EUROfusion

Fusion fuel cycle: critical system requirements

Alessia Santucci

ENEA, FUSEN-TEN, Italy

06 March, 2025

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.

Objective

This presentation explores, in a simplified way, **the complex interplay between plasma physics and tritium fuel cycle** in magnetic confined D-T fusion machine

Crucial role of the Fuel Cycle

3 Fuel Cycle technology Breakdown

3.1 Fuel Cycle overview

The plasma in a fusion machine needs to be continuously fuelled by deuterium and tritium and is processed in the fuel cycle for re-use for technical, safety and economic reasons.
The fuelling of a plasma in a fusion power plant will likely be done with a fixed deuterium and tritium ratio, and the plasma size requires that the fuel arrives directly to the core of the plasma. Reaching the core of a highly confined plasma requires the **injection of frozen solid deuterium and tritium pellets at very high speeds** through guiding tubes with complex shape.
For plasma control purposes, additional gases are injected, and a vacuum system is required to **pump the hydrogen isotopes with the additional 'impurity' gases** as well as reaction products.
Since a very small fraction of the fuel injected will be burnt (maximum a few percent), technologies which could **quickly separate hydrogen isotopes from other gases for direct fuel recycling** without further treatment would be of particular interest as is would keep tritium plant size and tritium inventories within acceptable limits.
The vacuum system transfers the gas mixture to the tritium plant for **separation of the impurity gases from the hydrogen as well as separation and purification of the hydrogen isotopes** for the purpose of rebalancing the injected D-T ratio.

Page 8/16

FUEL CYCLE TECHNOLOGY MAPPING 2025 series

This is a long process which mobilizes a large tritium inventory, which is costly, especially in the face of the current shortage of tritium for civil applications. **Accelerating fuel treatment is of interest to reduce the overall inventory** necessary to operate a fusion power plant. Similarly, keeping the tritium in the fuel cycle to reduce losses requires measures to **limit tritium permeation in the plant.**
Additional duties of a fusion tritium plant will be to **store fuel**, process tritium from the breeding blankets, air and **water detritiation** as well as **tritium measurement and accountancy**.

A large variety of technologies is used in the three fields of Fuelling, Pumping and Tritium processing. For most of them, the process know-how and manufacturing experience is currently still within research institutions throughout Europe.

Tritium consumption and production

Tritium Consumption

A **Fusion Power Plant (FPP)** would **consume about 153 g of tritium per GW** of fusion power **in a full power day**

A DEMO-like reactor (2 GW power plant) would require about **112 kg of tritium in a full power year**

$$D + T = He + n + 17.6\ MeV$$

Tritium Production

Production in fission reactors is **much smaller**

Light Water Reactors produce **~0.5-1 kg/year**, while CANDU reactors produce **~130 g per year**

The **cost is very high**, ranging **from 30 to 130 k€ per g**

Inner and Outer Fuel Cycle

It is **not feasible to supply a FPP** with such amounts **from external sources**, the fuel cycle of an FPP **needs to enable tritium self-sufficiency**.

This involves:

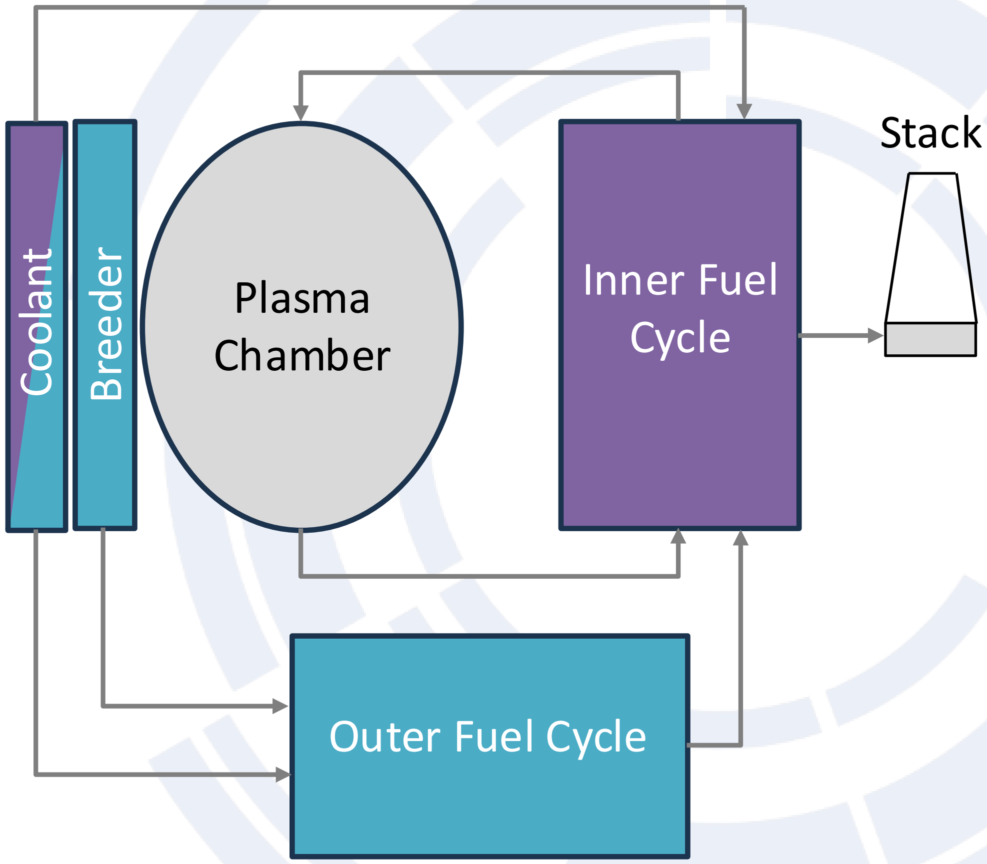
(i) A (almost) complete reuse of the tritium not consumed inside the plasma chamber

(ii) A minimization of the initial tritium supply (several kg) required to start the plant and to sustain plasma operation and associated tritium system

Inner Fuel Cycle

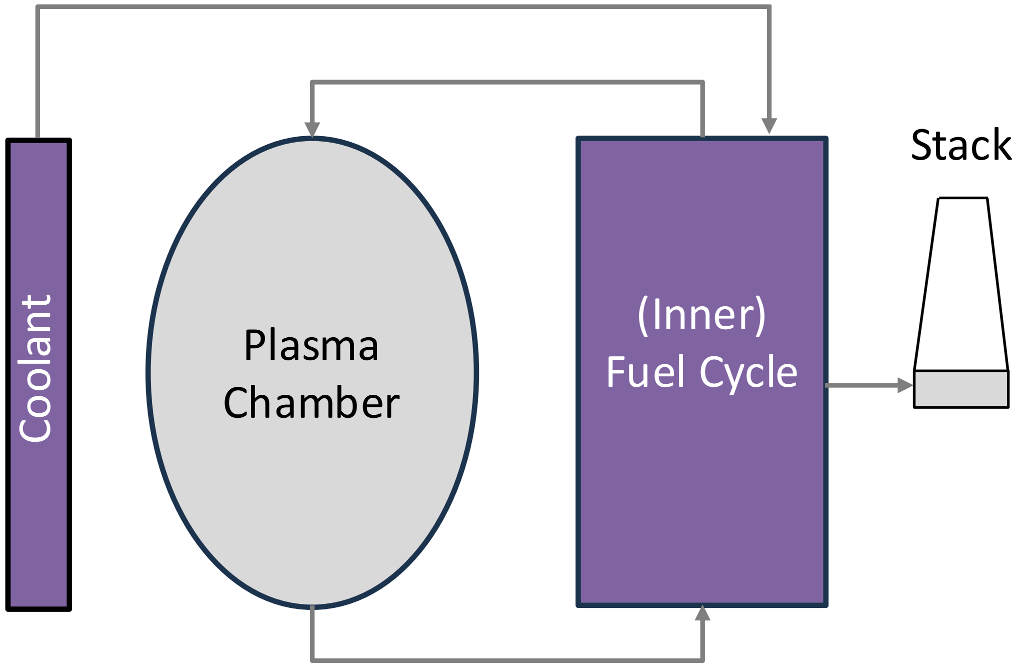
(iii) An on-site production of the tritium consumed during operation and of the one required to start other power plants

