MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Plasma fuelling on ITER and new requirements for DEMO

ASDEX Upgrade

P. T. Lang, L.R. Baylor, Ch. Day, E. Fable, T. Giegerich, A. Kallenbach, B. Ploeckl, W. Suttrop, H. Zohm, ASDEX Upgrade Team

Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy
IAEA Headquarters, Vienna, Austria
October 10. - 13., 2022

EUROfusion

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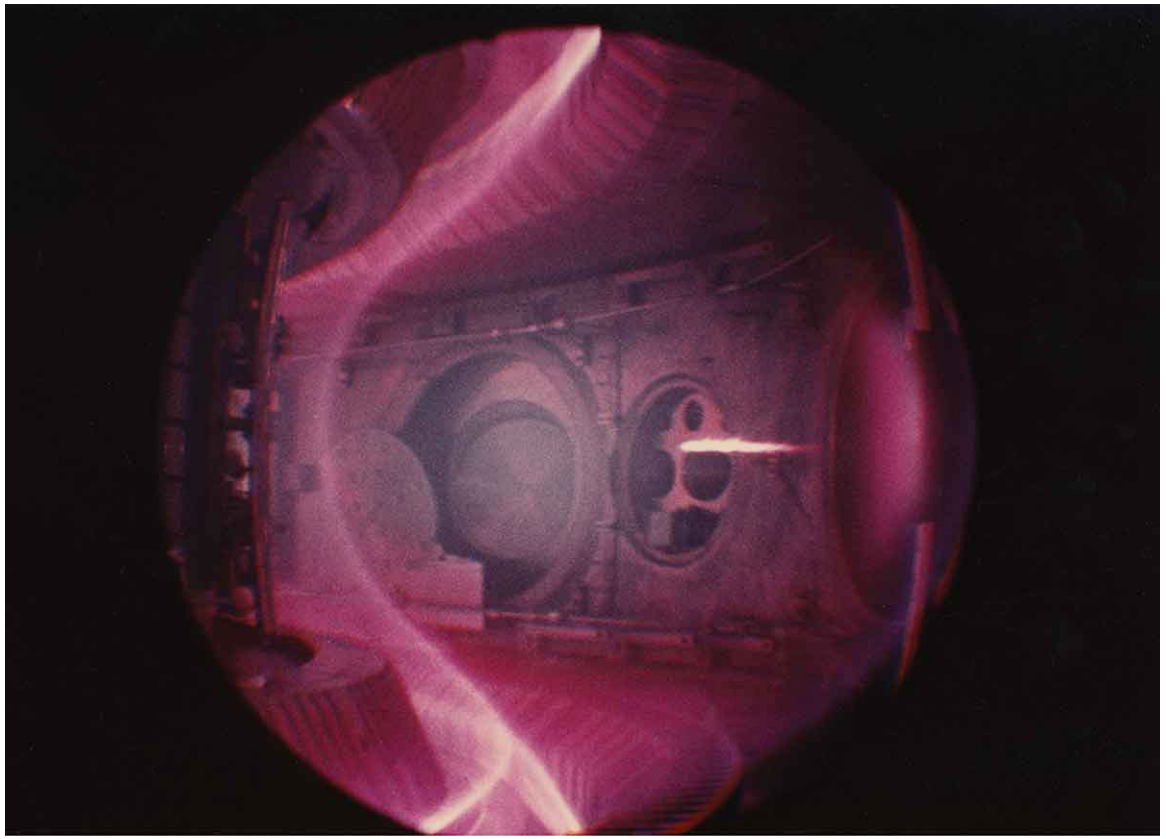
OUTLINE

- Fuelling a fusion reactor
- Pellet tool for fuelling
- ITER PLS – fuelling & ELM pacing
- ITER/ORNL technology
- EU-DEMO strategy
- Step-ladder approach
- DIPAK - PET



800 m/s D_2 pellet from LFS mid plane into an ASDEX plasma (1982)

S.K. Combs & L.R. Baylor, "Pellet-Injector Technology — Brief History and Key Developments in the Last 25 Years" Fusion Sci. Techn. ***73****, 493 (2018)*

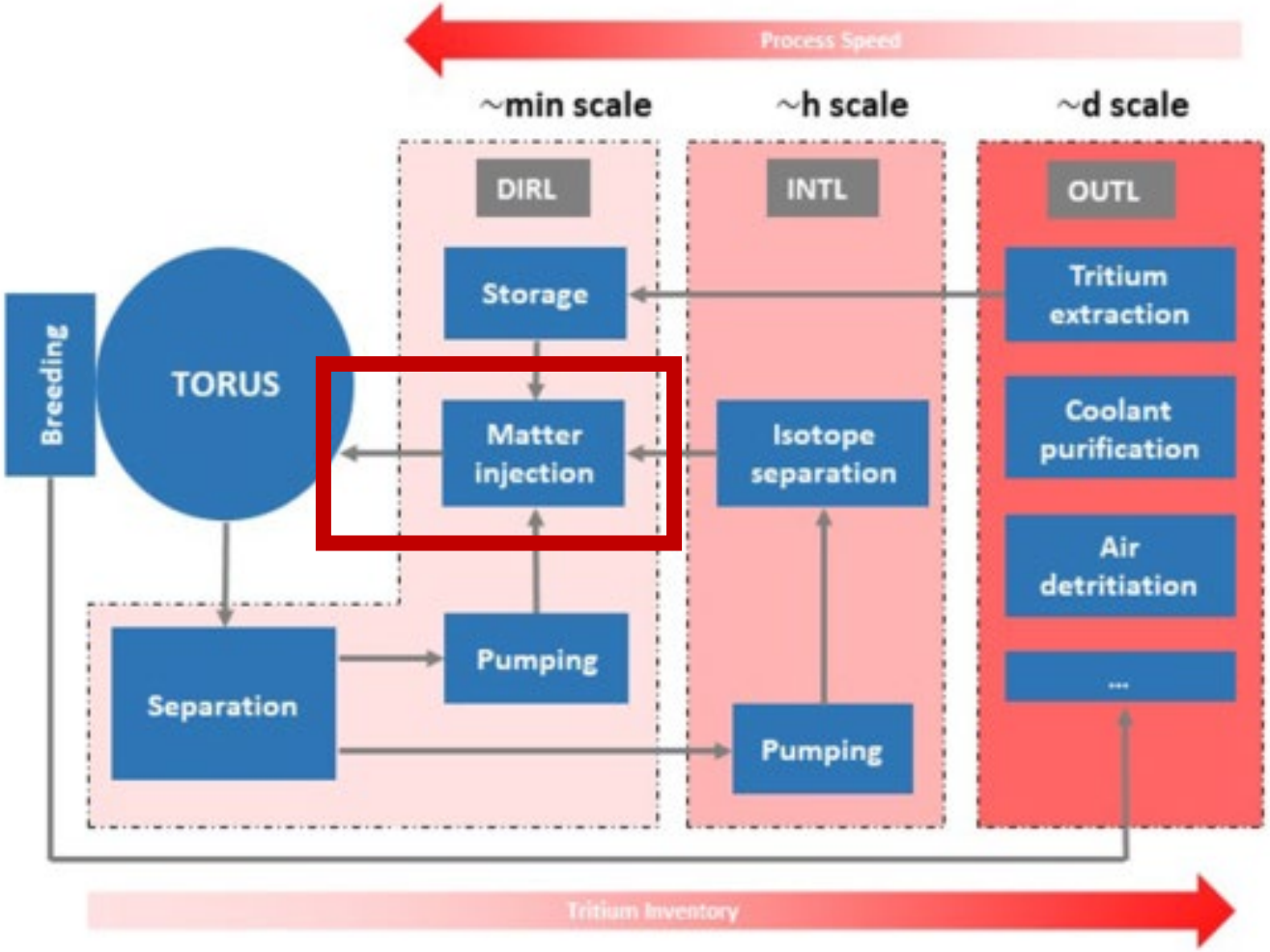
Fuelling a fusion reactor

Matter injection (input of material into torus vessel) tasks in ITER/DEMO:

- **Core particle fuelling of the burning plasma**
- **ELM control (potentially)**
- **Provide “plasma enhancement gases (PEG)” for radiative power dissipation and/or divertor buffering and/or performance enhancement**
- **Support ramp-up and ramp-down of the plasma**
- ***Disruption mitigation by e.g. Shattered Pellet Injector (SPI) or Massive Gas Injection (MGI)***

Chr. Day et al., “The pre-conceptual design of the DEMO tritium, matter injection and vacuum system”
*Fusion Eng. Design **179**, 113139 (2022)*

Fuelling a fusion reactor



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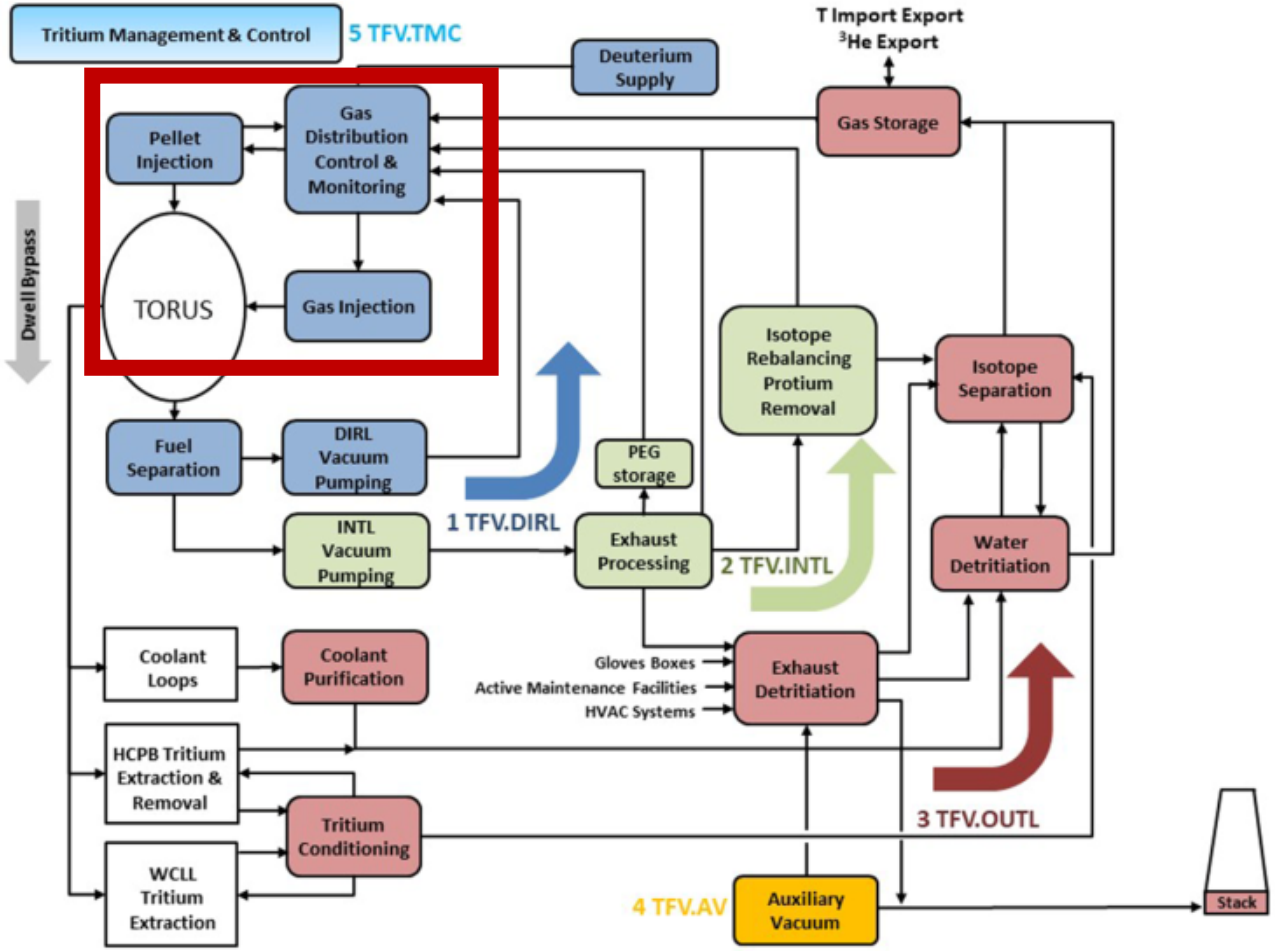
Fuelling a fusion reactor



Chr. Day et al., "The pre-conceptual design of the DEMO tritium, matter injection and vacuum system"
*Fusion Eng. Design **179**, 113139 (2022)*

Fuelling a fusion reactor

Matter injection (input of material into torus vessel) tasks in ITER/DEMO:

Core particle fuelling of the burning plasma

ELM control (potentially)

➔ Pellet injection

➔ Radiation hard valves and gas distribution systems

Provide "plasma enhancement gases (PEG)" for radiative power dissipation and/or divertor buffering and/or performance enhancement

Support ramp-up and ramp-down of the plasma

*Chr. Day et al., "The pre-conceptual design of the DEMO tritium, matter injection and vacuum system" Fusion Eng. Design **179**, 113139 (2022)*

Fuelling a fusion reactor

Matter injection (input of material into torus vessel) tasks in ITER/DEMO:

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ELM control (potentially)

Provide "plasma enhancement gases (PEG)" for radiative power dissipation and/or divertor buffering and/or performance enhancement

Support ramp-up and ramp-down of the plasma

➔ Pellet injection

*B. Ploeckl et al., "Matter injection in EU-DEMO: The Preconceptual Design"Fusion Sci. Techn **77**, 266 (2021)*

Fuelling a fusion reactor

Core particle fuelling in ITER/DEMO:

NBI - Very efficient but amount negligible (about 10^{20} /s ≈ 1% of need)

Gas puffing – Fading efficiency, hampered access to $n > n_{Gw}$

➔ Several techniques allowing for deep particle deposition analysed

ITER - Opted for inboard pellet injection (CT considered seriously as well)

