EUROfusion

The EU DEMO fuel cycle

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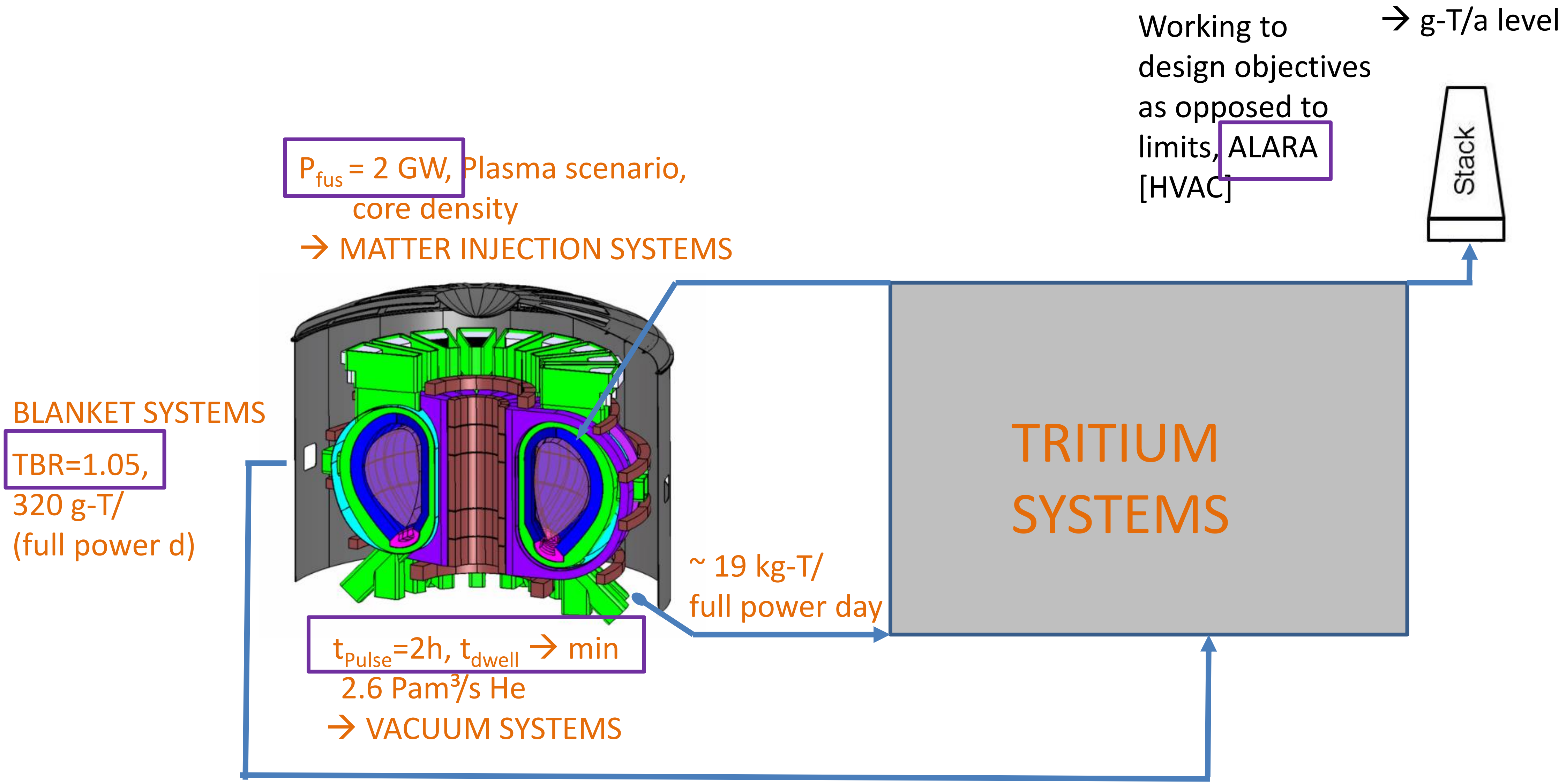
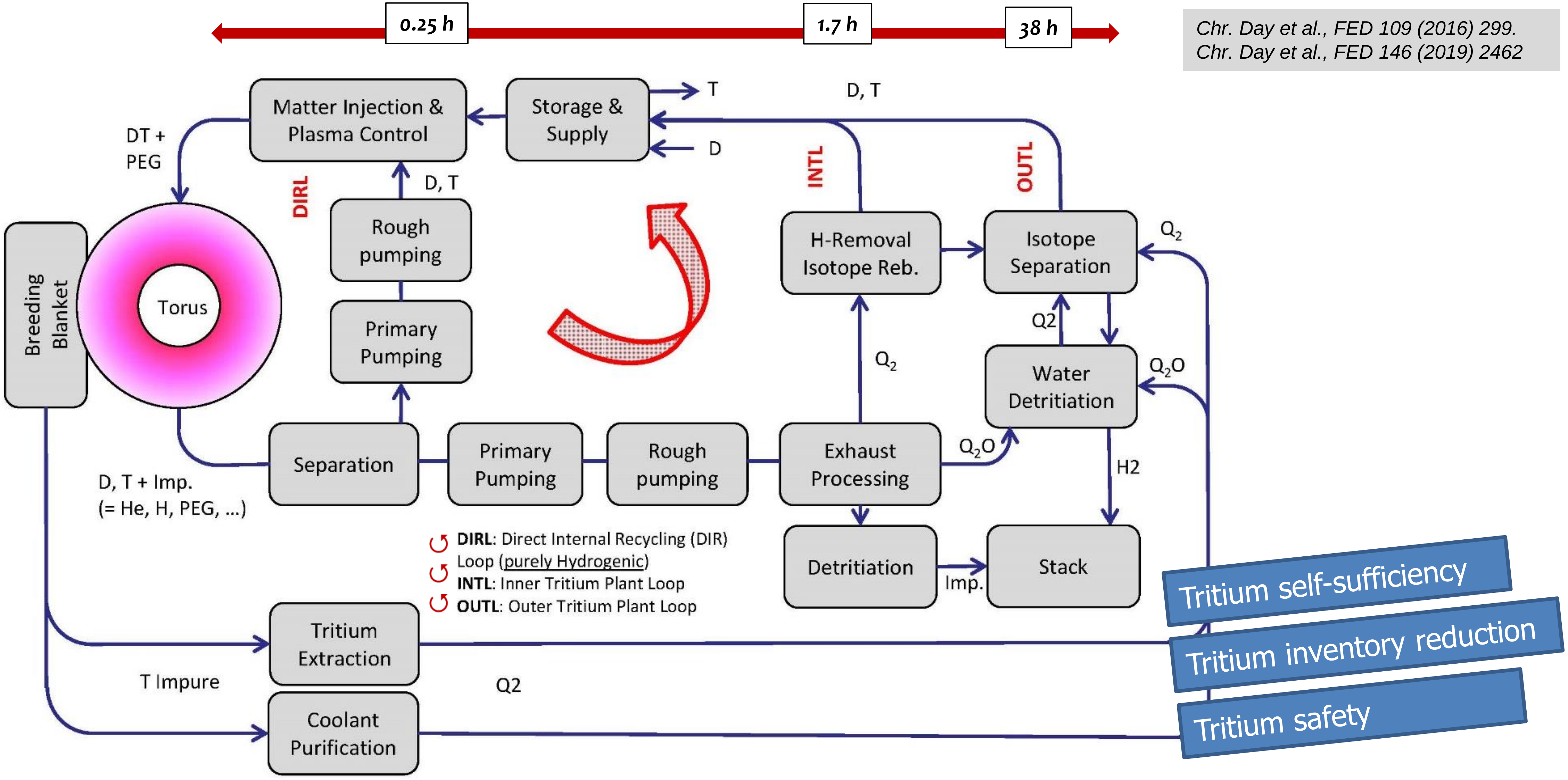
DEMO Fuel Cycle Requirements



Three-Loop Architecture of the DEMO Fuel Cycle

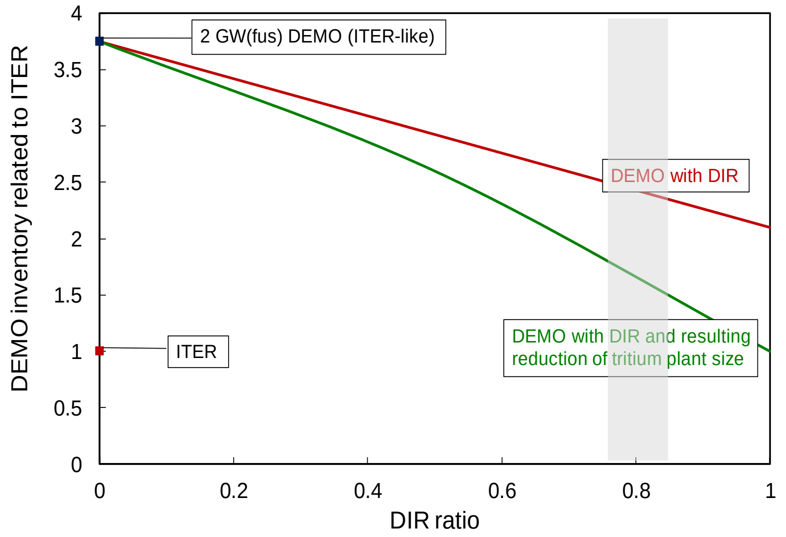
Chr. Day et al., FED 109 (2016) 299.
Chr. Day et al., FED 146 (2019) 2462