Outer Fuel Cycle



(Inner) Fuel Cycle

The main interface of the inner fuel cycle is the plasma chamber

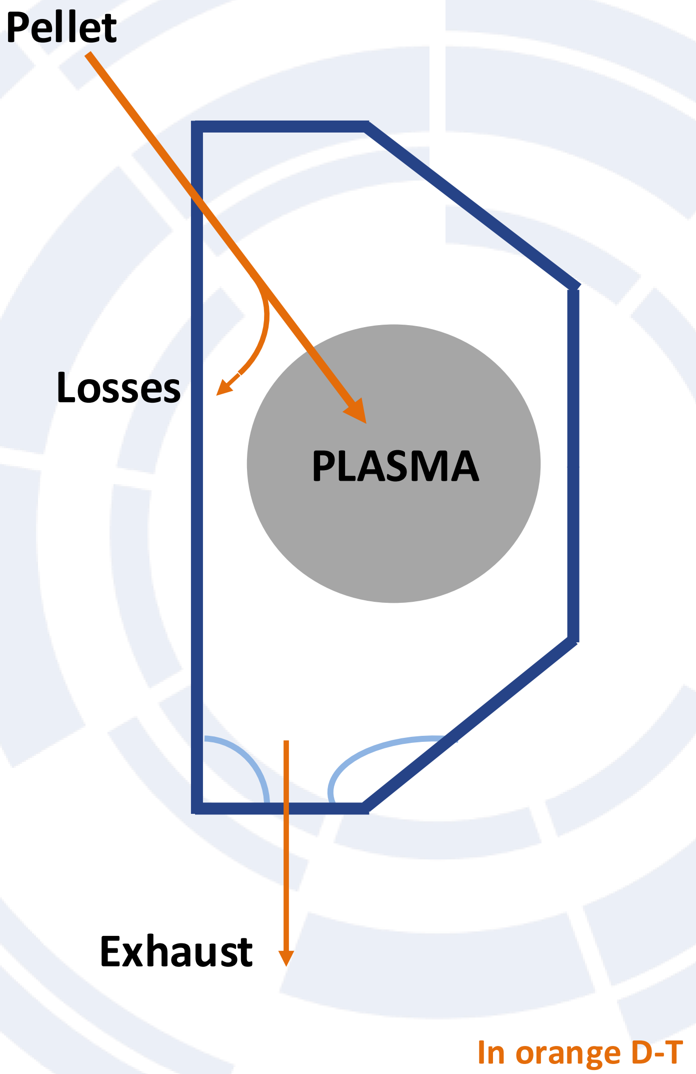


Plasma Chamber Topic	Fuel Cycle Topic
Plasma physics: Burn fraction Fuel delivery requirements Gas delivery in addition to DT (H, Ne, other) Plasma resilience to impurity build-up Plasma particle transport	**Fuel cycle technology:** Fuelling Isotope separation Loop configuration (direct internal recycle) Vacuum pumping Fuel clean-up (purification)
Plasma burn control: Plasma fuelling rate and isotopic mix control Power dissipation ELM control	**Fuel/exhaust actuator:** Fuelling and impurities feed control Isotope separation and/or direct recycle Pellet and gas injection
First wall: Be, W, Mo, low activation steel Low-Z first wall coatings Liquid metals Dust Redeposited layers Tritium retention	**Fuel cycle technology:** Fuel clean-up (impurity processing) Be and activated product clean-up technology (off normal) In-vessel tritium recovery (conditioning and remote handling) Tritium recovery from coolant Inventory measurement
Disruptions: Fuel and impurities released due to disruptions Optimization of disruption mitigation for fuel cycle compatibility	**Disruption mitigation:** Disruption mitigation technology Fuel clean-up (purification and impurity processing) Isotope separation Vacuum pumping

