ITER Tritium Plant

Operation and Analytical Needs

Robert Michling, Group Leader Process,
Tritium Plant Section

2023-05-25

iter
china eu india japan korea russia usa

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

Outline

1 - ITER Fuel Cycle

2 - Tritium Plant Systems

3 - Operation and Analytical Requirements

4 - Analytical Aspects “unresolved”

China EU India Japan Korea Russia USA

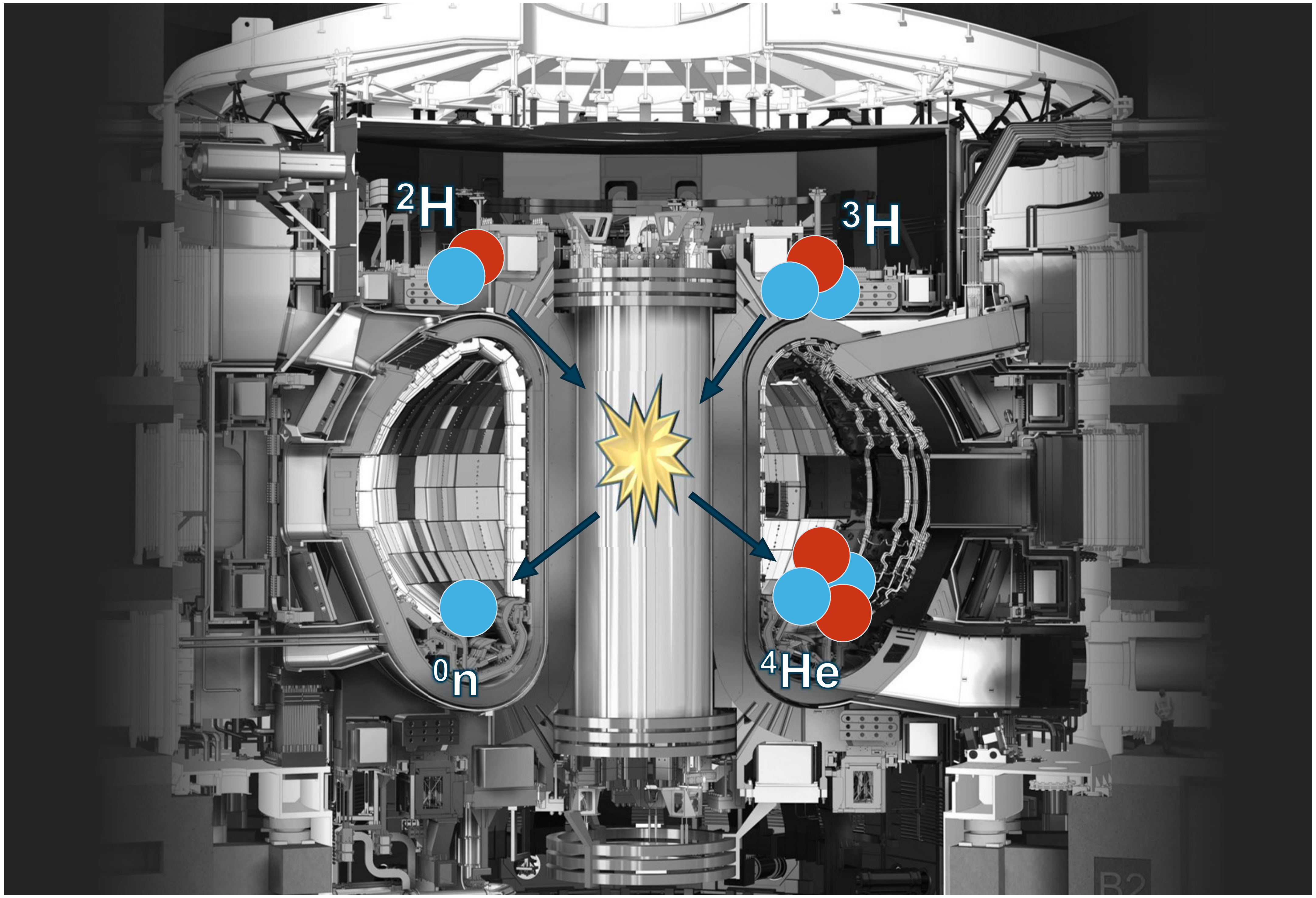
Fusion Reaction

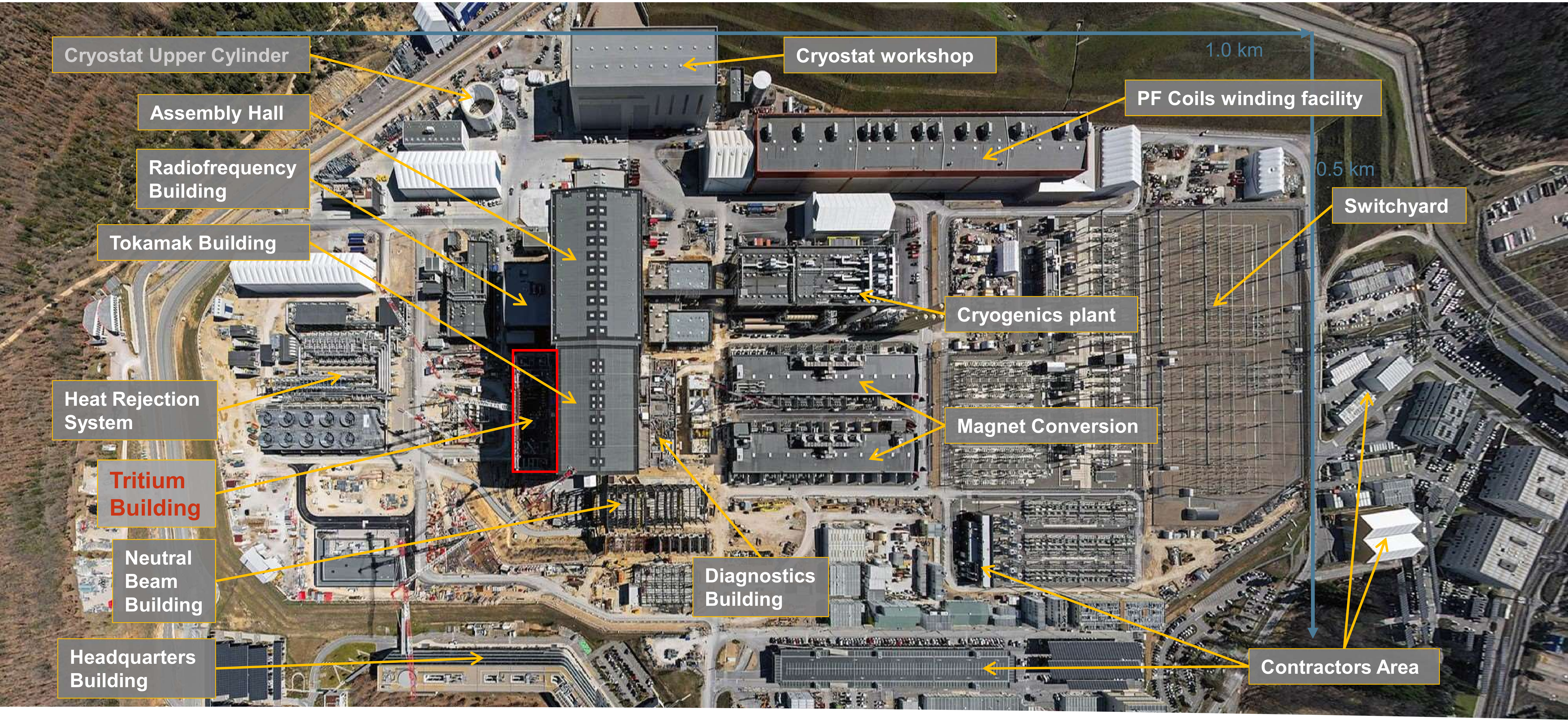
First phase:

- Assembly/commissioning
- H/H & D/D plasma

Second phase:

- Assembly/commissioning
- DT plasma
- Demonstration of Q = 10
  - (gained fusion energy vs. external plasma heating energy)





