FUSION FUEL CYCLE

IAEA-ICTP Fusion School 2025

Dr. Tim Teichmann,
Kyoto Fusioneering Europe GmbH

20th May 2025

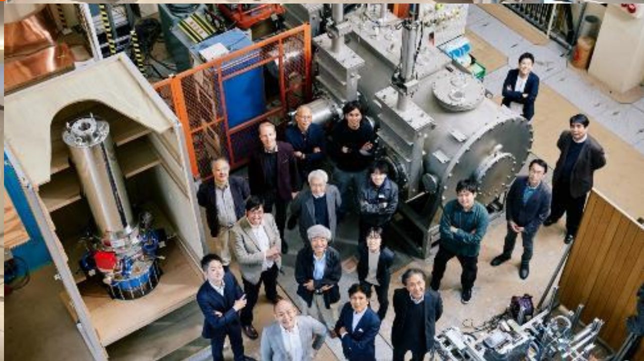
Kyoto Fusioneering

Company Overview and Mission

Members

150

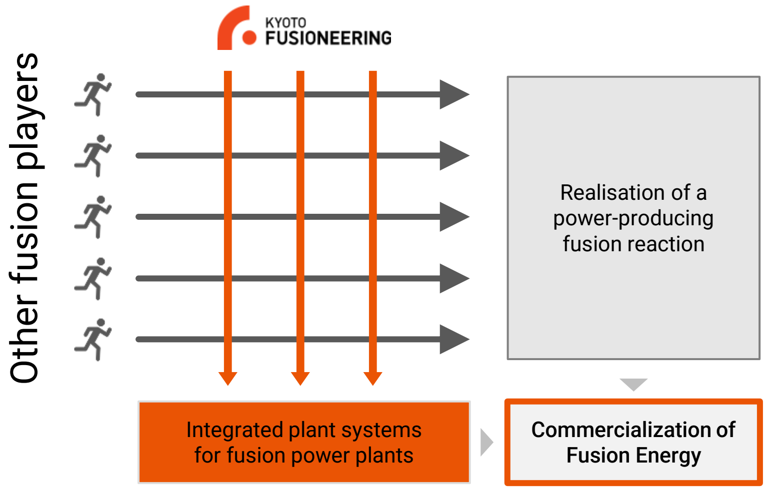
as of April1st 2025

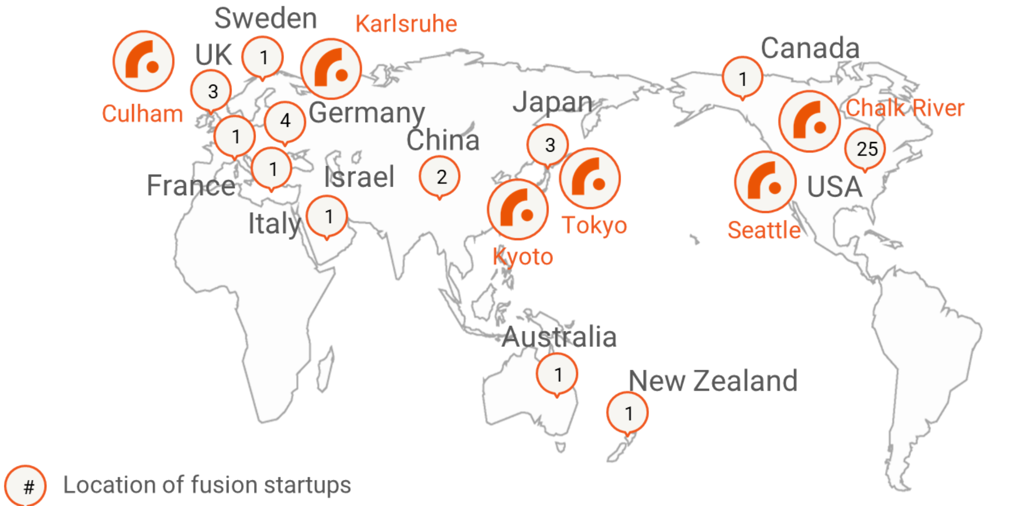


Company overview and mission

A pick-and-axe strategy for fusion development

With a **confinement concept-agnostic** approach to fusion plant technology development, KF is **complementary to the other private fusion programs** and is uniquely positioned to **generate revenue during each phase of development** while **avoiding the risks** of betting on a concept.



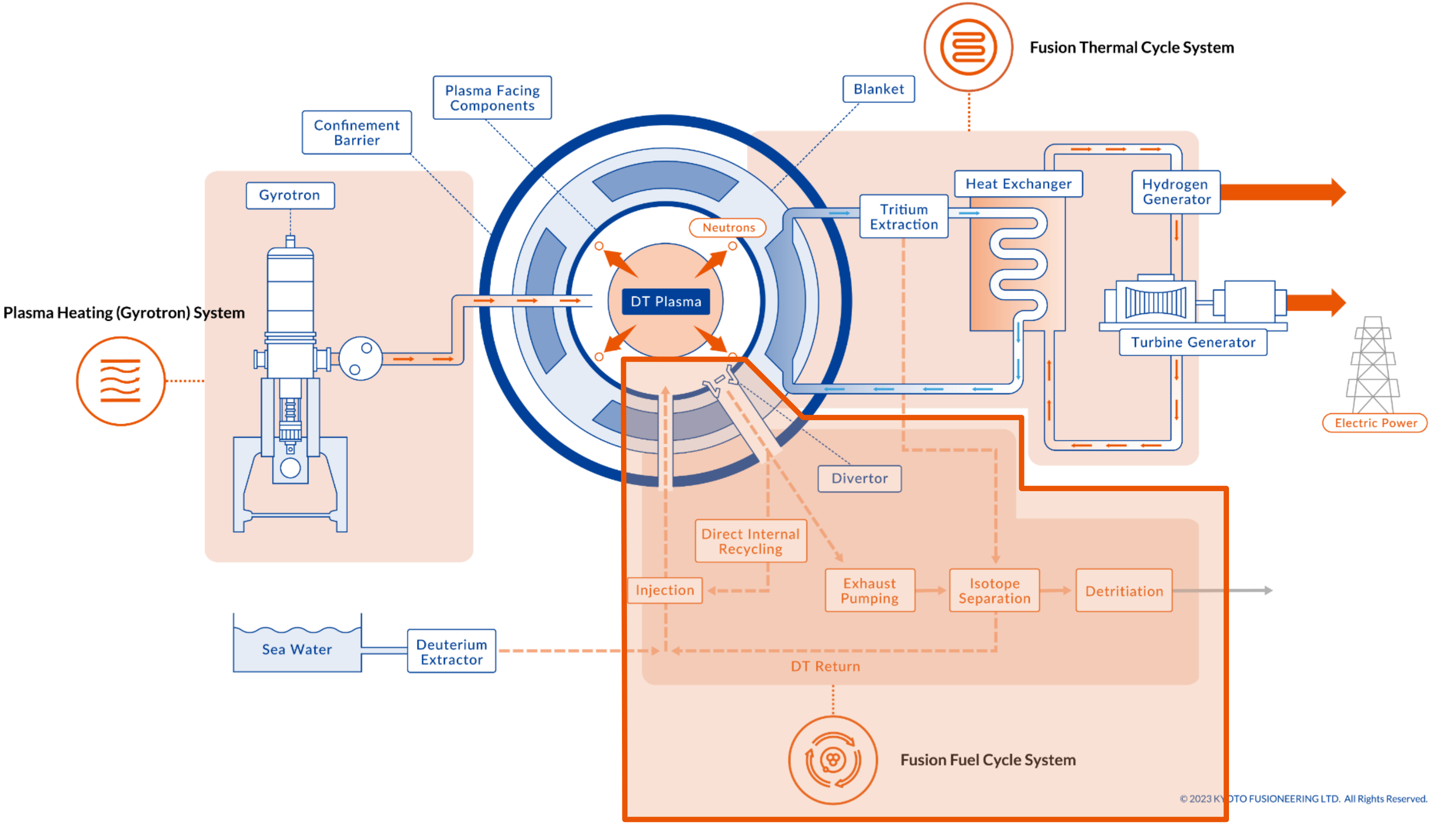


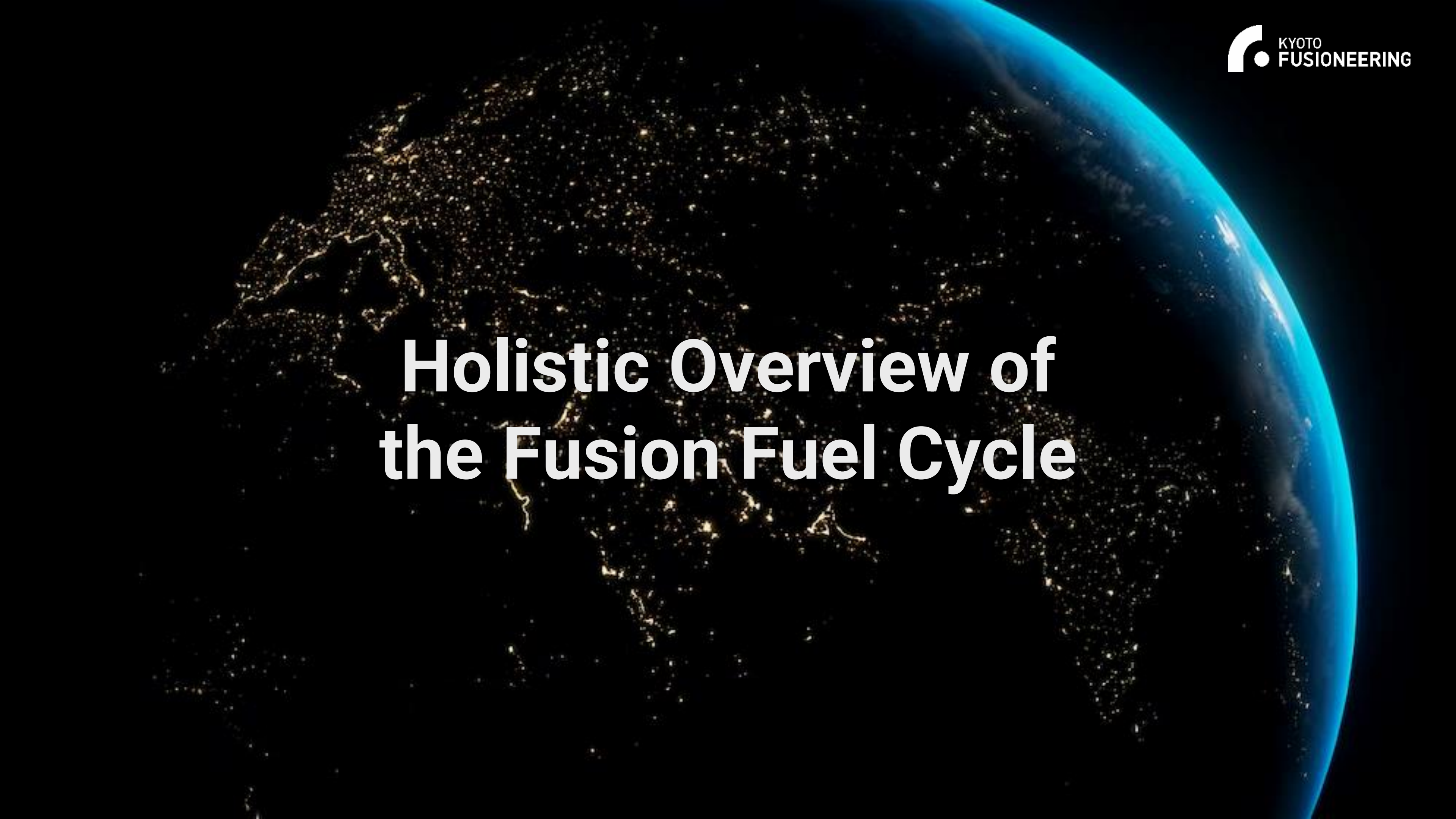
Source: The global fusion industry in 2024

The global distribution of the customers is reflected by a global representation of KF

Company overview and mission

Company mission

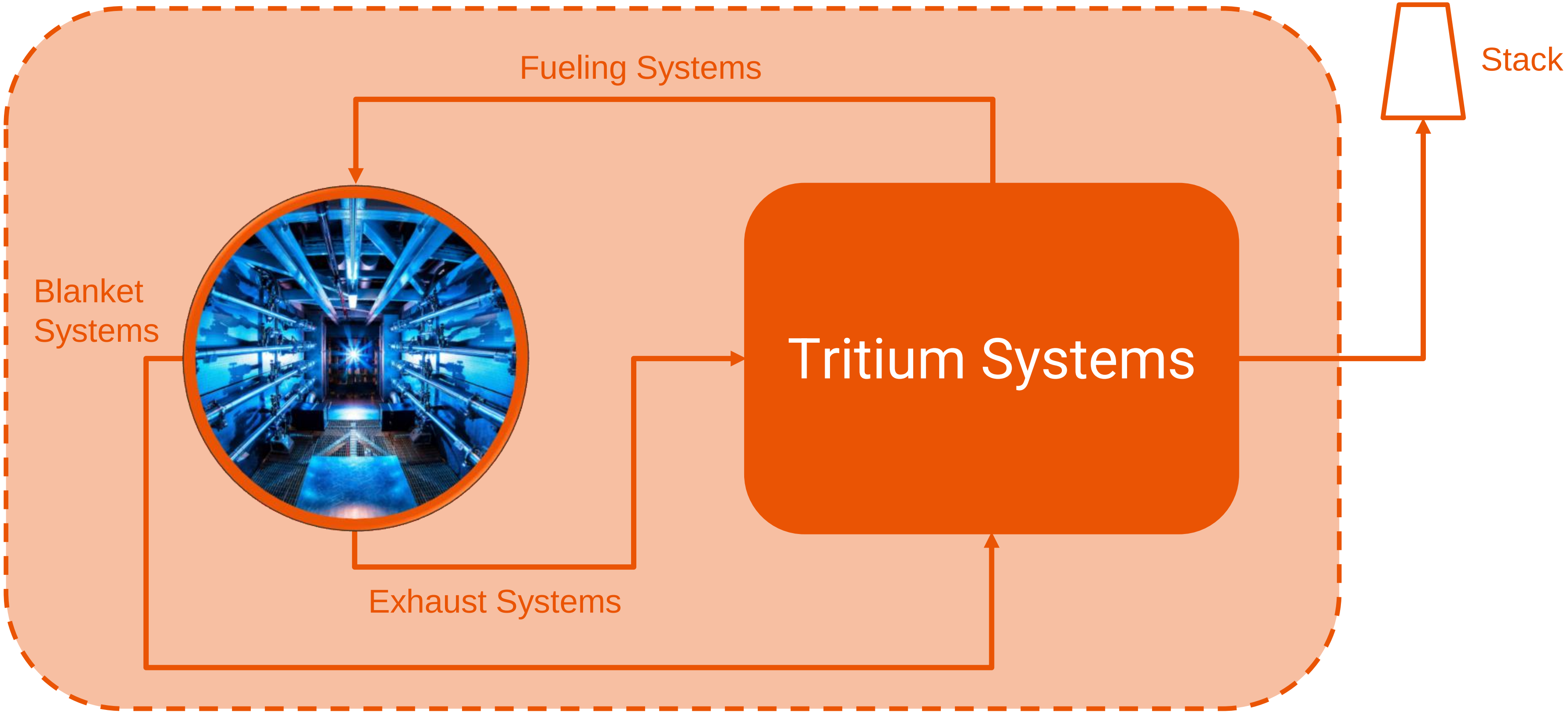




Holistic Overview of the Fusion Fuel Cycle

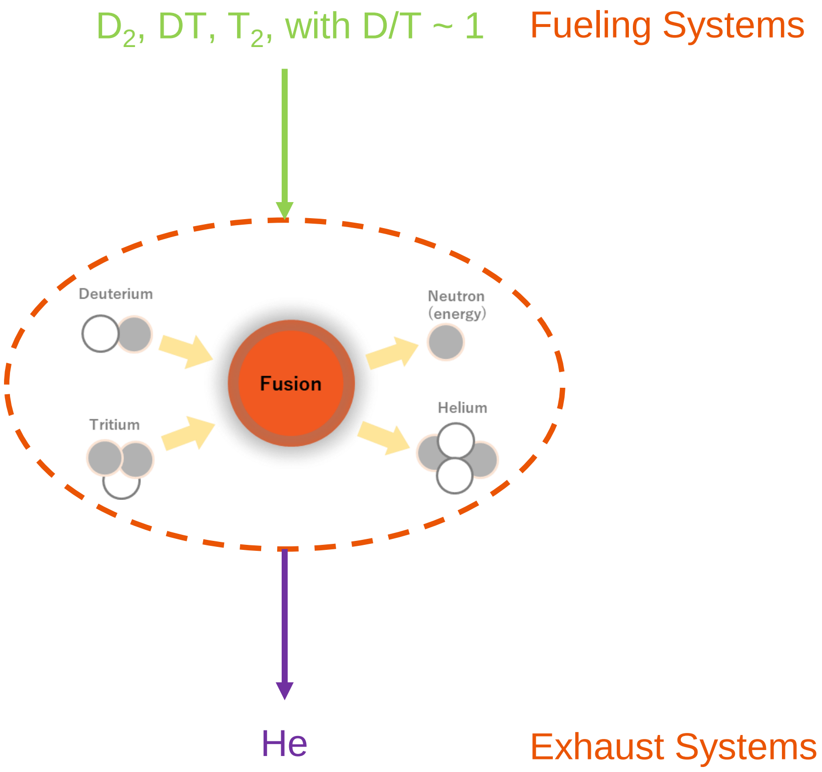
The fusion fuel cycle

Holistic high-level view



https://en.wikipedia.org/wiki/National_Ignition_Facility#/media/File:Preamplifier_at_the_National_Ignition_Facility.jpg

