P4B3 – Fuel Cycle & Tritium II

Admixed pellets for fast and efficient delivery of plasma enhancement gases: Investigations at AUG exploring the option for EU-DEMO

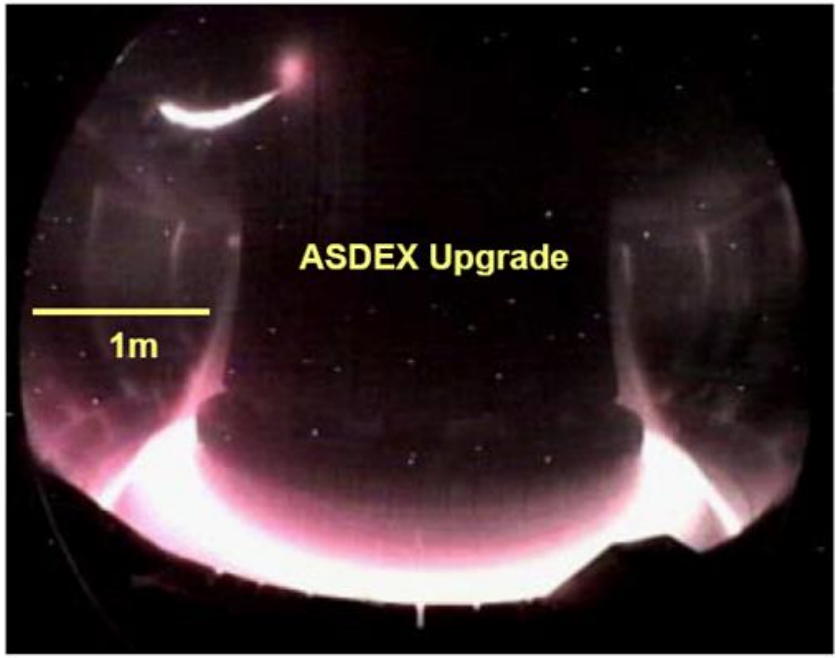
P. T. Lang, L.R. Baylor, Ch. Day, R. Dux, R.M. McDermott,
T. Giegerich, T. Gleiter, A. Kallenbach, B. Ploeckl,
V. Rohde, A. Zito, ASDEX Upgrade Team

15th International Symposium on Fusion Nuclear Technology
Las Palmas de Gran Canaria, Spain, September 13, 2023

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

OUTLINE

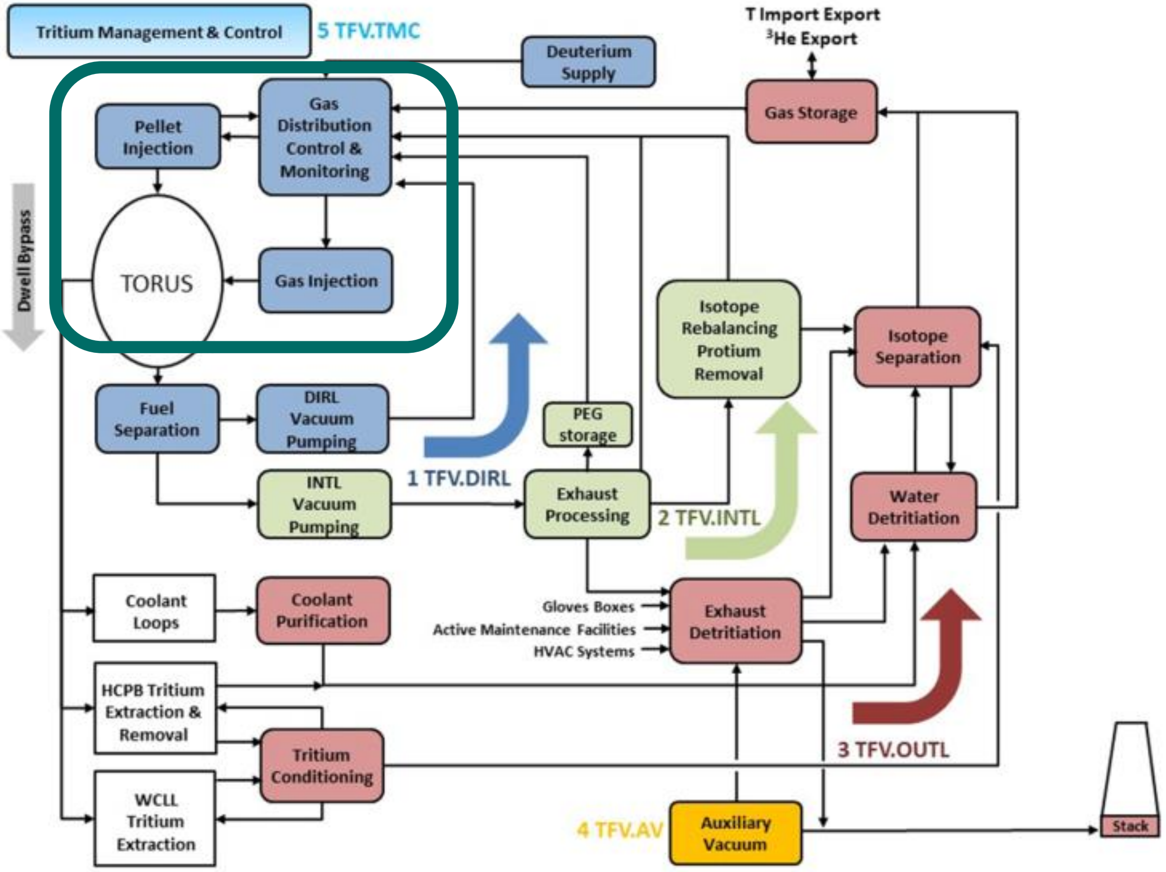
- Core fuelling as part of Matter injection in EU-DEMO
- Pellet tool potential
- Initial admix investigations at AUG
- Technology used: fuelling layout only
- EU-DEMO request: Xe admix
- Ar for efficient radiative power removal in AUG
- Amending the data set: Kr and Ne (ORNL)
- Admixed pellets: tool deserves to step up efforts



BROCKHAUS Mensch•Natur•Technik
"Technologien für das 21. Jahrhundert"
Leipzig; Mannheim 2000

Core fuelling & Matter injection in EU-DEMO

Projected EU-DEMO fuel cycle



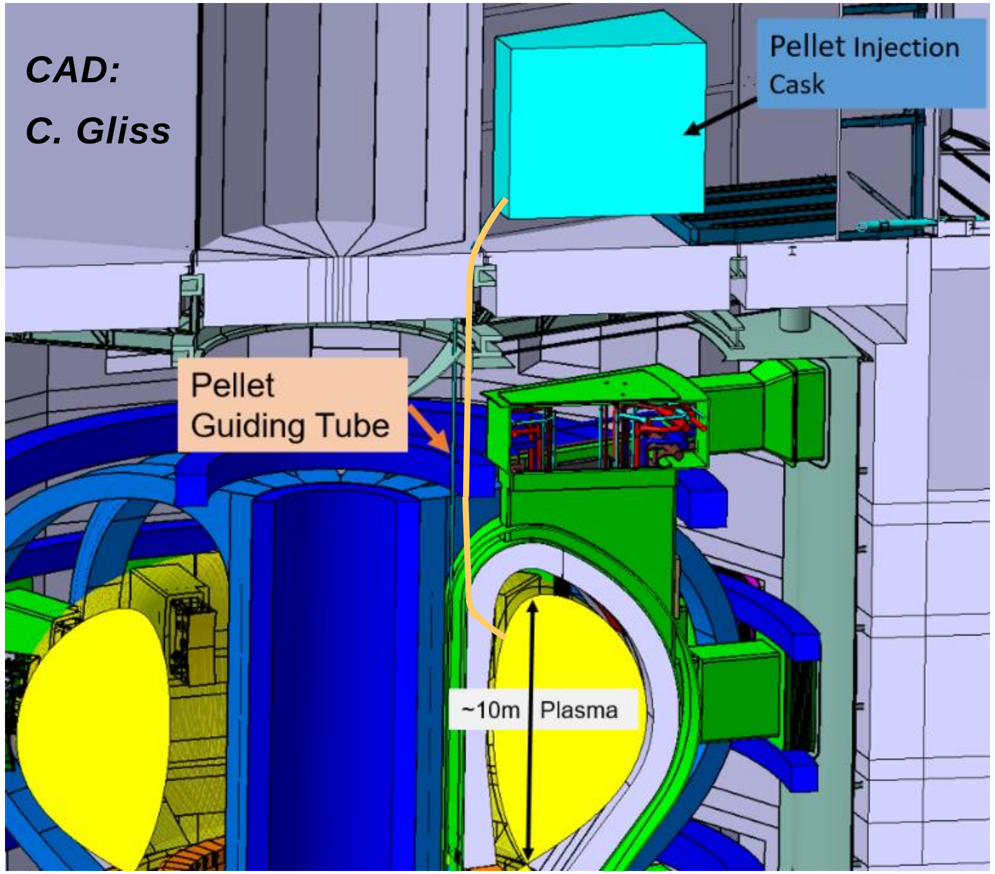
Chr. Day et al., Fusion Eng. Design **179** (2022) 113139

Matter injection tasks in ITER/EU-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)*

Pellet tool potential

Core fuelling system reference solution
Space reservation in EU-DEMO CAD



P. T. Lang et al., Fusion Sci. Tech. ***79*** *(2023) in print*

Pellet system in EU-DEMO (inboard injection):

- **Modelling shows requested core density can be achieved with feasible pellet flux $\Gamma_{Pel} \approx 7 \times 10^{21}$/s**

  For 2 GW DT fusion needed: 1.4×10^{21}/s

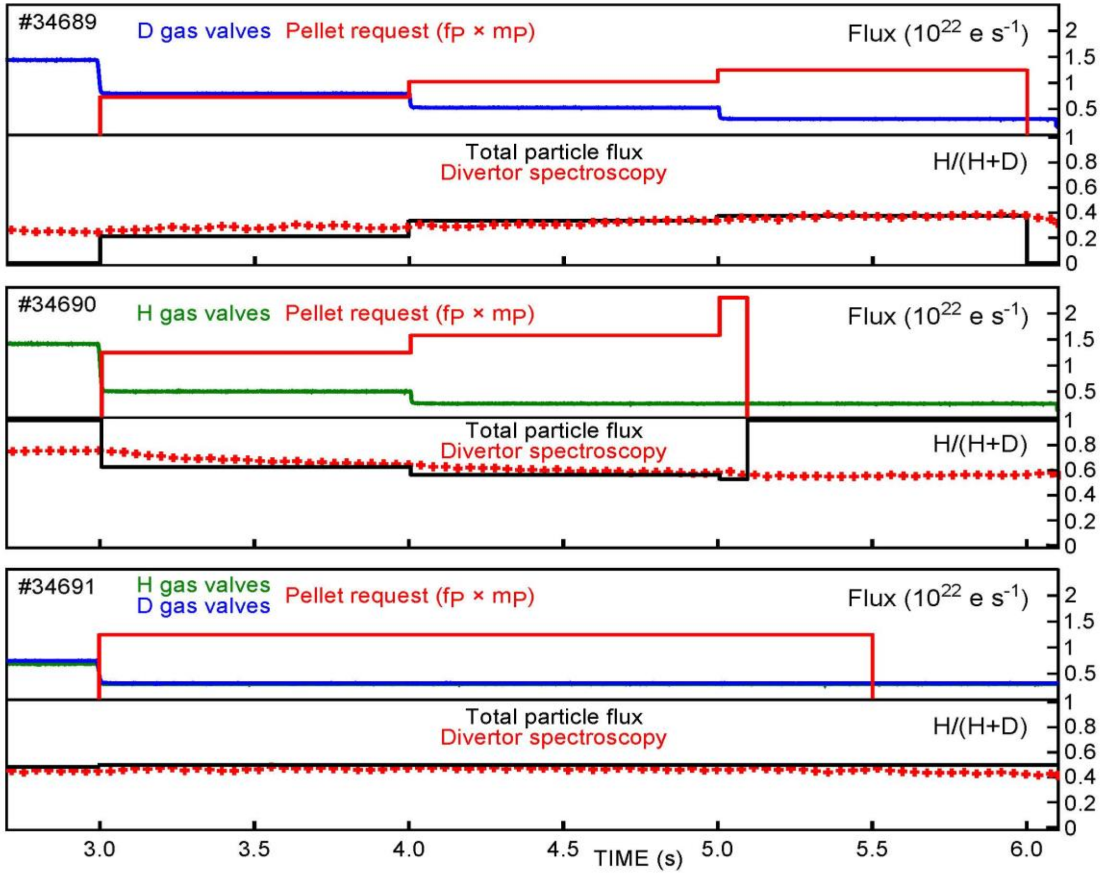
➔ **Headroom for integration of guiding system e.g. with respect to BB penetration**

➔ **Smaller pellet size = less perturbation still o.k.**

- **Solution for control (discrete events!) at hand**
- **Handling of "missed-out pellets" at hand**
- **Concept for multi-actuation pellet system elaborated (JT-60SA system)**