Tritium Inventory

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

2013: Motivation and Expectation

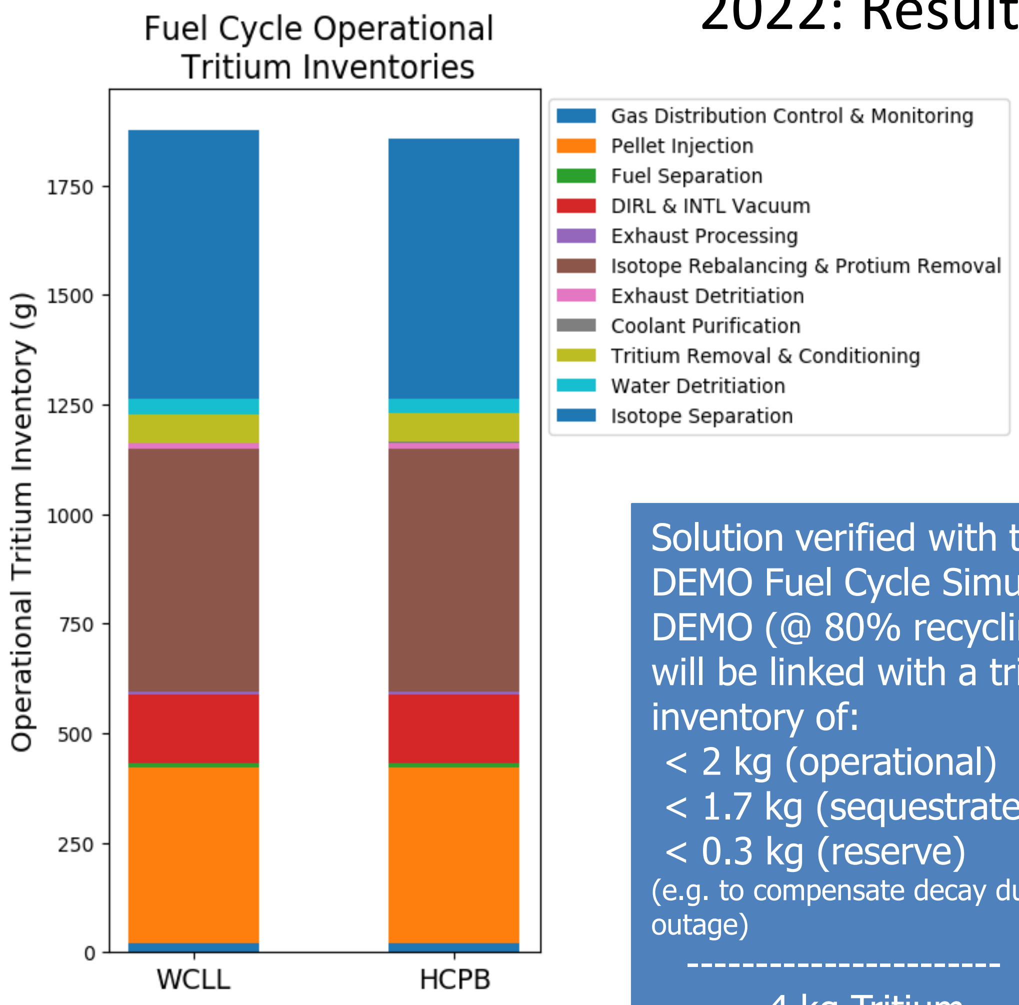


DIR Ratio R_{DIR}: Hydrogenic fraction that is separated from the exhaust gas stream and processed by the DIR loop.

- Consequences:
  - Main DEMO gas composition is fuel DT
  - more dynamics in the fuel cycle

J.C. Schwenzer et al, FST 78 (2022) 664.

2022: Result



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)

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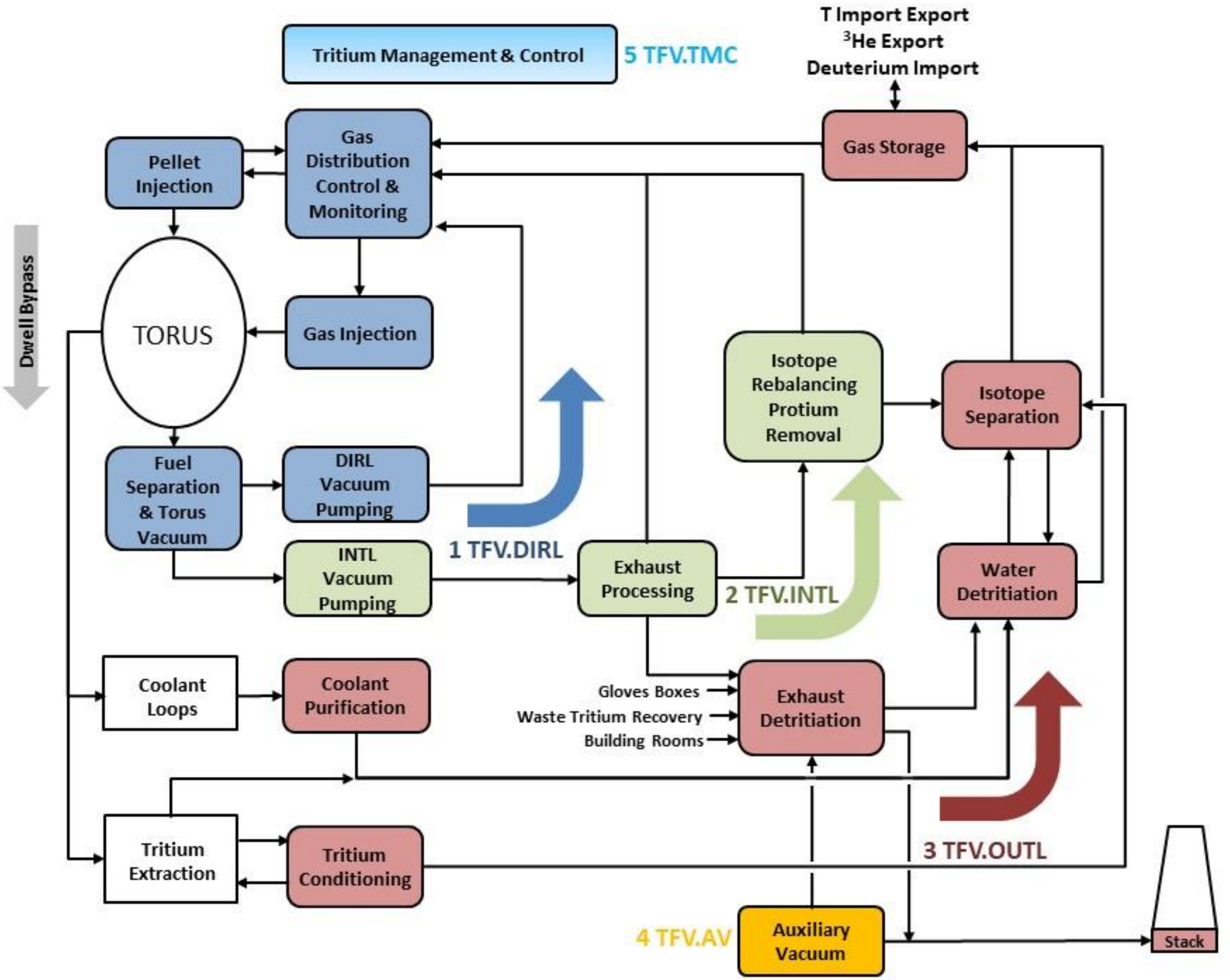
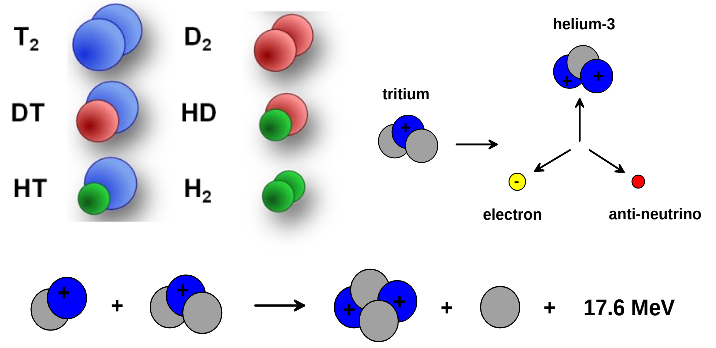
4 kg Tritium

