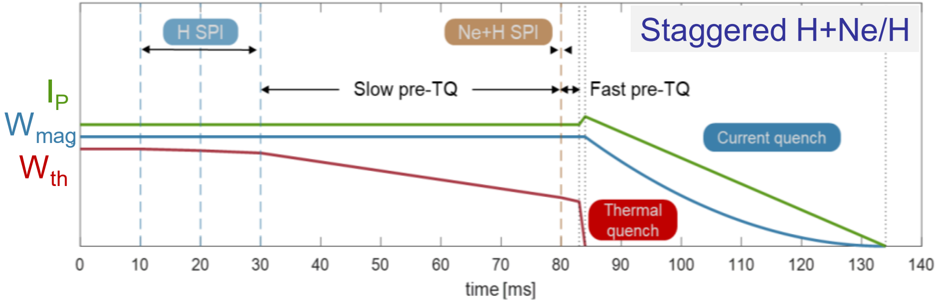
- SRO: DMS optimisation w/o risking water leaks is possible
- FPO: large thickness of upper W PFCs → lower risk of single RE event causing water leak
- Risks of additional RE-seeds in DT:
  - β-decay: as soon as T is used
  - Compton-scattering: risk increases gradually with increasing fusion power and activation

Injection schemes

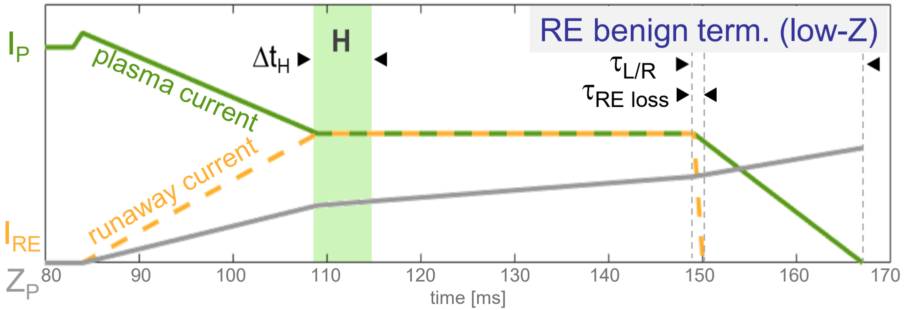


pre-TQ requirement:
0.27% Ne + 99.73% H (assimilated 2x10^{24} atoms)

- Fast pre-Thermal Quench (~ few ms)
- *BUT: Arrival time critical for multiple SPI*

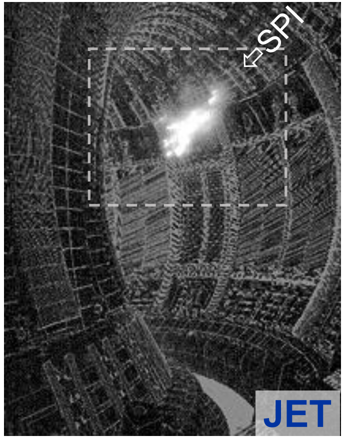


- Slow pre-TQ (several 10 ms) after H SPI
- Significant pre-TQ energy loss
- Dilution cooling aids RE avoidance (T_e < 1 keV)
- *BUT: plasmoid drift limits H-assimilation*

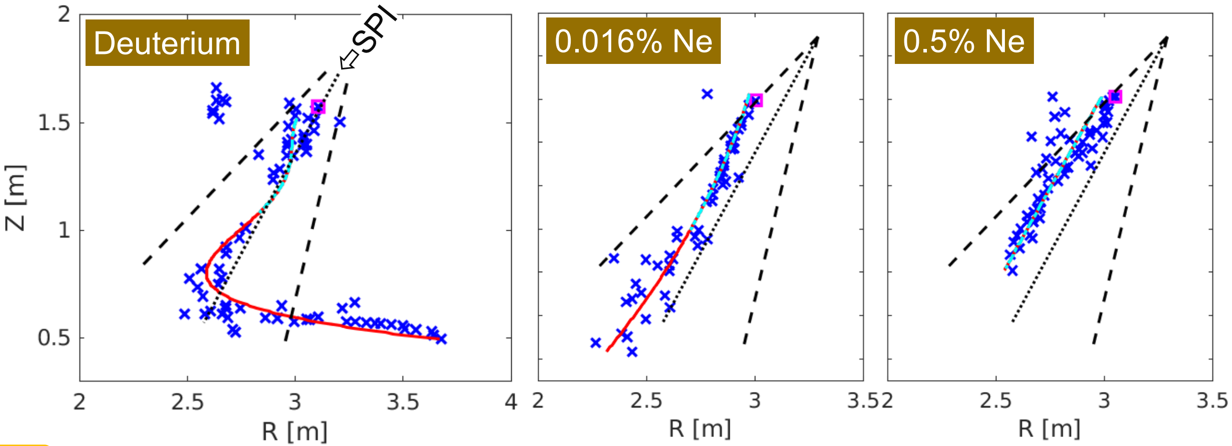


- H SPI leads to fully benign termination
- No re-avalanching
- Broad wetted area during final RE loss
- *BUT: small window for access to regime*

Staggered injection – plasmoid drift



Fragment tracking for Ne-doped SPI



➡ **M. Kong, Poster #2799**

X = inboard edge of D_α emission (fast camera)
Red curve: fitted curve

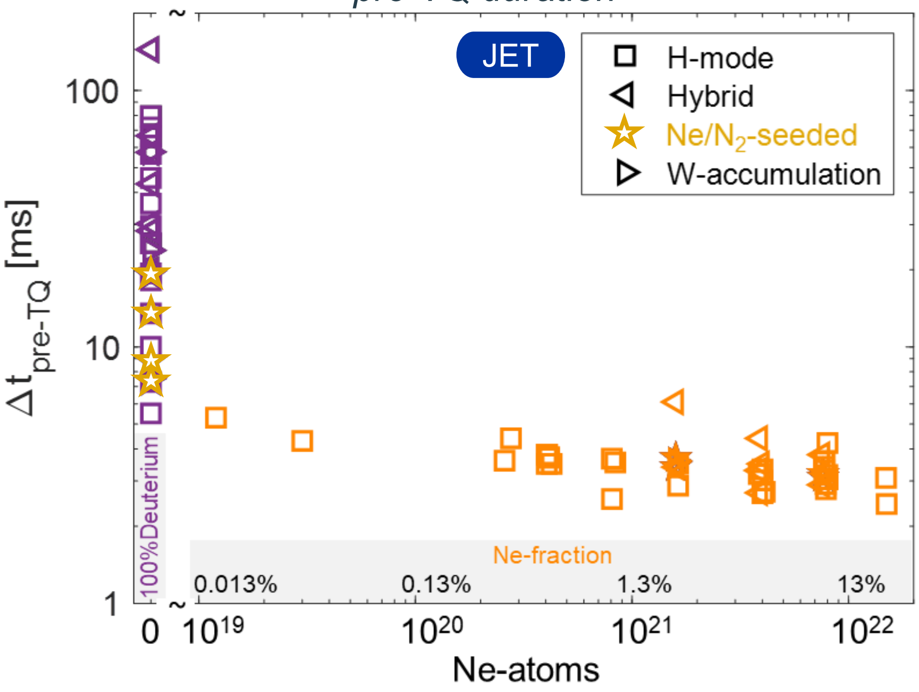
- SPI into H-mode (2.5 MA, W_{th}~4MJ)
- Trajectory with maximum emission in fast camera observation identified
- Scan of neon-fraction from 0 – 10%

➡ Adding Ne > 0.01% might reduce outward drift → but short pre-TQ

Staggered injection – pre-TQ dynamic

- Time until TQ examined for different target plasmas

pre-TQ duration



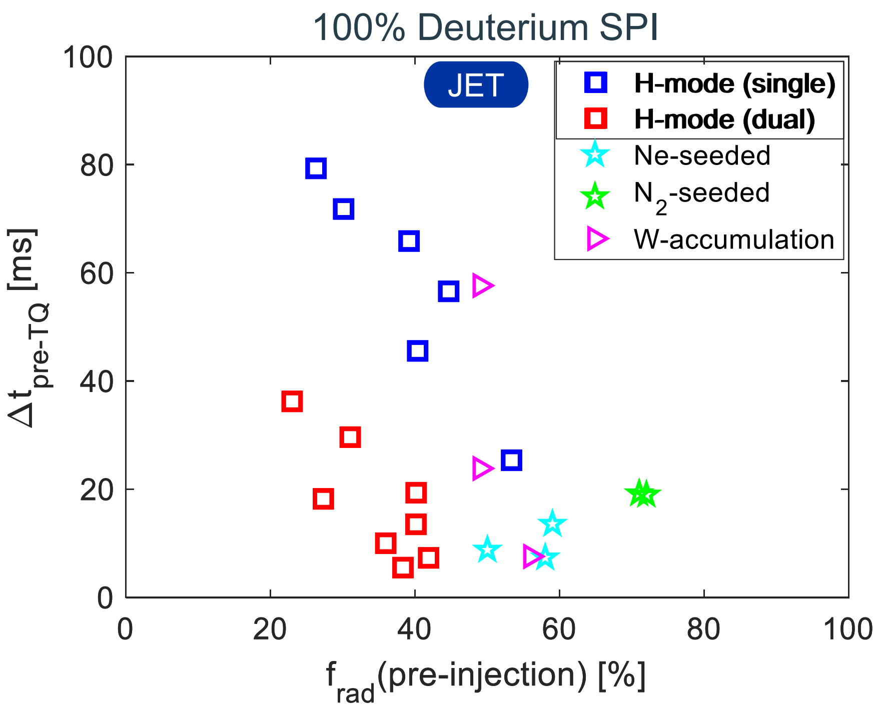
- **Ne/D-SPI:**
  - smallest Ne-doped SPI already drastically shorten pre-TQ
- **D-SPI:**
  - generally longer than Ne/D
  - large variation of pre-TQ duration!

Similar W_{th}~4MJ for H-mode and seeded plasmas

S. Jachmich et al, EPS 2024

Staggered injection – pre-TQ dynamic

- Radiated power fraction *before* SPI injection



➢ Earlier TQ-onset for dual-D injections
→ faster energy loss?

➢ pre-TQ very sensitive to intrinsic and seeded impurities

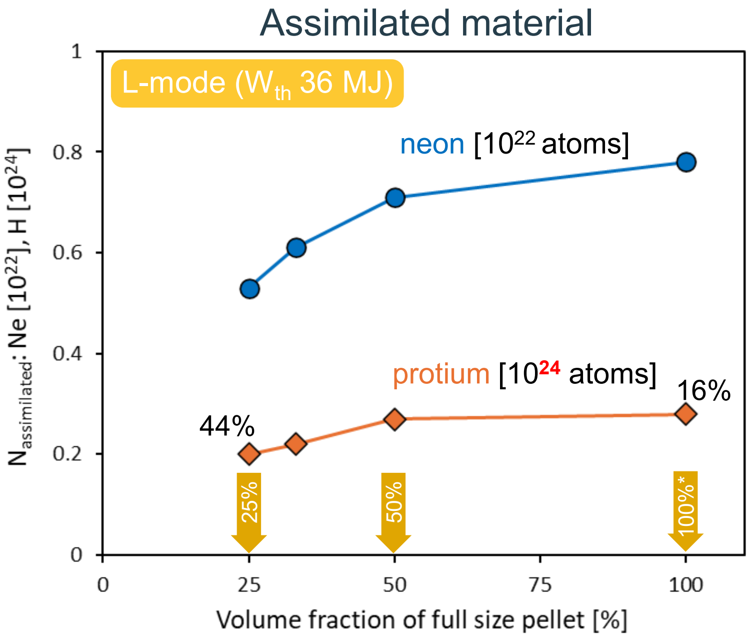
➡ Impedes staggered injection scheme

=> optimum injection scheme to be decided in real-time when disruption is detected

S. Jachmich et al, EPS 2024

Material assimilation – Pellet size

- 1D INDEX simulations of Ne+D SPI into ITER plasmas
- Low W_{th} and T_e limits material assimilation
- Fraction of assimilated material higher for small pellets, but possibly less core deposition



➡ Assimilation saturates for large pellets (>50%) in low energy plasmas

Note: assimilation fraction in DT H-mode ~ 78%

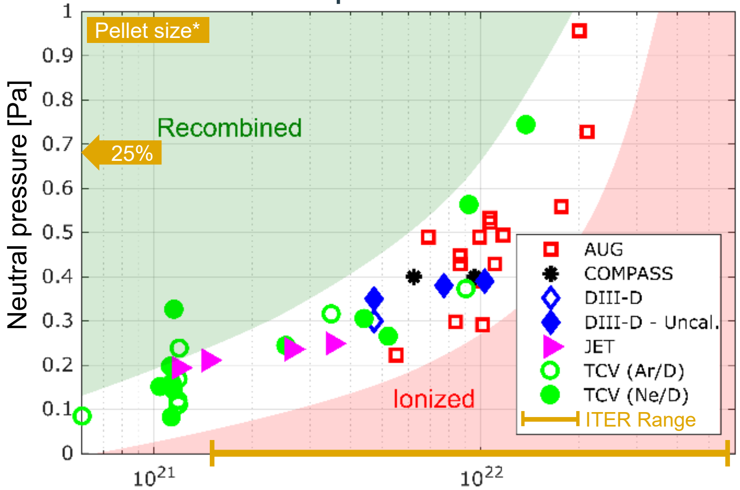
*w.r.t. full size DMS pellet

A. Matsuyama, TSDW 2025

RE benign termination limits

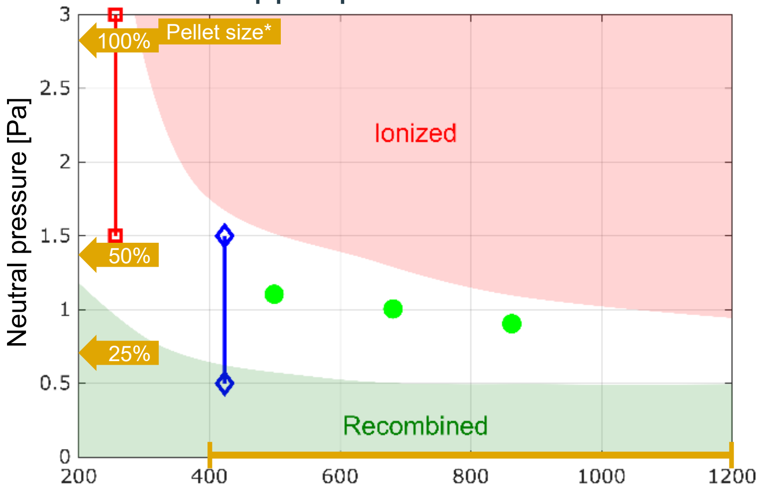
- RE benign termination: recombination of companion plasma + final low q_{edge} collapse
- Lower pressure limit: material amount to achieve recombination (→ less Ne beneficial)
- Upper pressure limit: RE ionisation causes ne rise → benign termination degrades

Lower pressure limit



*w.r.t. full size DMS pellet

Upper pressure limit



➡ U. Sheikh, Poster #2818

➡ pre-RE SPI impacts benign termination feasibility
=> need to minimise Ne and optimise H assimilation

Summary and Outlook

Summary and Outlook

- DMS is a key machine protection system for effective execution of the ITER Research Plan
- Design is close to completion and has reached maturity for manufacturing

