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EU-DEMO Fuel Cycle Operation Modelling and Design

Jonas C. Schwenzer

IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy

11 – 13 Oct. 2022

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Part I: Integral Fuel Cycle Modeling & Dependencies

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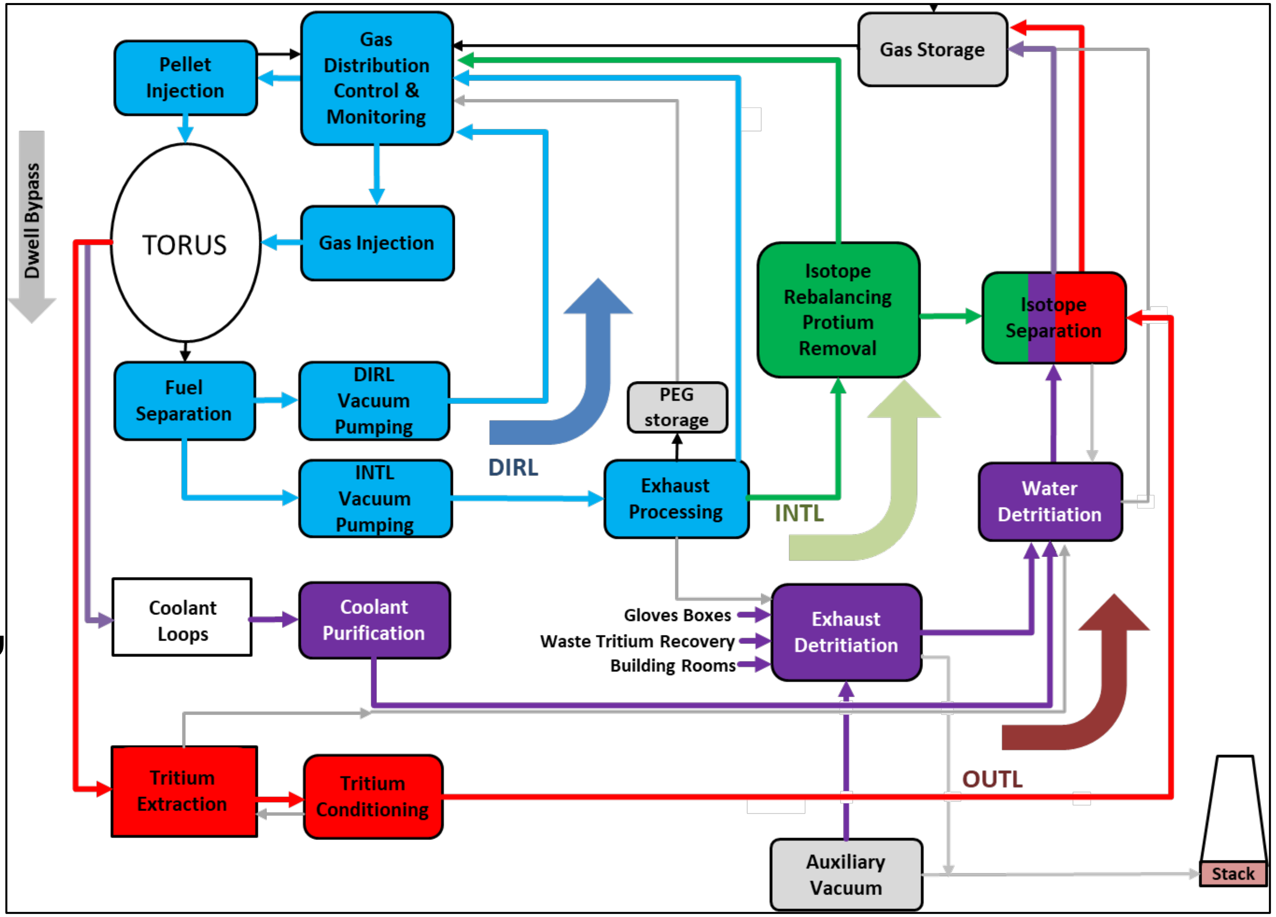
Fuel Cycle – Functional View

Systems in the fuel cycle serve different tritium processing functions:

- Machine Gas Throughput
- Fuel Rebalancing
- Tritium Extraction
- Tritium Recovery

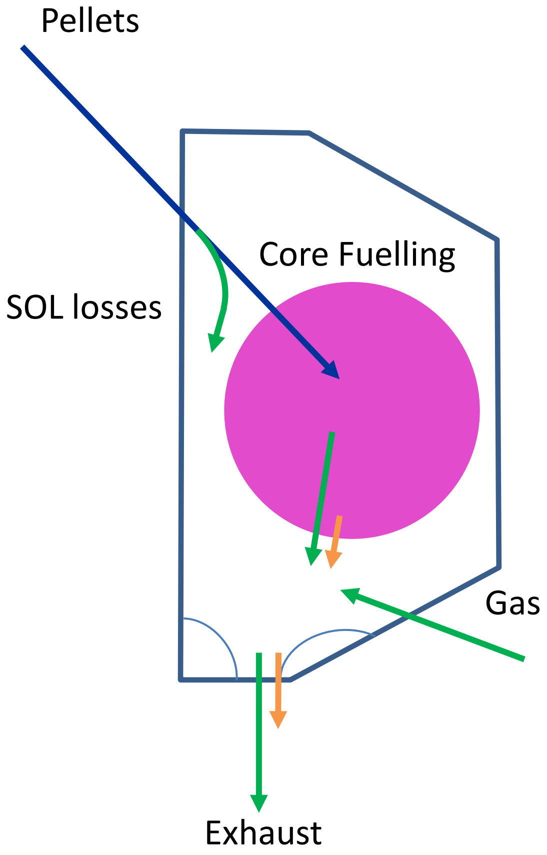
The incurred load on the fuel cycle scales with plant parameters via **“fuel cycle performance metrics”**