Current Fuel Cycle System Blocks Function/Technologies



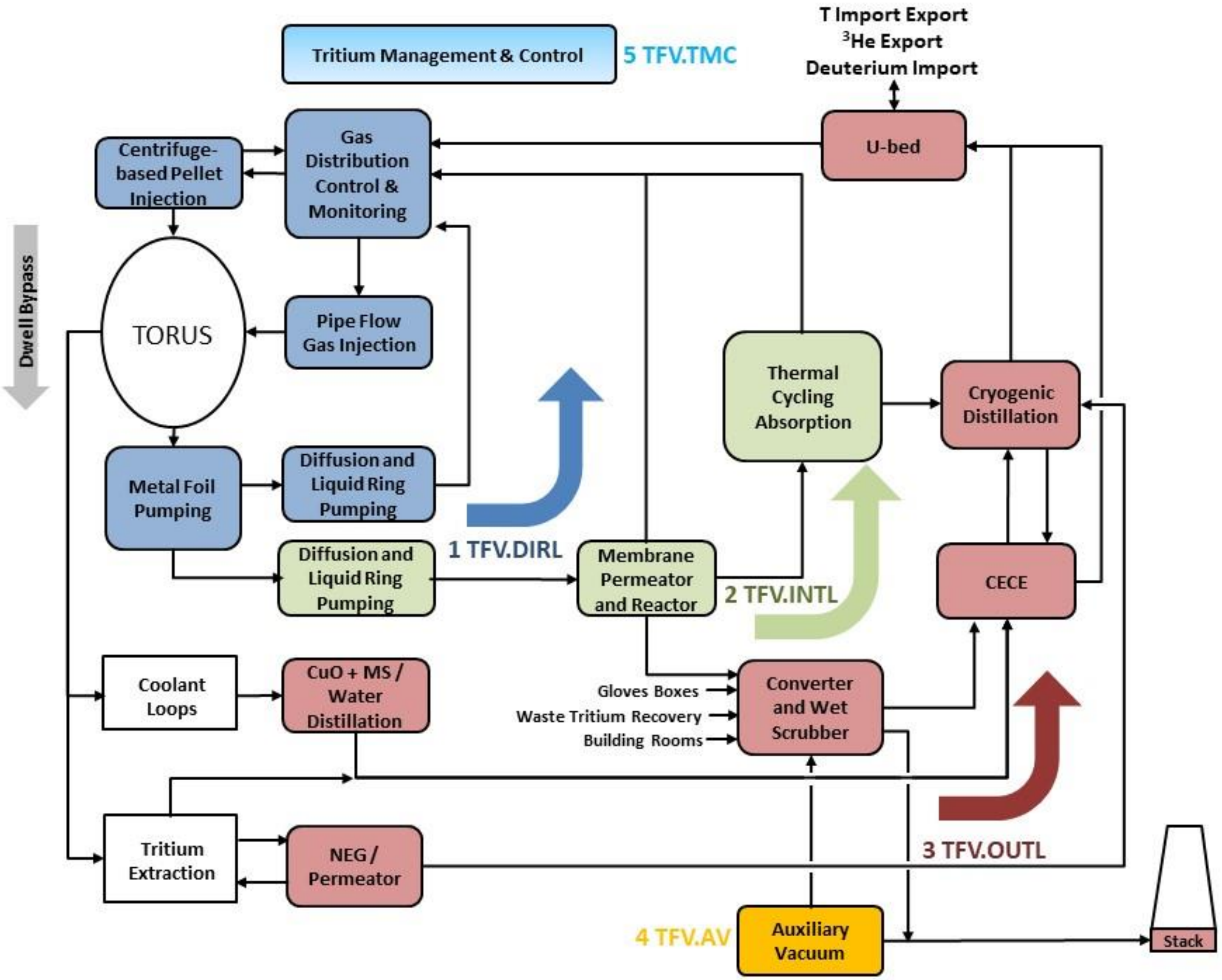
Chr. Day et al., *FED 179 (2022) 113139*

- Species to be processed in the fuel cycle:



Coolants + PEG + activated PEG + impurities

Current Fuel Cycle System Blocks Function/Technologies



Chr. Day et al., FED 179 (2022) 113139

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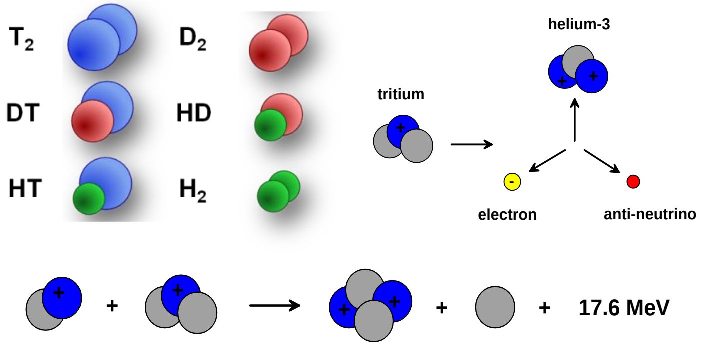
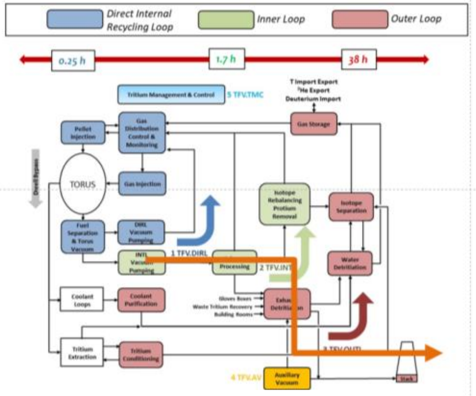
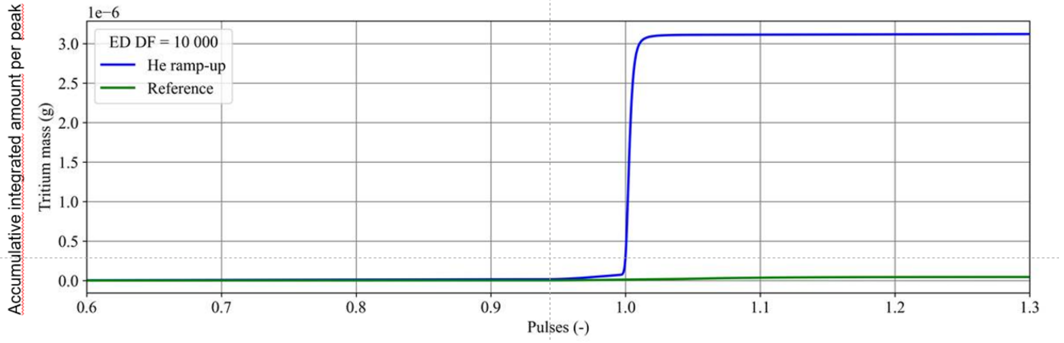


Coolants + PEG + activated PEG + impurities

Dynamic simulation and control

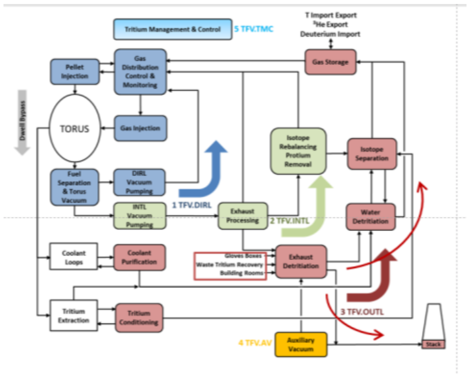
- Consequences of a linear He Gas injection ramp from t=0 to t=50s up to max (150 Pam³/s), followed by constant decline until t=100 s

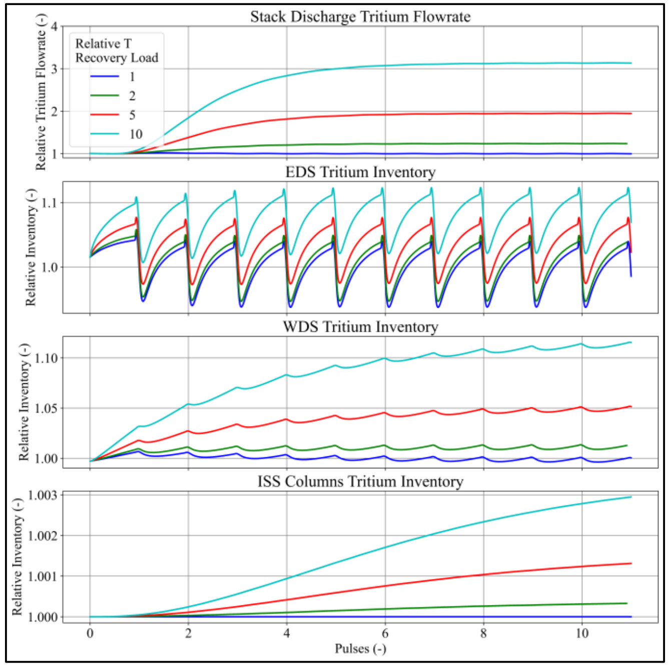




- Calculated already for a very efficient (=large, costly) EDS with a decontamination factor of 10^4, Each ramp-up adds 3 μg of tritium to the environment.
- For a full power year, this represents 15 mg (=1.5%) of the target budget of ~ 1g/a.
- For a more realistic EDS with decontamination factor of 1000, this effect becomes 15%.

- Consequences of an increase in the tritium influx from HVAC clients side on the outer loop





Maturation Assessment

Extracted from TRA Guide (GAO-20-48G), please find FOR INFORMATION the description of the technology readiness levels. The specific readiness level DEMO will use will closely reflect this.

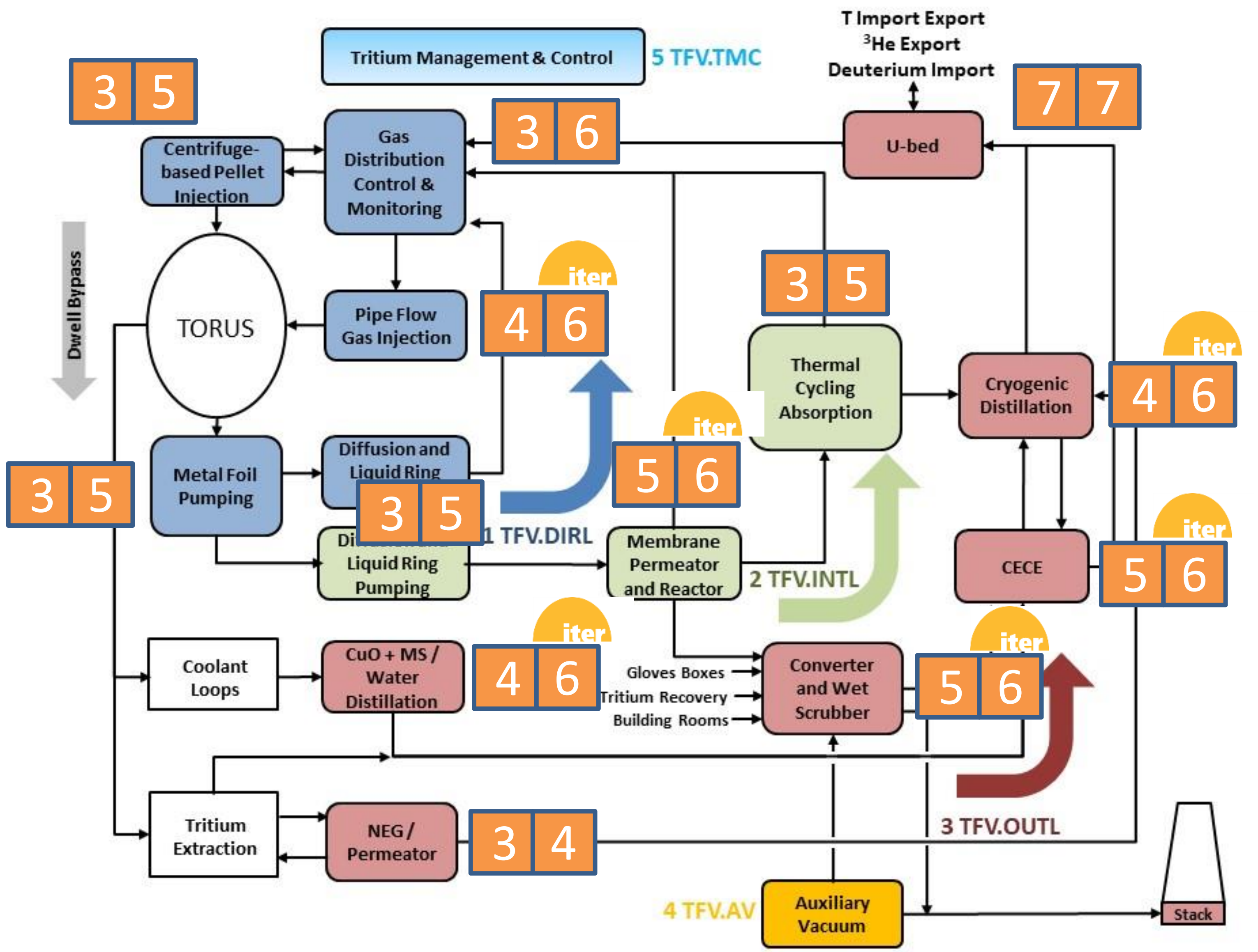
Technology readiness level (TRL)	Description
1 Basic principles observed and reported	Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
2 Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3 Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4 Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.
5 Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
6 System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7 System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
8 Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9 Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