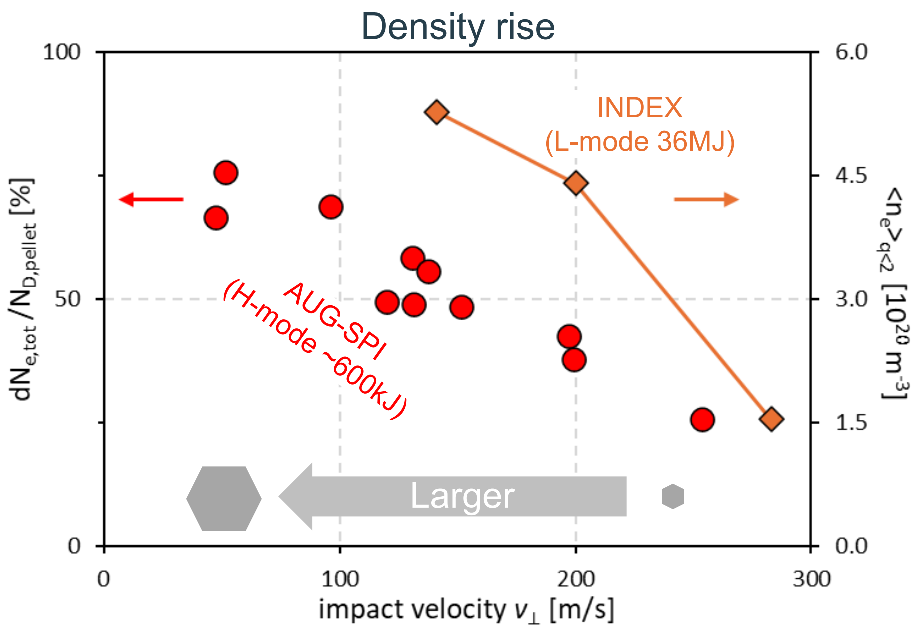
- Some remaining physics and technology questions guiding the design are being resolved in parallel to the manufacturing preparation phase
  1) Multiple mixed SPI for RE avoidance: Jitter for Ne/H mixed injection
  2) Staggered injection scheme: Efficacy of Ne-doping? Viable for low-W_{th} plasma (seeding, W-acc.,)?
  3) RE impact mitigation: Boundaries for benign termination (lower/upper limits, I_{RE}-dependence)?
  4) Pellet size optimization: Need to cover range of plasmas. Compatibility with RE benign?
  5) Routine operation of ITER DMS-like SPI on a tokamak
- Design needs to be tailored for the type of plasma and disruption phase
  → impacts choice for shattering geometry, pellet size, velocity (and fragment size)
- DMS is highly flexible and ITER 2024 baseline plan allows for full optimization of shattered pellet injection for disruption mitigation


Thank you!

Backup

Material assimilation – Fragment sizes

- 1D-INDEX simulations: enhanced assimilation large fragment size distribution
- AUG-SPI: similar trend for deuterium SPI into H-mode
- Cases with degraded confinement (e.g. W-accumulation) remain to be studied



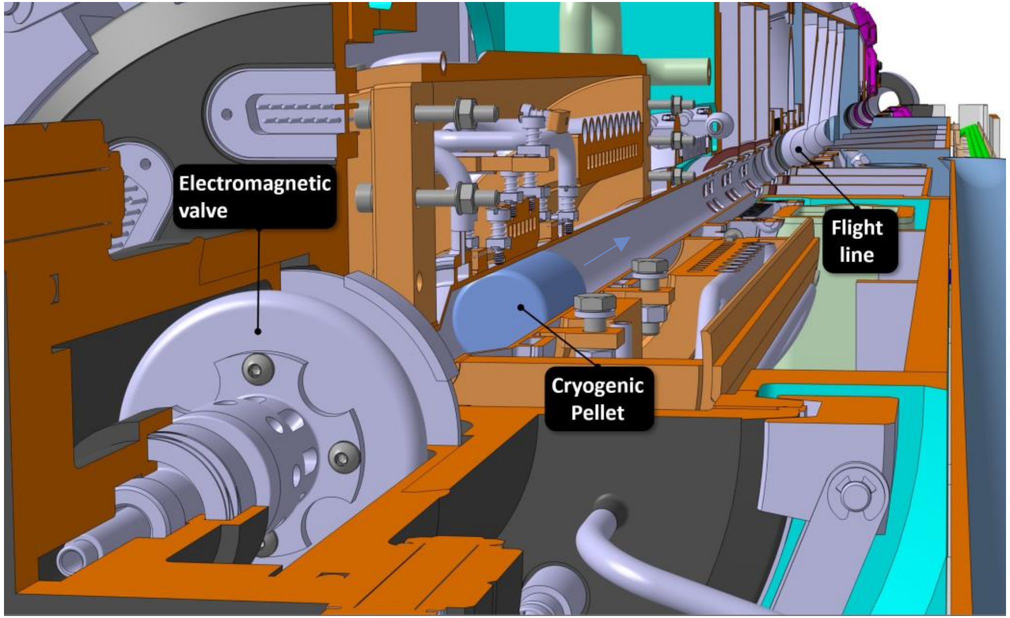
➡ Better assimilation for larger fragments

S. Jachmich, EPS 2023

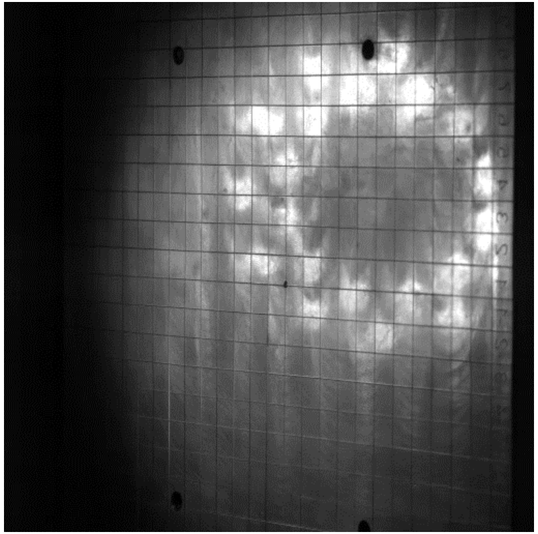
A. Matsuyama, IAEA TSDW 2025

Flight trajectory

- Maximum tolerable deviation from ideal pellet trajectory is 0.15°.
- Tests being conducted to assess and minimise deviation



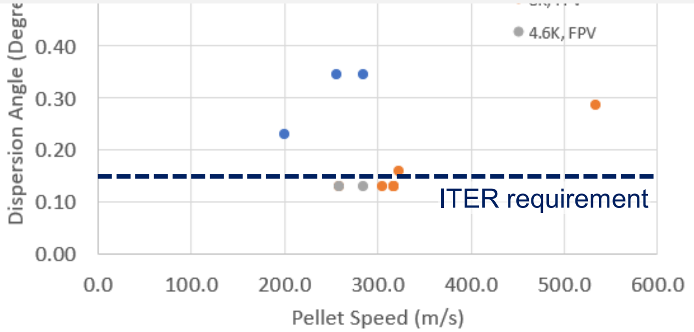
Cut through flight line

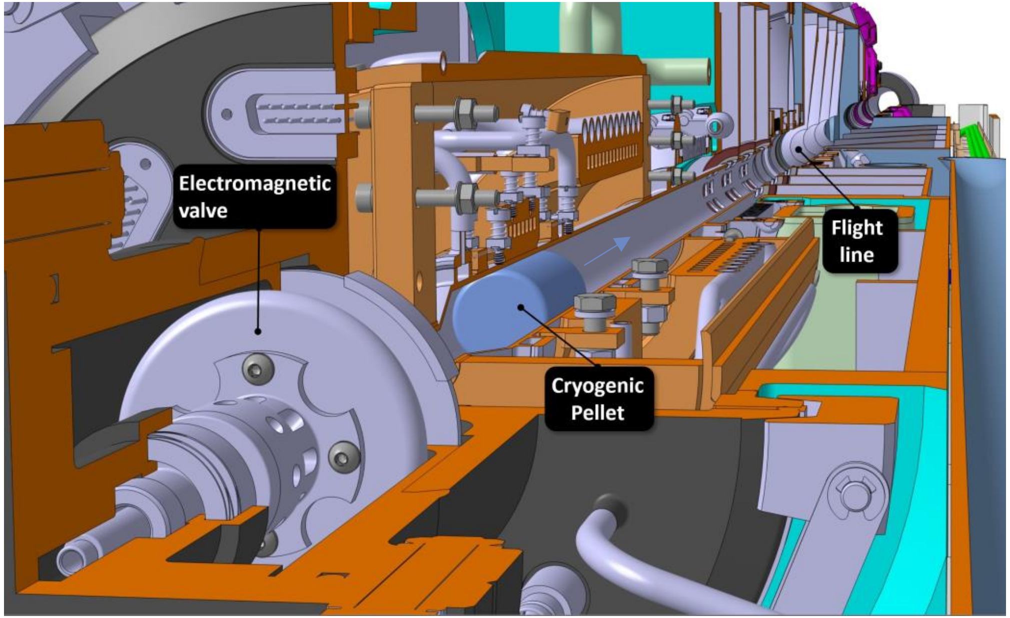


Target measurements (ORNL)

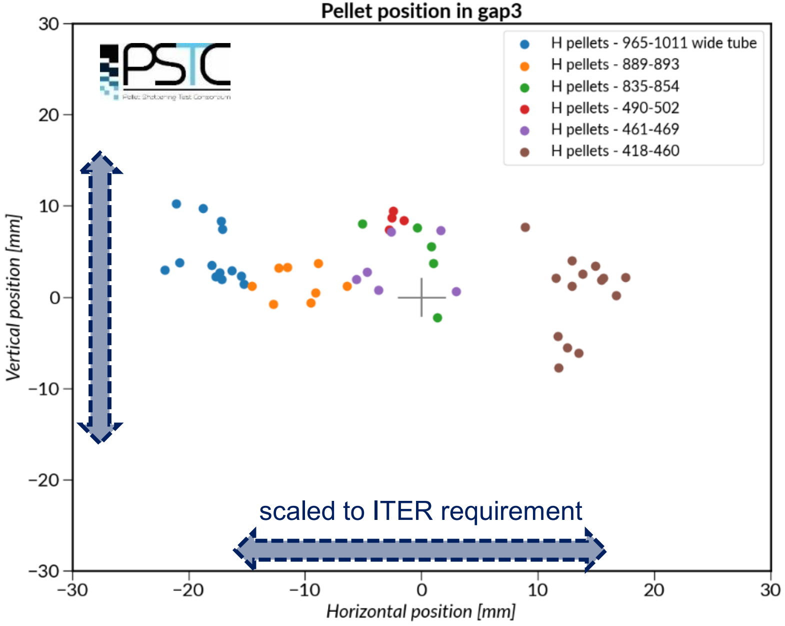
Flight trajectory

- Maximum tolerable deviation from ideal pellet trajectory is 0.15º.
- Tests being conducted to assess and minimise deviation





Cut through pellet flight line



Disruption mitigation functions:

- DMS action to result in disruptions with Cat-I electromagnetic loads and Cat-I heat loads
  → No consumption of disruption budget

Disruption mitigation methods:

Heat loads:

- Limit conducted energy of W_{th} during TQ to 20MJ through line radiation (pure Ne>$8x10^{21}$)
- Dissipate W_{mag} during CQ through line radiation (pure Ne>$2x10^{21}$)

→ *W-first wall: targets can be relaxed*

EM-loads:

- Control current decay time >50 ms and <150 ms ($5x10^{21}$< Ne < $3.5x10^{22}$)

→ *W-first wall: aim at upper current decay time limit to minimize RE generation due to avalanching*

RE-avoidance:

- Densify (raise n_e) and reduce T_e, e.g. through dilution cooling (H>$2x10^{23}$-$2x10^{24}$)

RE-impact mitigation: either through collisional drag (Ne) or recombination (H)

→ *Inertially cooled W-FW: test low-Z and high-Z mitigation schemes*

(quantities refer to assimilated material)

DMS Functional specifications

- Material delivery to the plasma:
  - required amount of low-Z (H or D) and high-Z (Ne)
  - pellet size and number of pellets/injectors,
  - injection scenarios, maximum jitter of pellet/fragment arrival
  - compatibility of injection schemes for various mitigation tasks

- Mass assimilation:
  - optimum fragment size and velocity distribution (pellet velocity, shatter angle) for pre-TQ and post-TQ injections
  - injection trajectory for different disruption types and activation times

DMS Functional specs – Total Mass

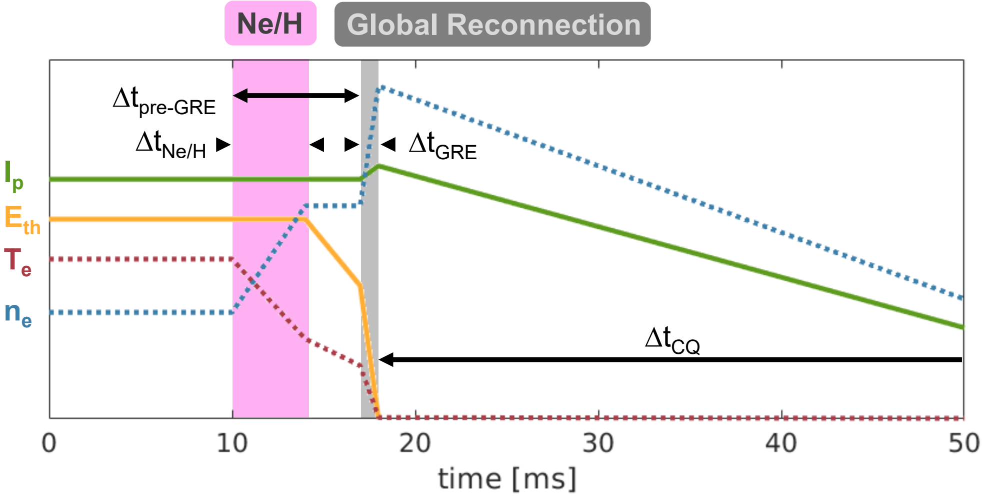
- Total mass *delivered* to plasma: ≥ 5×10^{24} H and ≥ 1×10^{25} Ne-atoms

- Required *assimilated* quantities:

	Function	Species	Quantity [atoms]	Injection Time	Reference
1	Thermal load mitigation *Thermal Quench*	Ne	>8×10^{21} (pure Ne) >1×10^{21} (with H)	pre-TQ	3D fluid simulations
2	Thermal load mitigation *Current Quench*	Ne	> 2×10^{21} (pure Ne)	pre-TQ or post-TQ	DINA
3	EM load mitigation *Current Quench*	Ne	> 5×10^{21} < 3.5×10^{22} (pure Ne)	pre-TQ / post-TQ	DINA
4	RE avoidance (collisional drag)	H	~2×10^{23} (non-nuclear) ~2×10^{24} (DT-ops)	pre-TQ	1D simulations
5	RE impact mitigation (high-Z)	Ne	~1×10^{25}	post-TQ	DINA
5	RE impact mitigation (low-Z)	H	~8×10^{23}	post-TQ	Simulations of RE + neutrals