Performance Metrics – Troughput I

Machine Gas Throughput:

- Fuelling and exhaust capabilities provided by systems for:
  - Matter Injection (Pellets & Gas)
  - Composition Control
  - Fuel Separation
  - Vacuum Pumping
  - Exhaust Processing
- System size (and complexity) scales with total throughput
  - Upper limit given by #ports for vacuum pumping



$$M_{MG} = \frac{F_{burn}}{\sum F_{fuel}} = \eta_f f_b$$

Performance Metrics – Troughput II

Machine Gas Throughput:

- Fuelling and exhaust capabilities provided by systems for:
  - Matter Injection (Pellets & Gas)
  - Composition Control
  - Fuel Separation
  - Vacuum Pumping
  - Exhaust Processing
- System size (and complexity) scales with total throughput
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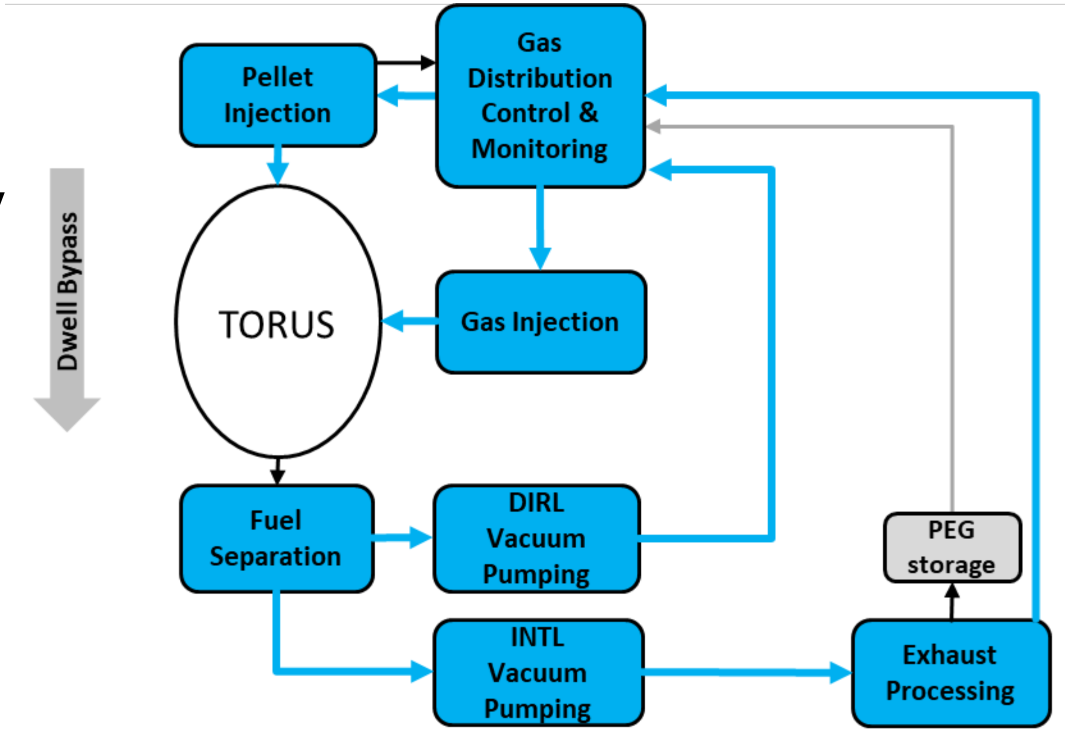


Fuelling to Torus (Up to):
380 Pa m³/s DT via Pellets
50 Pa m³/s DT via Gas Puffing

Burn-up (2GW):
2.68 Pa m³/s DT

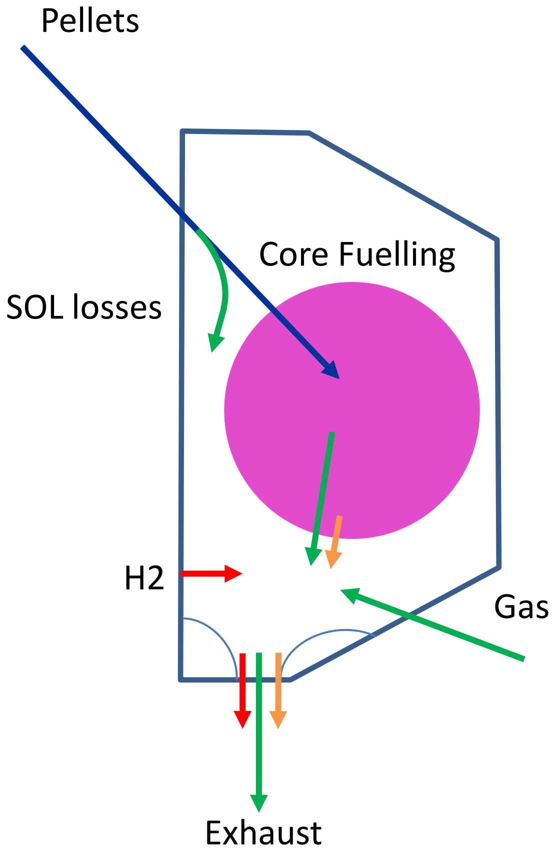
$$M_{MG} = \frac{F_{burn}}{\sum F_{fuel}} = \eta_f f_b$$

$$t_{MG} = 0.25\ h$$

Performance Metrics – Rebalancing I

Fuel Rebalancing:

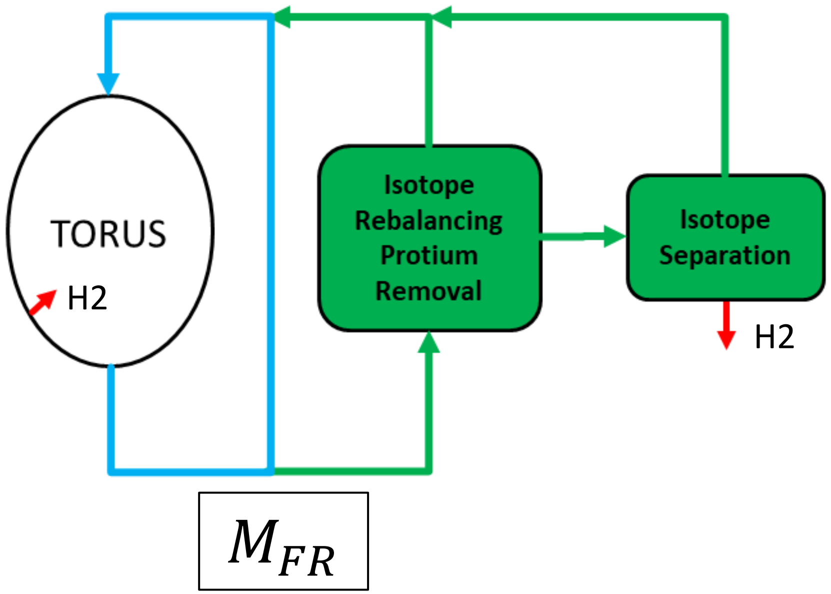
- Disproportionate sinks/sources of hydrogen have to be compensated to keep isotopic purity of fuel
  - Protium outgassing is always present in metal systems
  - Large surface areas at elevated temperature in torus



Performance Metrics - Rebalancing II

Fuel Rebalancing:

- Disproportionate sinks/sources of hydrogen have to be compensated to keep isotopic purity of fuel:
  - Protium outgassing is always present in metal systems
  - Large surface areas at elevated temperature in torus
- Excess H (or D/T) is removed in IRPR by processing a fraction of the fuel stream
  - Amount given by balances for each isotopic species
  - Total removal of all H uneconomical
    (→ Requires isotopic separation of all fuel (ITER-like)
- Implanted D/T may also outgas at disproportionate rates
  - Effect expected to change over lifetime

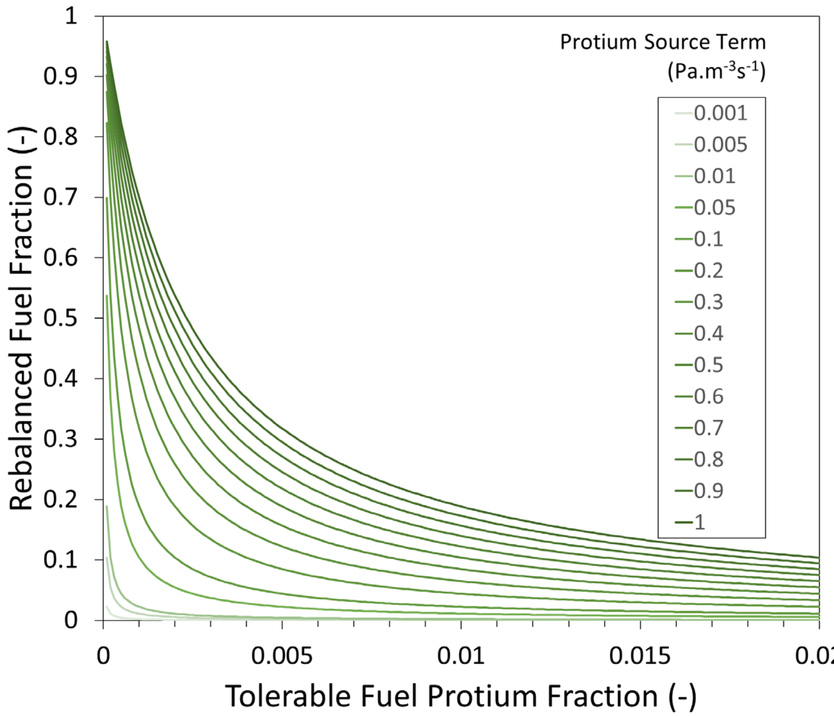


$$M_{FR,i} = 1 - \frac{F_{fuel} z_i}{F_{fuel} z_i + \Delta F_i}$$
$$t_{FR} = 14\ h$$

Performance Metrics - Rebalancing III

Fuel Rebalancing:

- Disproportionate sinks/sources of hydrogen have to be compensated to keep isotopic purity of fuel
  - Protium outgassing is always present in metal systems
  - Large surface areas at elevated temperature in torus
- Excess H (or D/T) is removed in IRPR by processing a fraction of the fuel stream
  - Amount given by balances for each isotopic species
  - Total removal of all H uneconomical (→ Requires isotopic separation of all fuel (ITER-like)
- Implanted D/T may also outgas at disproportionate rates
  - Effect expected to change over lifetime



$$M_{FR,i} = 1 - \frac{F_{fuel} z_i}{F_{fuel} z_i + \Delta F_i}$$

$$t_{FR} = 14\ h$$

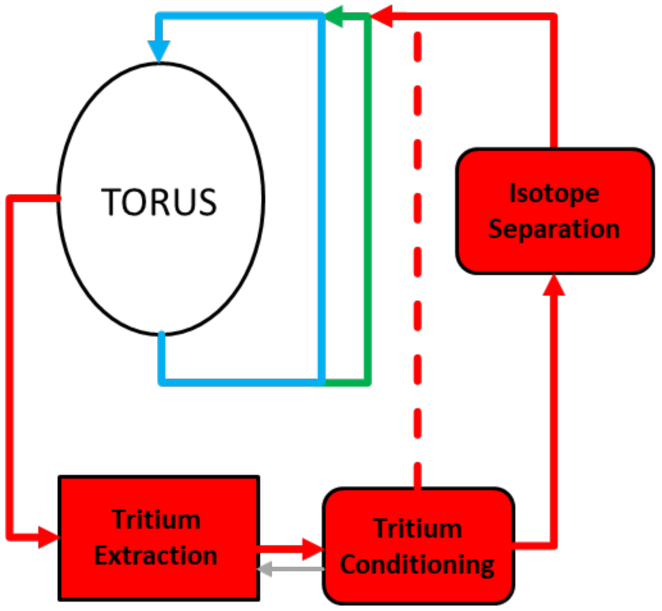
Performance Metrics - Extraction

Tritium Extraction:

- Extracted tritium requires further processing in fuel cycle
  - Separation from carrier gases
  - Isotopic separation from doping agents (H,D)
- TBR is fairly fixed [1.0 – 1.1]
  → Variations have only minor impact on tritium flowrate

➔Fuel cycle impact is mostly dependent on Tritium Extraction technology selection

- No isotope separation required if T>D and H< ϵ



$$M_{TE} = \frac{F_{ext}}{F_{burn}} (= TBR^*)$$
$$t_{TE} = \sim 40\ h$$

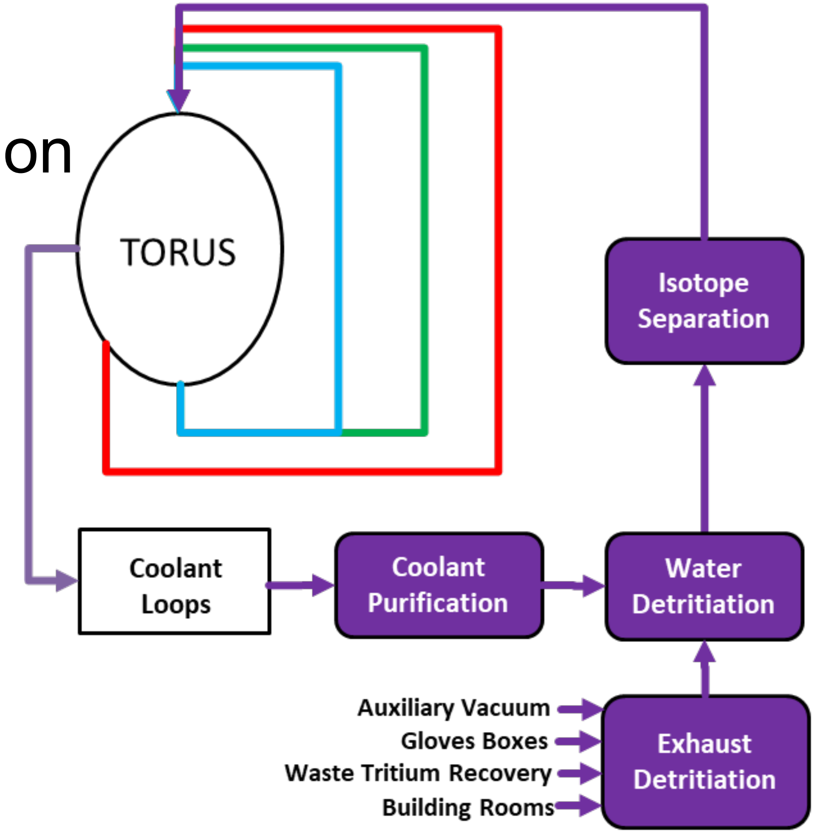
*at steady state

Not using hydrogen doping agents has the potential to significantly simplify the outer fuel cycle

Performance Metrics - Recovery

Tritium Recovery:

- Tritium may be lost from the fuel cycle due to permeation
- Laborious recovery required to limit discharges
  - All tritium is eventually converted to HTO
  - Conversion to hydrogen and isotope separation required
- Largest fuel cycle systems in terms of size and energy consumption



Minimizing Tritium permeation can yield significant gains in fuel cycle system size and energy demand

$$M_{TR} = \frac{F_{Rec}}{F_{burn}}$$

$$t_{TR} = \sim 146\ h$$

Summary Part 1

Part 1 Takeaway:

- Fuel Cycle is designed to support one optimal fuel composition of D/T/H
  - Shifts in isotopic ratio can be achieved but requires *hours* – *days* to perform necessary isotope separations
- Full understanding of **all** mass transport effects in Torus is essential for fuel cycle design
  - Use of hydrogens in other isotopic composition than that of the fuel is highly undesirable from a fuel cycle perspective
- Design & sizing of inner fuel cycle driven mainly by
  - Total machine gas throughput
  - Isotopic purity of exhaust

Part II Dynamic Simulation of Fuel Cycle Operation

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Introduction

- Dynamic process simulations of the fuel cycle are being developed for the evaluation and design of the fuel cycle
- The dynamics of the inner fuel cycle are governed by the **Torus Fuelling** and **Exhaust** streams

→ Dictated by the fuel demand of the plasma

But....

…I am not a plasma physicist…

…. And I have questions.

What does the fuel demand of a DEMO reactor look like?

