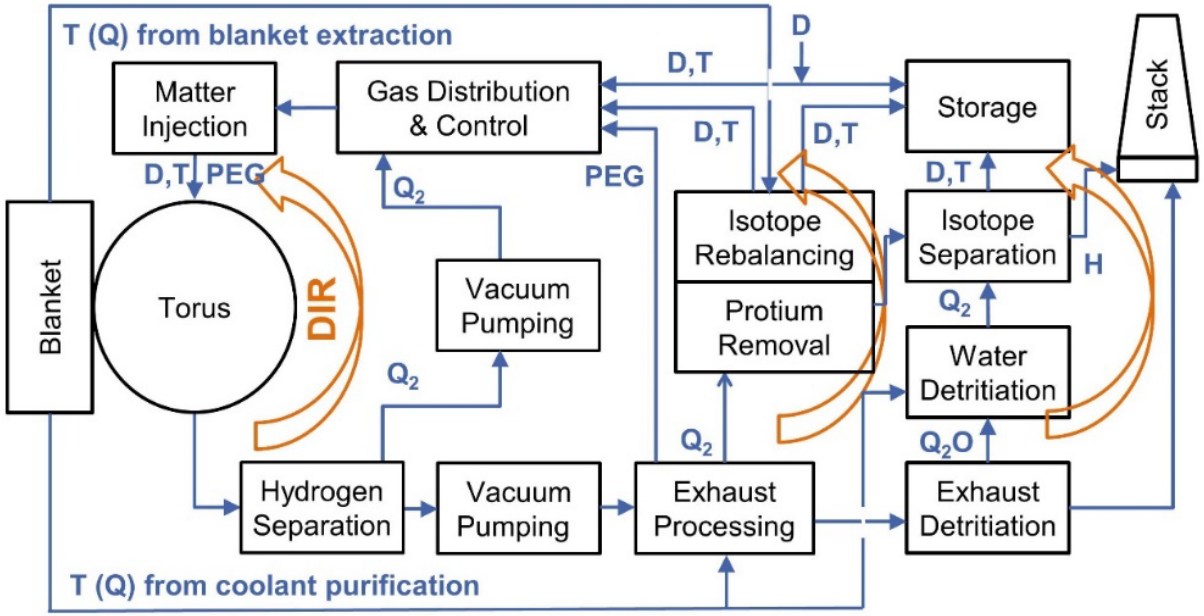
Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy

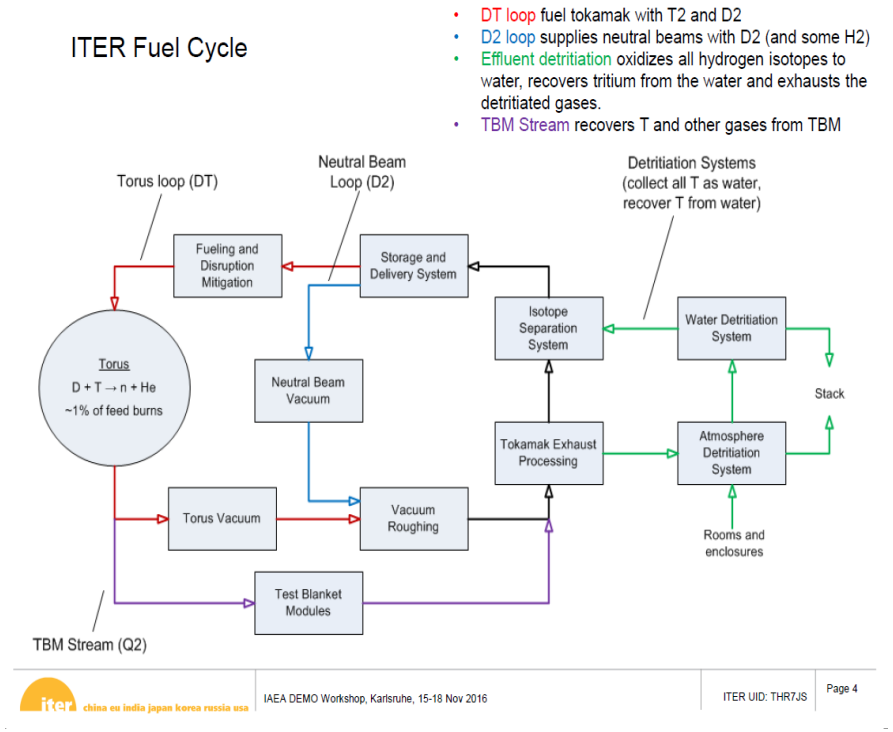
Oct 11 – 13, 2022
IAEA Headquarters
Europe/Vienna timezone

Enter your search term

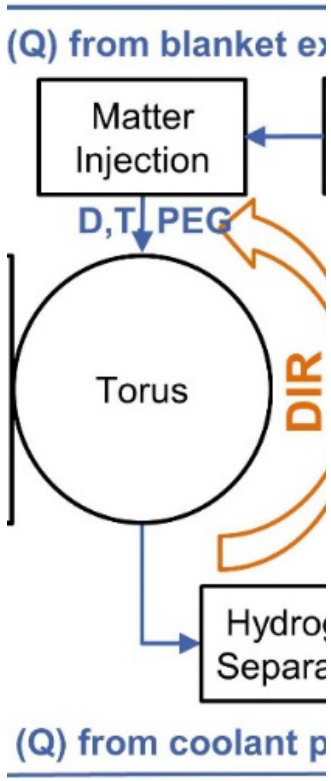
Day 2 of 3 - ITER and DEMO fuel cycles

Introduction Day 2



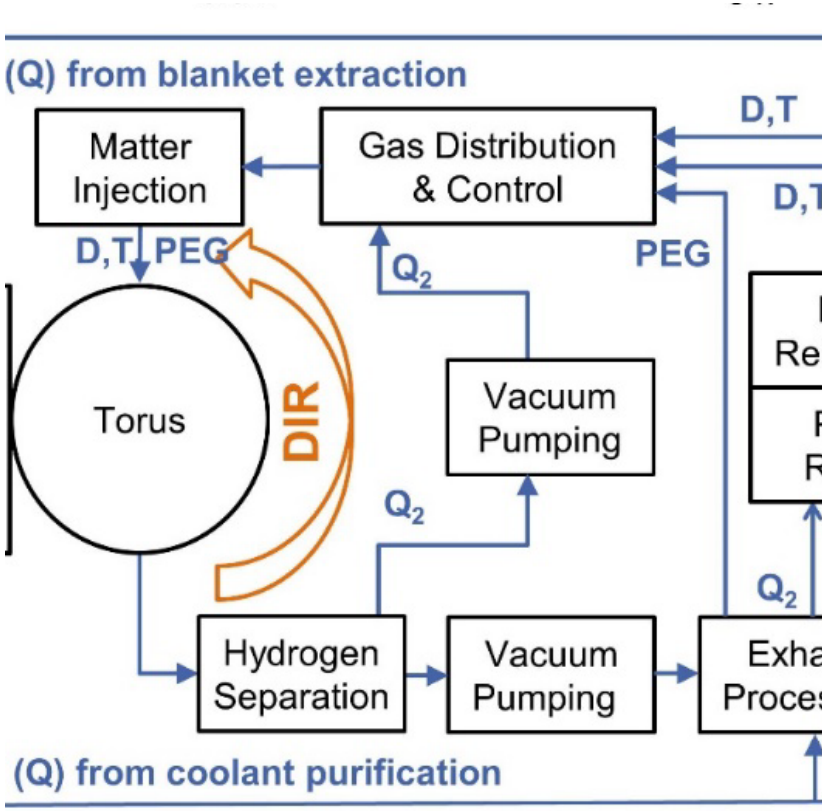


Introduction Day 2 – Recap of yesterday



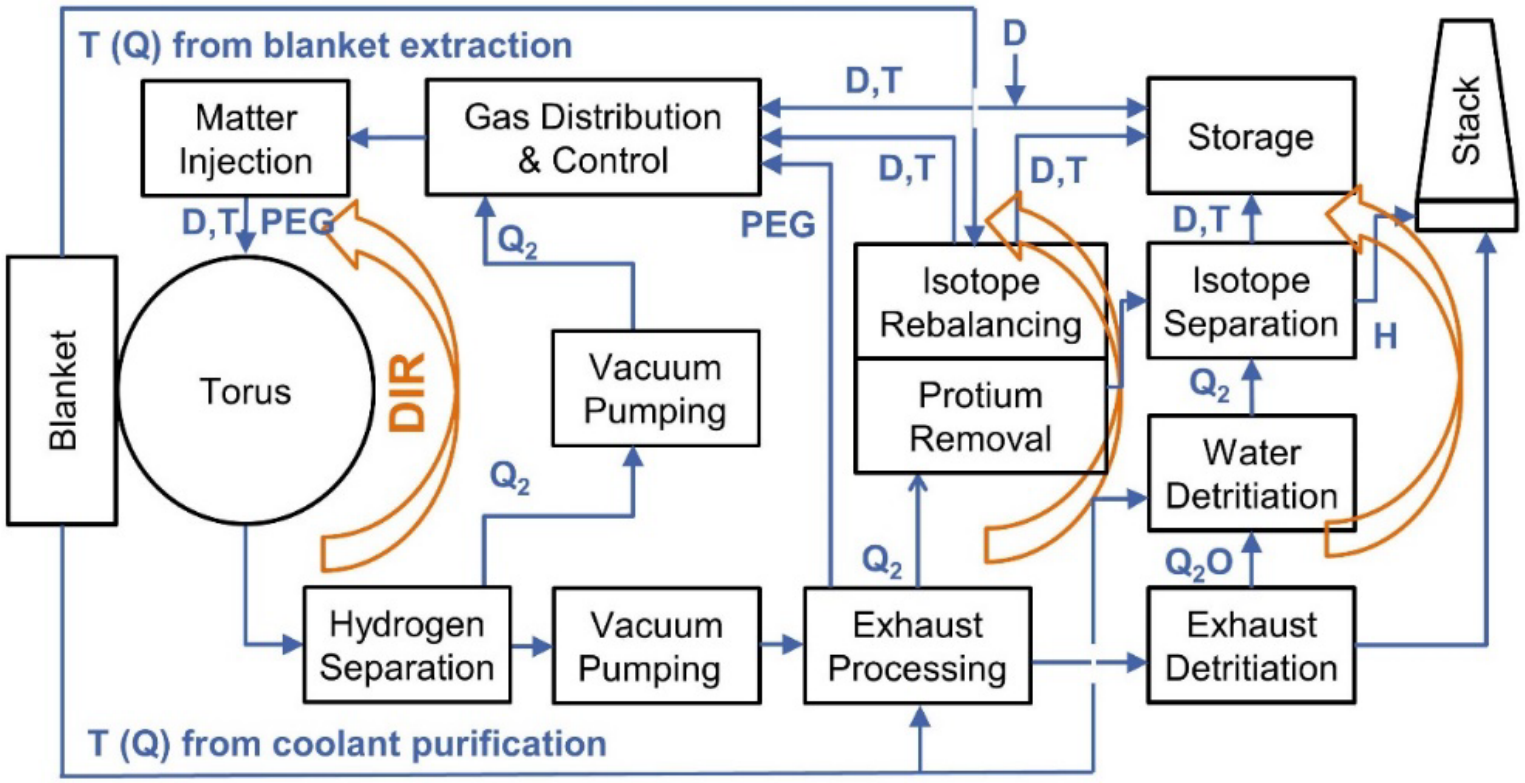
- Plasma needs in terms of
  - ….matter injection (fuelling, gas injection)
  - ….control (seeding)
  - ….exhaust (He exhaust)
- Plasma wall interaction and consequential build up of a residual tritium inventory
  - ….how to control
  - … how to get rid
- How to reduce throughput

Introduction Day 2 - Today



- 3 talks on DEMO
  - Overview
  - Fuelling
  - Pumping
- 2 talks on ITER
  - Overview
  - NBI
  - ELM pacing and disruption mitigation
- 1 talk on DEMO + ITER
  - Safety

Introduction Day 2 – Forecast Day 3



- View on tritium all over the place, including outer systems

Introduction Day 2 – Poster session

This paper presents an introduction to the key considerations stemming from physics decisions that impact the design

25. A Proposed Cryogenic Solution for Direct Internal Recycling
Dr Trey Gebhart (Oak Ridge Na
10/12/22, 1:40 PM
Interface btw Plasma Ph... Contr
Future deuterium-tritium fuele
closed loop fuel cycle. The DT
is to provide fuel to the plasm

5. Actuators for plasma c
Dr Thomas Giegerich (Karlsr
10/12/22, 1:40 PM
Interface btw Plasma Bu... Contr
The fuel cycle of the European
(DIRL) and the Inner Tritium Pl
act as actuators on the plasm

16. Assessment of fuel p
Juri IGITKHANOV (Karlsruhe I
10/12/22, 1:40 PM
Interface btw Plasma Bu... Contr
The minimization of the Fuel C
Recycling (DIR) concept by ad
systems [1]. The Fuel Cycle wi

18. Canadian Developme

18. Canadian Developments on Tritium Fuel Cycles for Fusion Energy
Stephen Strikwerda (CNL)
10/12/22, 1:40 PM
Interface btw Plasma Ph... Contributed Poster Posters
Since the beginning of the nuclear era, Canada has been a
CANDU nuclear power stations use deuterium oxide to ena
requiring the development of deuterium oxide production a

8. Current R&D Activities on Process Simulation f
Dr Jae-Uk Lee (Korea Institute of Fu...
10/12/22, 1:40 PM
Interface btw Plasma Ph... Contributed Poster Posters
Recently, as many countries are developing their demonstr
Korean-style demonstration fusion plant. For the fuel cycle
essential problem to be solved. Several activities related to

7. Experimental simulation and technological sol
Dr Teresa Beone (RINA Consulting - C...
10/12/22, 1:40 PM
Interface btw First Wall ... Contributed Poster Posters
Significant production of radioactive metal dust, mainly du
present in the vacuum vessel of DEMO while it is operating
dust. Therefore, the removal of tritium and the managemer

10. Impact of DEMO plasma operating phase on
Vincenzo Narcisi (ENEA)
10/12/22, 1:40 PM
Interface btw Plasma Ph... Contributed Poster Posters
Tritium permeation from Breeding Blanket (BB) towards Pr

1. Release of tritium from the Large Helical Device in the mid-term deuterium plasma experiment
Masahiro Tanaka (National Institute fo...
10/12/22, 1:40 PM
Interface btw First Wall ... Contributed Poster Posters
When a plasma experiment using deuterium (D) gas is conducted in a large fusion test device, a small amount of tri
is produced in the plasma. The produced tritium can be used to evaluate tritium behavior and inventory in fusion sys
as a tracer because of its small amount. As one of the large fusion test devices, the deuterium plasma experiment w

13. Self-consistent modelling of the interface between the divertor and the pumping system in DT
Christos Tantos (Karlsruhe Institute o...
10/12/22, 1:40 PM
Interface btw Plasma Ph... Contributed Poster Posters
DTT (Divertor Tokamak Test Facility) is a new facility, currently under build, in which various scaled experiments for
testing different magnetic configurations and alternative solutions for the power exhaust system of DEMO will be
performed. Although the divertor system is not finalized yet, the machine and port geometry set limitations on the

27. The DRGA as a burning plasma-compatible diagnostic system for time resolved monitoring o
core plasma, fuel-cycle processes
Christopher Klepper (Oak Ridge National ...
10/12/22, 1:40 PM
Interface btw Plasma Ph... Contributed Poster Posters
The Diagnostic Residual Gas Analyzer (DRGA), an integrated, multi-sensor diagnostic system, will access and samp
ITER sub-divertor region, in the ducts of the cryogenic pumps, out-of-site of the main plasma chamber. It will deliver
resolved neutral gas composition measurements directly related to fuel cycle processes in the core plasma, in plasm

26. Pellet ELM Pacing and Disruption Mitigation Impacts on the Fusion Fuel Cycle
Dr Larry Baylor (ORNL)

EUROfusion

Deuterium-Tritium Fuel Cycle – Overview and DEMO objectives

Christian Day

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

11 – 13 Oct. 2022

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

- Requirements
- Basic concept of a three-loop architecture
- Plasma physics and technology interface considerations
  - Fuelling efficiency
  - Total machine gas throughput
  - Matter injection
  - PEG activation
  - Particle exhaust
  - Protium removal

The event aims to review and discuss – in an integrated manner – plasma physics and technology aspects of the tritium fuel cycle in magnetic fusion reactors

EU-DEMO High Level Requirements

- Stakeholder ´requirements´ for the DEMO plant – DEMO plant shall…
  - ….adopt a tokamak architecture.
  - ….minimise its capital cost (CapEx and OpEx).
  - ….enable the extrapolation of key performance criteria for a FPP (DEMO must provide a solid basis, also in terms of the technologies involved).
  - ….during operation be able to export 300-500 MW electrical power to a national grid, continuously for a minimum period of 2 hours.
  - ….achieve an overall Availability Factor of at least 30%, between commissioning and decommissioning.
  - …be designed for an acceptable decommissioning cost and duration.
- Stakeholder ´requirements´ for the fuel cycle – DEMO plant shall….
  - ….breed tritium over and above that required for its Planne
    provide sufficient tritium to start up another plant.
  - ….ensure that it does not exceed its licensed tritium invento
  - ….provide a safe confinement of source terms (not require the evacuati
    members of the public under any event, ALARA).

