The ITER Disruption Mitigation System design progress and validation

Stefan Jachmich

for the DMS design team and ITER DMS Task Force collaborators

Thanks for the contributions from all collaborators

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.

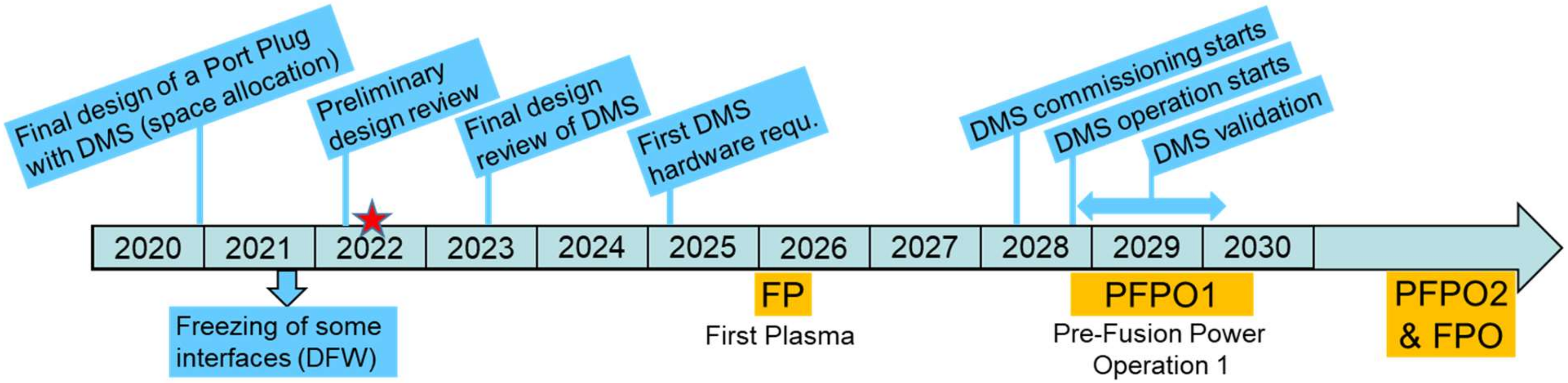
Outline

- ❑ Introduction
- ❑ Design progress of the ITER DMS
- ❑ Technology programme for design validation
- ❑ Conclusions

Introduction

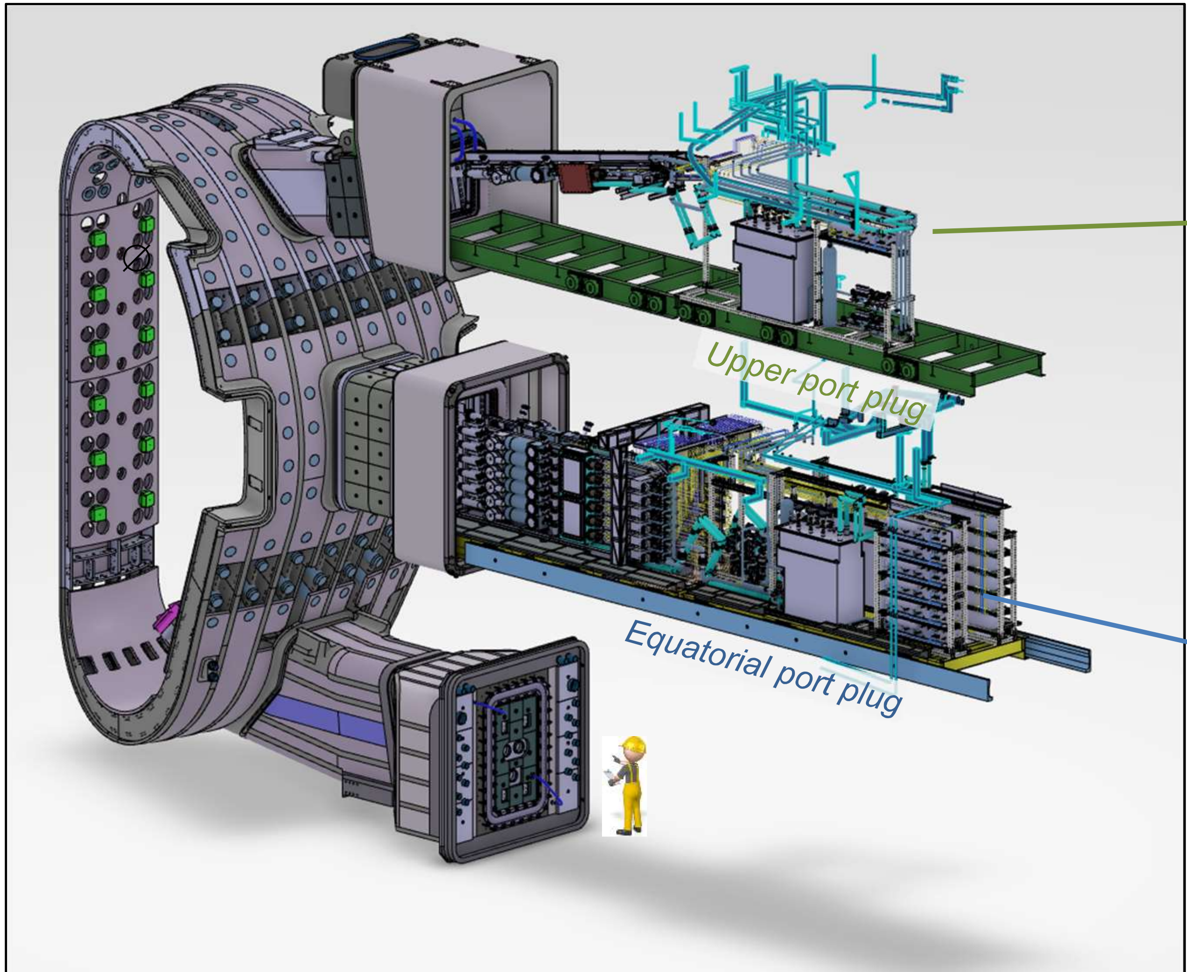
Introduction

- ITER requires a disruption mitigation system already from the early phases of plasma operation (>PFPO1)
- Chosen technique for injection of massive amount of material is Shattered Pellet Injection
- Design progresses in parallel with its validation and addressing technological challenges

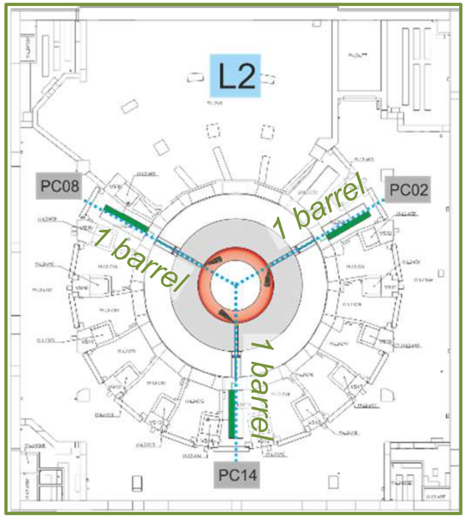


ITER DMS design

Overall DMS configuration



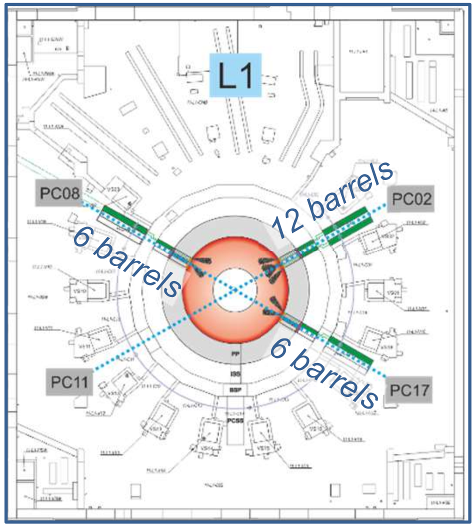
Vacuum vessel sector with EQ2 and UP2



Upper port injectors

$\varnothing$19 mm x L38mm pellets for post-TQ injection:

- CQ heat load mitg.
- CQ EM load mitg.



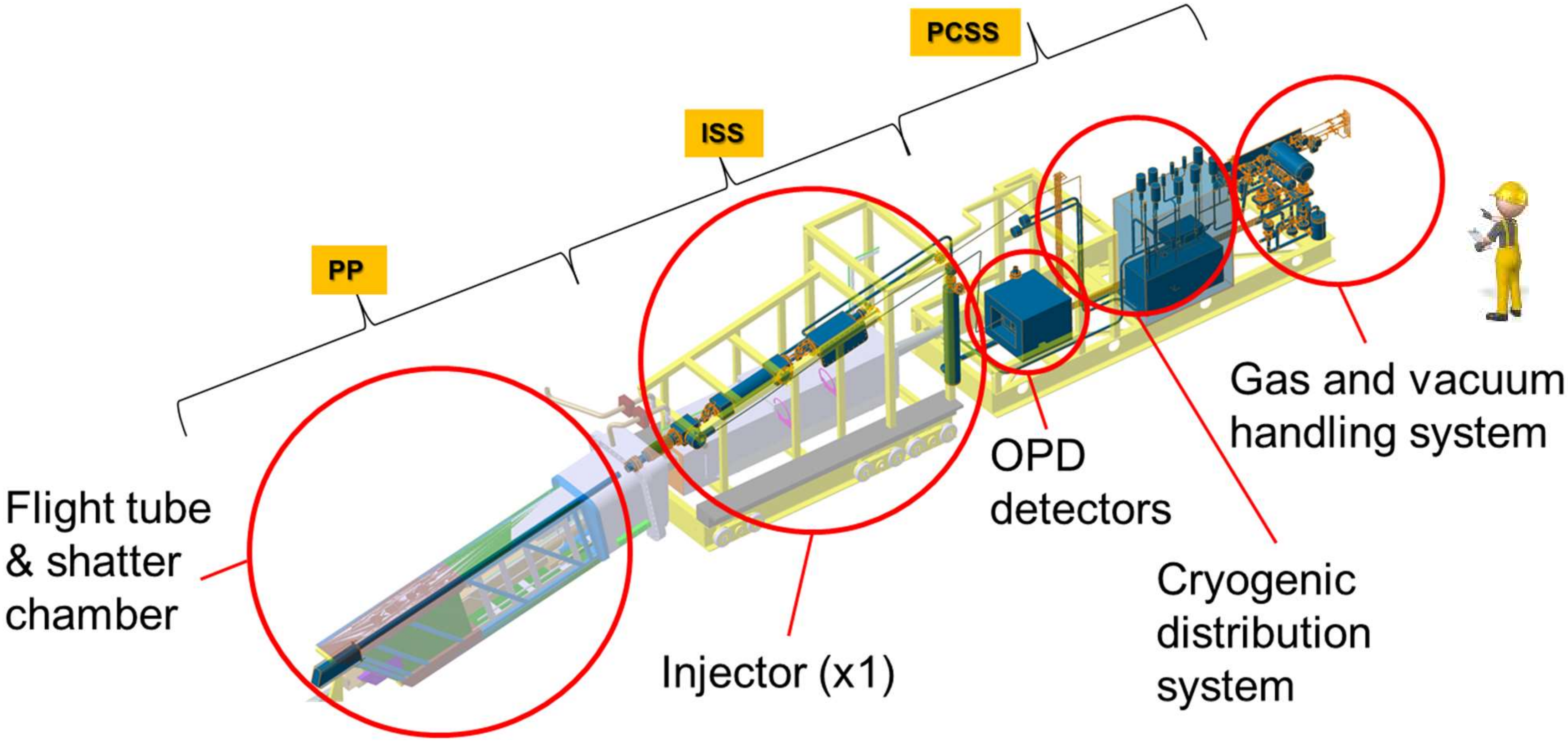
Equat. port injectors

$\varnothing$28.5 mm x L57mm pellets for

- TQ heat load mitg.
- CQ heat load mitg.
- CQ EM load mitg.
- RE avoidance
- RE energy dissipation