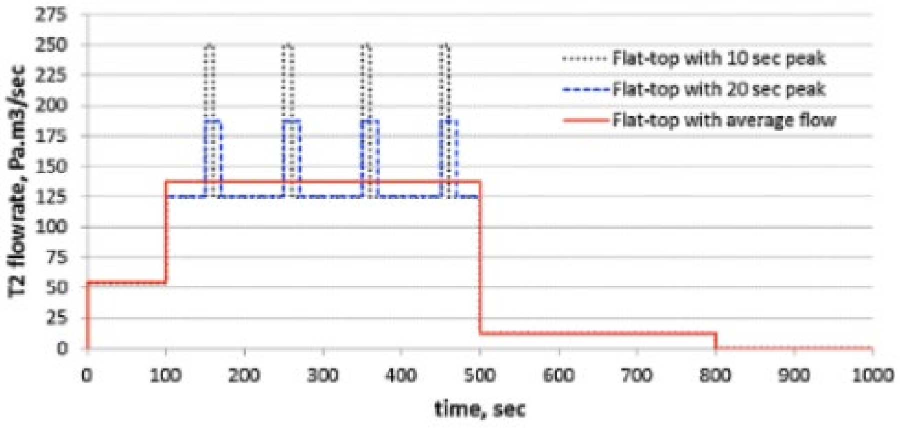


Fig. 2. Single T2 fuelling requirement for the inductive plasma operation.

Chang et al. Fus. Eng. Des. 98–99 (2015) 1733–1736

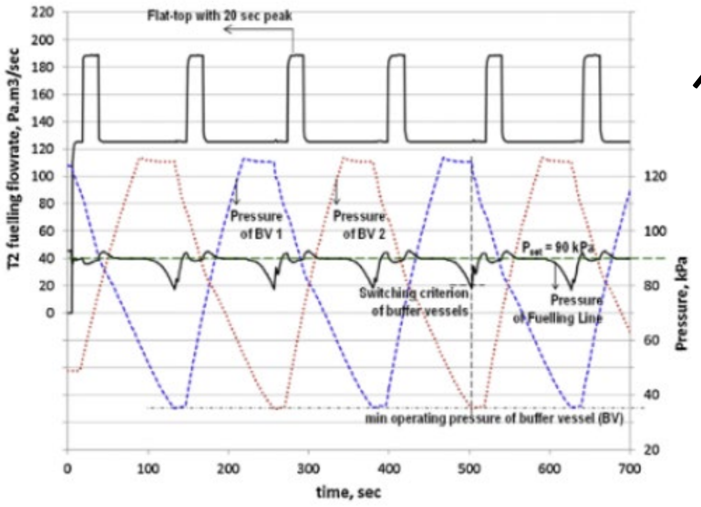


Fig. 5. T2 flat-top fuelling delivery experiment with 20 sec peak for the inductive plasma operation.

ITER

DEMO Fuelling – Current Understanding I

Gas Injection

- DT gas injected at the mid-plane area

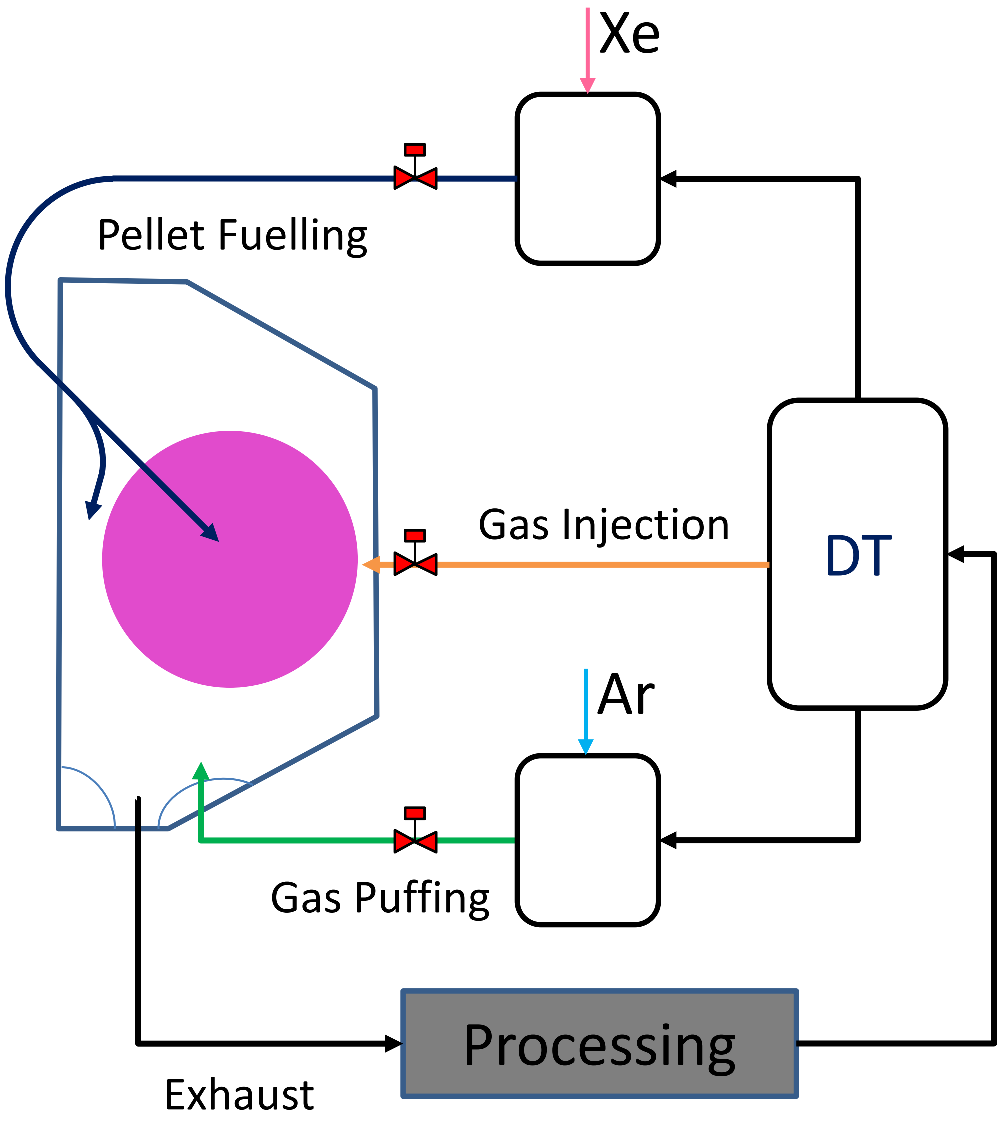
Gas Puffing

- DT + Ar gas injected at the divertor

Pellet Fuelling

- Frozen DT + Xe pellets injected at high speed into the plasma core

Fuelling time traces?