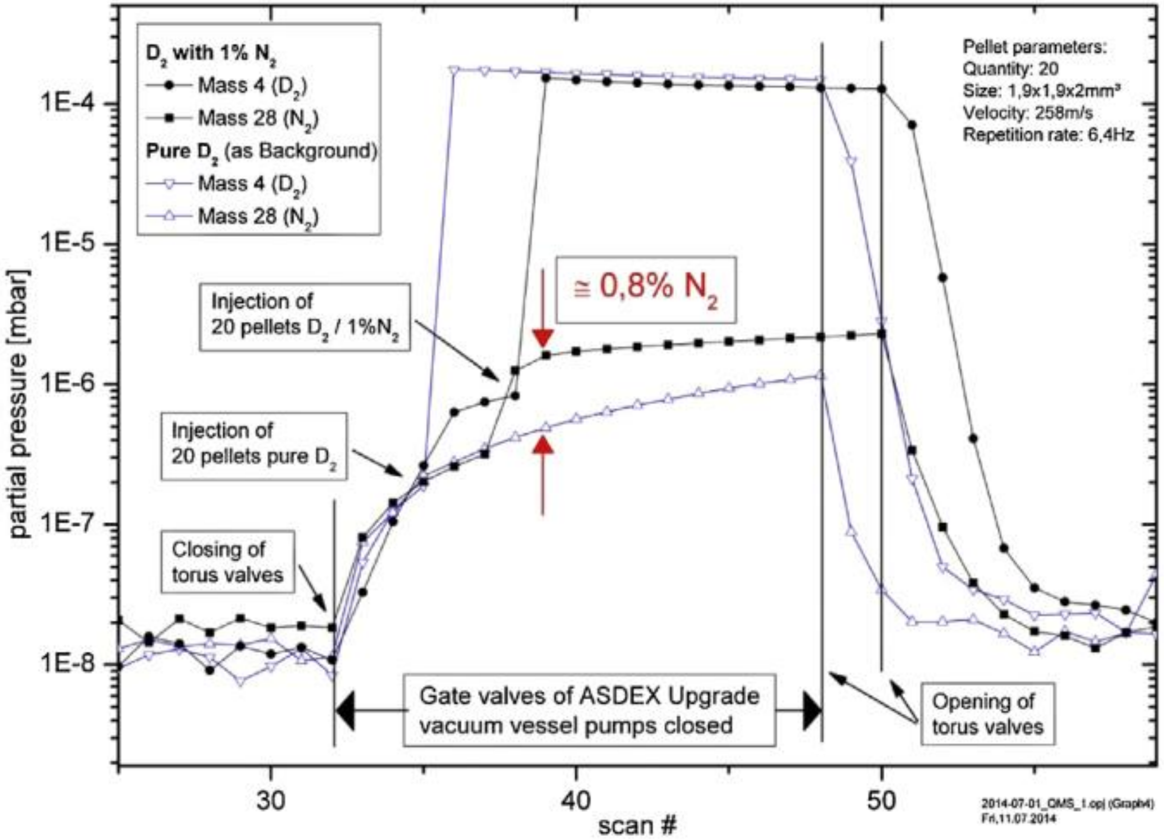
AUG pellet tool potential: H:D = 1:1 and N_2 admixture

Pellets (H_2,HD,D_2) produced with H:D=1:1
Applied to control core isotopic ratio



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

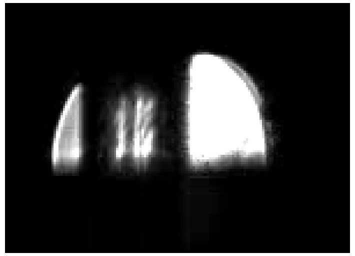
Tested admixing of N_2 in D_2 host fuelling pellet
N_2 stabilizes pedestal and enhance performance
1% N_2 in supply gas ➔ 0.8% N_2 in pellet

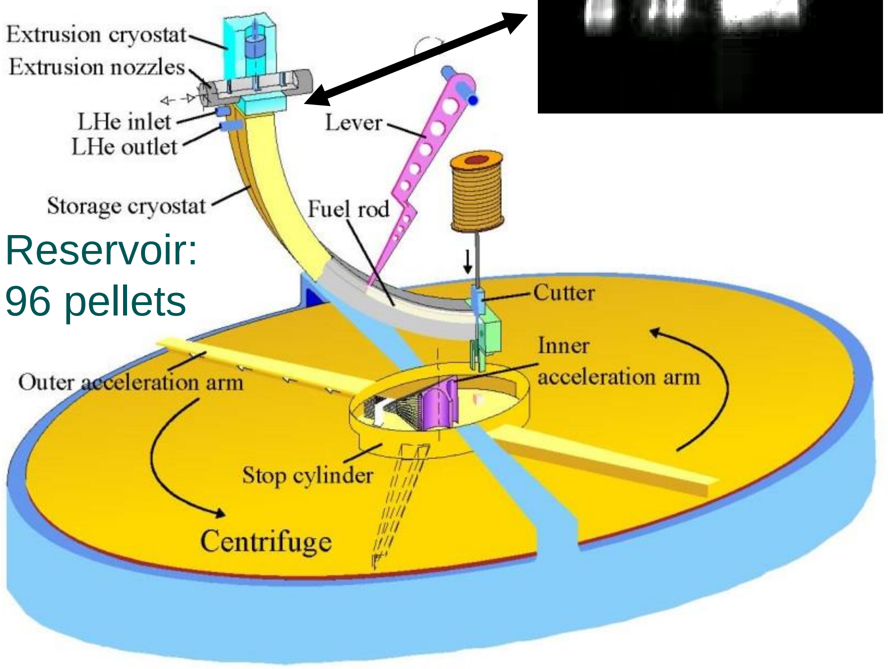


B. Ploeckl et al., Fusion Eng. Design ***96-97*** *(2015) 155*

AUG pellet launching system (PLS): Designed for fuelling

Stop cylinder centrifuge (precise announced arrival of pellets in plasma)
Ice produced in cold cryostat, then rod extruded into storage





Reservoir:
96 pellets

B. Ploeckl et al., Rev. Sci. Instr. ***84*** *(2013) 103509*

System designed 1986 for short pellet trains
Operation with either pure H_2 or D_2
Mechanics lay out for low H_2/D_2 pellet density
(e.g. "gas transparent" stop cylinder wall)
Local LHe cooling of "copper block" cryo

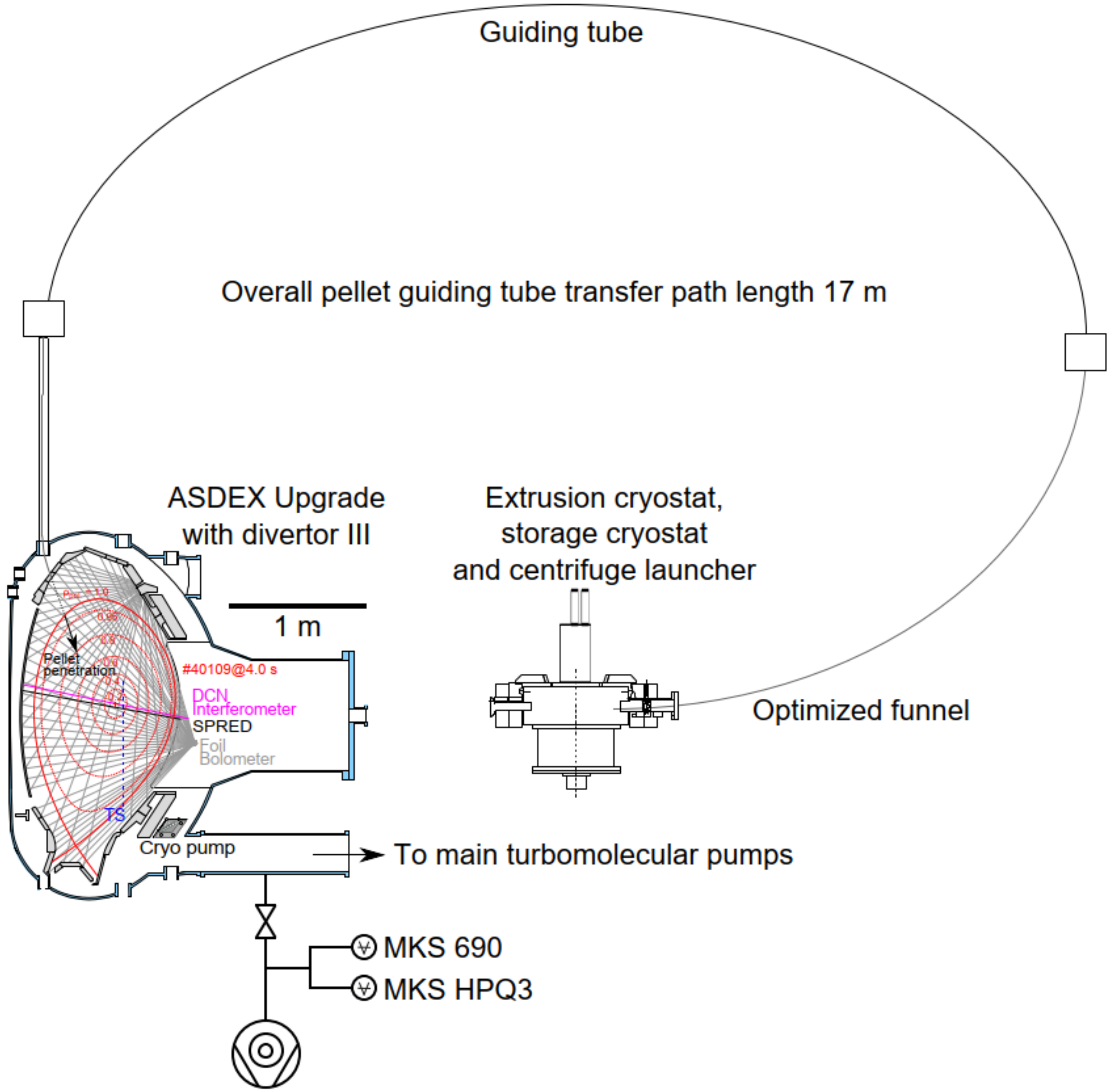
Gas mixtures:

- **H_2/D_2 at any ratio possible**

- **Admix gases with higher specific weight ρ**

➔ Restriction of concentration – ρ depended
Some admixed gas gets frosted in gas supply line
"Cryodistillation" due to not yet adapted design

AUG pellet launching system (PLS): Designed for fuelling



Looping guiding system
Up to 880 m/s injection speed from inboard

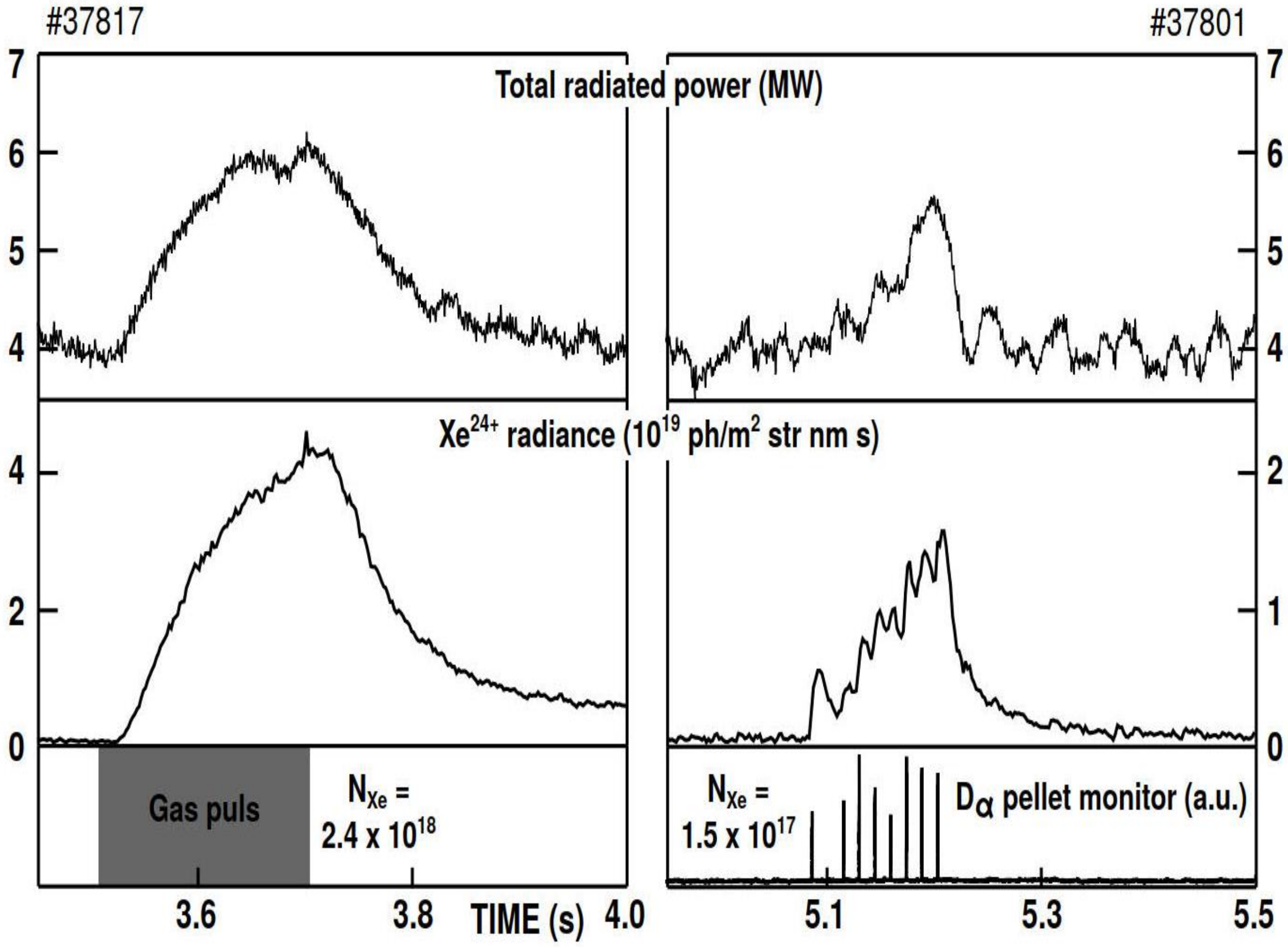
Injection scheme redesigned for
"Magnetic high field side injection"
➔ Plasmoid drift favours fuelling efficiency