EU-DEMO - SWOT analysis performed

Rank	Technology	
1st	Classical pellet injection	75%
2nd	Microwave, laser, railgun	
3rd	Gas puffing, supersonic jets	< 50% (with ´zeros´)
4th	Compact tori	
5th	Unmagnetized plasma jet	

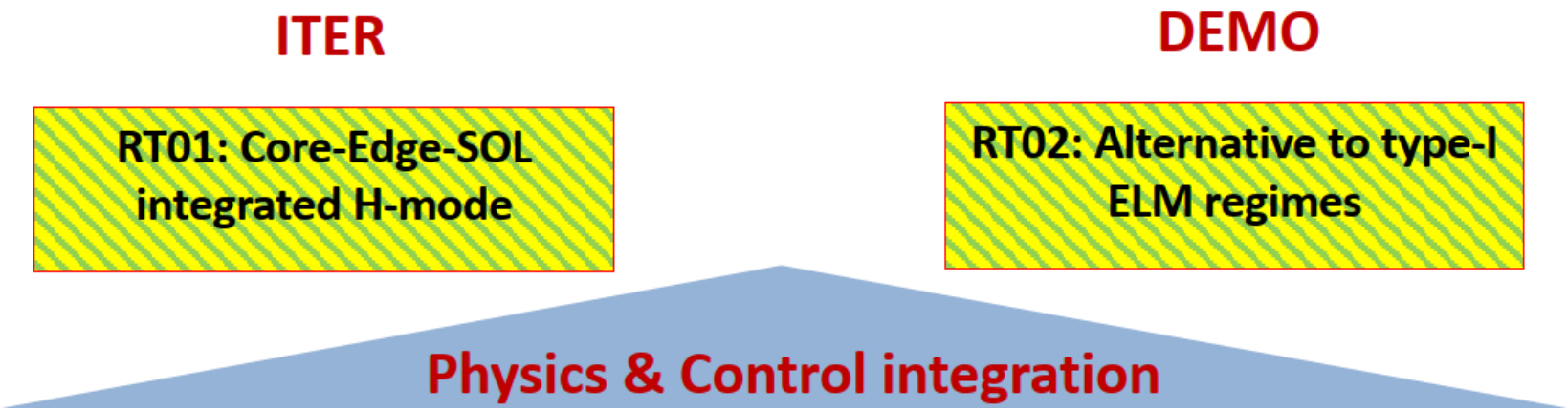
Chr. Day, "European R&D Programme of the DEMO inner Fuel Cycle", ISFNT-12 (2015)

Confirmed the ITER decision

Likely, ITER's decision deepened an already existing "maturity gap"

ELM pacing & mitigation

Different scenarios for ITER and DEMO (see e.g. WPTE Research Topics)



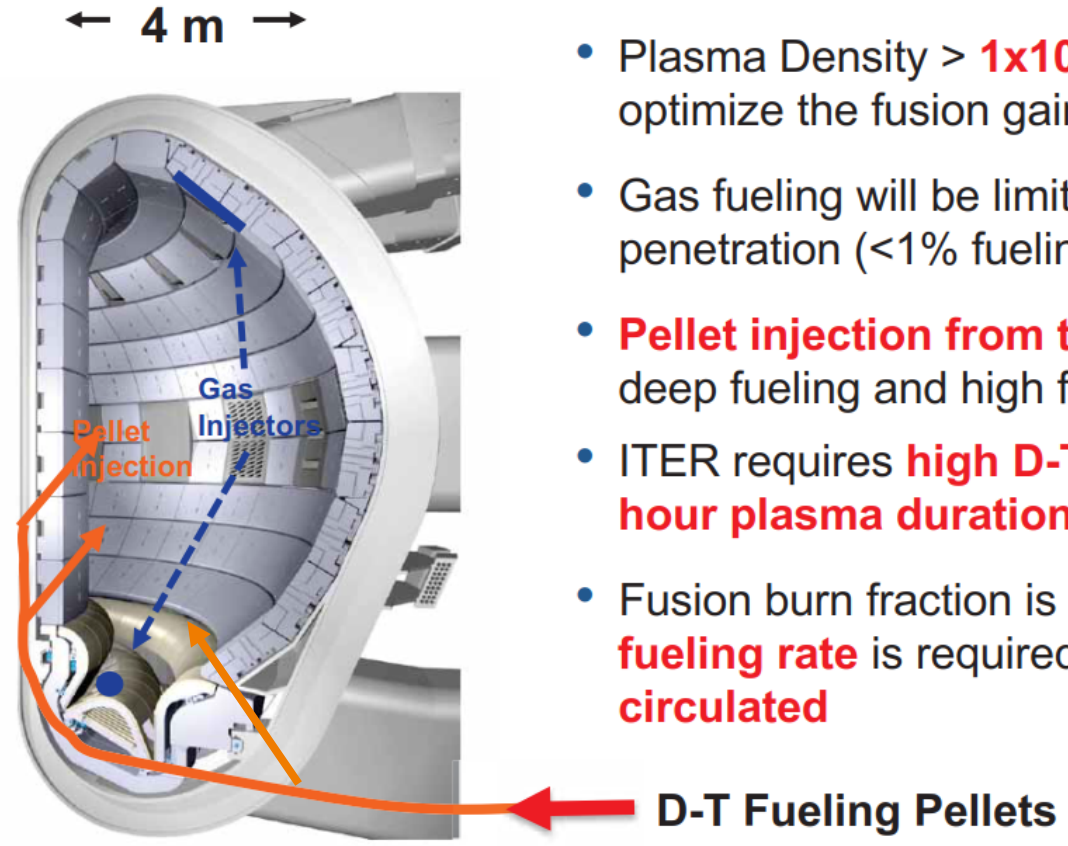
A. Kappatou, "Discussions about proposals", WPTE 2022/23 Programm Meeting

ITER – Pellet pacing requested, injection from the out- and inboard

EU-DEMO – Pellet pacing kept as "nice to have" option, injection from the inboard

ITER PLS: Fuelling

The ITER fuelling requirements form a significant challenge



ITER Cross Section

- ITER plasma volume is **840 m^3**
- Plasma Density > **1x10^{20} m^{-3}** with D-T in order to optimize the fusion gain (Q=10)
- Gas fueling will be limited by poor neutral penetration (<1% fueling efficiency)
- **Pellet injection from the inner wall** provides for deep fueling and high fueling efficiency
- ITER requires **high D-T mass flow** for up **to 1 hour plasma duration** with **high reliability**
- Fusion burn fraction is small ~ 1%, thus **high fueling rate** is required and **fuel must be re-circulated**

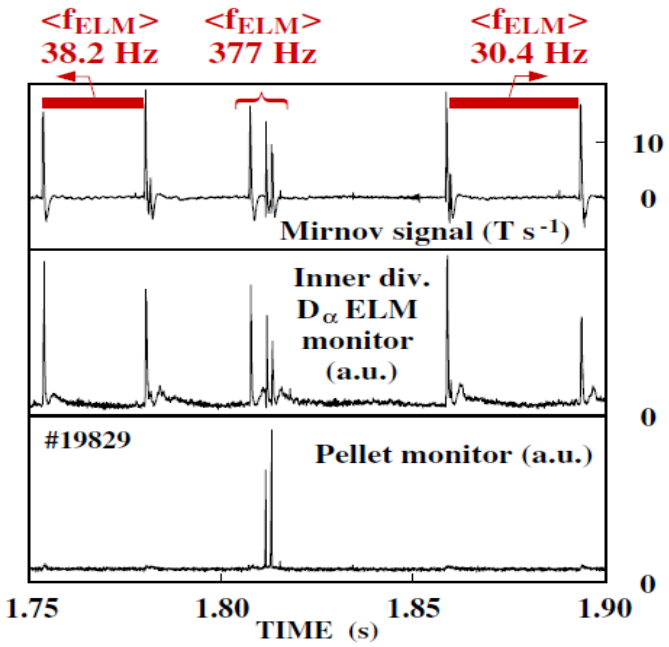
D. Rasmussen, "D-T Pellet Injection for ITER Plasma Fuelling"
Tritium Working Group, Oak Ridge, May 2018

ITER PLS: ELM pacing/mitigation

Reliable ELM pacing with C-wall (AUG, JET, DIII-D), mitigation (DIII-D)

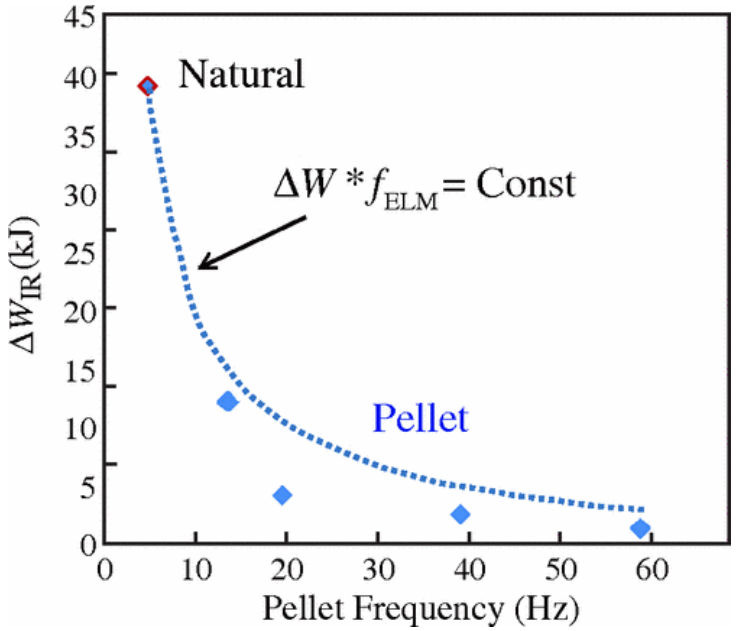
AUG-C:

Every pellet triggered an ELM



DIII-D: 12 x f^0_{ELM} by pacing

Energy flux to divertor mitigated accordingly



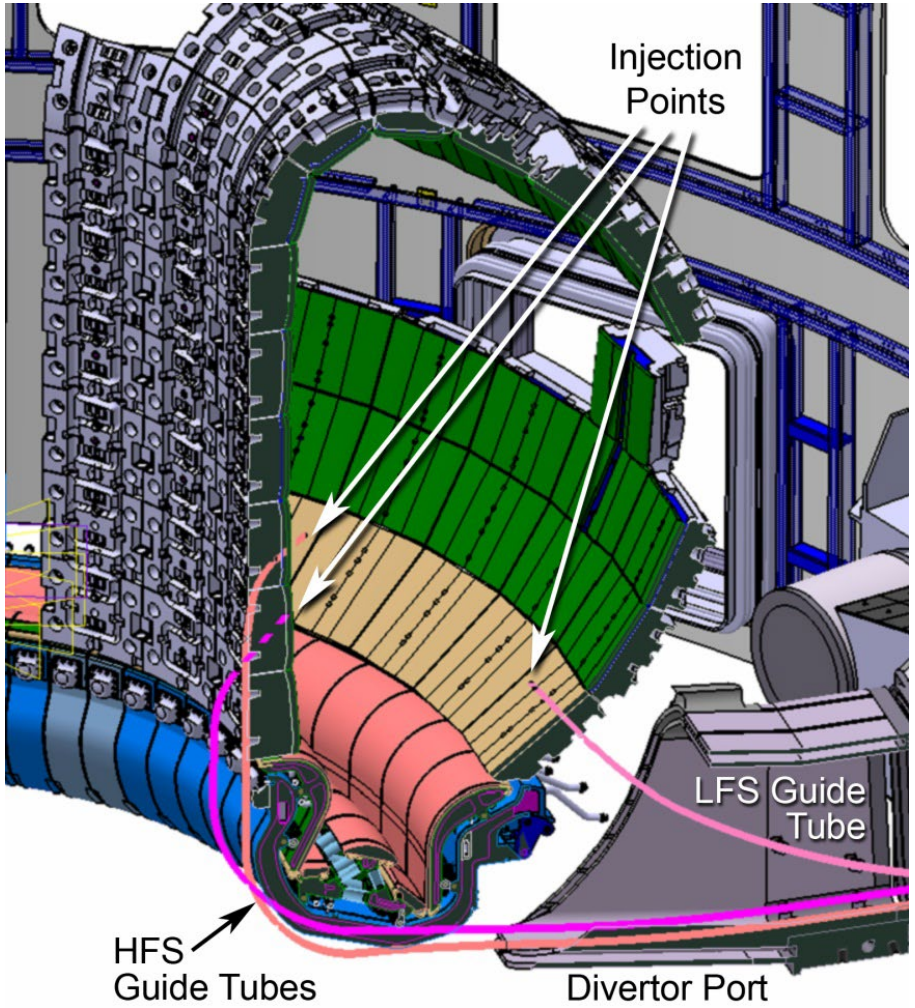
L.R. Baylor et al.: Phys. Rev. Lett 110 (2013), 245001

"-" Reliable triggering no longer observed in AUG-W or JET-ILW

"+" Impurity flushing works with "just" ELM pacing as well

ITER PLS: Fuelling & ELM pacing/mitigation

Design of the ITER pellet system



Maximum Fuelling Rate to Plasma

H_2 and D_2 pellet: 120 Pa m^3/s [6 x 10^{22}/s]
T_2 pellet : 110 Pa m^3/s

Number of Injectors

Core fuelling : 2 injectors (D_2 and T_2)
Back-up : 2 injectors (different tasks)