Injection scenarios – Mixed

- ➢ Ne/H mixed SPI pellets: standard for pre-TQ injection



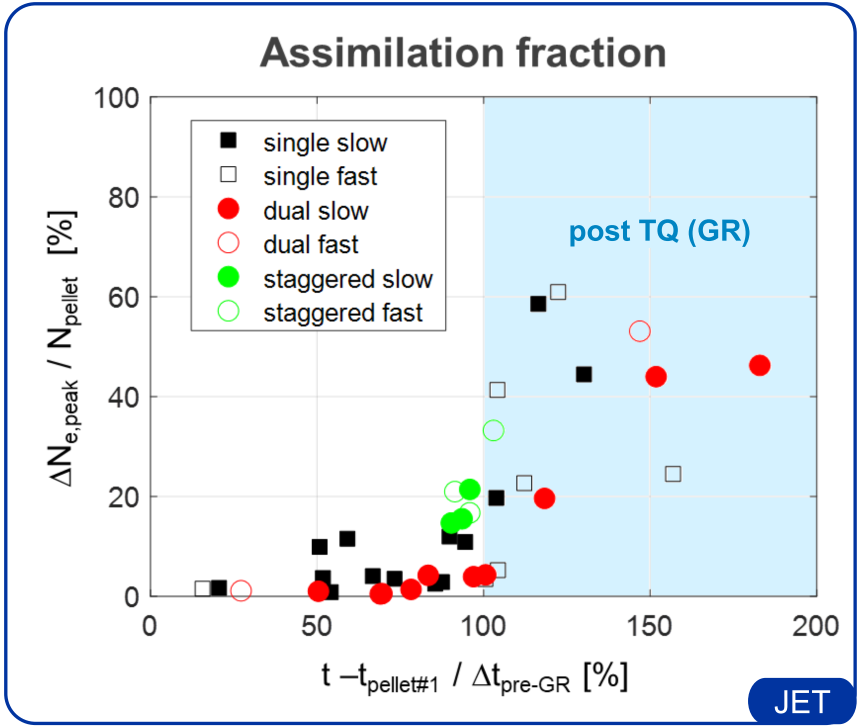
Mixed Ne/H:

- Protium delivered together with neon
- Late density rise
- Limited plasma cooling before GRE (TQ)
- Fast energy loss

➢ Multiple mixed SPI for RE avoidance:

- *Jitter constraint for Ne/H mixed injection for large range of plasmas*

Mixed injection – Density rise



JET Neon + Deuterium

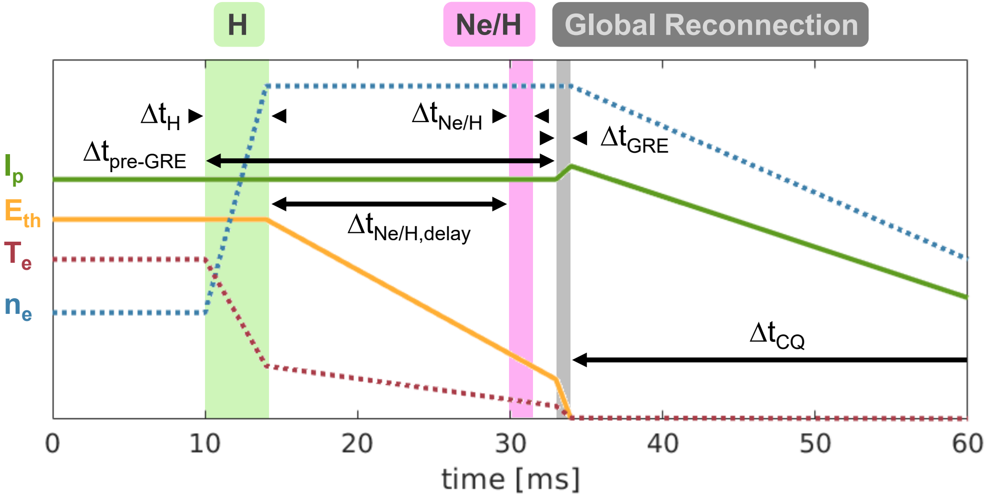
~300/450 m/s | 2.5 / 3.0 MA | 4 / 8 MJ (H-mode)

- Main density rise after global reconnection
  ➡ Runaway avoidance difficult

JET SPI science meeting Feb 2024

Injection scenarios – Staggered

- Staggered: H-pellet followed by Ne/H-pellet

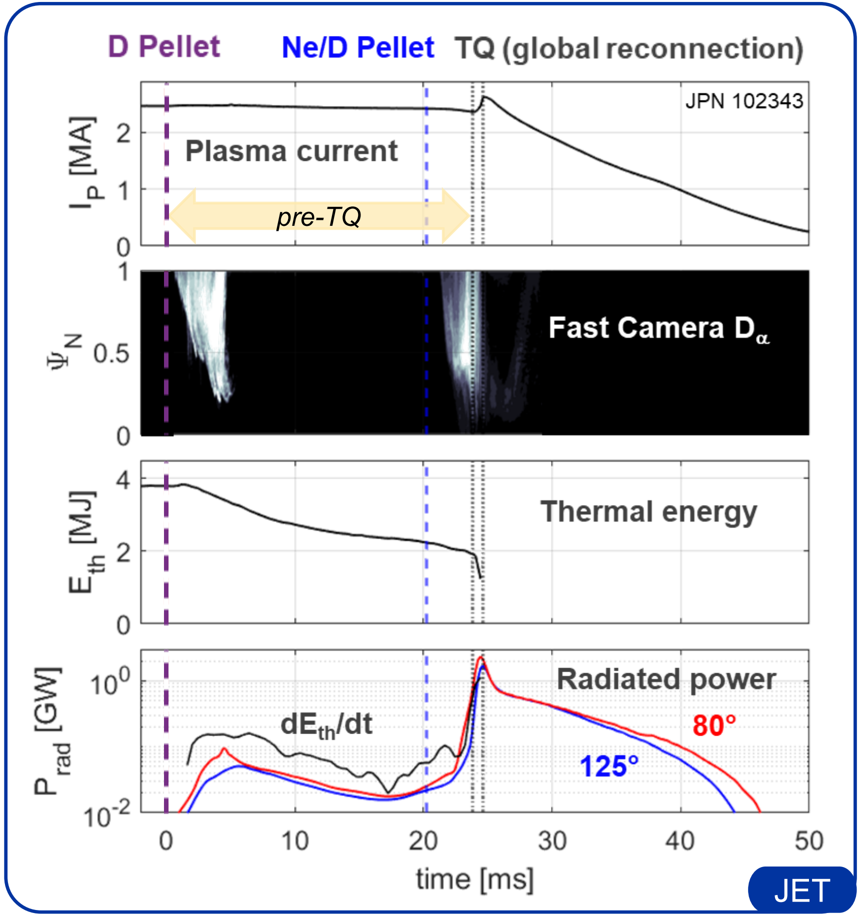


Staggered H + Ne/H:

- Global density rise
- Dilution cooling
- Slow energy loss

- Multiple SPI for RE avoidance:
  - *Viability of staggered injection scheme?*

Staggered injection



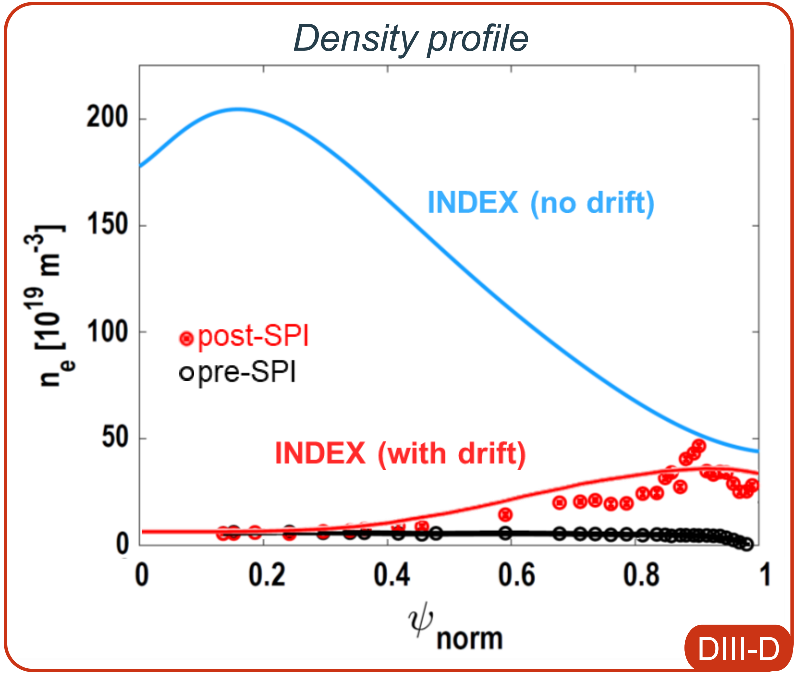
JET Staggered D + Ne/D

~350 m/s | 2.5 MA | 4 MJ (H-mode)

- 50% energy loss
- Dilution cooling to ~100 eV
- High radiation during TQ
- Current quench control

Staggered injection – Deuterium assimilation

- Mass assimilation strongly limited by plasmoid drift



DIII-D Deuterium SPI

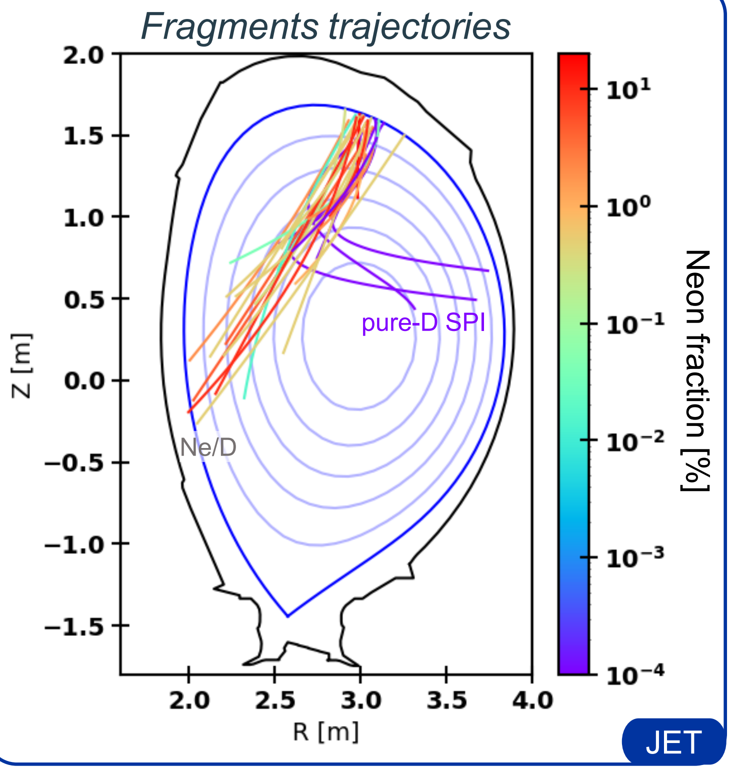
540m/s | 1.25 MA | 0.8 MJ (H-mode)

INDEX simulations with back-averaging drift model

- Drift reduces assimilation to ~10%
- Similar observation in ASDEX-Upgrade

A. Lvovskiy, A. Matsuyama, NF 2024

Plasmoid drift mitigation



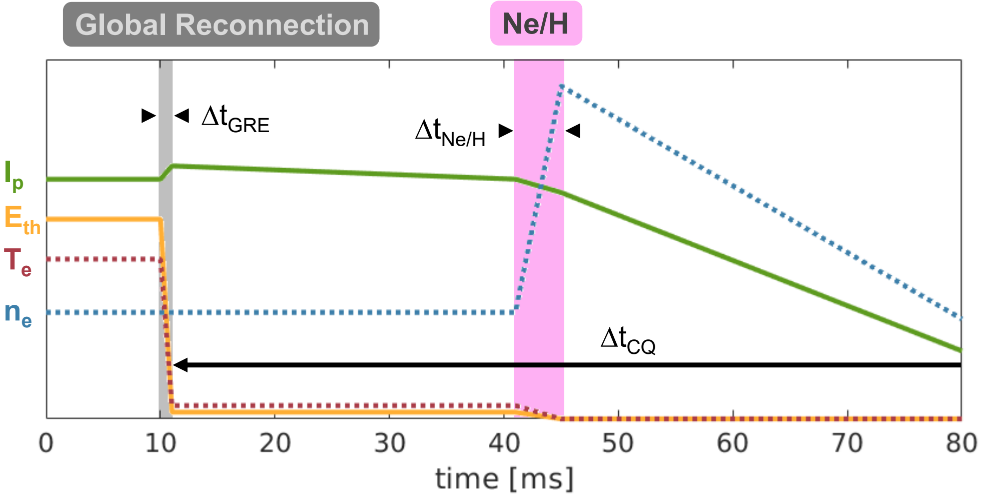
- Trajectory with maximum emission in fast camera observation identified
- Scan of neon-fraction from 0 – 10%

➡ Adding Ne > 0.1% reduces outward drift

➢ Plasmoid and rocket effect:
- *Methods for reduction (Ne-doping?)*
- *HFS-like injection beneficial?*

JET SPI science meeting Feb 2024

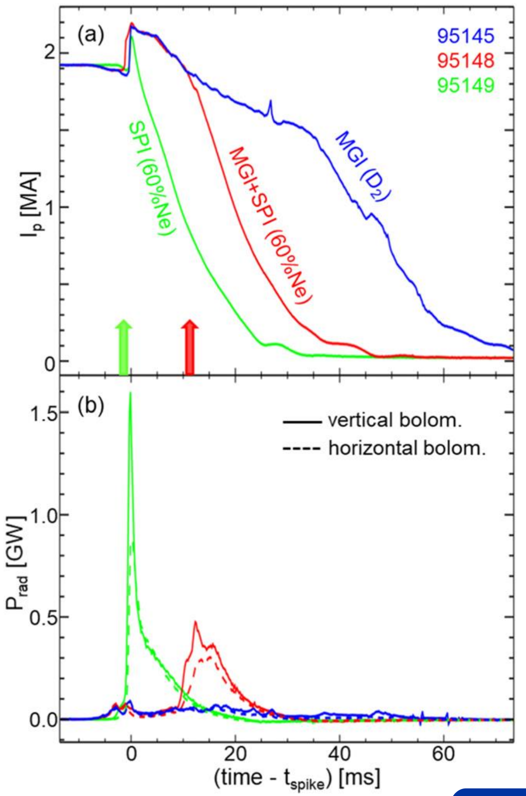
Injection scenarios – post-TQ



Post-TQ injection

- CQ heat and EM load mitigation
- High assimilation required despite low energy plasma