AUG equipped with versatile diagnostics
Pellet observation
Plasma characteristics

Dedicated "Residual Gas Analyser"
Quadrupol mass spectrometer
Refined calibration process
➔ Quantitative composition analysis

Test requested by EU-DEMO – Fuelling pellets with Xe

For radiative power removal EU-DEMO considers noble gases, Xe as “ultimate” challenge
Radiation potential disproportionate high for AUG ➔ Low concentration (0.2 mol% in gas)



Pellets can be produced

- **Sound shape and stable**
- **Fuelling impact preserved**
- **Concentration depletion in ice**
- **Concentration in rod inhomogeneous**

Comparison Gas - Pellets

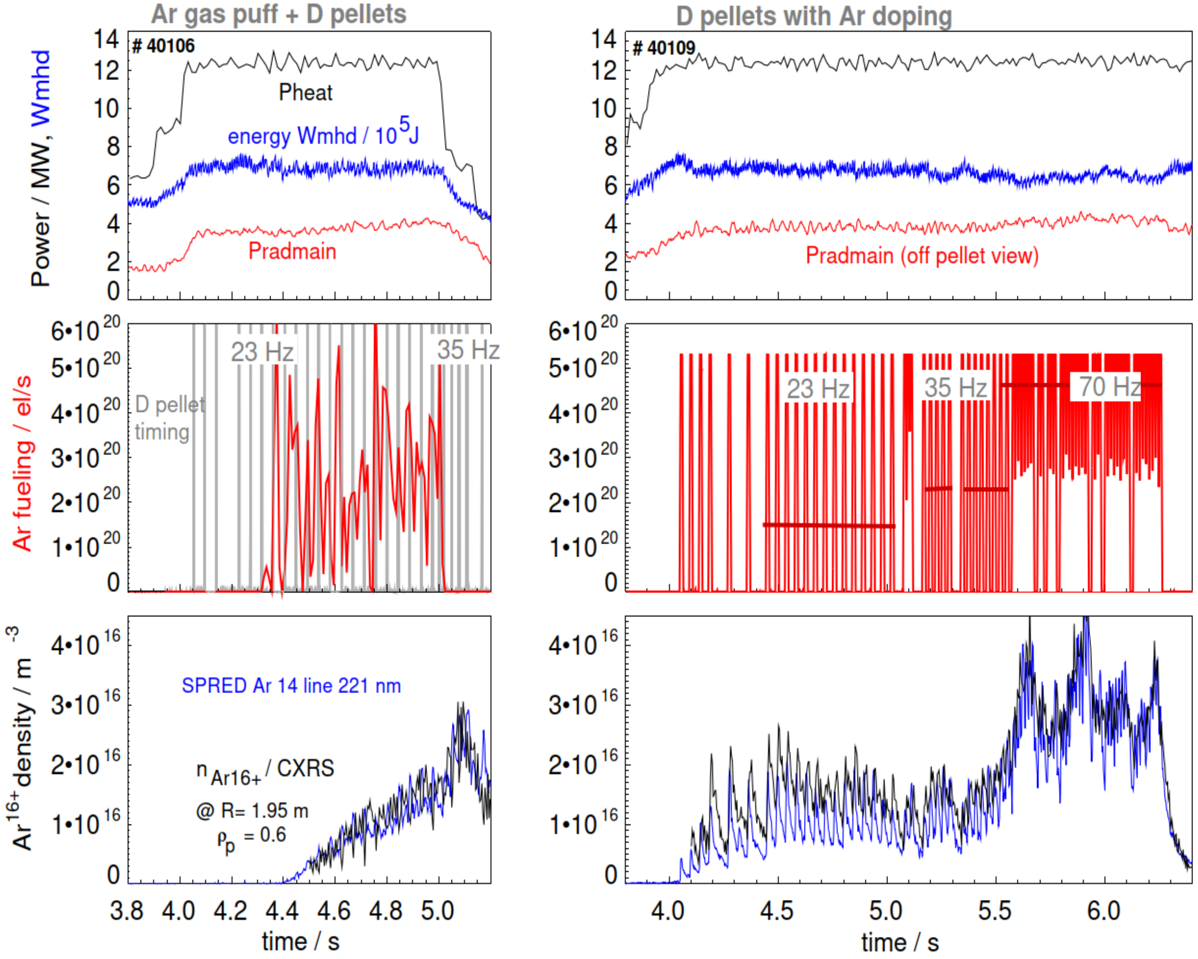
- **Pellets enable much faster actuation**
  Both for delivery and exhaust
- **Higher efficiency indicated**

50% effort with 6% consumption

P. T. Lang et al., Fusion Sci. Tech. ***77*** *(2021) 42*

First application at AUG – Actuation with Ar

First application for research topic "ELM suppression and avoidance scenarios": "Ar doped pellets for fast and efficient radiative power removal in ASDEX Upgrade"



Pellets with admixed Ar

- **High radiation efficiency (Modelling needed!)**
- **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

Low Ar concentration in pellet (0.1 at%)

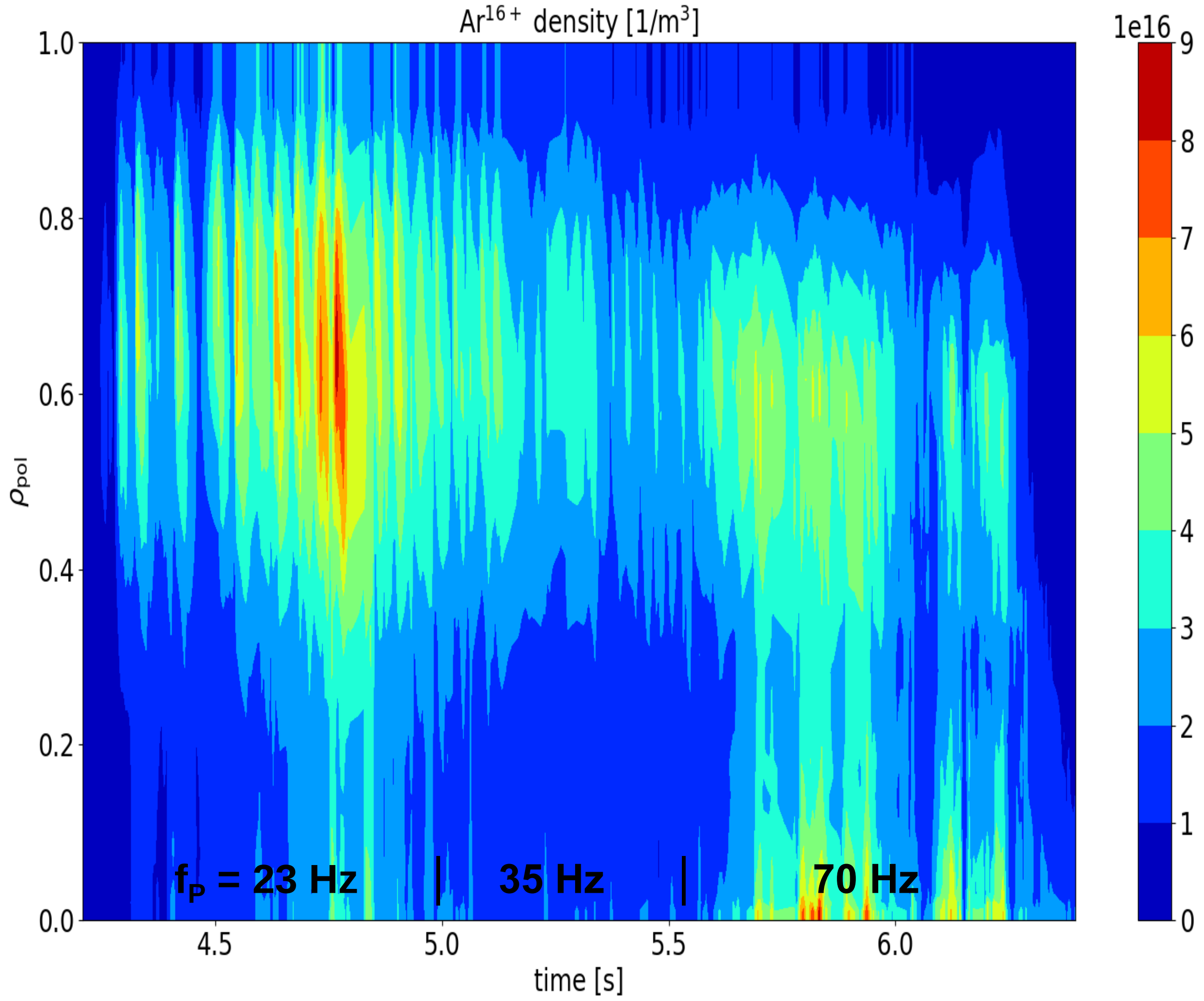
➔ **Higher Ar fraction or higher cooling factor using e.g. Kr**

➔ **Technical adaptation of centrifuge initiated**

First application at AUG – Actuation with Ar

Ar presence very well diagnosed in ASDEX Upgrade (Ar^{16+} CXRS)

R.M. McDermott et al., Nucl. Fusion ***61*** *(2021) 016019*



Pellets with admixed Ar

- **Ar and D deposition profiles correlate**

➔ Homogeneity within single pellet

- **Highest local/temporal Ar fraction (Ar/e^-) close to 10^{-3}**

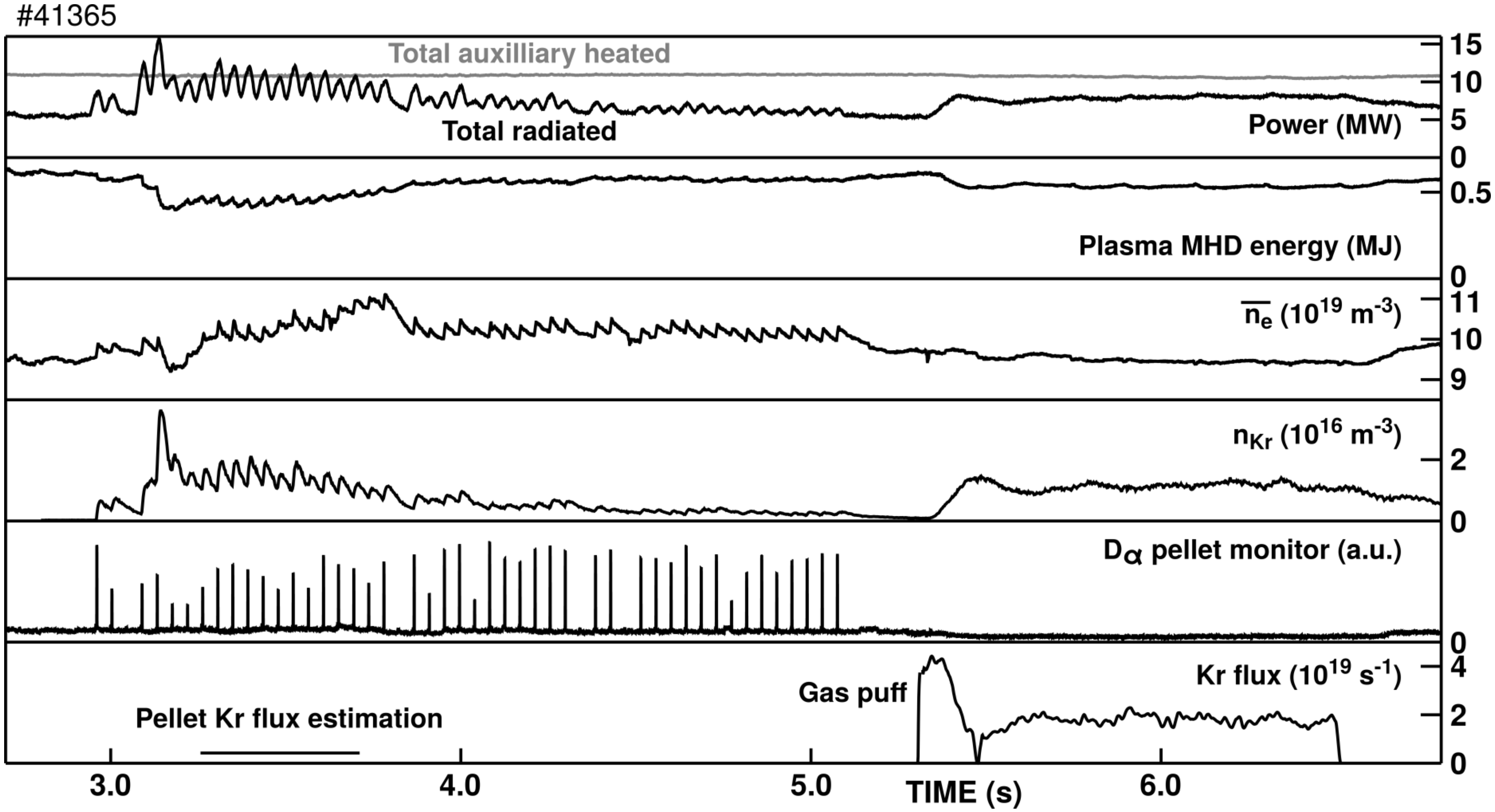
➔ Ar component fully deposited deep inside plasma