DEMO Fuelling - Current Understanding II

Flat Top (t_{FT} =7200 s):

- Pellet Fuelling 380 Pa m³/s
  - Core fuelling [10 – 50 Pa m³/s]
  - Fuelling & SOL losses [150 – 330 Pa m³/s]
- Gas Puffing 50 Pa m³/s
  - Detachment control

Dwell Phase (t_{Dwell} = 600 s):

- No fuelling
  - But: Outgassing of DT, H, Impurities

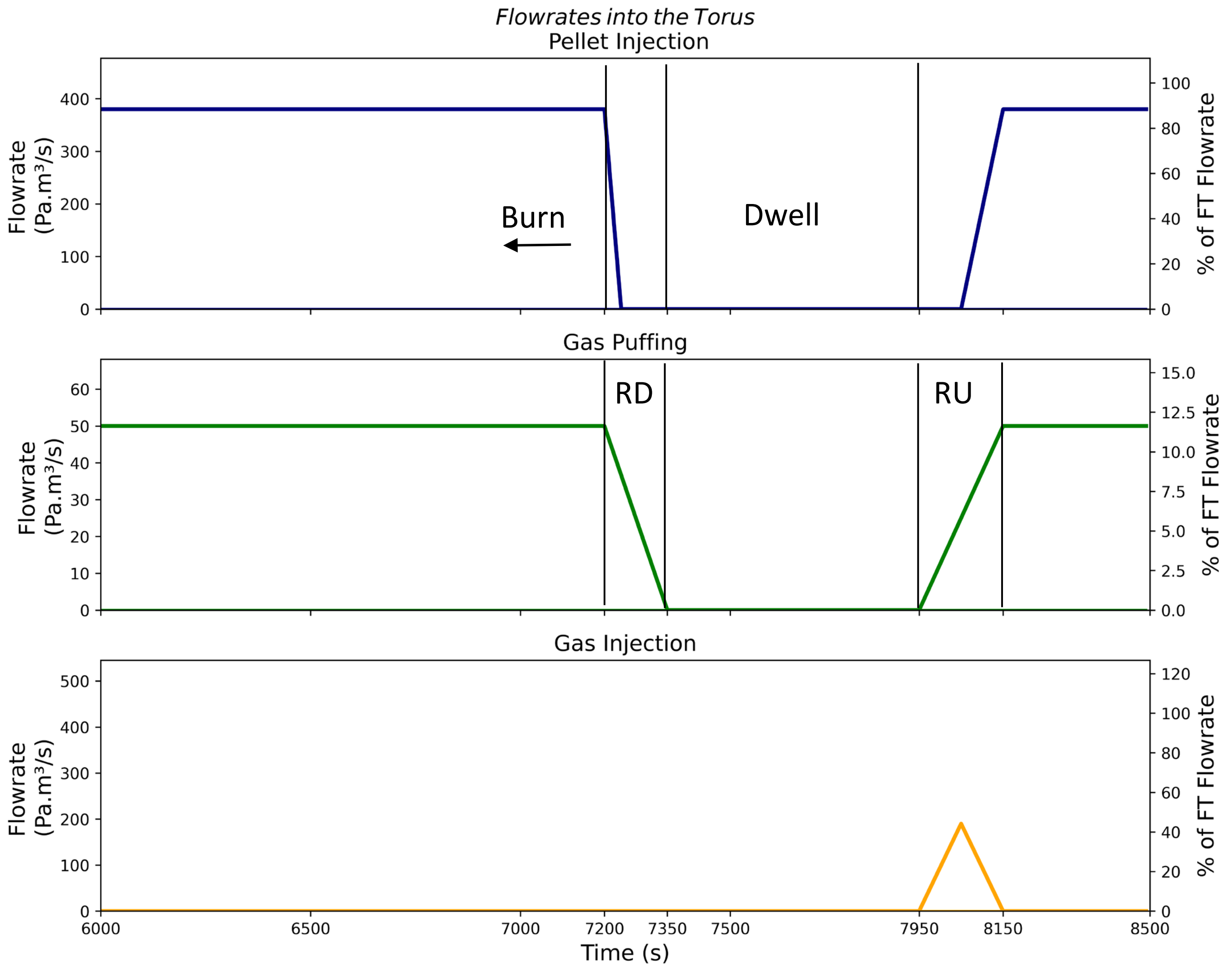
Ramp-Up (t_{RU} = 200s):

- DT is injected into the machine
- Gas puffing is ramped up
- Pellet fuelling is engaged once gas injection becomes insufficient

Ramp-Down: (t_{RD}= 150 s):