Tritium self-sufficiency

Tritium inventory reduction

Tritium safety

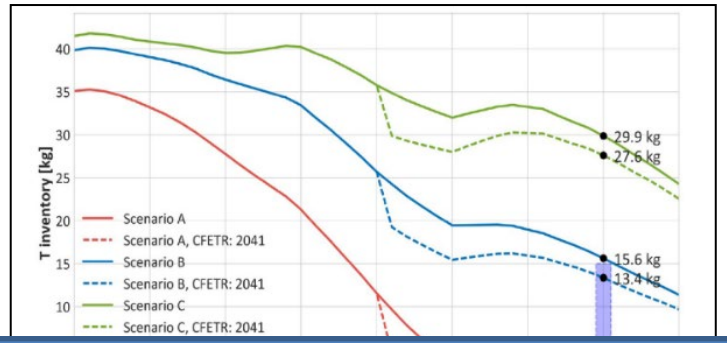
Implications

- Technology feasibility and viability:
  - Unit operations in the fuel cycle must work reliably (RAMI)….
  - …even when extrapolated (system sizing) to the DEMO→FPP level

´not 1 Mio m² membrane surface´

´not 1000 stages per distillation column´

- Allow start-up and licensing:
  - Tritium is a precious good, and availability gets critical
  - Safety and Licensing forces to reduce to a minimum
  - Accountancy needs



- Economic attractiveness:
  - CapEx vs OpEx
  - ´Durability´ of the components (in-vessel) and materia maintenance (Reliability growth)

DEMO is only repeating always the same plasma…and will provide operational flexibility only if clearly needed, e.g. for control

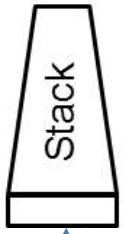
DEMO Fuel Cycle Holistic View

High level requirement

P_{fus} = 2 GW, Plasma scenario, core density
→ MATTER INJECTION SYSTEMS

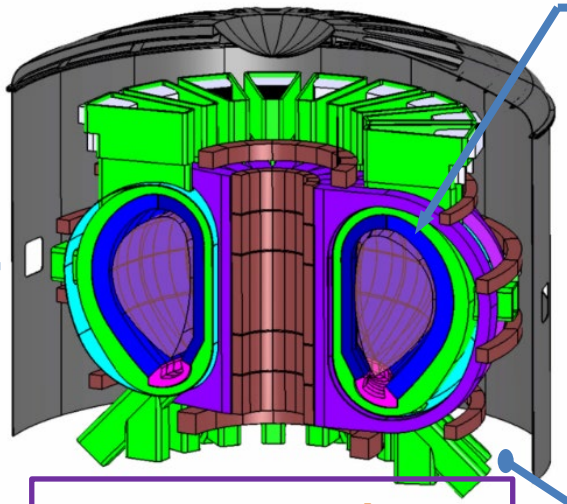
Working to design objectives as opposed to limits, ALARA [*DEMO PSRD*]

g-T/a level



BLANKET SYSTEMS

TBR>1,
320 g-T/
(full power d)

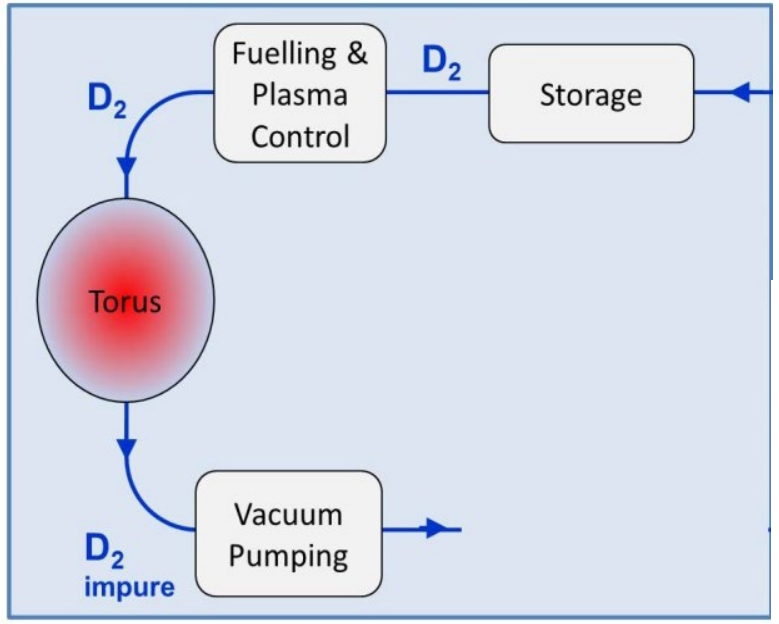


TRITIUM SYSTEMS

t_{Pulse}=2h, t_{dwell} → min
7.2 ·10^{20}/s He
→ VACUUM SYSTEMS

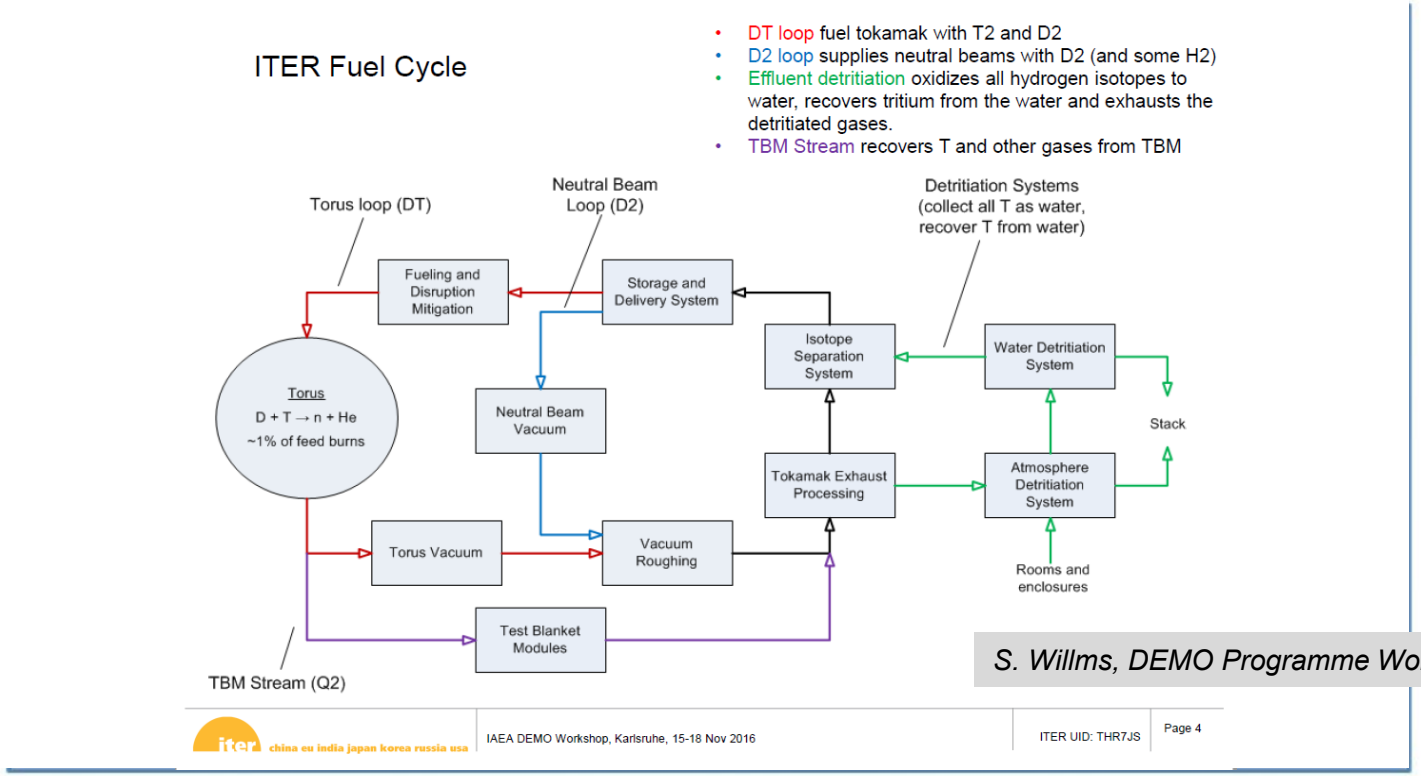
2.6 (5.2) ·10^{21}/s = 10 Pa·m³/s
Monatomic (diatomic)

The Fusion Fuel Cycle



Tritium in Fusion
TSTA (140 gT, 80s and 90s)
TFTR (some gT,-1997)
JET (some 10 gT, 90s -2023)
H3AT (2025?), STEP
SPARC (some gT, 2025?)
ITER (2035?, kgT level)

ITER // Fuel cycle not self sufficient



S. Willms, DEMO Programme Workshop, 2016.

Q=H/D/T; PEG=Plasma enhancement gas

Outline

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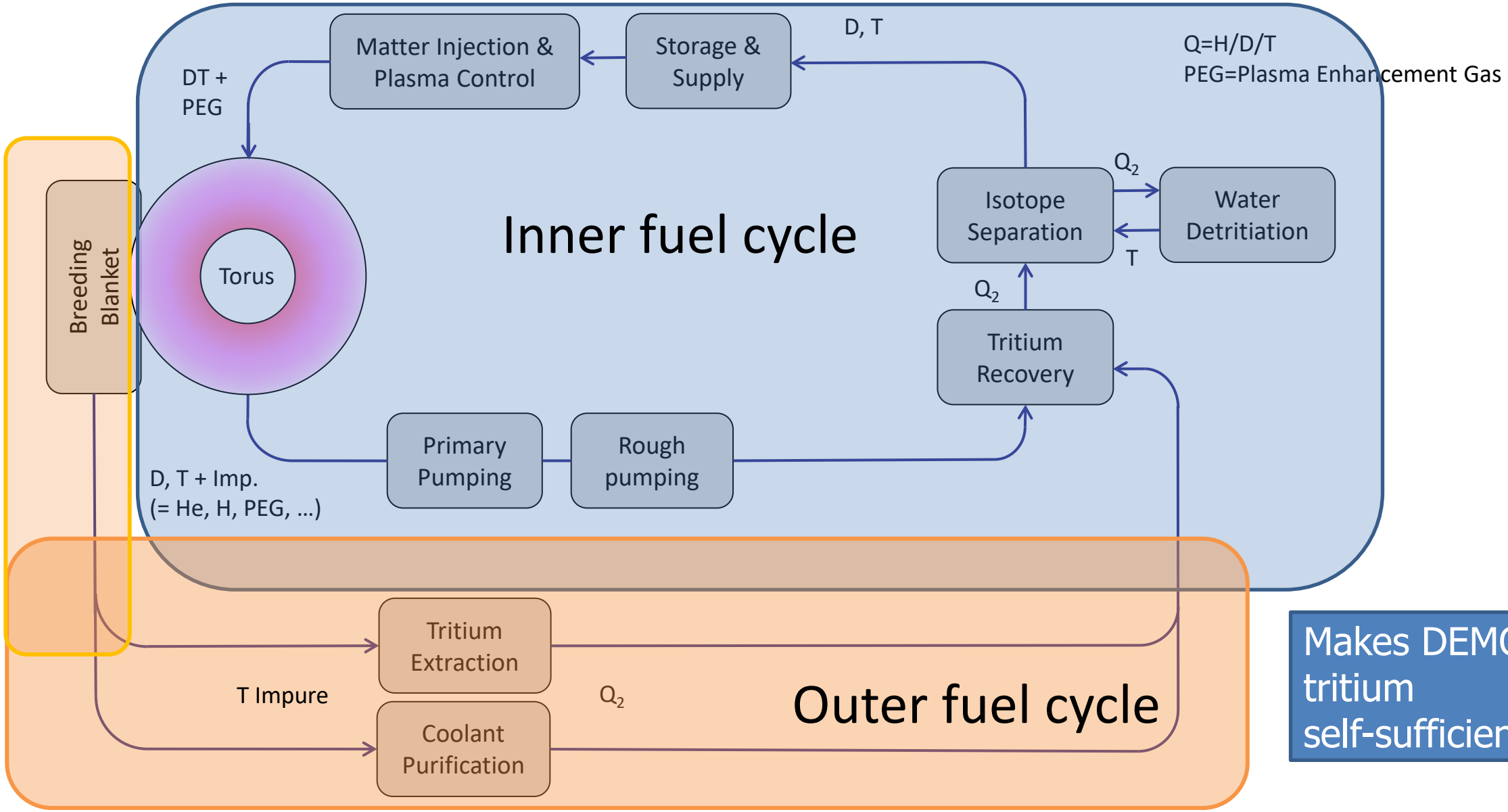
First Try – Scale-up from ITER + T-Breeding

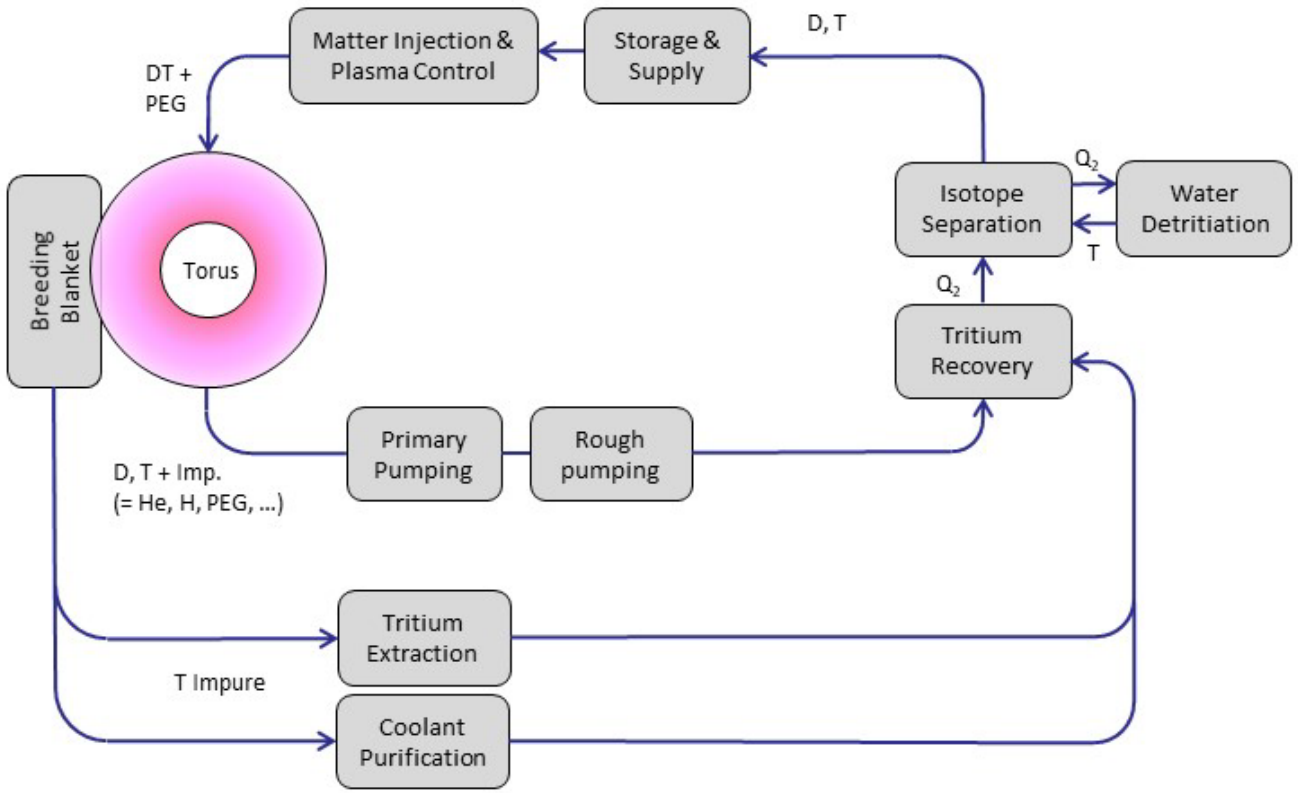


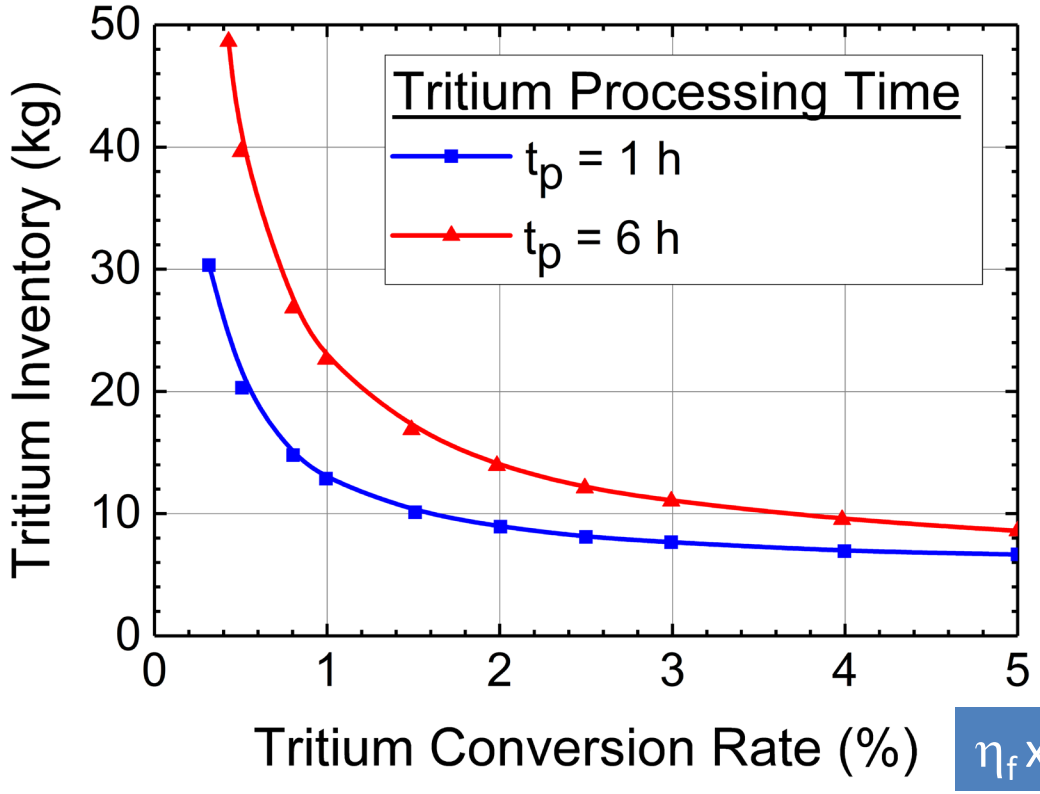
Makes DEMO tritium self-sufficient.

First Try – Scale-up from ITER + T-Breeding does not work

Chr. Day, Th. Giegerich, FED 88 (2013) 616.