Comparable Ar and D pellet particle sustainment times (≈ 30 ms)

Smooth Ar level only at sufficiently high pellet rate

Amending the noble gas scan – Kr admixed at AUG

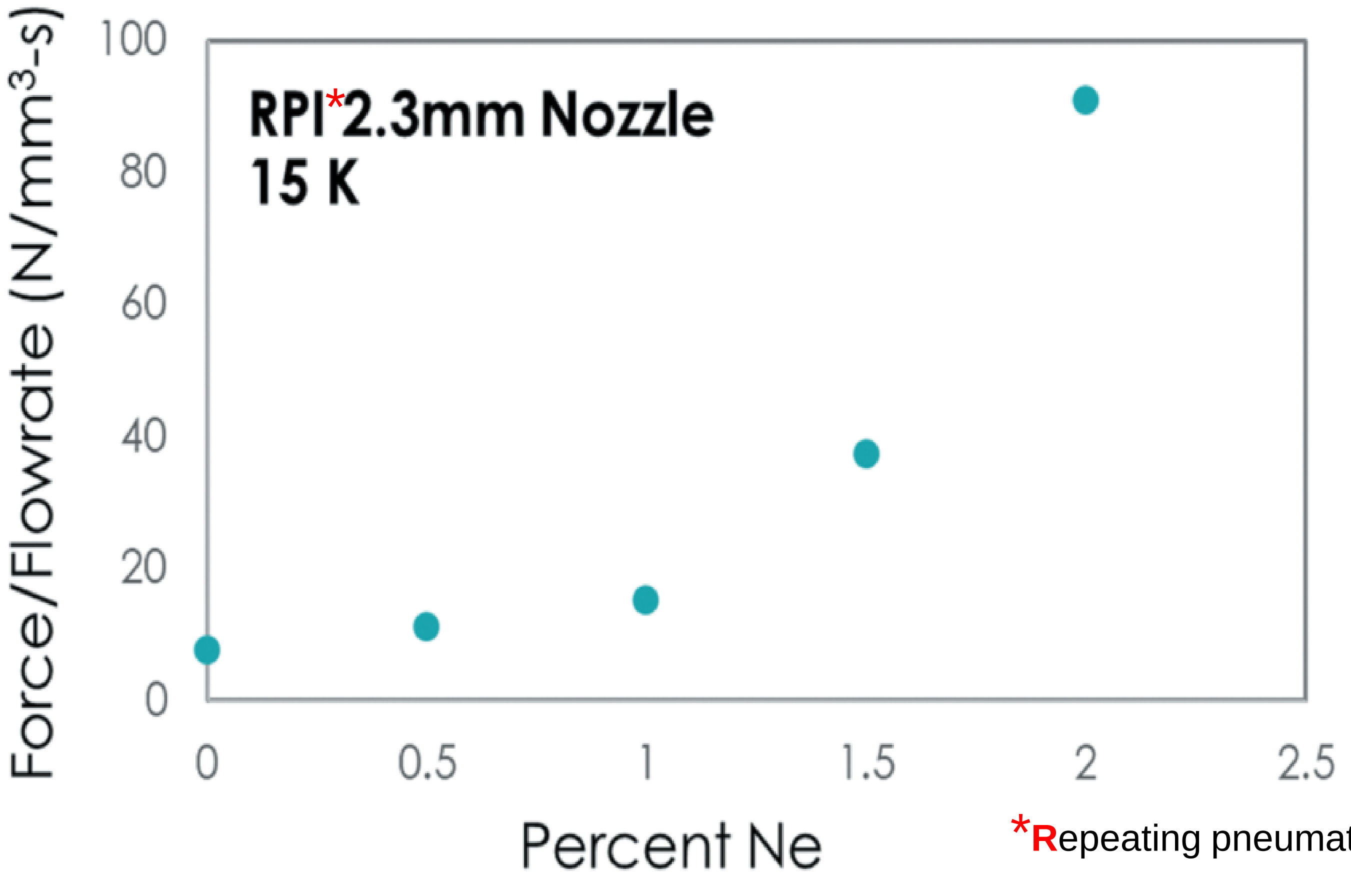
Kr admixed in D fueling pellets injected into AUG plasma



Reproducing Ar behavior: highly efficient, dwindling concentration within train

Amending the noble gas scan – Ne admixed at ORLN

Cooperation IPP/ORNL on steady state high throughput extrusion
Comparison of H_2, D_2 and Ne in D_2



Large batch piston extruder

Initial liquefier stage before solidifier

Eutectic point 18 K for 2.3 mol% Ne in D_2

Gas fully converted into solid

Increasing Ne concentration

➔ Increasing extrusion force/flow rate

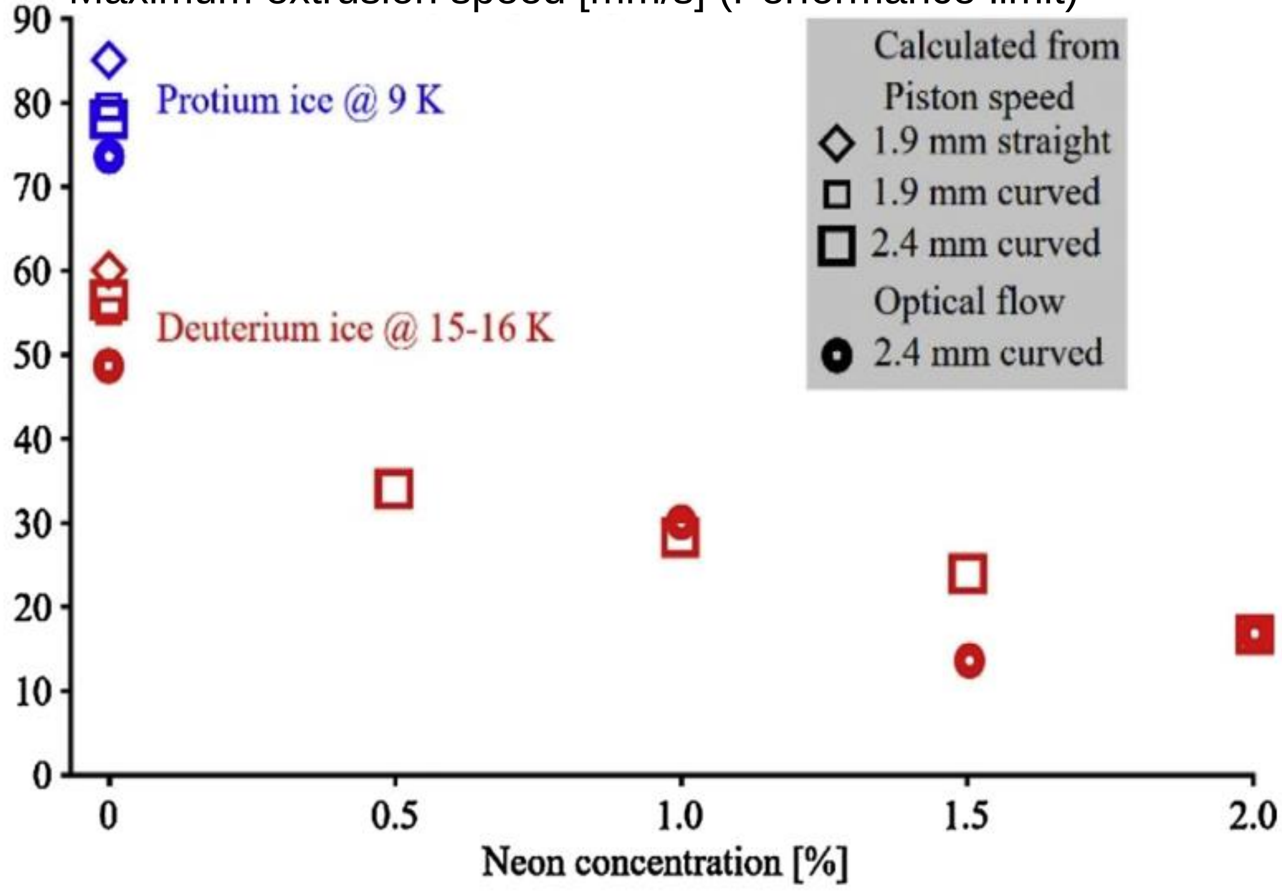
L.R. Baylor et al., Fusion Sci. Tech. ***77*** *(2021) 728*

*Repeating pneumatic Pellet Injector:
ORNL „workhorse" extruder

Amending the noble gas scan – Ne admixed at ORLN

Cooperation IPP/ORNL on steady state high throughput extrusion
Comparison of H_2, D_2 and Ne in D_2

Maximum extrusion speed [mm/s] (Performance limit)