- A systematic maturity assessment of all system block technologies was made in Nov 2022 together with an external panel. The final numbers were fixed in March 2023.

TRL=6 may require tritium.
TRL=7 does require triitum.

- The maturation assessment was used as a basis to define the near-term R&D programme.

TRL now vs planned

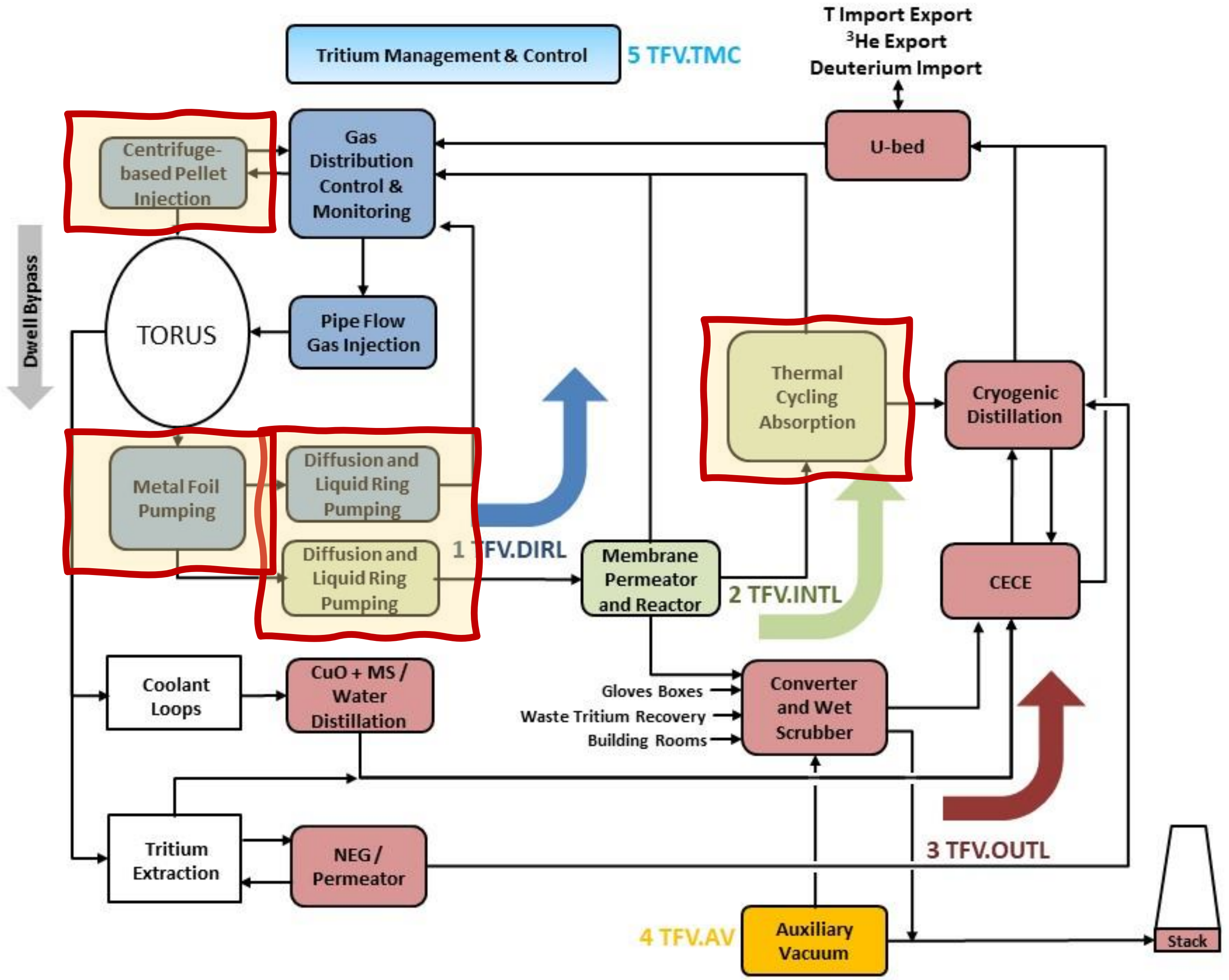


3 5

TRL now *TRL 2027*

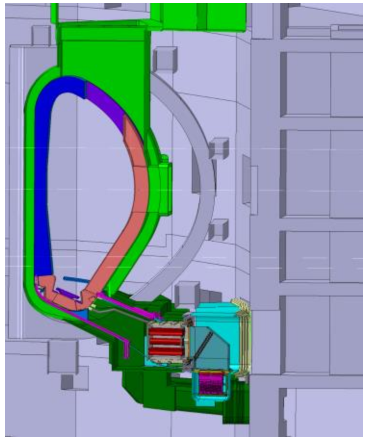
- Lowest TRL is TRL=3.
- Highest is TRL=7.
- Plan will lead to ~uniform TRL of all fuel cycle technologies.
- The inner loops are at lower TRL than the outer loop.
- The outer loop was more planned to rely on maturation work done for ITER [being revised now in view of ITER re-baselining].
- <u>Current R&D focus on novel inner loop technologies</u>.
- Always experiments + predictive simulation (scale-up)

R&D Status of low - TRL Inner Loop Technologies



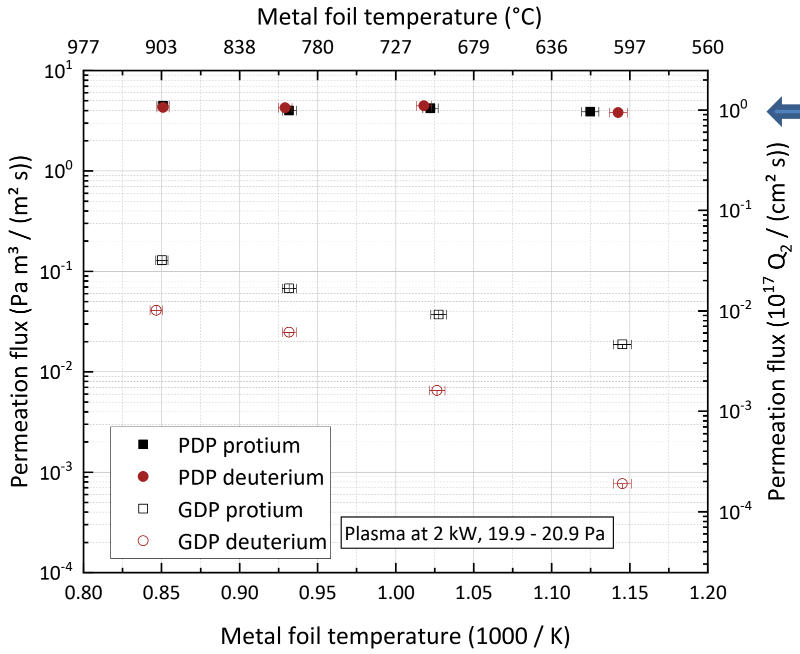
- Metal foil pumping (MFP) to enable Direct Internal Recycling
- Continuous vacuum pumping (instead of batchwise cryopumping) by use of mercury as operating fluid.
- Isotope rebalancing by temperature swing absorption (not all separation effort taken by cryogenic distillation)
- Continuous highly repetitive pellet Injection

Fuel Separation at Low Density – Metal Foil Pump



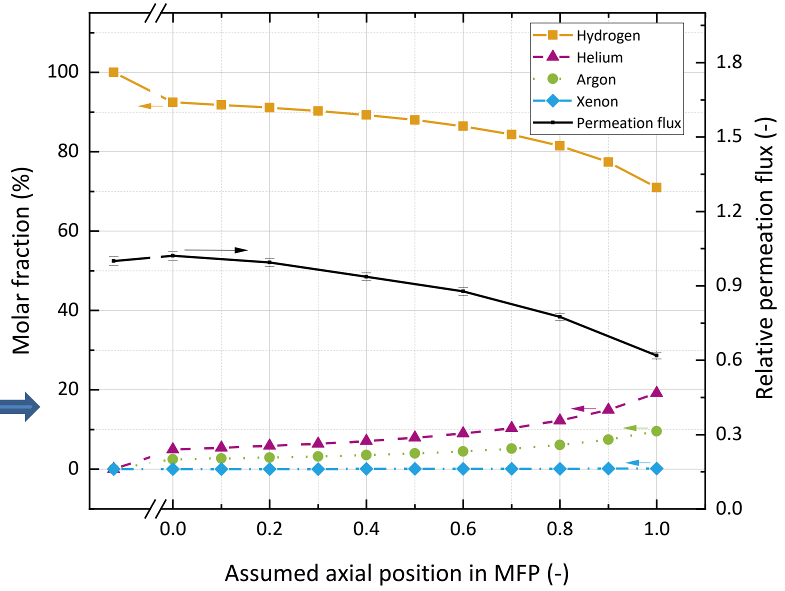
S. Hanke et al., FED 161 (2020) 111890..