Injection scenarios – post-TQ



JET

S. Jachmich, NF 2022

JET post-TQ injection

~550 m/s | 60%Ne SPI | 2.0 MA

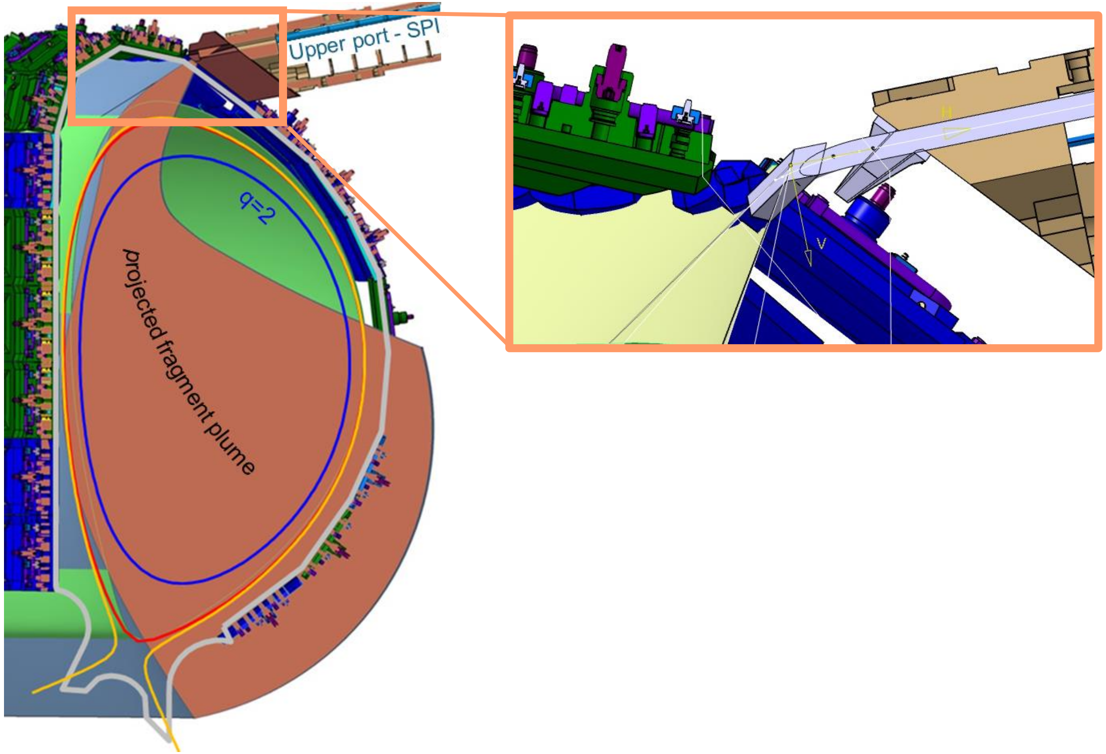
- JET X_R ~350 (20°), η_{gas}~95%
- ITER X_R ~110 (35°), η_{gas}~60%
- Smaller X_R in ITER, but also larger T_e

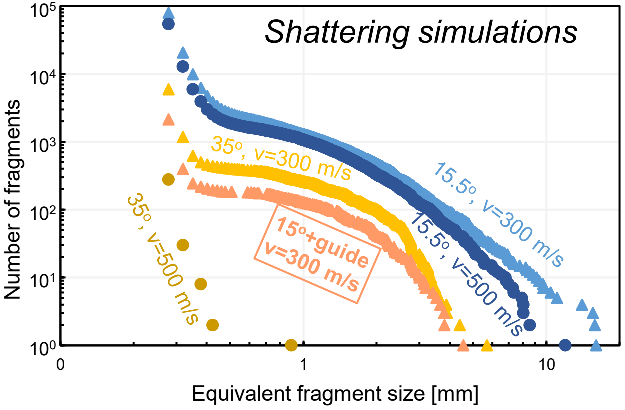
X_R prescribes fragment size probability distribution:

$X_R \propto$ smaller fragments

Injection geometry – upper ports

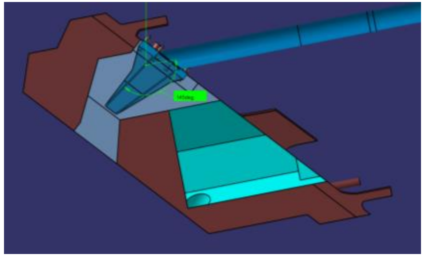
- Low Te in post-TQ injections requires small fragments and large gas fraction → steep impact angle
- But: plastic deformation of shattering unit over ITER operation lifetime
  → Revised design with double shattering geometry pointing toroidally



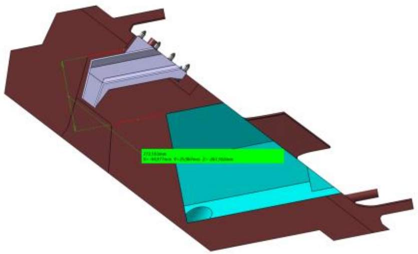


DMS Upper Ports – shattering

- Shatter pellets at low angle (15°) and guide fragments towards HFS to overcome plasmoid drift



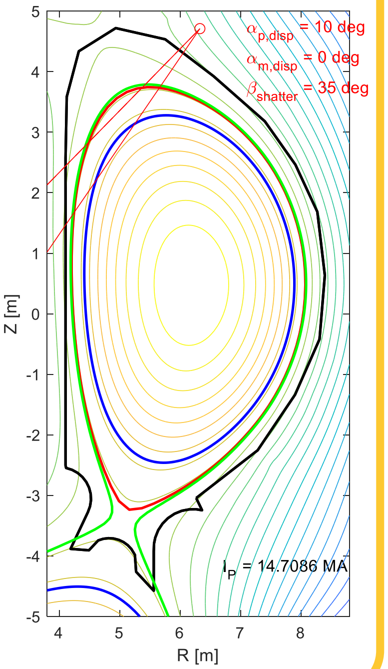
Possible shatter head = 35°

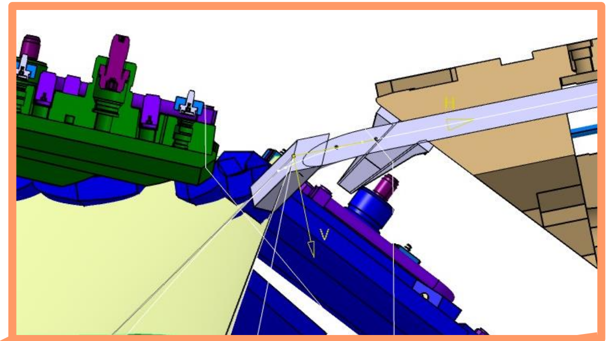


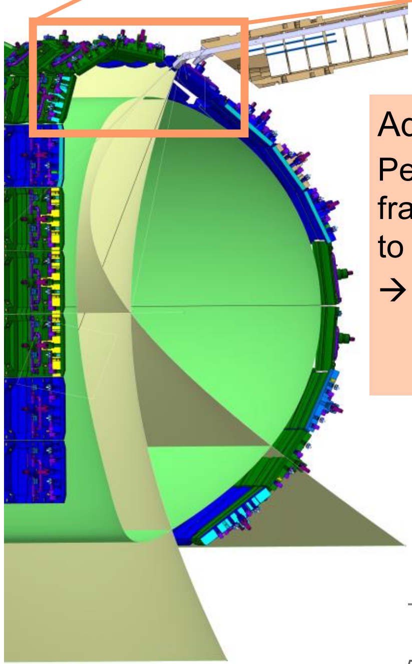
Original shatter head = 65°

post-TQ

Downward MD





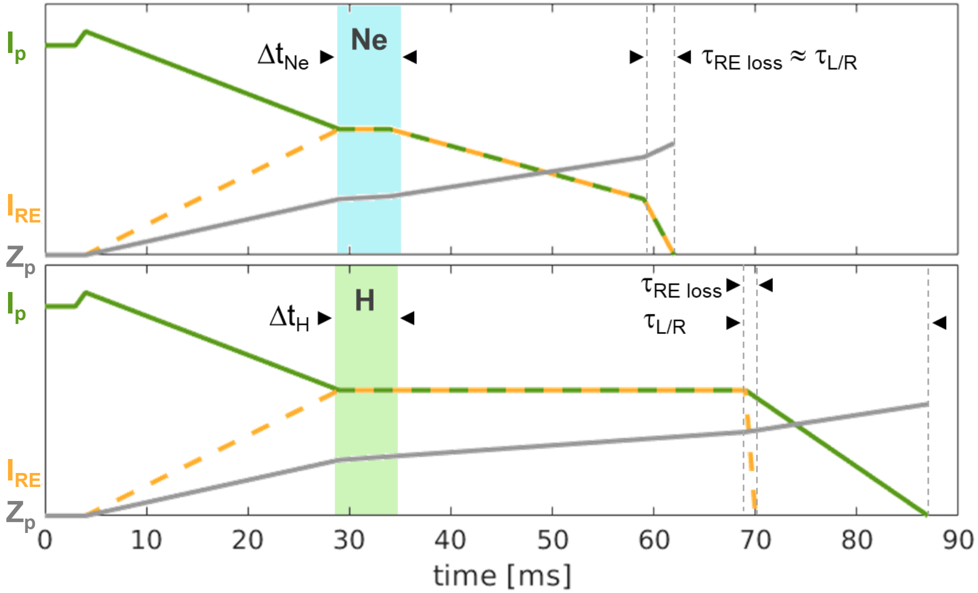


Advanced shatter head:

Pellet shattered at 15° and fragments directed sideways to intersect with plasma.

→ *HFS-like injection for reduction/avoidance of plasmoid drift.*

Injection scenarios – RE impact mitigation



RE beam injection

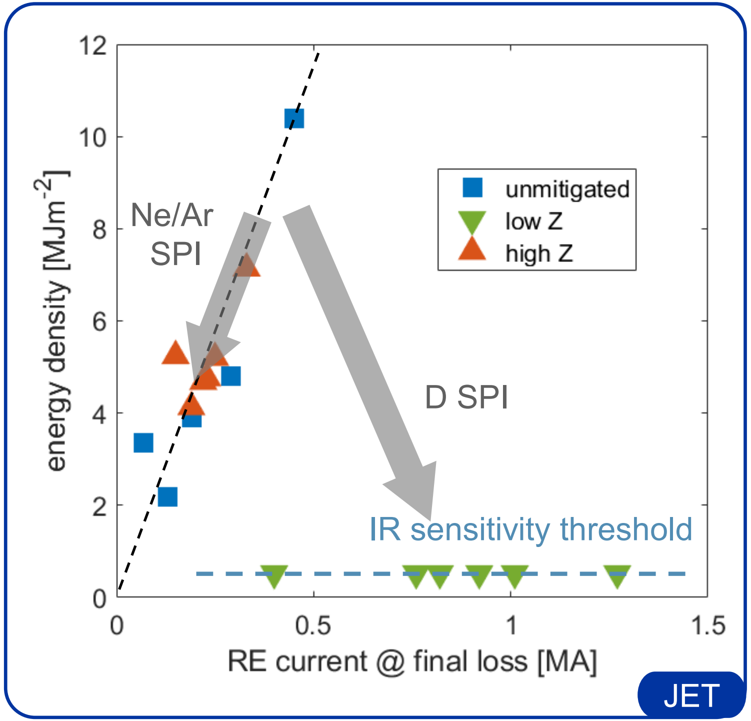
High-Z SPI:

- Neon SPI dissipates some energy
- Still significant impact during final loss

Low-Z SPI:

- H SPI leads to fully benign termination
- Purging of Neon (from earlier SPI)
- Triggering of fast MHD instability
- Expulsion of REs prior impact
- No re-avalanching
- Broad wetted area

RE impact mitigation



JET RE beam injection

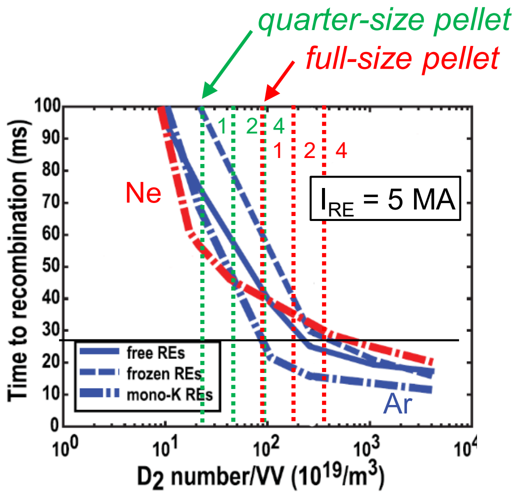
Ne or Ar injection:
→ finite energy deposition

D injection:
→ no measurable heat load despite higher I_{RE}

C. Reux, PPCF 2022

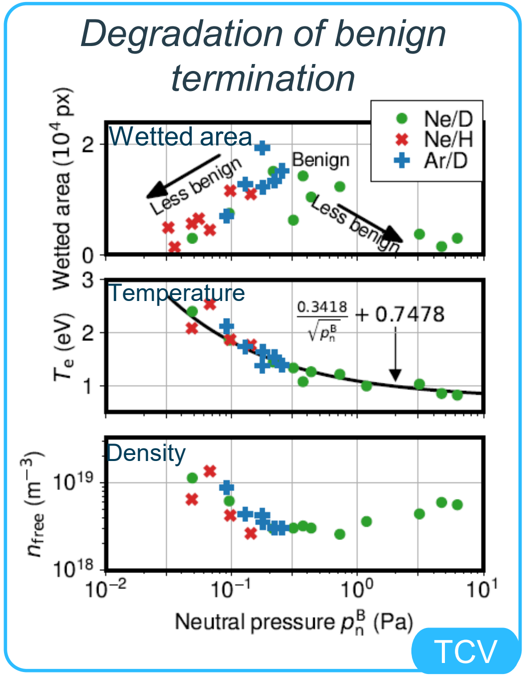
low-Z benign termination – lower limit

- Vertical movement of RE beam limits time for recombination: large pellets beneficial
- Small pellets effective up to I_{RE}~5MA
- Ne-amount injected for TQ and CQ mitigation defines required H-amount

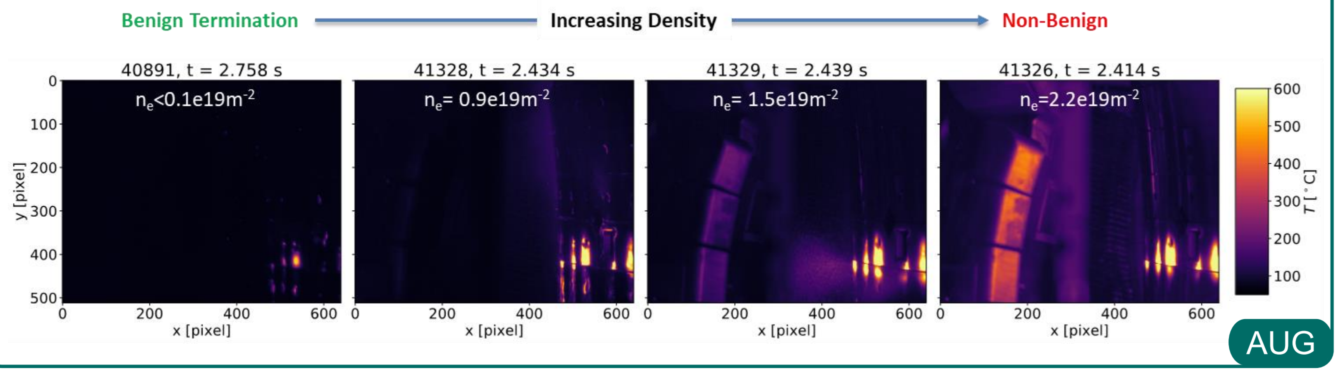


E. Hollmann, NF 2023

low-Z benign termination – upper limit



- RE avoidance scheme might cause too high neutral pressure
- Density rises again with neutral pressure due to reionization
- Reduces MHD growth and inhibits benign RE beam termination



➢ RE impact mitigation:

- *Boundaries for benign termination (low/up limits, I_{RE}-dependence)?*
- *Optimisation of injection (train of small H-pellets)?*
- *Any benefit from high-Z injection?*