Injection Frequency

16 Hz max. for core fuelling & ELM control

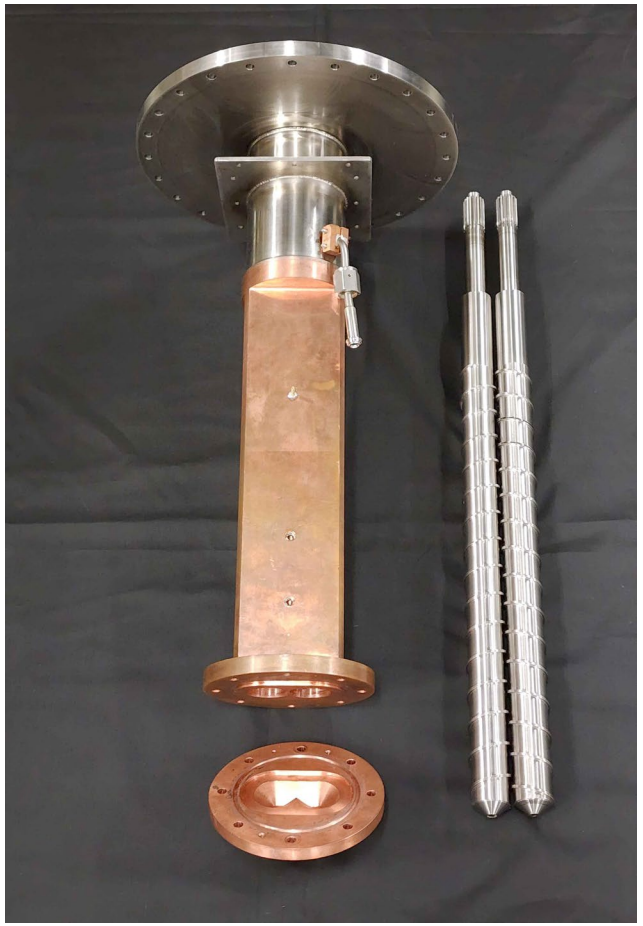
Pellet Speed

Reference : 300 m/s [HFS – fuelling]
Maximum : 500 m/s [LFS – pacing]

L.R. Baylor et al., Nucl. Fusion **47** (2007) 443

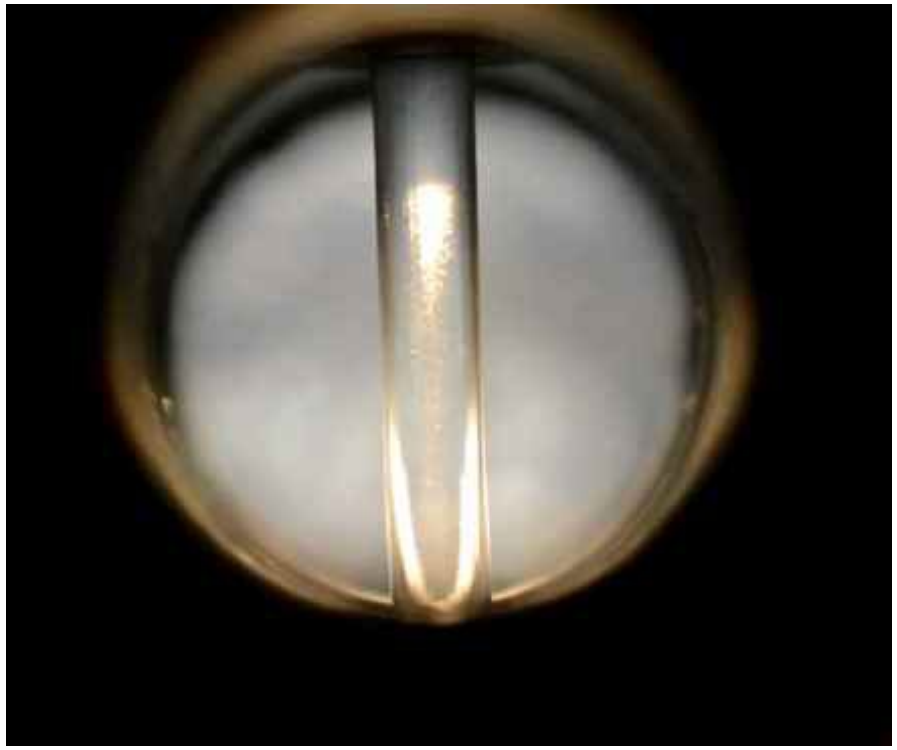
ITER/ORNL technology

Pellet source: screw extruder (similar solution likely for EU-DEMO)



← Twin screw extruder before final assembly

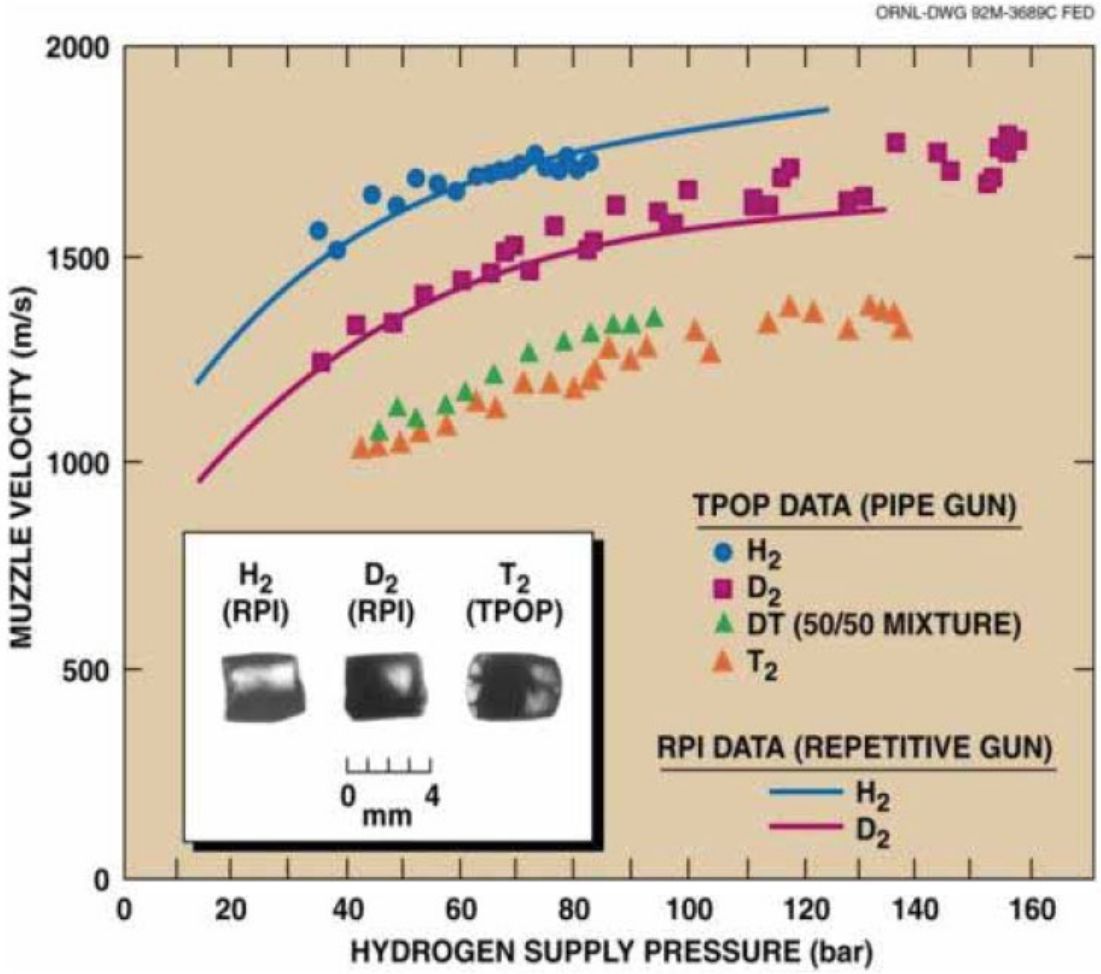
H_2 3mm ice rod extruded →



Nozzle head optimization ongoing applying POLYFLOW code

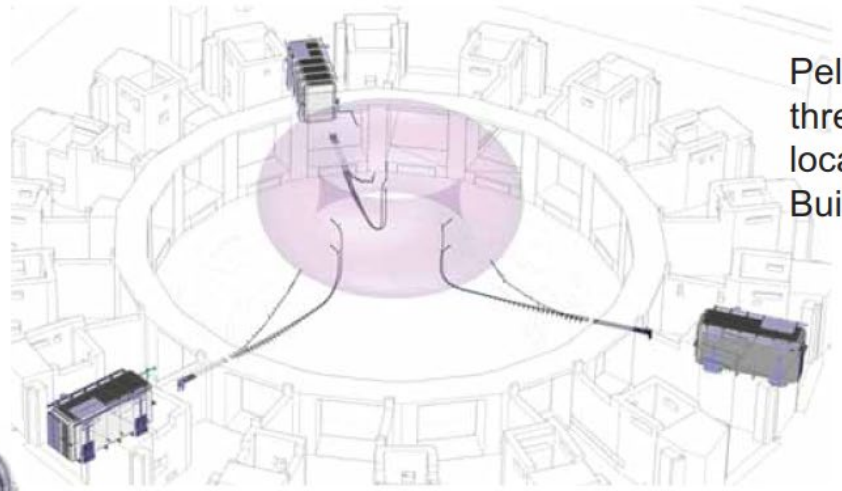
ITER/ORNL technology

Tritium proof-of-principle (TPOP) experiment: T-pellets can be formed and handled



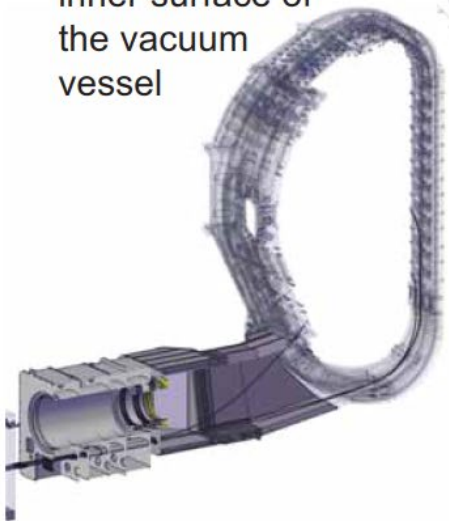
ITER/ORNL technology

Pellet launcher unit: cask solution (copied for EU-DEMO)

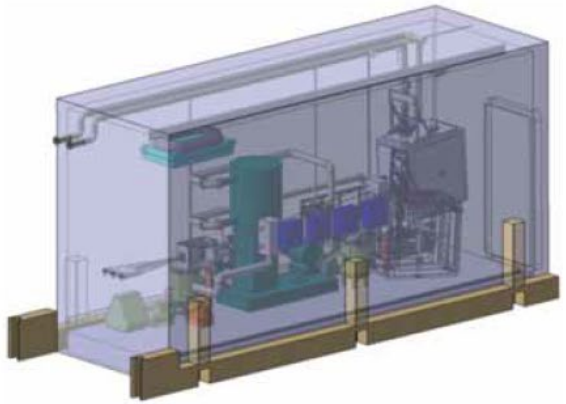


Pellet Injectors at three toroidal locations at Building Level B1

Pellet guide tubes enter through the vacuum pumping ducts and are mounted to the inner surface of the vacuum vessel



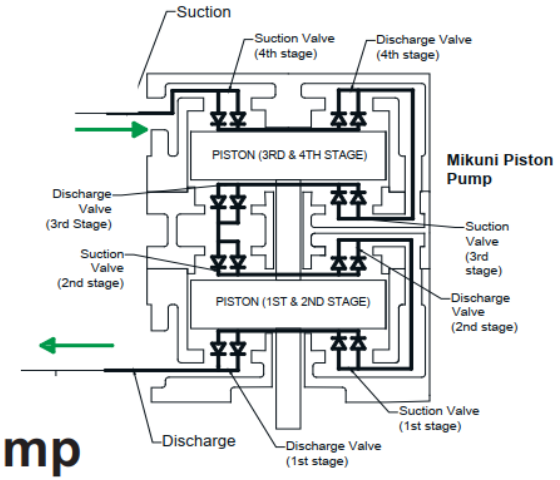
Pellet Injector subsystems are housed in tritium containment casks



ITER/ORNL technology

T technology available

- Piston pump ran for over one year until piston ring failure
- Mikuni company elaborated solution
- Further option for tritium pumping: scroll pumps
- T compatible cryogenic relief valves developed
- Lesson learned from ITER: PLS should be outside the bio shield to minimize radiation to the injector components.