M. Abdou et al., FED 100 (2015) 2



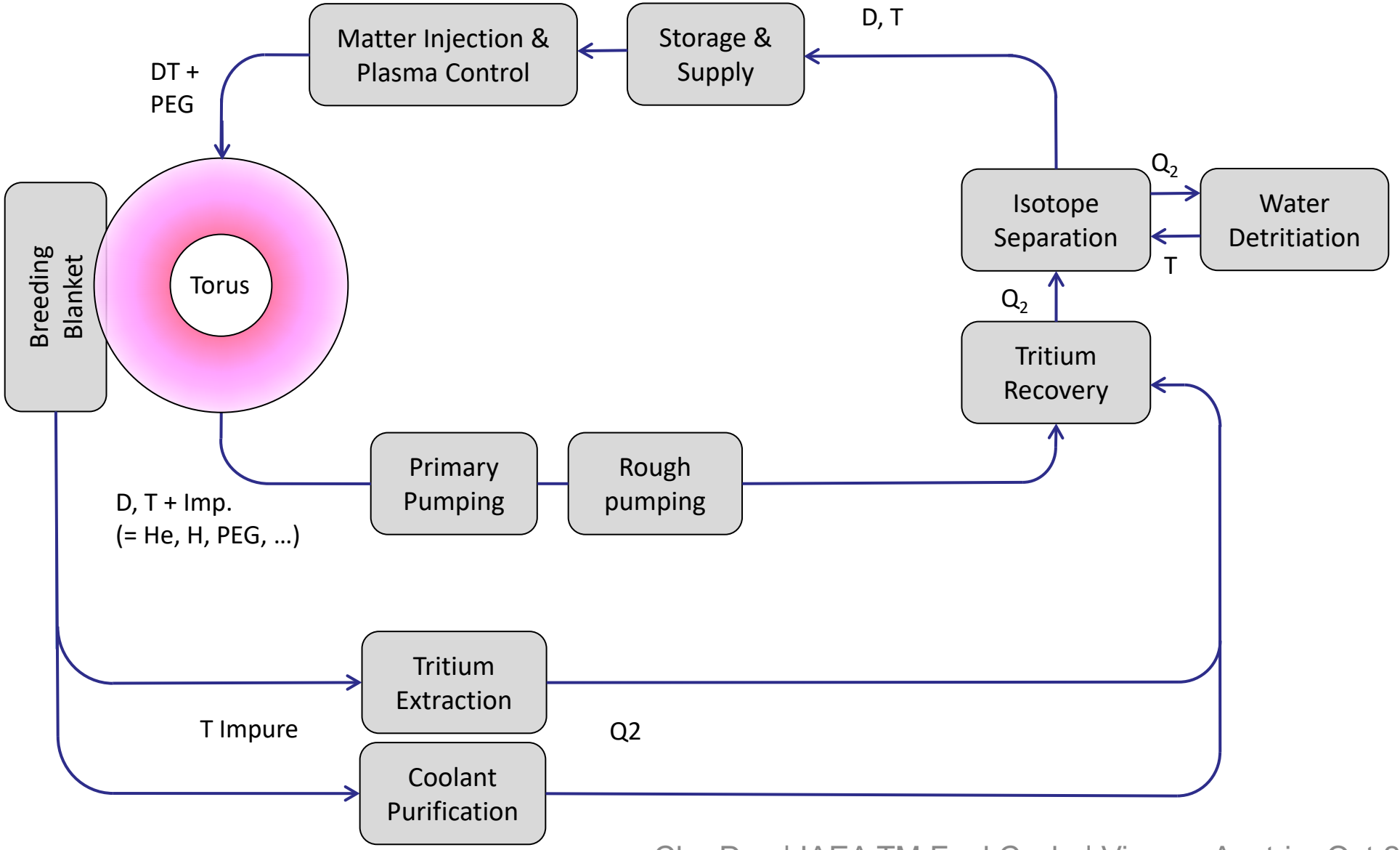


$\eta_f \times f_b$

(effective burn-up fraction x fuelling efficiency)

- Showstopper: Inventories are excessive for the achievable numbers of the tritium conversion rate (regulatory framework, tritium management and control)
- Approach: **Smart** architecture to reduce inventory.

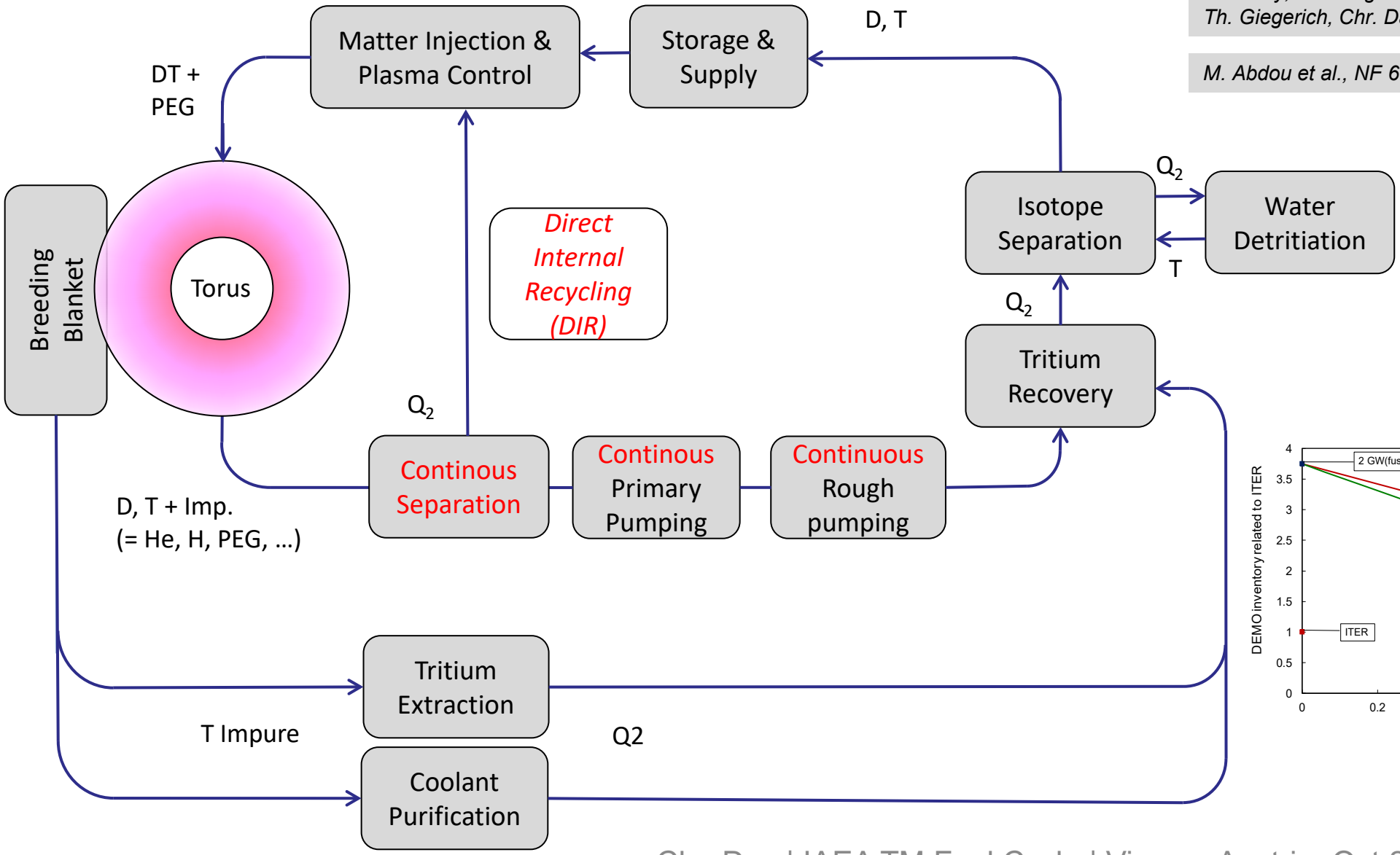
2nd Try – Make Architecture smart

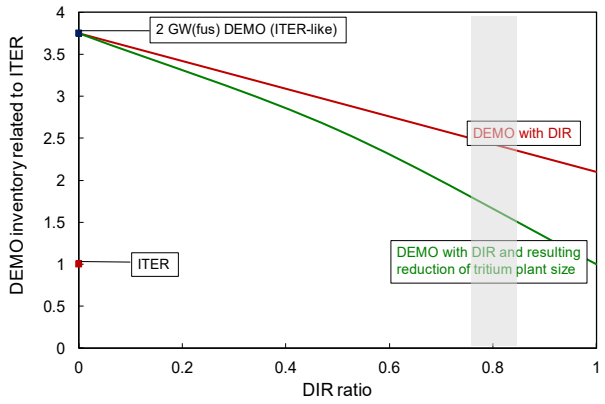


2nd Try – Make Architecture smart

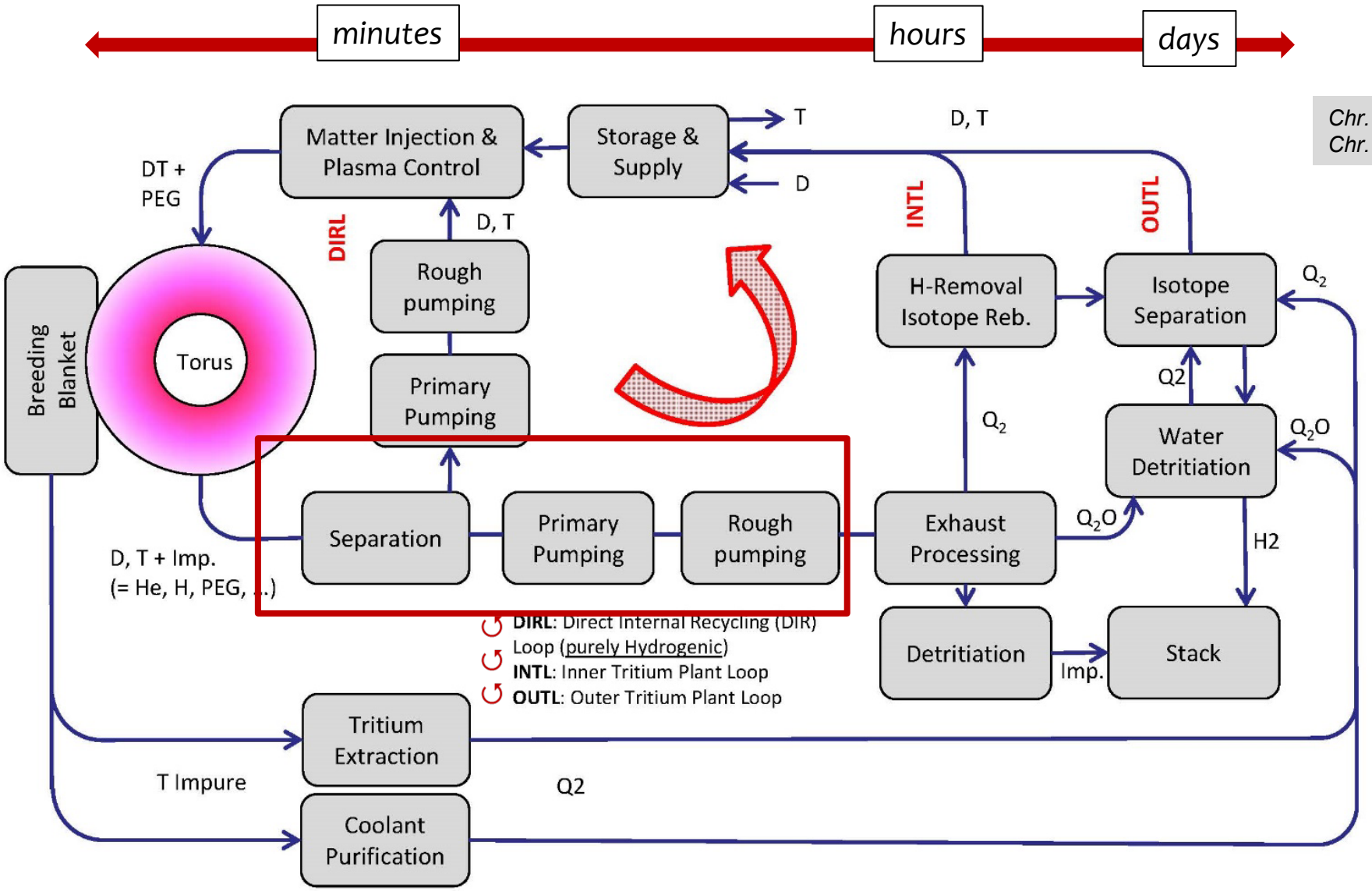
Chr. Day, Th. Giegerich, FED 88 (2013) 616.
Th. Giegerich, Chr. Day, FED 89 (2014) 1476.

M. Abdou et al., NF 61 (2021) 13001.



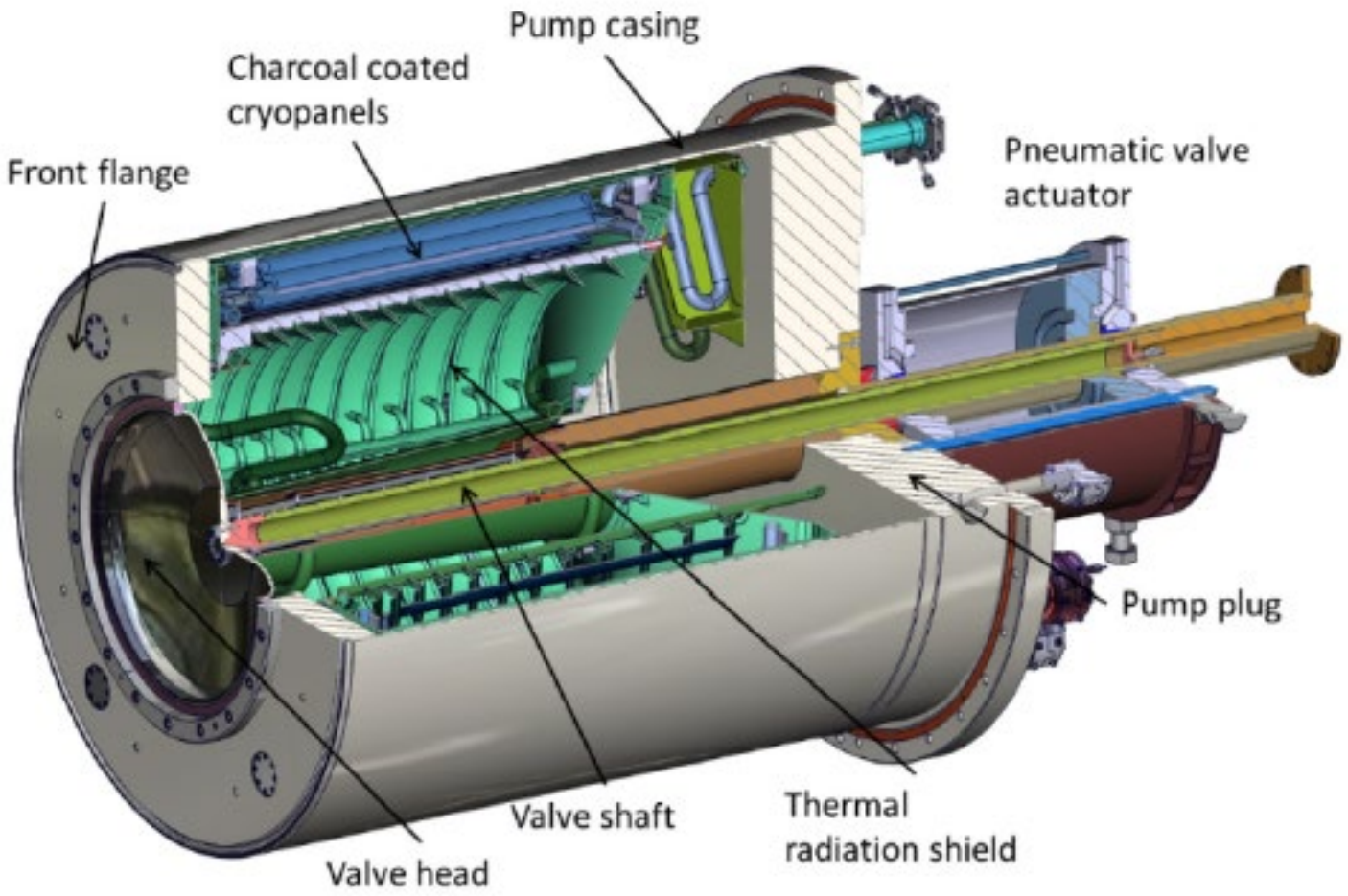


Three-Loop Architecture of the DEMO Fuel Cycle

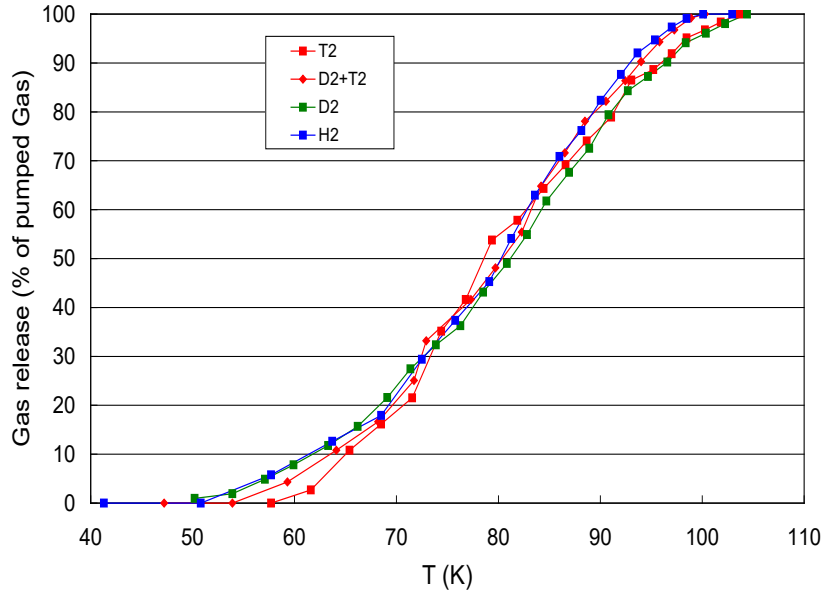


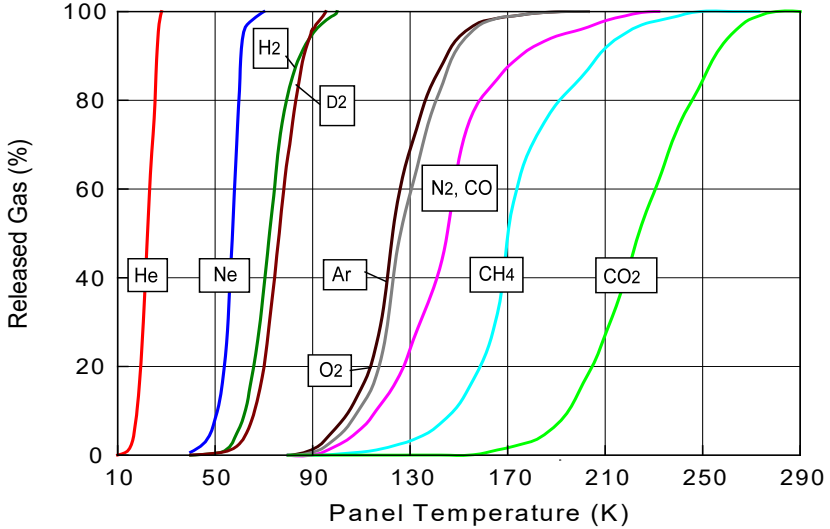
Chr. Day et al., FED 109 (2016) 299.
Chr. Day et al., FED 146 (2019) 2462.

The ITER Torus Cryopump



Chr. Day et al., FST 148 (2005) 29..





The ITER Torus Cryopump Operation Scheme

Cryopump operational pattern is determined by explosion safety considerations, not by saturation effects of the sorbent.