U. Sheikh, PPCF 2024
M.Hoppe, subm. PPCF

Total Mass – Number of pellets

- ❑ Total mass *delivered* to plasma: ≥ $5x10^{24}$ H and ≥ $1x10^{25}$ Ne-atoms

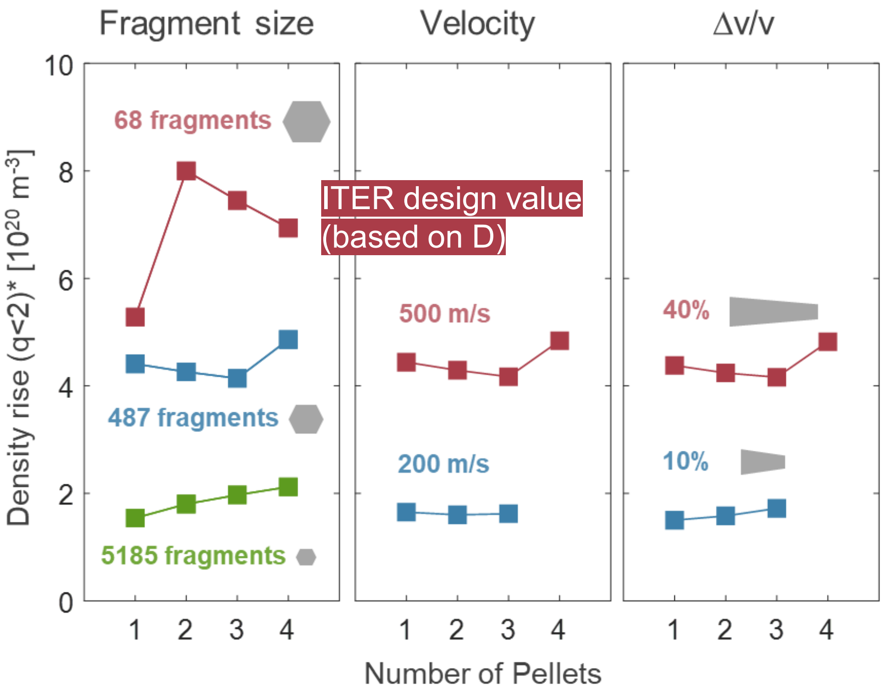
➢ Required number of pellets – EP-injectors (total of 24):

Injection scheme	Species and *assimilated* quantities	Number of required pellets	Port (Direction)	Redundancy
Staggered (H, then Ne/H)	$2x10^{23}$ H (non-nuclear)	2 (15% assim.)	Tangential	
	$2x10^{24}$ H (DT-ops)	8 (15% assim.)		
	$3.5x10^{22}$ Ne (max)	3 (diff. toroidal locations)		
Mixed	$3.5x10^{22}$ Ne (max) + $3x10^{24}$ H	3 (50% assim., diff. toroidal loc.)	Tangential	
RE high-Z	10^{25} Ne	14 (100% assim.)	Up+Down	
RE low-Z	$5x10^{23}$ H	2	Up+Down	
Total in EP ready to fire (max 24)	**Staggered + high-Z**	**19 (non-nuclear) or 25 (DT-ops)**		**5 or -1**
	Mixed + high-Z	**17**		**7**
	Staggered + low-Z	**7 (non-nuclear) or 13 (DT-ops)**		**17 or 11**
	Mixed + low-Z	**5**		**19**

Mass assimilation

Fragment plume characteristics

- ❑ Delivered pellet fragment size range: ≥ 0.5 mm and ≤ 5 mm



ITER / INDEX Neon + Deuterium SPI

15 MA | 35 MJ (L-mode)

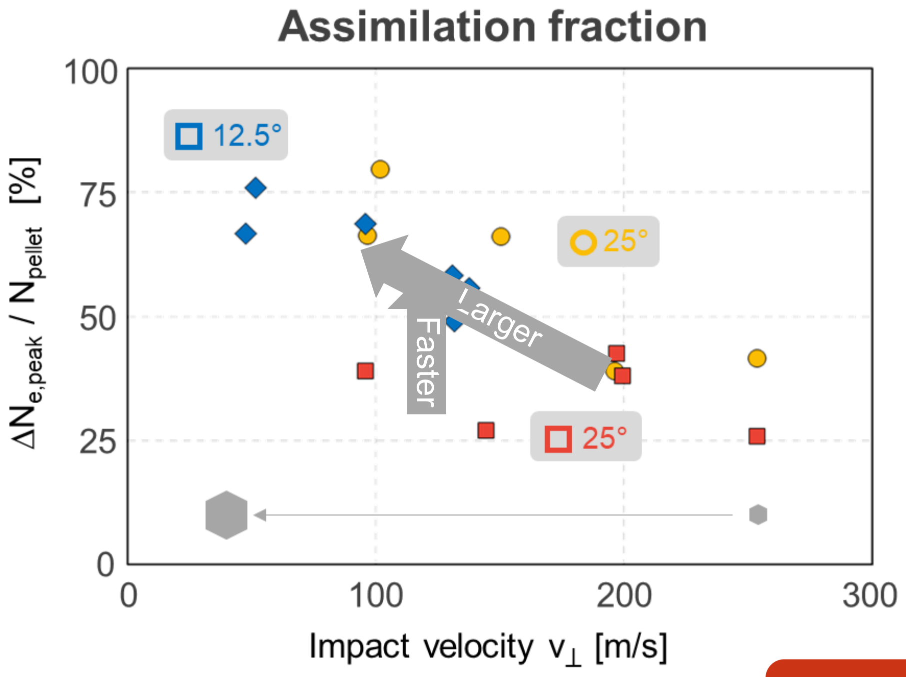
- Larger Fragments
- Higher Velocity
- Longer Plumes

A. Matsuyama, ITER_D_53DK9S

*before the global reconnection

Fragment size distribution

❑ Delivered pellet fragment size range: ≥ 0.5 mm and ≤ 5 mm



ASDEX Deuterium SPI

0.8 MA | 0.6 MJ (H-mode)

3 different shatter tubes: ○ 25° □ 25° □ 12.5°

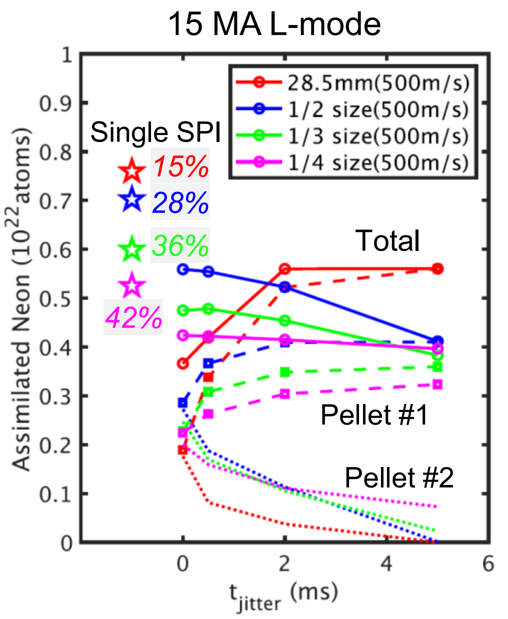
Assimilation from peak density (upper estimate)

Enhanced assimilation ➡
- Larger Fragments
- Higher Velocity

S. Jachmich, EPS 2023

➢ Fragment plume characteristics:
Optimum for large range of plasmas (seeding, instabilities, …)?

Mass assimilation – Pellet size



assimilated fraction

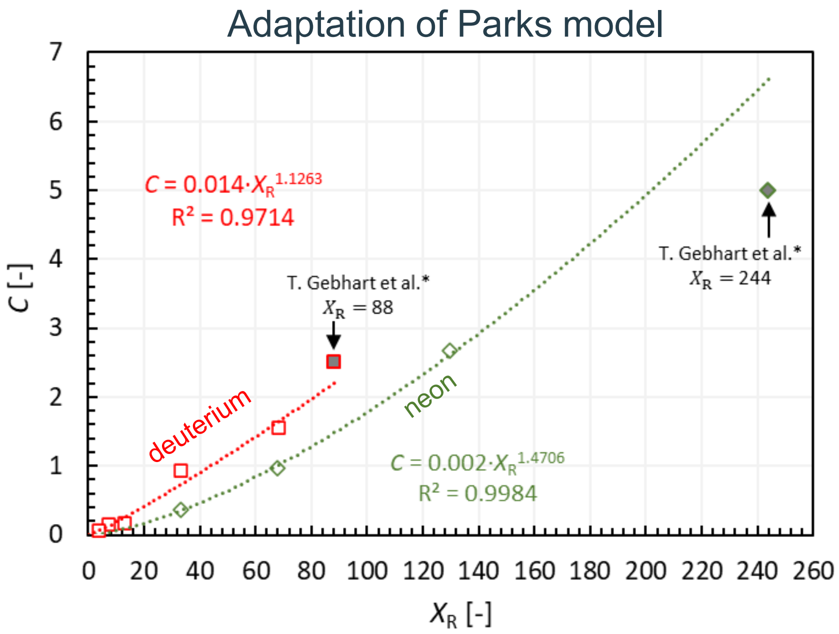
A. Matsuyama, ITER_D_53DK9S

- Very low assimilation fraction for full-size pellets in L-mode
- Smaller pellet helps assimilating second pellet (also longer pre-TQ)

➢ Pellet size optimization:
- *Better assimilation for low W_{th}-plasmas?*
- *Compatibility with RE benign termination?*

Pellet fragmentation

- Parks' model: $f(d) = \alpha d K_0([X_R/(L * C)]\, d)$; parameter C for PDF determined empirically for D and Ne
- Comparison with AUG-SPI lab experiment suggests dependence on $X_R(=v_\perp^2/v_{thr}^2)$
- Extrapolation compatible with original estimate
- *But:* C likely depend on more parameters (shatter head cross-section, pellet size, …)



➡ Improved predictions of fragment size distribution (FSD) with Statistical fragmentation model

Optimum pellet sizes

	Staggered	Mixed	RE mitigation
Baseline size 28.5 mm x 57 mm	Required to overcome reduced H assimilation at higher E_{th}	Synchronisation for multiple SPI too challenging Unnecessary VV pressure loading (low ablation fraction)	Re-ionisation due to too much mass (upper pressure limit)
Quarter Size 20 mm x 30 mm	May require too many pellets for H assimilation at higher E_{th}	Allows testing and applying multiple SPI at low/medium E_{th} Reduced VV pressure loading at low/medium energies	Likely essential, more flexibility in dosing (upper pressure limit)

- Two different pellet sizes → further assessment required to conclude
- Number of injectors is sufficient if low-Z RE mitigation is chosen

Summary of required R&D for ITER DMS

In addition to R&D mentioned above:

- ➢ Effect of vertical displacement during CQ on RE generation
- ➢ Alternatives for injection techniques (e.g. rail-gun) and for disruption mitigation methods

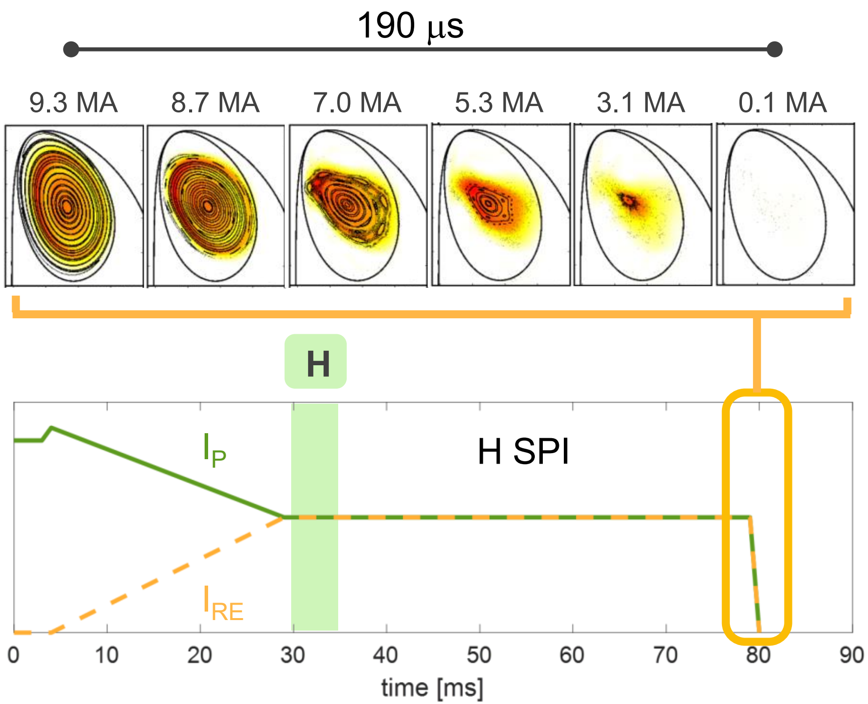
Outlook

- ➢ DMS enters manufacturing preparation phase:
  - Some design changes (e.g. pellet size) can still be implemented.
  - Studies on optimizing injection schemes are still required to help minimizing DMS commissioning time
- ➢ ITER DMS Task Force:
  - IO decided to continue the Task Force to coordinate the resolution of remaining issues and to support established collaborations.