Tritium Compatible Piston Pump

- Operated for nearly 15,000 hours over multiple years without significant performance degradation.
- No-load pressures between 0.1 Torr and 0.2 Torr
- Pumping speeds of 150 m3/h at suction pressure of 10 Torr.
- Pump operation stopped when noise developed within the pump housing.
- Disassembly found immovable tension rings within the outer grooves of the upper piston and broken Vespel rings
- Did not significantly degrade performance, but design improvement in these two areas could lead to longer operating periods and higher availability

EU-DEMO: Strategy

Make use of ITER/ORNL expertise & AUG/JT-60SA, JET HFPI, DIPAK-PET, … achievements

- **Similar/same extruder as ITER *(Option Thermal pellet formation)***
- **Acceleration system: Centrifuge step-ladder *(Option High speed gas gun)***
- **Similar cask system as ITER**
- **Single multi-species train injected from inboard**
- **Controller step-ladder**

EU-DEMO: Strategy

Generic view of core fuelling system options

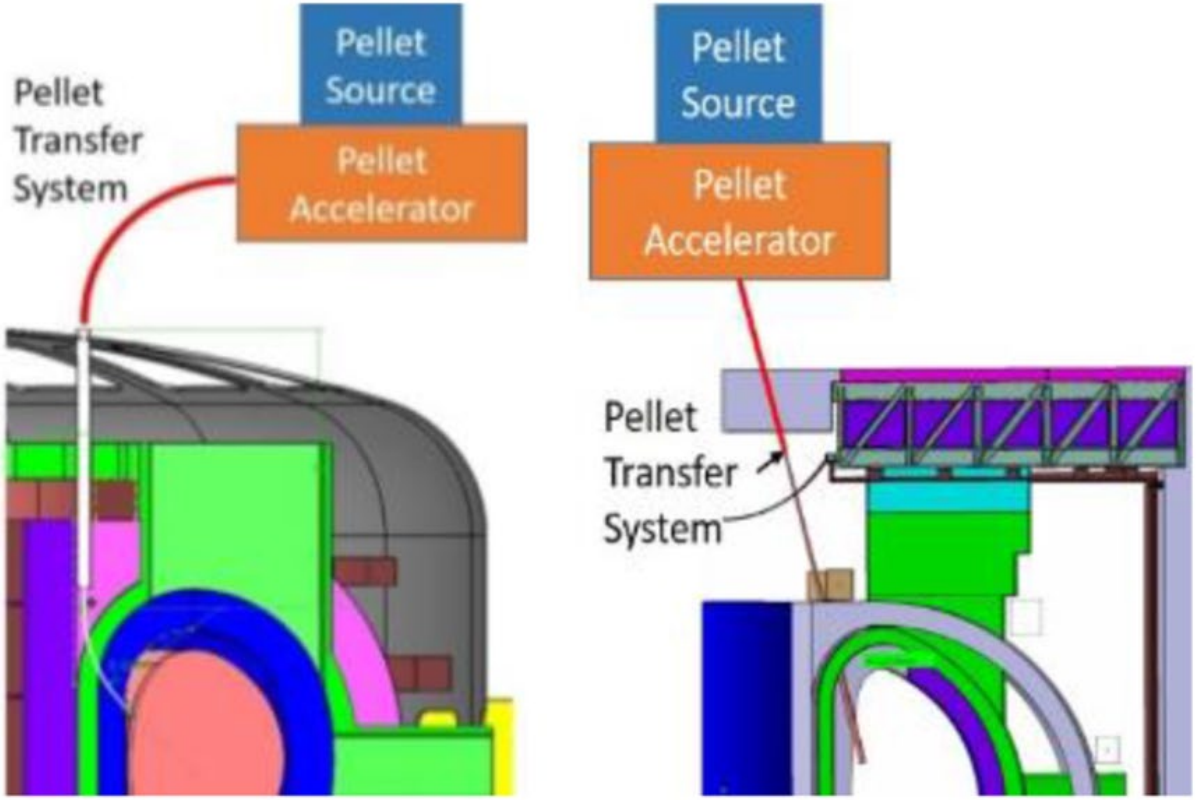
Reference solution:

Moderate pellet speed (1 km/s)

➔ Centrifuge

Optimised access

Space reservation o.k.



Direct line of sight (DLS) option:

Needs high pellet speed (3 km/s)

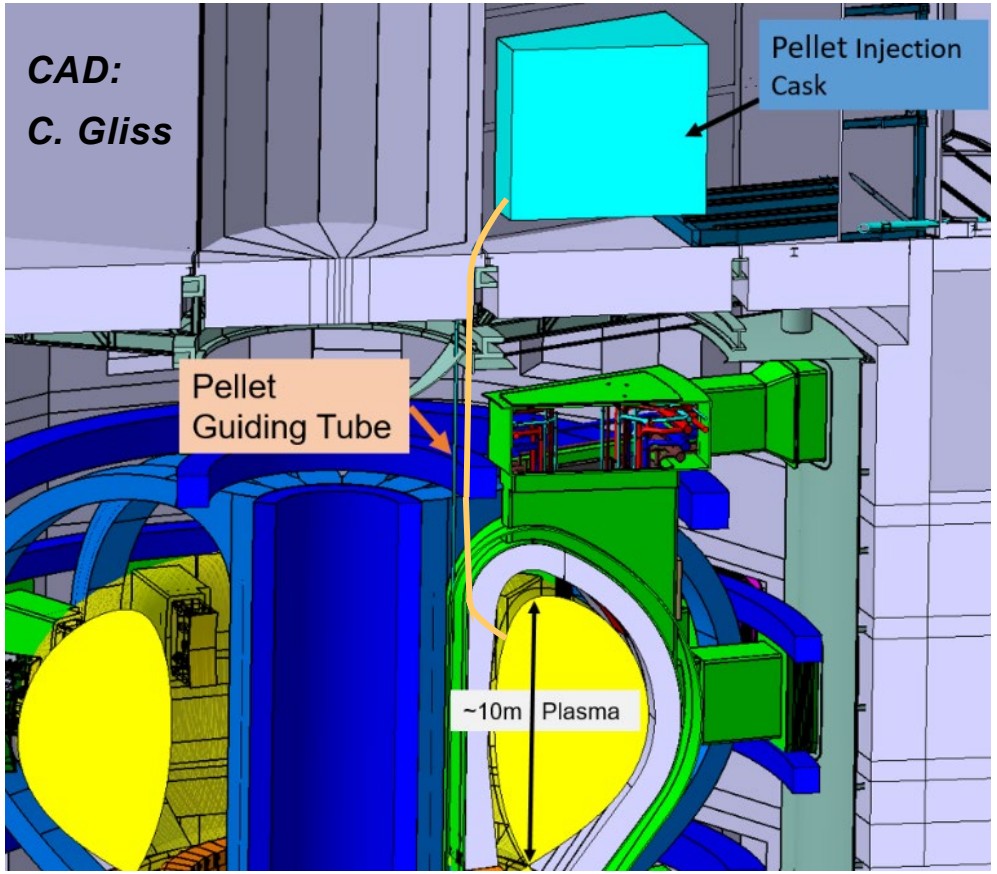
➔ Double stage gas gun

Access & Space reservation to be considered

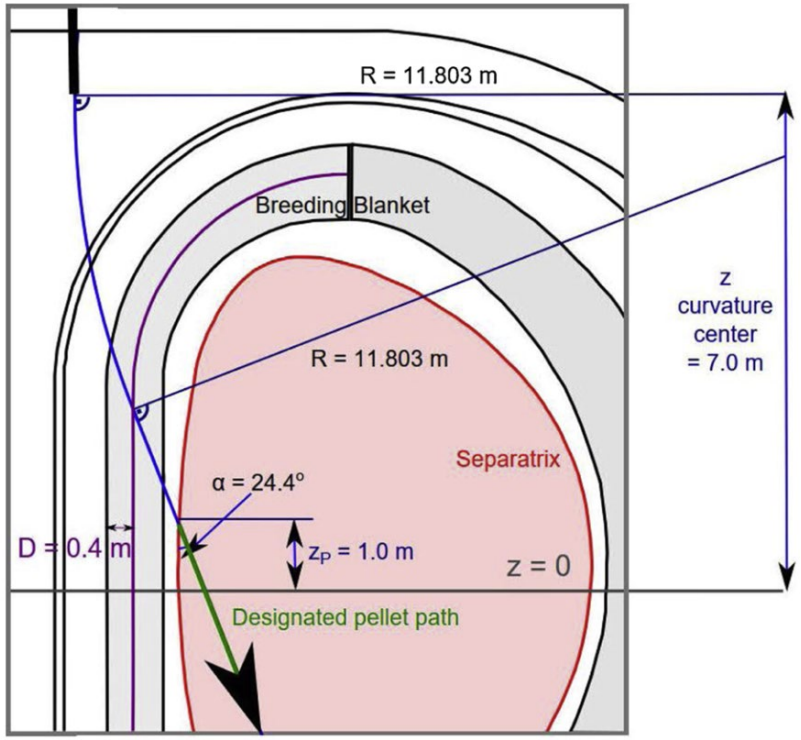
*Chr. Day et al., "The pre-conceptual design of the DEMO tritium, matter injection and vacuum system" Fusion Eng. Design **179**, 113139 (2022)*

EU-DEMO: Optimising Engineering & Physics

Core fuelling system reference solution



Space reservation o.k.



Injection trajectory can be optimised taking into account BB boundary conditions

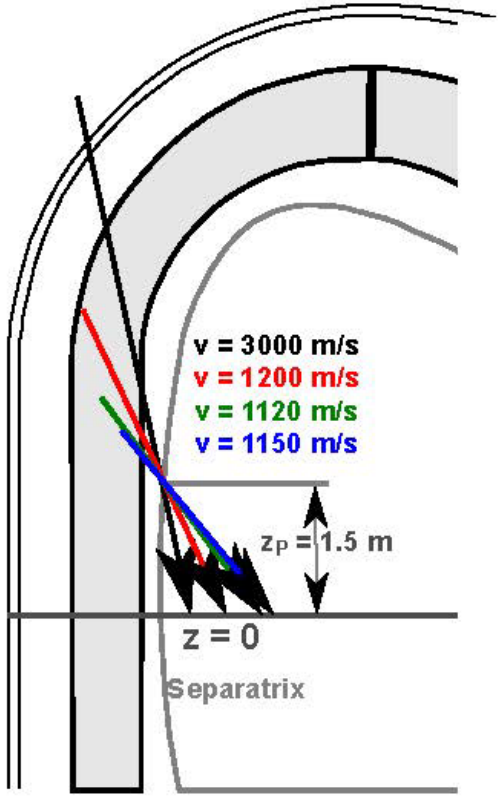
"Maximum transfer speed vs. Injection angle"

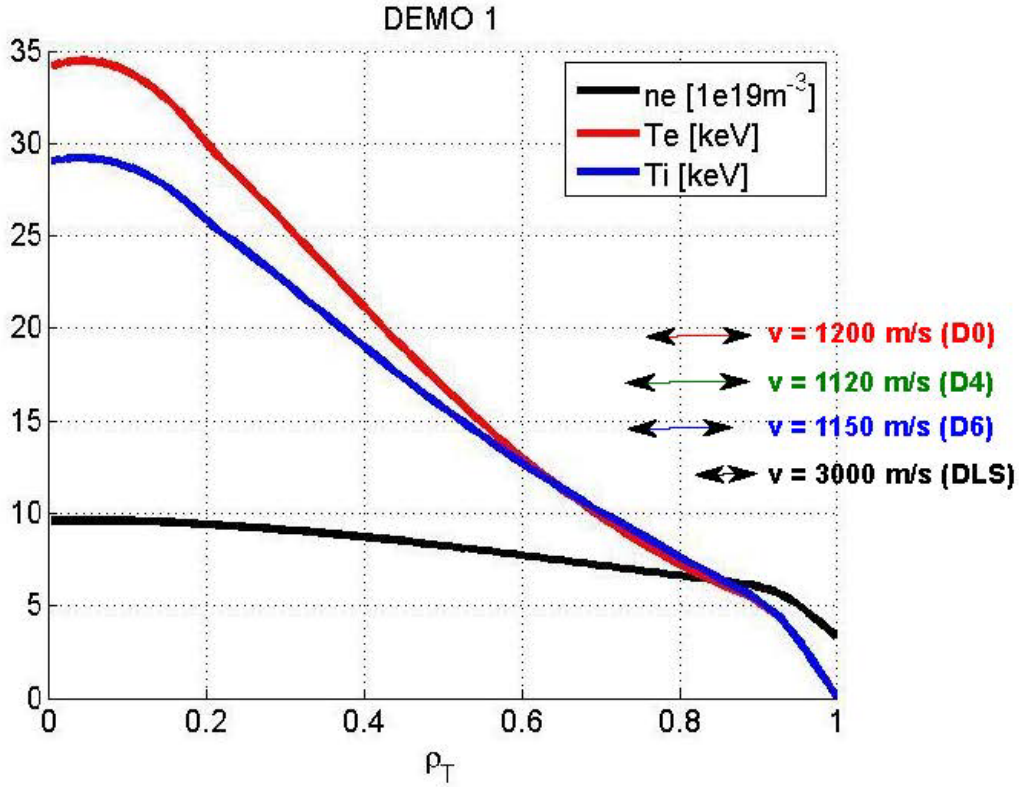
EU-DEMO: Modelling core fuelling

Combine ASTRA plasma transport code & HPI2 pellet ablation/deposition code

For any considered case: calculate pellet flux (m_P x f_P) needed to establish target core n_e

➔ Optimization by minimization of f_P (at fixed m_P)





All BB transfer options o.k.

DLS feasible as well

Initial m_P (6 x 10^{21}) too large

➔ Reduced to about 1/3

Flux needed to reach target:

7 x 10^{21}/s

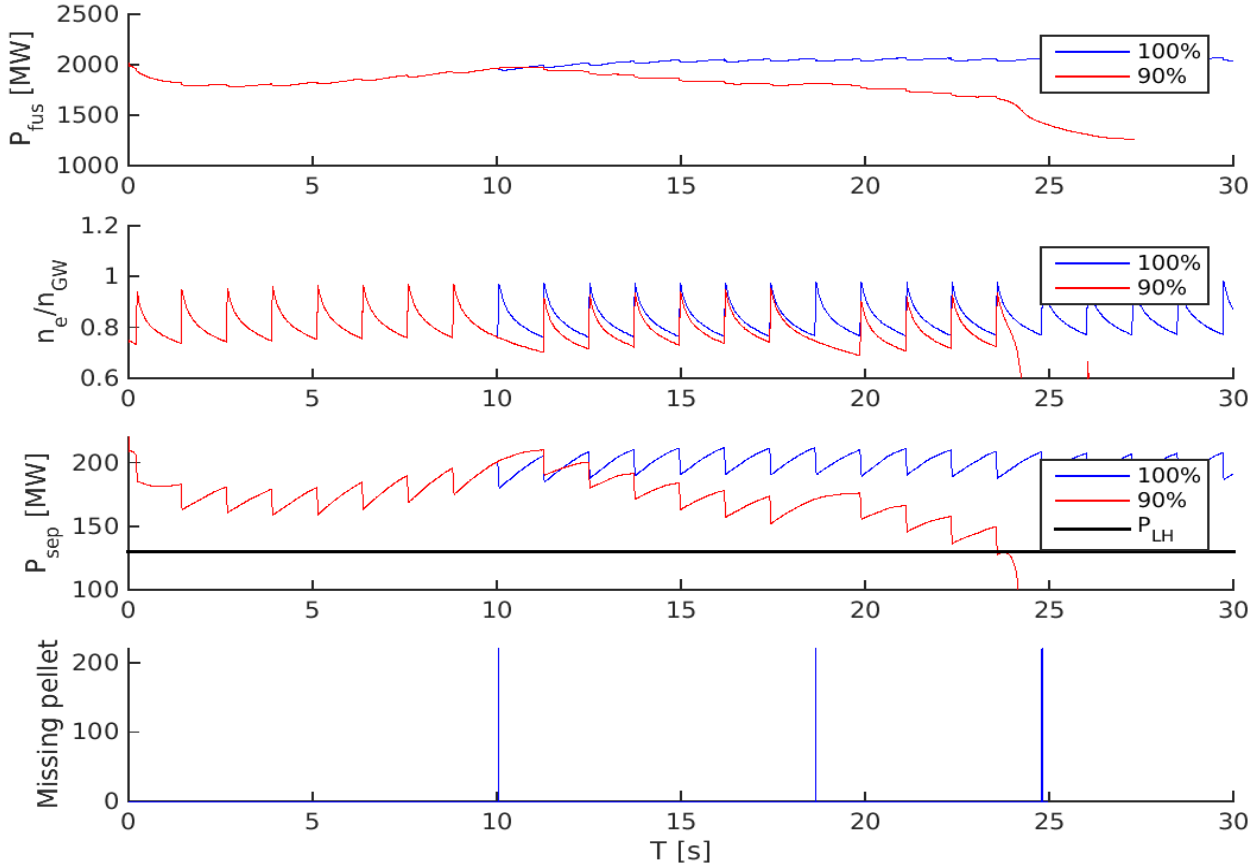
Is in the order of the needed fuel replenishment flux:

1.4 x 10^{21}/s for 2 GW DT fusion

EU-DEMO: Modelling core fuelling

Kinetic control model (ASTRA & Simulink) analysis of EU-DEMO 1:

- **Reduced pellet mass (2 x 10^{21}) o.k.**
- **Missed-out pellets can result in significant burn control problems**



Ideal pellet injector
100 % reliability
O.K. with smaller pellets

Realistic pellet injector
90 % reliability
Plasma lost within 20 s

From: F. Janky
"Kinetic Control"
5th IAEA DEMO
Program Workshop
May 2018, Daejeon

EU-DEMO: Pacing & PEG carrier pellets

ITER pacing solution:

Dedicated injection lines from LFS, HFS line can be used as well

M3D-C1 modelling of pellet perturbations shows higher sensitivity to LFS injection

DEMO strategy:

Use single injection line for any task

Layout optimised for particle fuelling

HFS injection showed higher trigger probability than LFS in JET-ILW (but all <1!)

Seems to be confirmed by JOREK simulations (spatial resolution limited)

High fuelling efficiency assumed plausible for seeding as well

Extra options („nice to have“) with little impact on effort

EU-DEMO: Multi-task PLS design

All pellets can be launched via same guiding tube
➔ All pellets can form a single train

Combine several pellet sources on a single centrifuge
➔ Precise pellet delivery (= efficient detection & e.g. notching)

Very suitable to minimize actuation cross-talk

AUG: Efficient test bed for actuator development
Feed back density profile control, RT missed-out detection, HD ratio control, …
But only single pellet source: best fuelling OR best pacing OR best seeding

JT-60SA required PLS for simultaneous density profile and ELM pacing
➔ Most suitable as potential multi-task DEMO prototype

EU-DEMO: The step-ladder concept

PELLET ACTUATOR development step by step:

AUG → JT-60SA → DEMO

Demonstrated:
- High core density
- ELM control
- Pellet resilient measurements

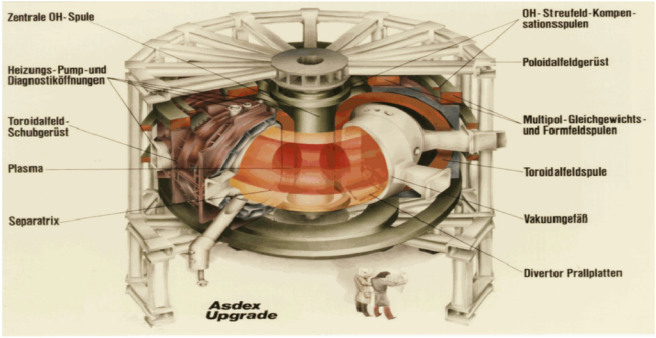
t < 10 s

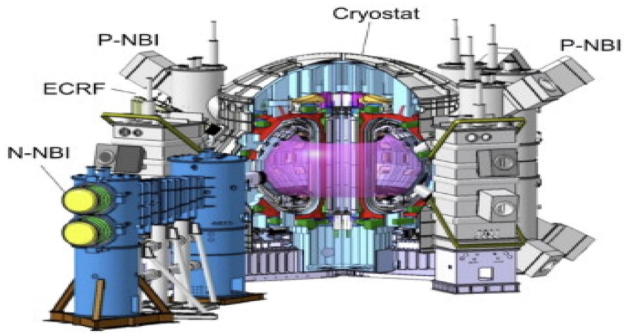
Commissioning ongoing:
- Simultaneous density & ELM control
- Pellet resilient feedback profile control

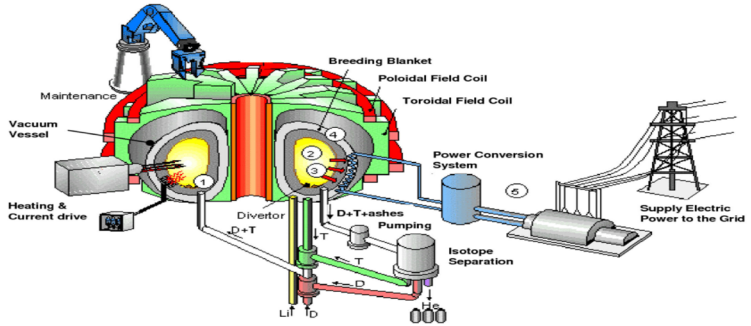
t < 100 s

Design study ongoing:
- Full pellet resilient feedback control
- Simultaneously keep D - T - He profiles

t ~ 2 h





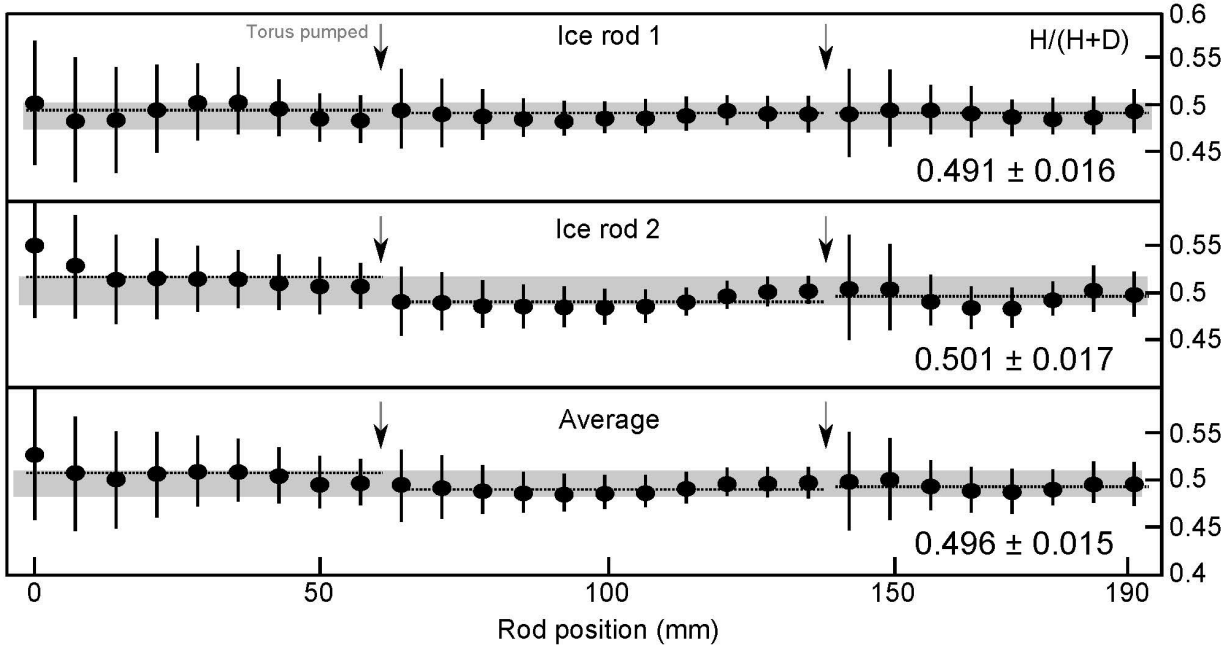


Challenges - Complexity - Sustainability

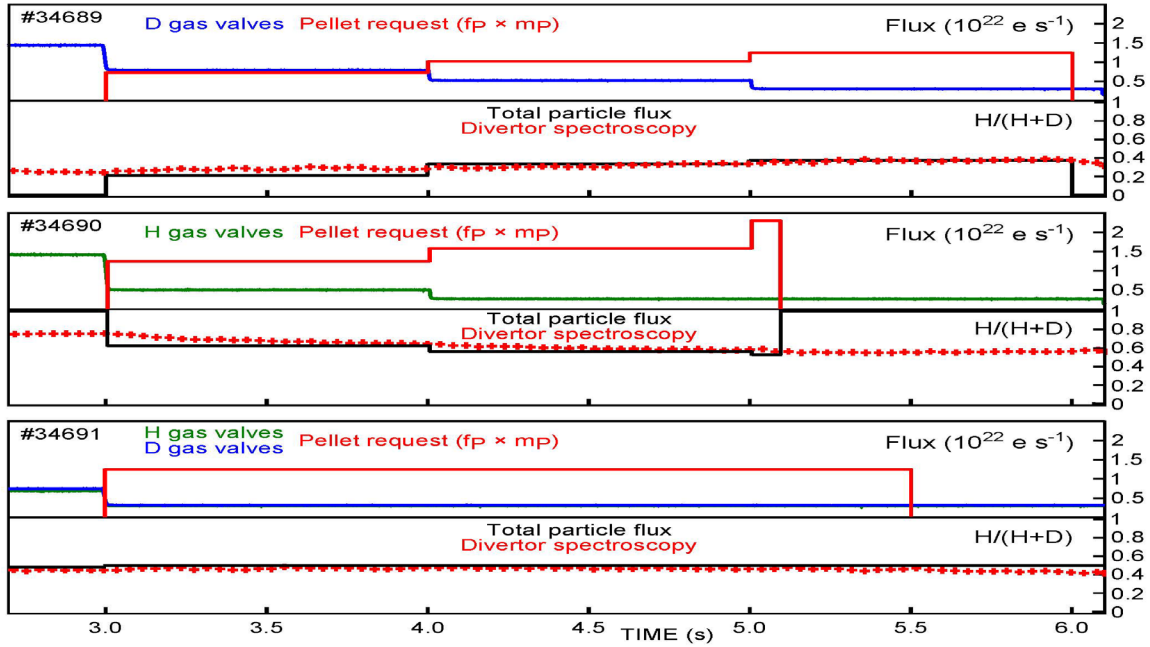
I = 1.2 MA R = 1.6 m	I = 5.5 MA R = 2.9 m	I = 20 MA R = 9.3 m

AUG: HD composition control by pellet fuelling

Production of H:D = 1:1 pellets from H:D = 1:1 H_2/HD/D_2 gas straight forward



Replacing a strong D or H or HD gas puff by pellets Plasma HD ratio approaches Flux HD ratio in high flux phase



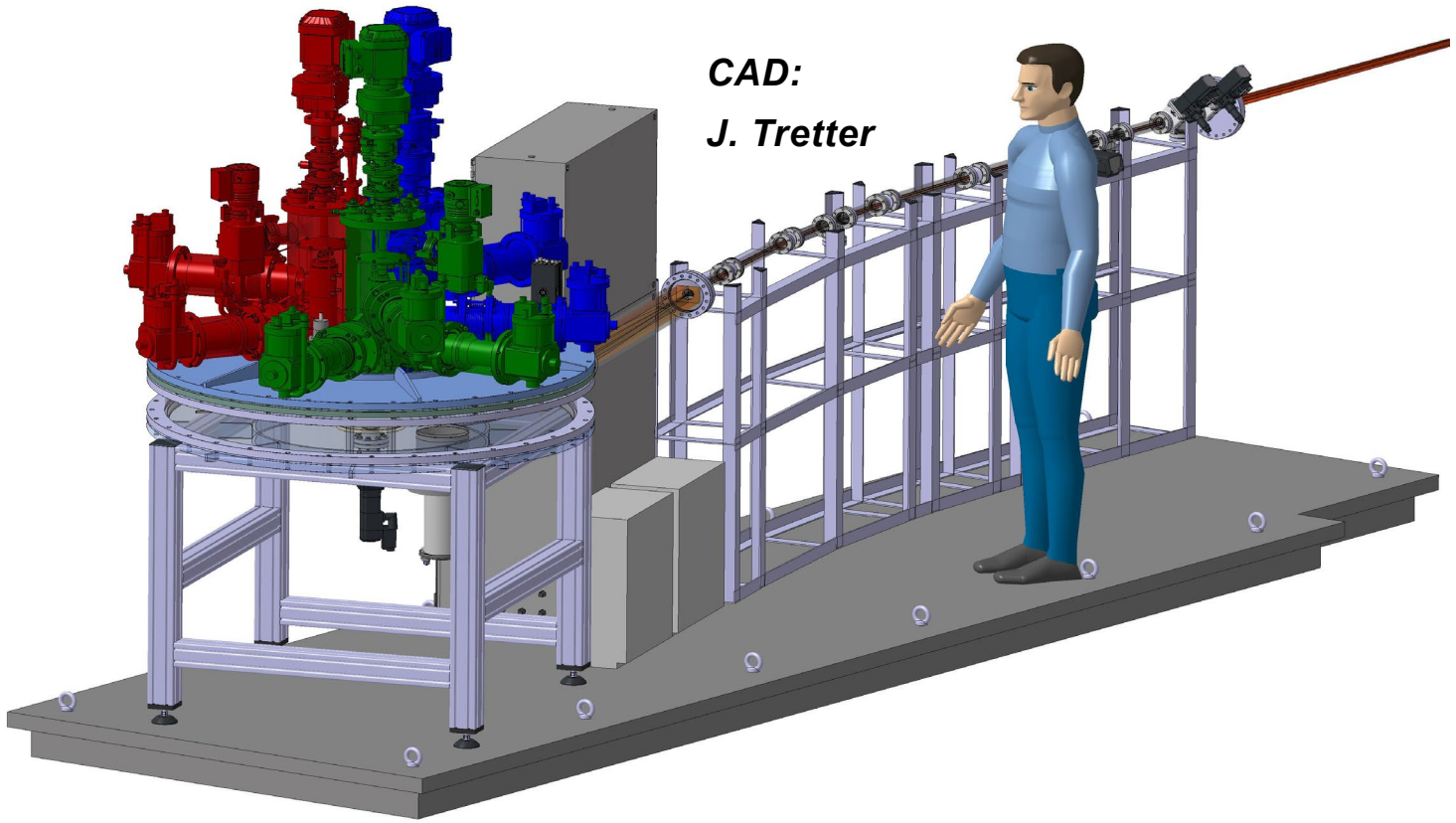
τ_E reduced in H with respect to D, likely no smooth transition w.r.t. M^α
Pellet particle sustainment time τ^*_P significantly stronger reduced than τ_E by H