- All active fuelling contributions are slowly disengaged

$\sum t$ = 8150 s $\sum F_{FT}$= 430 Pa m³/s



Results: Dwell Phase Pressure

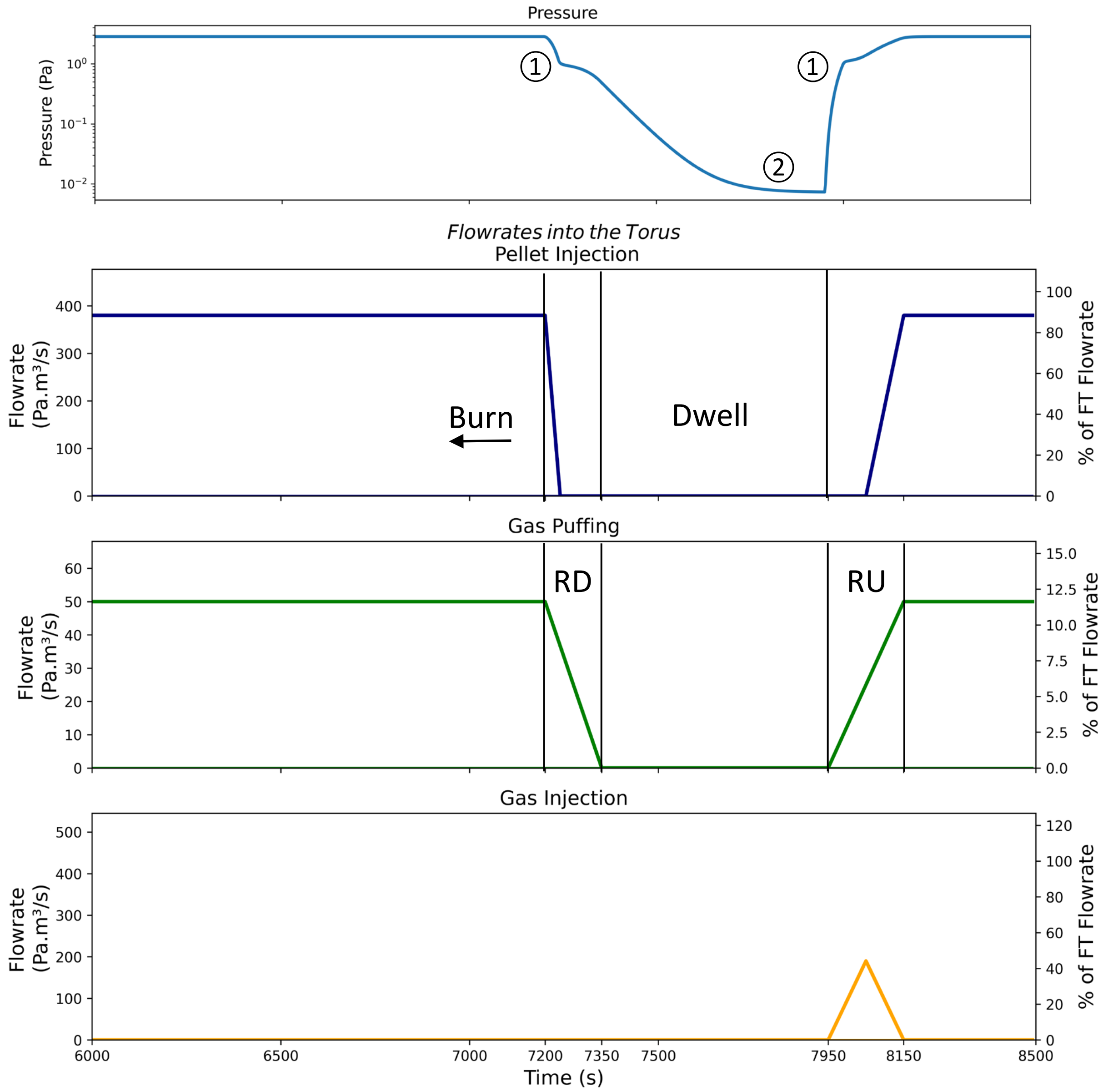
- The pressure at the sub-divertor governs the exhaust flowrate

① Metal Foil Pump only operates above a given pressure limit

② Residual pressure converges to a steady state pressure determined by outgassing rates

Assumptions:

- 0.23 Pa m³/s Outgassing (99% DT 1% H2)
- Constant pumping speed of backing pumps
- Negligible ^{4}He production during RU/RD
- No plasma interactions considered



Results: Dwell Phase Residual Gas Composition

Exhaust gas composition during burn phase (atom%):

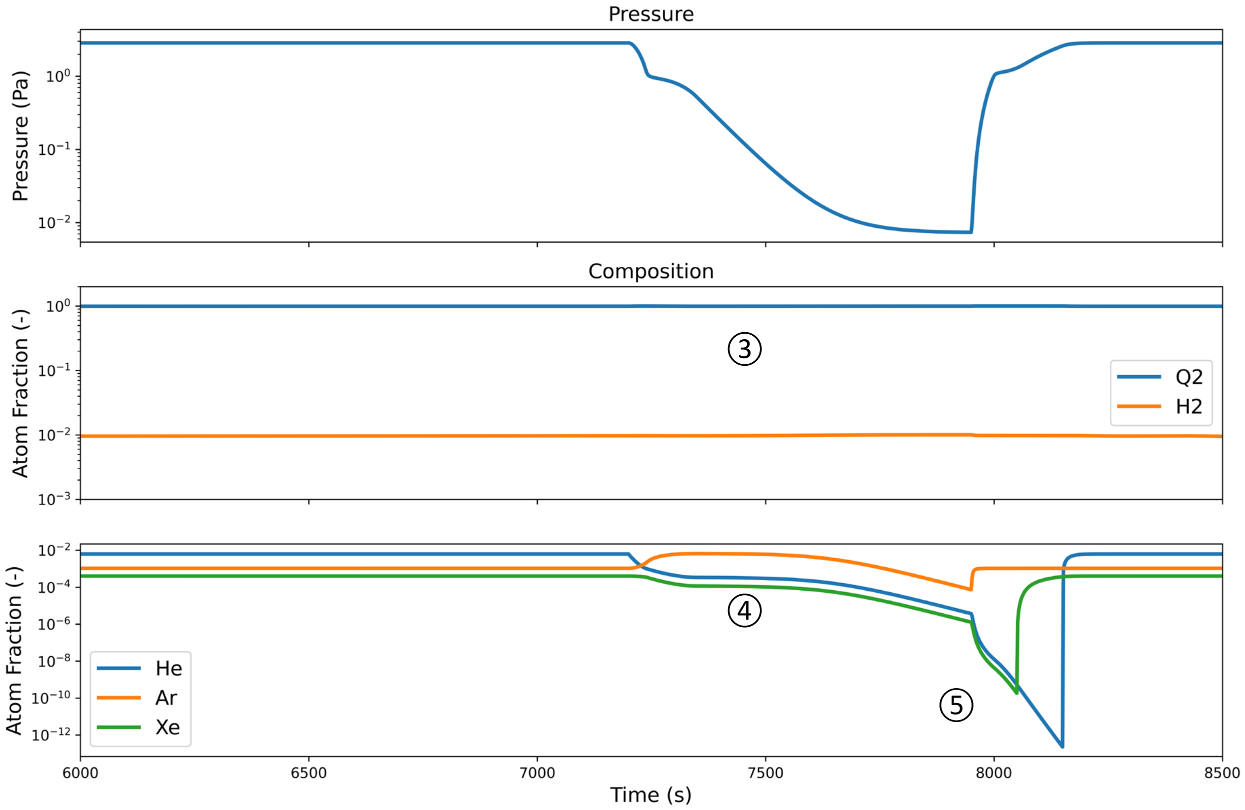
D	T	H	He	Xe	Ar
49.1%	49.1%	1%	0.6%	0.04%	0.1%