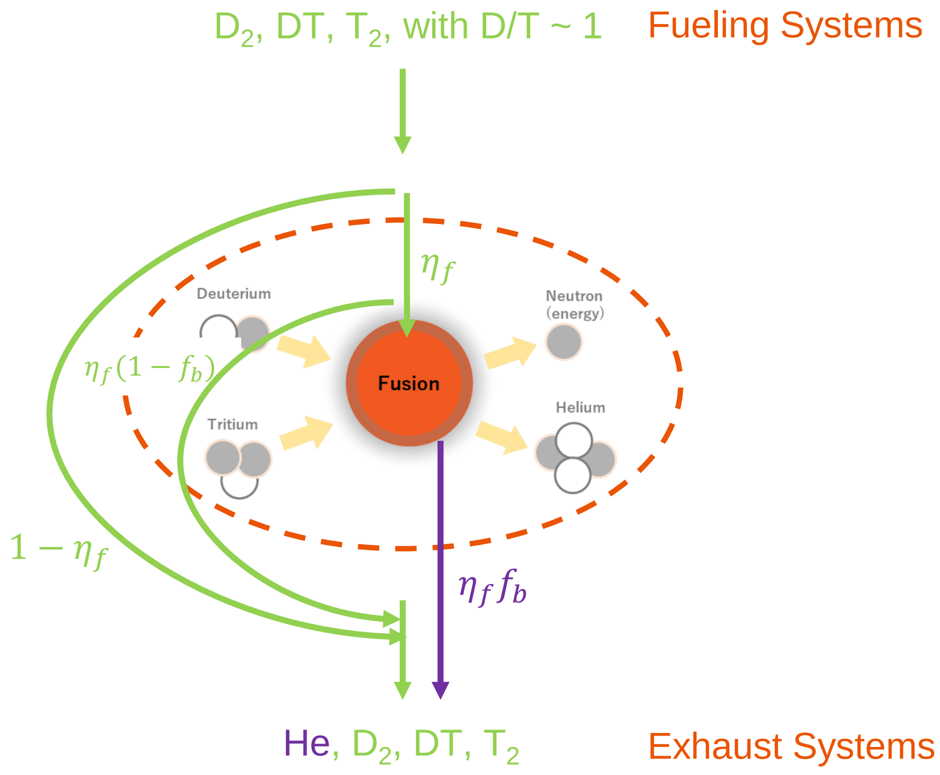
The fuel cycle as a service provider to the plasma



Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- Exhaust of products: He

The fuel cycle as a service provider to the plasma

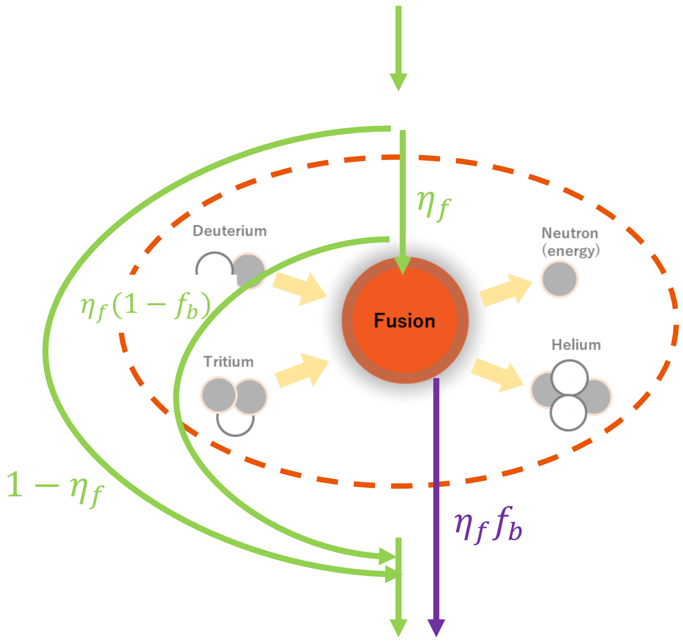


Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- Exhaust of products: He
- Limited fuelling efficiency (η_f) and burn-up fraction (f_b) of fuel (MCF: $\eta_f \times f_b \sim 0.01$ → ca. factor **100x** higher throughput than burn-up)

The fuel cycle as a service provider to the plasma

D_2, DT, T_2, with D/T ~ 1 Fueling Systems

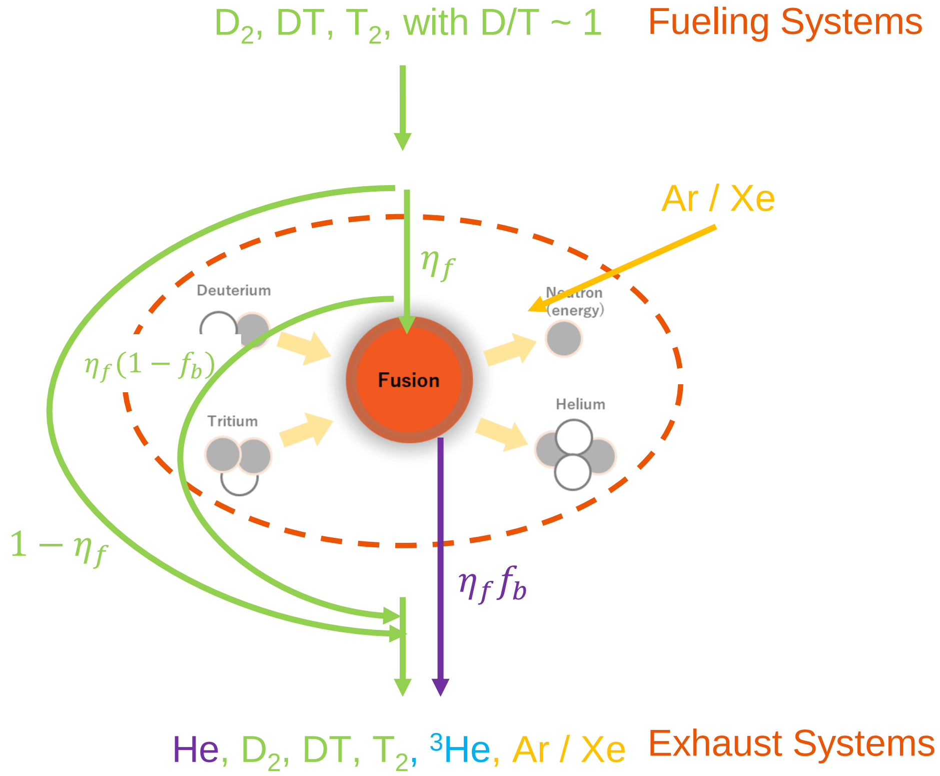


He, D_2, DT, T_2, ^{3}He Exhaust Systems

Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- Exhaust of products: He
- Limited fuelling efficiency (η_f) and burn-up fraction (f_b) of fuel (MCF: $\eta_f \times f_b \sim 0.01$→ ca. factor **100x** higher throughput than burn-up)
- Decay of tritium ($\tau = 12.3$ a)

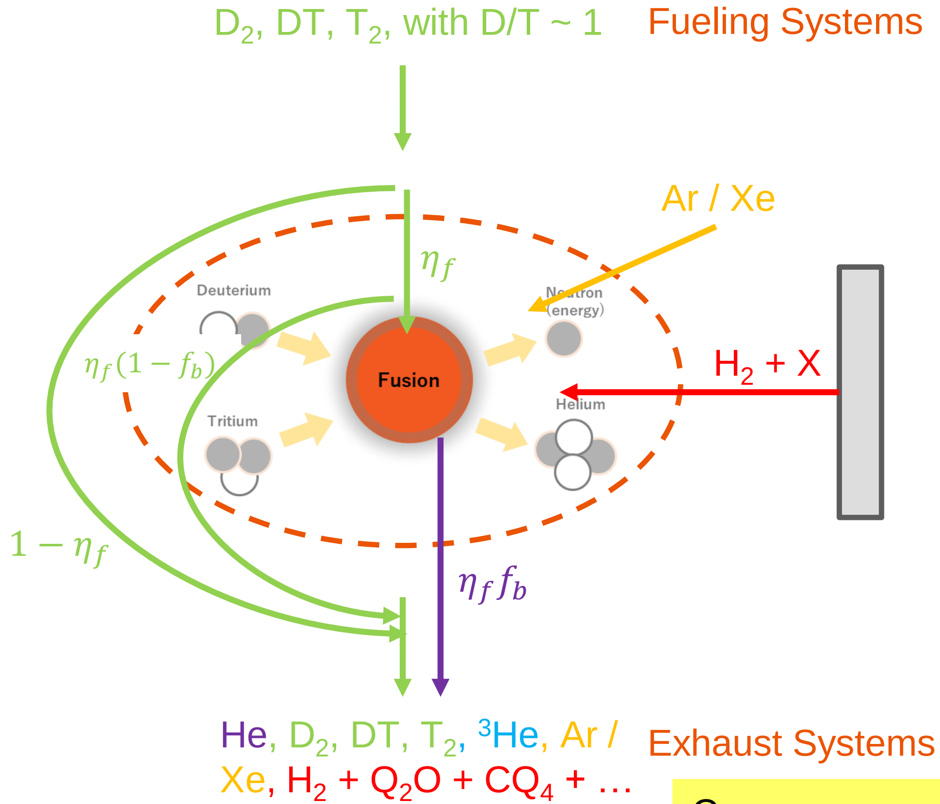
The fuel cycle as a service provider to the plasma



Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- Exhaust of products: He
- Limited fuelling efficiency (η_f) and burn-up fraction (f_b) of fuel (MCF: $\eta_f \times f_b \sim 0.01$→ ca. factor **100x** higher throughput than burn-up)
- Decay of tritium ($\tau = 12.3$ a)
- Plasma stability by enhancement gas (either admixed or gas puffing)

The fuel cycle as a service provider to the plasma

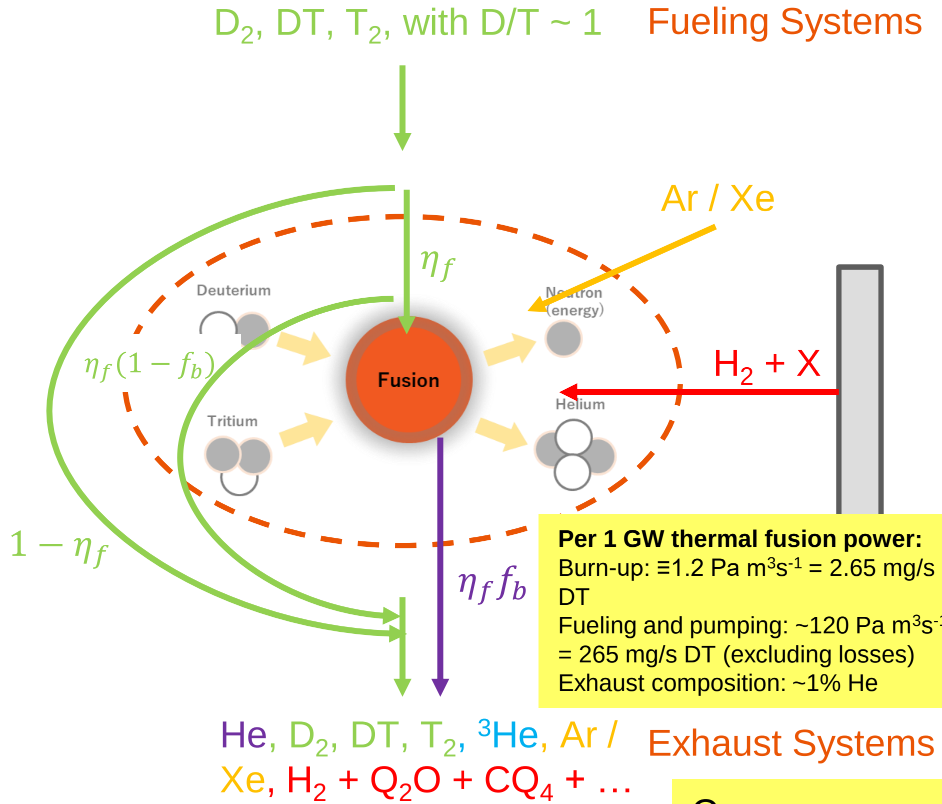


Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- Exhaust of products: He
- Limited fuelling efficiency (η_f) and burn-up fraction (f_b) of fuel (MCF: $\eta_f \times f_b \sim 0.01$→ ca. factor **100x** higher throughput than burn-up)
- Decay of tritium ($\tau = 12.3\ \mathrm{a}$)
- Plasma stability by enhancement gas (either admixed or gas puffing)
- Plasma interaction with and outgassing from structural materials, X = Q_2O, CQ_4, …

Common convention: Q = H, D, T

The fuel cycle as a service provider to the plasma



Per 1 GW thermal fusion power:
Burn-up: ≡1.2 Pa m^3s^{-1} = 2.65 mg/s DT
Fueling and pumping: ~120 Pa m^3s^{-1} = 265 mg/s DT (excluding losses)
Exhaust composition: ~1% He

Requirements and loads:

- Fueling with educts: D, T with D/T = 1
- Exhaust of products: He
- Limited fuelling efficiency (η_f) and burn-up fraction (f_b) of fuel (MCF: $\eta_f \times f_b \sim 0.01 \rightarrow$ ca. factor **100x** higher throughput than burn-up)
- Decay of tritium ($\tau = 12.3$ a)
- Plasma stability by enhancement gas (either admixed or gas puffing)
- Plasma interaction with and outgassing from structural materials, X = Q_2O, CQ_4, …

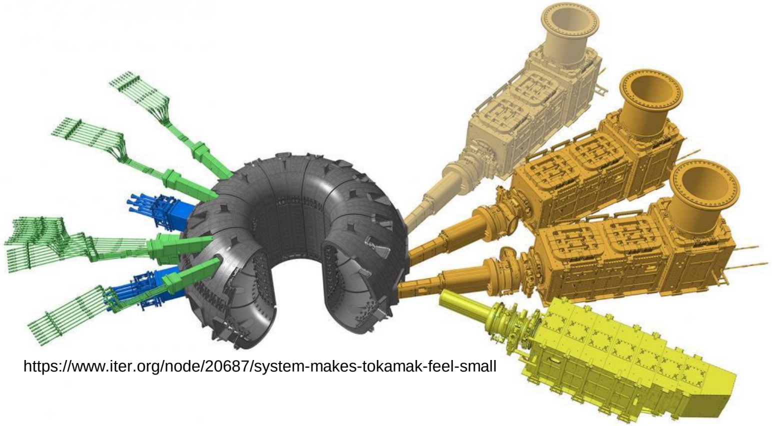
Common convention: Q = H, D, T

Fusion Fuel Cycle – Fueling (1/2)

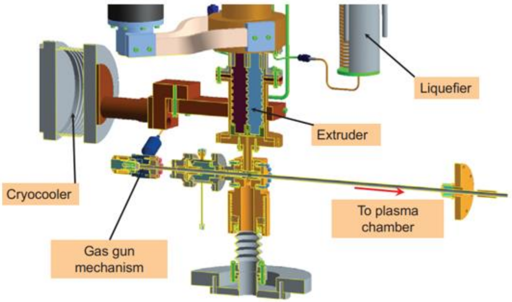
Magnetic Confinement (MCF)

- On high level comparable for Tokamak and Stellarator
- Main challenge: How to get the fuel nuclei to the plasma core
- Methods:
  - Neutral Beam Injection
    1. Ionization of DT gas
    2. Acceleration of positive ions (D^+, T^+)
    3. Neutralization with electrons, filtering of ions
    4. Injection of neutrals

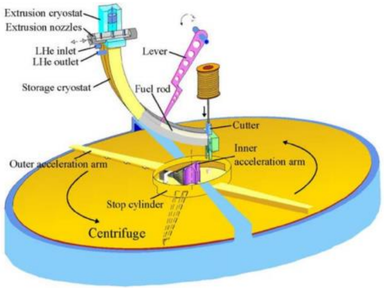
    Extremely inefficient, no solution for commercial reactor!
  - Cryogenic Pellet Injection System
    1. Freezing of DT gas to pellets
    2. Acceleration of pellets to 500-1000 m/s (= 1800-3600 km/h) with a) gas gun (blower, pneumatic) or b) centrifuge
    3. Injection of pellets to plasma via guide tube (Ø mm range)
       Injection from inboard HFS side (pellet ablation, E x B drift)



https://www.iter.org/node/20687/system-makes-tokamak-feel-small



David Rasmussen, US ITER Fusion Integration, "D-T Pellet Injection for ITER Plasma Fueling", TUG, Oak Ridge, TN, 2018