P.T. Lang et al., Nucl. Fusion 59 (2019) 026003

JT-60SA: Multi-task PLS design

Centrifuge capable to launch up to 100 Hz pellet up to 500 m/s

Can host up to three extrudes (initial configuration with two extruders)



Start up configuration:

Fuelling pellet source (Up to 20 Hz)

ELM pacing pellet source (Up to 50 Hz)

Simultaneous fuelling & pacing

Tailored single pellet train to minimize cross-talk

Manufacturing in progress

Plan:

Ready for shipment 12/2024

Closing the technology gap: DIPAK-PET

DIPAK-PET (Direct Internal Recycling Development Platform Karlsruhe-Pellet Injection Engineering Test Bed) is mimicking the DEMO fuel cycle

Main task: Dedicated survey of actuator development issues on Pellet Launching System

Following the recommendations of the TFV Design Review Panel related to technology

“Pellet survivability in a reactor environment should be tested carefully before deciding on a DEMO injection scheme. Losses in the delivery guide tube need to be determined since it will have a large impact on the resulting overall fuelling efficiency”

“Consider integration of the guide tube in the machine design in such a way to minimize number of curves, and take disruption forces into account”

Chr. Day et al., “The pre-conceptual design of the DEMO tritium, matter injection and vacuum system”
*Fusion Eng. Design **179**, 113139 (2022)*

Closing the technology gap: DIPAK-PET

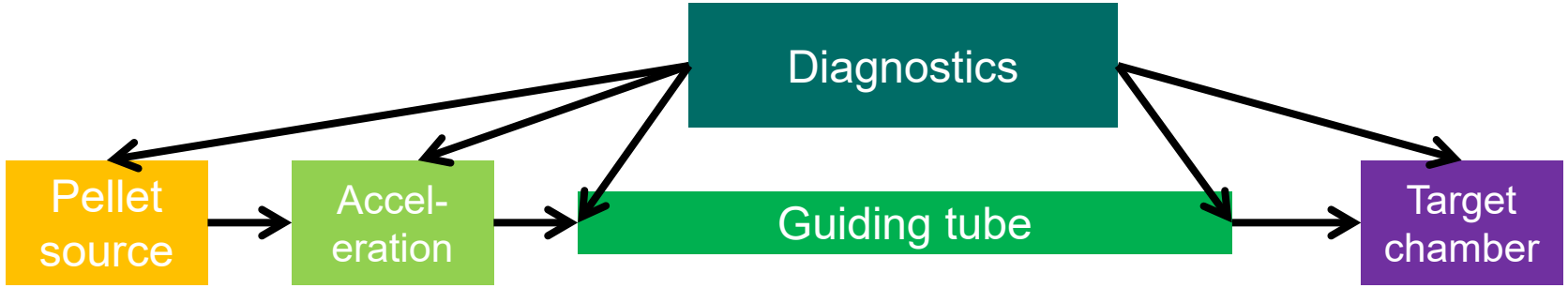
Proposal Pellet Engineering Test Bed

<u>Main focus on guiding tube:</u>

Investigation on shape and trajectory to get numbers for subsequent modelling activities

<u>Other components:</u>

Pellet source, acceleration system, target chamber and diagnostics



Look out for synergisms with the JT-60SA pellet system

ORNL project to demonstrate direct recirculation of exhaust gas to pellet formation (poster presentation by T. Gebhart)

EU-DEMO: TFV external technical review

Status at review:

Pre-conceptual design elaborated sound solution yet identified some important issues, currently not addressed on today's fusion devices

Identified gaps:

- **Quantification of transfer losses in guiding system**
- **Enduring pellet production with repeatable reliable high performance**
- **Tritium handling capability in the relevant operational regime**

Strategy to close gaps:

- **Final technology decision on pellet production and acceleration**
- **Demonstrate continuous operation at minimum pellet time scatter and highest efficiency in DIPAK-PET**

SUMMARY

- Matter injection assigned to gas puffing and pellet injection
- Pellet tasks: core fuelling & ELM pacing (ITER) & PEG (?)
- ITER/ORNL developing key technologies
- AUG/JT-60SA step ladder towards potential EU-DEMO PLS
- WP TFV to close technology gap with DIPAK-PET

THANKS FOR YOUR ATTENTION

AND

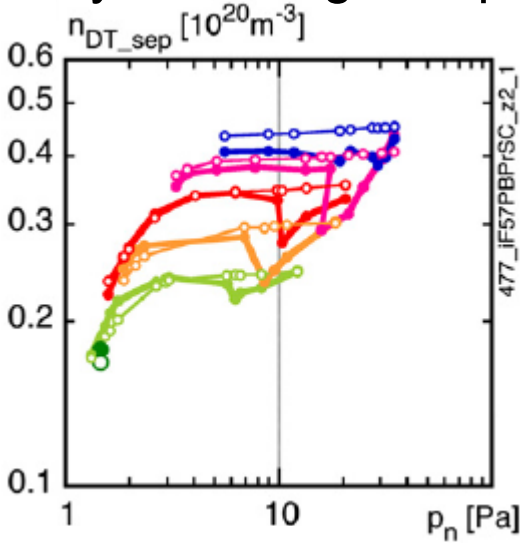
ANY QUESTIONS ?

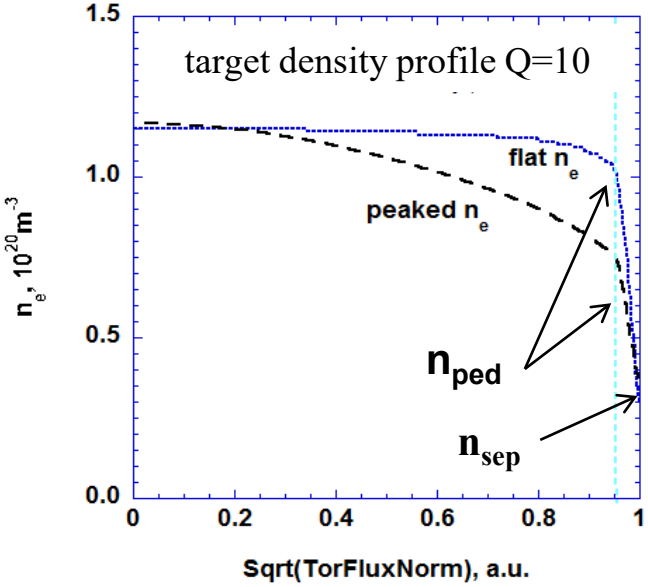
Back up slides

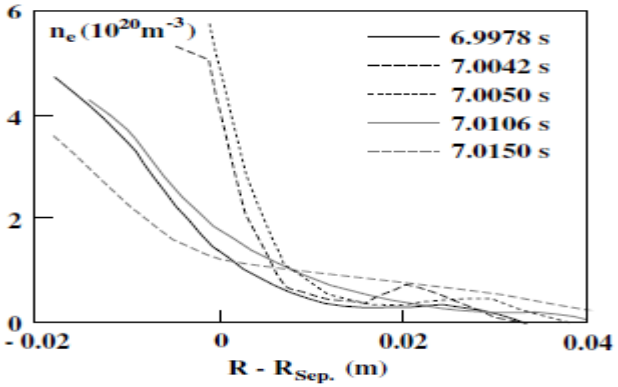
Gas puffing / Supersonic jets

Gas bleeding: simple and working well in all current devices
However: fuelling efficiency dwindling with plasma edge temperature

ITER SOL/Div simulations:
Saturation of gas fuelling from the edge [Pacher et al., 2011]
n_{sep} cannot reach values required for sufficient P_{fus}







Density evolution at plasma edge (Li beam) following injection of supersonic LFS gas jet [Lang et al., 2006]:
Self-blocking of the gas jet

Technology review

Document (on IDM) Technical Note TFV-F-02

EFDA WP11-DAS-HCD-FP: Assessment of the Fuelling System for DEMO (“Kovari-Report”)

List of suitable matter injection technologies

Conventional pellet injection (Ploeckl, Frattolillo, Szepesi)
Microwave and rail gun pellet injection (Bobashev)
Conventional gas puffing (Igitkhanov)
Supersonic gas injection (Lang)
Compact Tori Injection (Raman)
Unmagnetized plasma jet injection (Voronin)

Technology review: SWOT

Pairwise comparison to rank selection criteria for the DEMO matter injection system

Horizontal topic versus vertical top:
2: more important
1:equally important
0:less important

	Low developing effort/costs	Low development risk	Low manufacturing costs	Low operational efforts	Low maintenance requirements	Good maintainability	Low infrastructure necessary	Low power consumption	Low total cost of ownership	High operational reliability	Wide pellet parameter range	Fast changes of pellet parameters	Precision of pellet parameters	Low Tritium inventory	High fuelling efficiency	Compatibility with transfer system
Low developing effort/costs		2*														
Low development risk																
Low manufacturing costs																
Low operational efforts																
Low maintenance requirements																
Good maintainability																
Low infrastructure necessary (For removal of propellant gas, interaction with transfer system, intrinsic pumping requirements, effort to feed in pellets)																
Low power consumption																
Low total cost of ownership (Life time, operational coverage and waste management)																
High operational reliability (Coverage of period when fuelling flux is requested)																
Wide accessible pellet parameter range (Mass, speed, repetition rate)																
Fast changes of pellet parameters possible (Mass, speed, pellet material)																
Precision of pellet parameters (time jitter, mass, speed)																
Low Tritium inventory (Stored or trapped within entire launching system)																
High fuelling efficiency (Achieved core density/ applied particle flux at system input)																
Compatibility with pellet transfer system (Access to plasma)																

* Example: this means "Low developing effort/costs" is more important than "Low development risk"

ITER PLS: Fuelling & ELM pacing/mitigation

Parameter	Value
Plasma density <n>	0.5–1.2 10^{20} m^{-3}
Fuel isotope (pellet)	H_2, D_2, D-T, T_2 (90% T/10% D)
Maximum pellet fueling rate H_2, D_2, and DT T_2 (90% T/10% D) Impurity	 120 Pa-m^3/s (~1000 torr-L/s) 110 Pa-m^3/s 10 Pa-m^3/s
Pulse length	3000 s
Pellet size (nominal)	3 and 5 mm diameter 1.25 and 6 10^{20} atoms $\Delta n/n$ ~ 1.3% and 6.6%
Maximum injection frequency Core fueling ELM triggering Impurity injection	 4 Hz 16 Hz 5 pellets
Pellet speed Reference Maximum	 300 m/s 500 m/s
Number of injectors	2 initially (up to 6 for D-T phase)

D. Rasmussen, "D-T Pellet Injection for ITER Plasma Fuelling"
Tritium Working Group, Oak Ridge, May 2018

PEG carrier pellets

Supply of PEGs via gas puffing could be slow and wasteful

➔ Request by EU-DEMO :

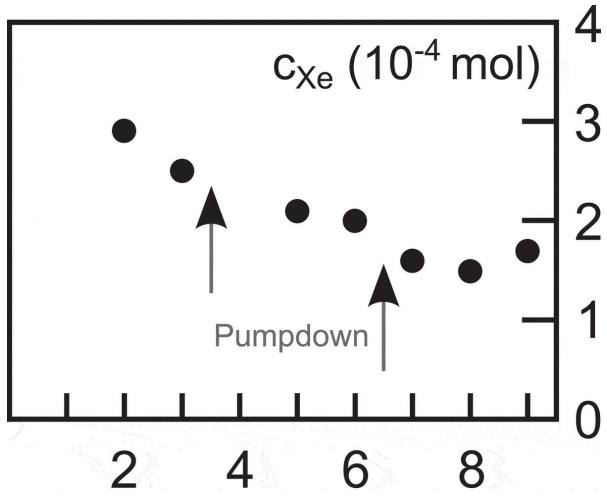
Test technical feasibility of Xe doped fuelling pellets ✓

Technique applied at AUG for fast and efficient radiative power removal

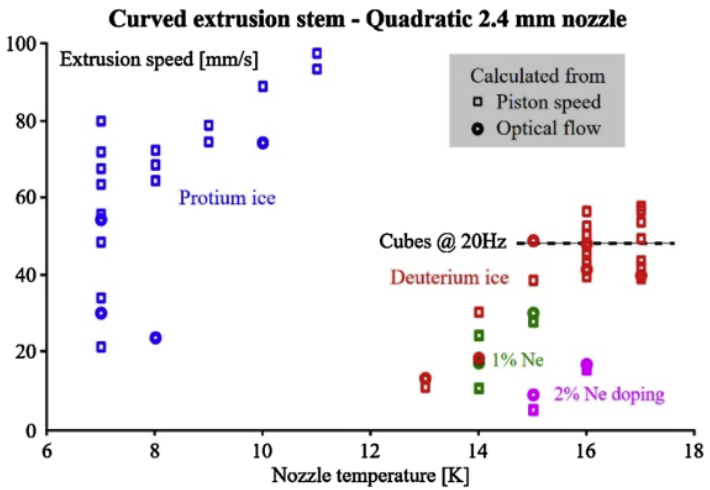
A. Kallenbach et al., Nucl. Fusion **62** (2022) 106013