Large batch piston extruder

Initial liquefier stage before solidifier

Eutectic point 18 K for 2.3 mol% Ne in D_2

Gas fully converted into solid

Increasing Ne concentration

➔ Increasing extrusion force/flow rate

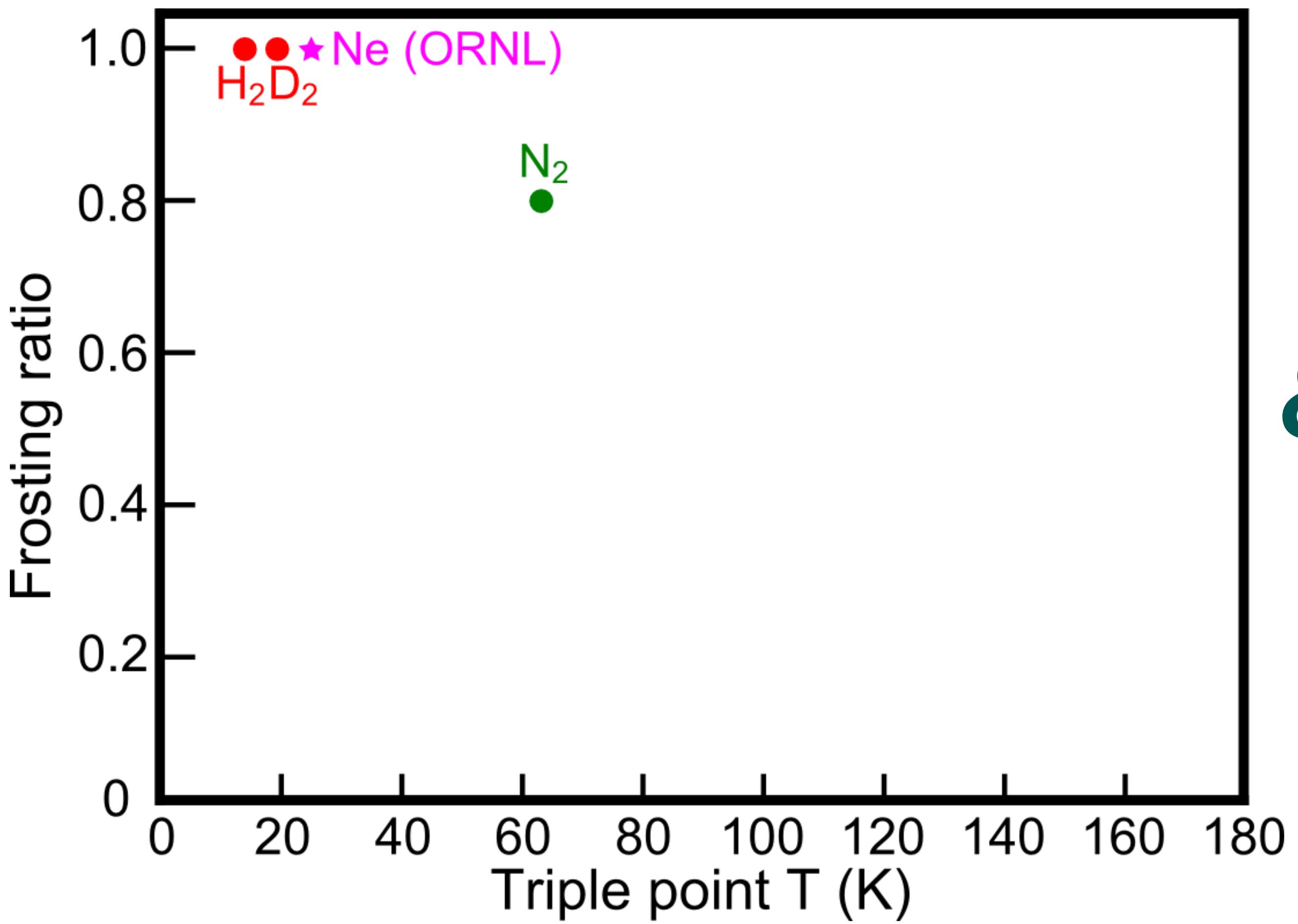
➔ Decreasing max. extrusion speed

*P.T. Lang et al., Fusion Eng. Design **166** (2021) 112273*

Less max. throughput for admixed ice

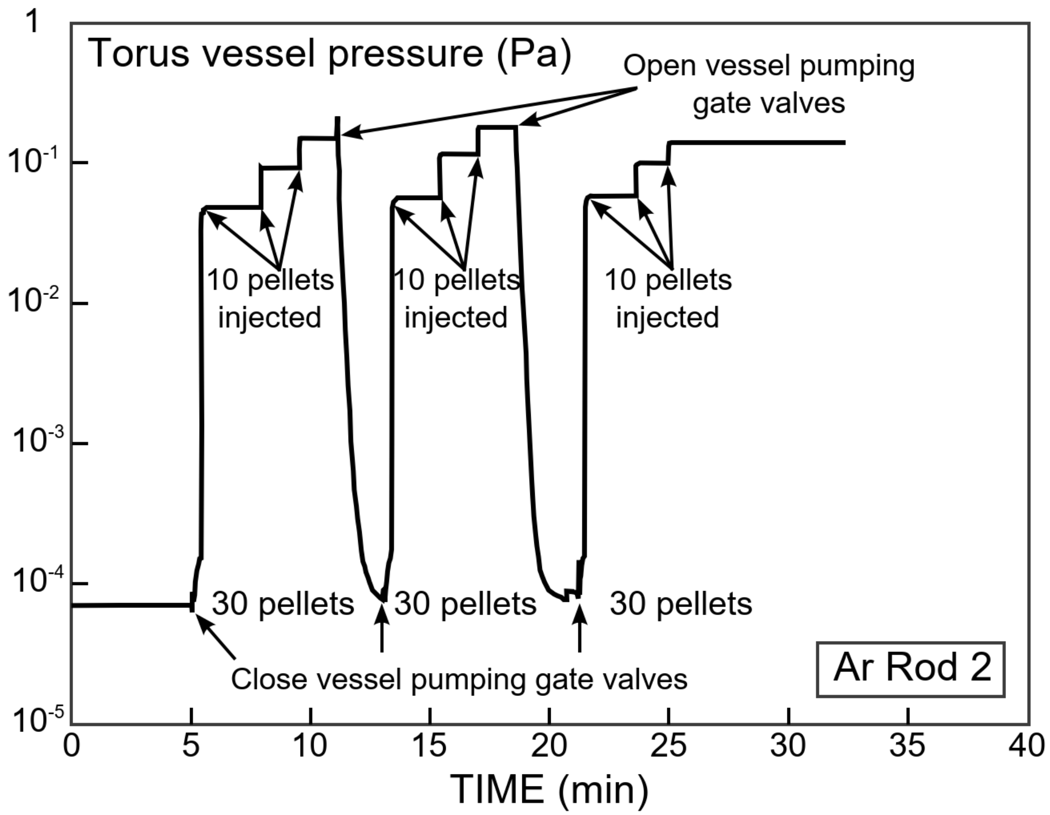
Compiling the collected data

H_2/HD/D_2 and Ne/D_2 gas can be frosted while keeping the stoichiometry
N_2 in D_2: about 80% of initial concentration kept during frosting



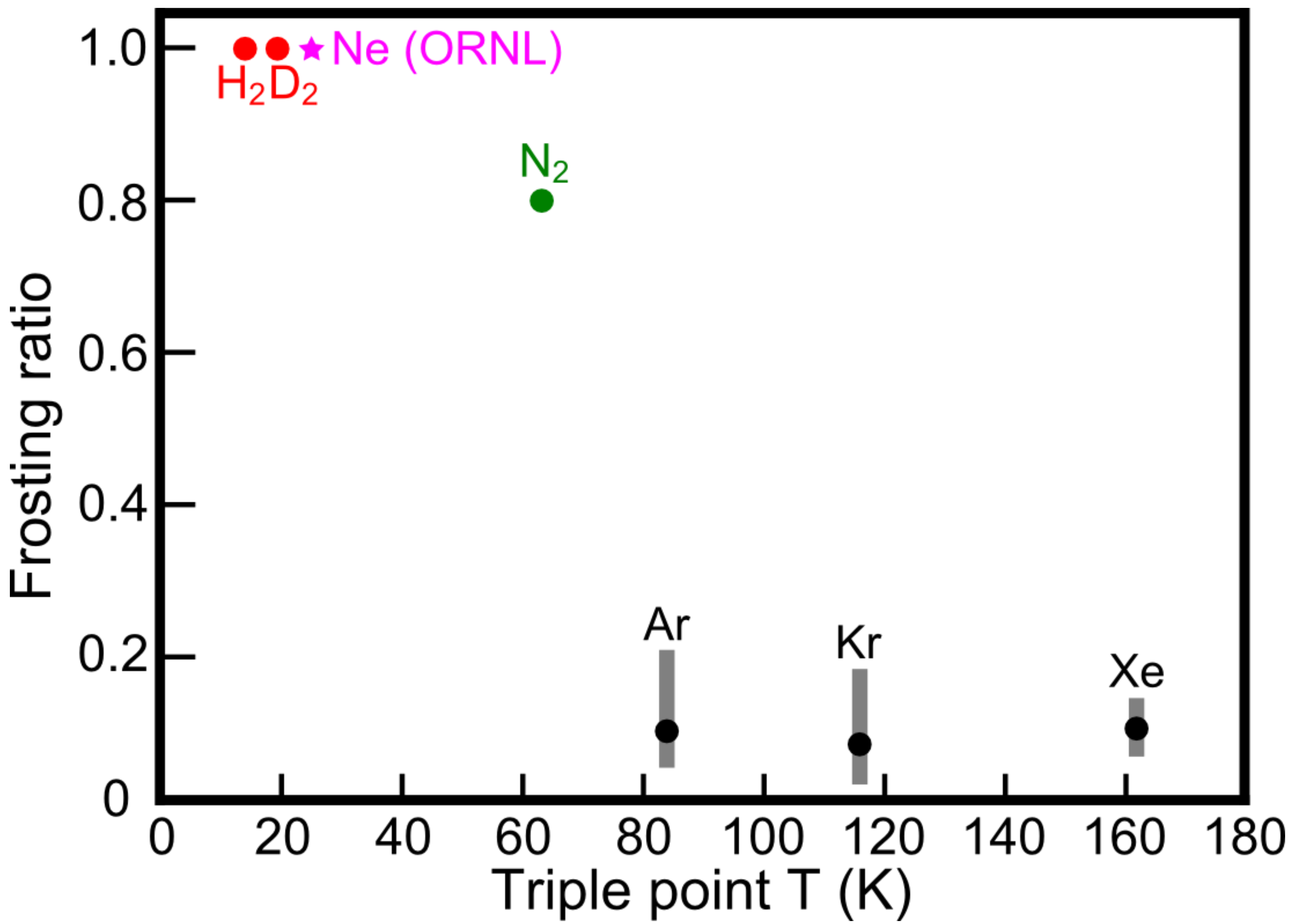
&

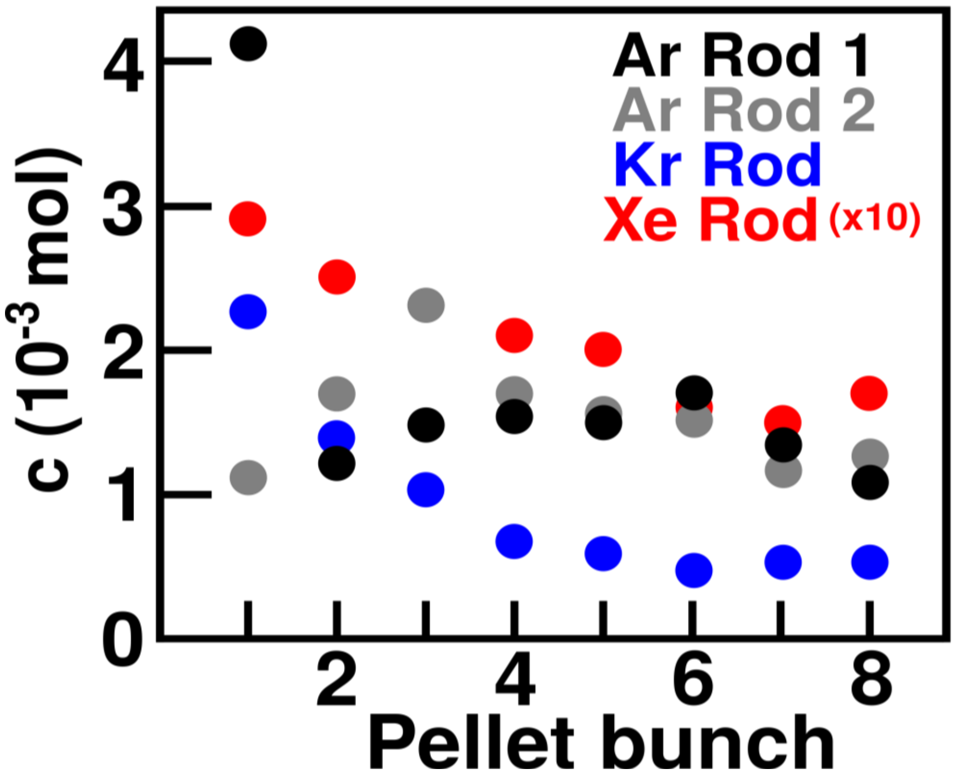
Ar / Kr / Xe



Compiling the collected data

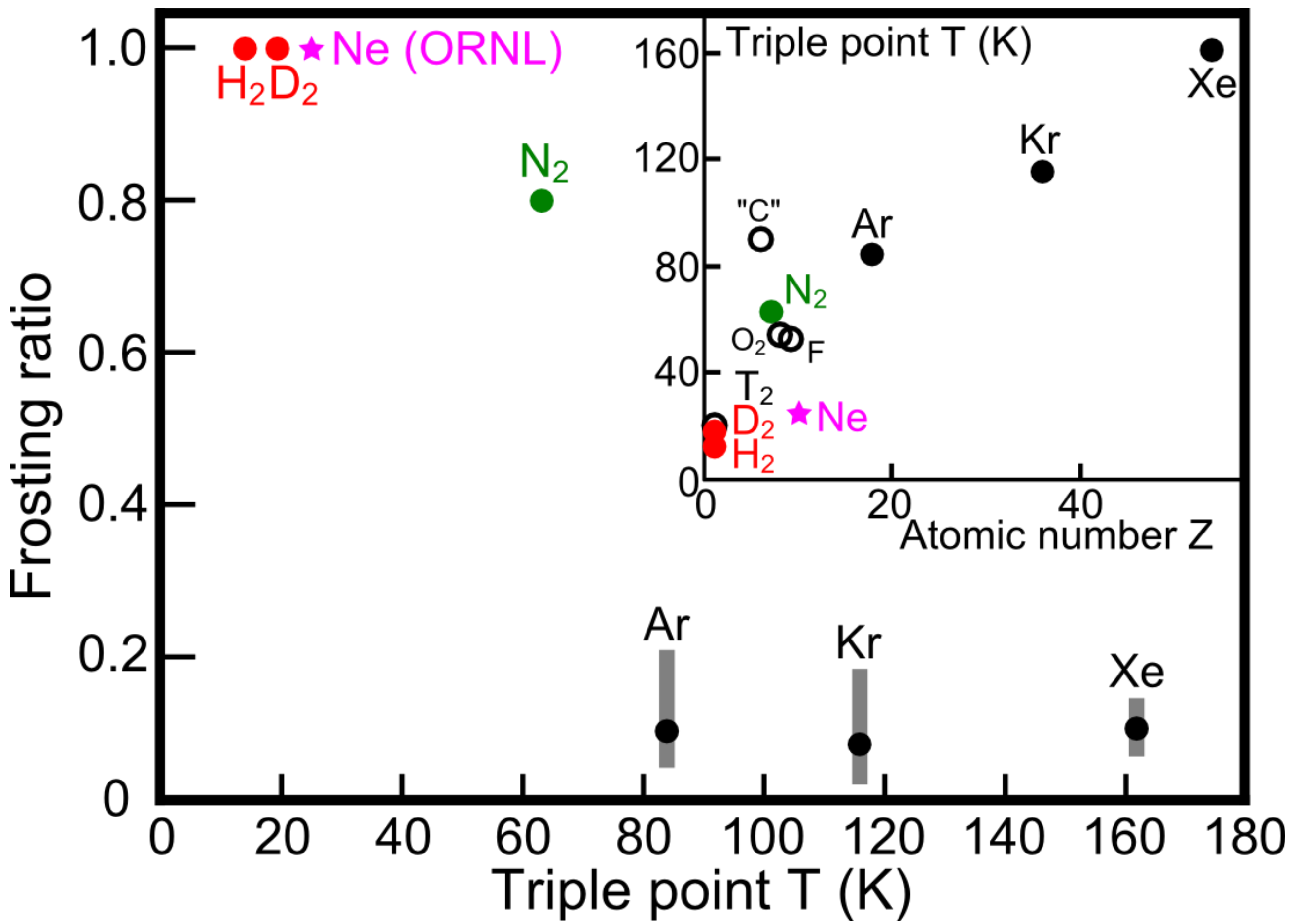
H_2/HD/D_2 and Ne/D_2 gas can be frosting while keeping the stoichiometry
AUG PLS: admix fraction in ice gets reduced with e.g. increasing triple point temperature





Compiling the collected data

H_2/HD/D_2 and Ne/D_2 gas can be frosting while keeping the stoichiometry
AUG PLS: admix fraction in ice gets reduced with e.g. increasing triple point temperature



Gas	Atomic charge Z	Atomic weight (amu)	Concentration in D_2 supply gas (mol%)	Triple point temperature [K]
Ne	10	20.18	1.937 ± 0.039	24.6
Ar	18	39.95	2.037 ± 0.041	83.8
Kr	36	83.80	1.278 ± 0.026	115.8
Xe	54	131.29	0.205 ± 0.004	161.4