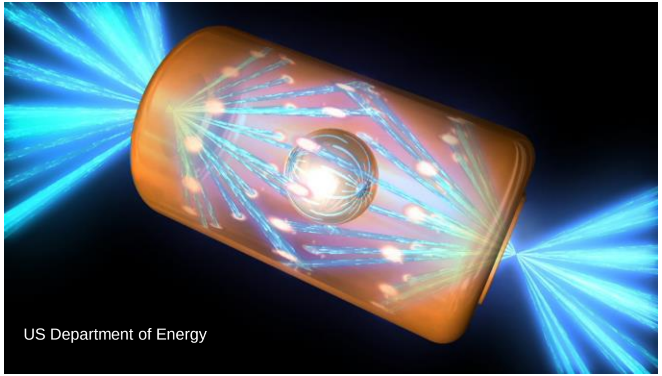


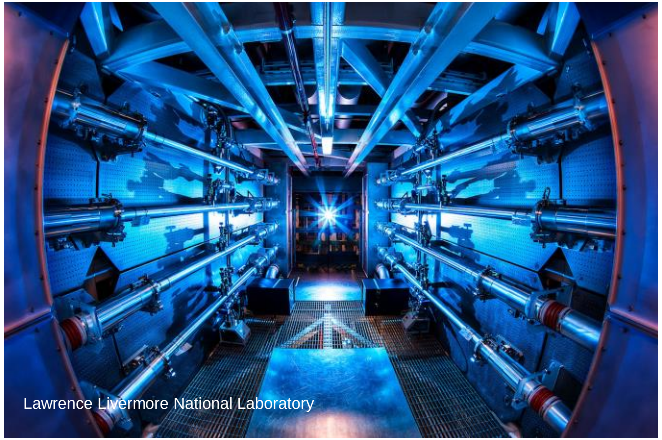
P. Lang et al., EURO*fusion*, "A flexible pellet injection system for the tokamak JT-60SA: The final conceptual design", 2017

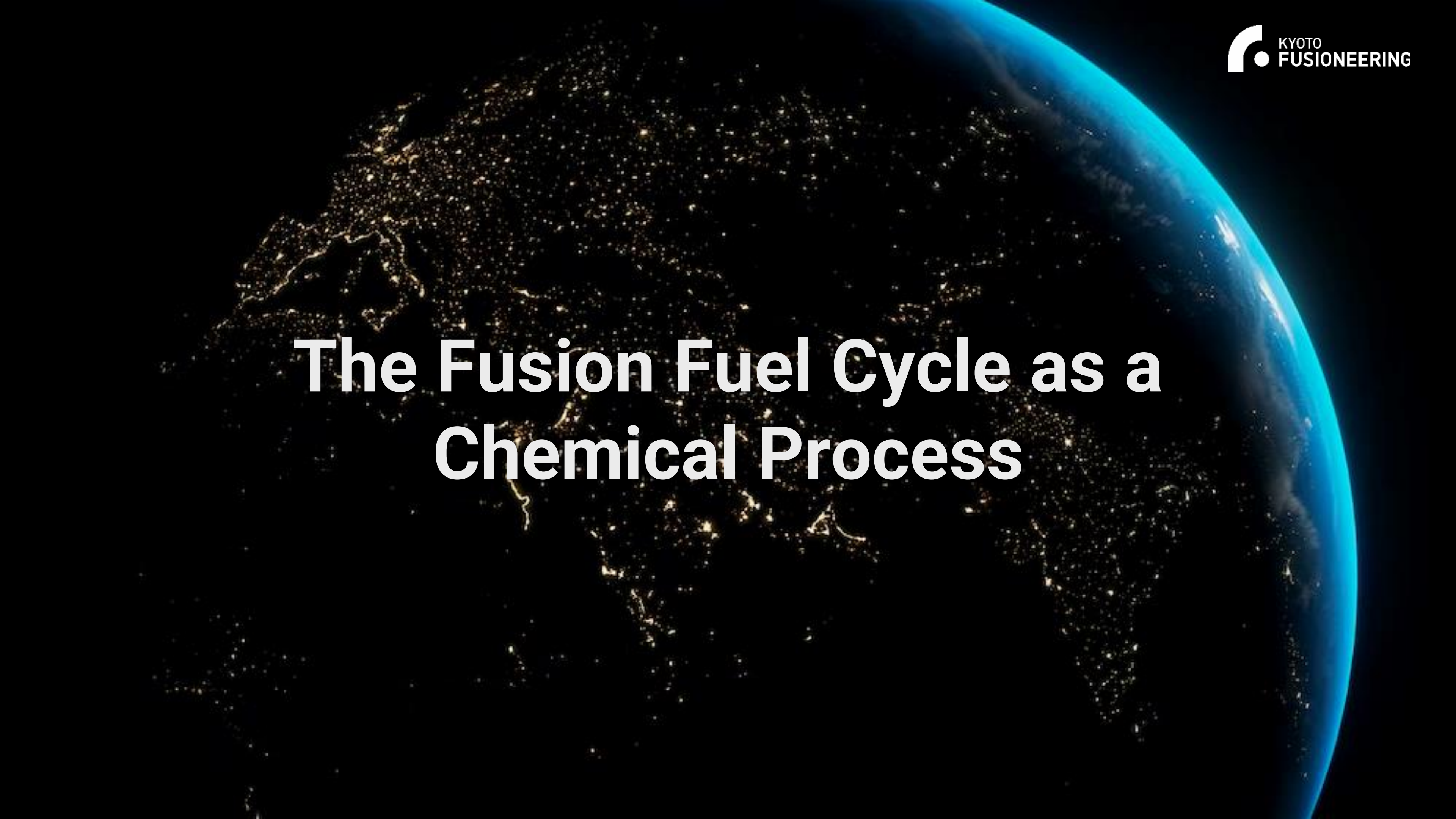
Fusion Fuel Cycle – Fueling (2/2)

Inertial Confinement (ICF)

- Comparable for most inertial confinement concepts
- …, but of course the devil lies in the details
- Main challenges:
  - High frequency (order of 10 Hz) for deployment of targets
  - … which equals 1 million targets per day per power plant
  - Target properties (homogeneity, …) to allow absorption of driver beams (direct/indirect drive)
  - Debris/vaporized material from targets (indirect drive, ablator), which the fuel cycle needs to keep at acceptable levels and process it


US Department of Energy


Lawrence Livermore National Laboratory

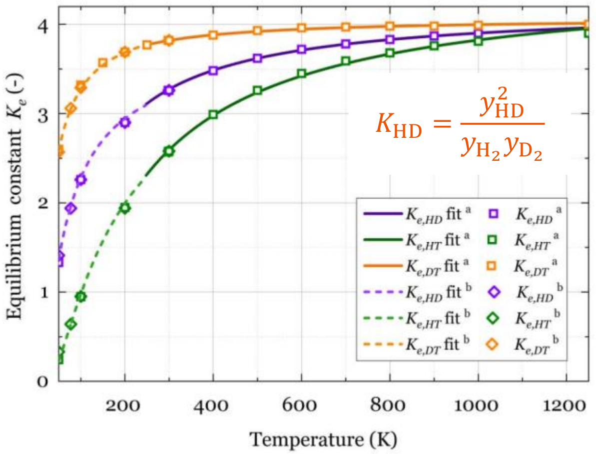


The Fusion Fuel Cycle as a Chemical Process

Tritium chemistry and materials compatibility

Isotope exchange, radio-catalysis

- Recalling the exhaust mixture anticipated out of most fusion reactors: He, D_2, DT, T_2, ^{3}He, Ar / Xe, H_2 + Q_2O + CQ_4 + …
- Tritium properties:
  - Isotope exchange:
    - $\mathrm{H_2 + D_2 + T_2 \rightarrow H_2 + HD + HT + D_2 + DT + T_2}$
    - $\mathrm{T_2 + HX \rightleftharpoons HT + XT}$
  - Oxidation (like "normal" hydrogen):
    - $\mathrm{2T_2 + O_2 \rightarrow 2T_2O,\ 3T_2 + N_2 \rightarrow 2NT_3}$
  - β-decay induced self-radiolysis:
    - $\mathrm{T_2 \rightarrow T_2^+ + e^-,\ T_2 + T_2^+ \rightarrow T_3^+ + T\cdot}$ (radical)
    - $\mathrm{T_2O \rightarrow T_2O^+, T_3O^+, T_2O_2}$ (corrosive)
  - Induced polymerisation
    - $\mathrm{T_2 + CH_4 \rightarrow CH_xT_y}$
    - $\mathrm{2CQ_4 \rightarrow C_2Q_6 + Q_2, CQ_4 + C_2Q_6 \rightarrow C_3Q_8 + Q_2, \ldots}$
    - → Very restricted use of polymers in tritium systems



B. J. Peters, "Development of a Hydrogen-Selective Vacuum Pump on the Basis of Superpermeation", PhD Thesis, 2020

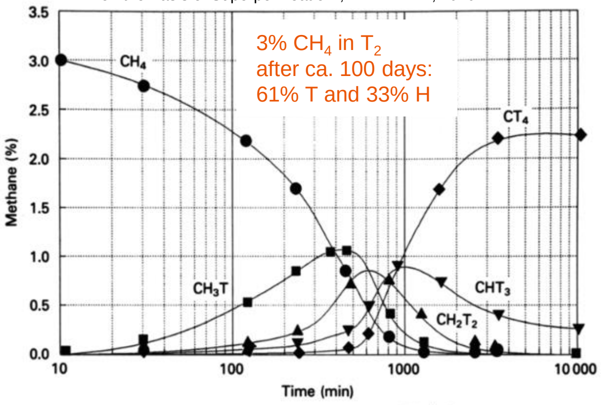
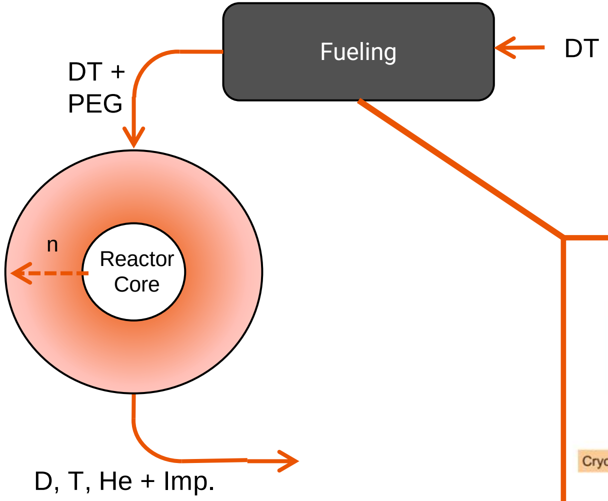


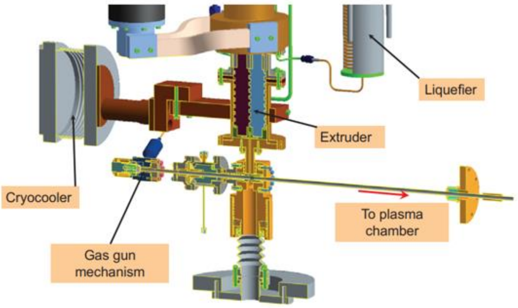
Fig. 2. Evolution of CT_4 from 3.0% CH_4 in T_2.

G. T. McConville and D. A. Menke, "Exchange of Dilute CH4 in Tritium Gas", Fusion Technology 23(3), 1993

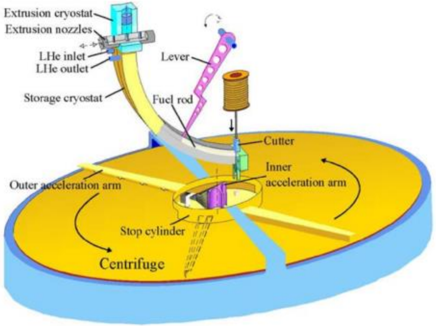
The Fusion Fuel Cycle

Let’s build a fuel cycle…





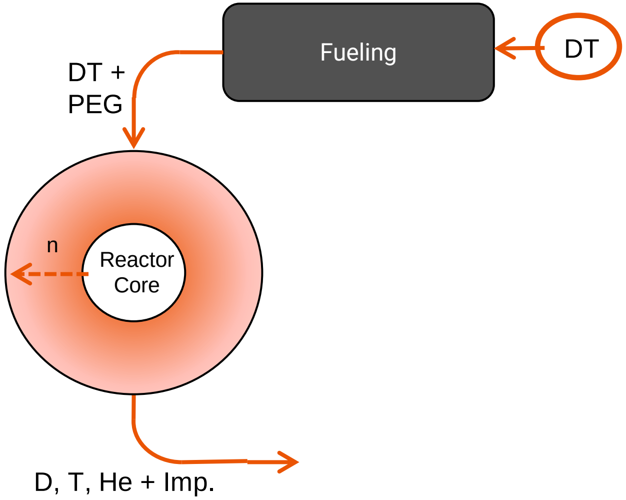
David Rasmussen, US ITER Fusion Integration, “D-T Pellet Injection for ITER Plasma Fueling”, TUG, Oak Ridge, TN, 2018



P. Lang et al., EURO*fusion*, “A flexible pellet injection system for the tokamak JT-60SA: The final conceptual design”, 2017

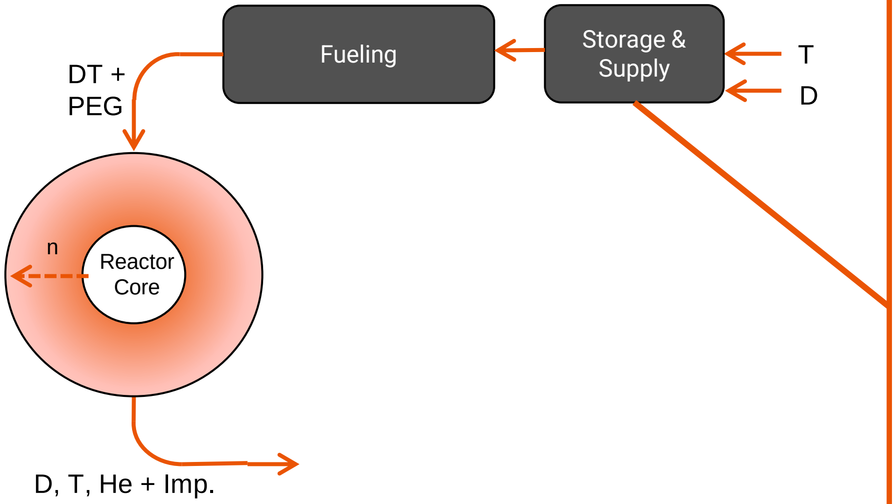
The Fusion Fuel Cycle

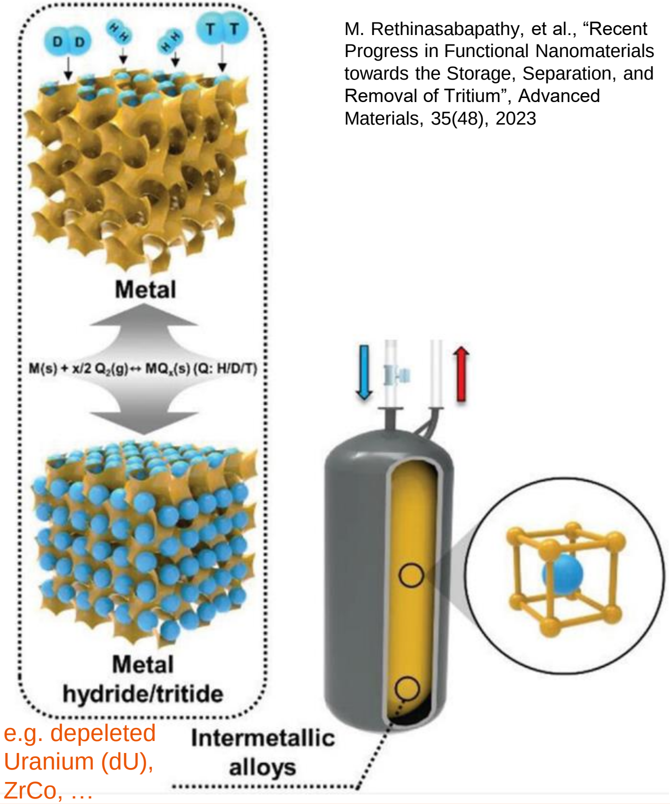
Let's build a fuel cycle…



The Fusion Fuel Cycle

Let's build a fuel cycle…



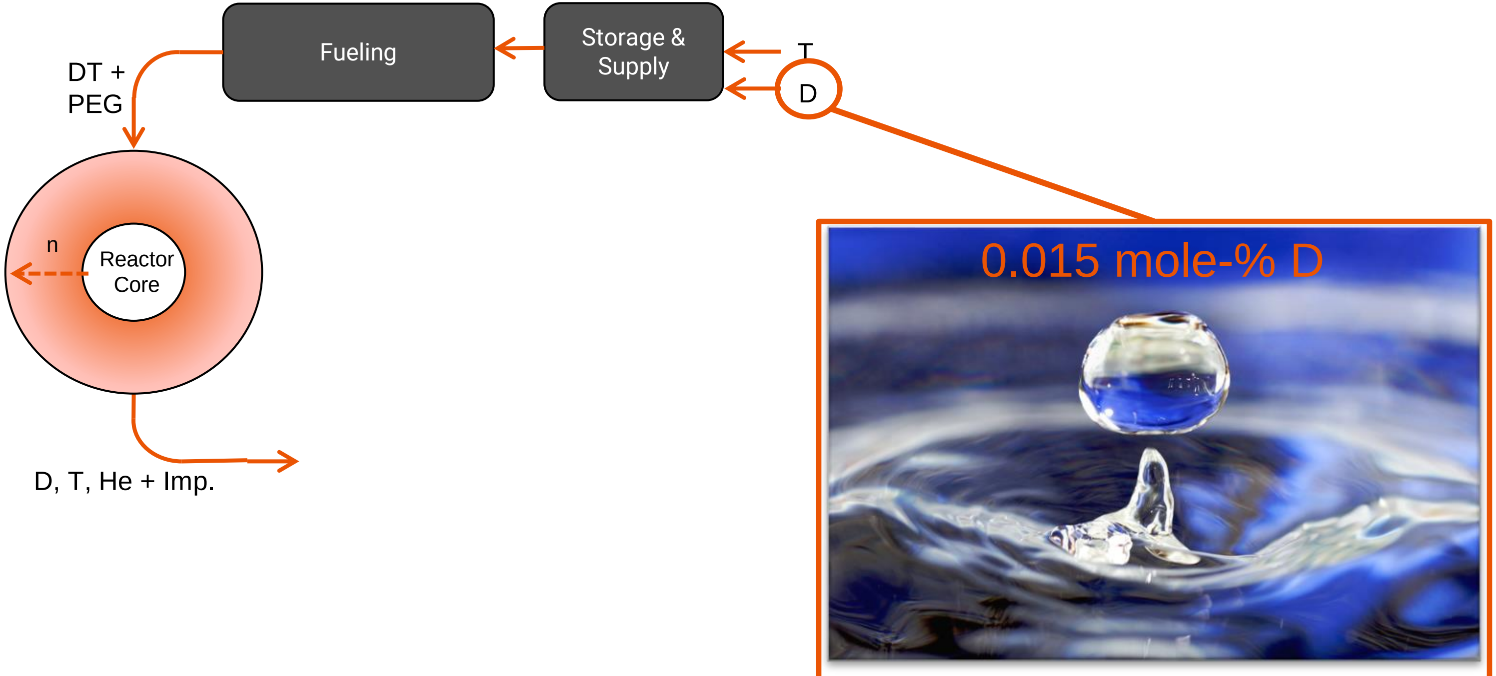


M. Rethinasabapathy, et al., "Recent Progress in Functional Nanomaterials towards the Storage, Separation, and Removal of Tritium", Advanced Materials, 35(48), 2023