Advantages: Efficient, fast delivery (AUG: fast exhaust)

Technical issues: Inhomogeneous and imperfect doping



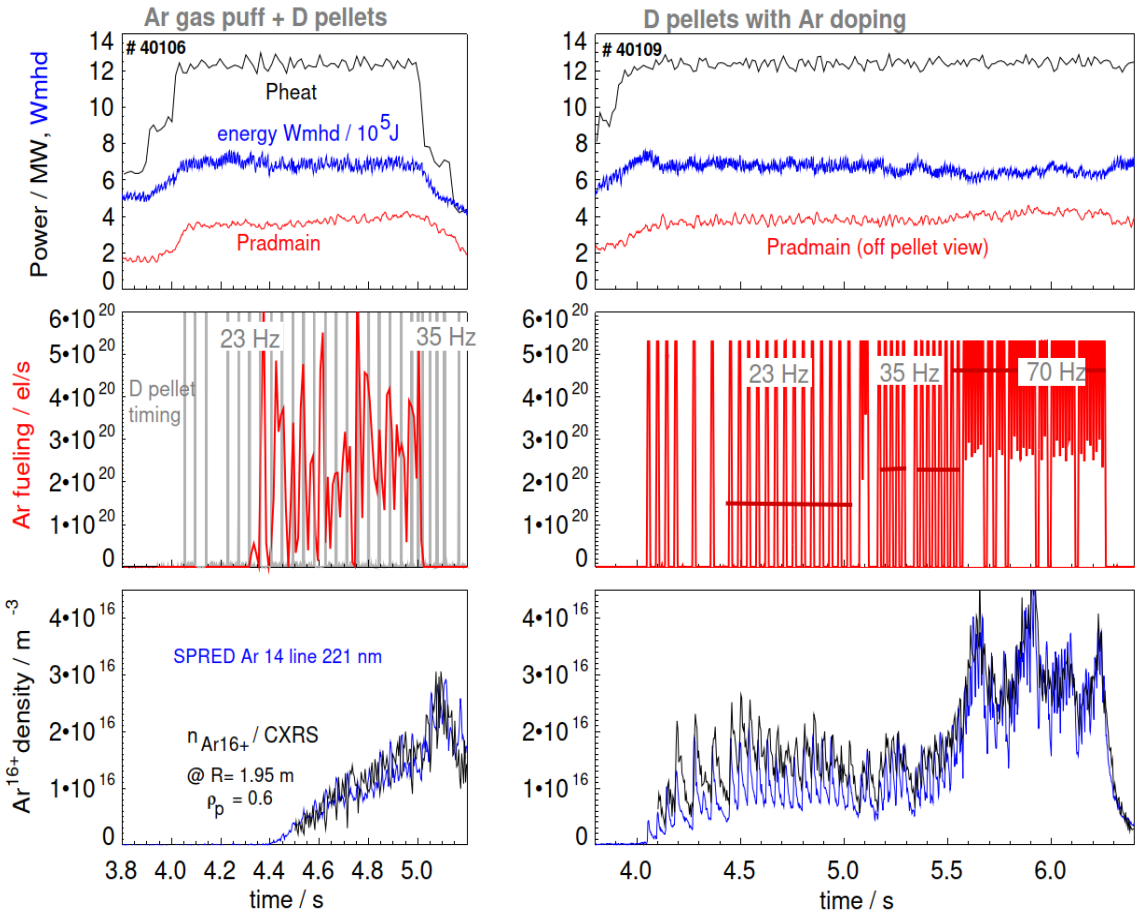
Slowing down extrusion



Approach deserves further considerations and efforts

Multi-actuating pellet system

Pellet actuation beyond fuelling:
“Ar doped pellets for fast and efficient radiative power removal in ASDEX Upgrade”



Ar doped pellets

- High radiation efficiency
- Very fast radiation rise
- Compatible with QCE H-Mode

→ Favourable for fast control tasks

A. Kallenbach et al., Nucl. Fusion **62** (2022) 106013

Yet insufficient radiation power

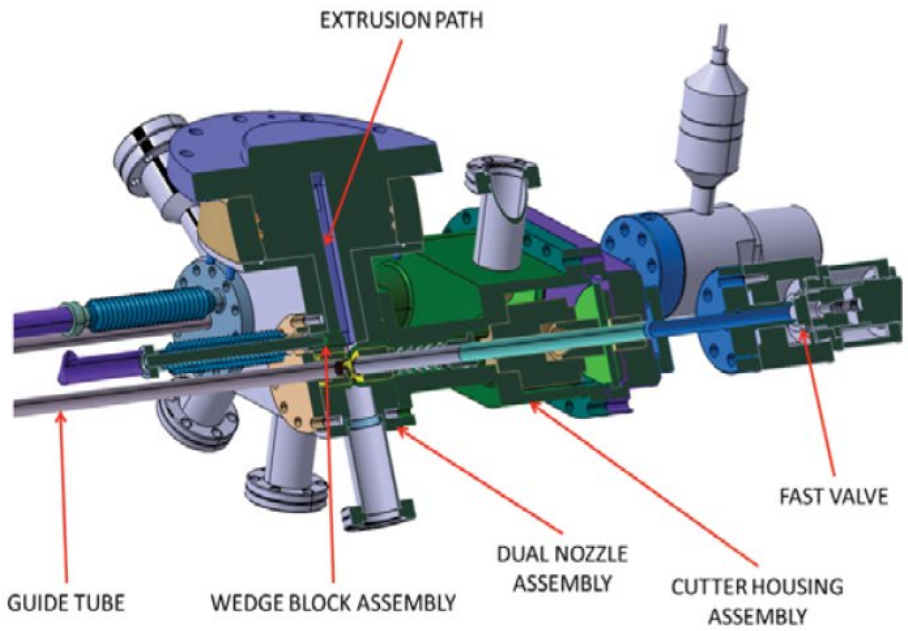
Due to low doping grade (0.1 at%)

→ Higher Ar fraction or
higher cooling factor using e.g. Kr

→ Technical adaptation of centrifuge
in progress

ITER/ORNL technology

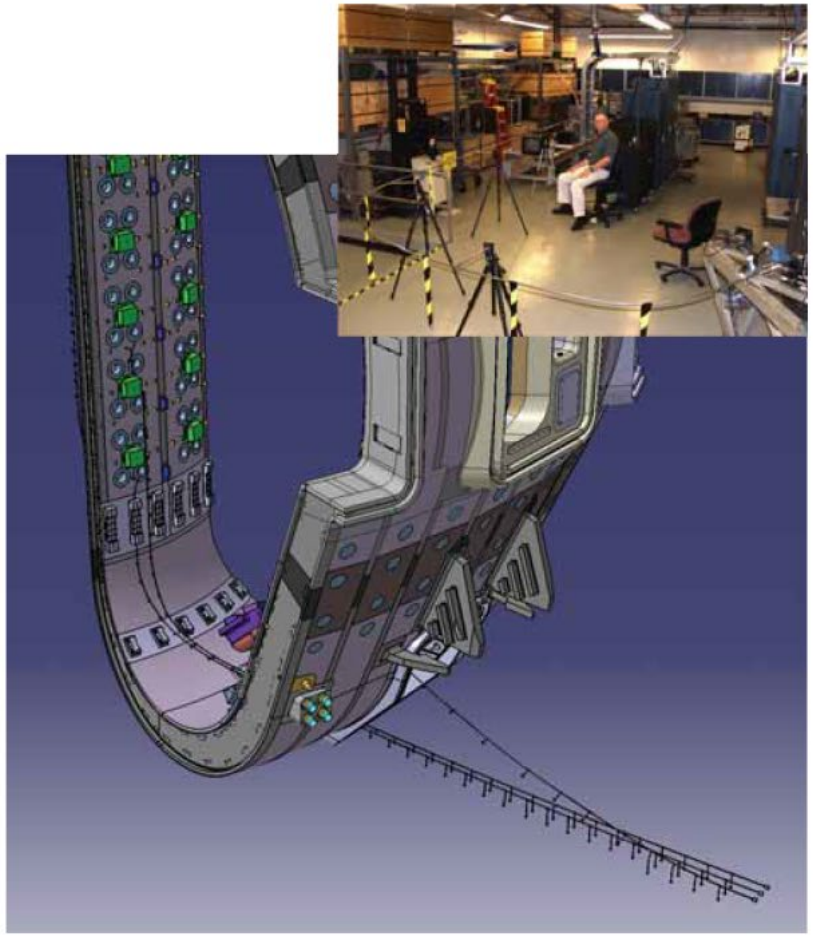
Pellet accelerator: repetitive gas gun



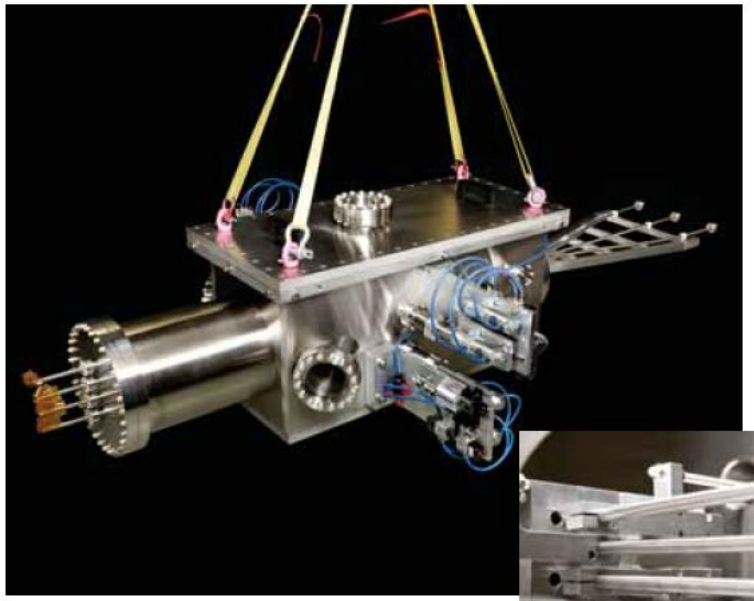
Dual nozzle, cutter and gun sub-assembly

ITER/ORNL technology

Pellet transfer systems: “transfer matrix”



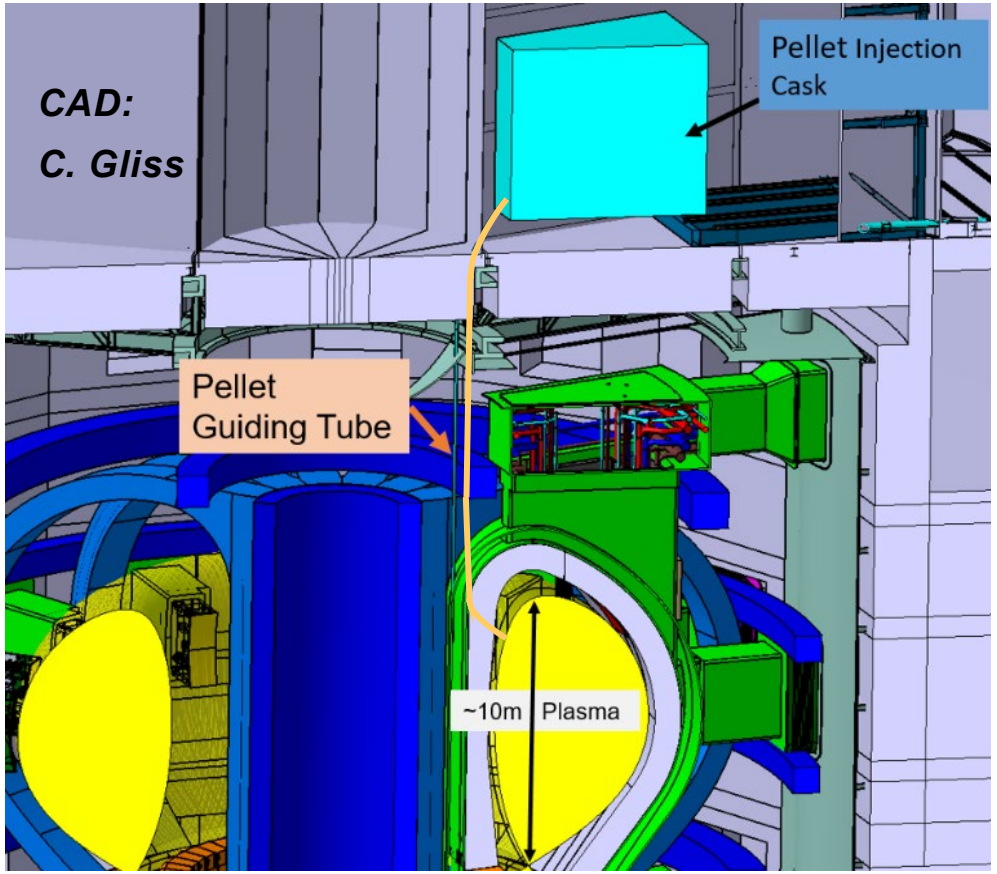
Guide tube mockup for speed limit determination