Summary of required R&D for ITER DMS

- Effect of vertical displacement during CQ on RE generation
- Alternatives for injection techniques (e.g. rail-gun) and for disruption mitigation methods
- Multiple mixed SPI for RE avoidance:
  - Jitter constraint for Ne/H mixed injection for large range of plasmas
  - Viability of staggered injection scheme?
- Plasmoid and rocket effect:
  - Methods for reduction (Ne-doping?)
  - HFS-like injection beneficial?
- RE impact mitigation:
  - Boundaries for benign termination (lower/upper limits, I_{RE}-dependence)?
  - Optimisation of injection (train of small H-pellets)?
  - Any benefit from high-Z injection?
- Pellet size optimization:
  - Better assimilation for low W_{th}-plasmas?
  - Compatibility with RE benign termination?
- Fragment plume characteristics:
  - Optimum for large range of plasmas (seeding, instabilities, …)?
- Development of RE beam scenario

RE mitigation – low-Z benign termination



JOREK 3D RE fluid / ITER

RE mitigation by H/D SPI successful in experiments

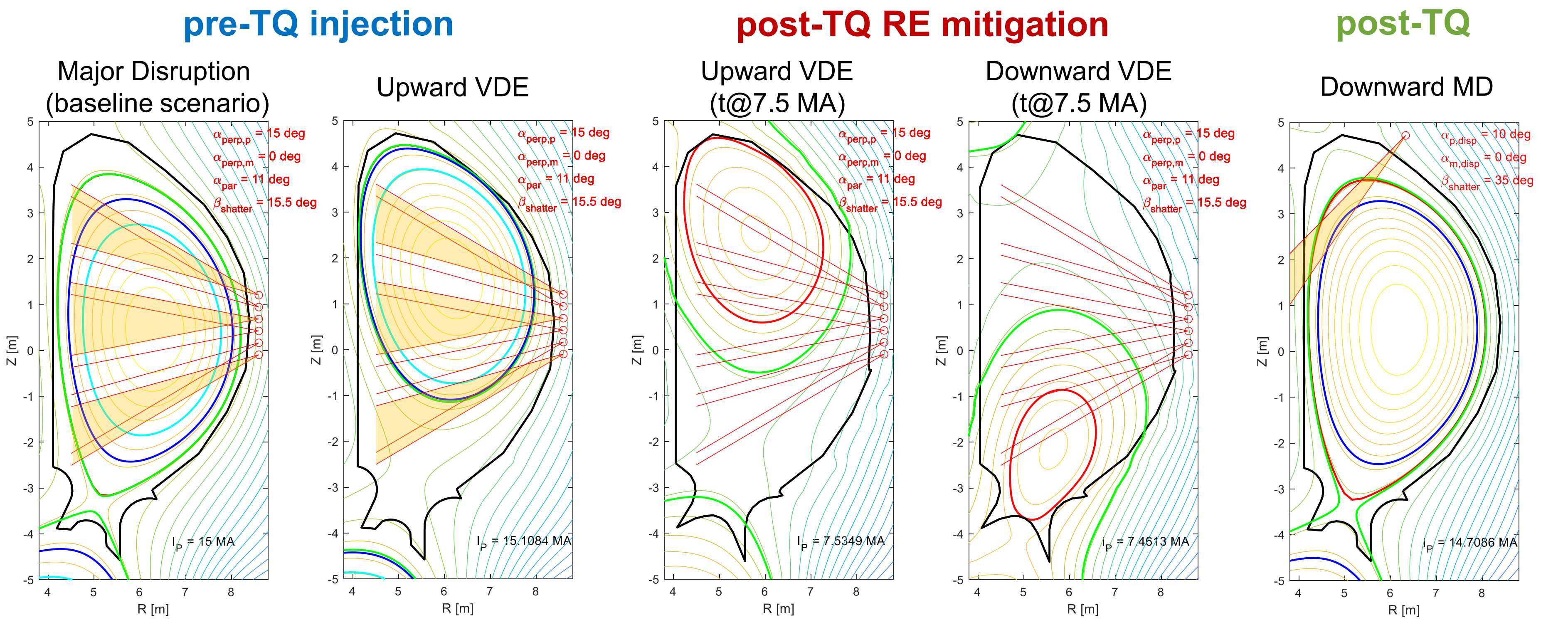
H SPI flushes Ne ➡ no RE reformation

High density and resistivity ➡ more violent MHD, larger RE footprint

E. Nardon, IAEA FEC 2023
V. Bandaru, NF submitted 2024

Injection trajectories

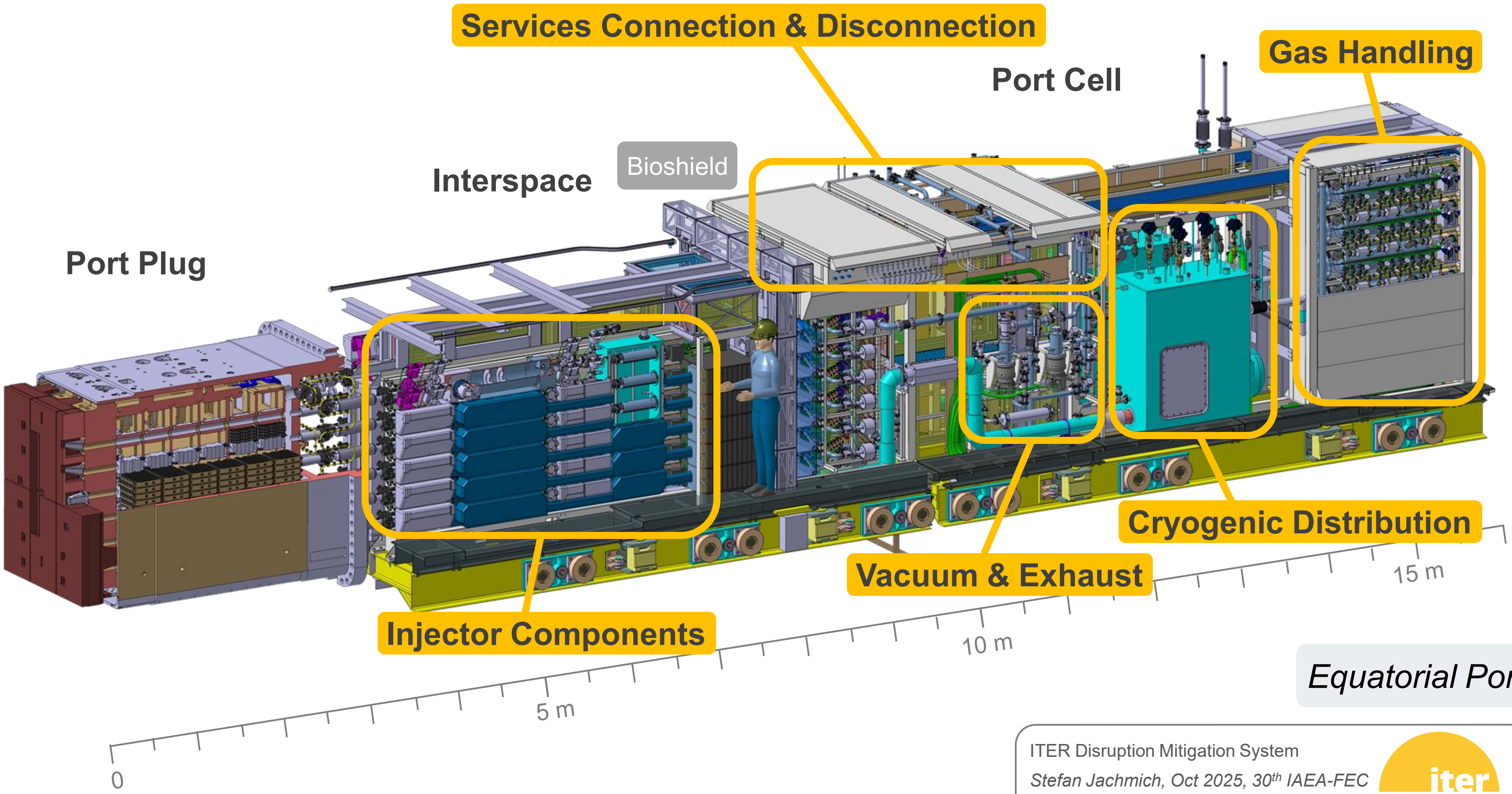
- ❑ Intersect with plasmas that are vertically stable or vertically displaced



ITER DMS design requirements

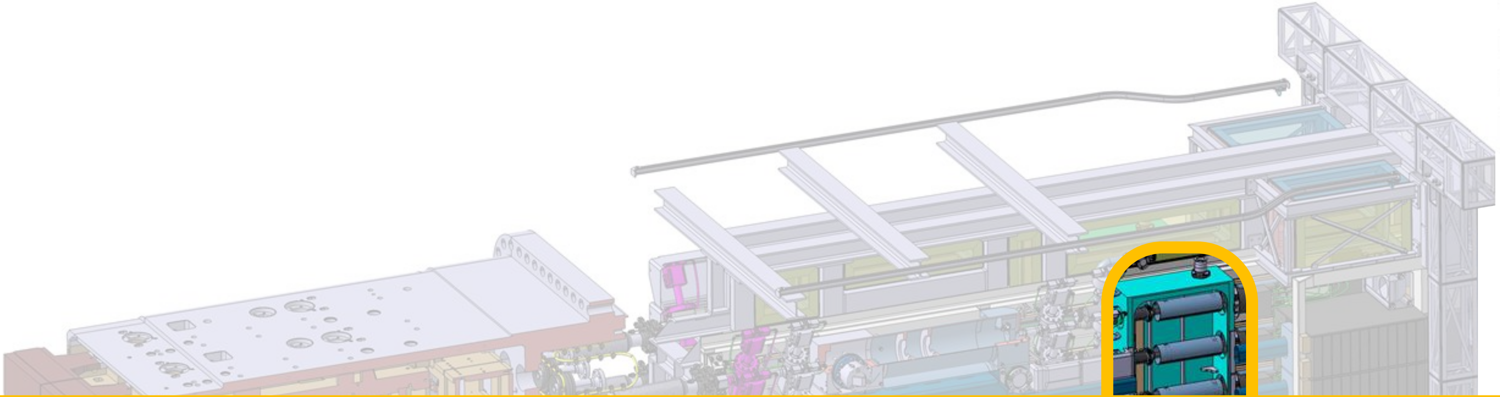
Parameter	Requirement	Component
Pellet formation time	Goal is: ≤30 min	Cold cell assembly, Cryo system
Amount of injected material	≥ 5×10^{24} H-atoms and ≥ 1×10^{25} Ne-atoms	Pellet size, # of injectors
Maximum H-shell thickness for Ne-pellets	≤ 5% Ne-atoms	*Launch Ne-pellets with max 0.25 mm H-shell*
Jitter in pellet delivery	≤ 2 ms (=Σ variation of v_{pellet}, breakaway, …)	Propellant, breech volume, …
Fragment injection duration	≤ 2 ms (=> $\sigma_{v,frag}$ <~ 60-80%)	Shatter unit *(fragment velocity distribution and intact pellets)*
Pellet flight time	≤ 50 ms (=> v_{pellet} >120 m/s)	Propellant valve
EP-only: fragment size distribution	≥ 0.5 mm and ≤ 5 mm	Shatter unit + v_{pellet}
EP-only: maximum gas production	≤ 20% of pellet material	Shatter unit + v_{pellet} (→ *low impact vel.)*
EP-only: maximum propellant flow	≤ 1×10^{25} H-atoms/sec	Propellant suppressor
UP-only: fragment size distribution	Predominately < 0.5 mm (maximum gas)	Shatter unit + v_{pellet} (→ *high impact velocity)*

ITER Disruption Mitigation System

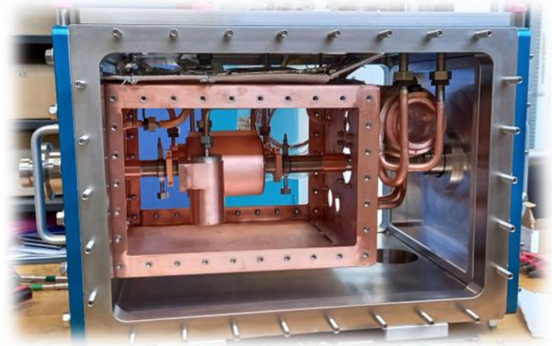


Equatorial Port 02

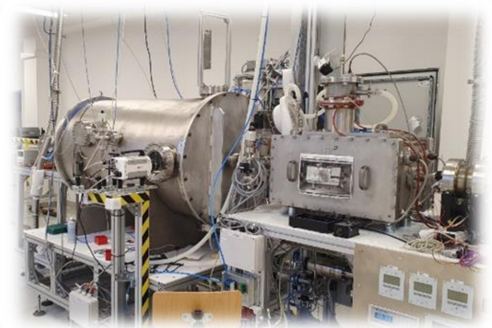
ITER DMS: Cold cell assembly



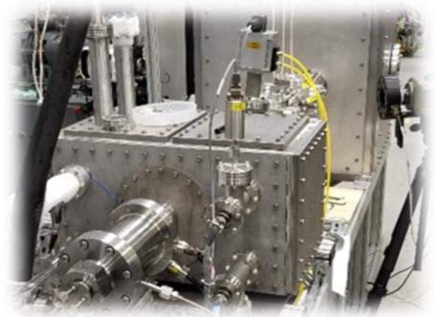
Pellet formation



TYFANIES (CEA-Grenoble)



DMS Support Lab (CER Budapest)



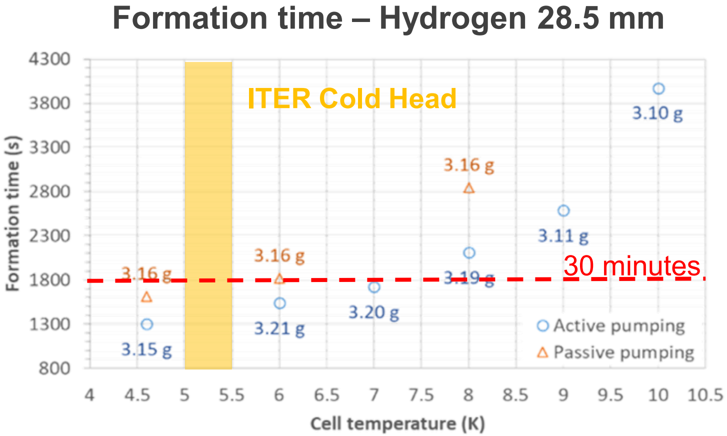
ITER SPI test bed (ORNL)

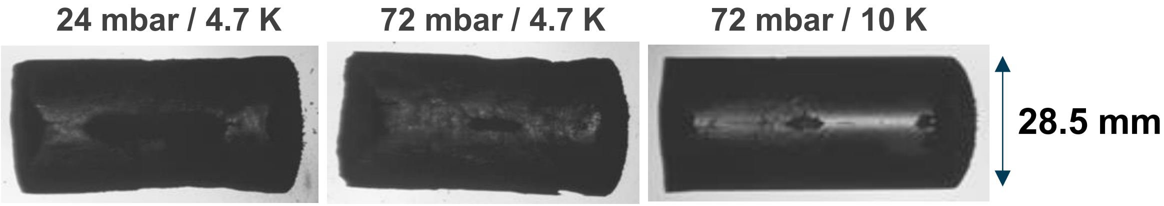
Test benches for ITER-size pellets

ITER DMS: Cold cell assembly

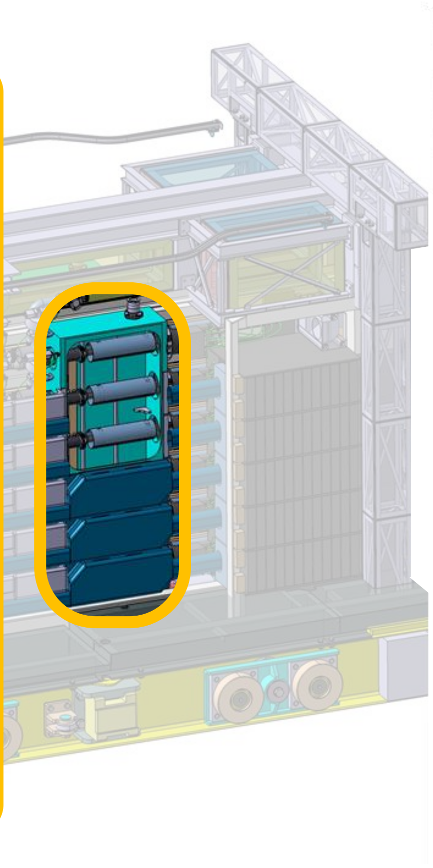
Pellet formation

- Temperature
- Pressure
- Desublimation duration
- Gas injection configuration
- Gas pumping
- Pellet thermalisation