SUPERPERMEATION
(PLASMA DRIVEN PERMEATION, PDP)
Driving force:
Energetic flux → allows compression



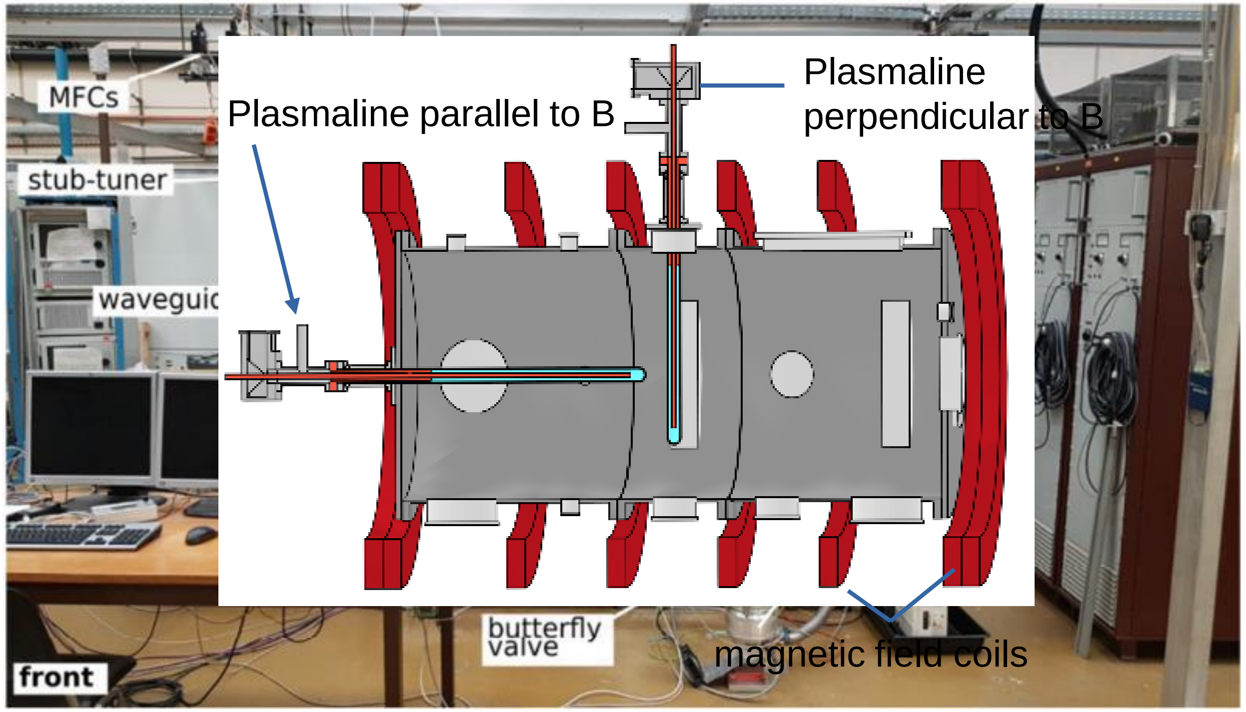
- No isotopic effect
- Temperature independence
- Fluxes > 4 Pa m³ / (m² s)
- → # pumps okay, no issue

- Permeation flux change vs noble gas enrichment
- Approximately linear dependence of flux with hydrogen partial pressure
- → no issue

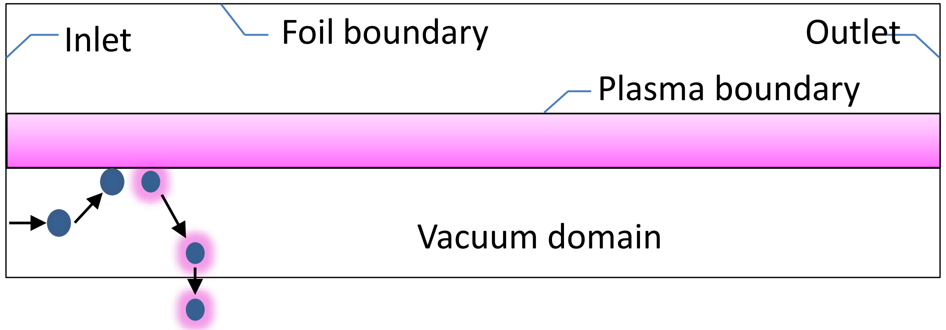


Fuel Separation at Low Density – Consideration of B field

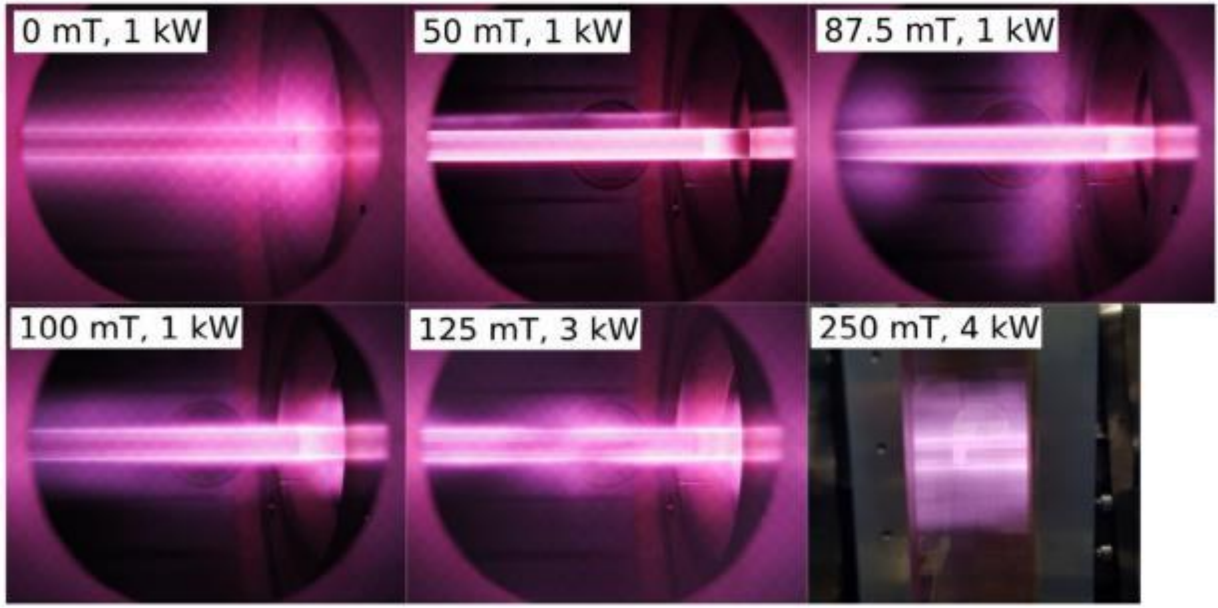
Y. Kathage et al., Plasma 6 (2023) 714

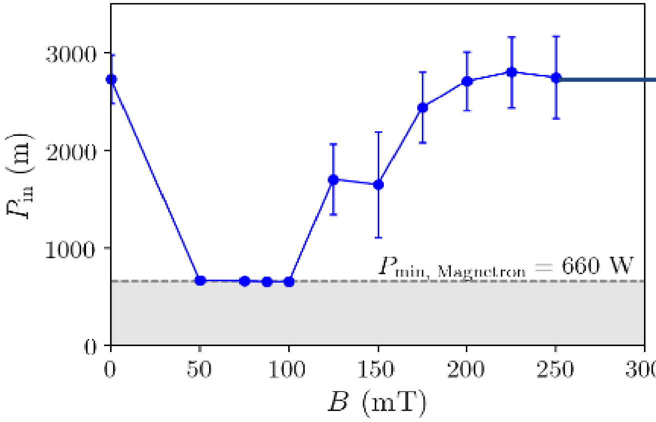


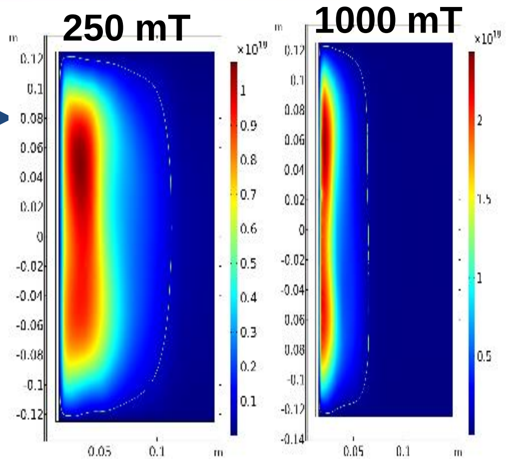
Particle Model in plasma and field



Parallel B-field @ 10 Pa







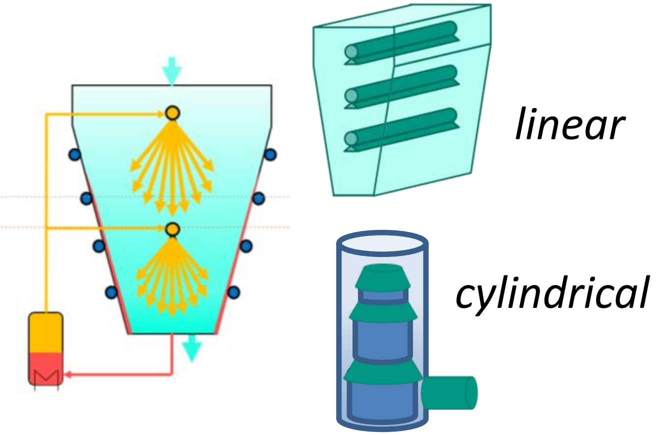
Microwave Power Needed for Ignition of a Stable Plasma at p = 10 Pa

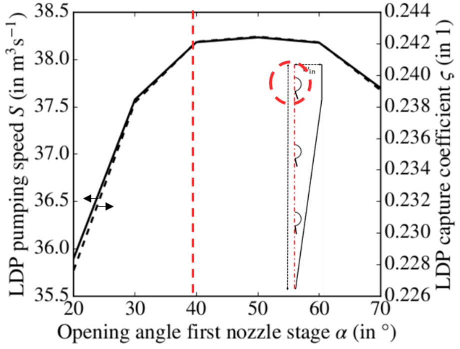
Continuous Vacuum Pumping – First Stage

- **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.