Pump No					3000 secondes																				
	77	78	79	80	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
18	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR
4	DP	DP	DP	DP	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR	WU	EV	CD	P	P	P	P	DP
6	DP	DP	DP	DP	P	P	P	P	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR	WU	EV	CD	DP
10	DP	DP	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR	WU	EV	CD	P	P	P	P	P	P	DP
12	DP	DP	DP	DP	P	P	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR	WU	EV	CD	P	P	DP
16	EV	CD	DP	DP	P	P	P	P	P	P	HR	WU	EV	CD	P	P	P	P	P	P	P	P	HR	WU	EV
-					150 s																				

Staggering interval of 150 s

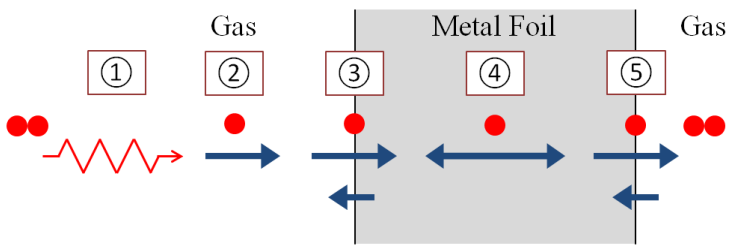
P – Plasma Exhaust Pumping
HR – Helium Recovery + contingency
EV – Evacuation
WU –Warm Up
CD – Cool Down
DP – Dwell Pumping

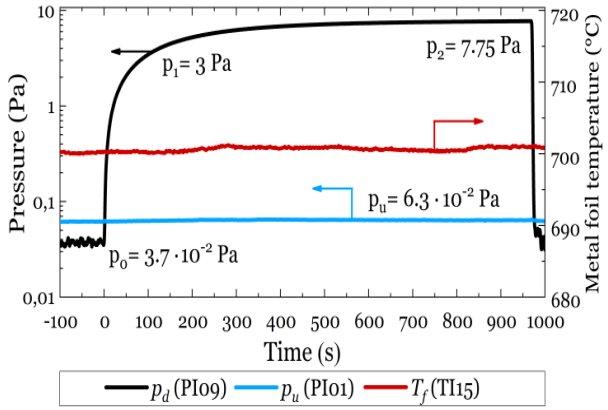
With this trick a quasi continuous pumping speed is provided with batch regenerating cryopumps, however, at a constant inventory.

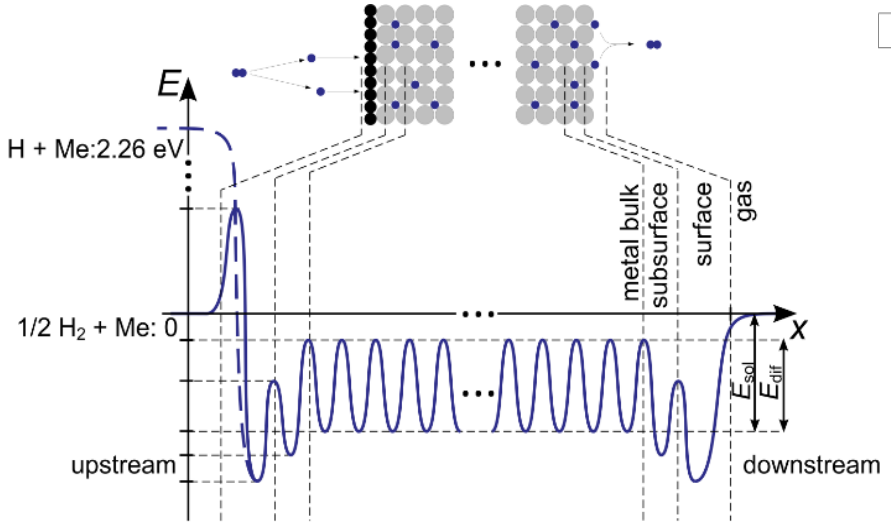
Concepts for Fuel Separation at Low Density

Superpermeation

A.I. Livshits et al., J. Nucl. Mat 170 (1990) 79.
S. Hanke et al., FED 161 (2020) 111890..





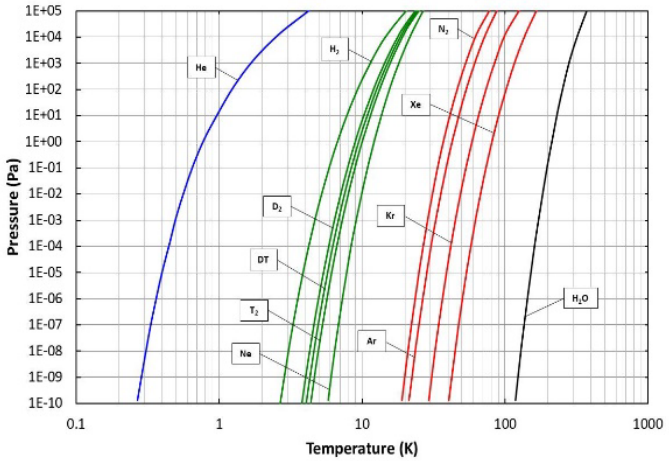


SUPERPERMEATION
Driving force:
Energetic flux

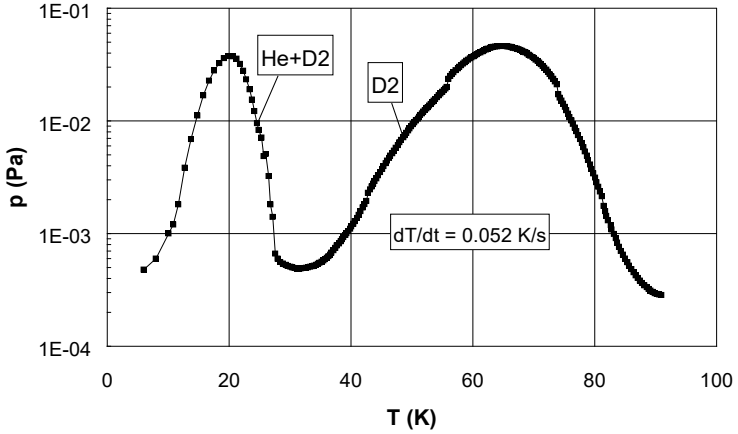
CLASSICAL PERMEATION
Driving force:
Pressure gradient

Cryogenic Pumping

Gas → condensed

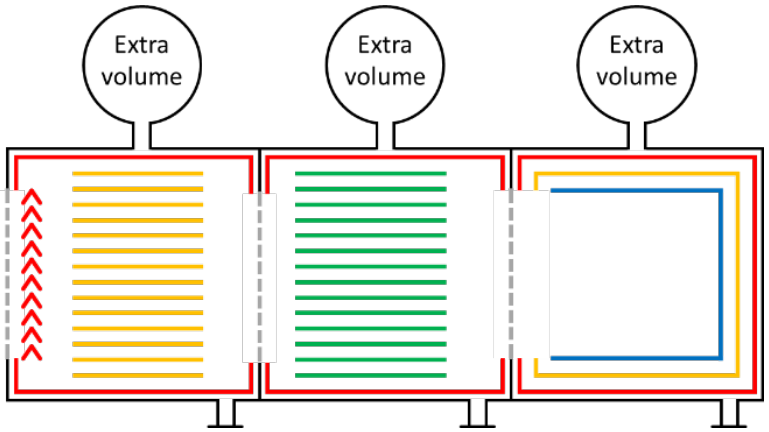


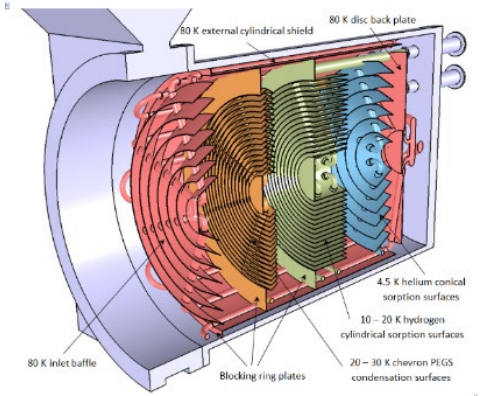
Re-adsorbed → gas

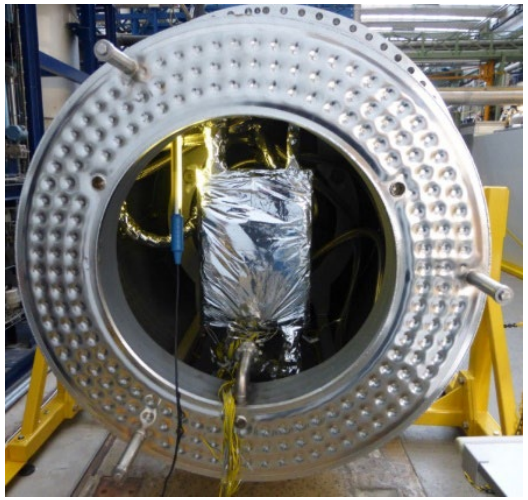


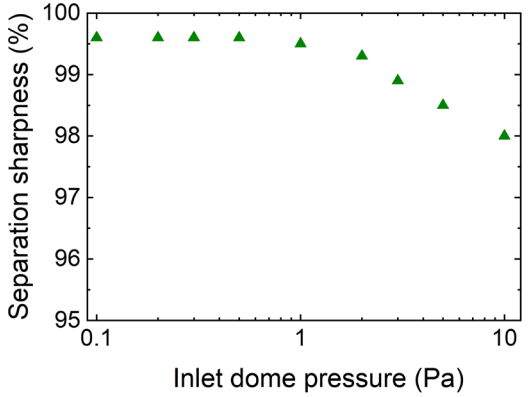
The Multi-stage Cryopump

- Multi-stage concept allows for pumping different gas species at different surfaces :
  - PEGs (Plasma Enhancement Gases) condensation stage (20 – 30 K)
  - Hydrogen sorption stage (unknown, but intermediate temperature)
  - He sorption stage (< 5 K)
  - + Inlet baffle and thermal shield (80 K) for thermal radiation heat load reduction and pumping of heavy gas impurities



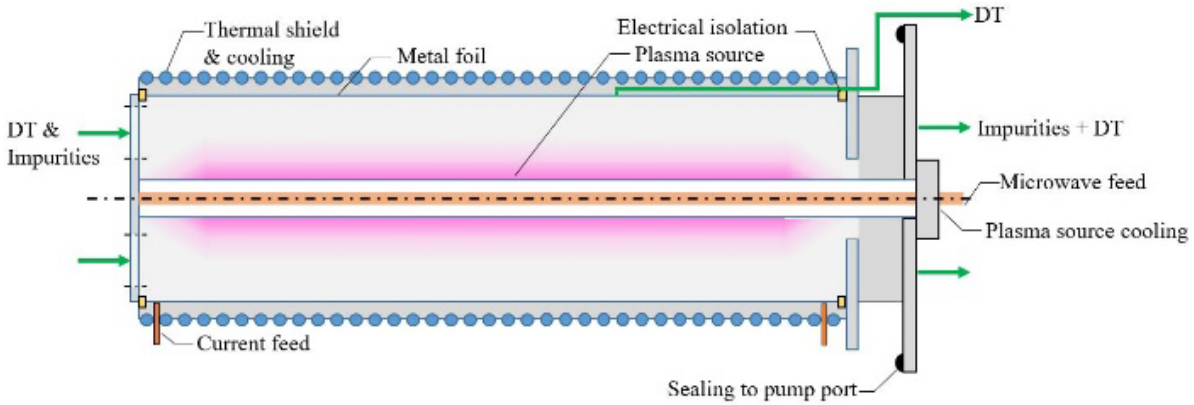


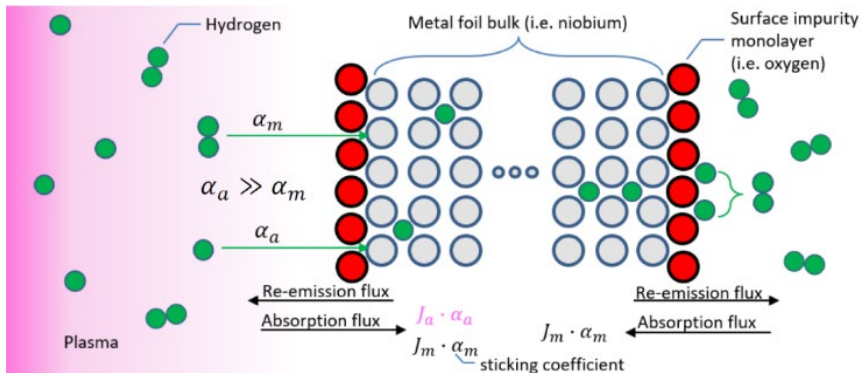


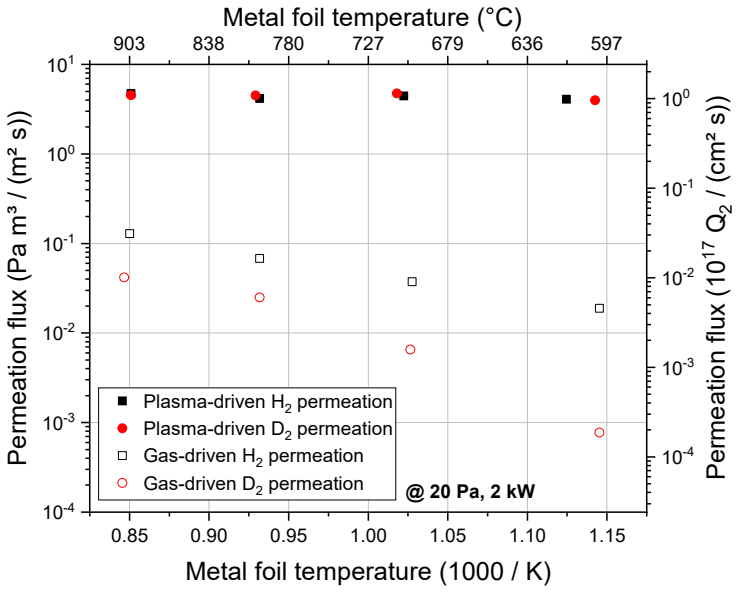


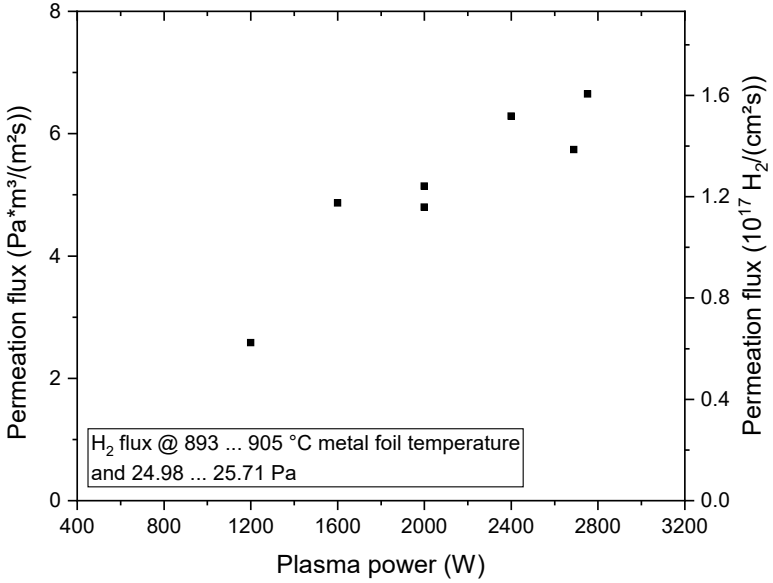
M. Scannapiego, Chr. Day, IOP Conf. Series 278 (2017) 012160.