Table taken from IAEA TECDOC IAEA-TECDOC-2049

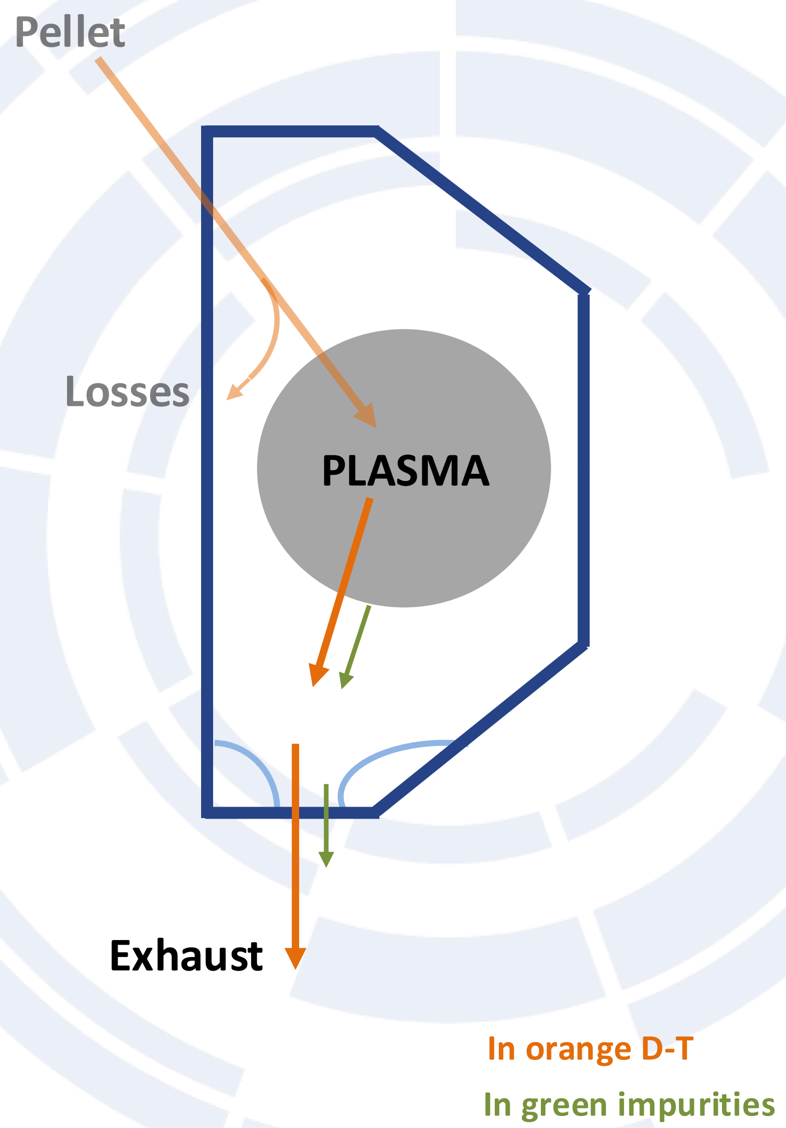
Plasma fuelling

- To keep plasma core density constant, there is the need to **deposit a given flow of fuel particles into the core**.
- The fuel cycle technology providing this function is **high velocity** (of the order of 1 km/s), **high frequency** (in the order of 10 Hz) pellet injection of solid DT pellets into the plasma.
- The **injection** needs to happen **from the high-field side** of a tokamak to achieve efficient fuelling. This is difficult to access, and it results in **additional losses from the pellets** being transported through guiding tubes.
- The resulting **plasma density** achieved for a given pellet fuelling rate **depends on the fuelling efficiency**, which is the **fraction of pellet particles that are retained in the plasma during the injection process**.
- A very important point, is the **tolerable amount of protium in the fuel** that has a significant **impact on** the dimensioning of **the isotope separation systems.** Current numbers are in the order of 1%.