③ Residual gas species in dwell phase are pre-dominantly hydrogens (>99%)
④ Noble gas background drops to <0.01% during dwell (flushed out by outgassing)
⑤ He is purged out during ramp-up

Assumptions:

- 0.23 Pa m³/s Outgassing (99% DT 1% H2)
- Constant pumping speed of backing pumps
- Negligible ^{4}He production during RU/RD
- No plasma interactions considered

Dwell Phase Composition

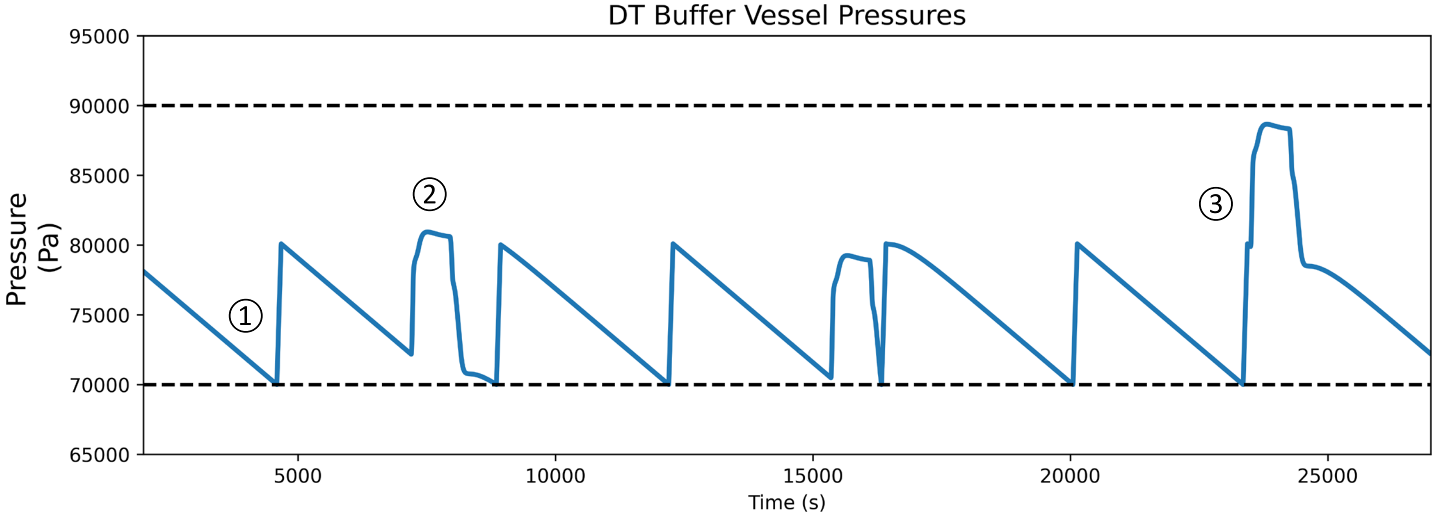


Results: Buffer Vessel Pressure

- The inner fuel cycle (DIRL + INTL) operates fully continuous (w/o hydride storage)

→ Pressure oscillations need to be buffered to allow stable operation of fuel composition control system

$$\Delta p V_{buffer} \geq \Delta p V_{PC}$$
$$\Delta p V_{PC} \approx 3Pa \cdot 6400\, m^3$$



① The vessel pressure slowly drops due to burn-up. Once the lower threshold is reached DT is replenished from storage.
② During burn/dwell cycling the buffer vessel pressure first increases and then drops again due to the changing fuel demand.
③ The buffer vessel needs to be sized large enough to not hit the upper pressure threshold even if recently filled up.

$$\rightarrow V_{buffer} \geq 1\, m^3$$

Conclusions & Outlook

- Inner fuel cycle transient behaviour governed by the plasma fuelling scheme
- Ramp-up and ramp-down fuel demand determine the fuel cycle dynamics
- Fully continuous operation possible

Detailed design and engineering of systems requires sound understanding of

- Fuelling transients
- Required control capabilities of fuelling systems

Thank You!
Questions?