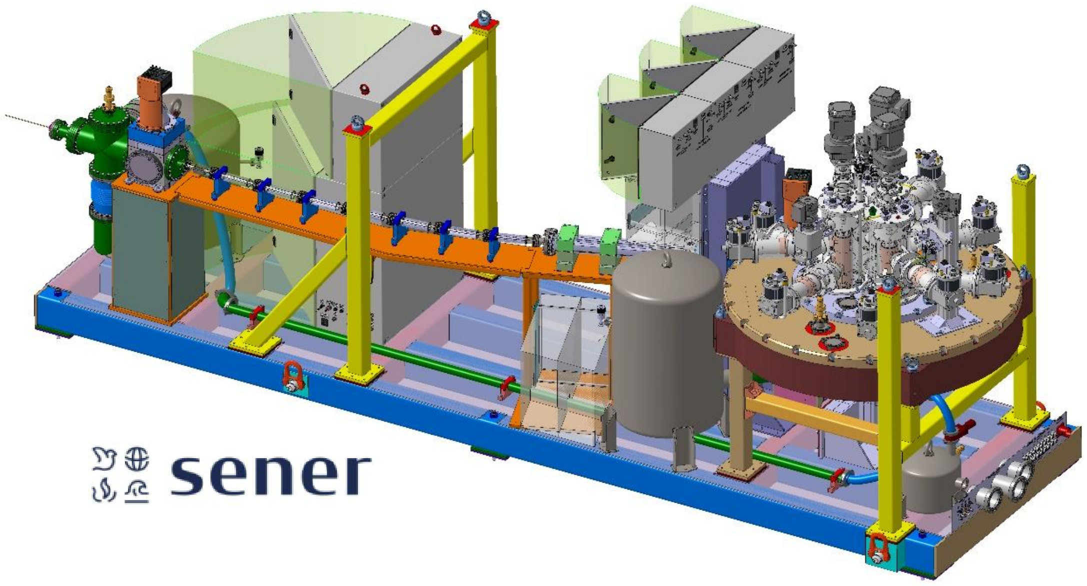
Outlook

Admixing works already using “simple” fueling systems

Admixed solids composed from immiscible crystallites but show high mechanical resilience!

Better adapted extruders to yield homogeneous admixed concentration

Multi-purpose pellet launching systems (as e.g. the JT-60SA PLS)



PLS system for JT-60SA under construction
Commercial manufacturing (SENER) under F4E
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
Third (admixed) pellet source can be added

G. Olivella et al., “Design and development of a hydrogen pellet centrifuge accelerator for the JT-60SA”, PS4.41, this conference (Friday)

SUMMARY

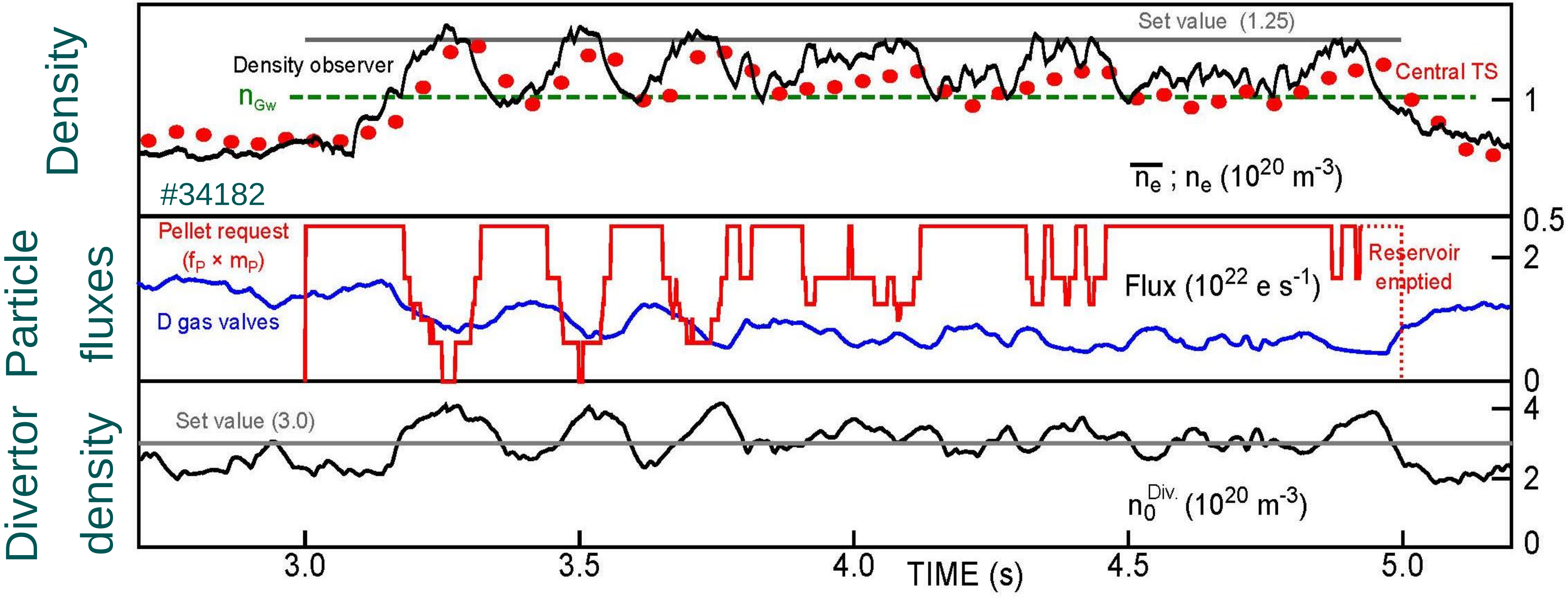
- Fusion power plants need versatile matter injection system
- Pellets optimized for core fuelling – can be applied for PEGs too
- AUG PLS (and ORNL extruder) indicate technical potential
- Technical efforts needed to improve the performance

➔ An investment likely to bear fruit!

Backup slides

Pellet actuation for fuelling: AUG leading the EU-DEMO relevant research

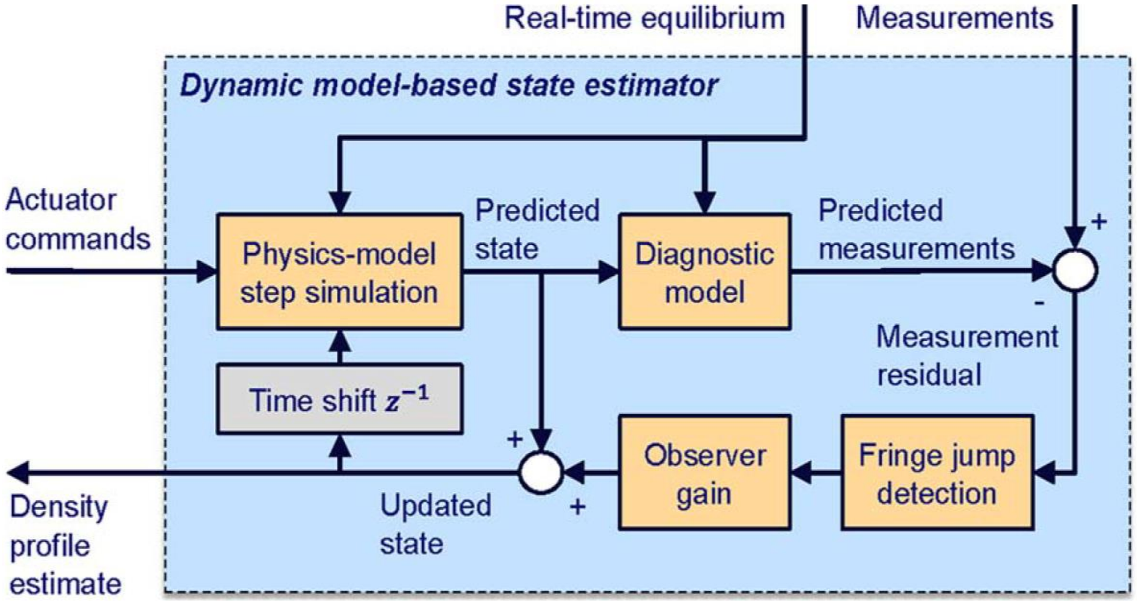
Plasma fuelling and density control to maximise fusion power:
Robust model-based density real-time control algorithm developed and tested on ASDEX Upgrade for ITER and DEMO

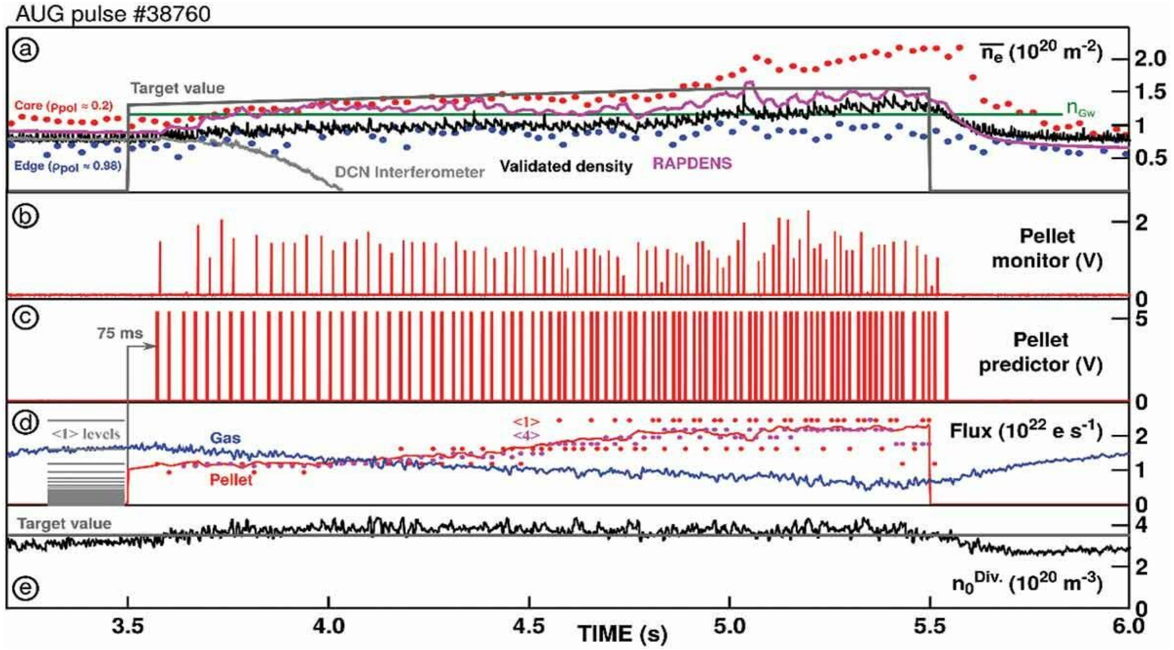


X. Litaudon, Invited talk, SOFT 2018
"European Integrated Programme in support to ITER: Overview Medium Size Tokamaks and JET results"

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*

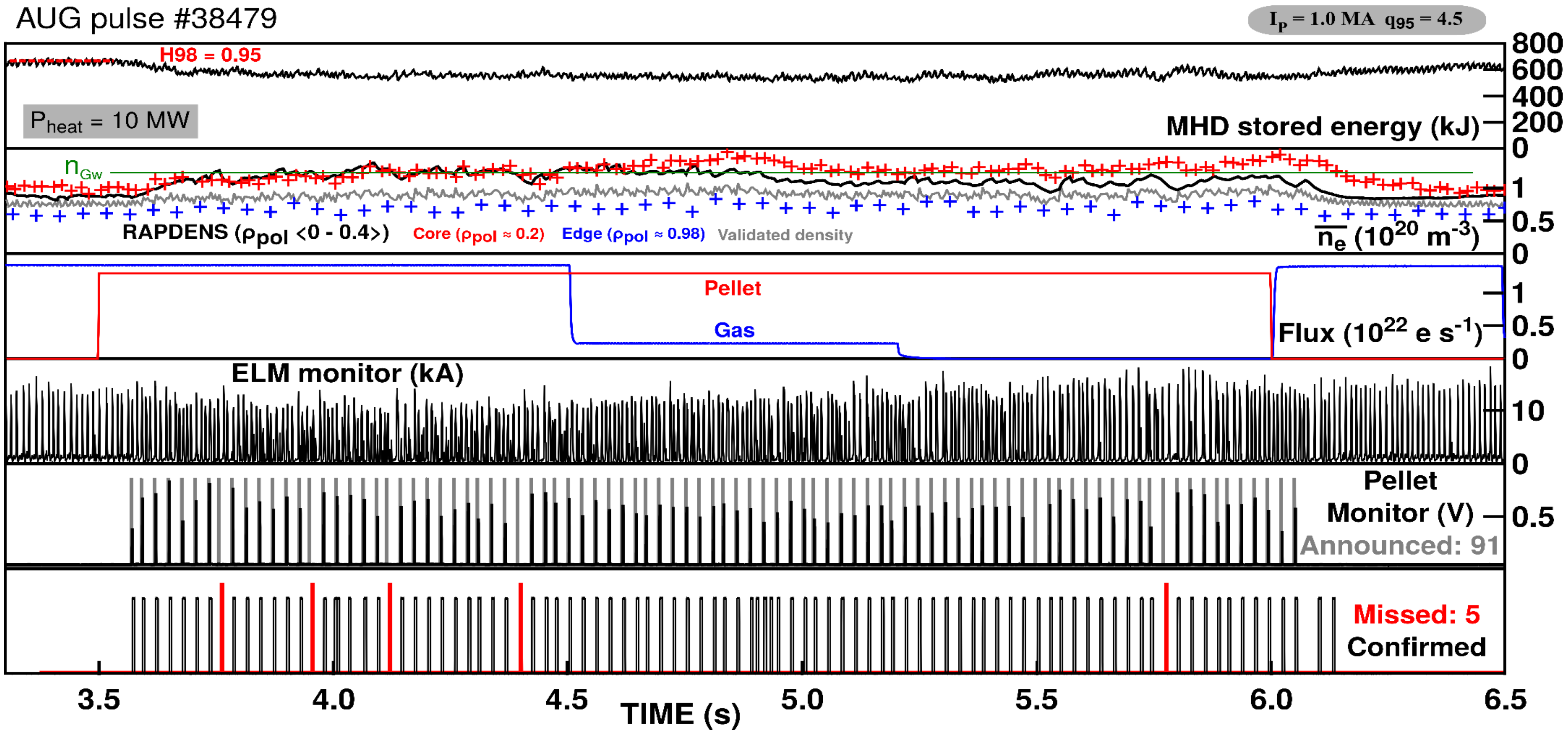
P.T. Lang et al., Fusion Sci. Technology 78 (2022) 1