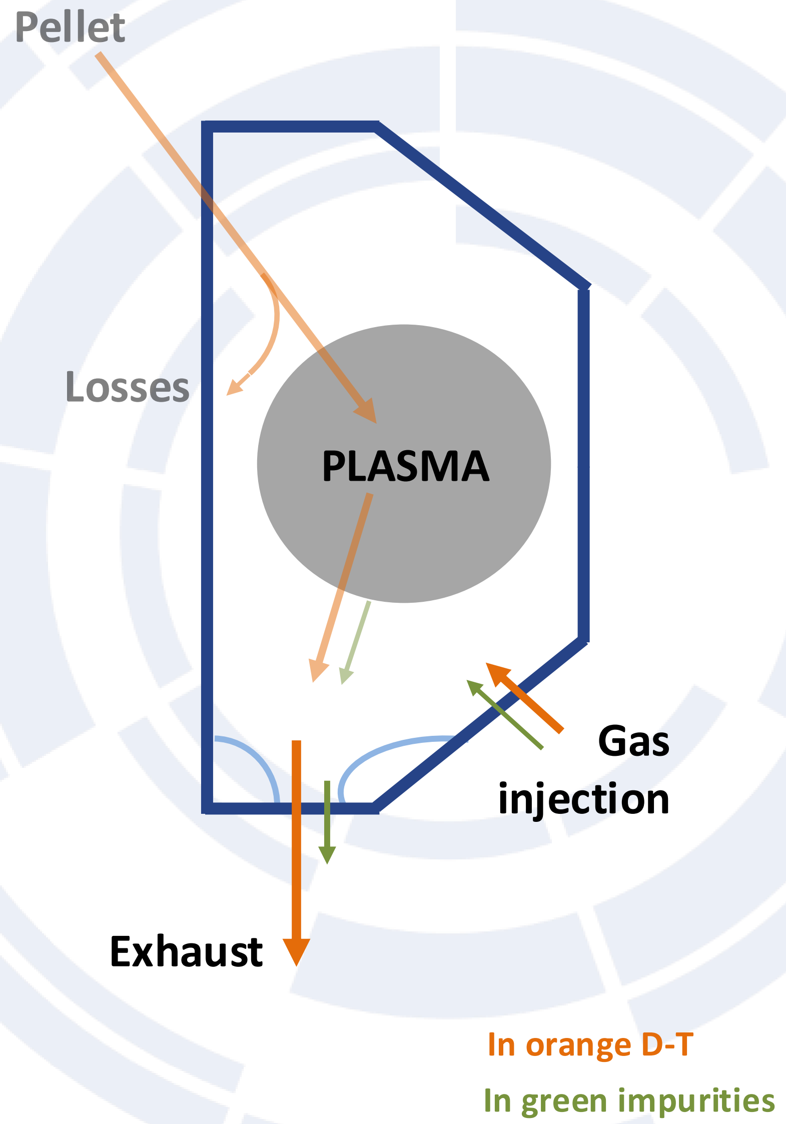
Burning rate

- **Not all fuel that reaches the plasma core is consumed**.
- The reacting fuel fraction depends on:
  - Cross section of the D-T reaction
  - Plasma density
- **Production of helium** as a result of the fusion reaction.
- **Production of protium** from secondary reactions.
- The results is that a certain **fraction of the D-T will leave the plasma core** and a certain **amount of impurities are produced**.



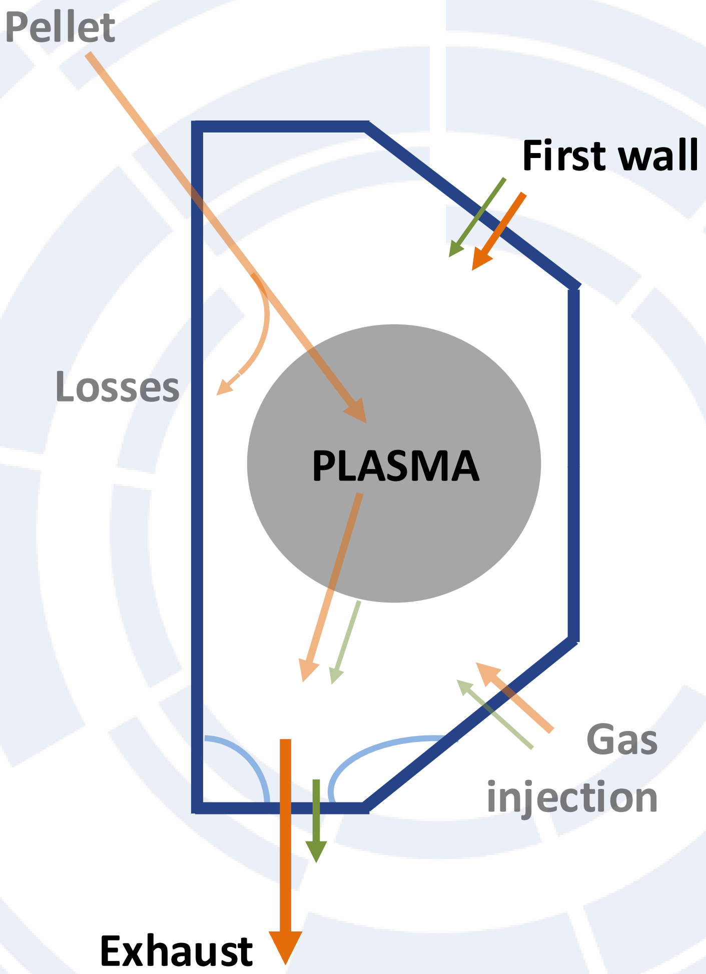
Injection of additional gases

- **Gas injection into the divertor** volume is expected to provide stable **control of the plasma detachment**, which is essential **to reduce the heat flux on the divertor** target plates below the limits of the materials' resistance.
- The divertor puffing rate **impacts on the divertor pressure**. Because the pumping speed grows with increasing divertor pressure, there is a **direct impact on the particle exhaust via vacuum pumping**.
- The use of such **plasma enhancement gases results in additional separation** needs on the fuel cycle exhaust processing side.