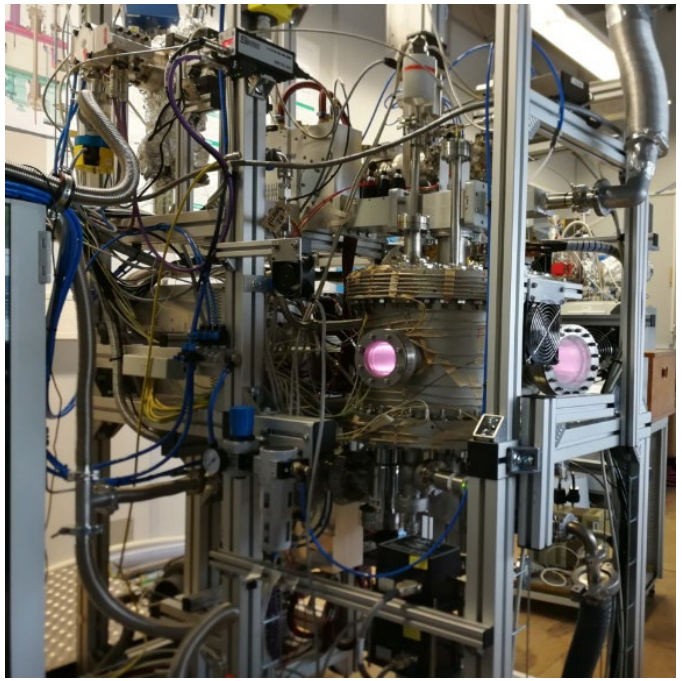
The Metal Foil Pump



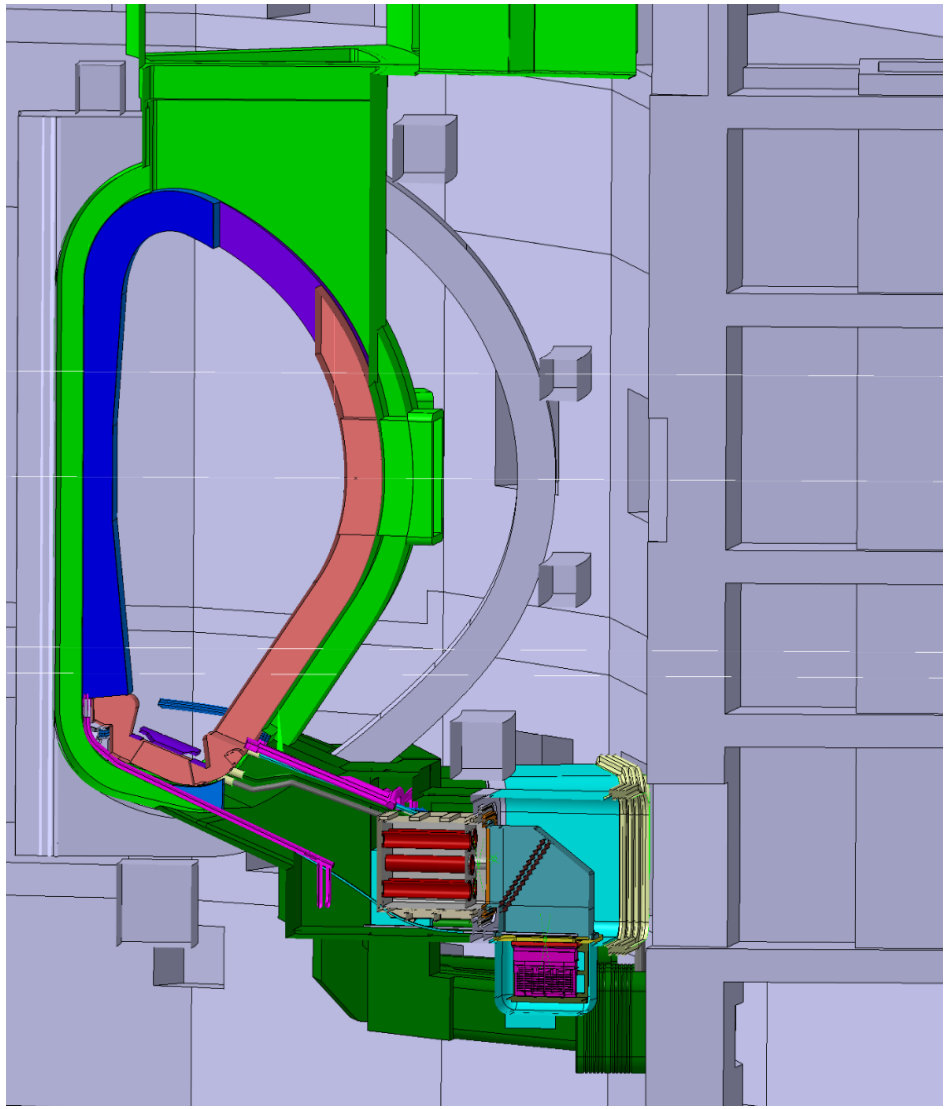




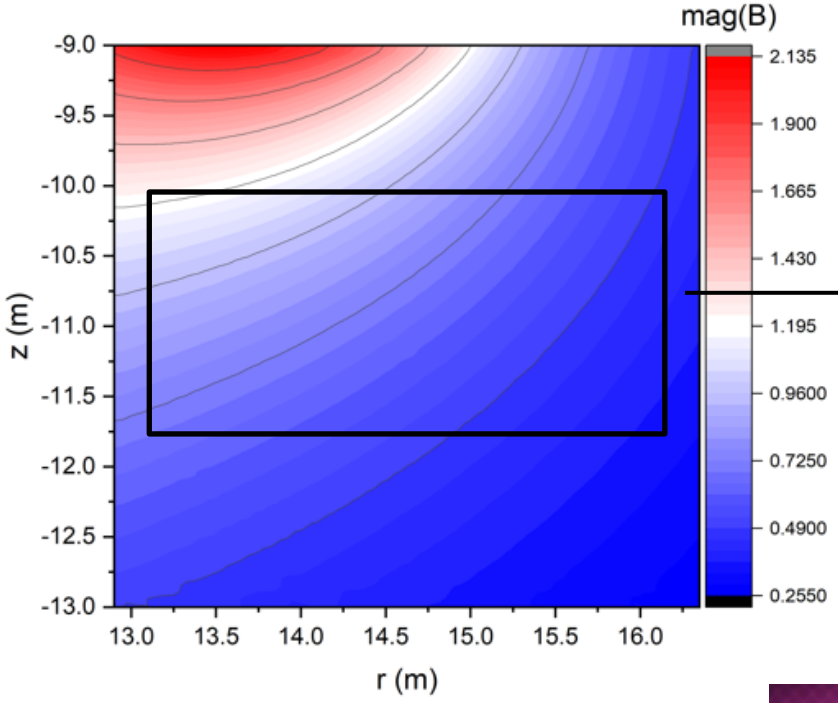




Integration and Magnetic Field

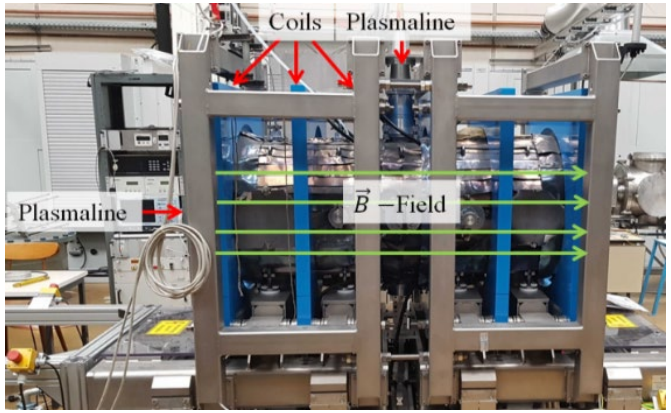


Y. Kathage et al., SOFT 2022.



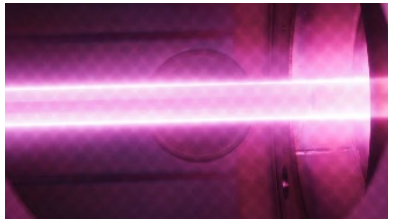
Approximate MFP Location:

- ~ 1.2 T max
- ~ 0.4 T min
- B-field gradient mostly parallel to pump duct



10 Pa

3 kW, no B

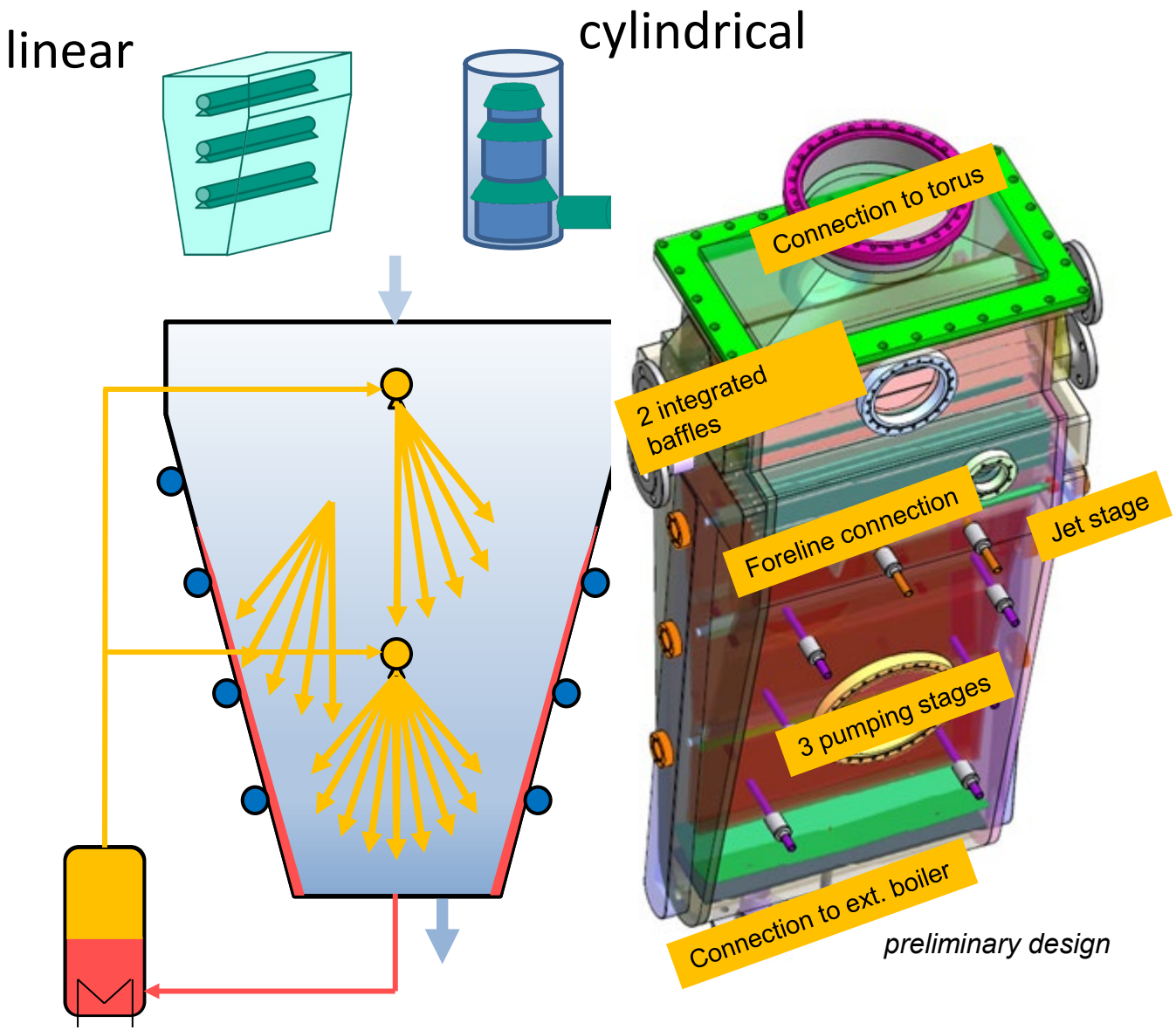


3 kW,
B=250 mT ll

Continuous Vacuum Pumping – First Stage

- **Principle:** momentum transfer from mercury vapour to pumped gas
- Evaporate mercury in boiler, accelerate vapor by expansion through nozzle in pumping direction, transfer momentum by gas-vapor collision.

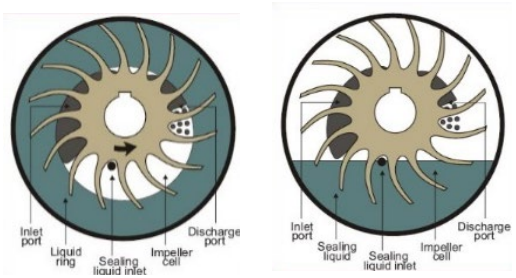
- Decision in favour of mercury requires to understand
  - performance,
  - operation and handling, incl. workers´ safety,
  - legal implications,
  - waste implications.



Continuous Vacuum Pumping – Roughing Stage

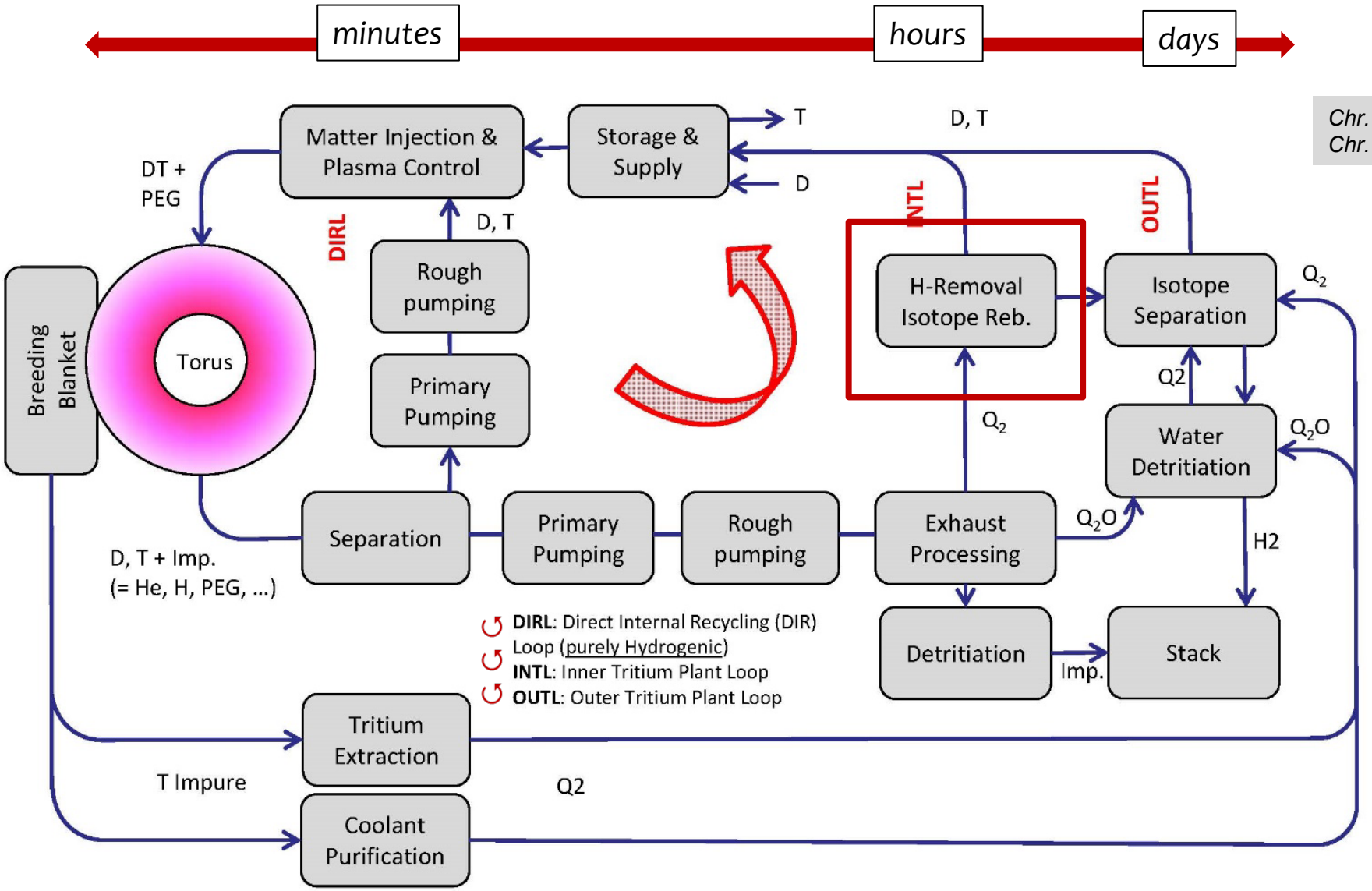
T. Giegerich et al., FED 109-111 (2016) 359..

- Commercial liquid ring pumps known to have excellent reliability
- A full stainless-steel liquid ring pump with liquid metal (mercury) as working fluid developed, manufactured and installed at KIT
- The first pump-down curve with a mercury ring pump ever was measured in Dec 2013.
- Now we are in the second pump generation, stable performance.



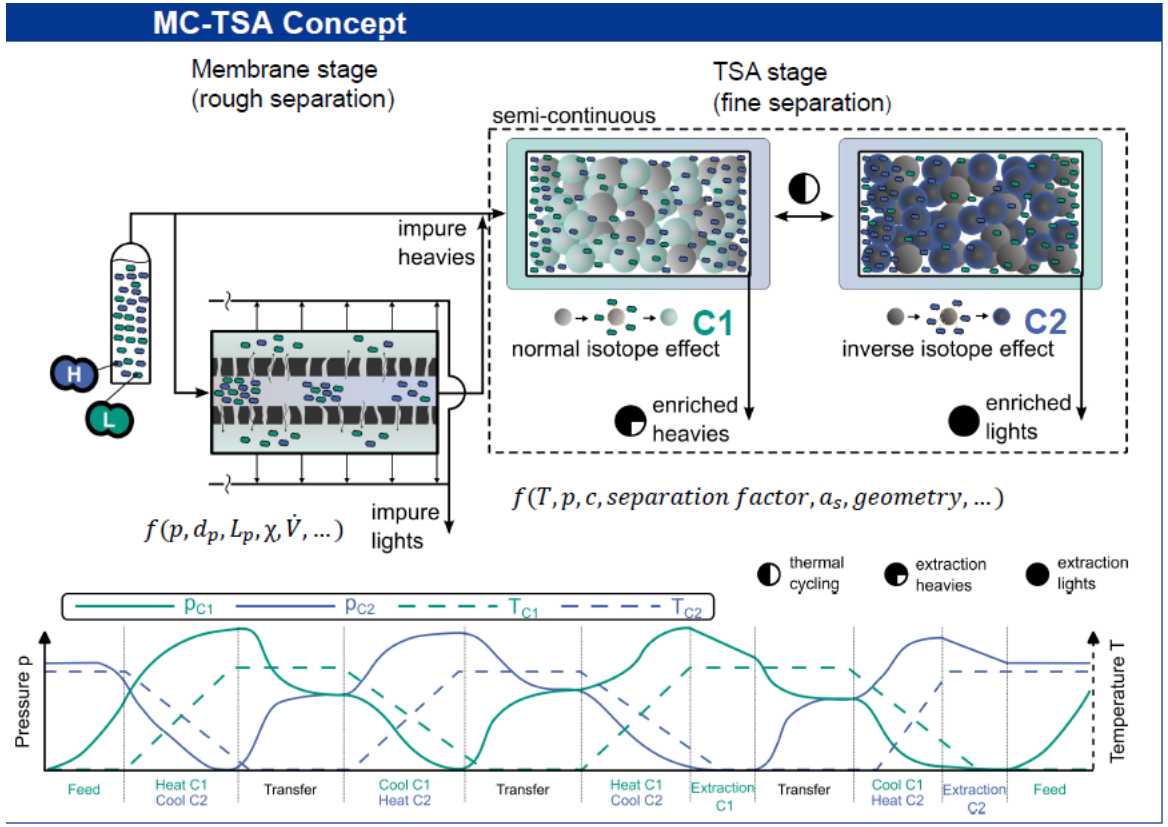
Arrangement of 2 Ring pumps and 1 booster diffusion pump for JET

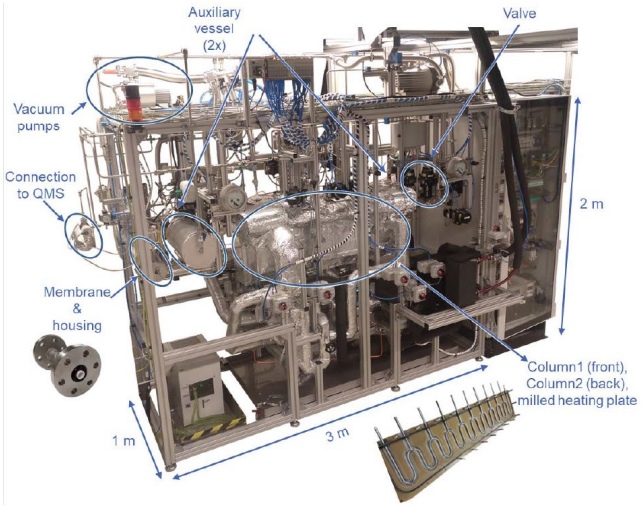
Three-Loop Architecture of the DEMO Fuel Cycle



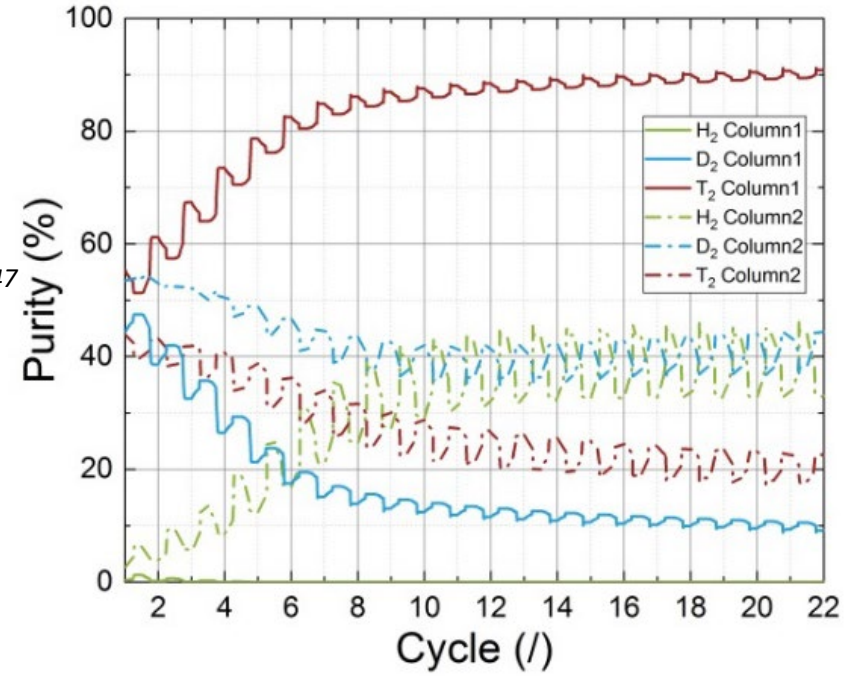
Chr. Day et al., FED 109 (2016) 299.
Chr. Day et al., FED 146 (2019) 2462.