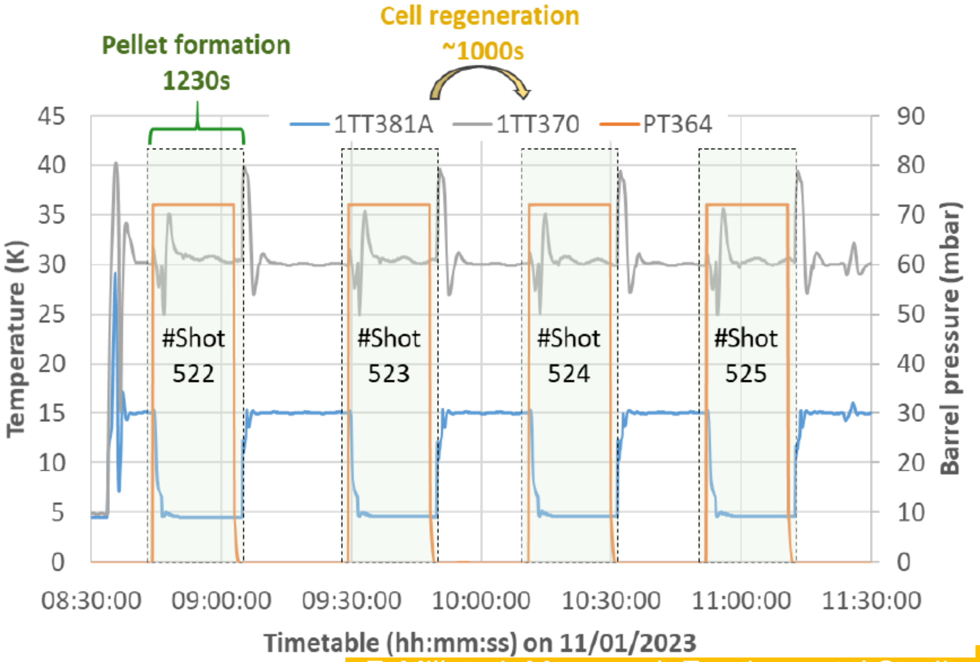
F. Millet, J. Manzagol, Fundamental Studies Lab (CEA)



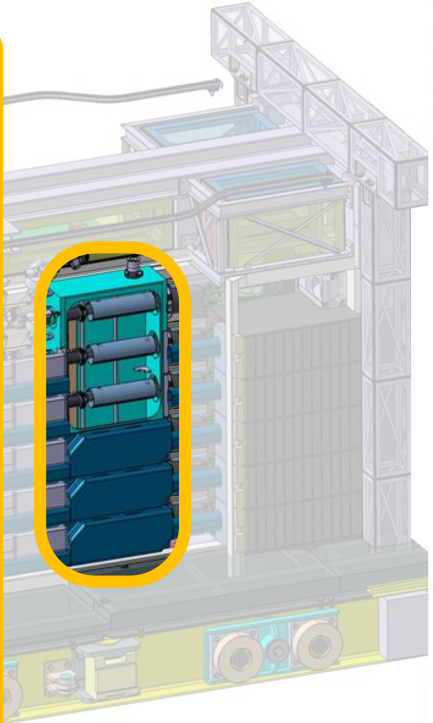
ITER DMS: Cold cell assembly

Pellet formation

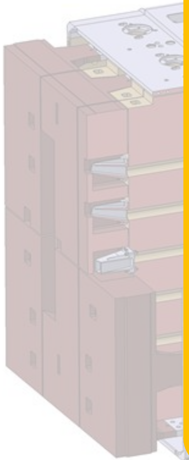
- Reproducibility



F. Millet, J. Manzagol, Fundamental Studies Lab (CEA)



ITER DMS: Propellant Valve

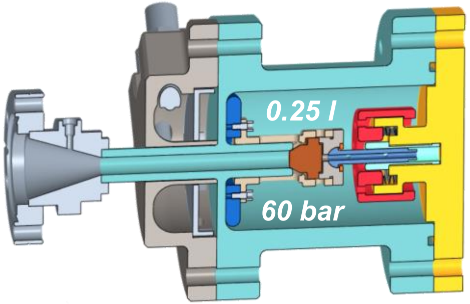


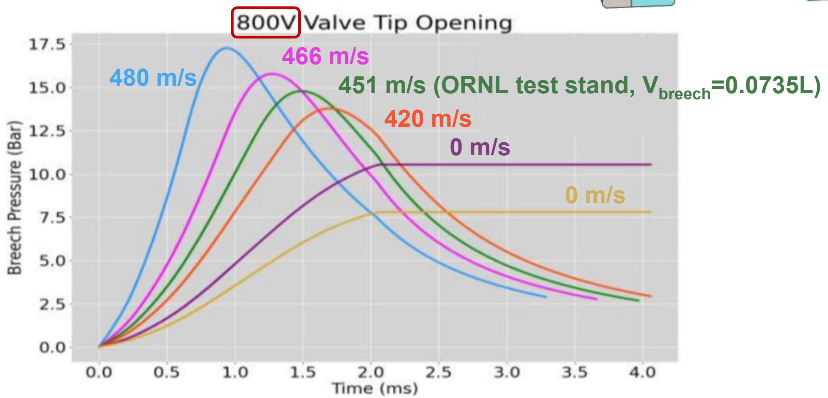
Propellant Valve

Flow rate ➡ Integrity

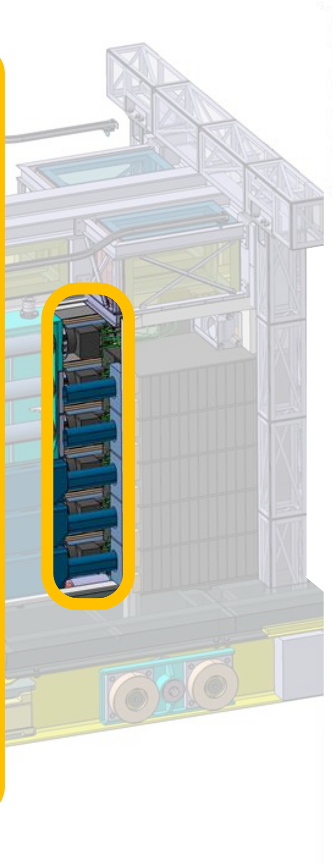
Quantity ➡ Velocity

Volume ➡ Break-away





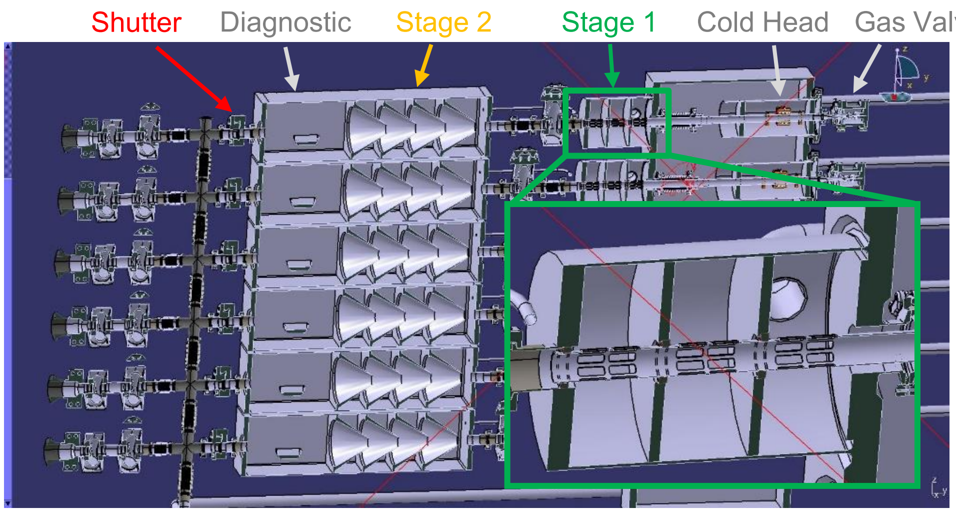
T. Gebhart (ORNL) , IAEA FEC 2023



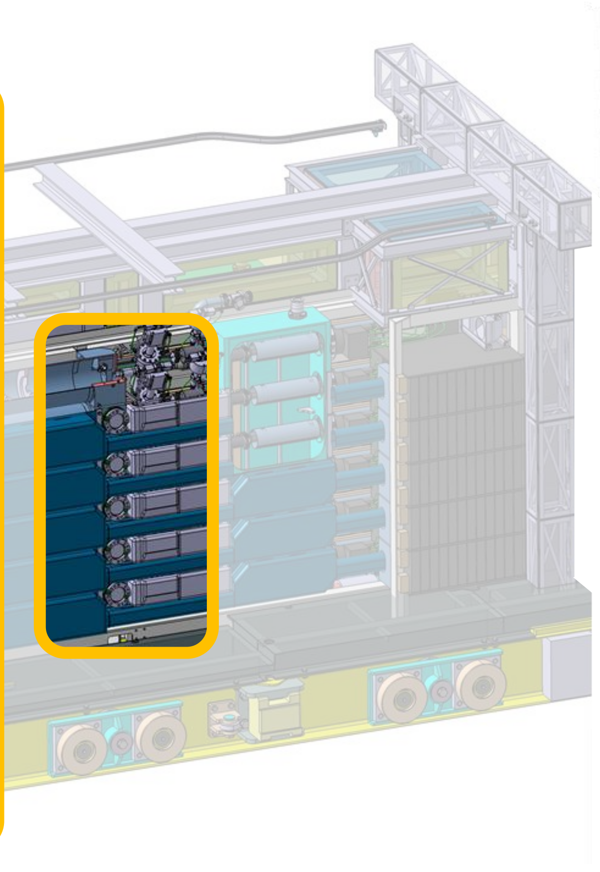
ITER DMS: Propellant gas retention

Propellant Retention

- Pellet Trajectory Control
- Mitigation process



A. Horvat (CAPUS), M. Dibon & DMS design team



➢ Design being tested in ORNL, Support Lab and CEA

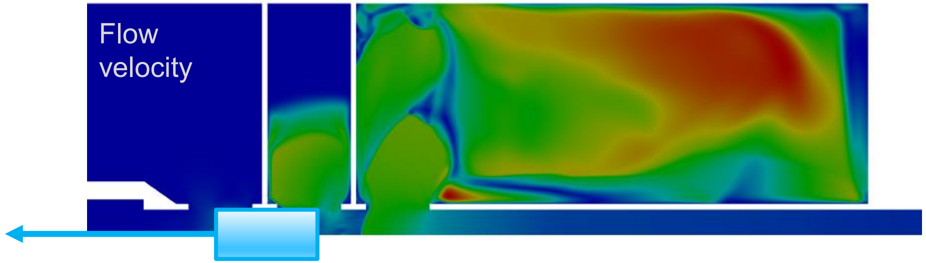
ITER DMS: Propellant gas retention

Propellant Retention

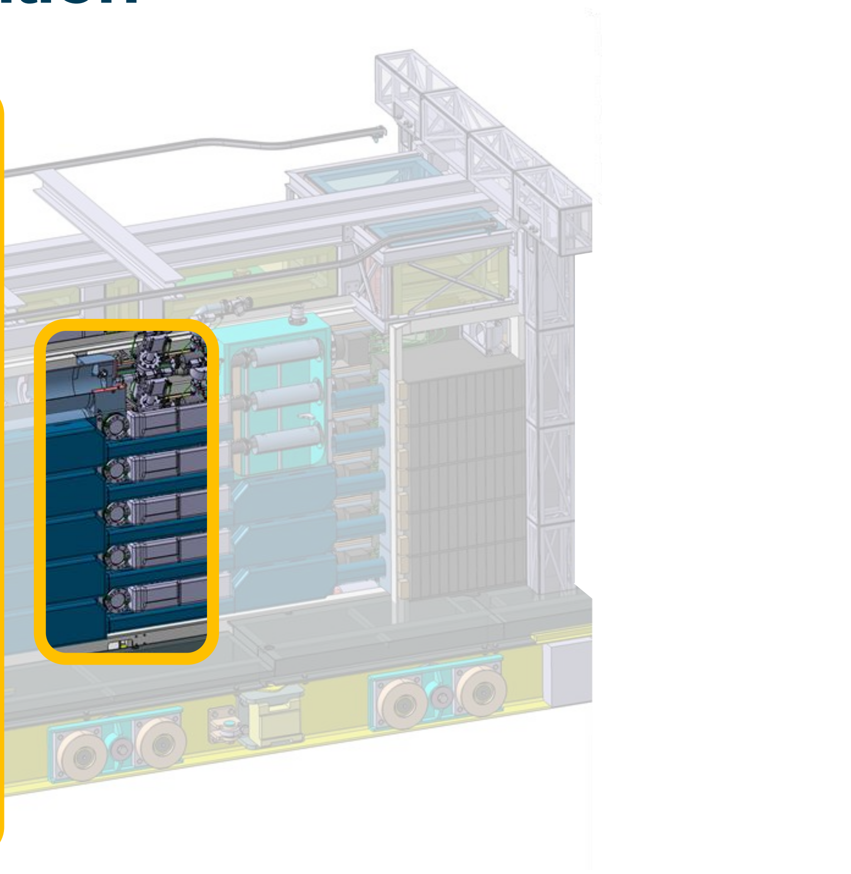
Pellet Trajectory Control

Mitigation process

CFD Simulation of stage 1



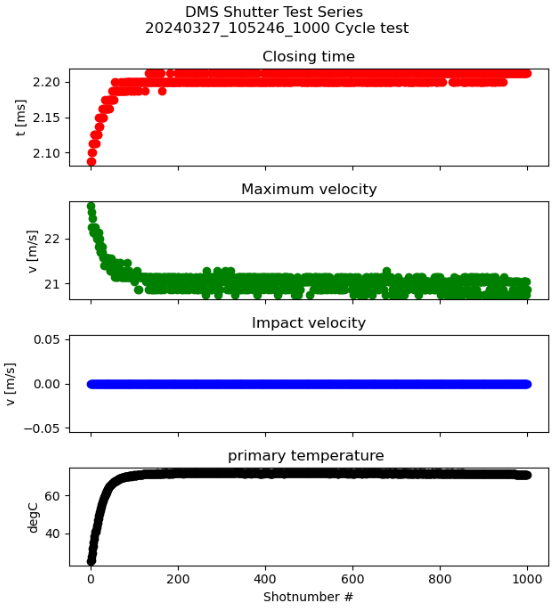
A. Horvat (CAPUS), M. Dibon & DMS design team

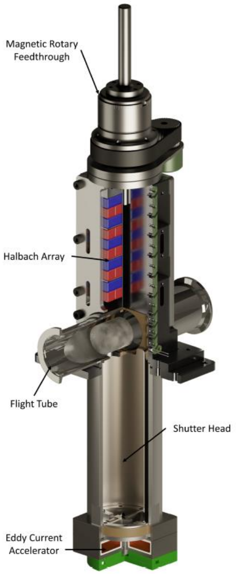


ITER DMS: Fast shutter as backup

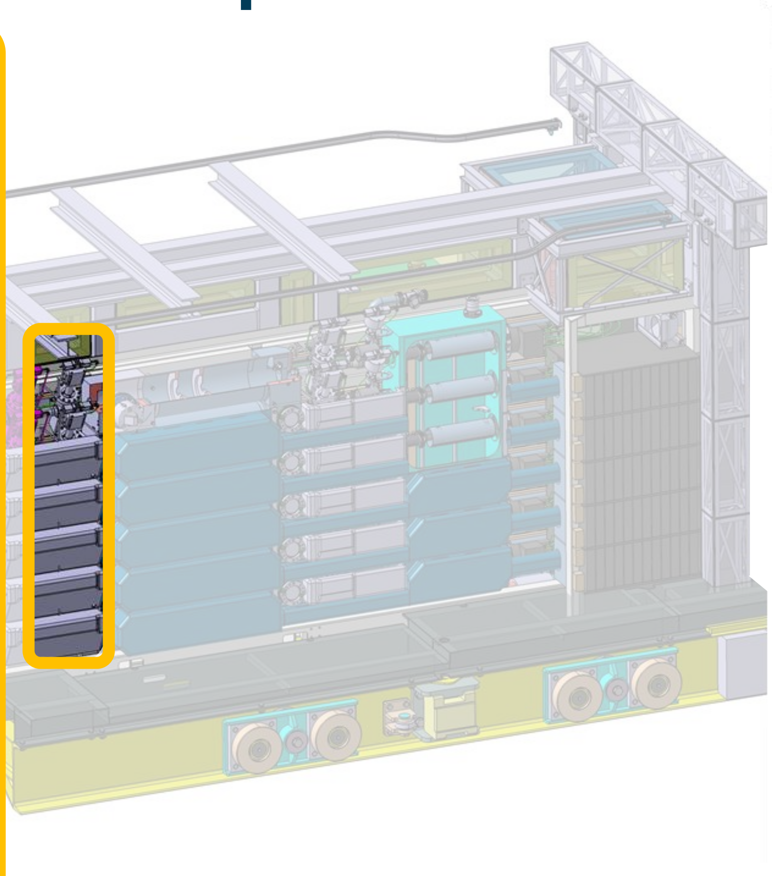
Propellant Retention

- Closes within 2ms after pellet
- Prototype built and tested for >10,000 cycles
- Triggered through OPD