Facility NEMESIS@KIT

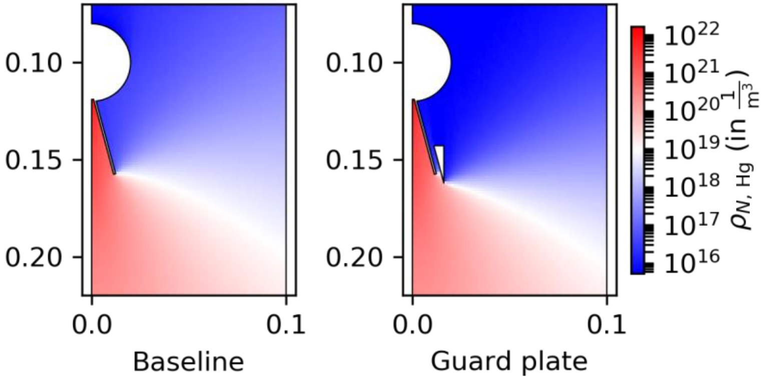




Understanding the influence of the nozzle angle on achievable pumping speed

T. Teichmann, Chr. Day, FED 169 (2021) 112694.

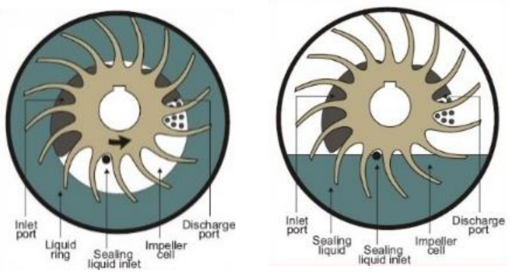
Reduction of backstreaming by simulation supported design measures



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.



Facility THESEUS@KIT

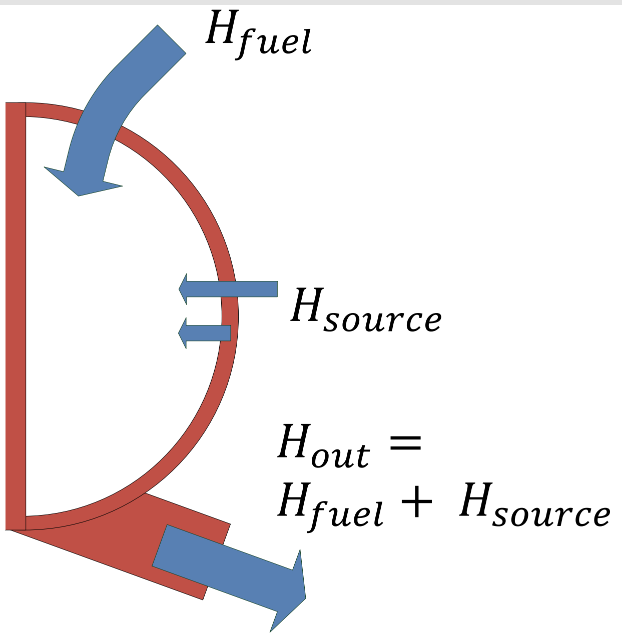
Arrangement of 2 ring pumps and 1 booster diffusion pump

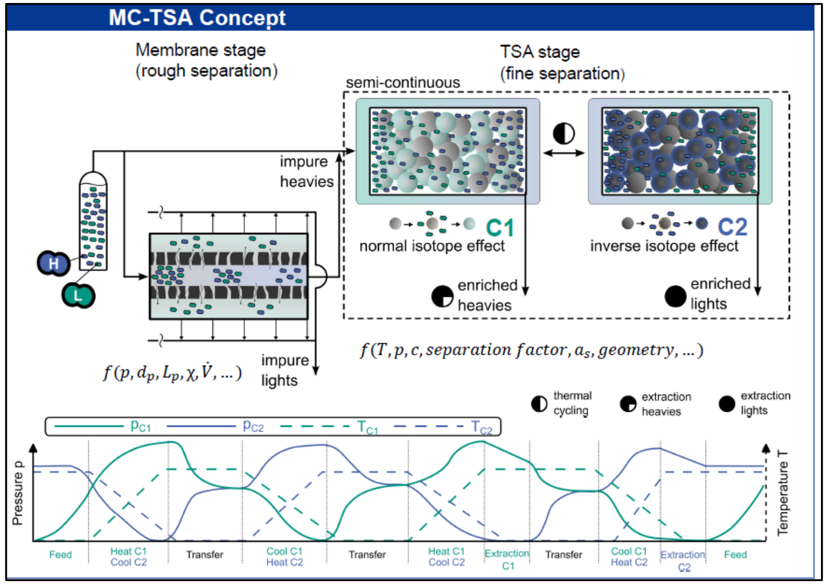
Isotope Rebalancing and Protium Removal (IRPR)

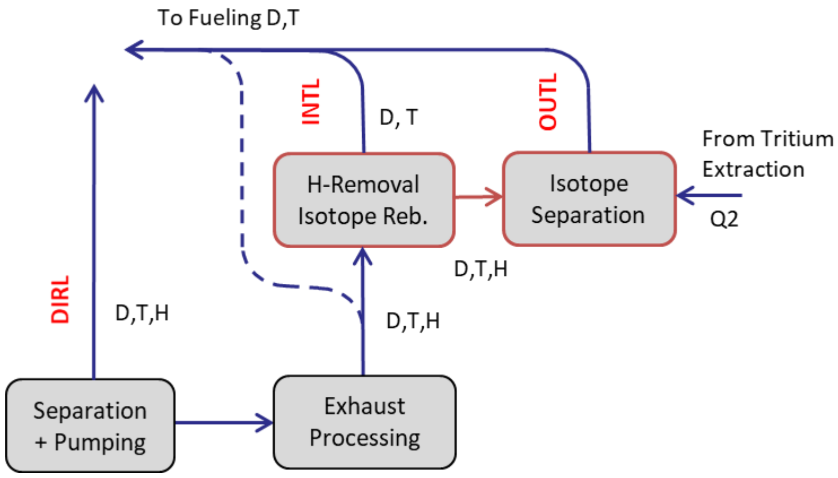
- Limiting the fuel protium content to 0 is not feasible from a fuel cycle perspective, as it induces high isotope separation efforts (potential showstopper).
- H will enter the exhaust gas (outgassing, isotope exchange).
- From plasma stability reasons, ~ 1% H in fuel can be accepted.
- The size of the IRPR system block scales with the protium removal figure of merit:

$$R_H = \frac{\dot{H}_{fuel}}{\dot{H}_{fuel} + \dot{H}_{source}}$$

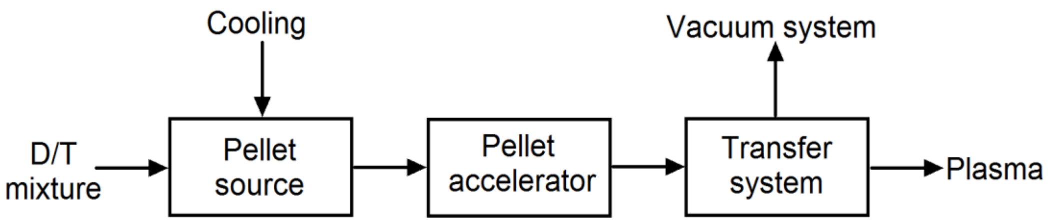
- The technology chosen is membrane-coupled temperature swing absorption, featured by operation above room temperature with two pairing materials at opposite absorption behaviour