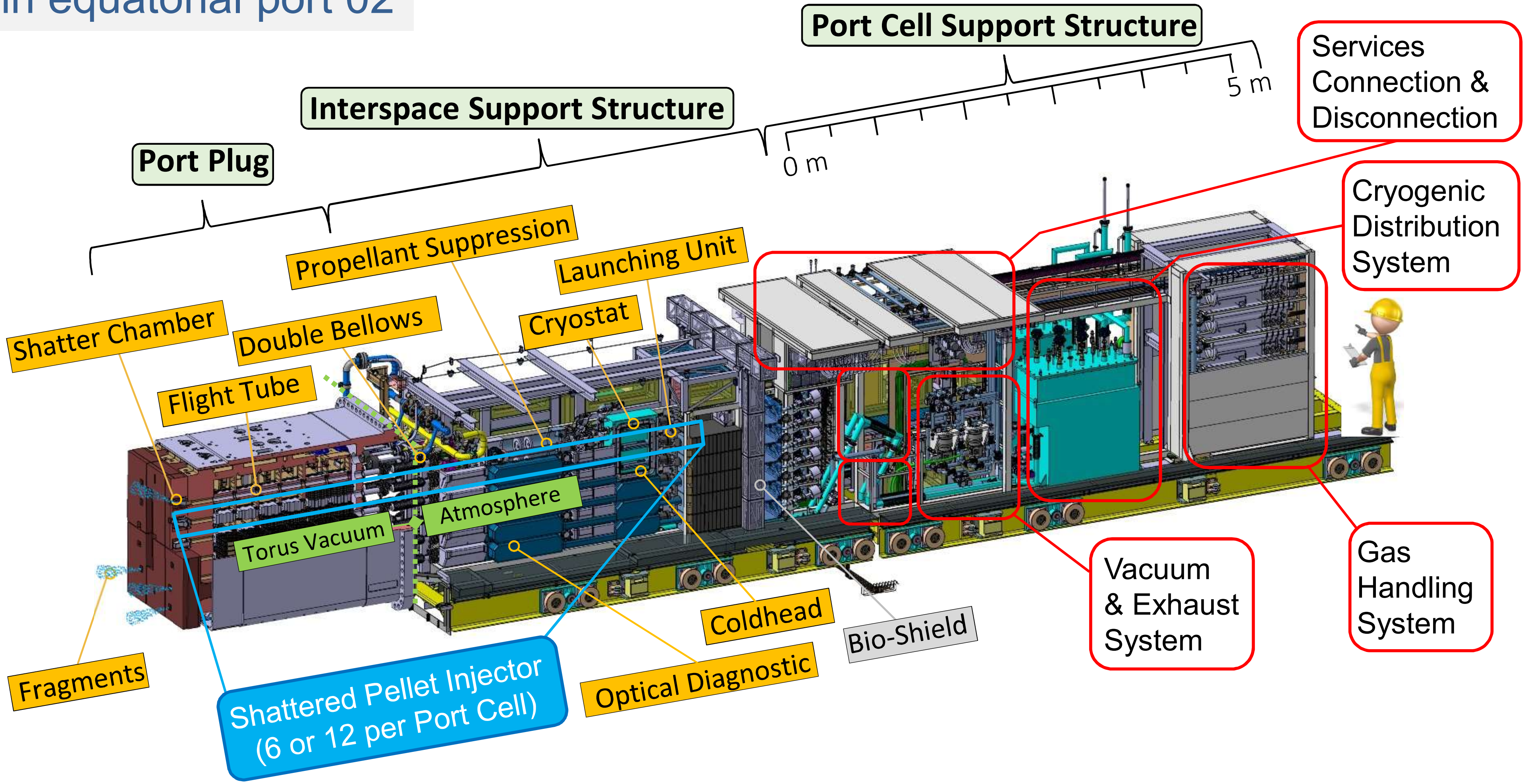
Upper port injector design

DMS in upper port 02 (overall)



Equatorial port injector design

DMS in equatorial port 02



ITER DMS design parameters

- Present design values are subject to validation (→ ITER DMS Task Force experiments and theory & modelling)
- Implementation constraints design of various components (→ slides on technology programme)

Other exemplary parameters:

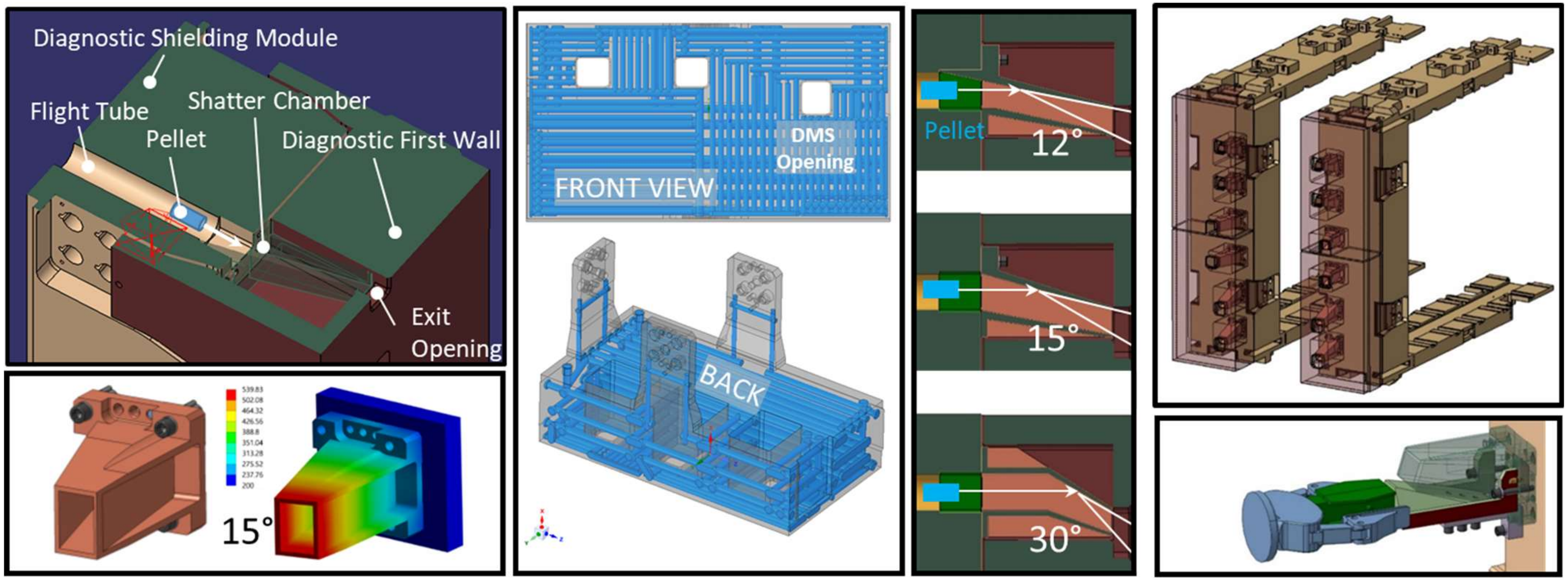
- Response time: <50 ms (=$t_{arrival} - t_{trigger}$)
- Pellet velocity: min = 120 m/s, present target = 500 m/s (for H and Ne/H-pellets)
- Pellets must be delivered reliably and intact to shattering chamber
- Injectors should be able to be triggered independently, including prescribed delay (called “sequence”) to execute different injection schemes:
  EQ: mixed (3x Ne/H-plts), *staggered* (H -> Ne/H, >6plts), *RE high-Z* (>7x Ne-plts), *RE low-Z* (>1 H-plts),
  UP: *Post-TQ* (1x Ne/H-plt)
- plus many more ….

Design challenges (some)

- Schedule – Detailed design of Pellet Shatter Chamber
- Integration – Neighbour to other systems
- Radiation – Vacuum Extension
- Accessibility – Service connections
- Harsh Environment – Instrumentation & long distances
- Reliability – Control System

Design challenge: *Schedule & Integration – Shattering chamber*

- ITER: complex machine environment.
- Many design activities are schedule driven.
- Early common procurement of the Diagnostic First Wall: shatter chamber design needed to be detailed early on.
- Plasma operation requires implementation of active cooling → constraining SPI injection directions

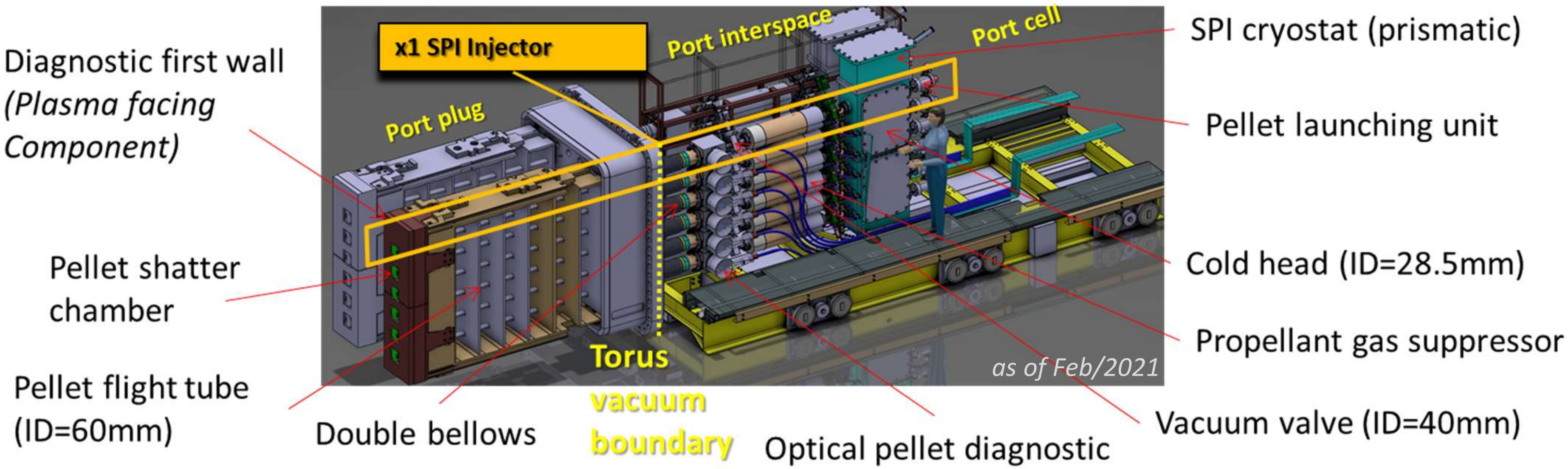


Technology programme of ITER DMS Task force for design validation

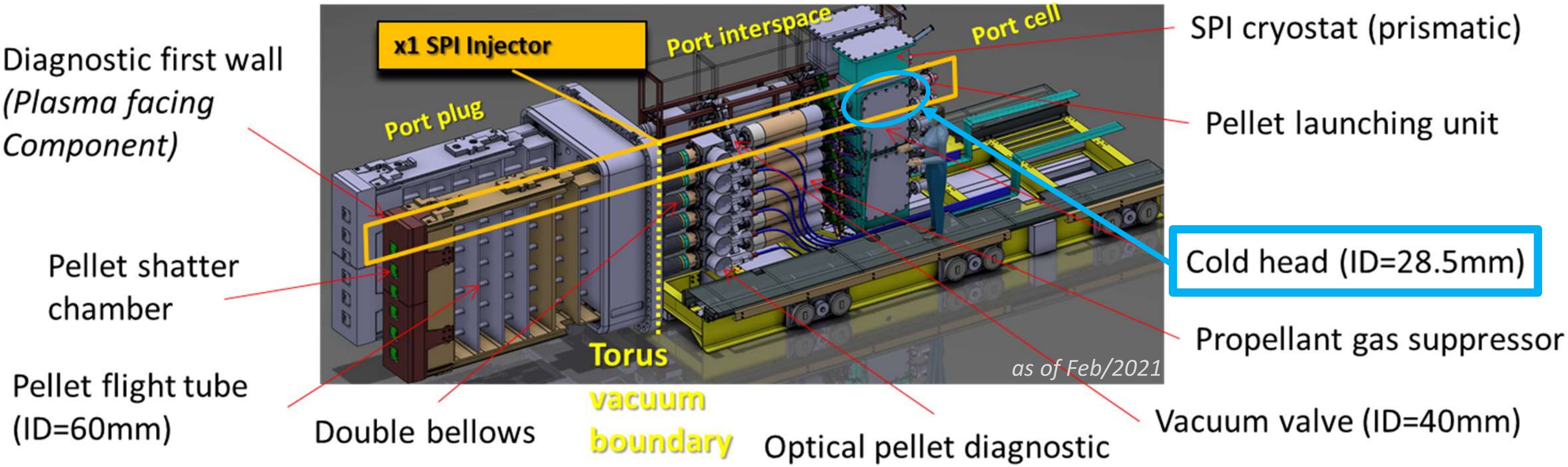
Note: due to lack of time only a few highlights will be shown!