Membrane coupled temperature swing absorption





Feed:
H_2:D_2:T_2 = 2:51:47



T extracted for return to adjust the composition of the DIR return gas

H and D to isotope separation in 3rd loop

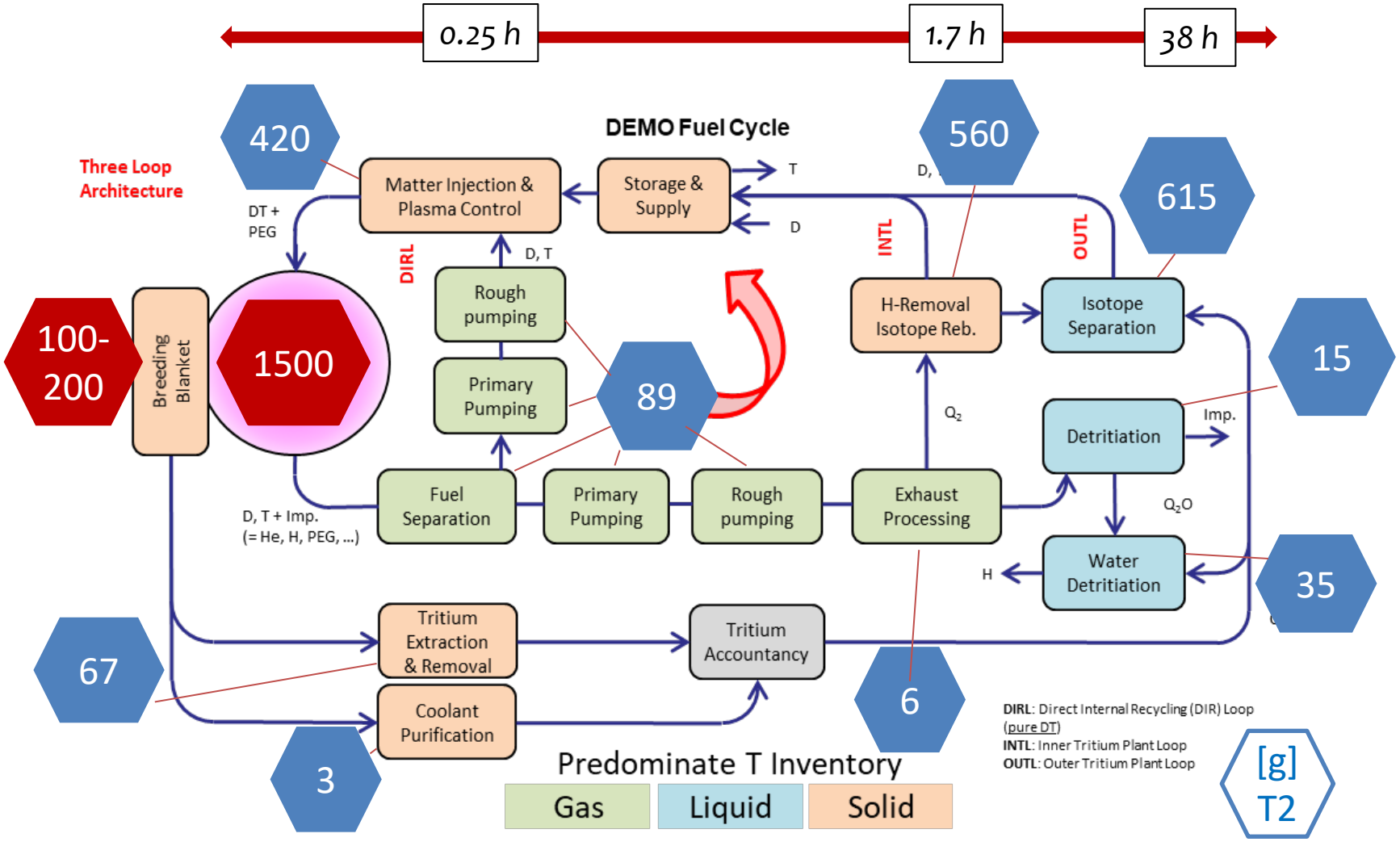
- Novel process features:
- Operation above room temperature with two pairing materials
- Pd + TiCr

A. Uihlein, SOFT 2022.

The issue of tritium inventory - solved

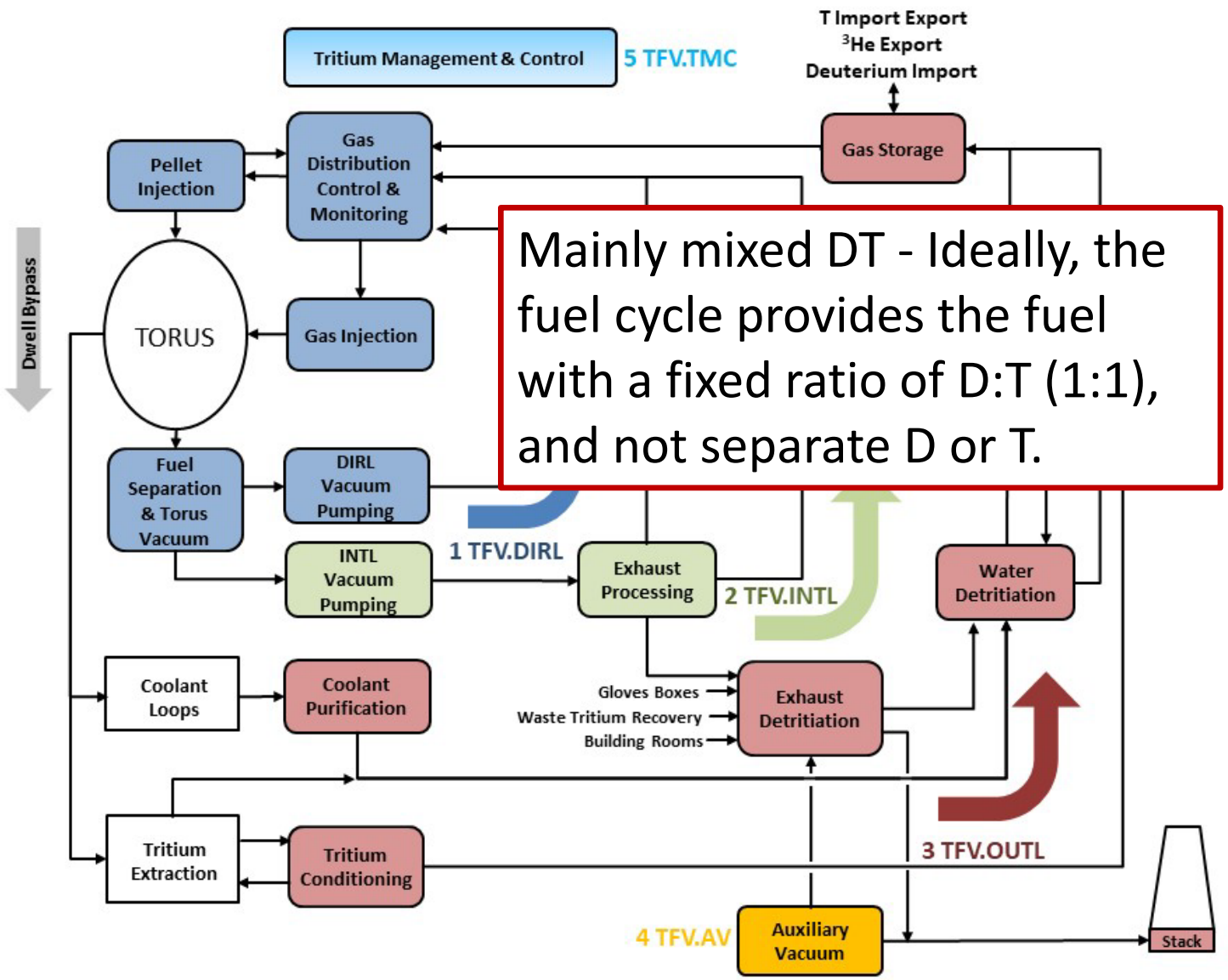
- 2021 – Verified solution

Chr. Day and TFV team, The pre-concept design of the DEMO tritium, matter injection and vacuum systems, Fus. Eng. Des. 179 (2022) 113139.



Solution verified with the DEMO Fuel Cycle Simulator:
DEMO (@ 80% recycling) will be linked with a tritium inventory of:
< 2 kg (operational)
< 1.7 kg (sequestrated)
< 0.3 kg (reserve)
(e.g. to compensate decay during outage)
---
4 kg Tritium
(similar to ITER)

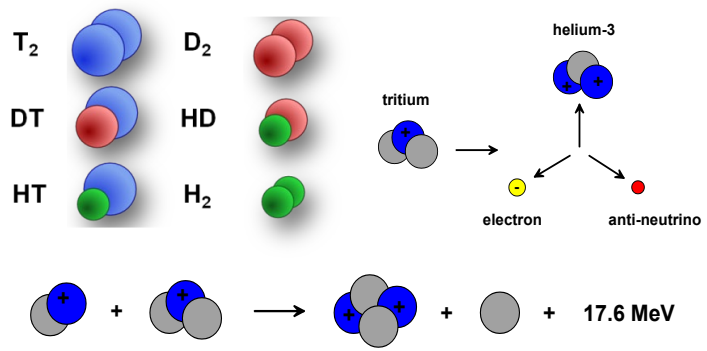
The Fuel Cycle – Current EU-DEMO Design



Mainly mixed DT - Ideally, the fuel cycle provides the fuel with a fixed ratio of D:T (1:1), and not separate D or T.

Physics: The plasma has to be operated stably and at high core density.

Engineering: The fuel cycle scales with throughput (2 inlet points) and chemical composition of the gases to be treated.



Coolants + PEG + activated PEG + impurities

Tritium Reactivity

- **Even if relatively weak,** the energy of decay electrons is sufficient to promote radiochemical reactions

- **Self-radiolysis of T_2 and T_2O**
  - $T_2 \rightarrow T_2^+ + e^-$ // $T_2 + T_2^+ \rightarrow T_3^+ + T$ // $T_3^+ + e^- \rightarrow 3\ T$
  - $T_2O \rightarrow T_2O^+, T_3O^+, T^\cdot, OT^\cdot, T_2O_2$ …highly corrosive

- **Reaction with oxygen, nitrogen**
  - $2\ T_2 + O_2 \rightarrow 2\ T_2O$ // $3\ T_2 + N_2 \rightarrow 3\ NT_3$

- **Hydrocarbon formation, "polymerisation"**
  - $T_2 + CH_4 \rightarrow CH_xT_y$
  - $2\ CQ_4 \rightarrow C_2Q_6 + Q_2$ // $CQ_4 + C_2Q_6 \rightarrow C_3Q_8 + Q_2$ … to continue
  - …aldehyde formation if presence of oxygen

Outline

- Requirements
- Basic concept of a three-loop architecture
- Interface considerations
  - Fuelling efficiency
  - Total machine gas throughput
  - Matter injection
  - PEG activation
  - Particle exhaust
  - Protium removal
  - Tritium management and control

Engineering the Fuel Cycle Systems

- As stated above, we have to address throughput and composition.

- Throughput:
  - DEMO working ´point´: given by the $\eta_f \cdot f_b$, among others, but how?
  - T fraction in torus exhaust corresponds to a throughput of >10 kg-T / d
  - Extracted T from breeding blanket corresponds to a throughput of ~ 0.3 kg-T / d (Relative weight of the two input streams).

- Chemical Composition:
- Two challenges:
  - One is to separate the non-hydrogenic and the hydrogenic fraction.
  - The second is to manage the different isotopes, in particular the protium content.

Importance of the Fuelling Efficiency (1)

In the core

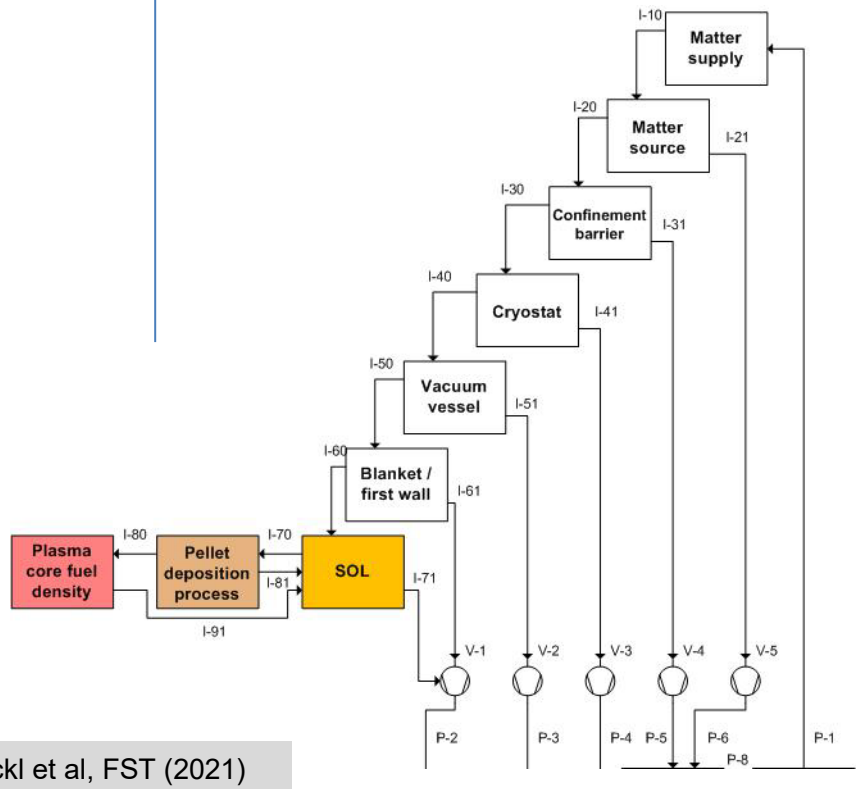
x +

In the SOL

x +

In the pellet generation process

½ x to 2x



B. Ploeckl et al, FST (2021)

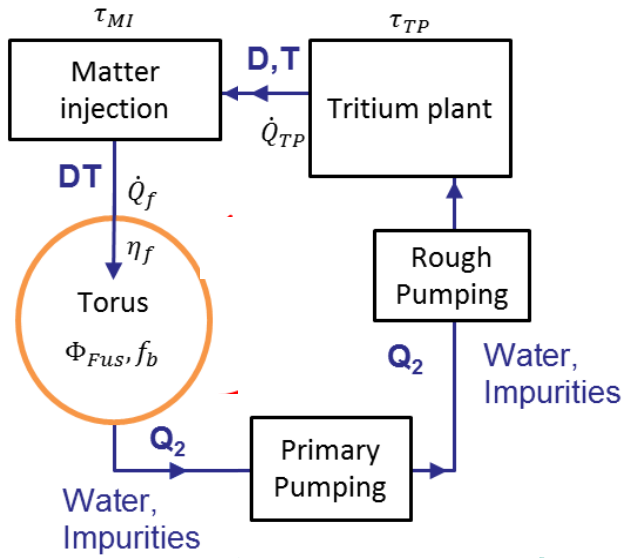
- We have significant losses in pellet generation and transport → efficiency η_f = 33% or even much less.

Fuelling Efficiency η_f :
Fuel Flux accepted by the core / flux leaving the injection system

But the throughput ~ scales with the fuelling efficiency.
Too low efficiency means too high gas throughput.
There is an upper limitation on the throughput simply coming from gas dynamics of vacuum pumping.