e.g. depeleted Uranium (dU), ZrCo, …

The Fusion Fuel Cycle

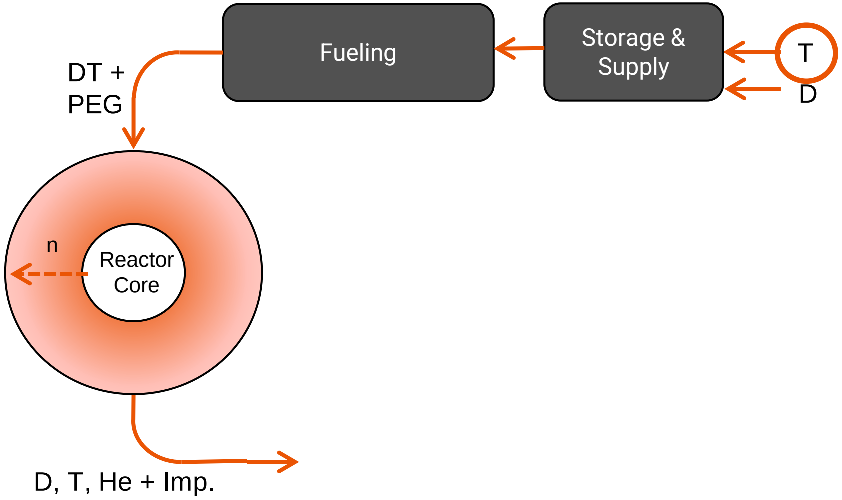
Let's build a fuel cycle…



https://en.wikipedia.org/wiki/Water#/media/File:Water_drop_001.jpg

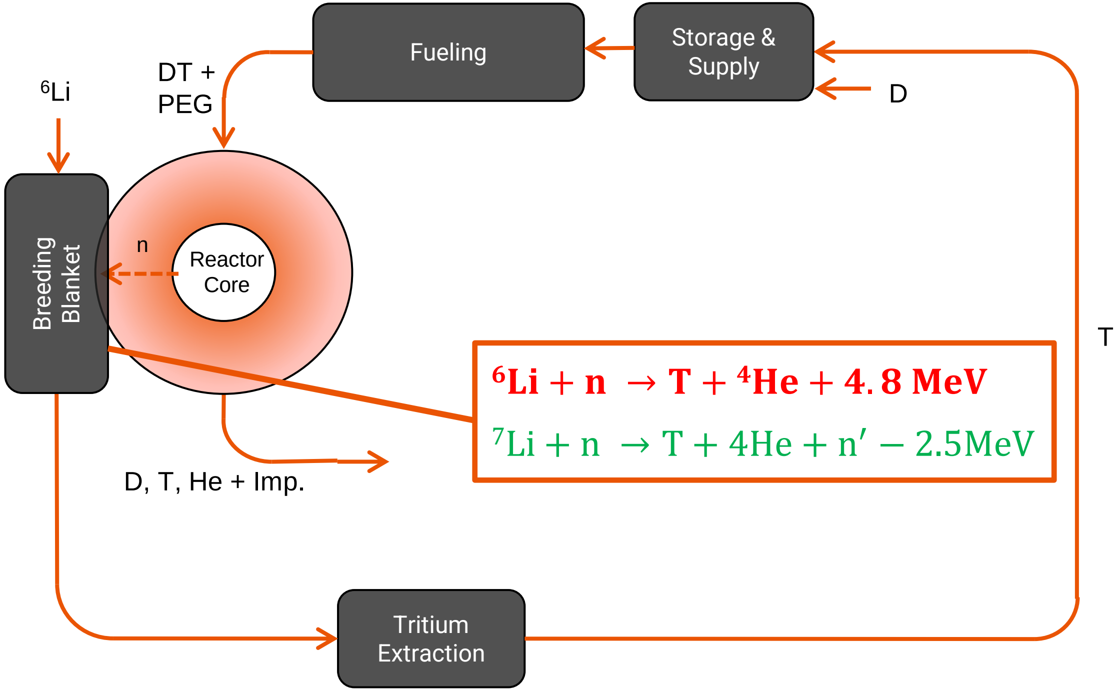
The Fusion Fuel Cycle

Let's build a fuel cycle…



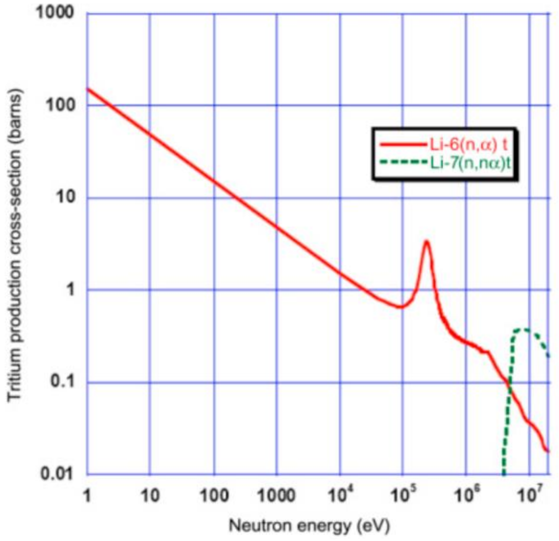
The Fusion Fuel Cycle

Let's build a fuel cycle...



$$\mathbf{{}^6Li + n \rightarrow T + {}^4He + 4.8\ MeV}$$

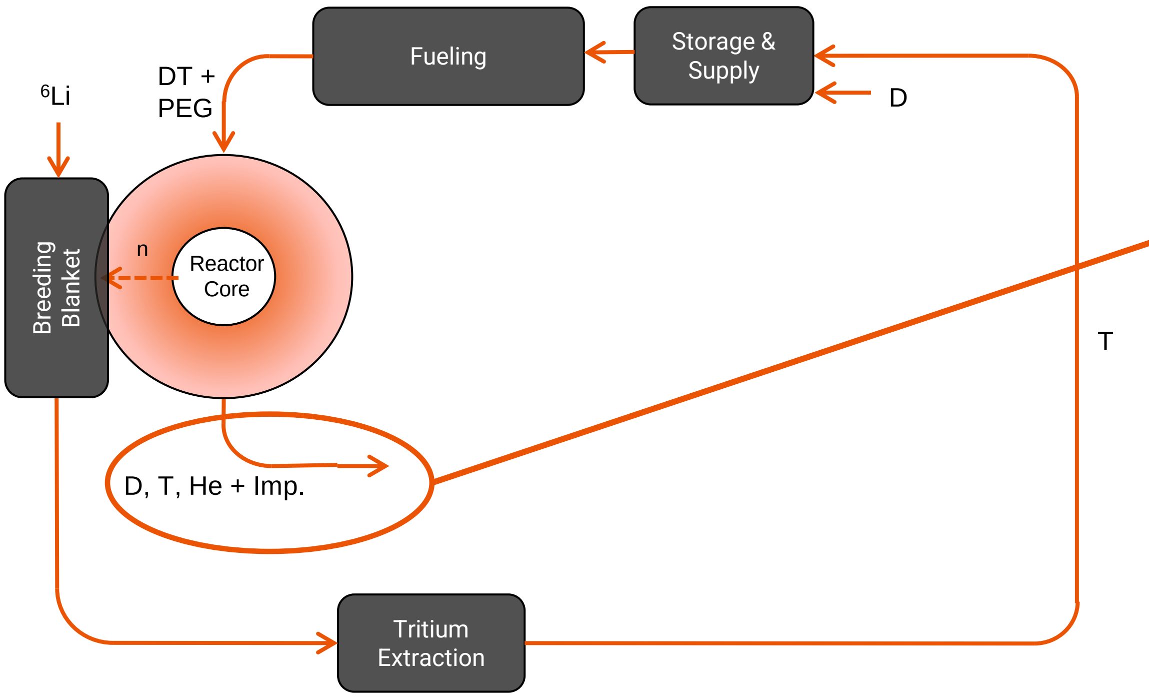
$$^7\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + 4\mathrm{He} + \mathrm{n}' - 2.5\mathrm{MeV}$$



R. Yoshioka, et al., "Molten Salt Reactors and Thorium Energy, 7 – Materials", Pages 189-207, 2017

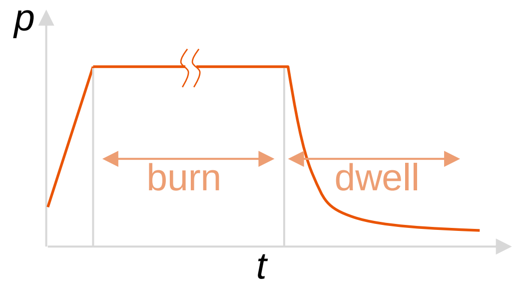
The Fusion Fuel Cycle

Let's build a fuel cycle...



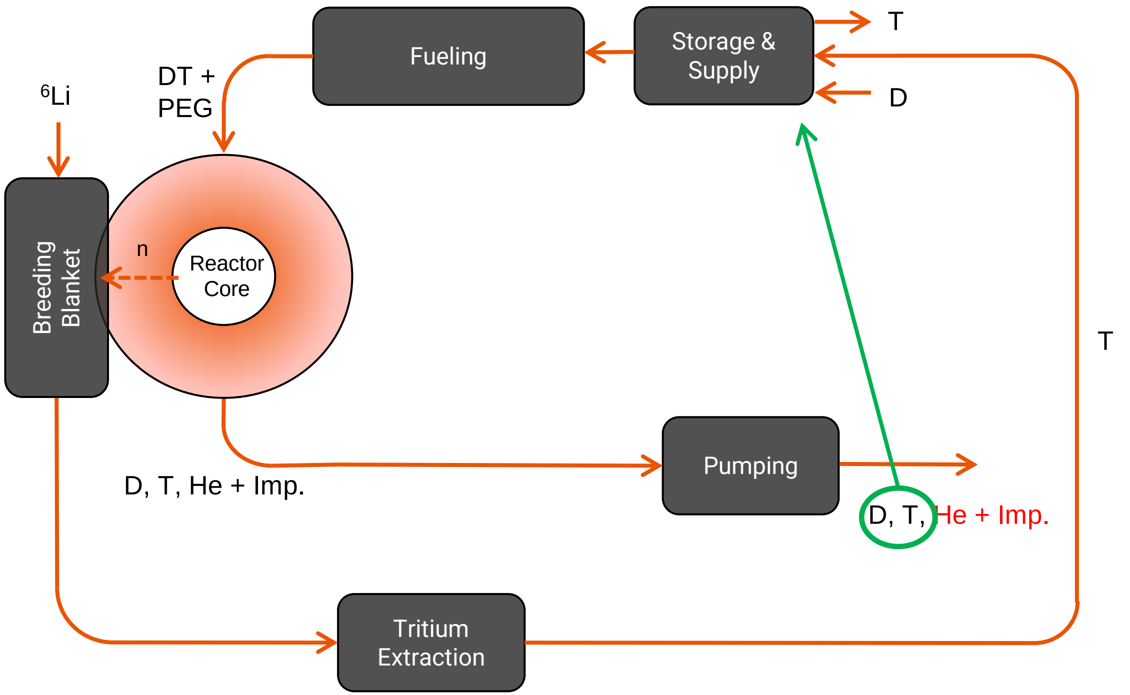
Magnetic confinement fusion:

- Burn phase:
  - Task: Remove He and impurities from plasma to keep it going
  - Throughput: >100 Pa m^{3}s^{-1} per GW fusion power (see above)
  - Vacuum: ~ 1 Pa
- Dwell phase:
  - Task: Create conditions for next plasma ignition as fast as possible
  - Throughput: low
  - Vacuum: ~ 1 mPa