First Wall

- **Tritium will be retained in the traps** (produced during manufacturing or induced by neutron irradiation) **of the metal first walls** causing causes critical processes (erosion, transport, deposition and co-deposition, implantation, diffusion, permeation and dust formation) and tritium **retention**.
- This will lead to a significant **build-up of tritium inventory in the wall**.
- Tritium trapped in the chamber materials can also act as a source term of **tritium release during any unintended event**.
- **Outgassing** from the first wall is the **main load on the vacuum pumping systems during the dwell phase**. Consequentially, if too strong, outgassing can become a design driving feature and potentially increase **the dwell/burn time ratio**.

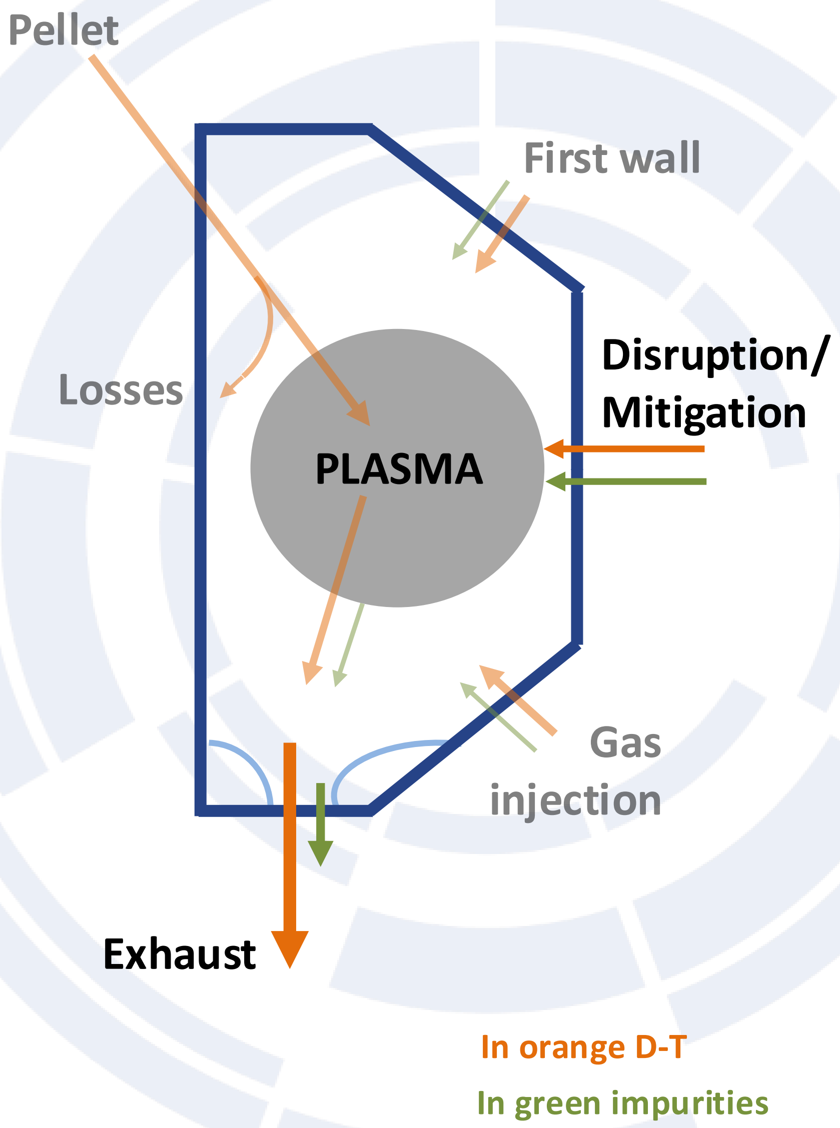


In orange D-T

In green impurities

Disruption/Mitigation

- Disruptions are the result of rapid losses of the thermal and magnetic energy stored within the plasma.
- Disruptions occur when: (i) a plasma stability limit is reached; (ii) when systems malfunction and plasma control is lost; or (iii) when unintended material enters the plasma.
- The **mitigation of disruptions** is a critical area of current research.
- Methods have been developed to potentially mitigate disruptions. These **methods include injecting radiating material** deep into the plasma to rapidly radiate the plasma thermal energy. The quantity of material injected will be on the order of **two orders of magnitude more than the content of the burning plasma** and, therefore, **pumping out this gas will** take some time and **impact the overall fuel cycle of a tokamak** based FPP.
- Because **disruptions are not present in stellarators**, an FPP based on such type of fusion concept would **not need to address this challenge in the fuel cycle**.