Overview

- Pellet injector technology is well known, but does not exist for ITER-size pellets and environment
- Present technology R&D addresses specific issues of various SPI components
- Purpose:
  - ➢ DMS SPI baseline: validate design
  - ➢ Risk mitigation: enable alternative concepts
- Present DMS design requirements form the basis for the validation



Pellet formation



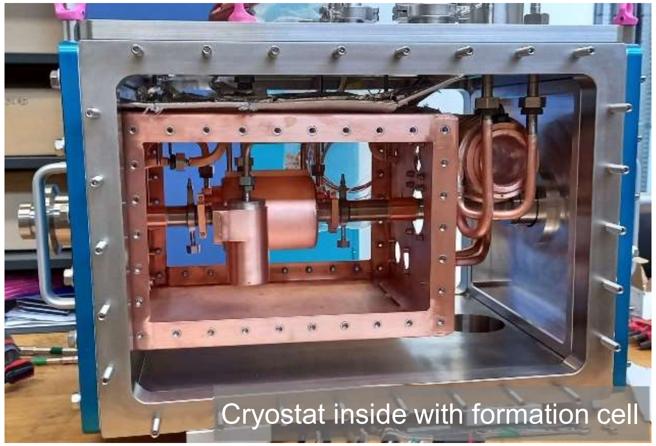
Pellet formation – *baseline*

Pellet formation time shall be minimized; goal is ≤ 30 min.

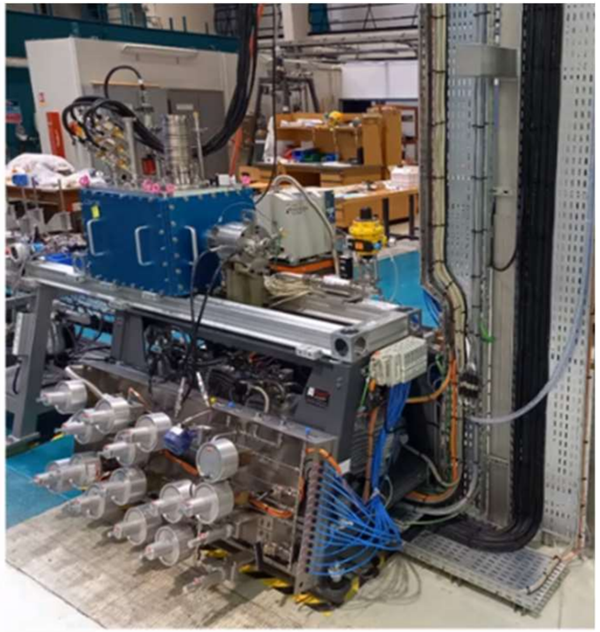
- ITER-DMS:
  - – Main pellet species hydrogen has low triple point and low thermal conductivity
    - → long formation times and/or poor solidity for D=28.5mm
    - → use of gas pre-coolers and thermal intercepts
  - – Pellet formation times governed by
    - achievable cold zone temperature
    - available cooling power
    - barrel material and wall thickness
    - mass flow and/or barrel pressure
  - – Recently formation of 28.5 mm H-pellet has been demonstrated in two laboratories (EK-CER and DSBT).
- Strategy:
  - – Study pellet formation in dedicated test laboratory (→ DSBT/CEA-Grenoble)
  - – Additional input from other test benches using different cold head and barrel design (*see talks by S. Zoletnik and T. Gebhart*)

Pellet formation (1) – *baseline*

- "Fundamental studies" (DSBT/CEA-Grenoble, France):
  - Experimental tests of pellet formation (and other SPI technologies) require tremendous hardware installations
  - Test bench to study and optimise pellet formation process (incl. accel.)
  - Condensation tests with 10mm pellets completed
  - First formation of hydrogen pellet with ∅ 28.5mm two days ago


Cryostat inside with formation cell

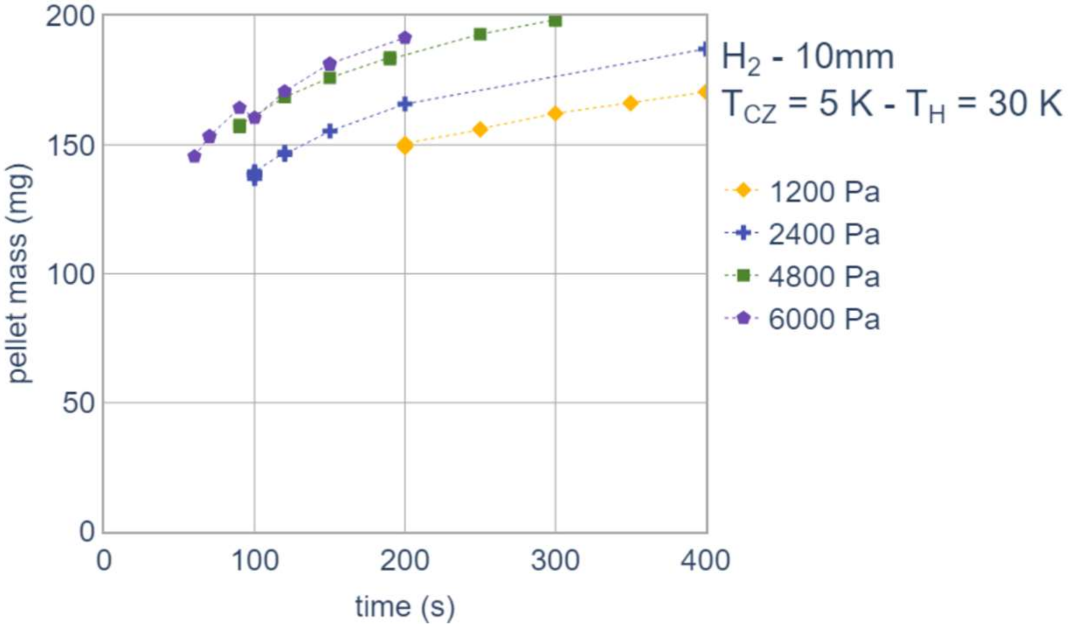

"DMS Fundamental Studies" test bench at DSBT, CEA-Grenoble



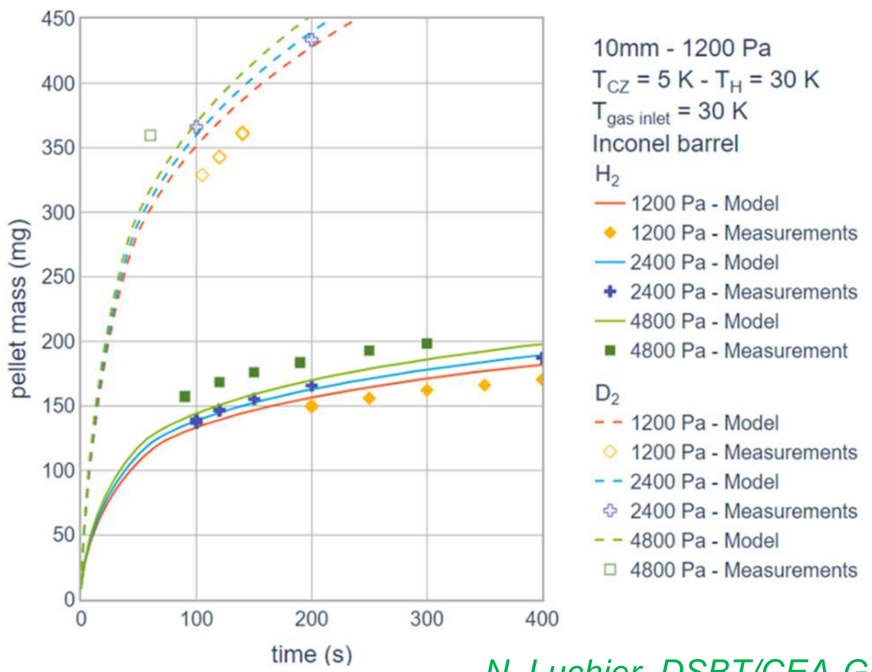
Pellet formation (2) – *baseline*

- Extensive modelling carried out for comparison with experiments: sensitivity studies for formation profile and time
- Model based on Hertz-Knudsen equation using finite elements with COMSOL
- Benchmarking needed for sticking coefficient and thermal conductivity
- Formation times explored for range of temp., barrel pressures, species

Experimental results with D=10 mm H-pellets



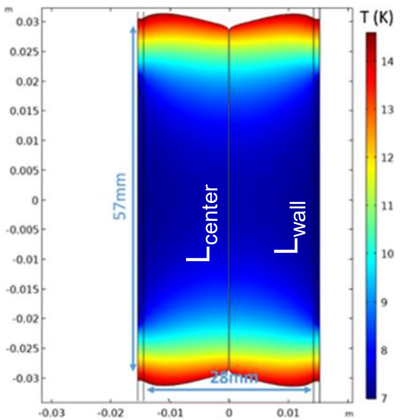
Comparison with model



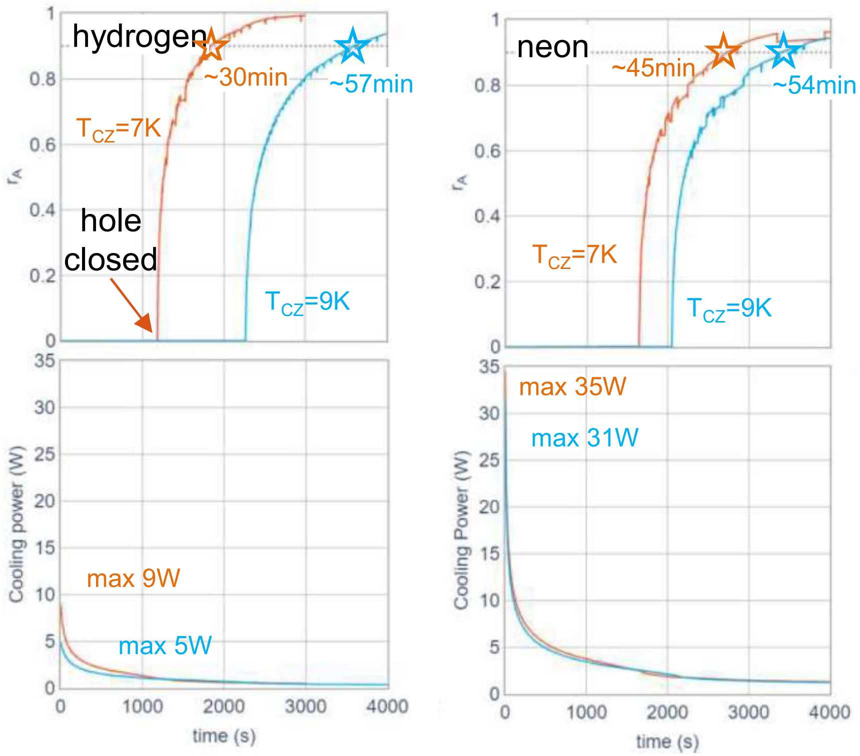
N. Luchier, DSBT/CEA-Grenoble

Pellet formation (3) – *baseline*

- Predictions for 28.5mm x 57 mm pellet

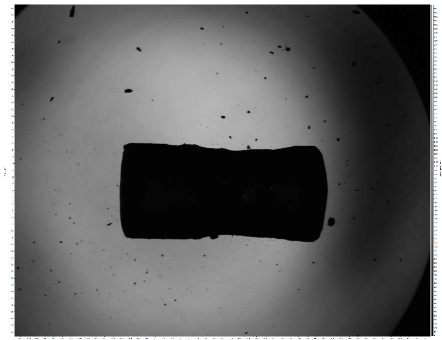


$r_A = L_{centre}/L_{wall}$



First results:

- Experimental example:
  - Hydrogen at T_{cz} ~5 K
  - $p_{desublimation}$ = 24 mbar
  - $t_{desublimation}$= 20min
  - $t_{pumping}$ = 10 min
  - mass = 3.1 g,
  - velocity = ~480 m/s



Shot256-2CAM569_10001

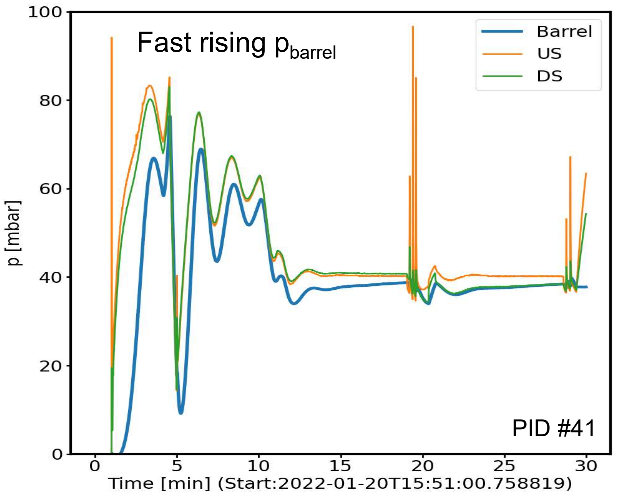
J. Manzagol, DSBT-team (CEA-Grenoble)

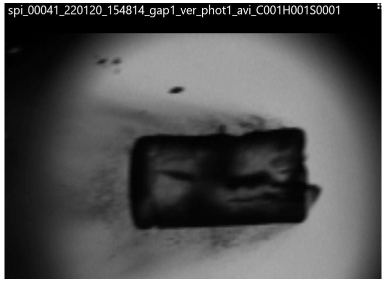
Result: Formation times of H-pellets ~30 min feasible provided $T_{CZ} \leq 7K$

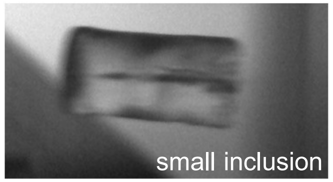
Note: Modelling by Support Laboratory gave similar results (S. Zoletnik et al., EPS 2021)

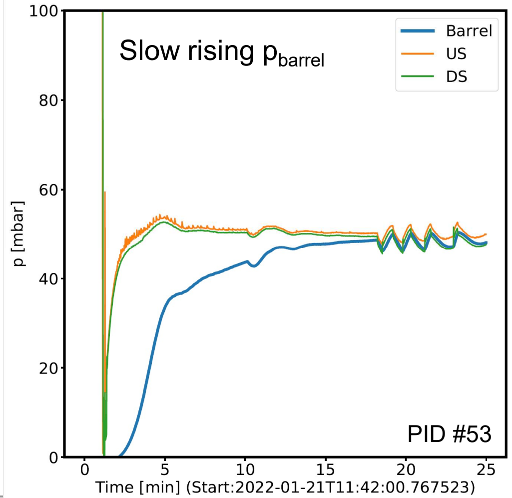
Pellet formation (4) – *baseline*

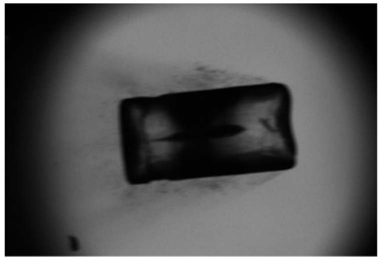
➢ Support Laboratory (EK-CER): data for H-pellets (D=19mm):

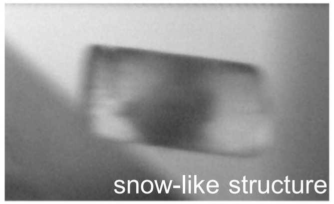


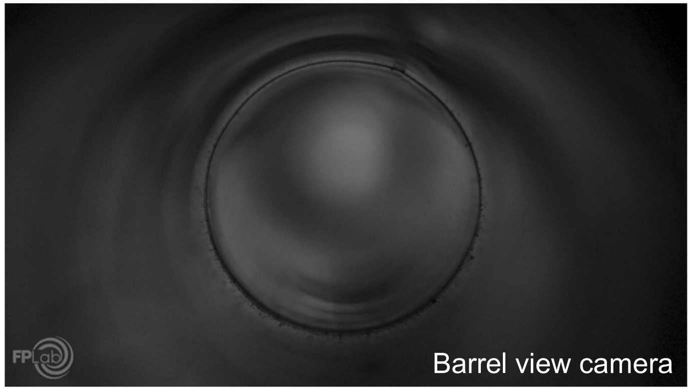












EK-CER, Hungary

Results:

- H-pellets with D=19mm formed in 25-30 min @5K
- Crystal structure sensitive to formation recipe

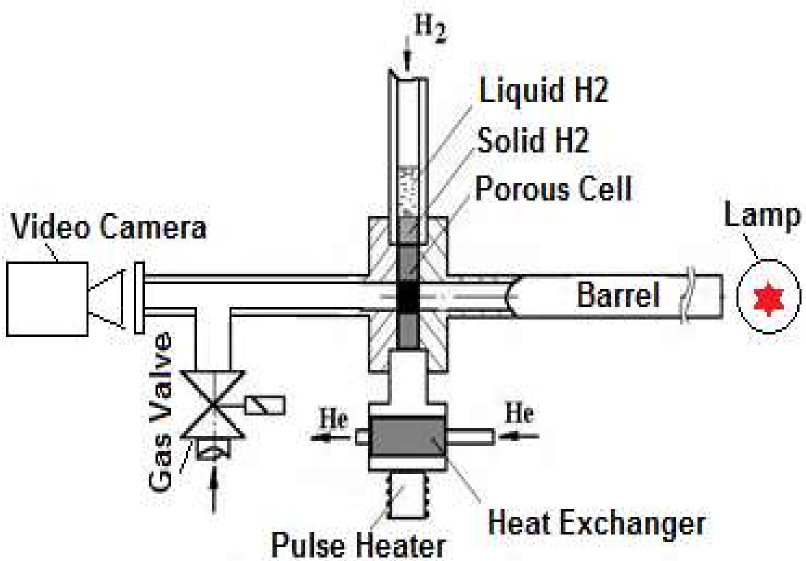
Note:

- *Barrel in SLB not optimised for fast formation times*
- *Recipes will be developed by DSBT/CEA-Grenoble*
- *H-pellet (D=20mm) formed in ORNL at 8K while staying at low barrel pressure (10 mbar)*

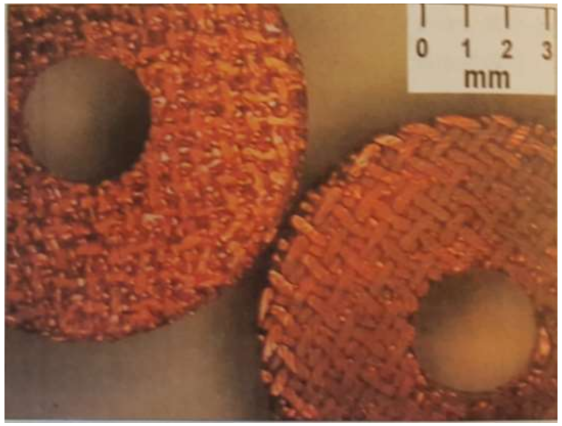
Pellet formation (5) – *alternative concepts*

- "Porous cold head development" (PELIN, Russia):
  - Pellet gas is stored in porous cell
  - Released into condensation cell through heat pulse into cell
  - Significantly reduction of formation times to a few minutes expected

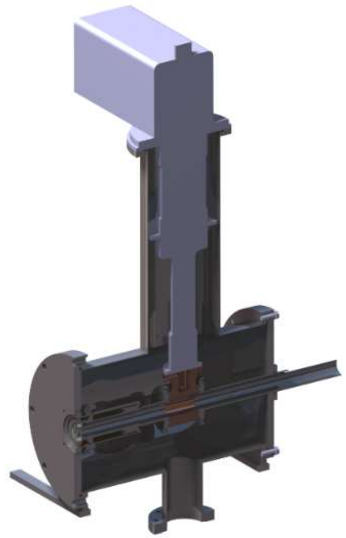
→ to be demonstrated on large pellets (for D=2.5mm t_{cycle}~1 sec possible)



Principle of porous cold head



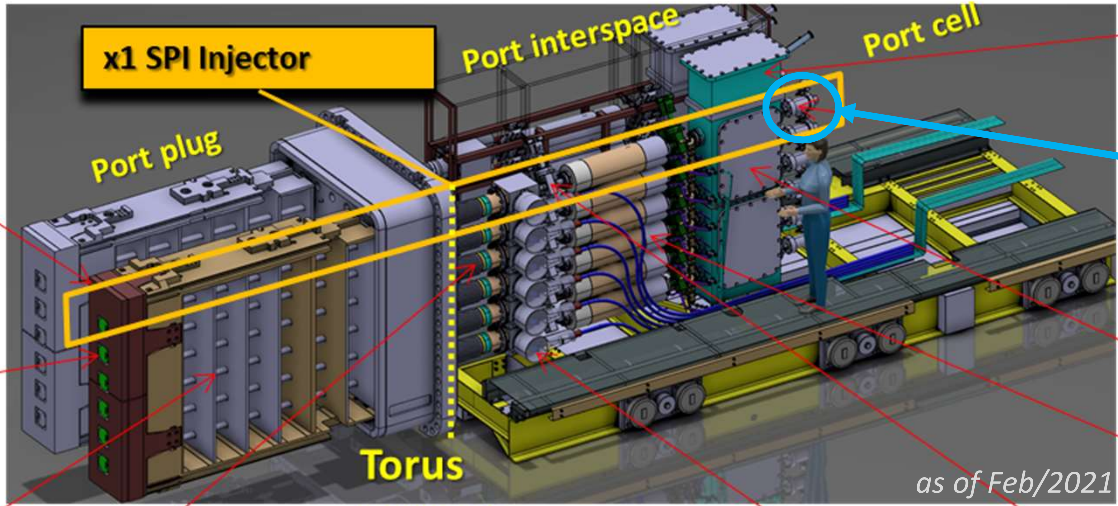
Examples of porous cells



Conceptual design

I. Vinyar, PELIN, Russia

Pellet dislodging and acceleration



Diagnostic first wall *(Plasma facing Component)*

Pellet shatter chamber

Pellet flight tube (ID=60mm)

Double bellows

Optical pellet diagnostic

SPI cryostat (prismatic)

Pellet launching unit

Cold head (ID=28.5mm)

Propellant gas suppressor

Vacuum valve (ID=40mm)

Pellet dislodgment and acceleration

- *Reliable release of pellet and avoidance of pellet breakage*
- *Minimize propellant gas*
- *Pellet delivery time minimized and ≤ 50 ms*
- *Total jitter ≤ 2 ms (activation + velocity dispersion)*
- *High accuracy for pellet flight*
- *Fulfil large number of duty cycles (>10000)*

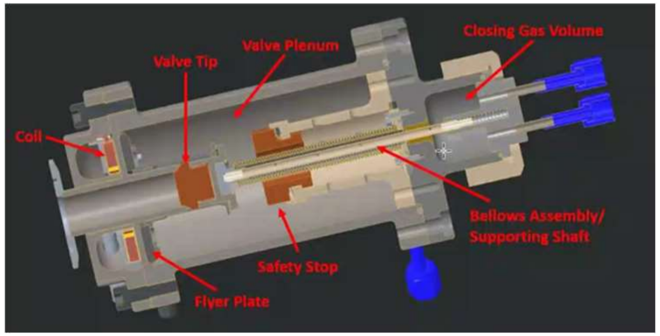
➢ ITER-DMS - Baseline:

– use gas puff delivered from Flyer Plate Valve for pellet release and acceleration

– Pellets will be kept at formation temperature over several hours and cannot be raised upon firing (unlike in current SPI systems)

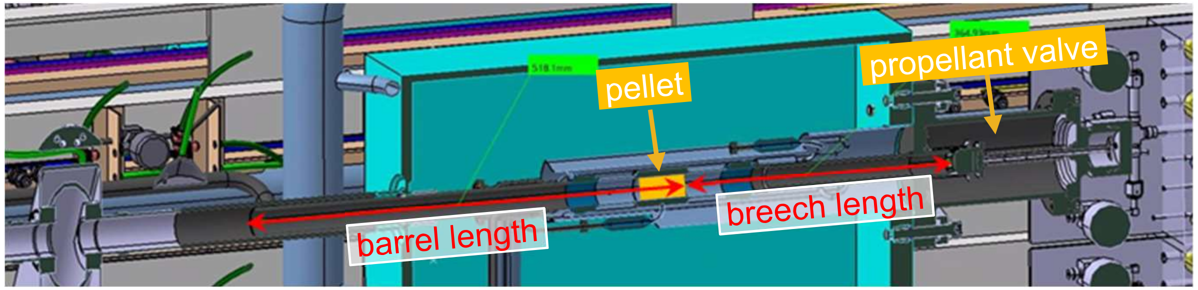
– Lifecycle tests in ambient magnetic field in Oak Ridge National Lab to start in July 2022

Flyer plate valve



see talk by T. Gebhart, ORNL

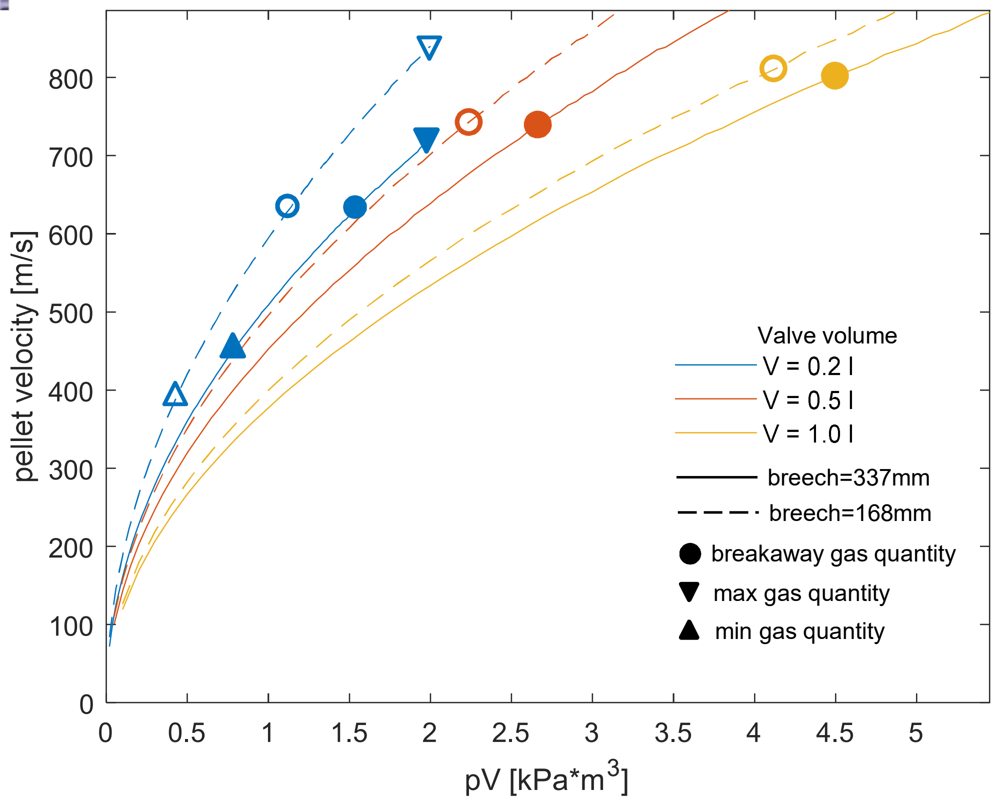
Pellet dislodgment and acceleration (2) – *baseline*



- Assessment of velocity range using analytical model
- Assumptions:
  - Immediate pressure equilibration after valve opening
  - Pressure at start of pellet movement corresponds to valve pressure scaled down by sum of V_{valve} and V_{breech}
  - Adiabatic expansion of gas, no flow restriction through orifice
- If propellant valve stays open => v_{pellet} too high (●,○)
- Reducing breech volume increases velocity range
- Closing valve allows access to lower velocities

→ Limitation of breech volume reduction driven by acceptable barrel temperature gradient, space restrictions, insulation issues, etc.

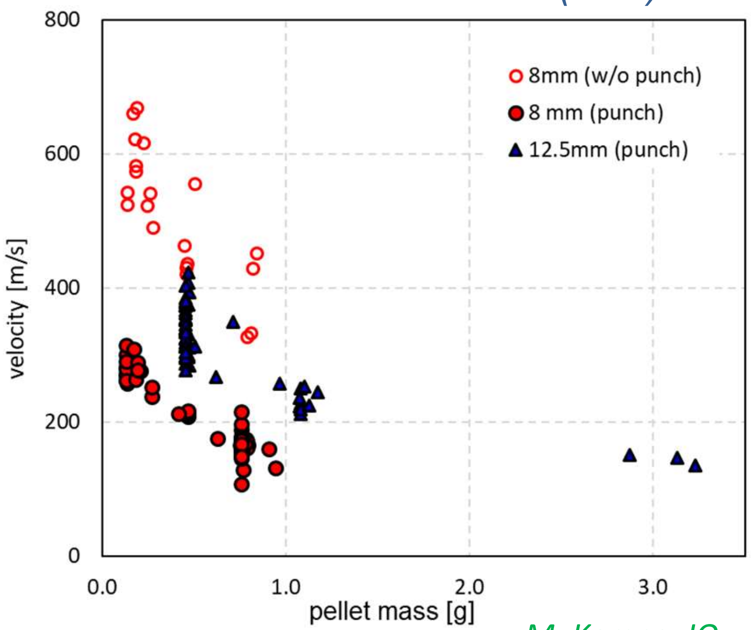
Velocity range for H-pellets



Pellet dislodgment and acceleration (3) – *baseline*

- Velocity variation of pellets released without or with punch, but accelerated through gas puff, has been measured.
- Gas release: resulting jitter in pellet arrival is within range of requirement.

Pellet velocities (JET)



M. Kemna, IO

Pellet velocities (JET)

Pellet	Release	velocity [m/s]	jitter* (veloc.) [ms]	jitter (release) [ms]
8mm 10%Ne	gas	620 ± 39	1.5	0.8
12.5mm 100%D	punch	339 ± 37	3.9	N/A
8mm 100%D	punch	278 ± 17	2.7	N/A
8mm 100%Ne	punch	166 ± 24	10.6	N/A

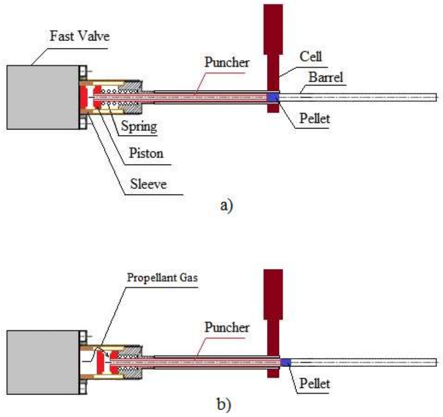
Lab tests with reduced breech

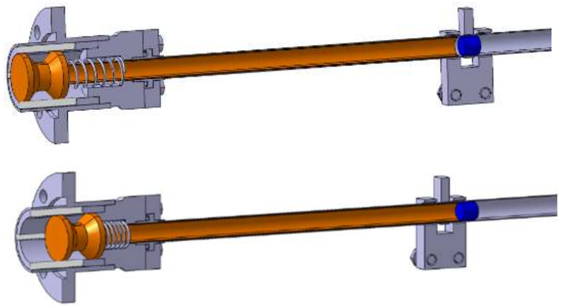
Pellet	Release settings	velocity [m/s]	jitter* (veloc.) [ms]
8mm 100%D	58bar 1.2ms	602 ± 8	0.3
	58bar 2.0ms	569 ± 8	0.3
	50bar 1.4ms	495 ± 17	0.8
	58bar 1.4ms	414 ± 17	1.2
	50bar 1.2ms	374 ± 8	0.7

** velocity jitter is scaled to ITER DMS flight distance*

Pellet dislodgment and acceleration (4) – *alternative concepts*

- "Hollow punch development" (PELIN, Russia):
  - Separation of pellet release and acceleration
    - → better control over velocity
    - → easier access to low velocity range
    - → reduction of required propellant gas
  - Demonstrated for pellets up to D=8mm (*c.f. talk by P. Heinrich on AUG-SPI*)



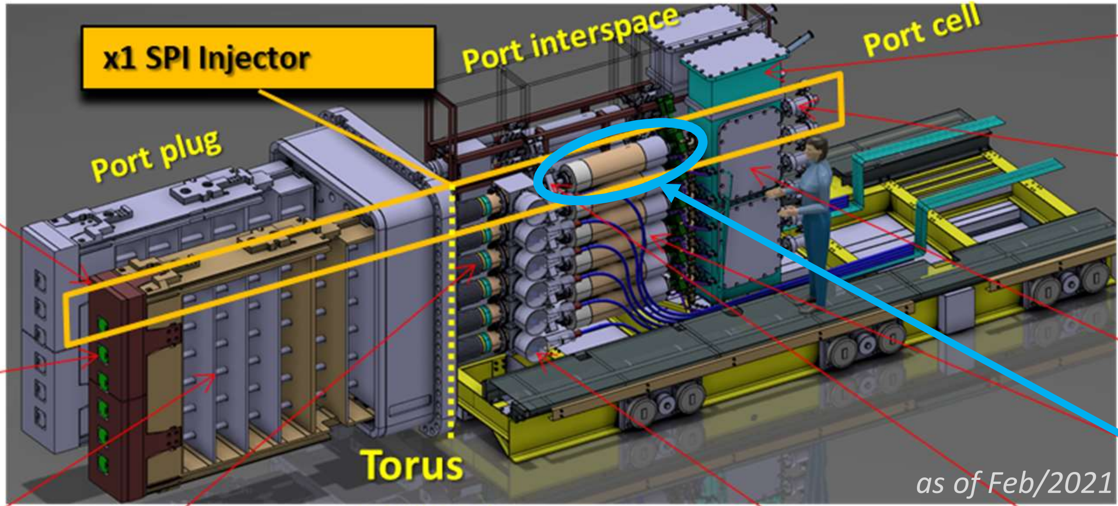


I. Vinyar, PELIN, Russia

- Fast flash heating:
  - Develop system to raise barrel temperature within 1-2ms
    → lower shear force
  - Planning to launch study in 2022

- Mechanical pellet launcher:
  - System avoiding any propellant gas for dislodging and acceleration
  - Expect project to start 2022