The Fusion Fuel Cycle

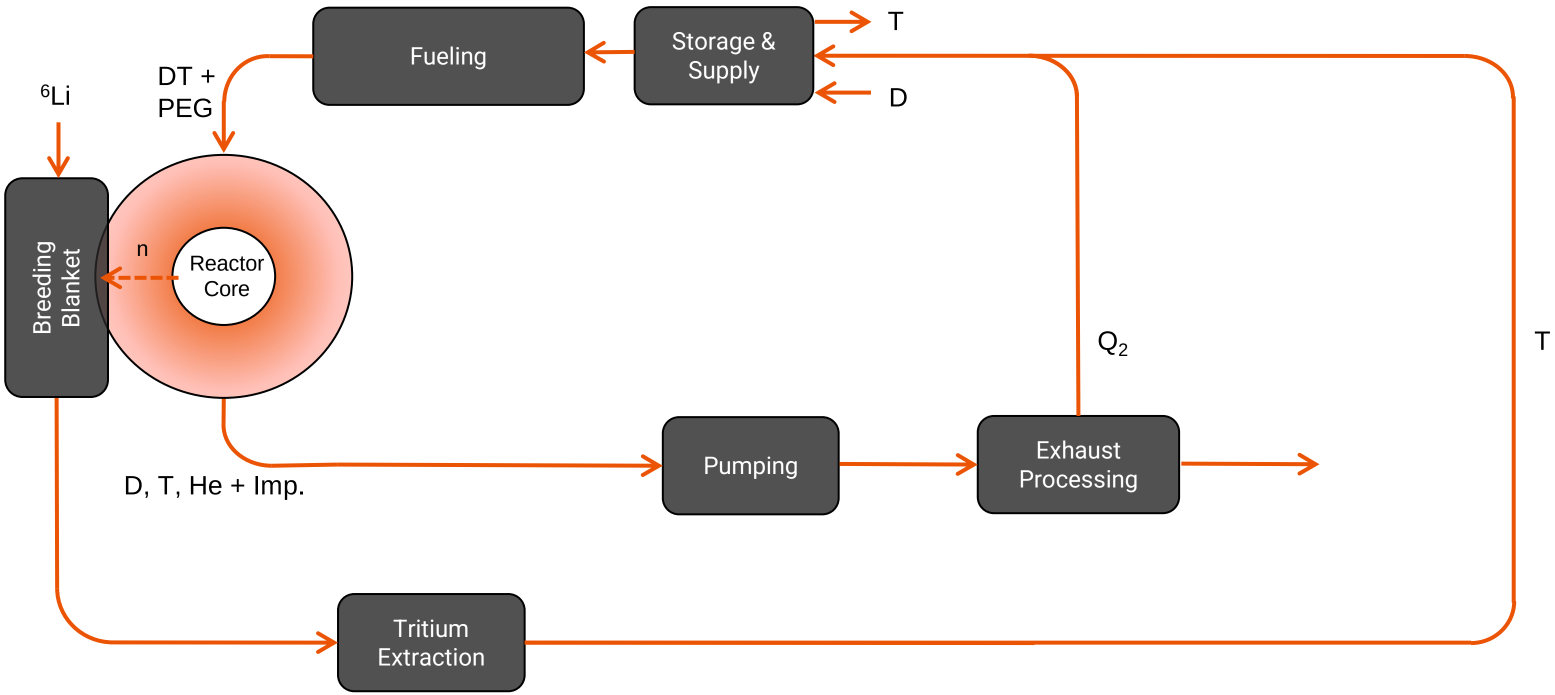
Let's build a fuel cycle…



Q_2

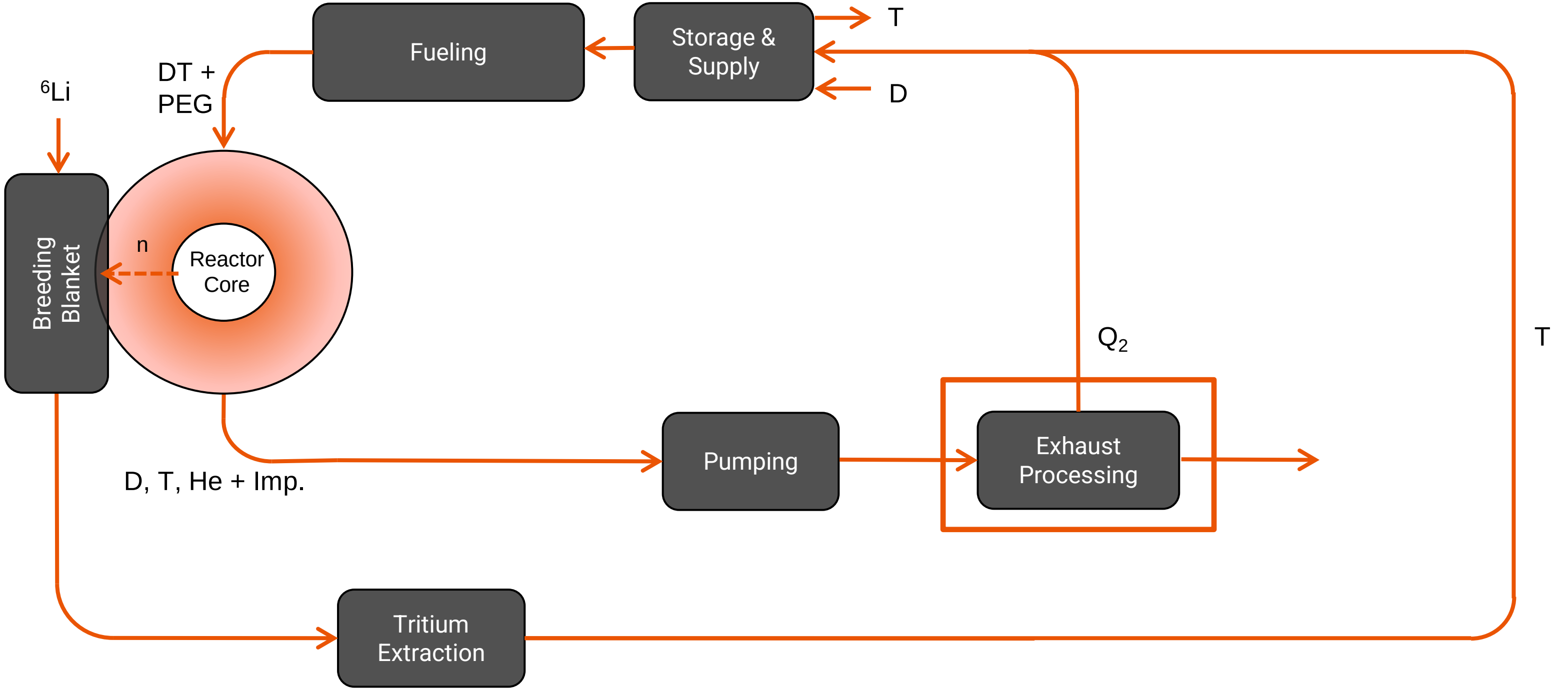
The Fusion Fuel Cycle

Let's build a fuel cycle...



The Fusion Fuel Cycle

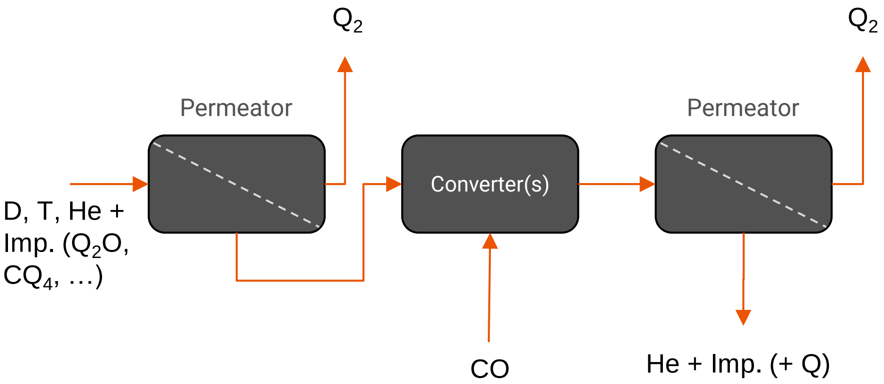
Let's build a fuel cycle…



The Fusion Fuel Cycle

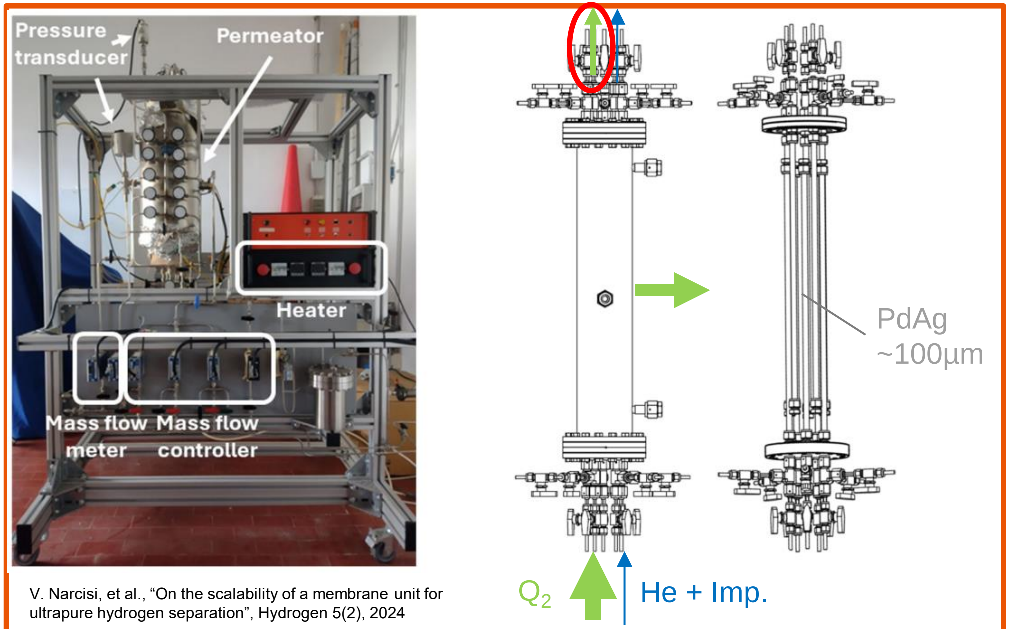
A closer look into exhaust processing

- Main functions of the exhaust processing system:
  1. Separation of Q_2 by selective membrane permeation
  2. Chemical conversion of Q-containing species to Q_2
     - Hydrocarbon cracking: $CQ_4 \leftrightarrow C + 2Q_2$
     - Steam Reforming: $CTH_3 + H_2O \leftrightarrow 2H_2 + HT + CO$
     - Water Gas Shift: $Q_2O + CO \leftrightarrow Q_2 + CO_2$
     - Isotope exchange: $XQ_y + H_2 \leftrightarrow XH_y + Q_2$ (e.g. $Q_2O \rightarrow H_2O$, $CQ_4 \rightarrow CH_4$)
  3. Usually implemented as multi-stage process to recover as much as possible tritium

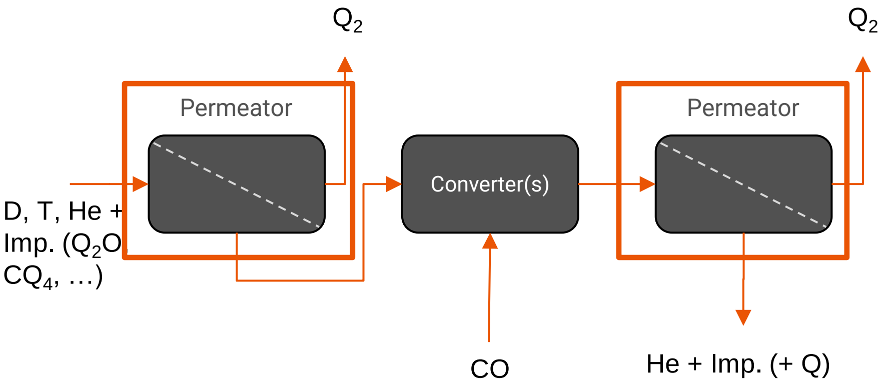


The Fusion Fuel Cycle

A closer look into exhaust processing

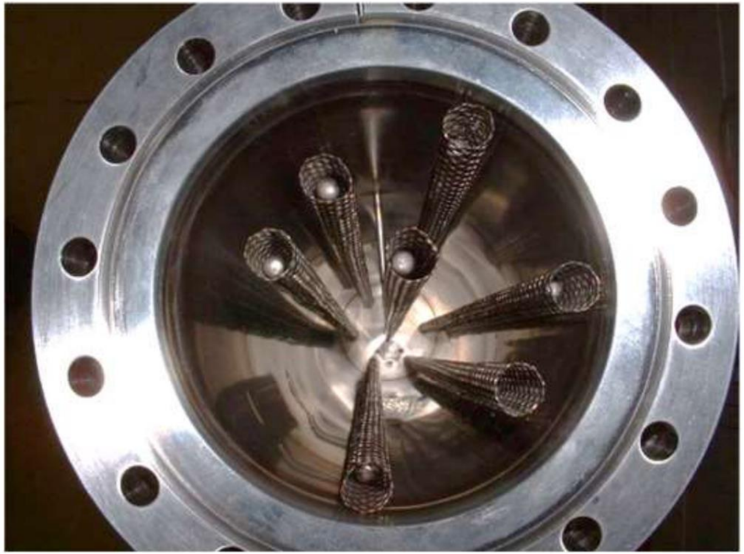


V. Narcisi, et al., "On the scalability of a membrane unit for ultrapure hydrogen separation", Hydrogen 5(2), 2024



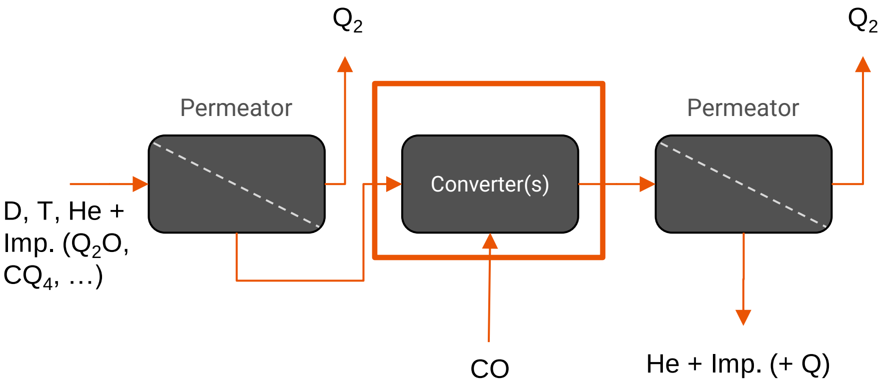
The Fusion Fuel Cycle

A closer look into exhaust processing



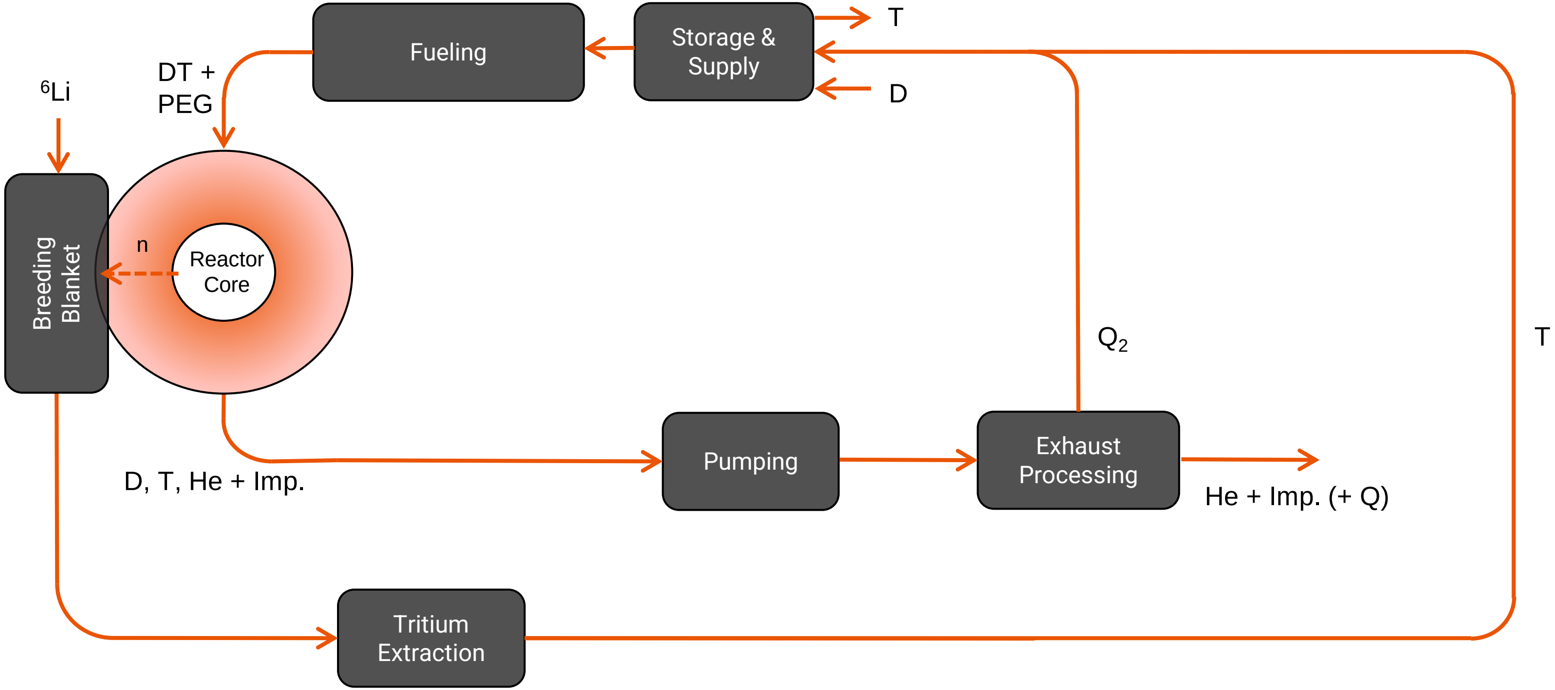
R. Michling, "ITER Tritium Plant – Operation and Analytical Needs", 25th May 2025