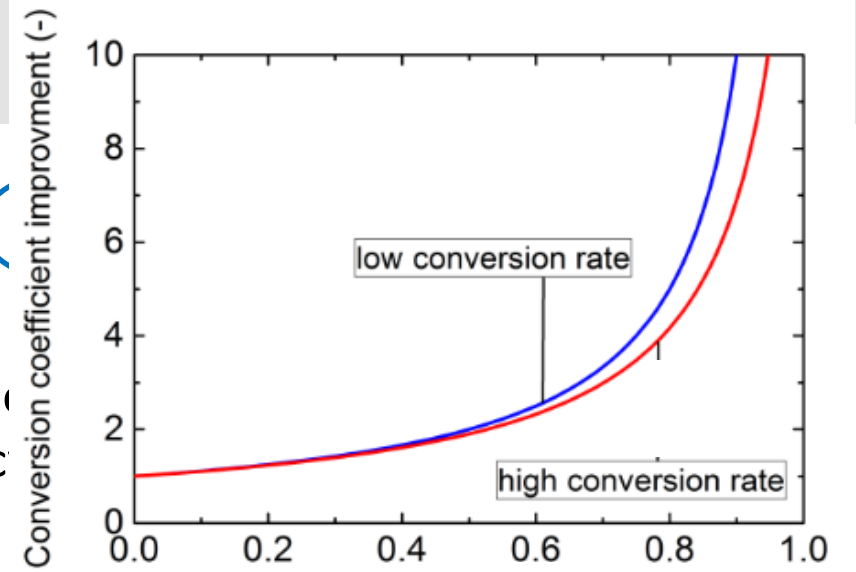
Importance of the Fuelling Efficiency (2)

ITER



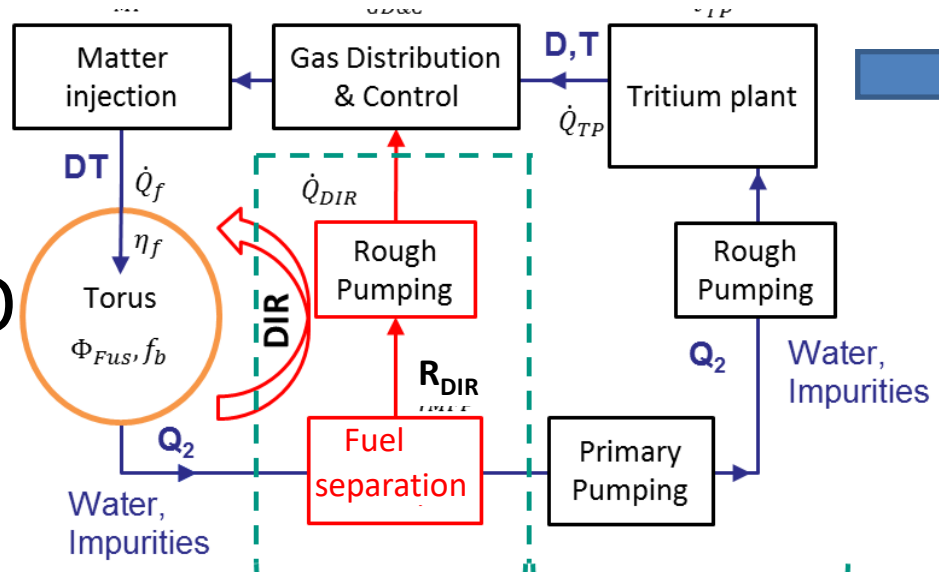
$$\frac{\Phi_{Fus}}{\dot{Q}_{TP}} =$$

Tritium Conversi
fuelling efficienc



R_{DIR}

DEMO



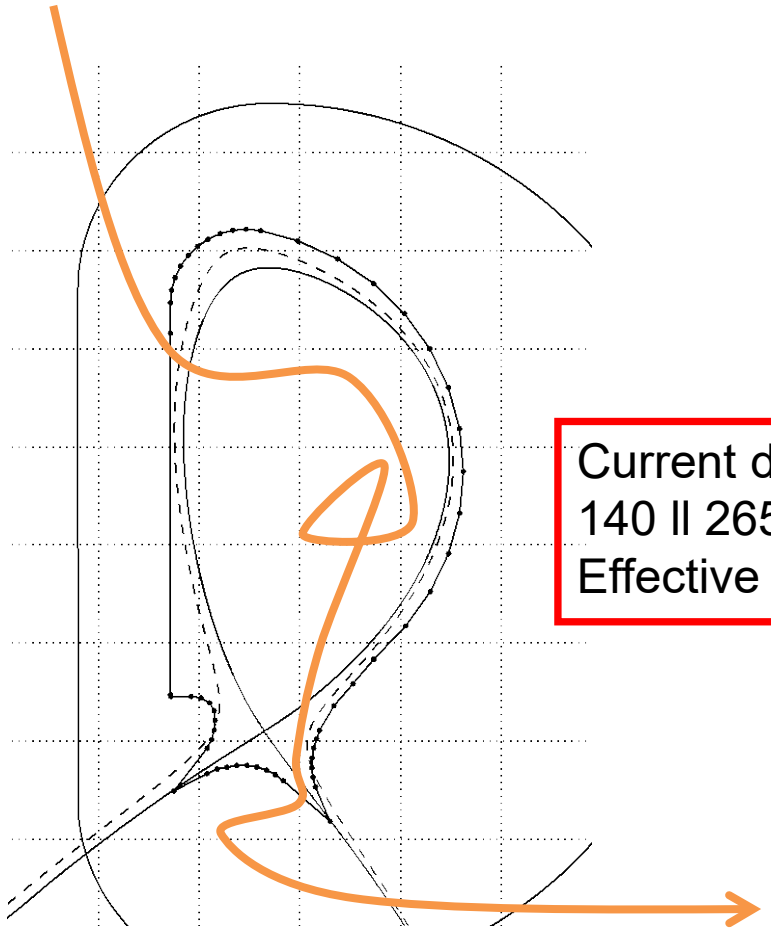
$$\frac{\Phi_{Fus}}{\dot{Q}_{TP}} = \frac{1}{1-R_{DIR}\cdot(1-\eta_f f_b)}\,\eta_f f_b.$$

DIR Ratio R_{DIR}: Hydrogenic fraction that is separated from the exhaust gas stream and processed by the DIR loop.

B. Peters, FED 136 (2018) 4067

Total Machine Gas Throughput

Core fuelling + losses + plasma enhancement gases + buffering + helium and impurities



Current design window:
140 ll 265 ll 430 Pam³/s total
Effective f_b=1.9 / 1.0 / 0.6%

- For steady state DEMO operation, fuel replenishment due to DT burn is rather small:
- 2037 MW = $7 \cdot 10^{20}$ reactions/s = 2.6 Pa·m³/s He
- Too small theoretical core fuelling rates are overruled by He streaming requirement (7% in core) →
- Radiation control core & divertor → Xe and Ar
- Allowed H is 1%
- Divertor buffering for detachment control → more hydrogens
- [no NBI, no N_2]

DEMO Matter Injection

Gas Injection

- DT gas injected at the mid-plane area

Gas Puffing

- DT + Ar gas injected at the divertor

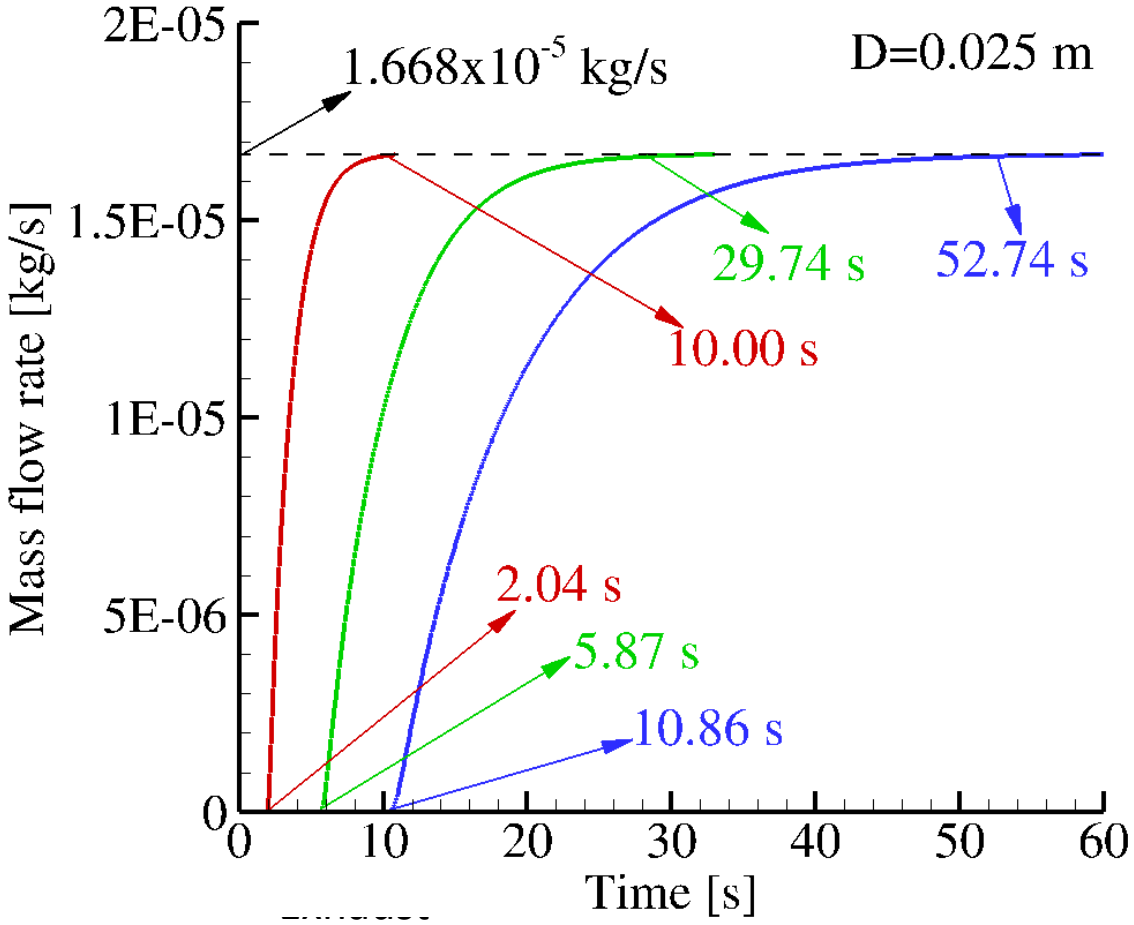
Pellet Fuelling

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

Understanding the timescales of the fuelling actuators is necessary

See poster by Thomas Giegerich

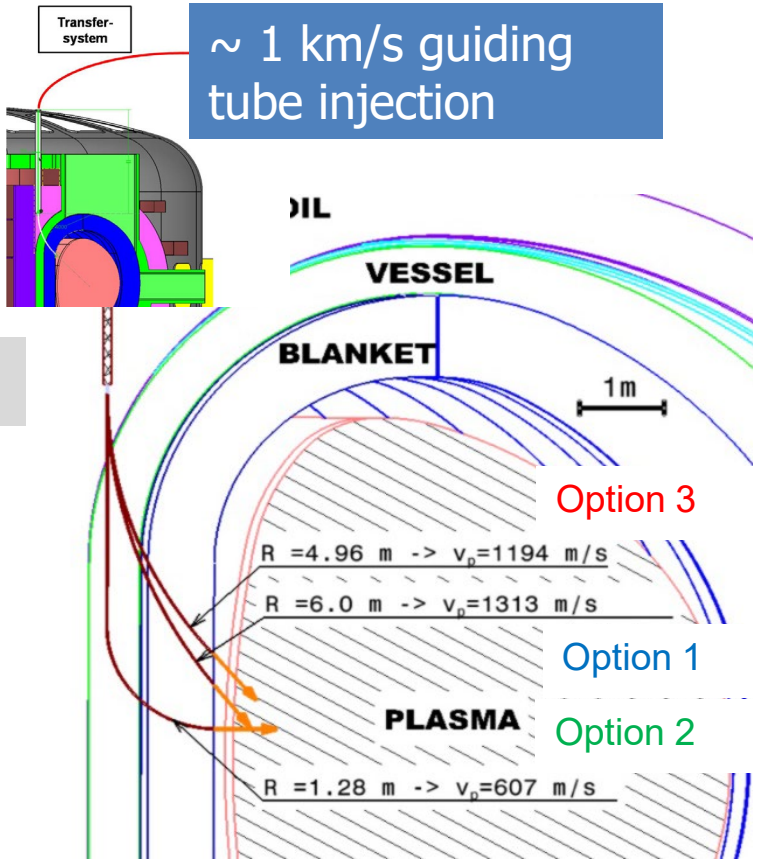
Gas injection @ 0.9 bar supply pressure over long distances



C. Tantos, DPG 2022

Translation to Velocity introduces Pellet Technology Choice

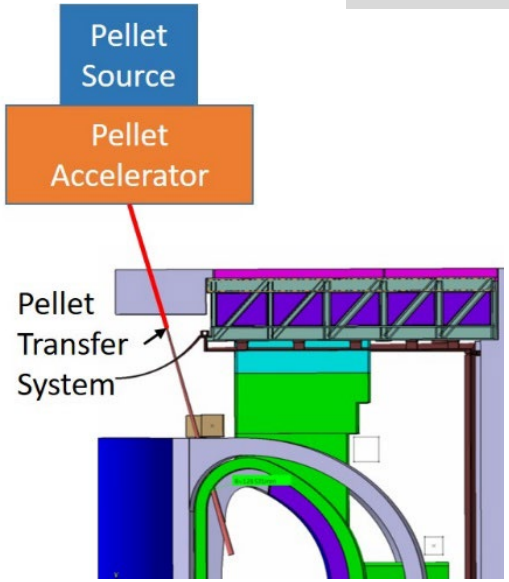
~ 1 km/s guiding tube injection



P.T. Lang et al., FED 156 (2020) 111591.

High speed (several km/s) direct line injection

A. Frattolillo et al., FED 162 (2021) 112138.

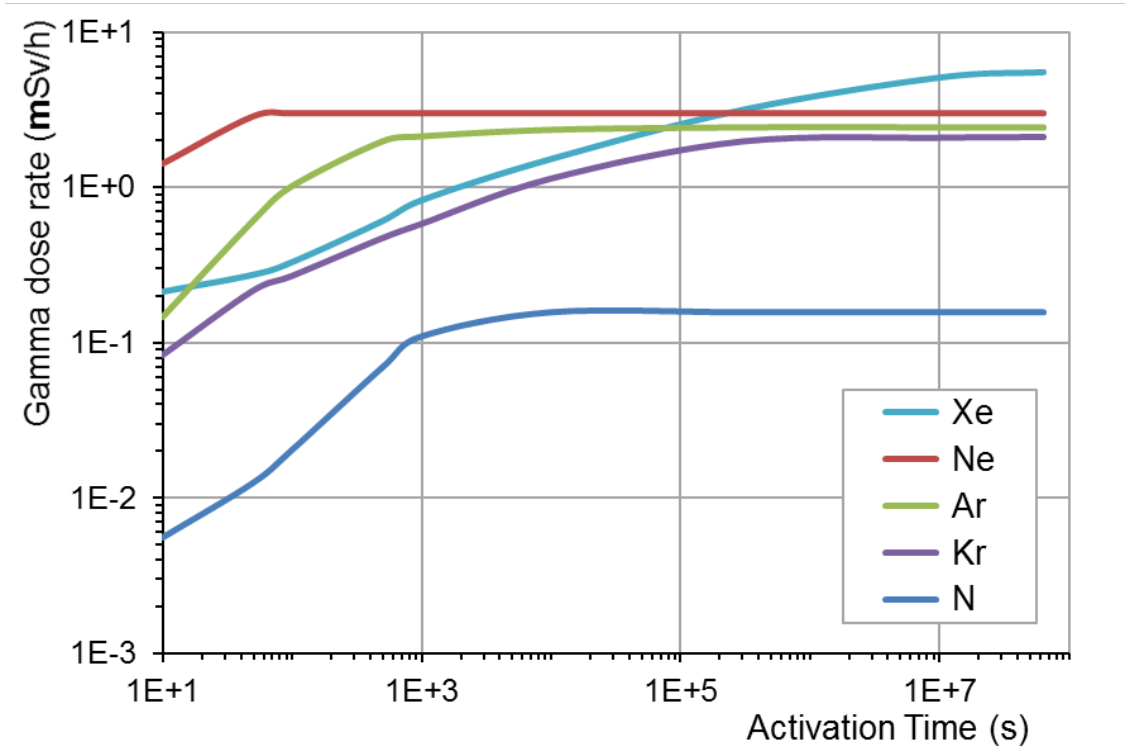


- Minimum tube bend radius R > 6 m
- Maximum distance to mid plane z < 1.5 m
- Intersection pellet path – separatrix α = 90°

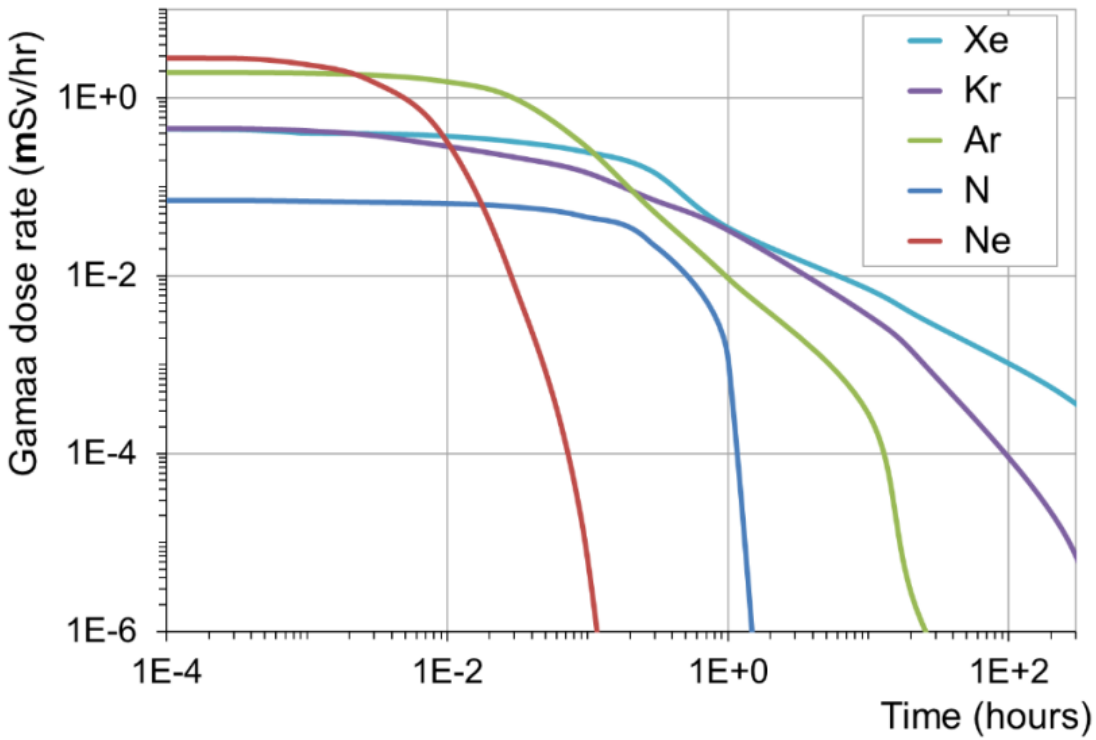
- Injection via upper vertical port found to be insufficient
- Integration path found

Peter Lang will be talking about this in the next talk

Radiation Control Gases



R.J. Walker, FED 130 (2018) 155.