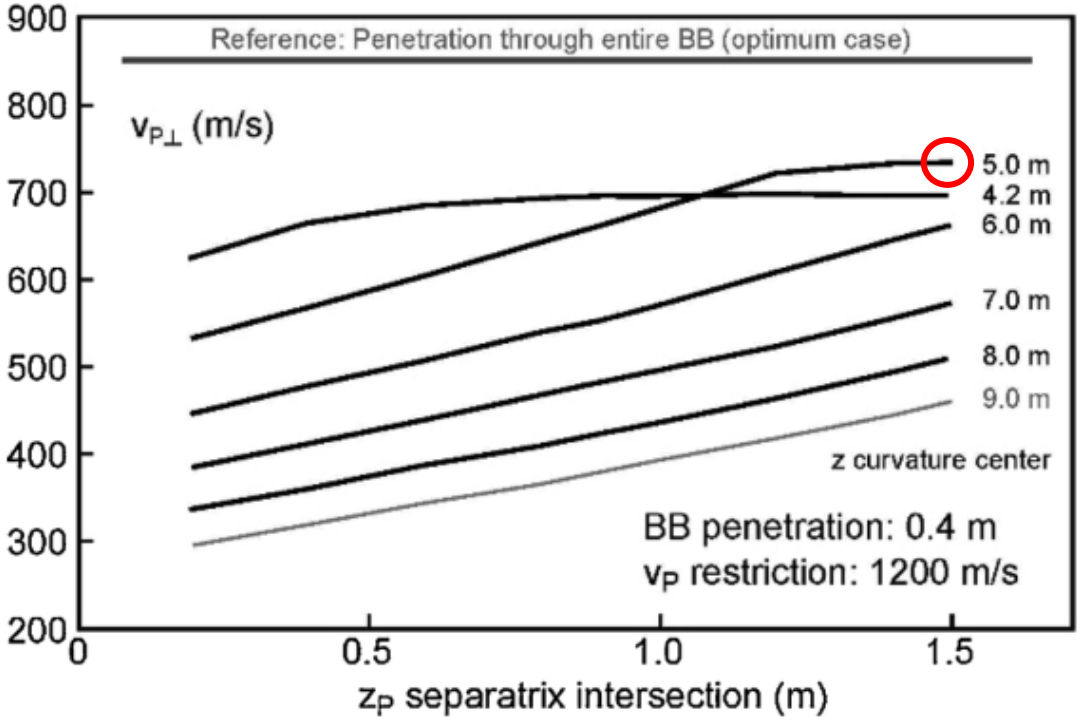
Guide tube selector

EU-DEMO: Strategy

Core fuelling system reference solution



Space reservation o.k.

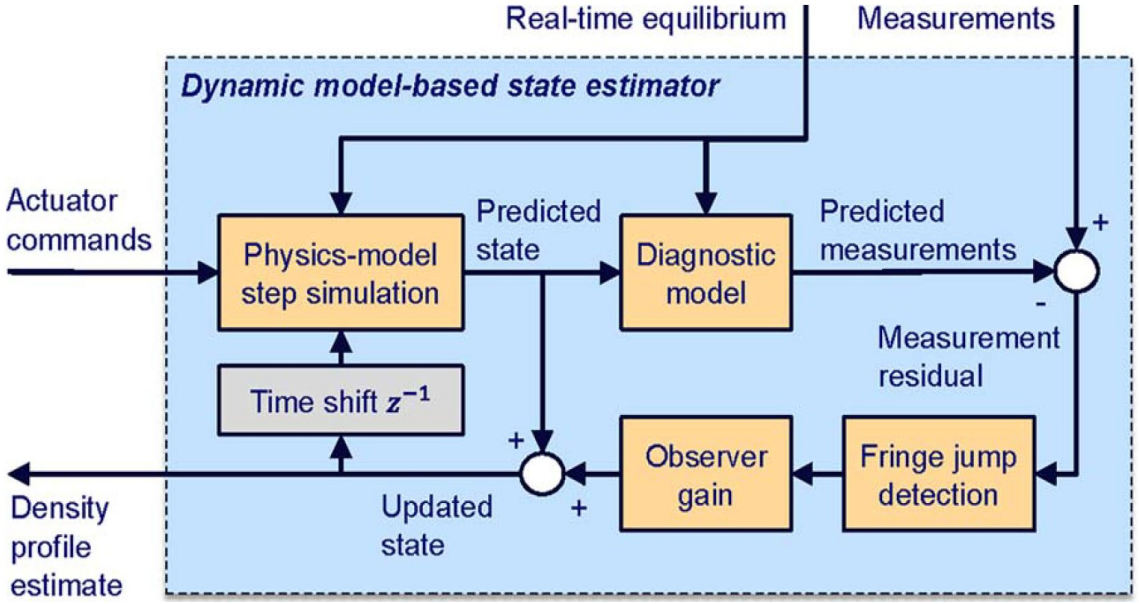


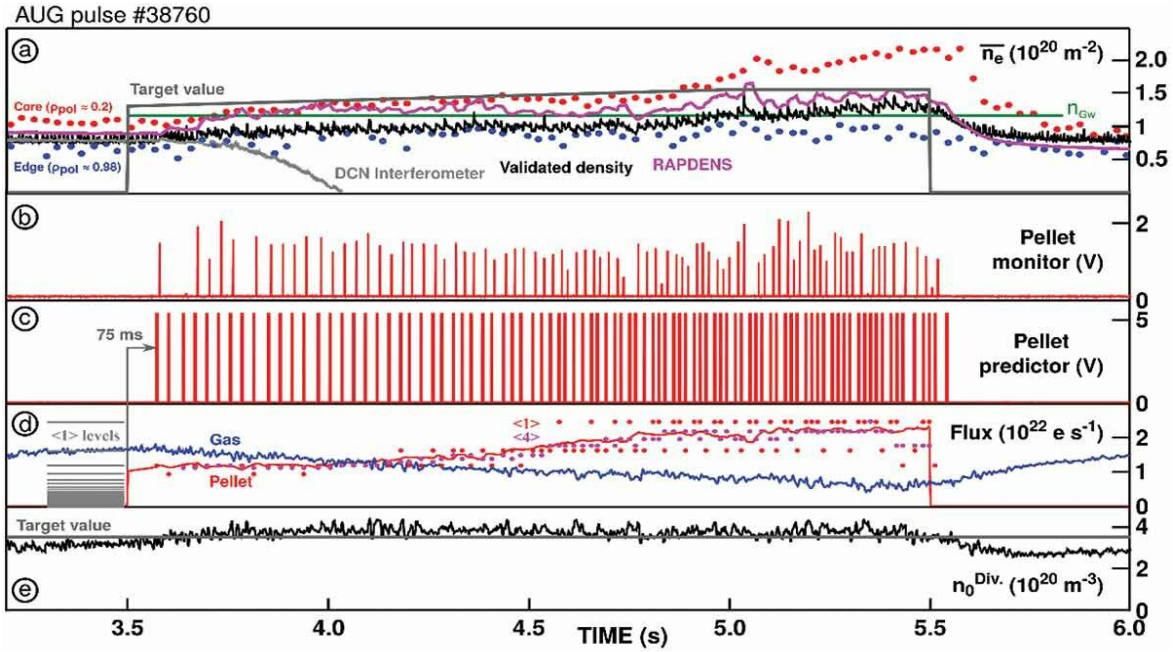
Injection trajectory can be optimised taking into account BB boundary conditions

"Maximum transfer speed vs. injection angle"

AUG: Real-time density control

Heuristic control-oriented tokamak particle transport model (AUG&TCV) used in the Extended Kalman Filter framework to estimate the density profile





T.C. Blanken et al., Fusion Eng. Design 126 (2018) 87

P.T. Lang et al., Fusion Sci. Technology 78 (2022) 1

➔ Use n_e <preselected 1D region> as parameter for core density control via pellets

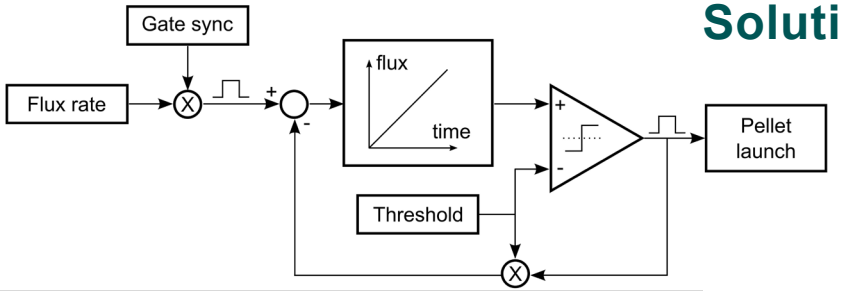
➔ Use neutral gas density in divertor (pellet resilient) for edge density control via gas

Commissioning of model for MIMO control in progress

JT-60SA: Multi-task control

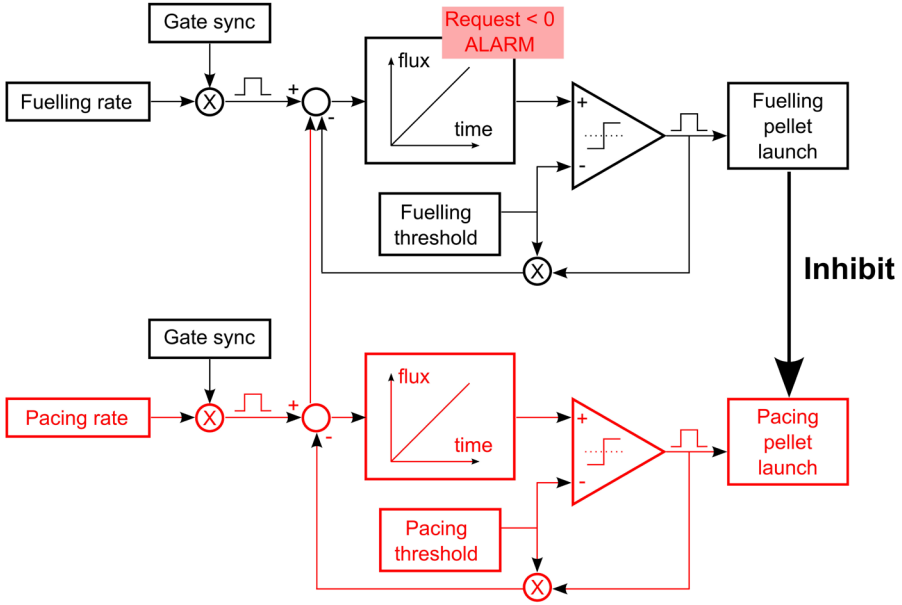
Extend proven AUG solution for fuelling & pacing
Solution can be extended to multi-task control

Fuelling source

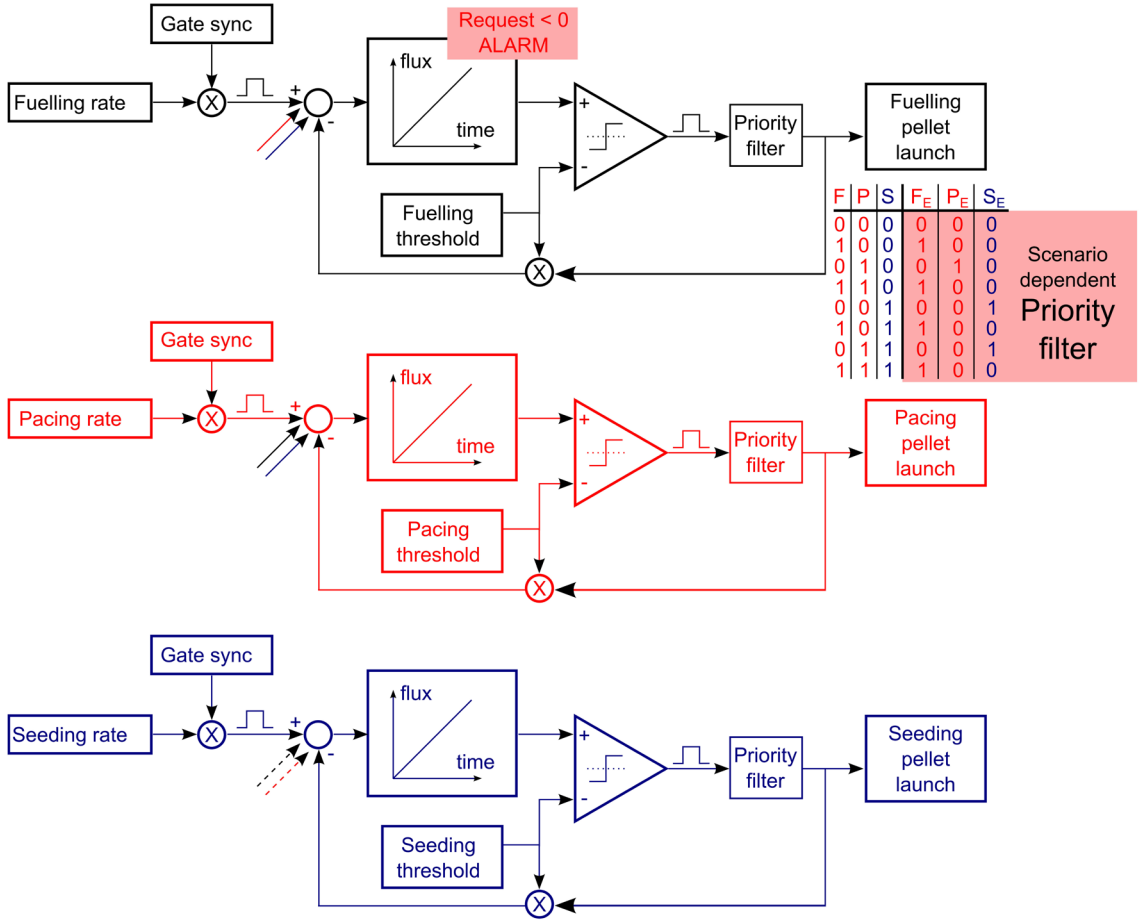


B. Ploeckl et al., Fus. Sci. Techn. 77 (2021) 199

Fuelling and pacing source



Multi sources



F	P	S	F_E	P_E	S_E
0	0	0	0	0	0
1	0	0	1	0	0
0	1	0	0	1	0
1	1	0	1	0	0
0	0	1	0	0	1
1	0	1	1	0	0
0	1	1	0	0	1
1	1	1	1	0	0

Scenario dependent Priority filter