Unloaded Palladium Membrane Reactor



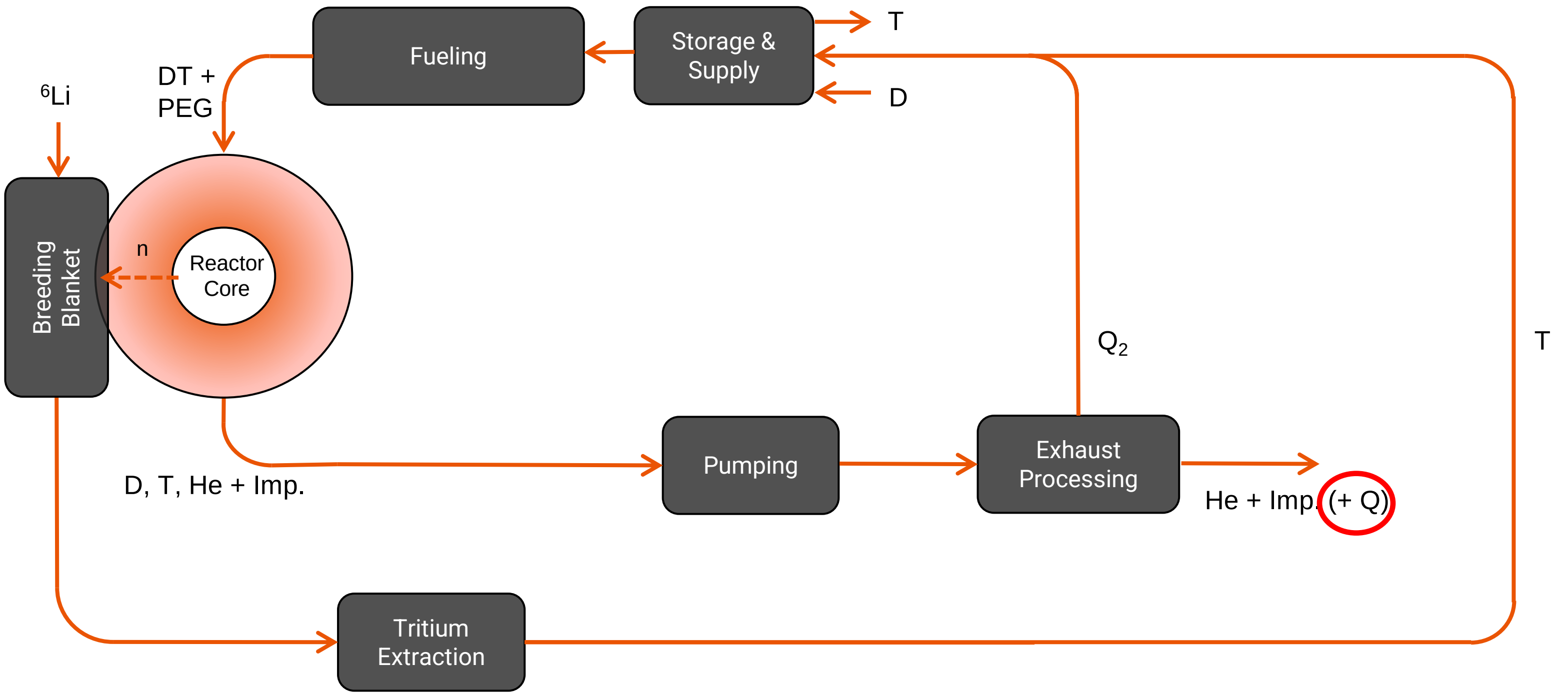
The Fusion Fuel Cycle

Let's build a fuel cycle…



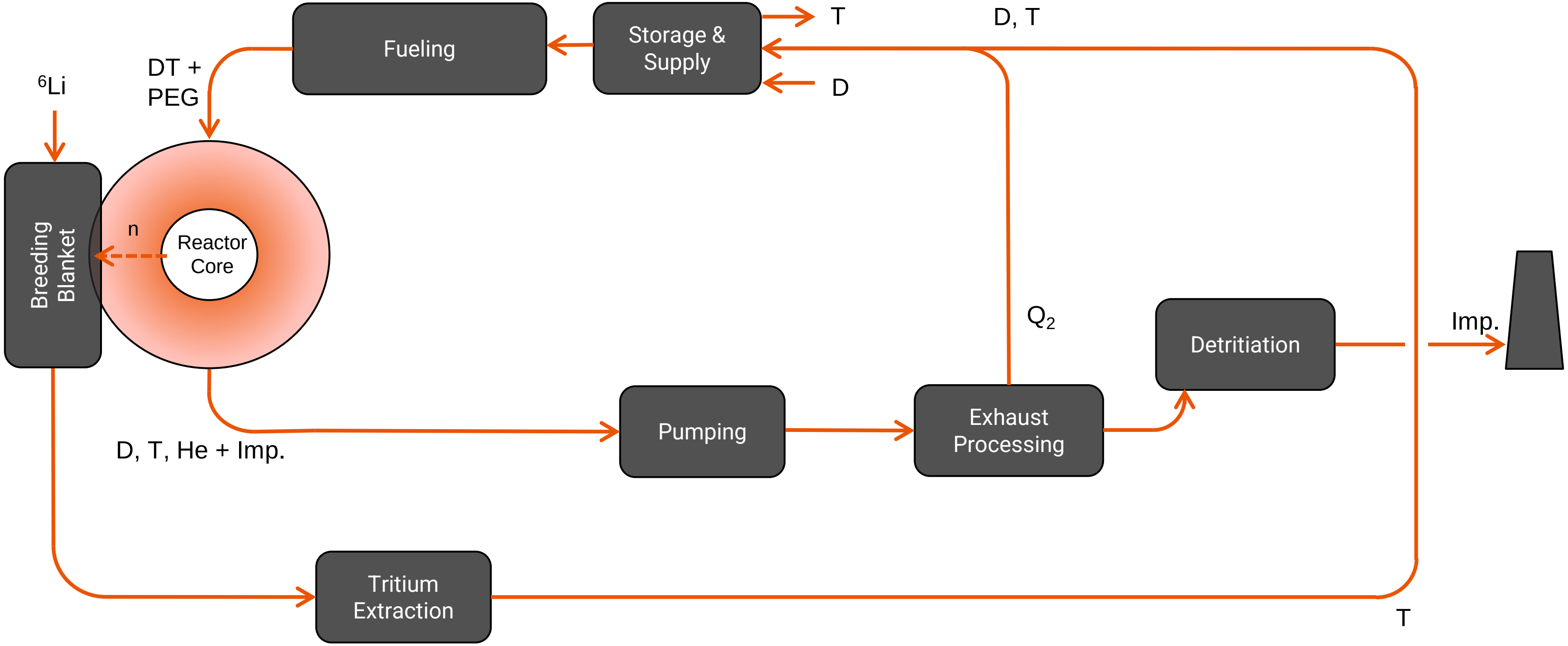
The Fusion Fuel Cycle

Let's build a fuel cycle…



The Fusion Fuel Cycle

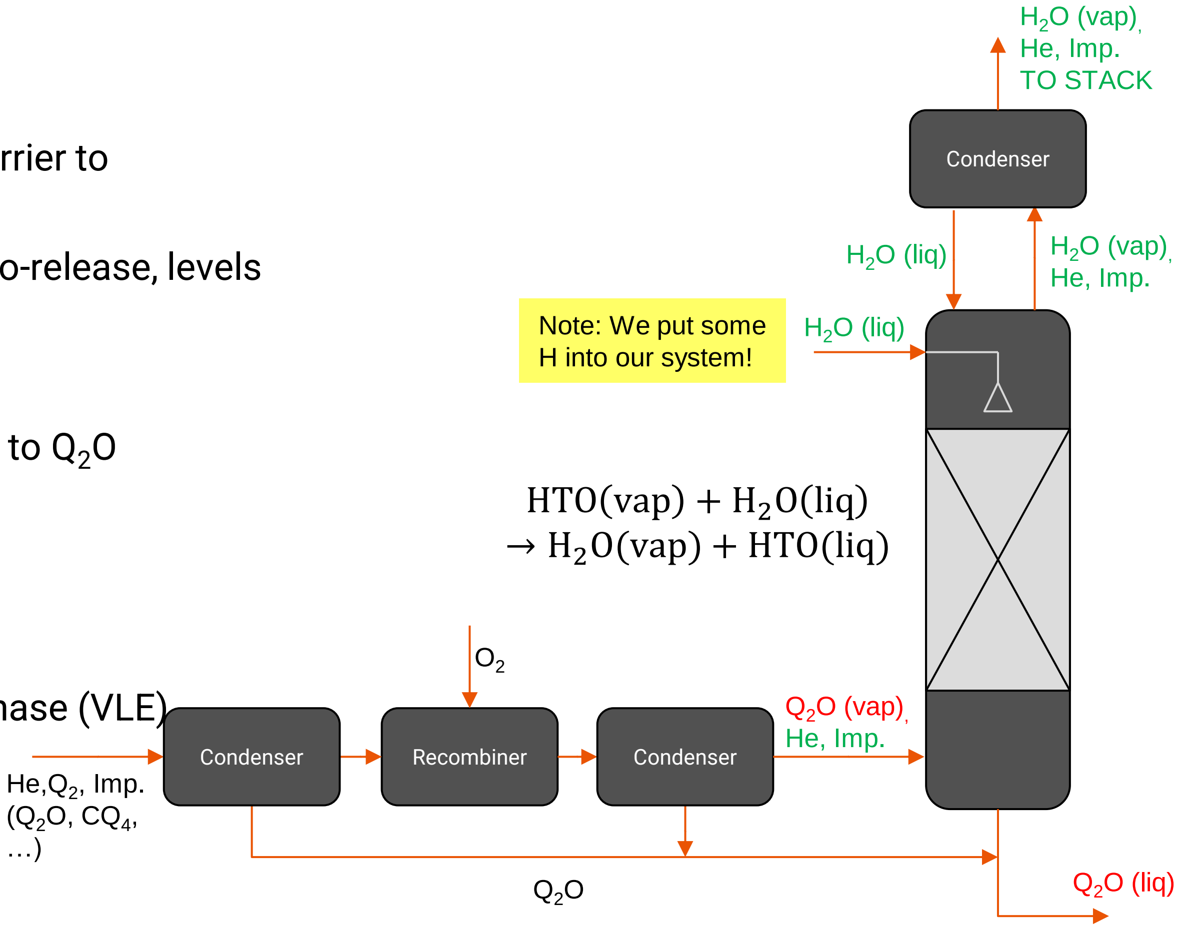
Let's build a fuel cycle...



The Fusion Fuel Cycle

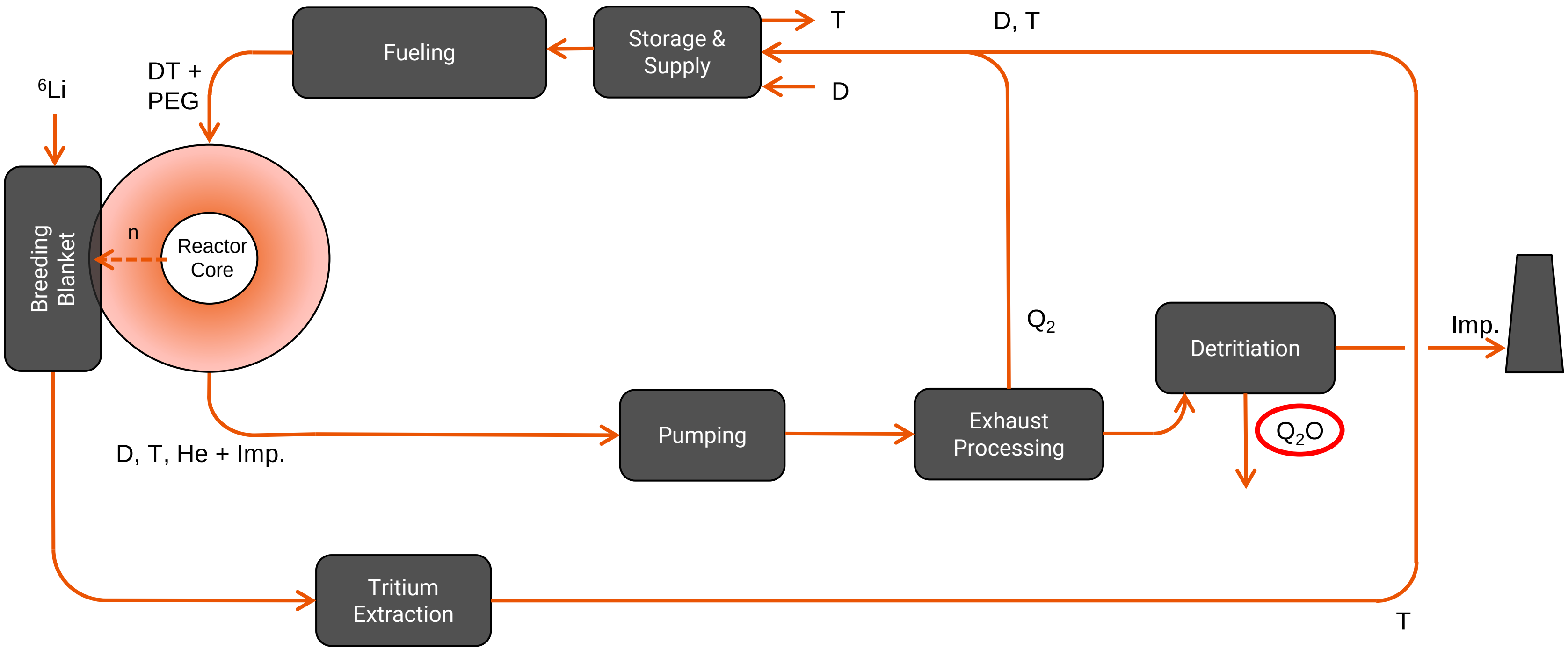
A closer look into the Detritiation System

- The detritiation system is the last barrier to environment
- Remove tritium down to trace, safe-to-release, levels
- Process steps:
  1. Condensation of Q_2O
  2. Conversion of tritiated species to Q_2O (controlled oxidation)
     - $2Q_2 + O_2 \rightarrow 2Q_2O$
     - $CQ_4 + 2O_2 \rightarrow CO_2 + 2Q_2O$
  3. Condensation of Q_2O
  4. Wet Scrubbing of gas/vapor phase (VLE)



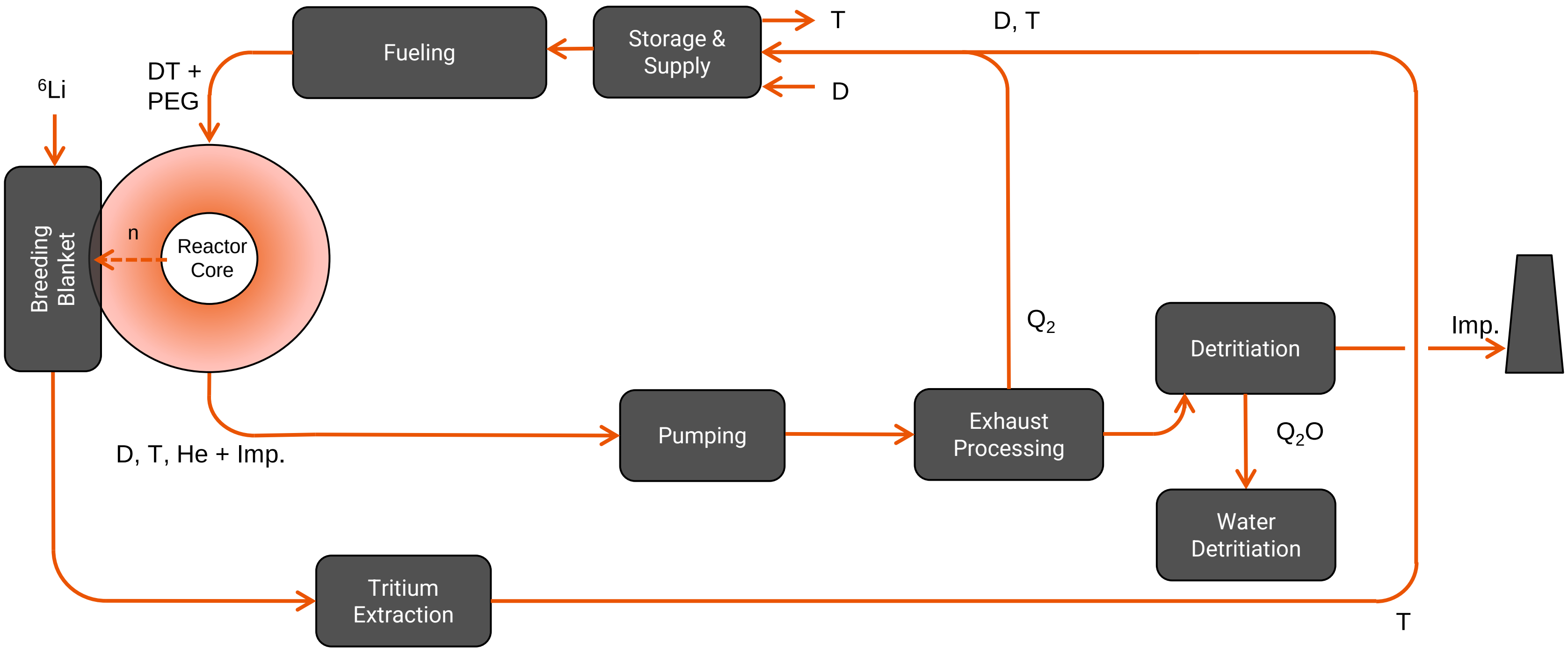
The Fusion Fuel Cycle

Let's build a fuel cycle…



The Fusion Fuel Cycle

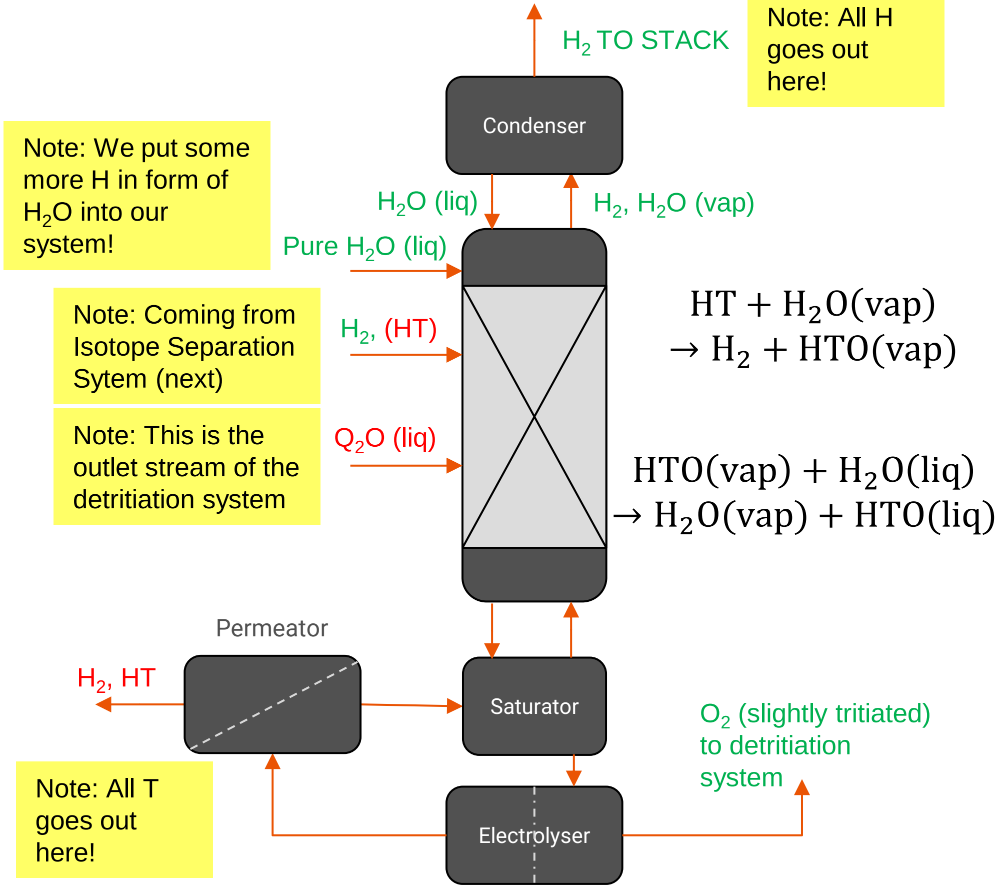
Let's build a fuel cycle...