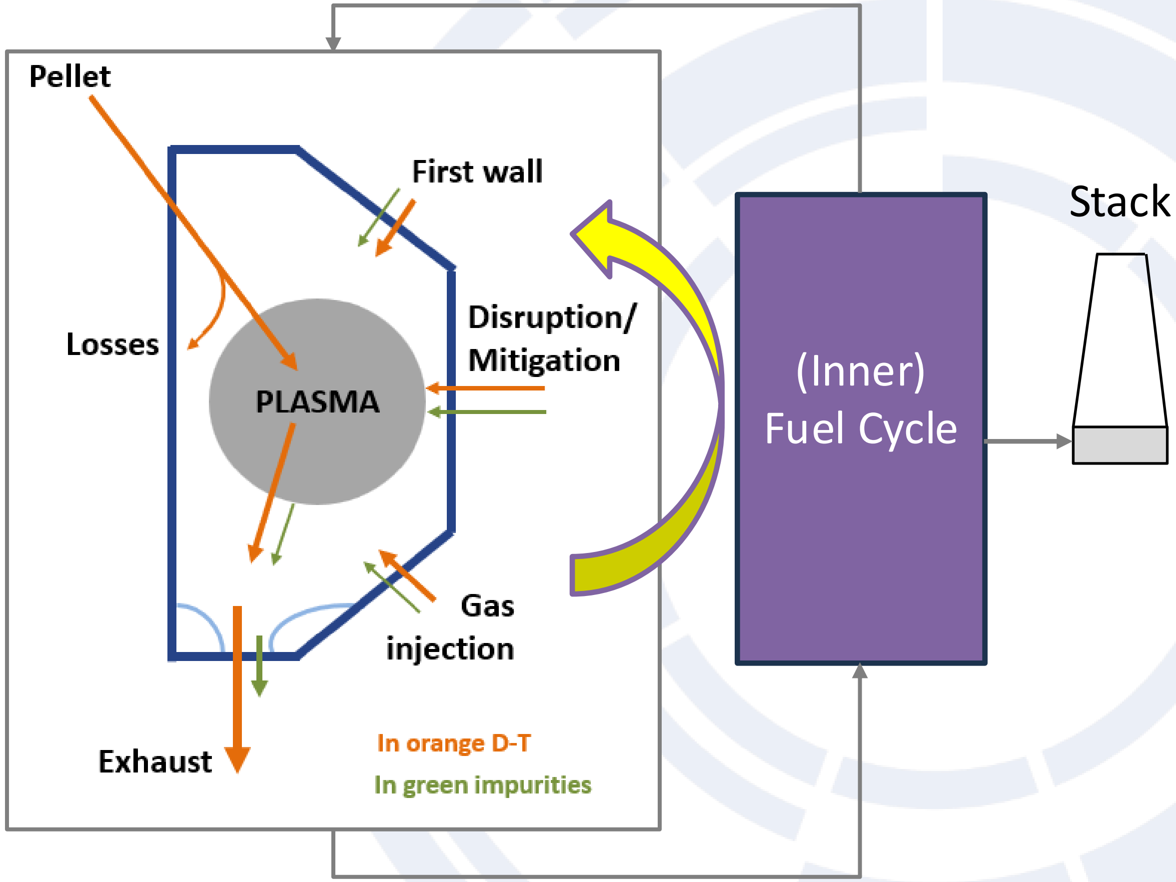
(Inner) Fuel Cycle

- Only a very small fraction of the fuel injected inside the plasma

$$\text{Tritium burn fraction} = \frac{\text{tritium burning rate}}{\text{tritium fueling rate}} = \text{few }\%$$