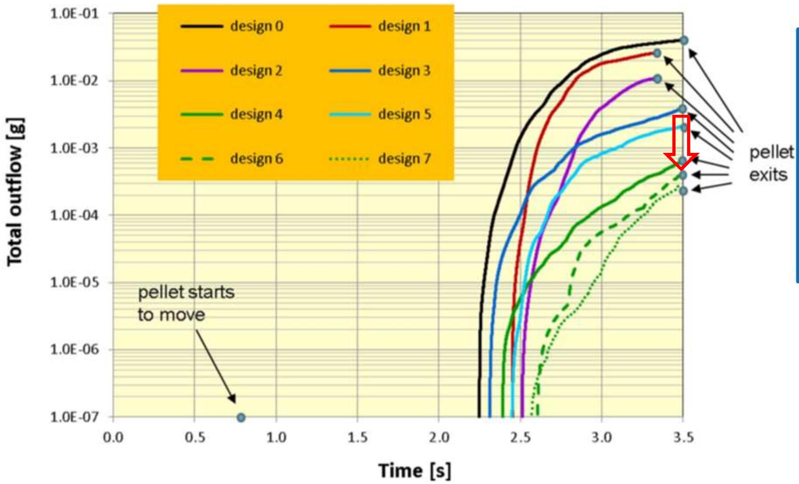
Pellet gas suppression

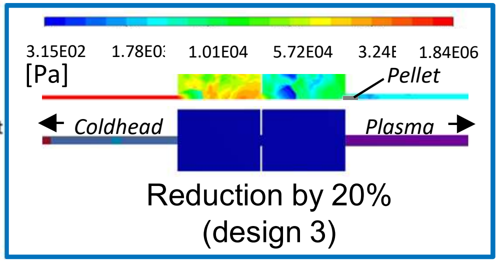


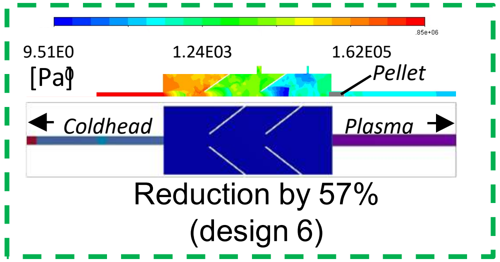
Propellant gas suppression

Propellant flow into plasma before fragment arrival: minimized and ≤1x10^{25} H-atoms/sec

- ITER-DMS – *baseline*:
  - Propellant suppression volume limited to 50L (for comparison JET~1000L, AUG~300L)
  - Fast shutter being developed: closes within ~1ms to retard propellant gas
  - Assess propellant gas flow through modelling and benchmark against measurements of ITER-like DMS gas suppression



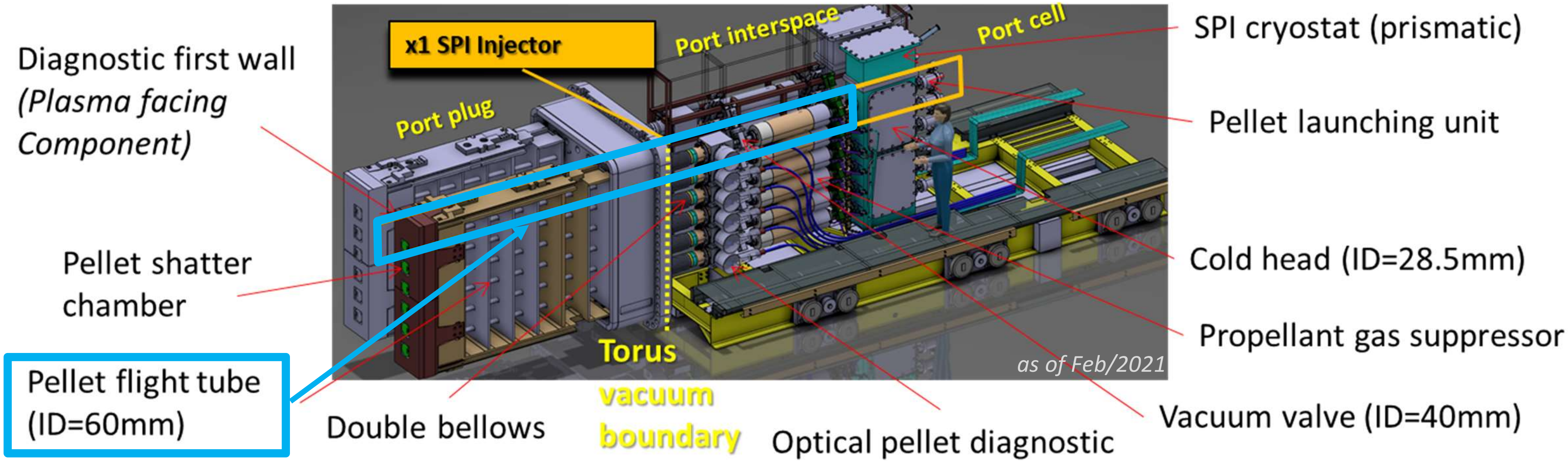




A. Horvat, CASPUS

- *Alternative concept*: guide tubes → study planned to address issue of gaps and "recapturing" pellet

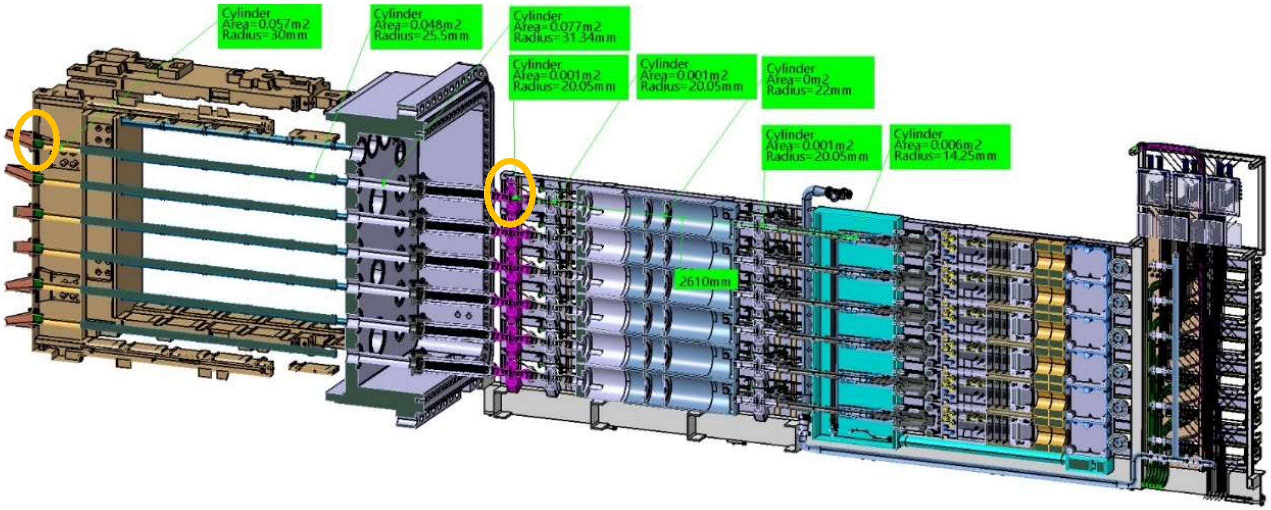
Pellet flight line



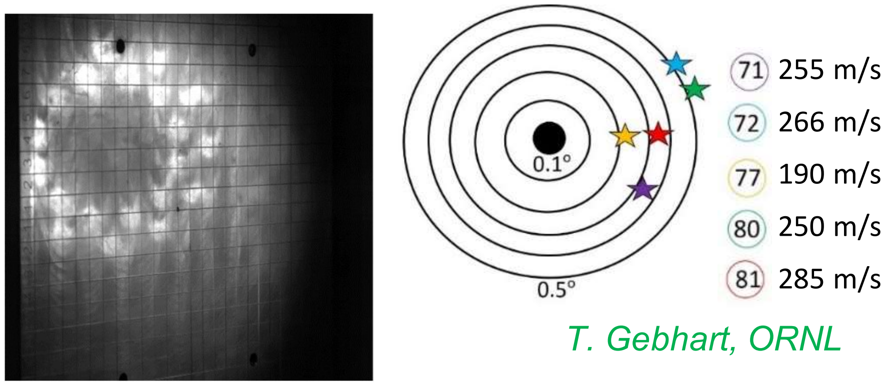
Pellet flight line

Minimize pellet trajectory dispersion and ≤ 0.15°

- ITER-DMS – *baseline*:
  - Pellets are delivered in free flight to shattering section (avoids structures like funnels)
  - Most restricting diameters of 40 mm at 2.18 m and 60mm at 6.0m limit the allowable dispersion to 0.15°
  - Measurements indicate dx~±0.11°, dy ~±0.21° achievable (assuming potential misalignment)
- *Alternative concept*: guide tubes