The Fusion Fuel Cycle

A closer look into the Water Detritiation System

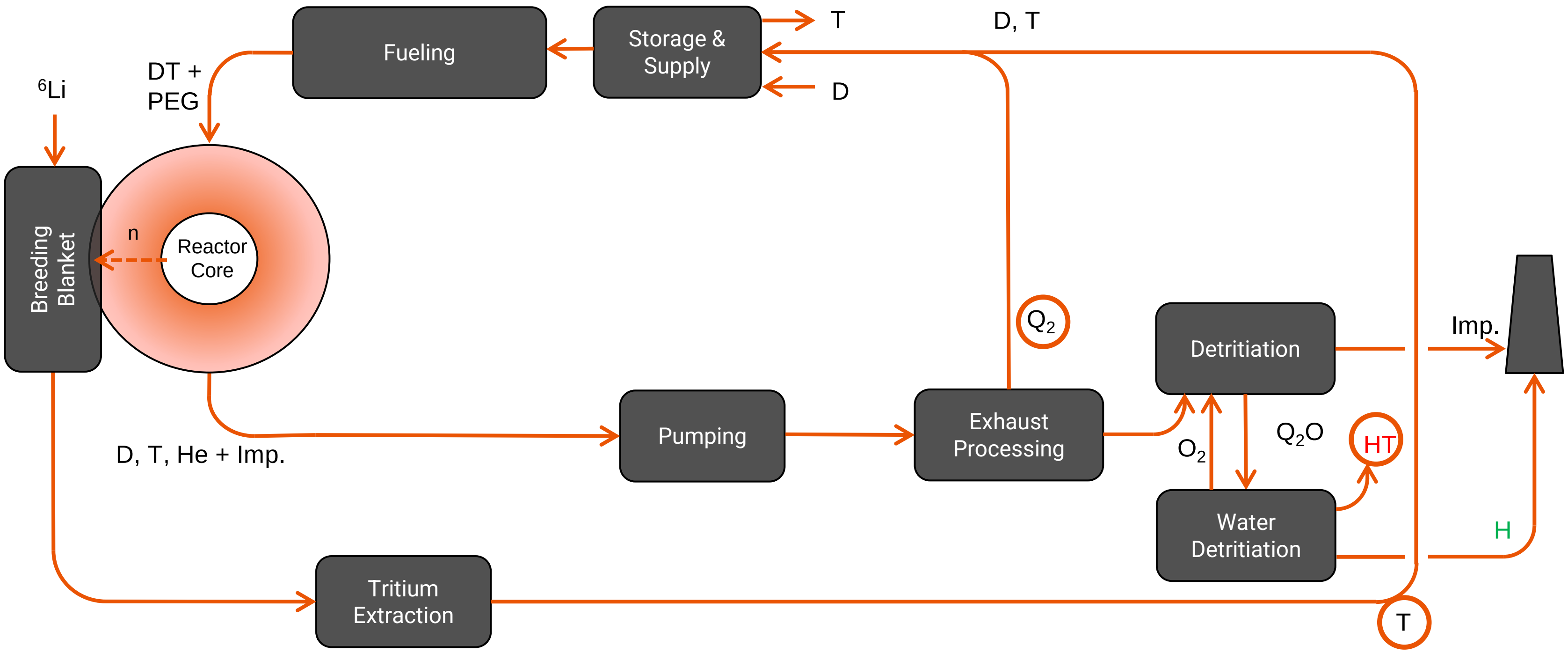
- The Water Detritiation System's (WDS) main function is to remove DT from tritiated water
- Process steps of Combined Electrolysis Catalytic Exchange (CECE) Process:
  1. Liquid Phase Catalytic Exchange (LPCE):
     a) Catalytic (platinum) exchange between gas phase Q_2 and vapor phase Q_2O (vap): $\mathrm{HT} + \mathrm{H_2O(vap)} \rightarrow \mathrm{H_2} + \mathrm{HTO(vap)}$
     b) Heavier isotopes preferentially accumulate in the liquid phase (VLE): $\mathrm{HTO(vap)} + \mathrm{H_2O(liq)} \rightarrow \mathrm{H_2O(vap)} + \mathrm{HTO(liq)}$ – similar to Wet Scrubber (see above)
     - LPCE contains sections with hydrophobic catalyst to promote a) and sections with packing to promote b)
  2. Electrolyser:
     - Enrichment of heavier Q species in the liquid phase due to isotopic effect
     - Generate tritiated hydrogen from tritiated water



The Fusion Fuel Cycle

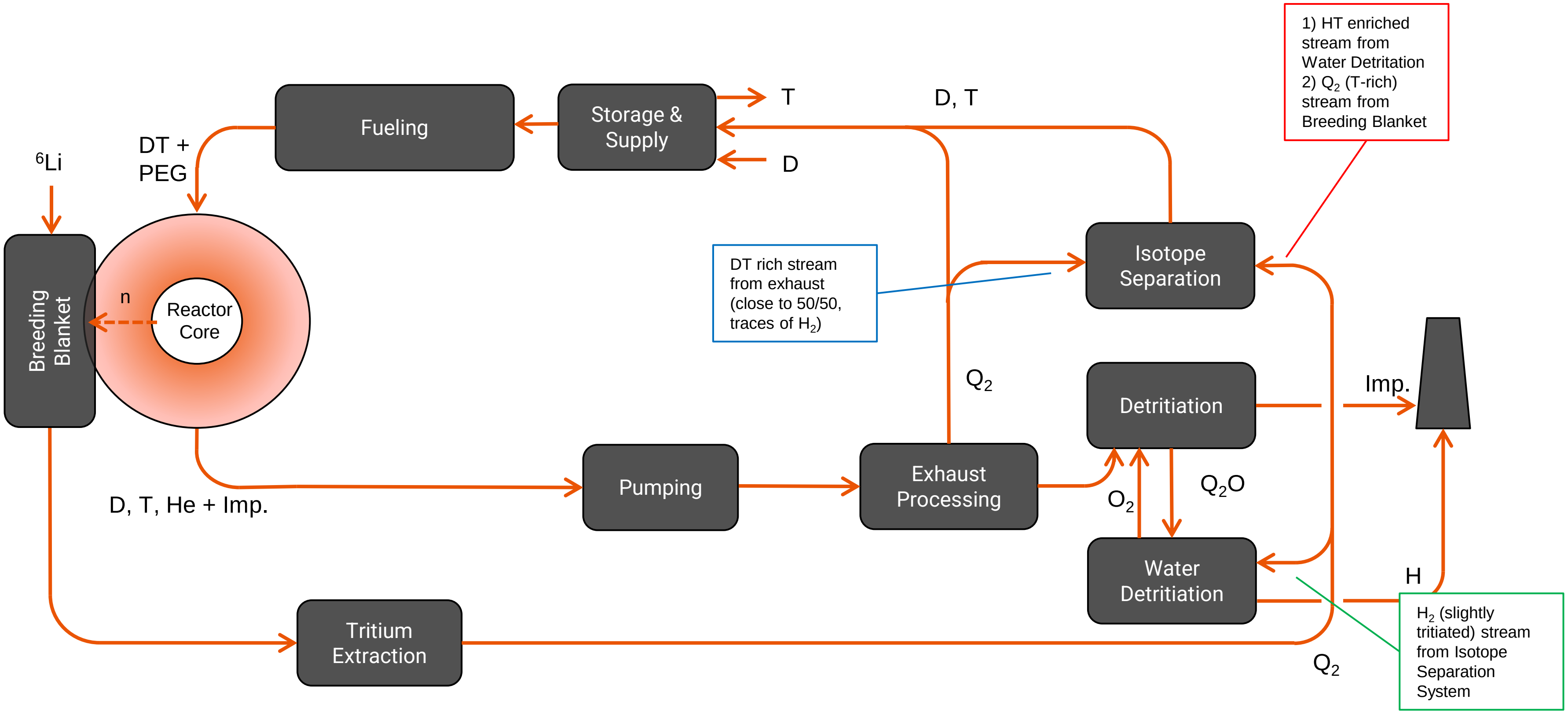
Let's build a fuel cycle…

Note: Need
a) Remove H
b) D & T rich streams to allow fueling composition adjustment
→ Q_2 Isotope Separation System



The Fusion Fuel Cycle

Let's build a fuel cycle…



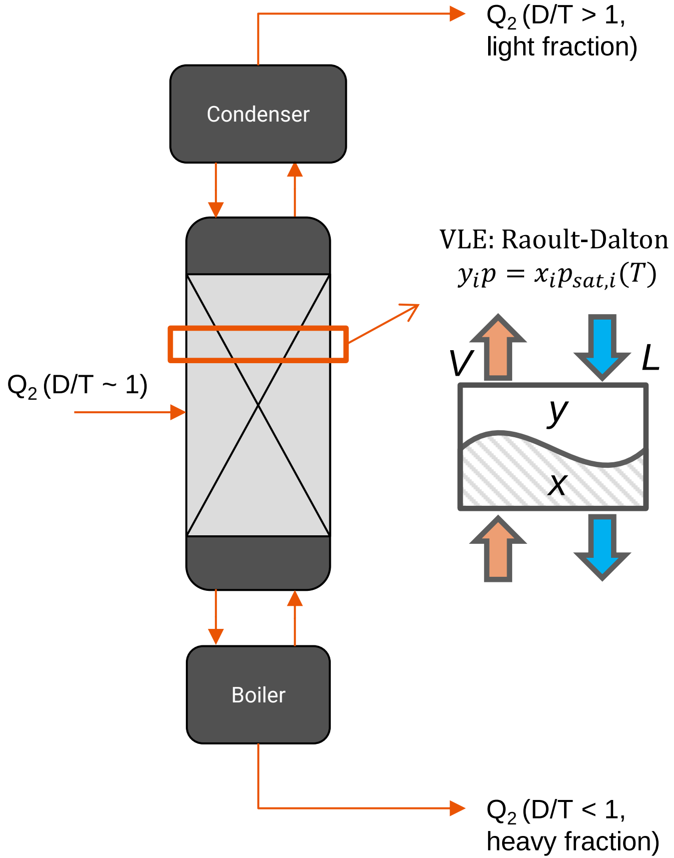
The Fusion Fuel Cycle

A closer look into the Isotope Separation System

- The Isotope Separation System (ISS) has the main function to separate Q_2 into H, D, T heavy streams
- The process relies on cryogenic distillation (rectification) of hydrogen
  - Normal boiling points:
    - H_2: 20.4 K
    - HD: 22.1 K
    - HT: 22.9 K
    - D_2: 23.6 K
    - DT: 24.3 K
    - T_2: 25.0 K

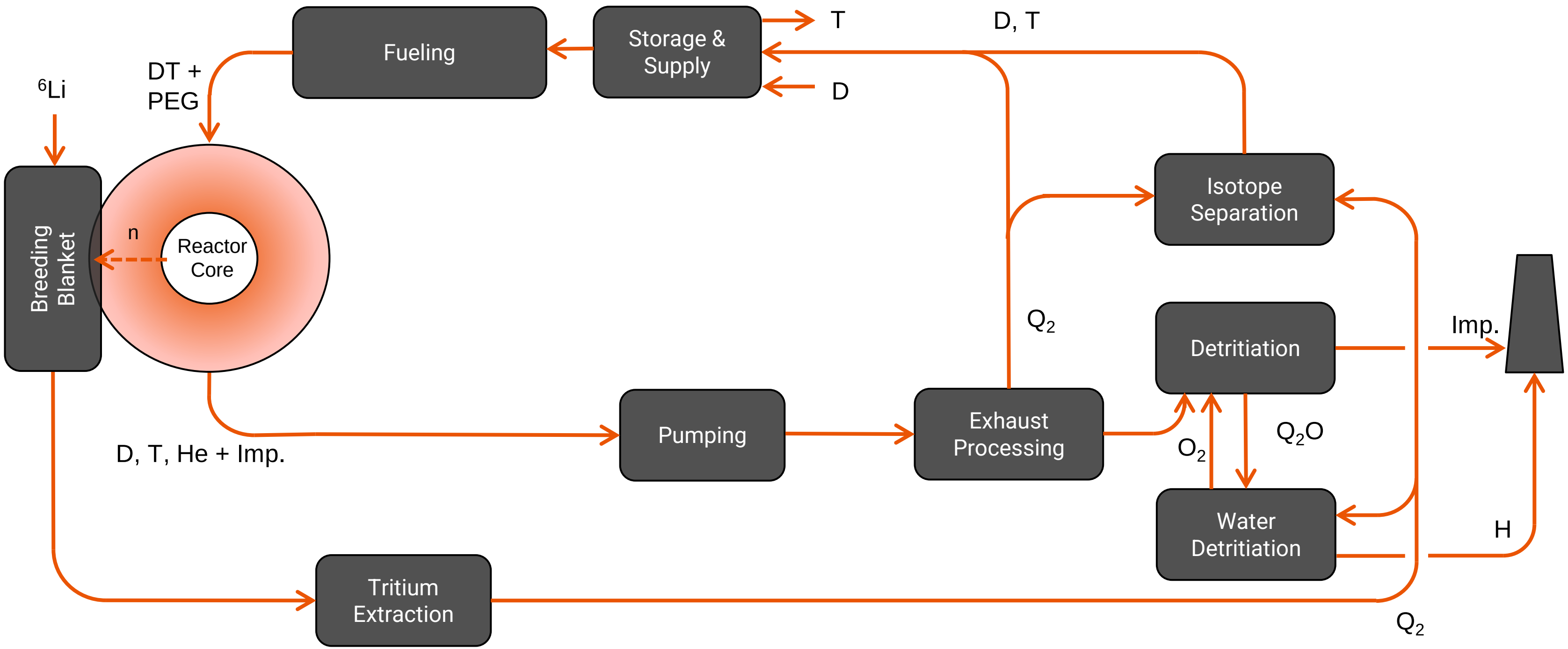
close molecular mass,
close boiling points,
hard to separate

  - One column contains a larger (~100) number of consecutive equilibrium stages
  - Usually, several columns in series depending on
    - Feeds (composition, flow rate)
    - Required purity of product streams (e.g. D/T ratio)



The Fusion Fuel Cycle

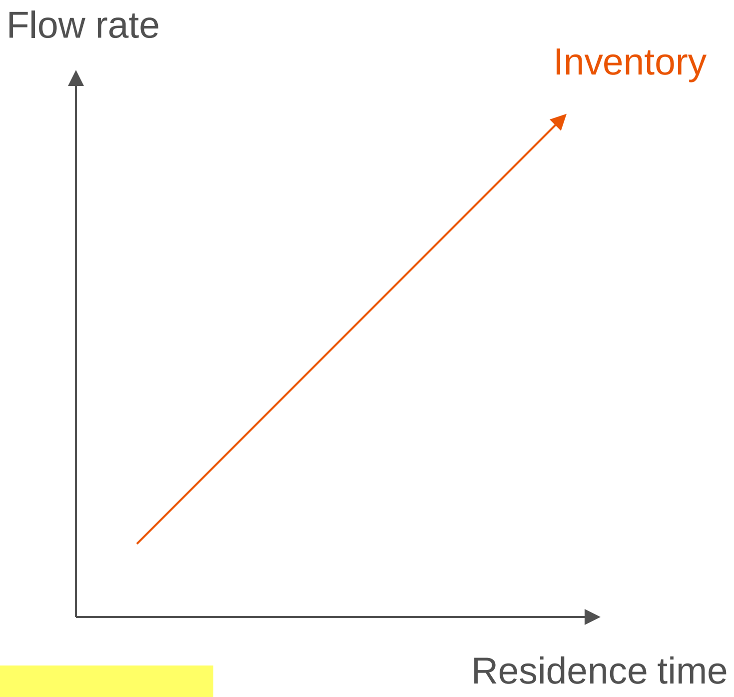
We built a fuel cycle… and let's make it even better



The Fusion Fuel Cycle

Tritium inventory

- The fuel cycle processes tritium and we would like to minimize the amount of tritium that is needed to run the plant
- So, where is the tritium? Inventory is determined by:
  a) **Flow rate** of tritium in/out the respective system determines the size → **higher flow rate = higher inventory**
  b) **Residence time** of tritium in the respective system = how long does a fluid parcel on average stay in the system → **longer residence time = higher inventory**