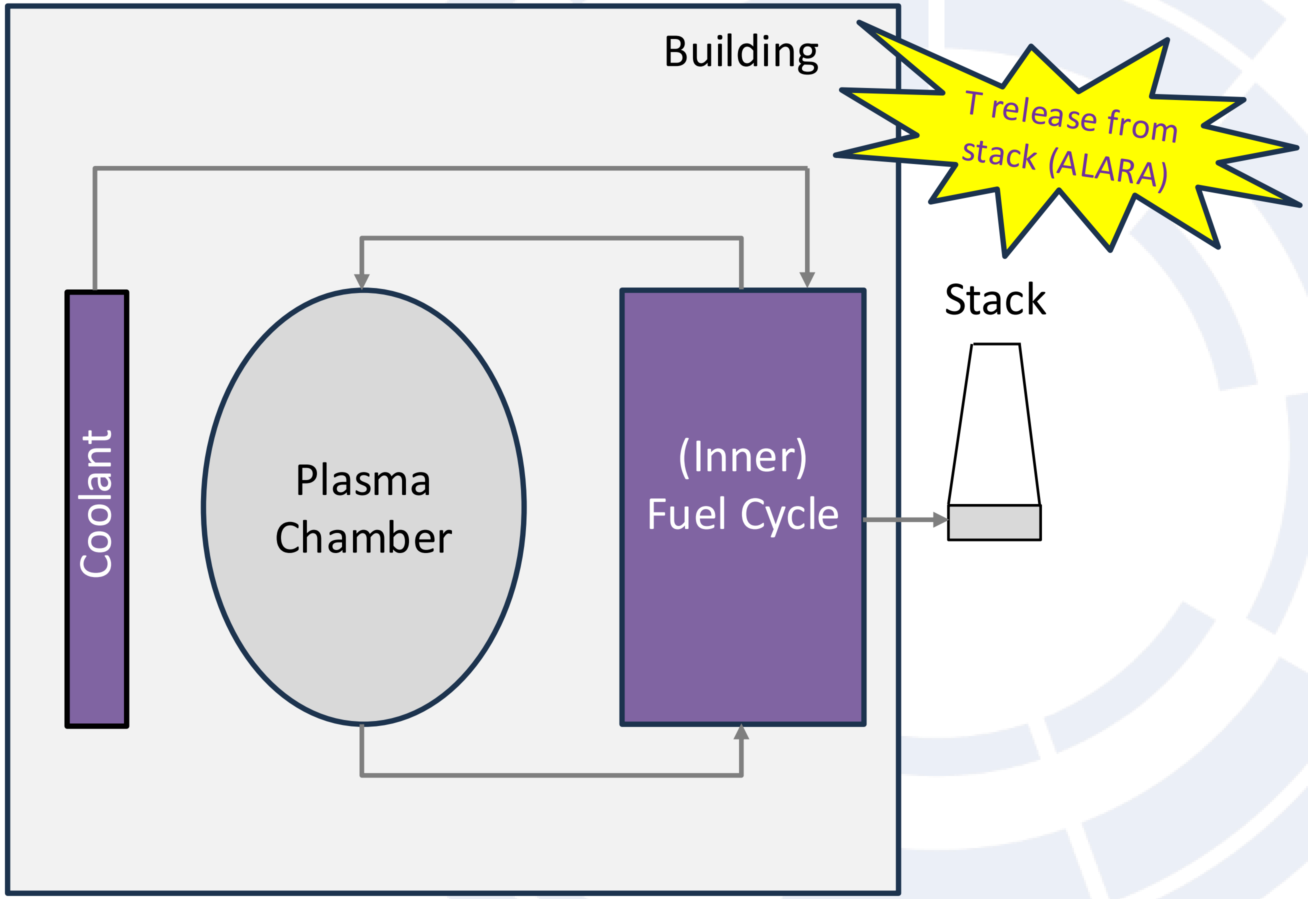
In ITER ~ 0.36%, In DEMO ~ 1-2%

- The vacuum system transfers the gas mixture to the tritium plant for **separation of the impurity gases from the hydrogen as well as separation and purification of the hydrogen isotopes** for the purpose of rebalancing the injected D-T ratio.



(Inner) Fuel Cycle

- Additional duties of a fusion tritium plant will be to store fuel, process tritium from the breeding blankets, **process contaminated air from building ventilation, tritiated water** as well as **tritium measurement and accountancy**.
- From first wall and blanket region, **tritium can permeate into coolant.** Once in the coolant circuit, tritium will permeate either across the coolant tubes or into the secondary coolant loop, from which it can reach the external environment.



FAIRNESS

Transparency
Collaboration
Loyalty

OPENNESS

Open doors
Open hearts
Open minds
Open ears

COMMITMENT

Ownership
Critical thinking
Determination
Respect

DIVERSITY

Cooperation
Equal opportunities
Inclusion