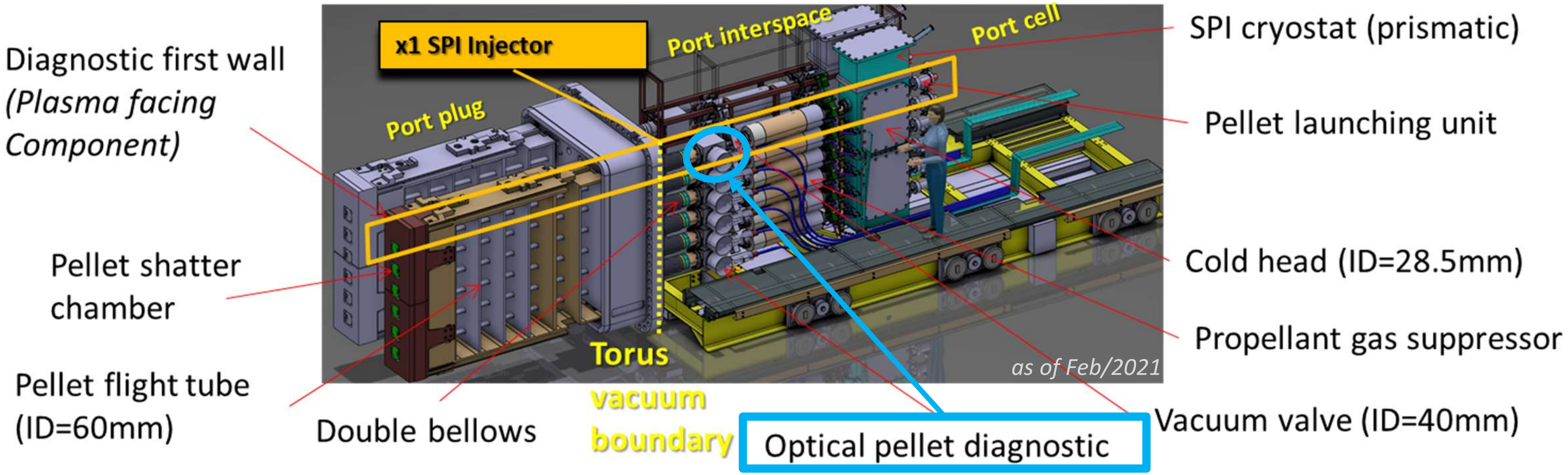


dispersion measurements



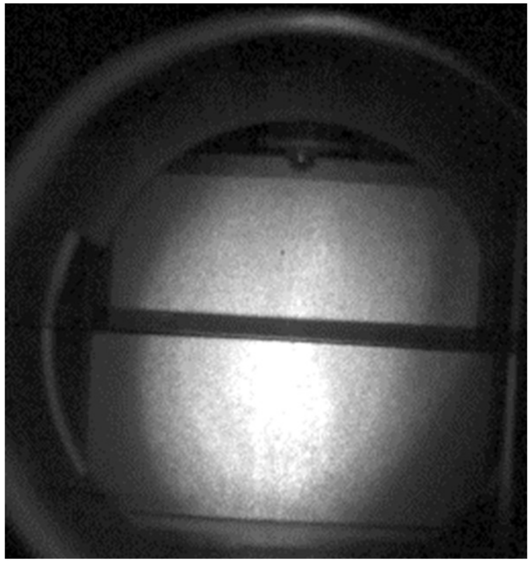
T. Gebhart, ORNL

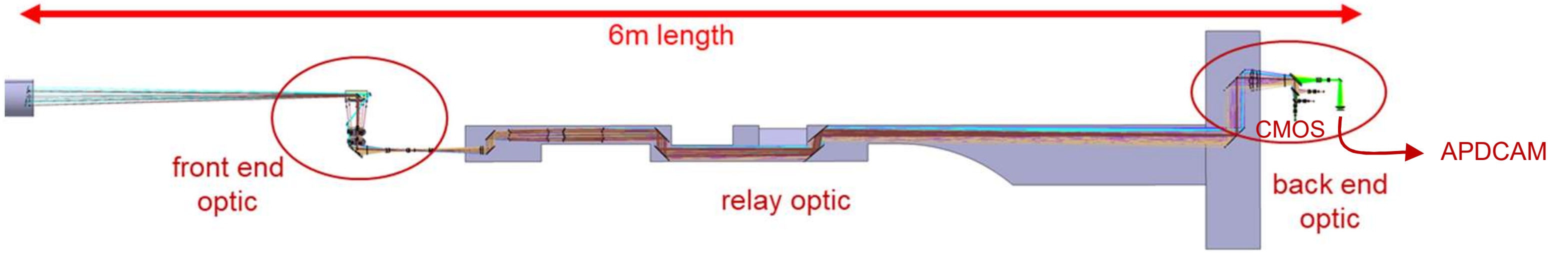
Pellet diagnostic

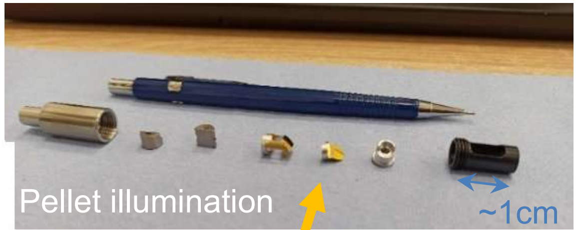


Pellet Diagnostic – *baseline*

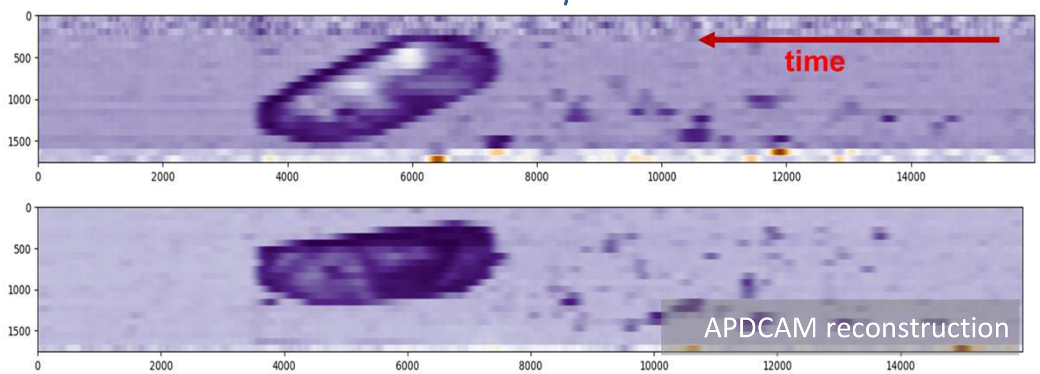
- Optical Pellet Diagnostic: Two sided pellet observation, determine several parameters (integrity, velocity, trajectory, …).
  - – Proof-of-principle suitable for ITER environment (radiation and limited space).
  - – Dual concept of sacrificial H-res CMOS in PC and APDCAM outside of PC

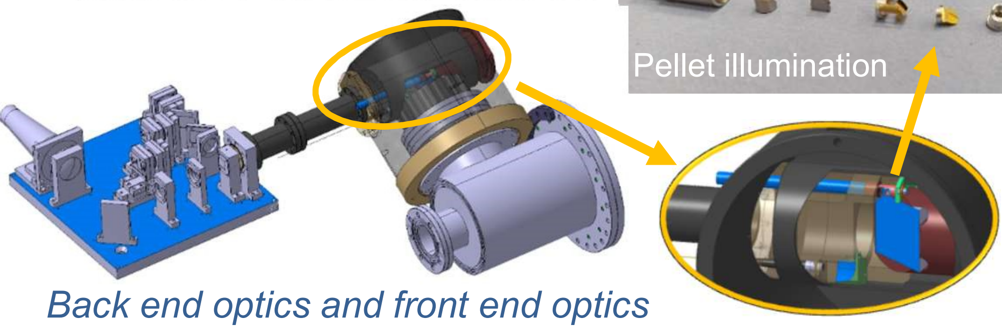






APDCAM outside of port cell to survive FPO

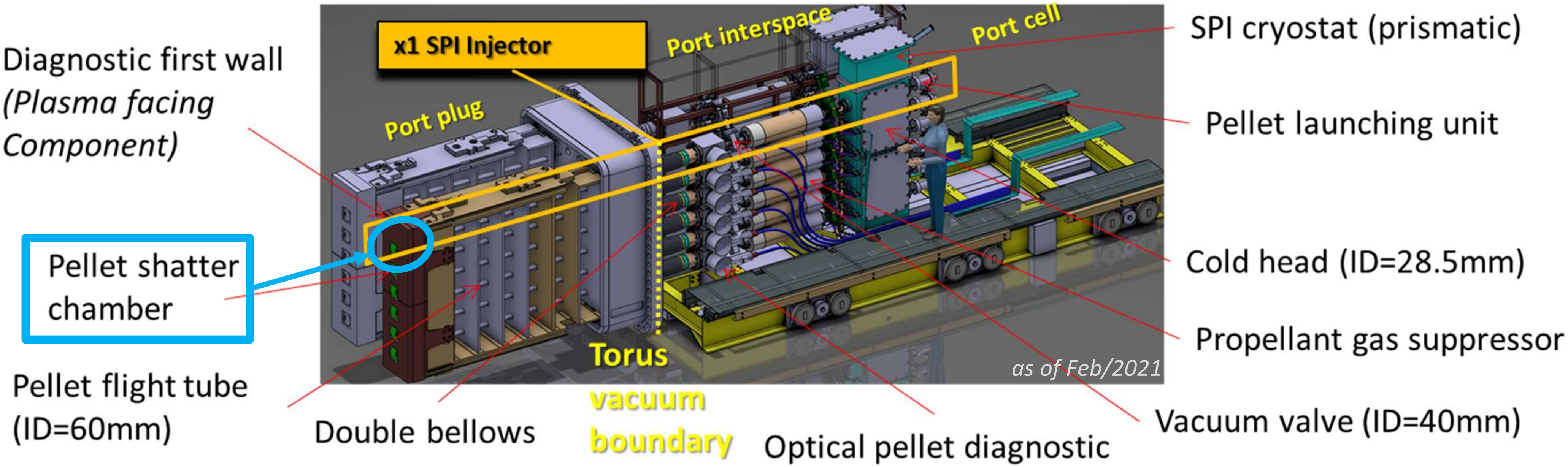




Back end optics and front end optics

D. Dunai, Fusion Instruments (Hungary)

Shattering unit



Shattering unit

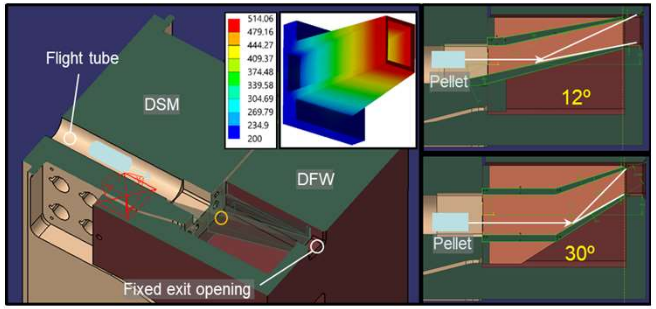
Equatorial port injectors: majority of mass in fragments > 2mm
Upper port injectors: fragment size predominantly <0.5 mm (→ gas)

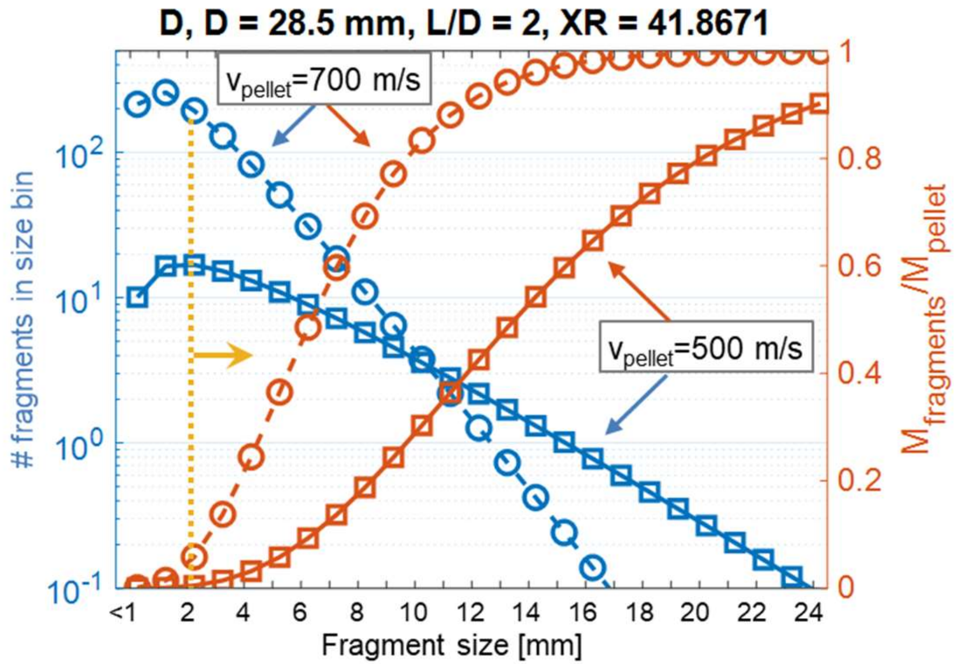
- ITER-DMS – *baseline*:
  - Design restricted by space (cooling channels) and heat load limits
  - Additional limitation by achievable pellet velocities
  - Design choice, α=15°, based on statistical fragmentation model (c.f. P. Parks)

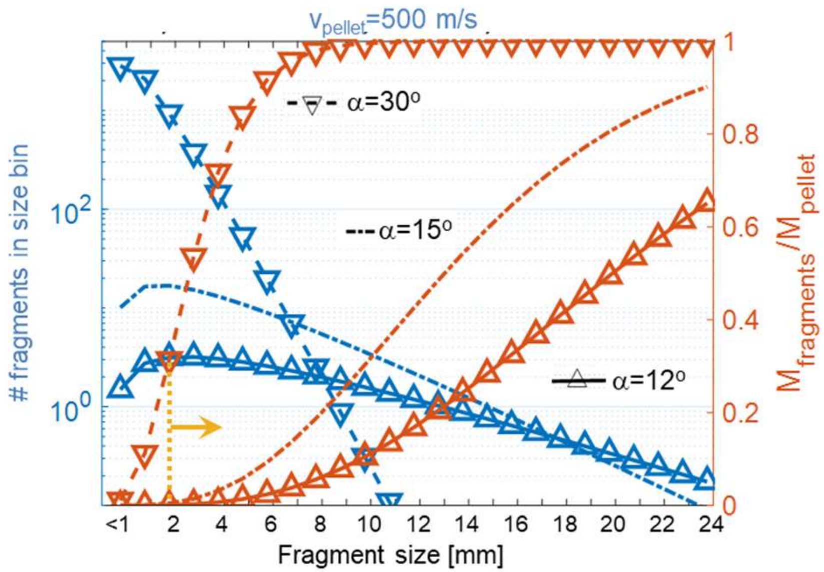
- Strategy:
  - Characterise H-pellet fragment plumes in lab tests (*see talk by S. Zoletnik*) together with data contributed from tests in IPP-Garching and ORNL
  - Develop model for simulating pellet shattering (*see talk by P. Matura*)
  - Test different shattering unit geometries

Shattering unit – *baseline: Equatorial Ports*

- Shattering angle of 15º most suitable for H-pellet velocities of ~500 m/s.
- Park's statistical fragmentation model predicts for this impact 125 fragments → probabilistic occurrence of fragments >15mm.
- Despite of DFW design freeze, possibility to accommodate other angles → fragmentations ranging from few large fragments (24) to producing huge number of gas/micro-fragments (~6500).