➔ 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

Missed-out detection: Example from AUG

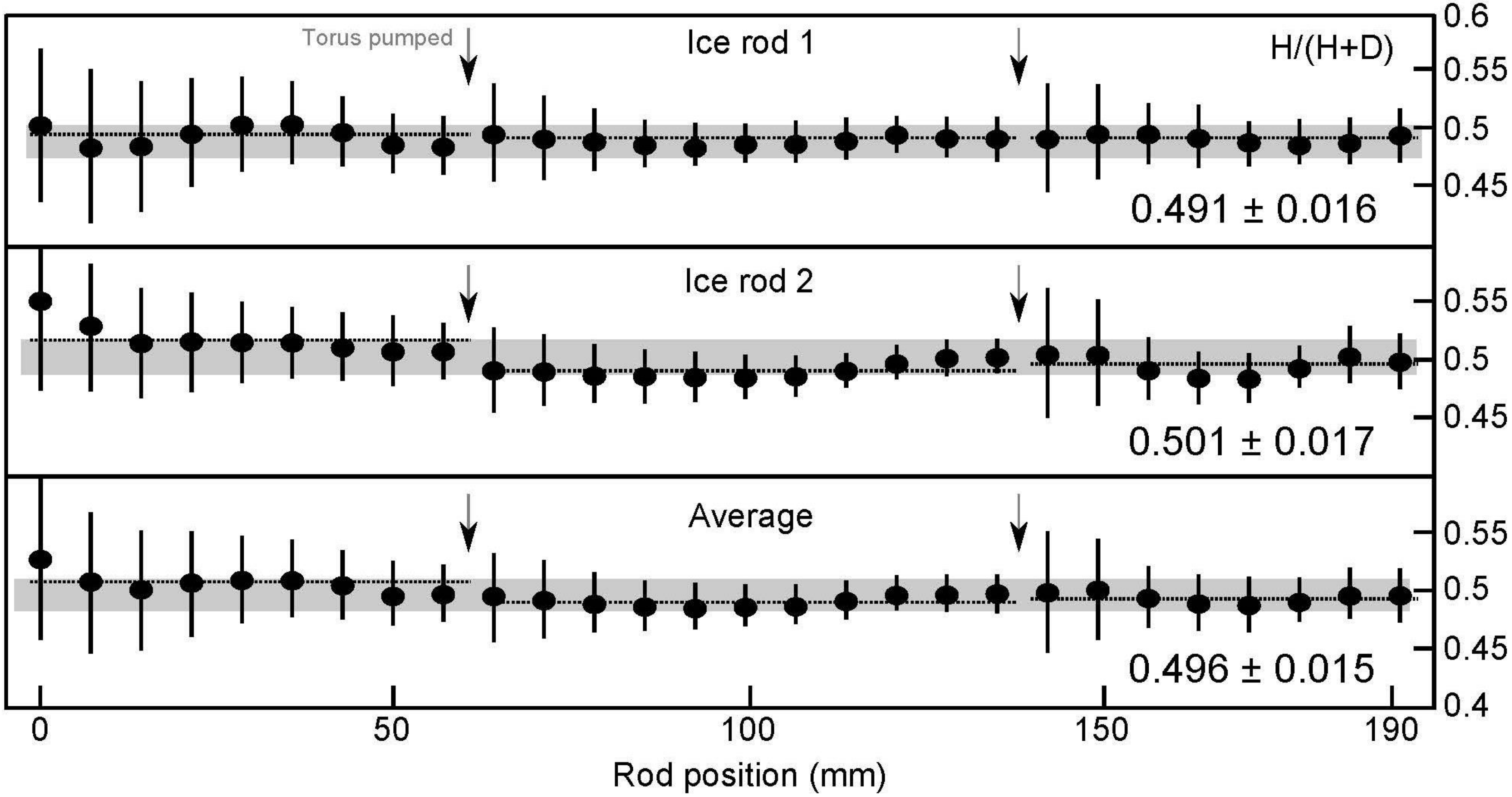


Stable high-density operation with core density derived in Real-Time
Missed-out pellets detected in RT - but causing no problem in AUG

P.T. Lang et al., Fusion Sci. Technology, in press

Isotope ratio control: Pellet analysis

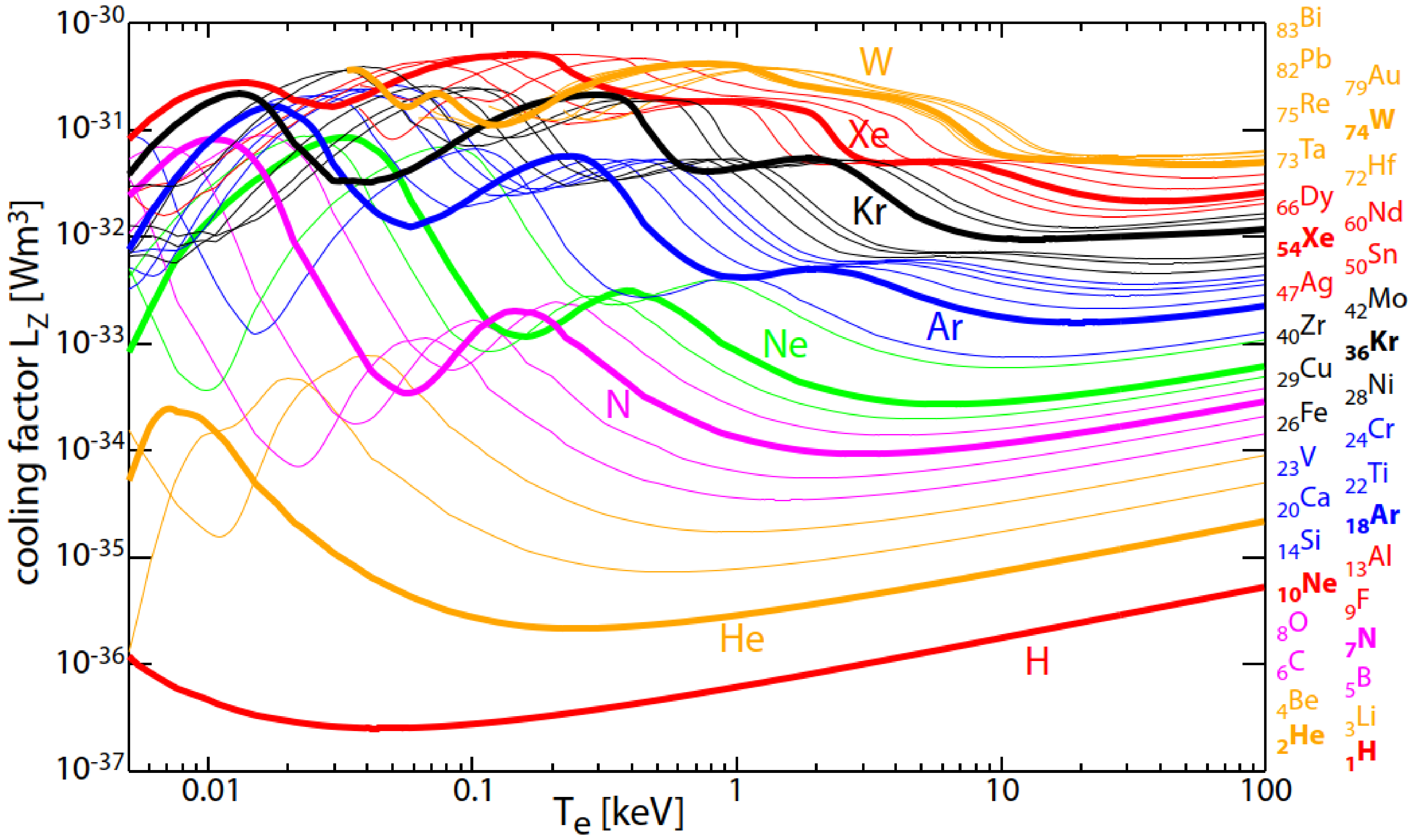
HD-Pellets: Qualifying the actuator



Pellet injection into AUG vessel
Gas analysis by RGA

HD pellets with H:D ratio very close to 1:1

Radiation predictions for different elements



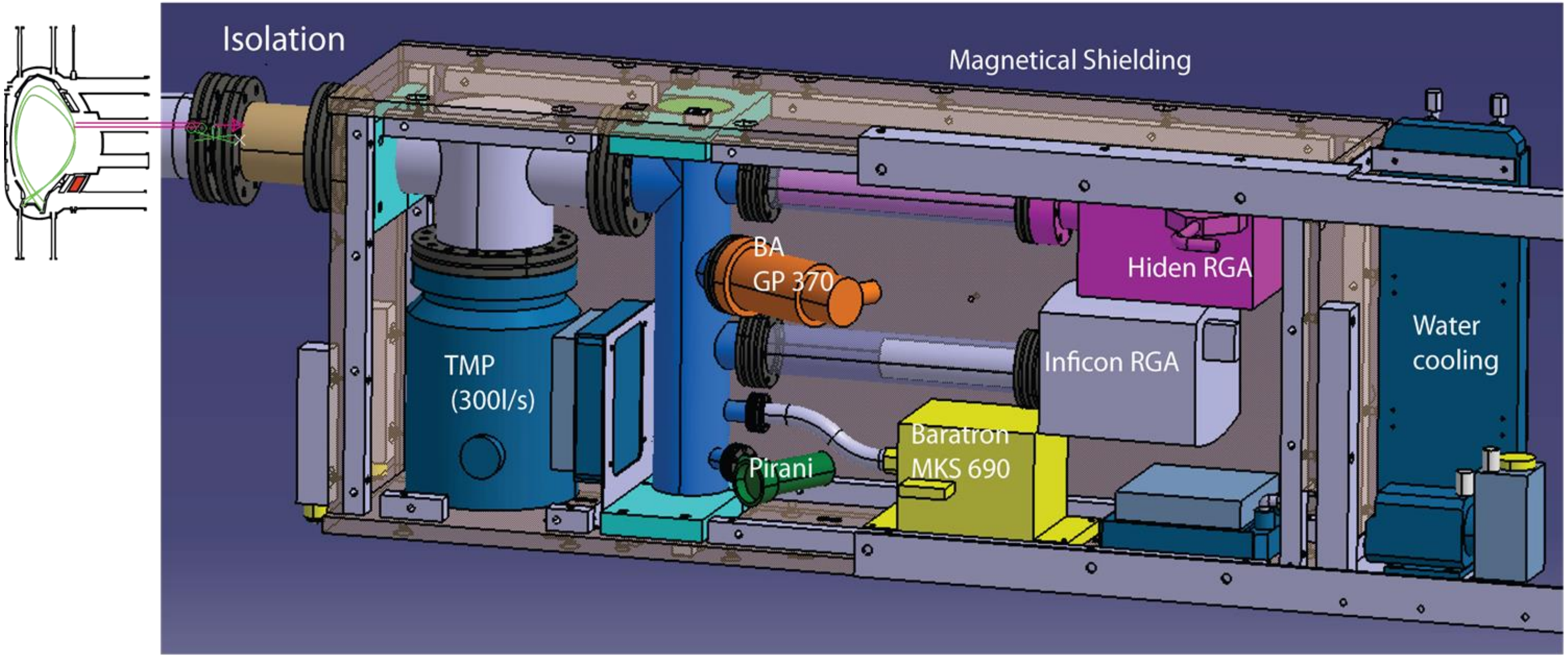
Improvement beyond "simple" Z scaling

Investigation of "cooling factor" for 35 relevant elements by Cowan code via ADAS infrastructure
➔ Produces good radiation predictions