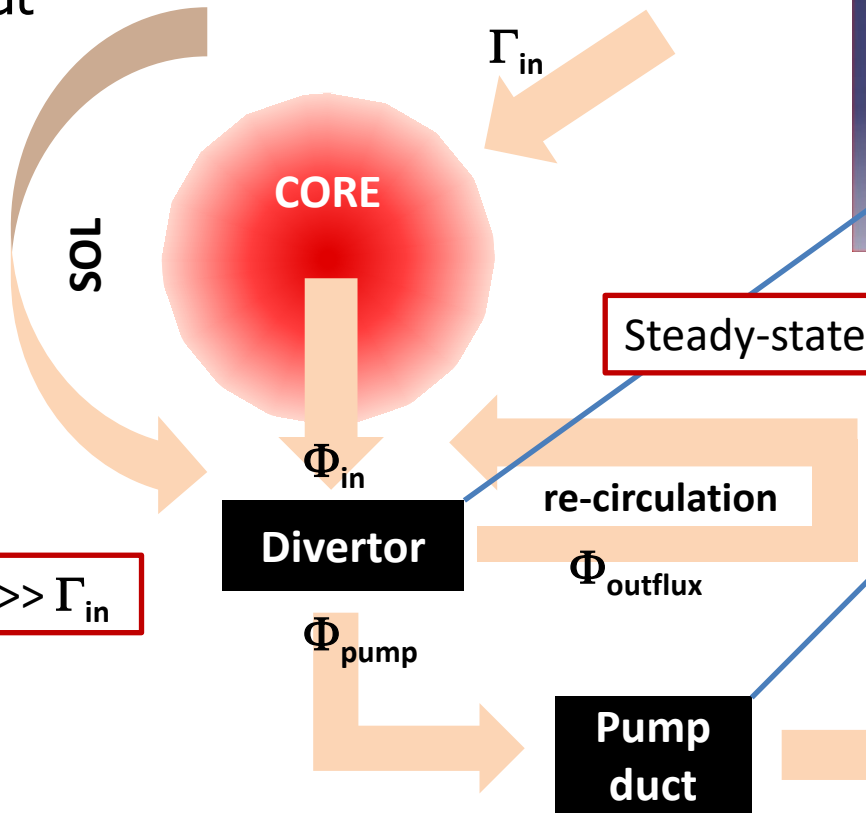


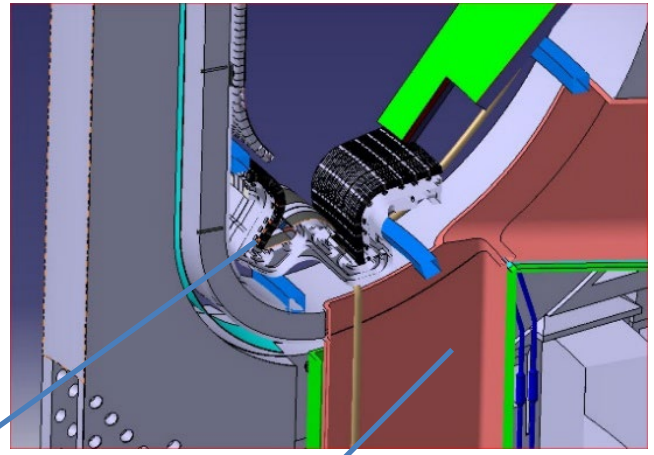
Decay following 500s of n radiation

- Core radiator: Krypton is more favourable than Xenon (=current EU-DEMO choice).
- Divertor radiator: Neon is more favourable than Argon (=current EU-DEMO choice)

Translation towards Exhaust Parameters

- How does the throughput unfold in divertor pressure x pumping speed?
- At which pumping speed can the machine gas throughput be pumped? (Competition against recycling and conductance losses)





Steady-state: $\Gamma_{in} = \Phi_{pump} \cdot L_{p,t} \cdot N$

N=Number of ports

Consider: $\Phi_{in} >> \Gamma_{in}$

Much progress has been made to come up with self-consistent neutral gas contours in the subdivertor volume.

Throughput = pressure x pumping speed

Stylianos Varoutis will be talking about this in this session.

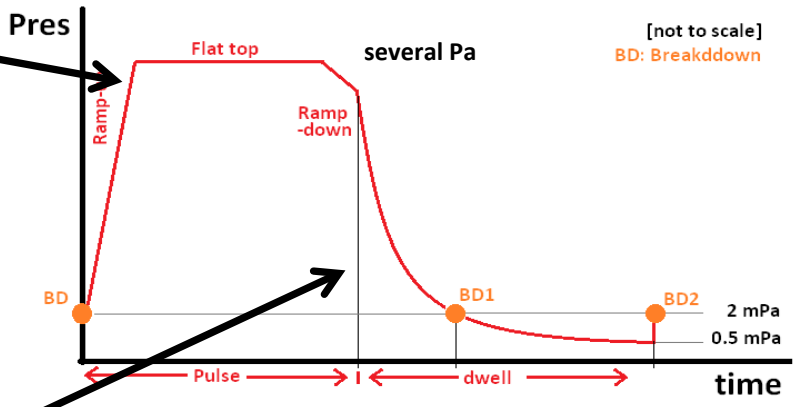
See poster by Christos Tantos.

Management of two different Tasks by one Vacuum System

Pumping requirements during burn phase

- need to remove He and unburnt fuel (D_2, T_2) and impurities from plasma

→ Moderate fine vacuum during pulse



Challenge Throughput = Design driver

Pumping requirements during dwell phase

- need to pump down to a suitable pressure to re-start the next plasma discharge. ECRH assisted break-down at 1-2 mPa. (depends on how the discharge is started)

→ Moderate high vacuum in between the pulse,

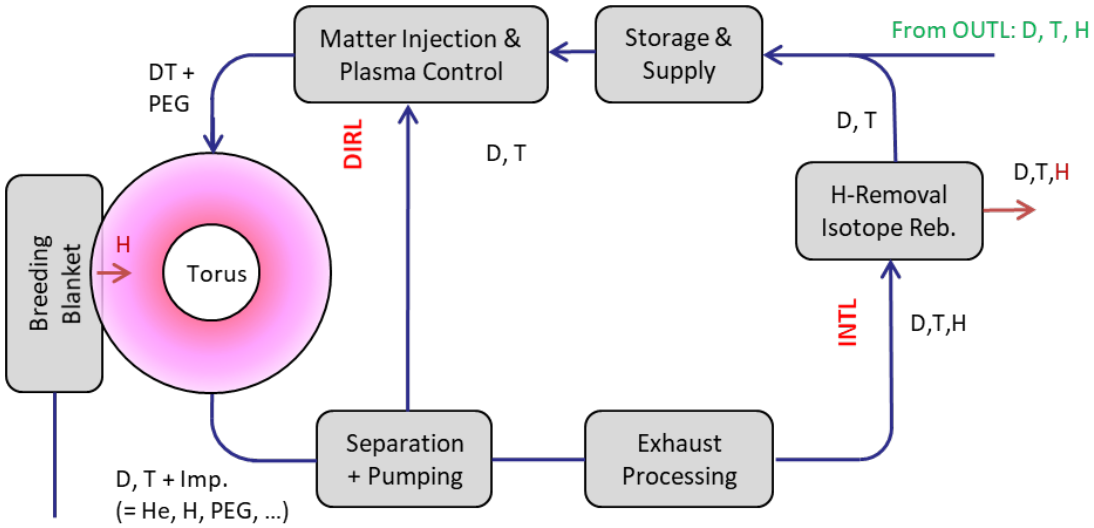
Challenge Outgassing, in particular of neutron damaged, hot materials

Not necessarily at present devices, both operational phases must be serviced by the same system (JT-60SA, DTT have separate). But it is essential for DEMO, where the first wall should be closed with blankets.

K. Battes et al., FED 100 (2015) 431.

The Protium (H_2) Removal Task

- Protium impurities in the plasma fuel have to be limited
- Protium source terms are:
  - From OUTL
    - Overall small quantities
    - Controlled via ISS system performance
  - Permeation in the Torus
    - H_2/H_2O may be used as doping in T purge
    - High temperatures drive permeation
  - Outgassing of Metals
    - Thermal outgassing occurs at high temperatures & very low pressures → First Wall
    - T_{FW} = 300 – 450 °C; p_{dwell} < 2mPa



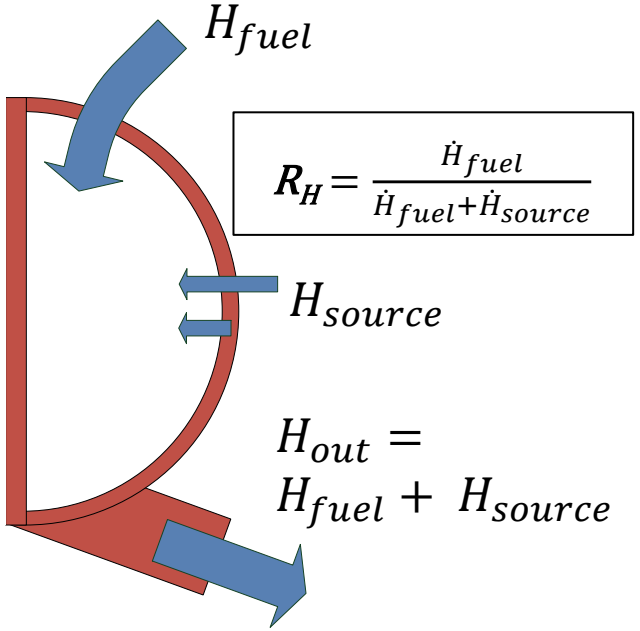
See poster by Juri Igitkhanov.

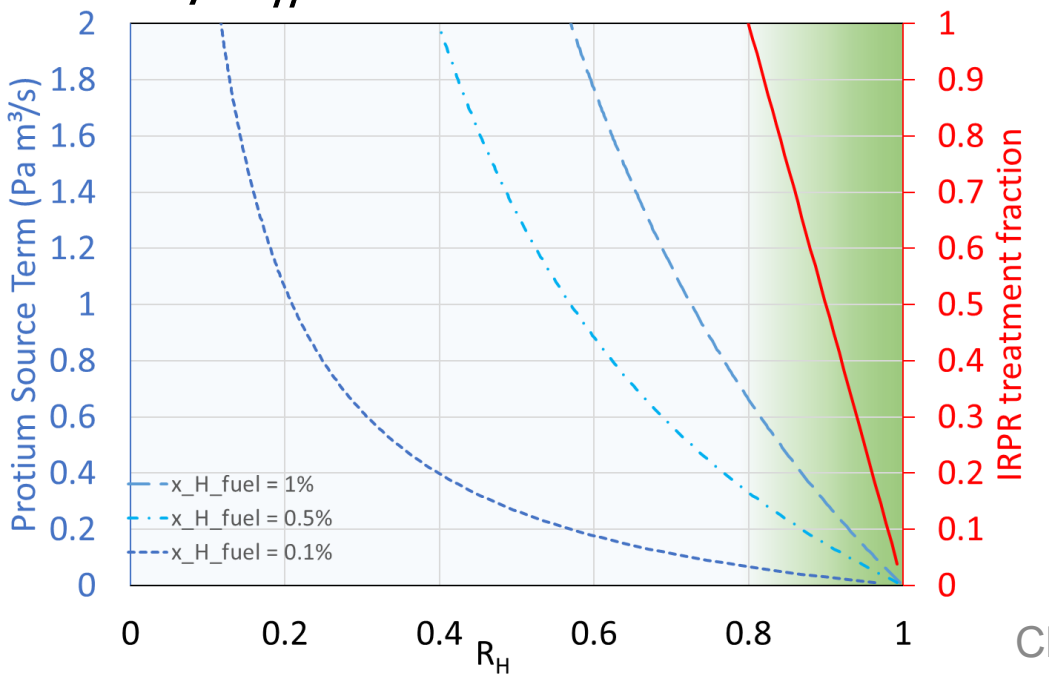
All protium that enters the fuel cycle has to be removed to avoid build-up

Effect of the Protium Ratio R_H on IRPR

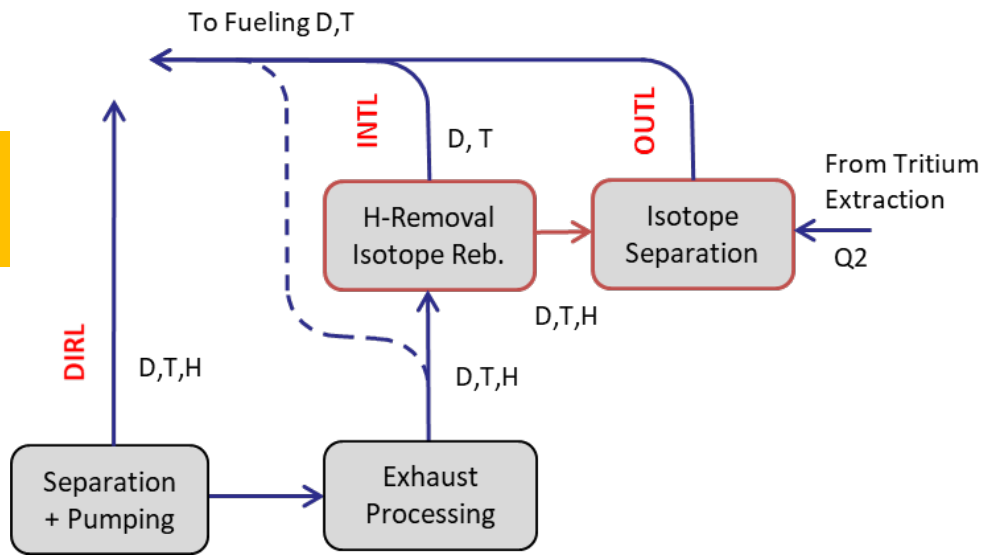
- Limiting the fuel protium content to 0 is not feasible from a fuel cycle perspective, as it induces high isotope separation efforts
- Required processing effort is inverse proportional to R_H.
- Determines load on IRPR (2nd loop)
  - Subsequent load on ISS (3rd loop)
- Ideally $R_H > 0.95$

Protium Ratio R_H:
Protium Stream that comes with the fuel / protium stream in the exhaust gas.

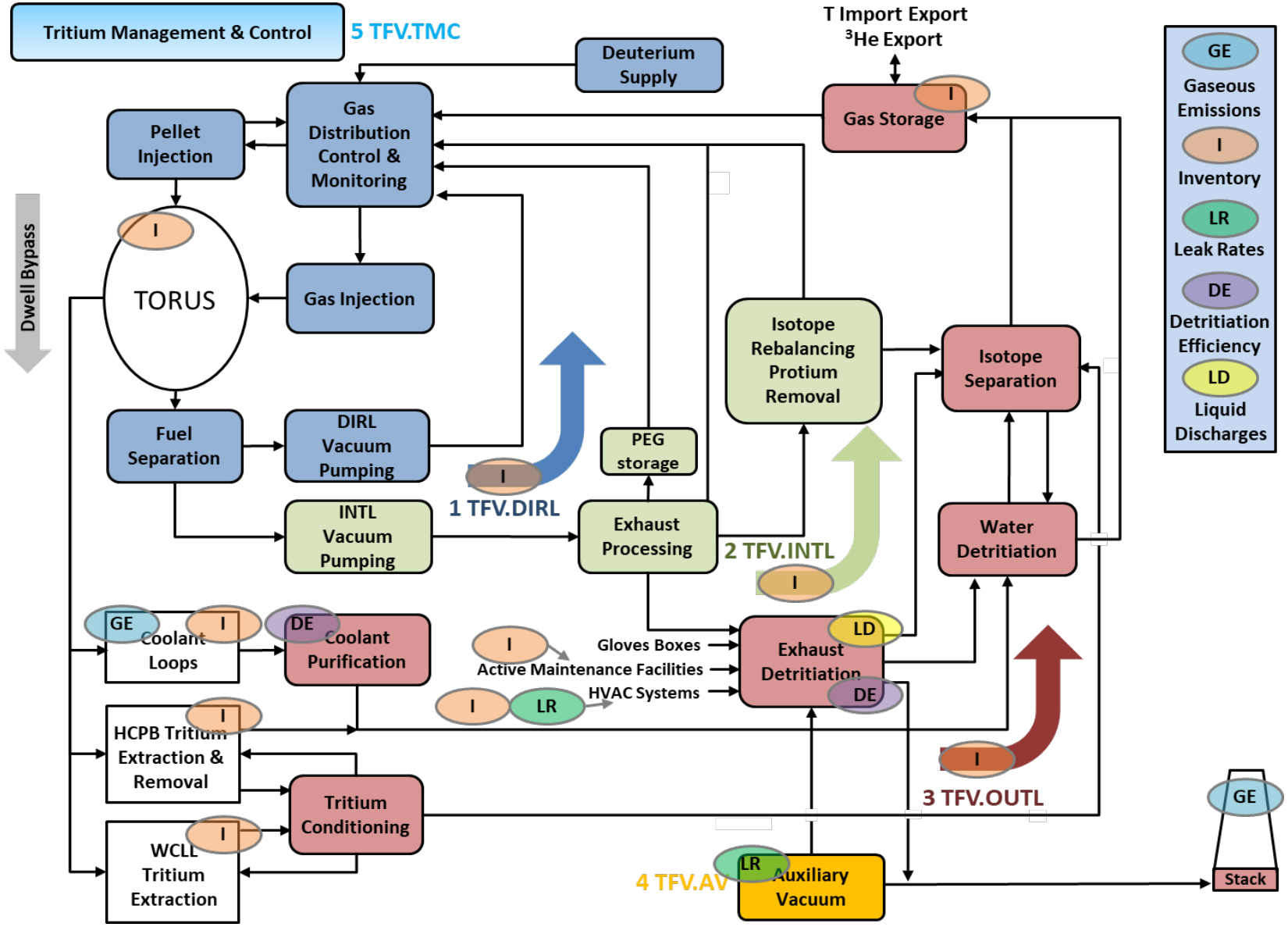




Talk by
Jonas Schwenzer



Operation of the Loops Requires Control



Finally: Integrate and add control (real time, online) and sensors (operability)

Conclusions

- A three-loop fuel cycle architecture with Direct Internal Recycling is considered to be a the only efficient tool to make up a too low burn-up fraction and still avoid excessive tritium inventories.
- The current tritium inventory for DEMO is found to be comparable with ITER.

- Due to the additional loops and additional system blocks / technologies, we have more degrees of freedom, on how to distribute the requested performance loads.
- The vacuum system is pretty flexible in terms of oscillations of the incoming loads/pressures (e.g. as a result of a plasma control action).
- H2 and D2 imbalances make the DIR concept less attractive.

thank you!

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

Oct 11 – 13, 2022
IAEA Headquarters
Europe/Vienna timezone

Enter your search term

Day 2 of 3 - ITER and DEMO fuel cycles

- Discussion -

Bullet points of discussion

- Some general challenges to the fuel cycle have been identified:
  - Flowrate (may be excessive, DIR, tritium conversion rate)
  - Species variety (seeding gases,…)
  - purity requirements (e.g. 0.02% T in D)
  - Fast sequence of loads asking for different fuel cycle responses (cryopump regens + NBI return gas + exhaust gas clean-up …)
  - Transient events and consequences (ramp-up/-down, ELMs, disruptions)
  - ELMs and disruptions

- Such challenges have to be addressed in trade-offs between physics and technology.

- 2 personal takeaways:
- Gas injection in the divertor area for detachment control is critical if needed in fast timescales (transients)
- H content in the plasma can be seen as within the He concentration range