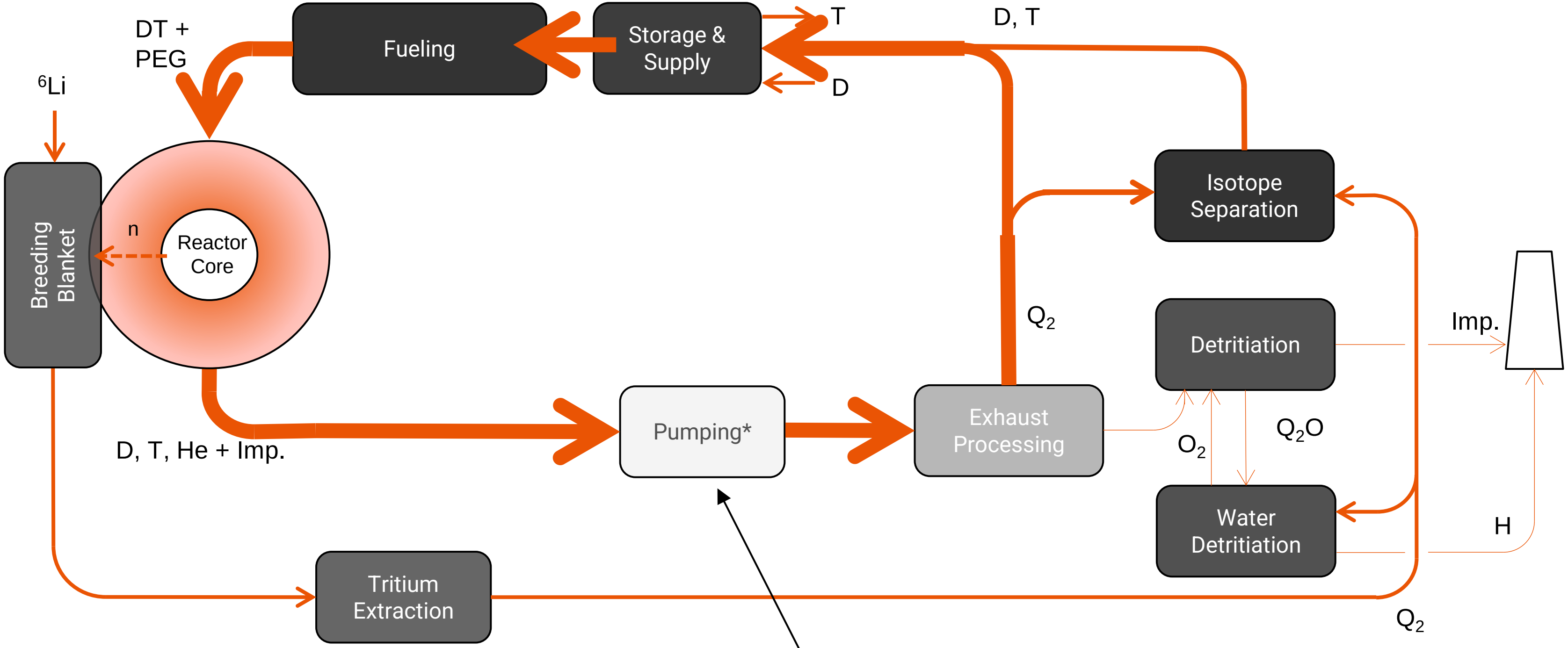


Note: Inventory reduction is achieved by:
a) Optimizing systems to have a low residence time
b) Reducing the flow rate to systems with a high residence time (bypassing)
c) Reduction of overall flow rate

The Fusion Fuel Cycle

Flow rates and residence times

Line thickness: Low to **high** tritium flow rate
Unit color: Low to high residence time
Inventory = Flow rate x residence time

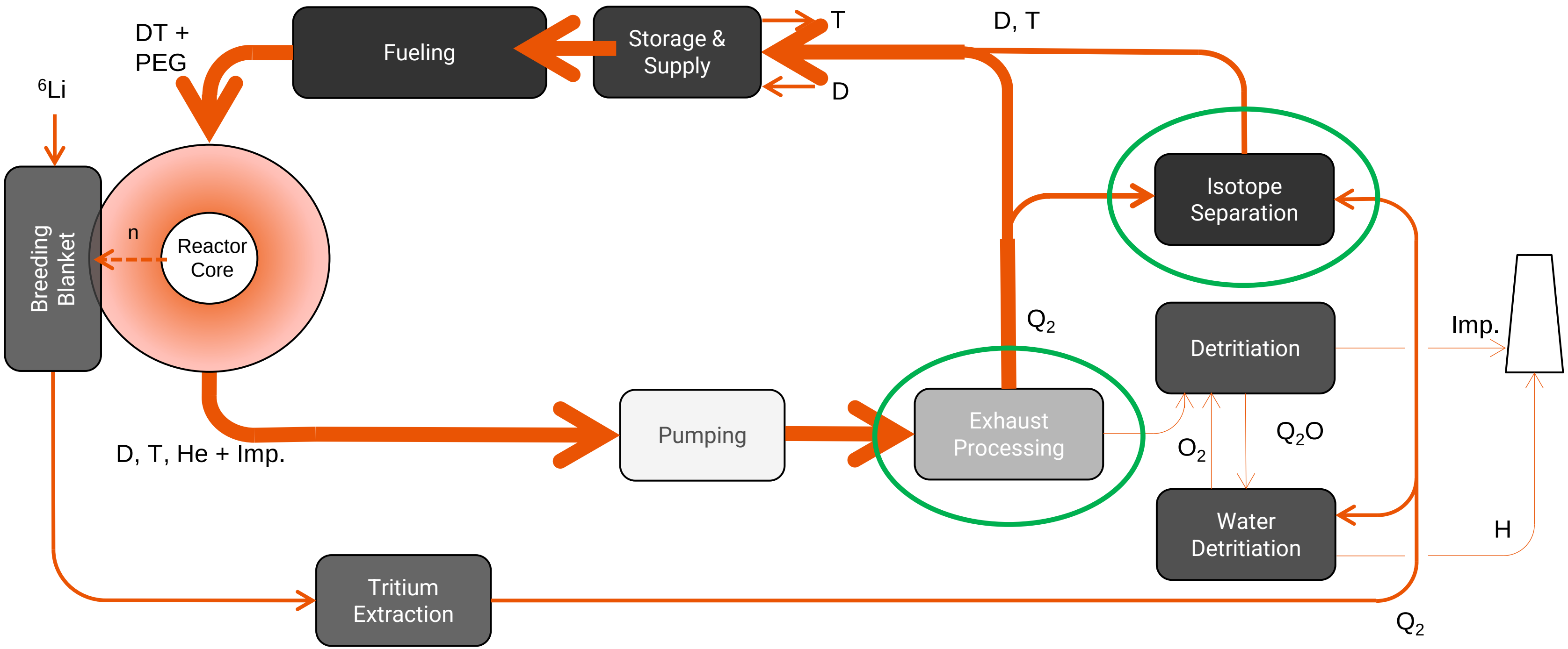


If we select continuous pumping technologies!

The Fusion Fuel Cycle

So, how can we reduce the tritium inventory?

Line thickness: Low to **high** tritium flow rate
Unit color: Low to high residence time
Inventory = Flow rate x residence time

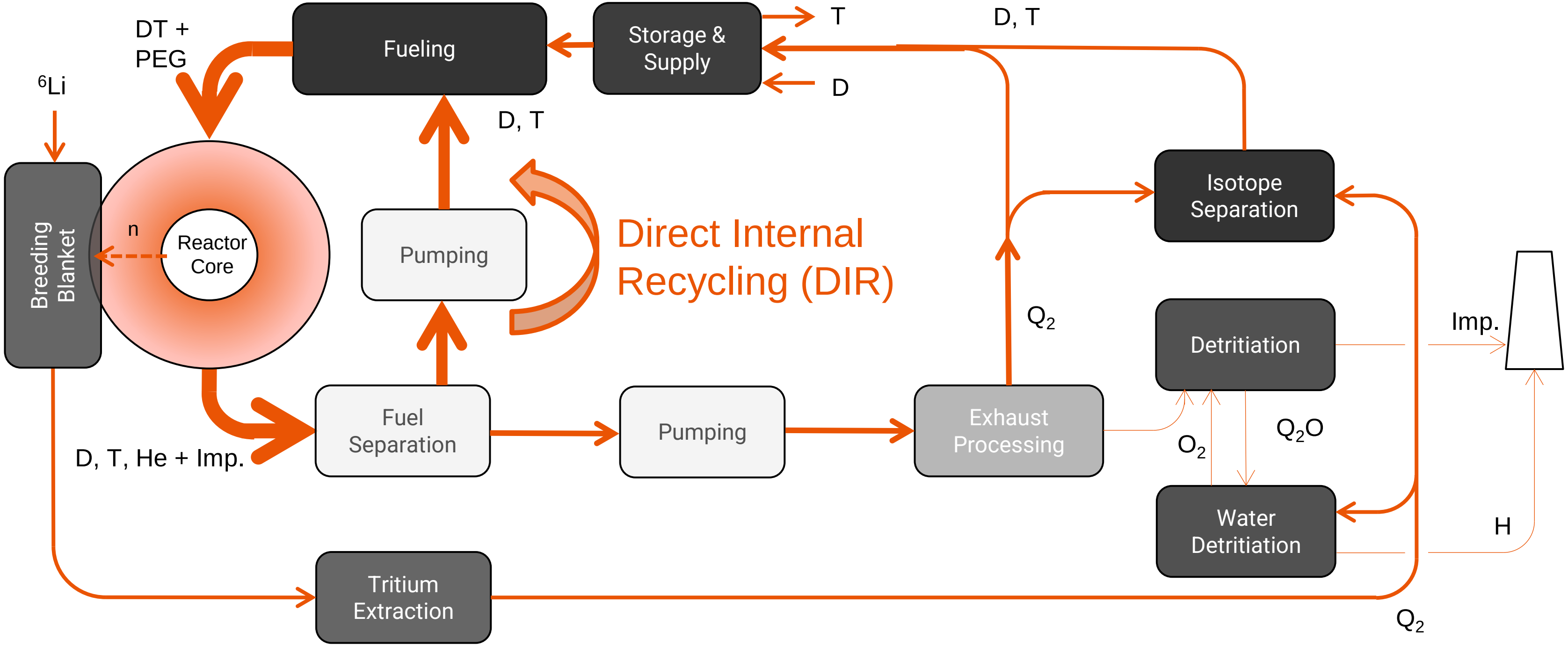


The Fusion Fuel Cycle

So, how can we reduce the tritium inventory?

Line thickness: Low to **high** tritium flow rate
Unit color: Low to high residence time
Inventory = Flow rate x residence time

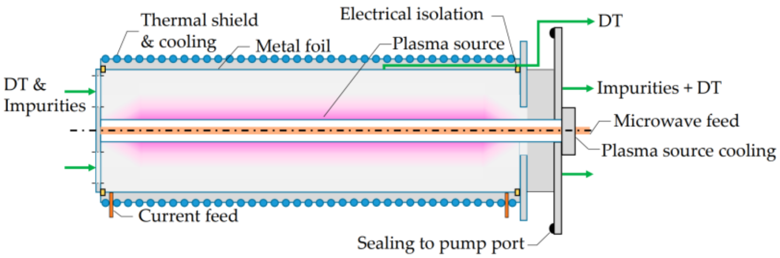
KYOTO FUSIONEERING



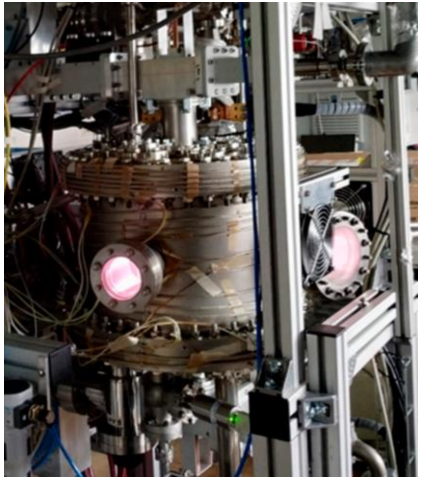
The Fusion Fuel Cycle

A closer look into Direct Internal Recycling

- DIR requires ultra-pure separation of hydrogen because we want to minimize the processing time (i.e. residence time)
- Currently, two main technologies are under development:
  - **Metal Foil Pump (MFP)**
    - Superpermeation of energetic hydrogen atoms/ions through metal foil
  - **Proton Conductor Pump (PCP)**
    - Electrochemical separation of Q protons through a solid-oxide proton conductor



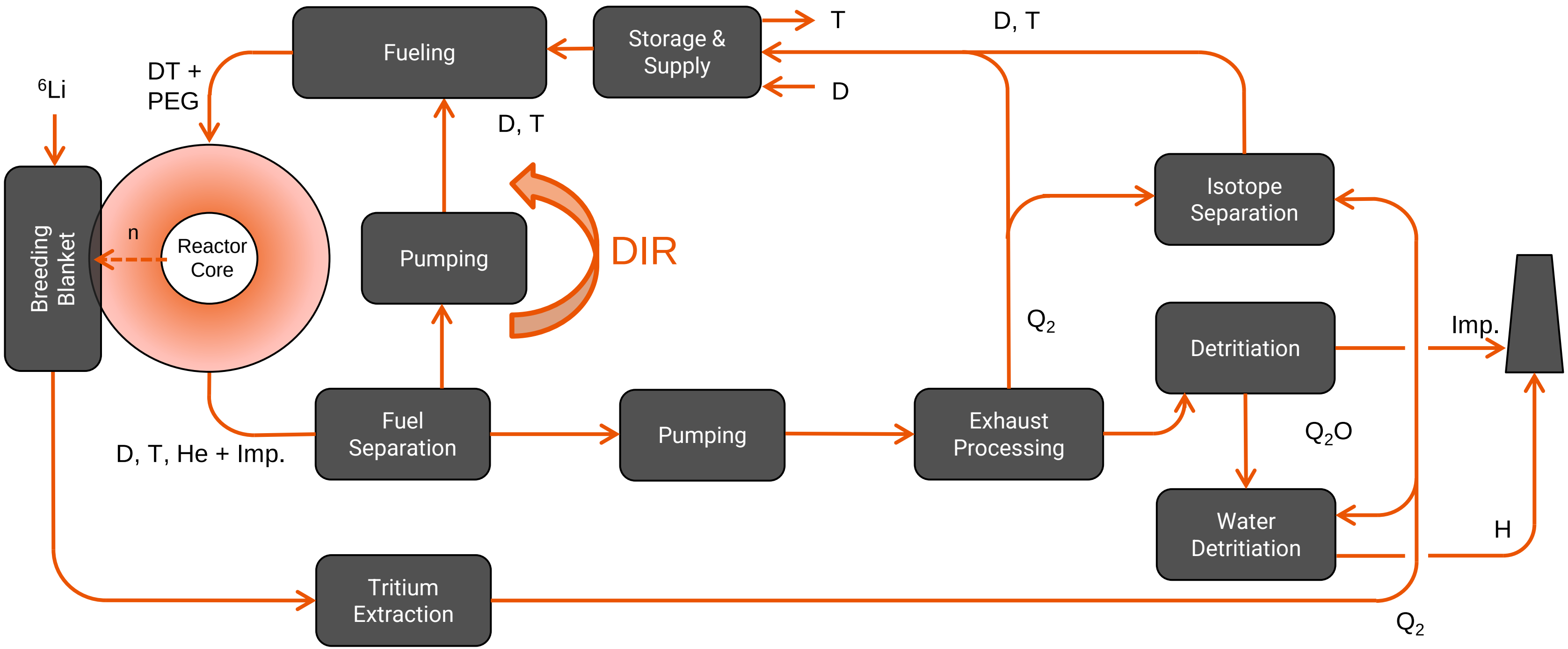
Y. Kathage, et al., "Experimental Progress in the Development of a Metal Foil Pump for DEMO", MDPI Plasma, 6(4), 2023.



"Advancing Fusino Technology – Kyoto Fusioneering's Approach to Accelerating Commerical Viability", Kyoto Fusioneering Whitepaper, 2024, available at https://kyotofusioneering.com/en/whitepaper

The Fusion Fuel Cycle

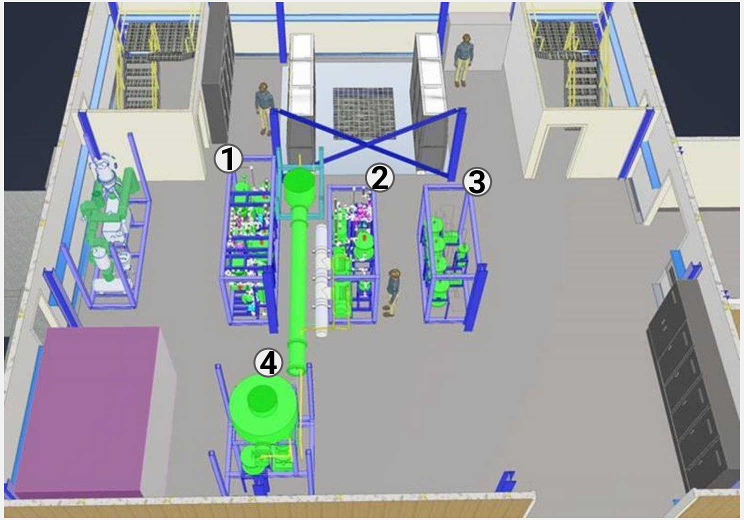
A prototypical fuel cycle for DT based magnetic confinement fusion power plants



The Fusion Fuel Cycle

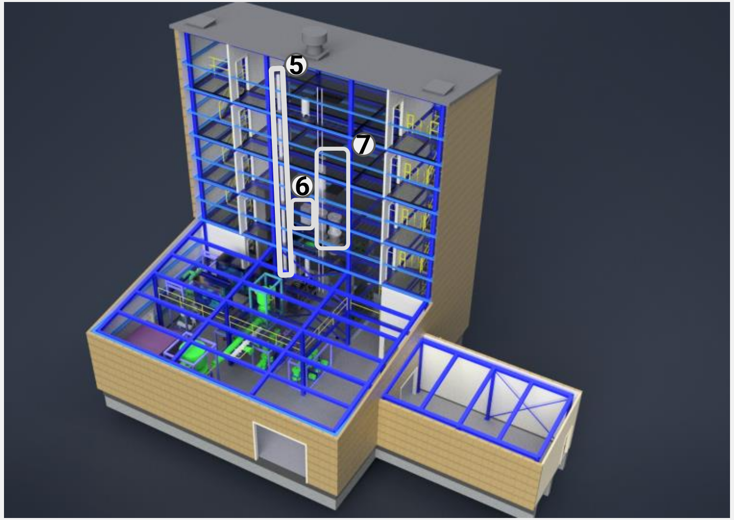
What's next? Integrated testing!

UNITY-2 Main Floor



① Direct Internal Recycling
② Proton Conductor Pump
③ Exhaust Processing
④ Pellet Injector System

UNITY-2 Tower



⑤ Water Detritiation System
⑥ Detritation System
⑦ Isotope Separation System

Canadian Nuclear Laboratories + KYOTO FUSIONEERING = FUSION FUEL CYCLES

Thank you!

Questions?