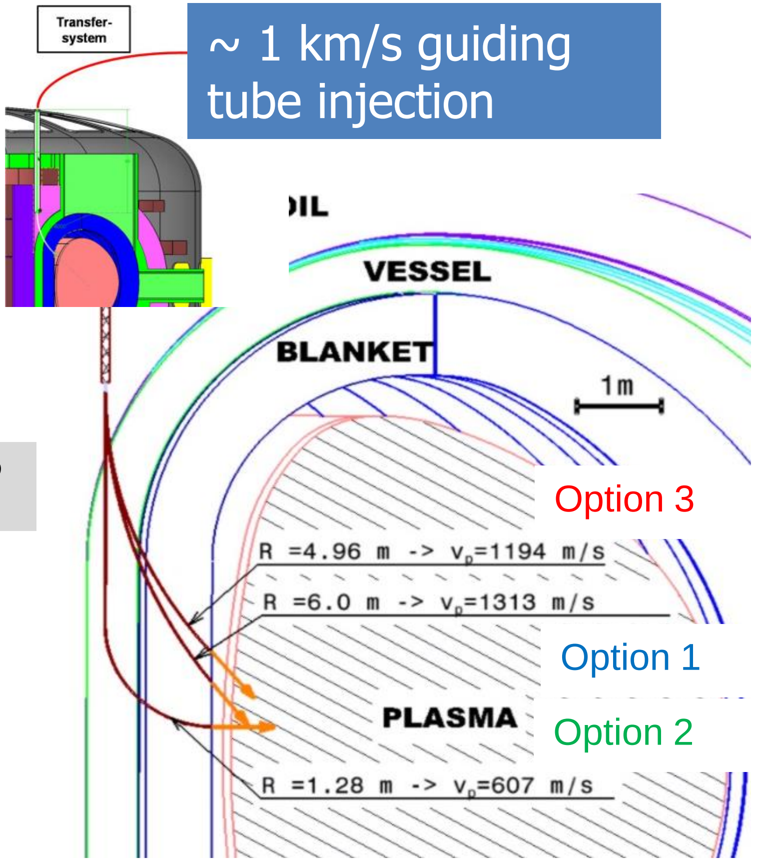


Pellet Injection Technology



- Continuous highly repetitive pellet injection technology is being developed with the following targets:
- Reduce inventory
- Noble gas admix
- Appropriate extrusion technology
- Optimize cryoneeds → cryogen free
- Avoid additional acceleration gas loads → centrifuge
- Tritium compatible drive and levitation of rotor arm
- Reliable pellet puncher design

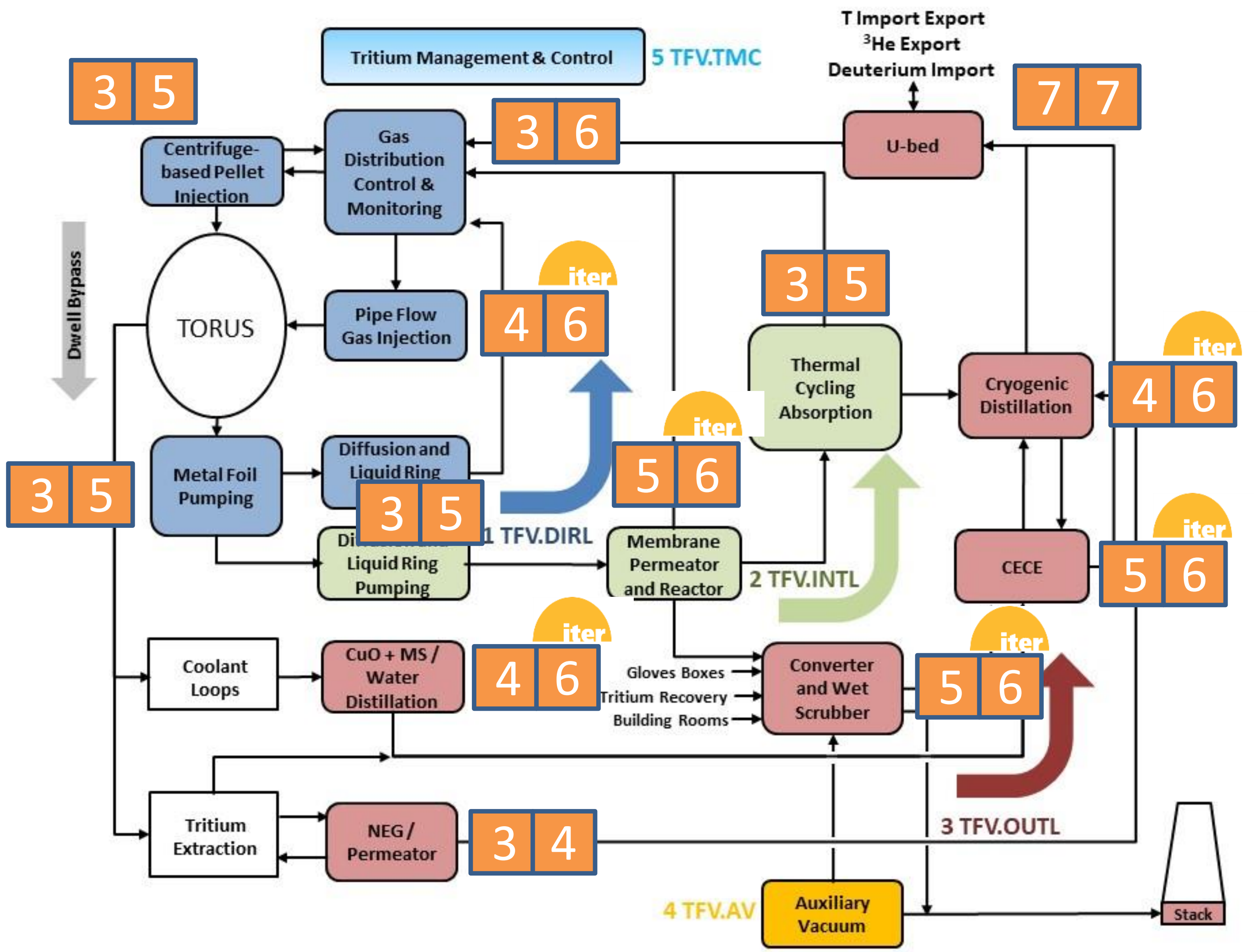
P.T. Lang et al., FED 156 (2020) 111591.



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

Karlsruhe Institute of Technology
MAX PLANCK INSTITUTE FOR PLASMA PHYSICS
Centre for Energy Research

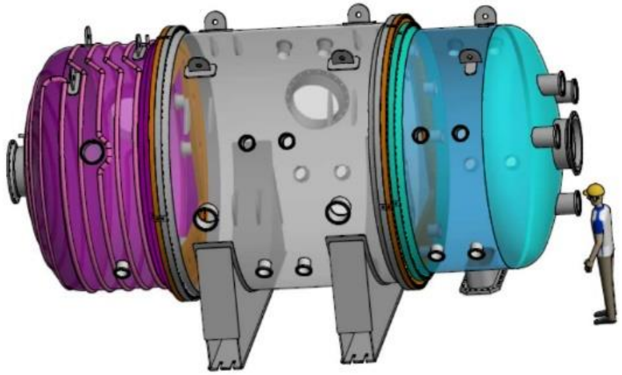
Next Steps: Integration → TRL 6

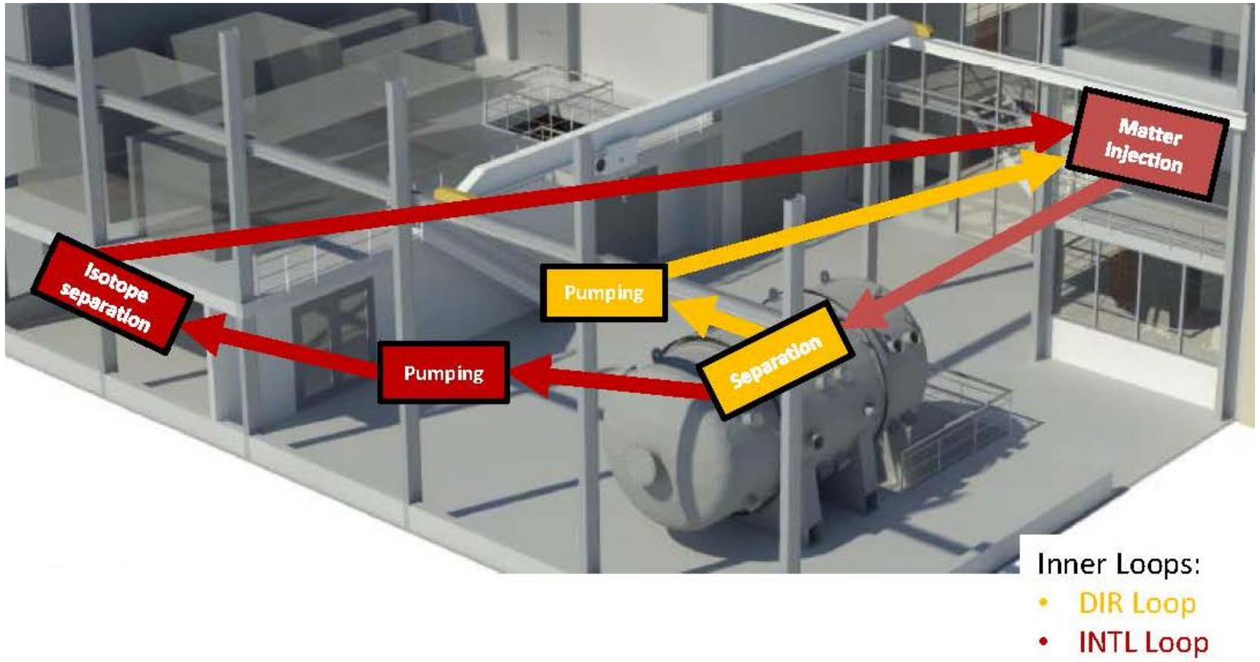


The next maturation level requires to add to single technologies TRL the aspect of integration and operation readiness.

Test Facility DIPAK@KIT

Central Test unit: Vacuum vessel, Hydrogen licensed,
Sufficiently large to test pumps individually + the pump cask
+ pellet injection = Full replication of the DIR-loop
Requires Gas / mercury / HVAC / Cryo-infrastructure /
a cavern for diffusion pumps and a platform for pellet injection.