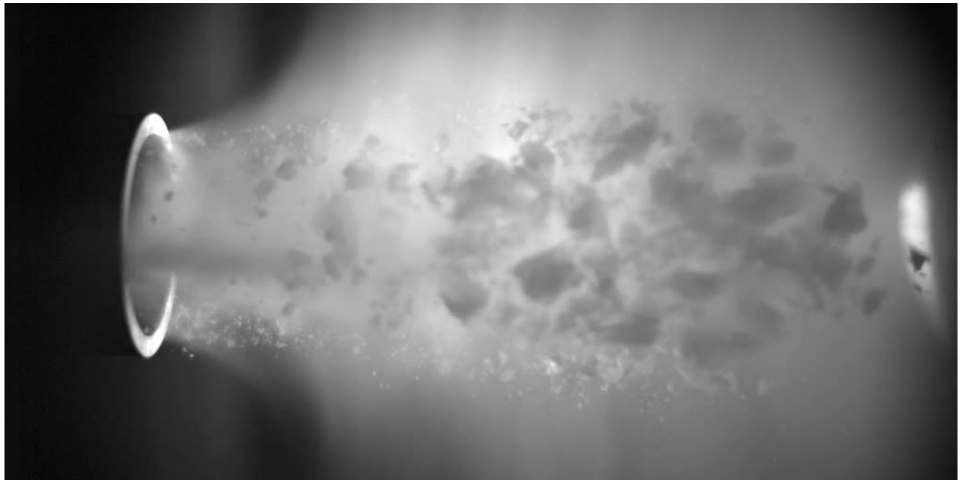




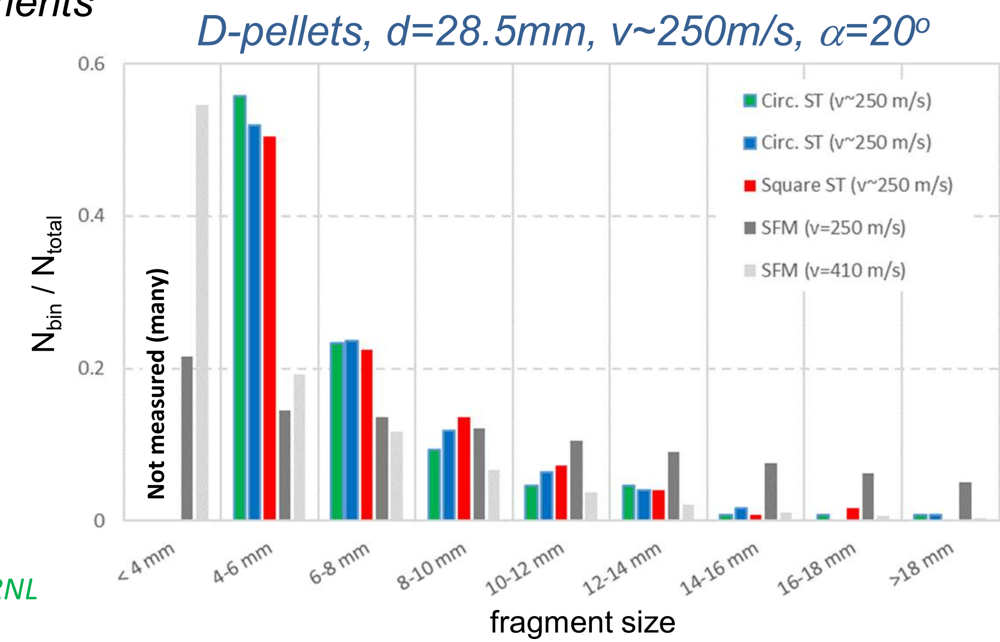
Note: for α=30º large fraction of material (~70%) is still in fragments >2mm.

Shattering unit – *validation*

- Fragment size distribution not predicted by statistical fragmentation model (SFM) [P. Park].
  Note: Good predictions found for smaller pellet sizes.
- High number of small fragments would suggest higher fragmentation similar to a 50% higher impact velocity
- *Note: diagnostic limitation is likely towards small fragments*



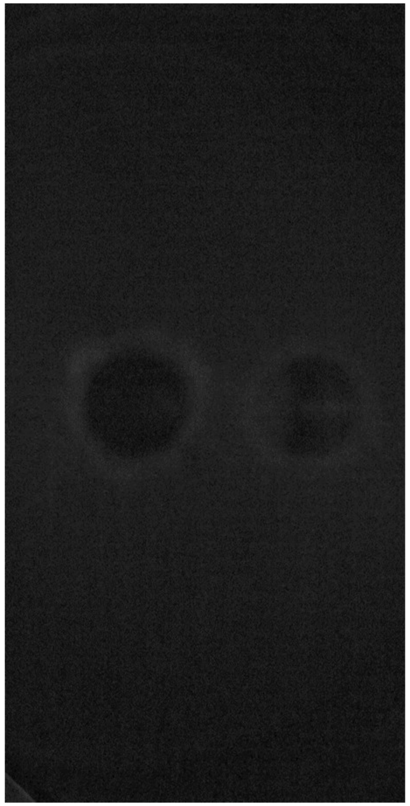
T. Gebhart, ORNL

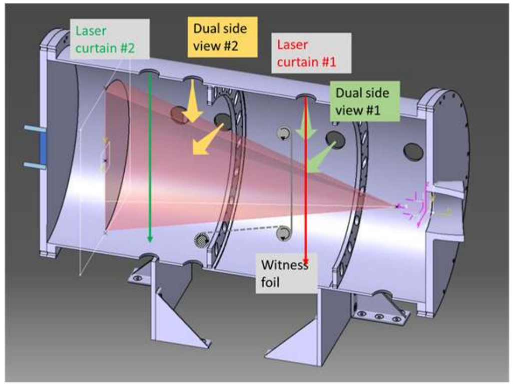


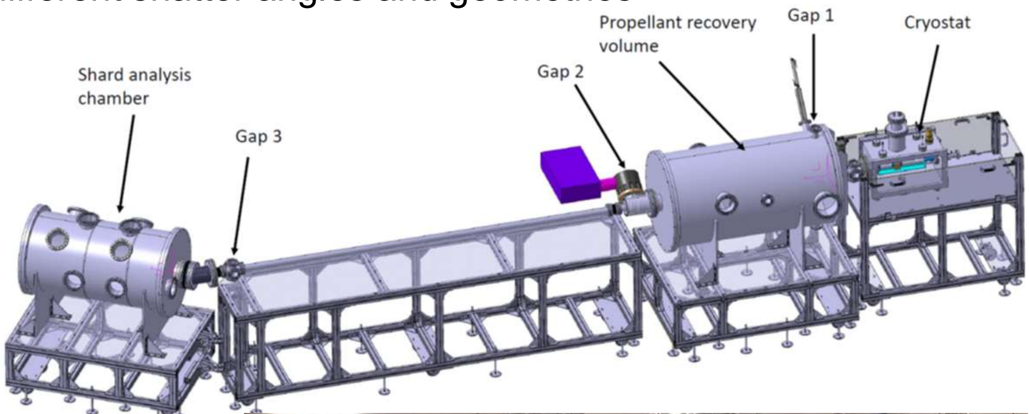
→ dedicated *experiments* and *modelling* to improve understanding of fragmentation process and to optimise shattering unit design

Shattering unit – *validation: experiments*

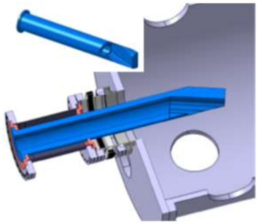
- “Support Laboratory” (CER/Hungary): *see talk by S. Zoletnik*
  - flexible design of shattering analysis chamber to accommodate different shatter angles and geometries
  - large suite of diagnostics to characterise fragment plume
  - observation of fragmentation process







Special shatter section for fragmentation observation



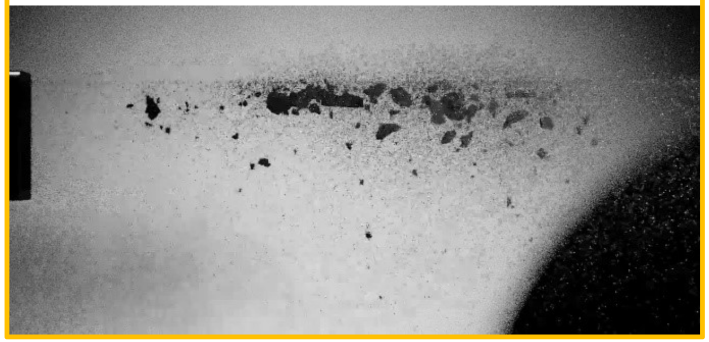

Assembled test bench(Feb 2022)

Shattering unit – *validation: simulations*

- "Pellet shattering simulation" (EMI-Fraunhofer/Germany): *see talk by P. Matura*
  - develop model based on Discrete Element Method
  - Unknown material properties are determined through optimisation loop of comparison with experimental data
  - validate against laboratory tests (AUG-SPI, ORNL, Support Laboratory)
  - simulation provide 3D characteristic of fragment plume, but diagnosed experimentally with limited sensitivity and spatial resolution

    → synthetic diagnostic

Rendered image of simulation

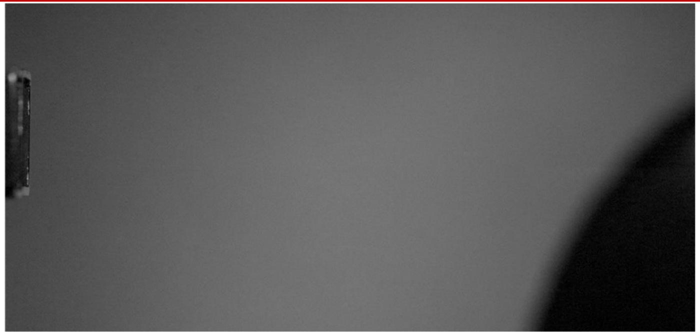


Simulation

Material parameter used: K = 9.8 MPa, σ_f = 6.45 MPa

Discretization h = 0.096 mm → ~ 500.000 particles

Experiment



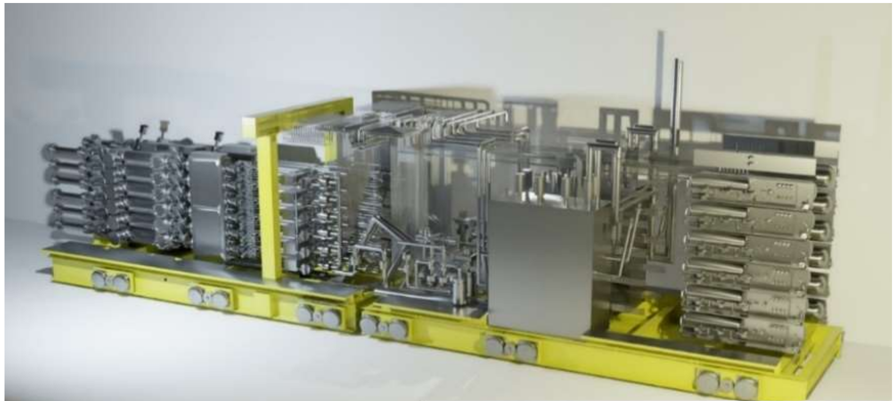
Neon pellet, ∅ 8 mm, L/D~1.1, v~160 m/s, 25° (AUG-SPI lab #718)

Conclusions

Conclusions

- ITER DMS design based on Shattered Pellet Injection technology has achieved high maturity and approaches final design review in 2023.
- Challenges originating from FOAK due to its size and integration complexity are addressed through a number of studies
- ITER DMS Task Force has launched extensive R&D on shatter pellet injection technology ongoing to validate baseline design
- Number of feasibility studies and development of alternative concepts launched as risk mitigation
- Besides of proof-of-principle development, reliability assessment is an important part of the programme
- Many activities are performed in parallel to provide input to design in a timely manner
- Broad range of expertise from experts world-wide acquired
- Variety of newly installed SPI systems in laboratories and on tokamaks help understanding the complex interplay between pellet formation, launching, trajectory and shattering

Questions?



ITER-DMS with 12 SPIs and services