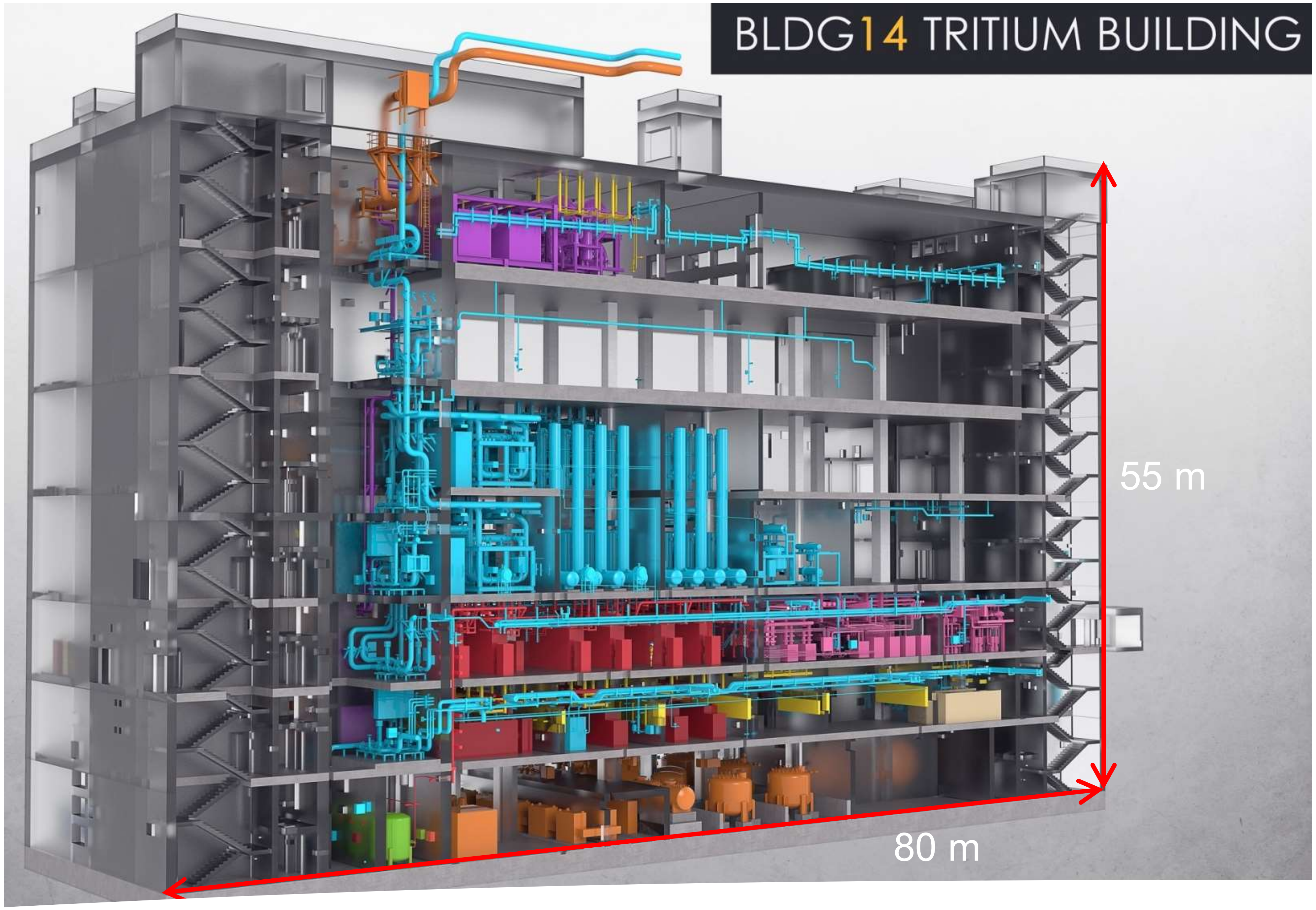
The ITER site

The Tritium Plant

Tritium building houses all Fuel Cycle process systems

- Storage
- Purification
- Separation
- Transfer (partially)