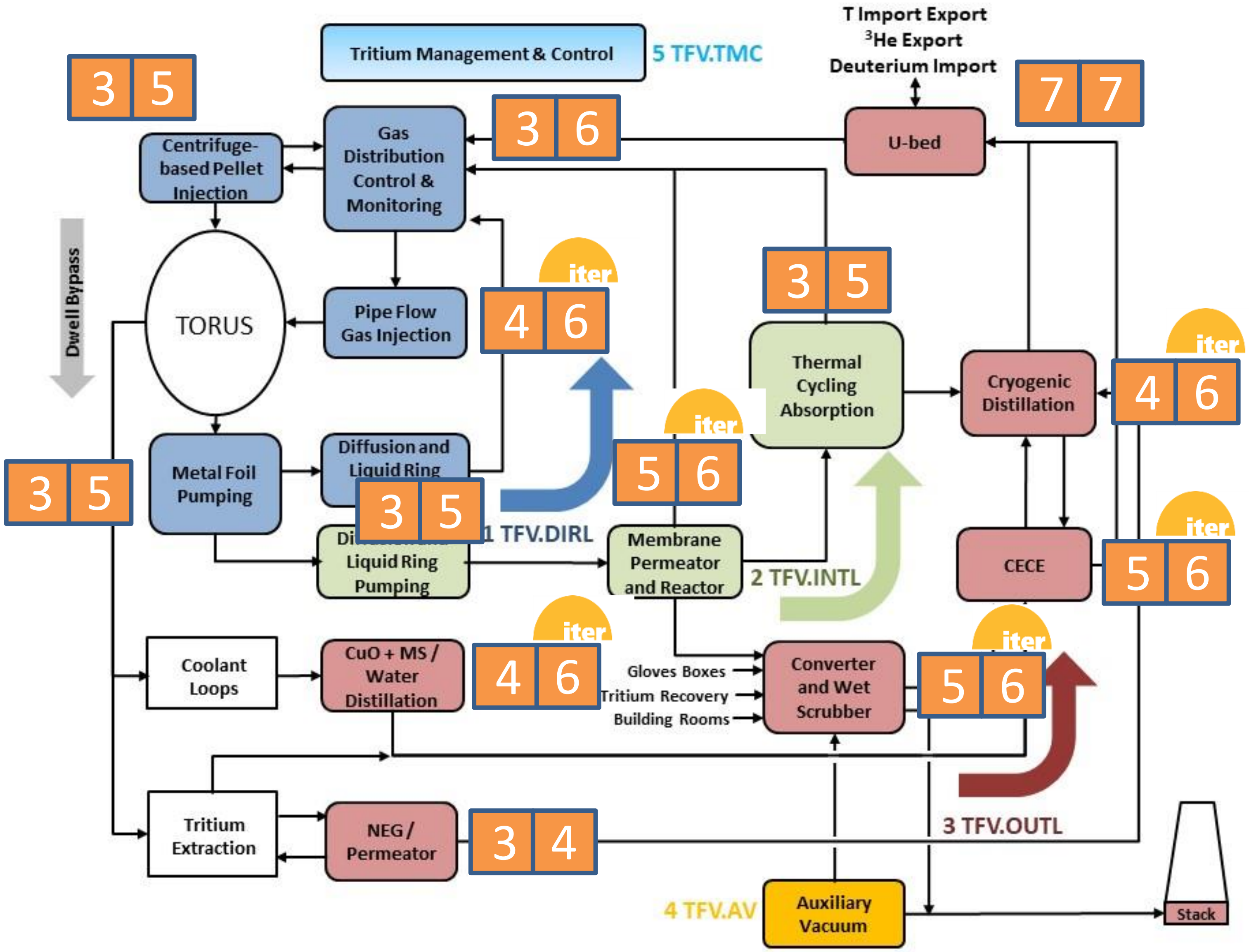


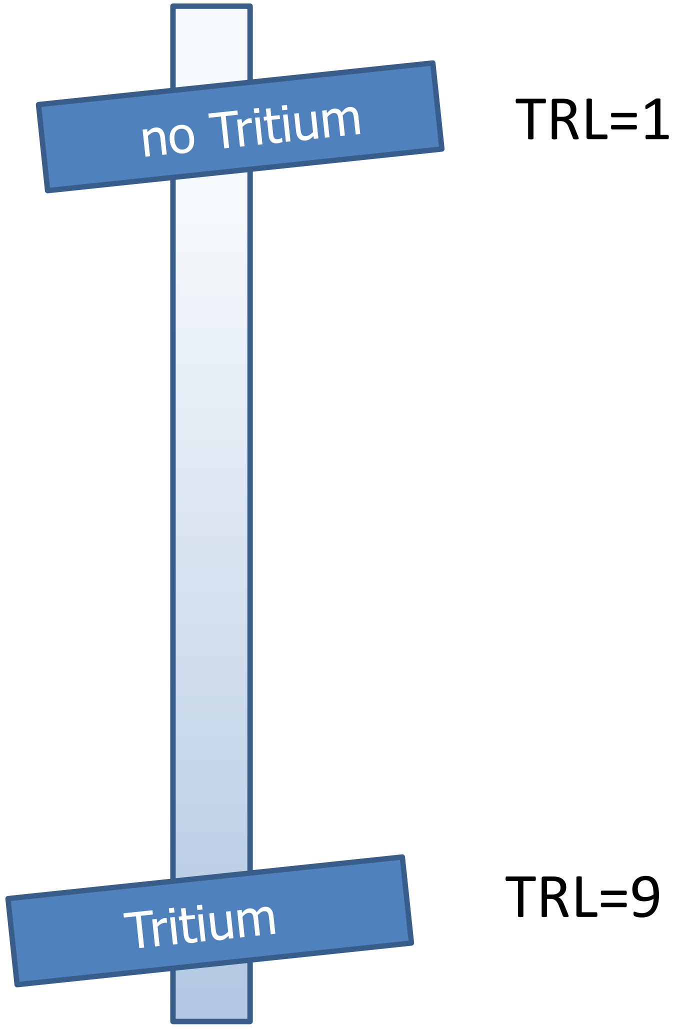


Pellet Engineering Test Bed (PET) will be integrated in new research facility DIPAK (Direct Internal Recycling Integrated Development Platform Karlsruhe)

(smaller vessel for pre-test)

Next Steps: Tritium → TRL 7

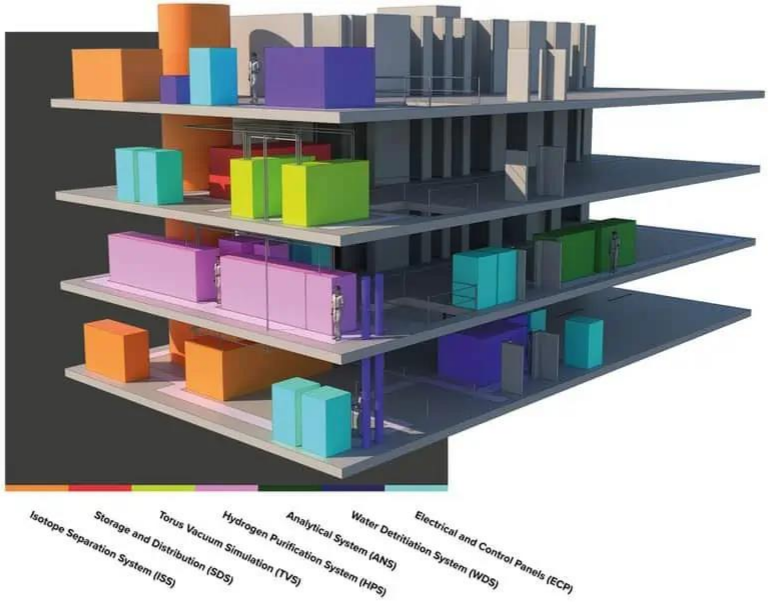




Demonstrate the complete fuel cycle…or distributed

Various Options, strategy to be agreed to be fast:

H3AT

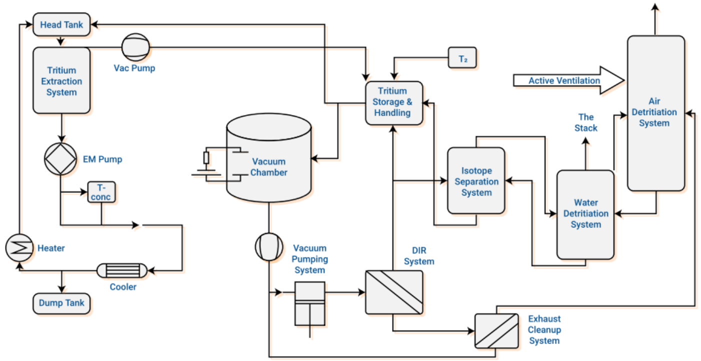


DT pellet injection, outer loops
No plasma

UNITY-2

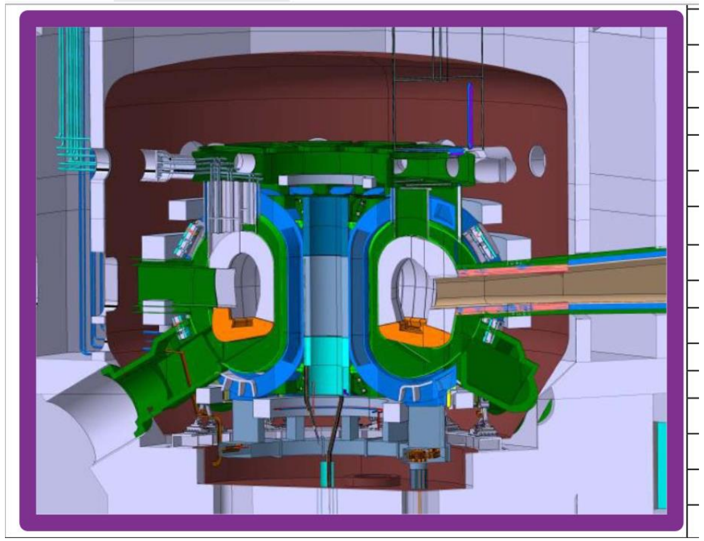
KYOTO FUSIONEERING

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens



Inner loops including DIR technologies, no plasma

VNS study



Plasma, field, but no DIR (non relevant architecture)

BEST

- Pulsed, plasma, field, tritium,…
- Although some technology decisions may be different than the ones taken for EU-DEMO, BEST is providing an environment closest to a fully integrated test.

thank you!