A. Zsakai (CER)



ITER DMS: Optical pellet diagnostic

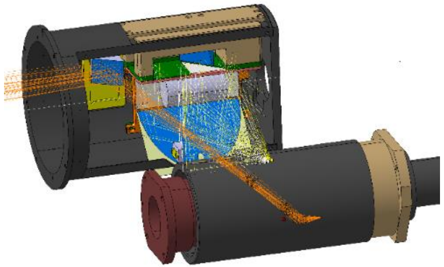
Optical Diagnostic

Integrity

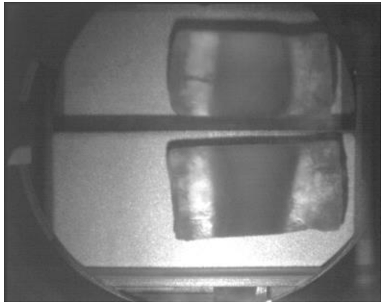
Trajectory

Fast Shutter

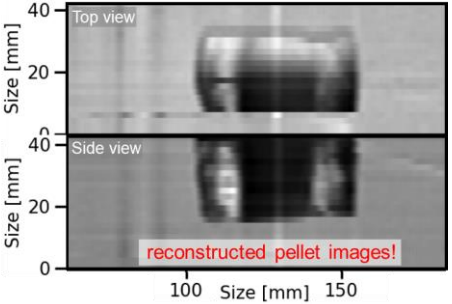
Velocity



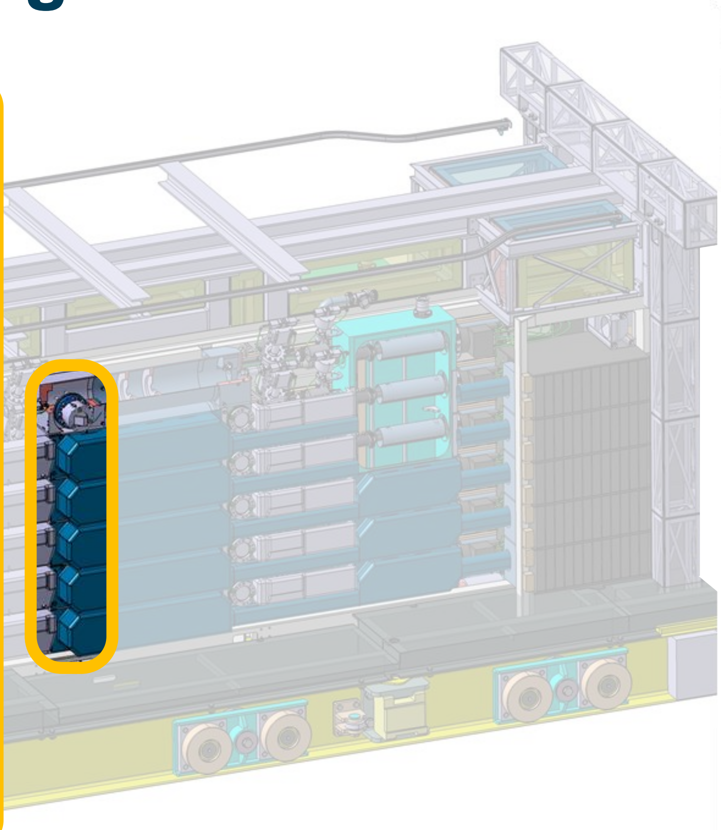
CMOS camera



Photodiode array



D. Dunai, S. Zoletnik et al, Fusion Instruments

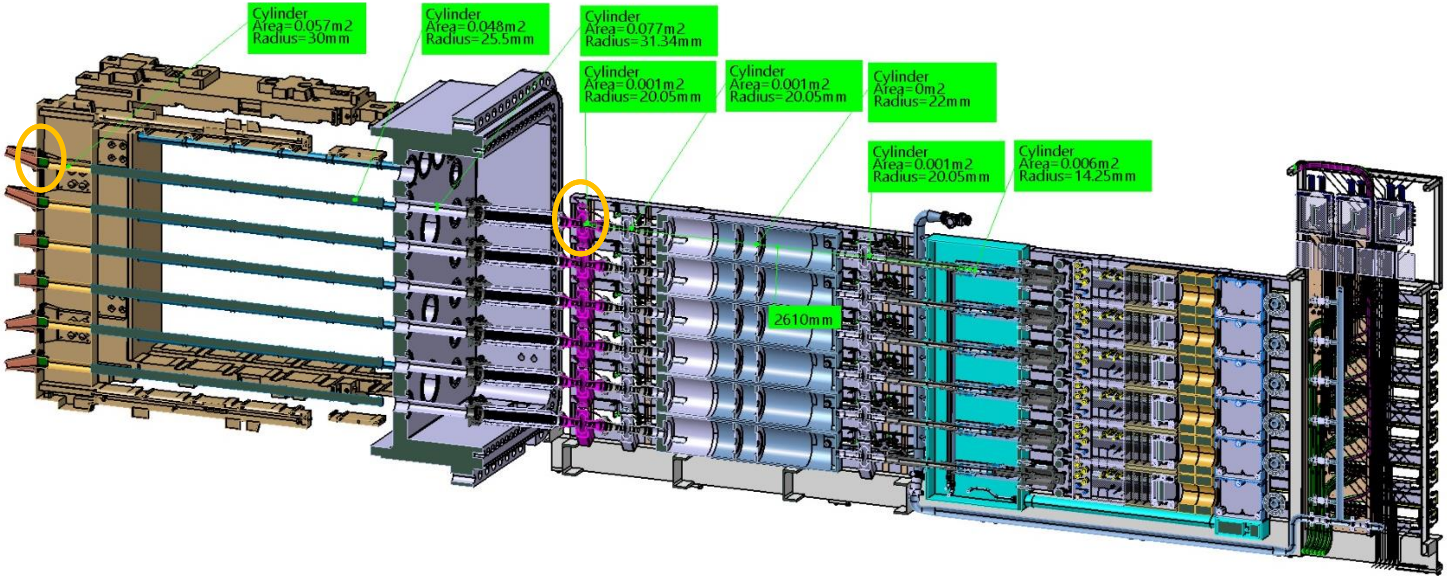


ITER DMS: pellet trajectory accuracy

- Flight path restricted by gate valve and shatter chamber entry:

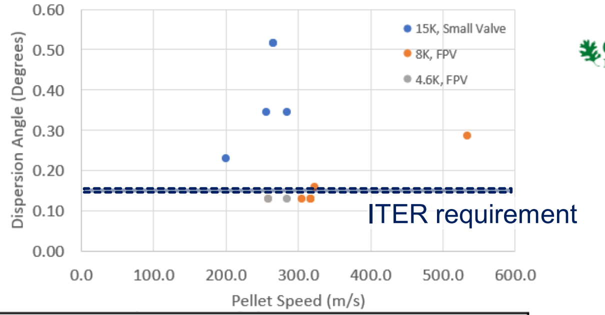
  EP: 0.15° for 40mm gate valve and 0.15° for 60mm shatter chamber entry

  UP: 0.15° for 40mm gate valve and 0.21° for 90mm shatter chamber entry.

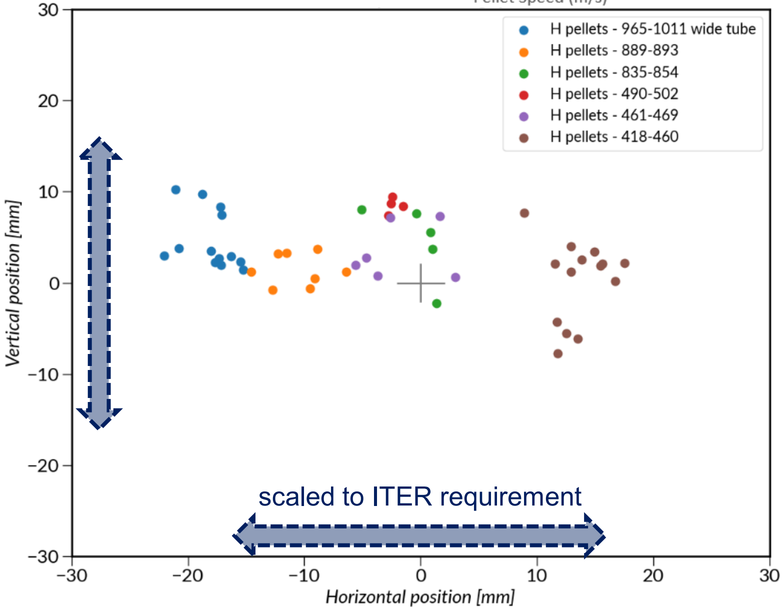


ITER DMS: pellet trajectory accuracy

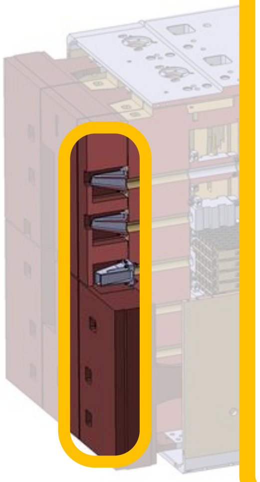
- Initial test firing on target disc (ORNL):
  - Taking into account potential misalignment → dx~±0.11°, dy ~±0.21° based on large D-pellets
  - Measurements with new FPV are ongoing



- Support laboratory (CER):
  - Pellet position assessed in last observation prior shatter chamber entry
  - Data are grouped by test bench interventions
  - Deviation within limits required for ITER-DMS
  - Empirical observation: all pellets are reaching shattering chamber

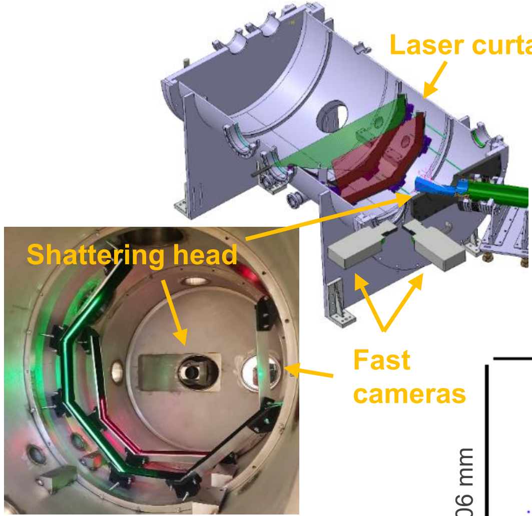


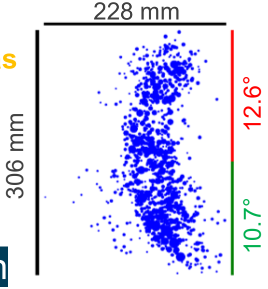
ITER DMS: Shatter chamber



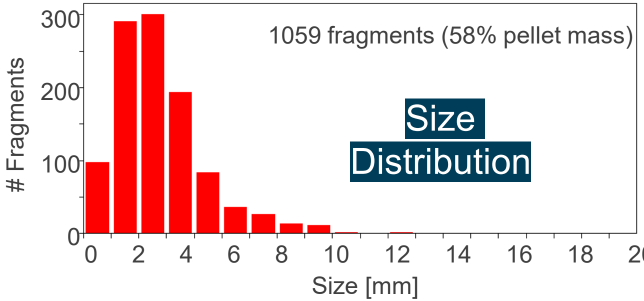
Pellet Shattering

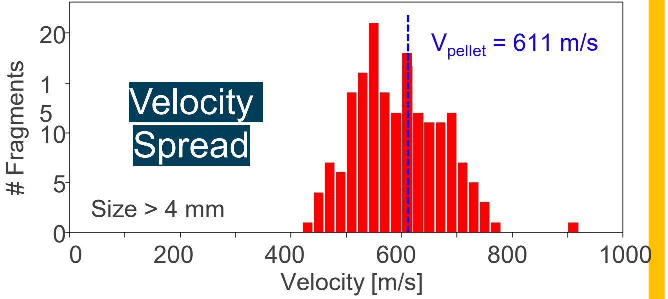
H pellets with 15.5° ITER-like shatter head





Spatial Distribution





S. Zoletnik, T. Szepesi & Support Lab Team (EK-CER), IAEA FEC 2023

ITER DMS: Shattering validation

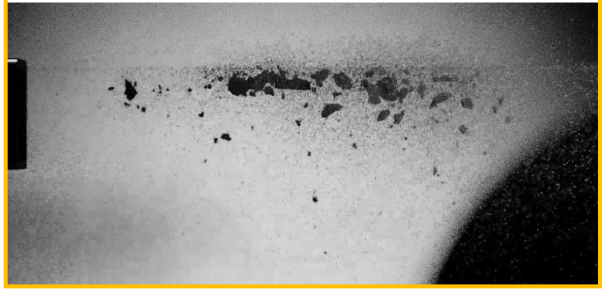
- "Pellet shattering simulation" (EMI-Fraunhofer/Germany):
  - – model based on Discrete Element Method
  - – experimental data (AUG-SPI, ORNL, Support Laboratory, …) → determine material properties
    → validate fragmentation model
  - – *simulation*: 3D-characteristic of fragment plume
    experiment: limited sensitivity and resolution
    → synthetic diagnostic

Simulation

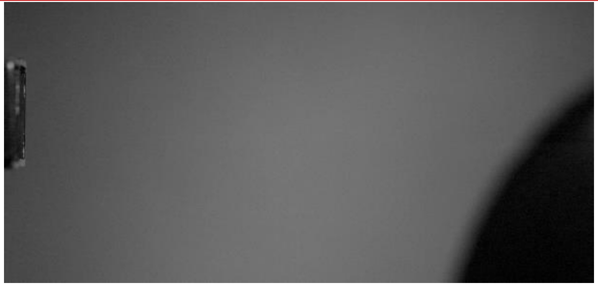
Material parameter used: K = 9.8 MPa, σ_f = 6.45 MPa
Discretization h = 0.096 mm → ~ 500.000 particles

P. Matura, IAEA-TM "Disruptions", 2022

Rendered image of simulation



Experiment



Neon pellet, ∅ 8 mm, L/D~1.1, v~160 m/s, 25° (AUG-SPI lab #718)