T. Puetterich et al., 42nd EPS Conference on Plasma Physics, P4.111

AUG: RGA system

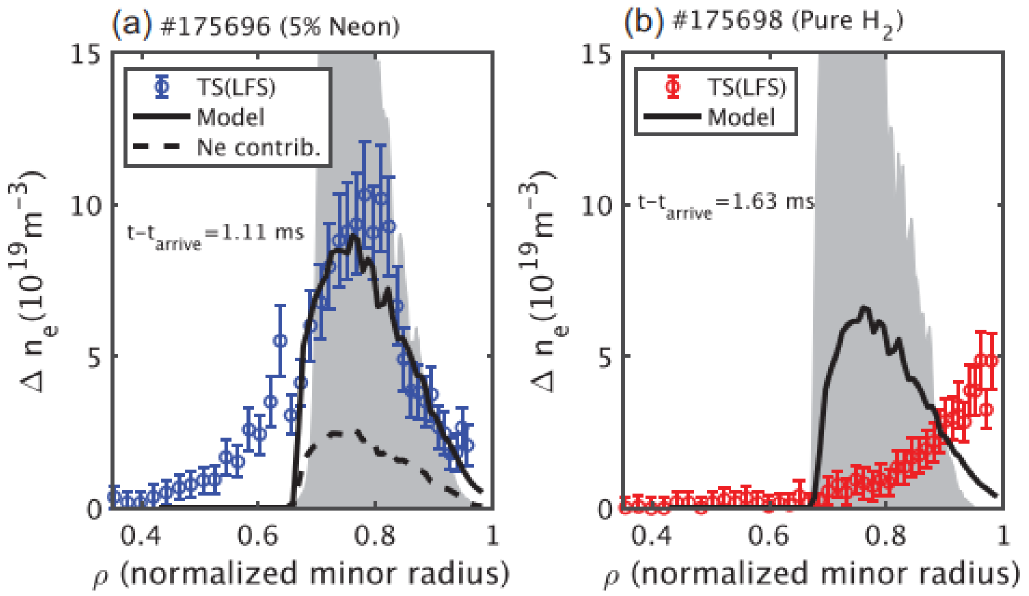
Composition of the gas coming from sublimated pellets measured through a calibrated differential pumping Quadrupole Mass Spectrometer (QMS).
Sophisticated sniffer probe residual gas analysis system(s)
Calibration with reference gases and versus Baratron at RGA



PEG carrier pellets – JT-60SA multi-purpose PLS

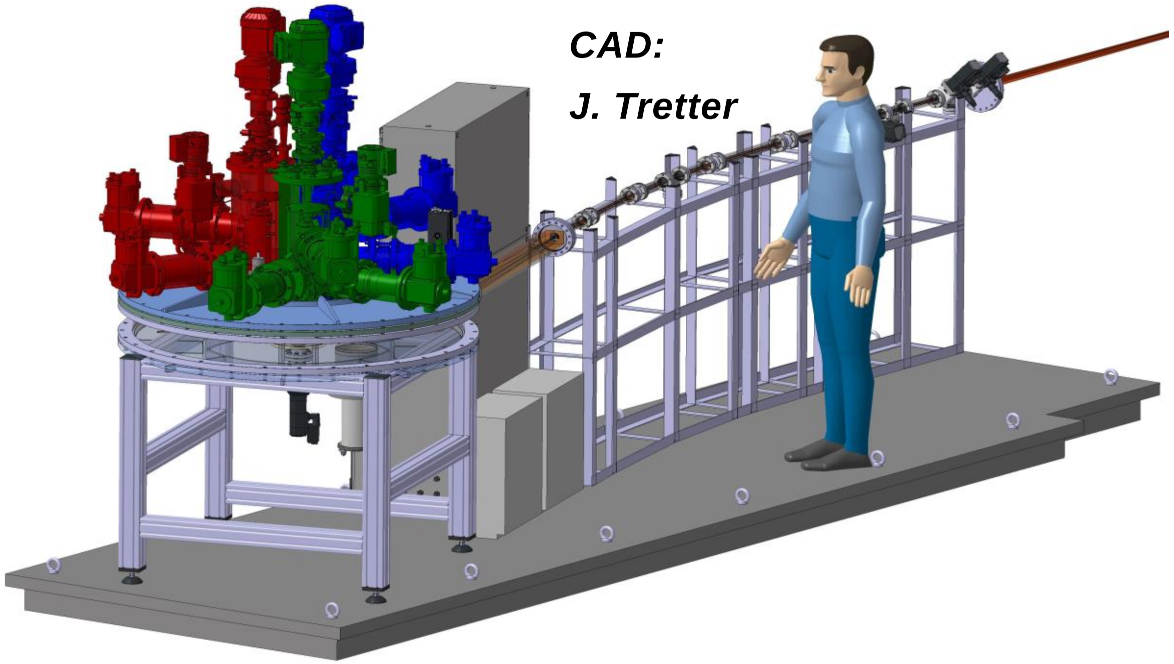
Ne doped H_2 pellets in LHD from LFS

- **Reducing plasmoid drift**
- **Enhances core density assimilation**



A. Matsuyama et al., Phys. Rev. Lett. **129** (2022) 255001

A. Matsuyama et al., Phys. Plasmas **29** (2022) 042501

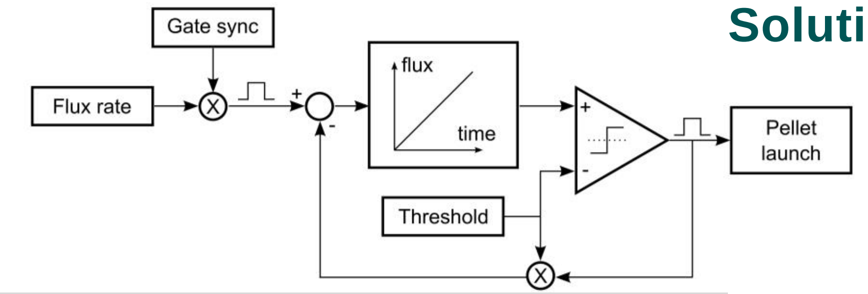


Start up configuration:
Fuelling pellet source (Up to 20 Hz)
ELM pacing pellet source (Up to 50 Hz)
Simultaneous fuelling & pacing
Tailored single pellet train to minimize cross-talk

Multi-purpose PLS: Control scheme

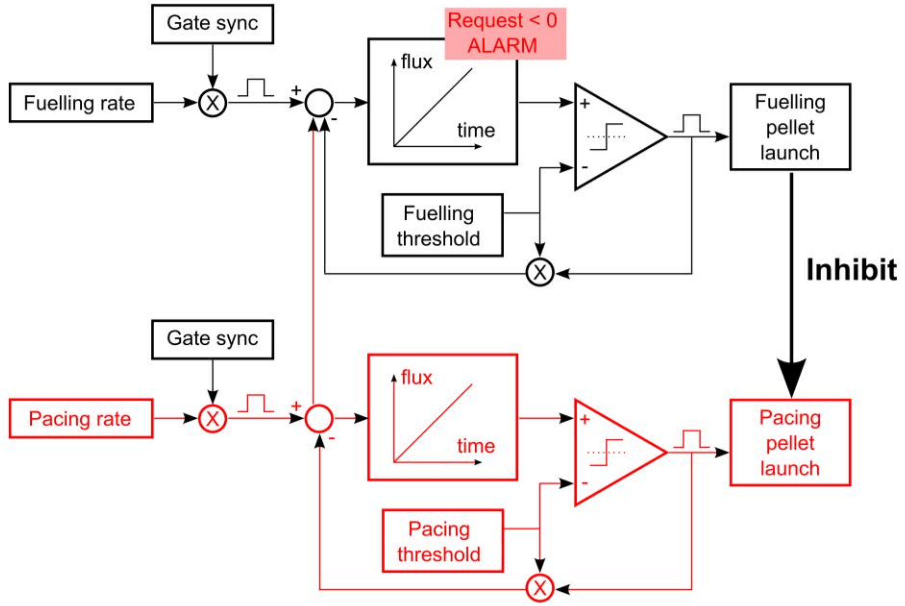
Extend proven AUG solution for fuelling & pacing
Solution can be extended to multi-task control

Fuelling source

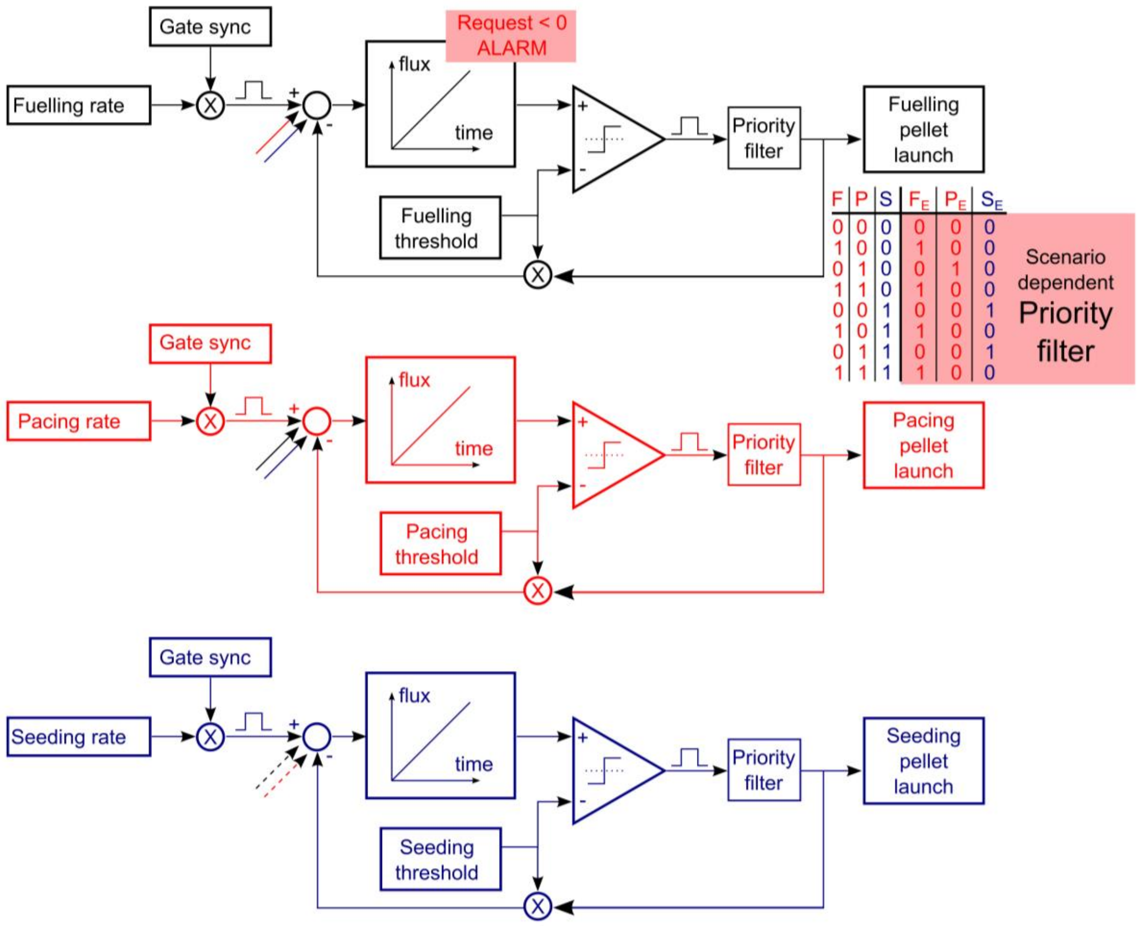


B. Ploeckl et al., Fus. Sci. Techn. 77 (2021) 199

Fuelling and pacing source



Multi sources



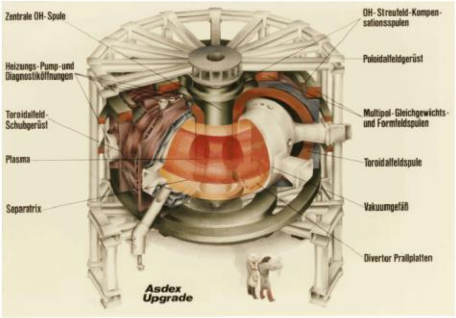
Multi-actuating pellet system: Step-by-step approach

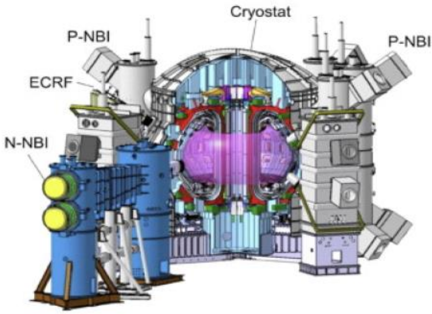
Multi-tasking pellet system to cover issues beyond pure core particle fuelling

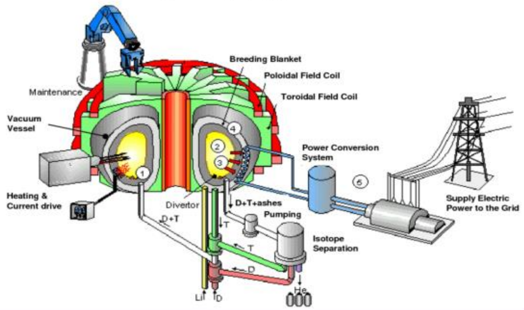
PELLET ACTUATOR development step by step:

AUG → JT-60SA → DEMO

AUG	JT-60SA	DEMO
Demonstrated:	Commissioning ongoing:	Design study ongoing:
● High core density	● Simultaneous density & ELM control	● Full pellet resilient feedback control
● ELM control	● Pellet resilient feedback profile control	● Simultaneously keep D - T - He profiles
● Pellet resilient measurements		
t < 10 s	**t < 100 s**	**t ~ 2 h**







Challenges - Complexity - Sustainability

AUG	JT-60SA	DEMO
I = 1.2 MA R = 1.6 m	I = 5.5 MA R = 2.9 m	I = 20 MA R = 9.3 m