- Recovery

Fuelling and Vacuum are located close to the torus in the Tokamak building

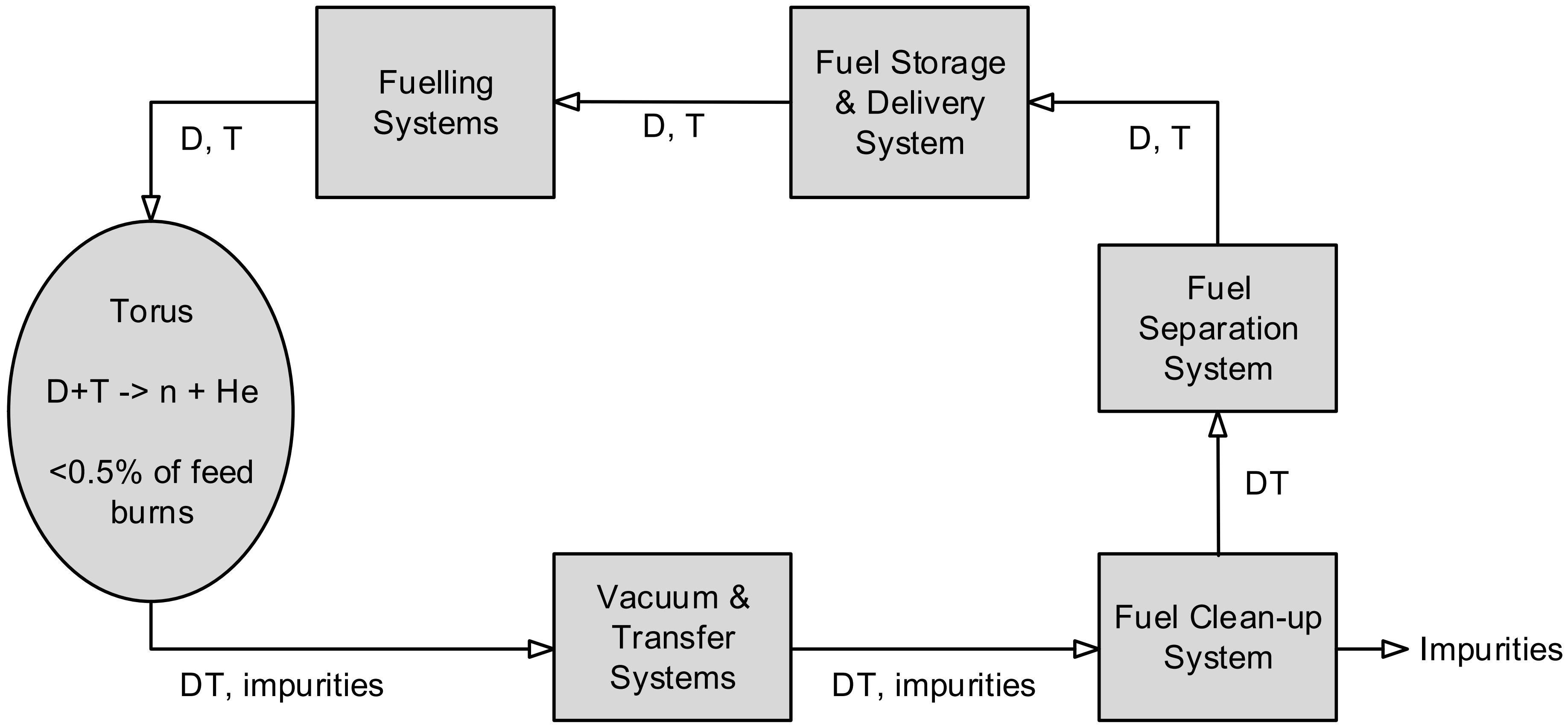


Simplified Fuel Cycle (1st layer)

Fuel - Deuterium and Tritium .

- Fuel Pellets for Core Fuelling
  - Separate D and T pellets
- Gas puffing for Edge fuelling and control
  - Various gas mixture (D & T, others)
- “Shot” fuelling and exhaust pumping
  - Extraction of unburnt fuel and impurity (He ash, others)
- Separation of unburnt fuel and separation of D & T
- Refuelling of D & T during the same plasma shot

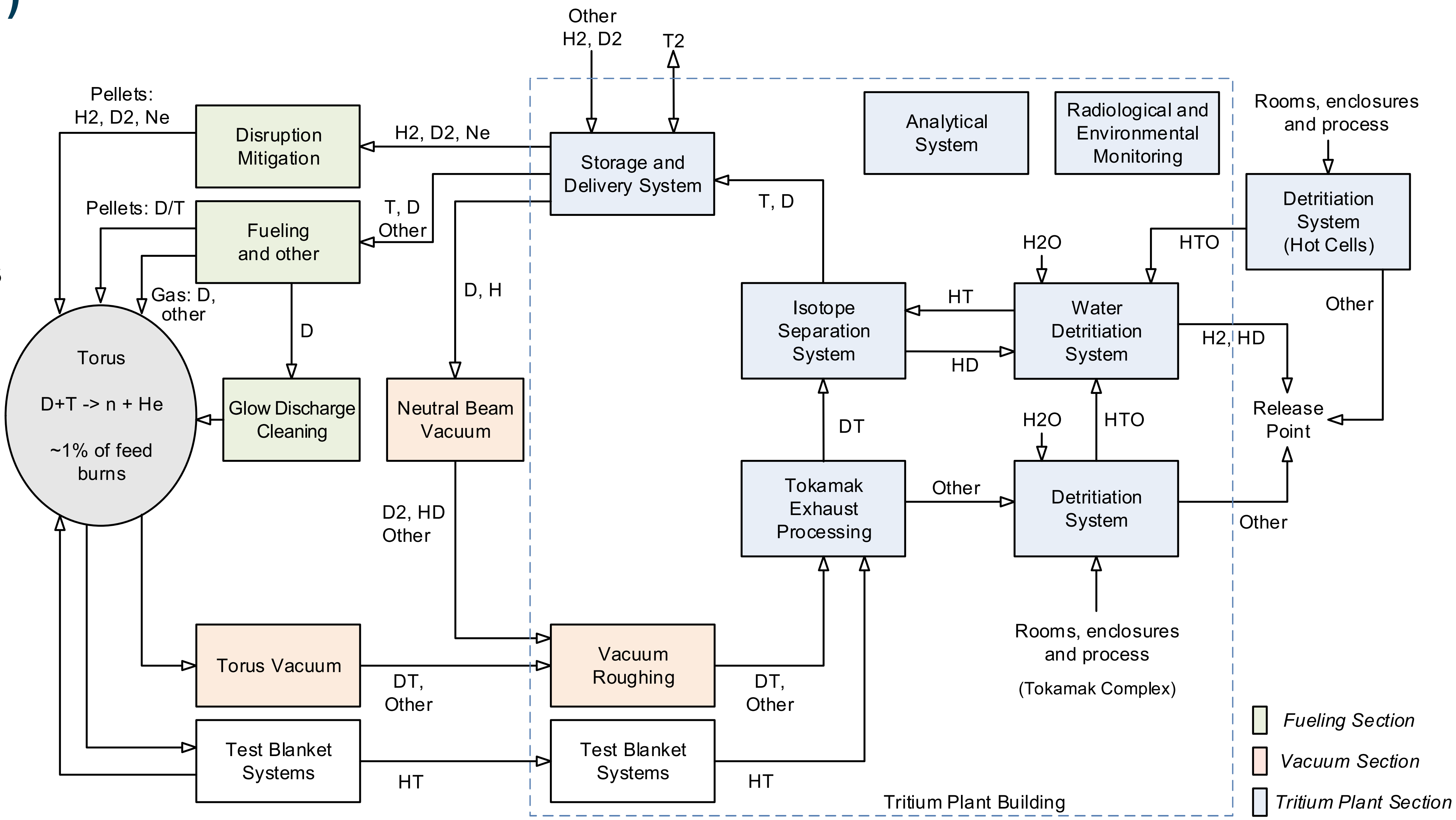
→ Closed continuous fuel cycle for a defined duration (up to 3400 s)



Detailed Fuel Cycle (2nd layer)

Fuel - Deuterium and Tritium

- Lines of Fuel supply
  - D & T fuel
  - Heating and Diagnostic Systems
  - Protection System (DMS)
  - Others
- Torus pumping by cryo-pumps
- Neutral Beams pumping by cryo-pumps
- Tritium Plant for Fuel purification, separation and supply
- Plant systems for auxiliary support



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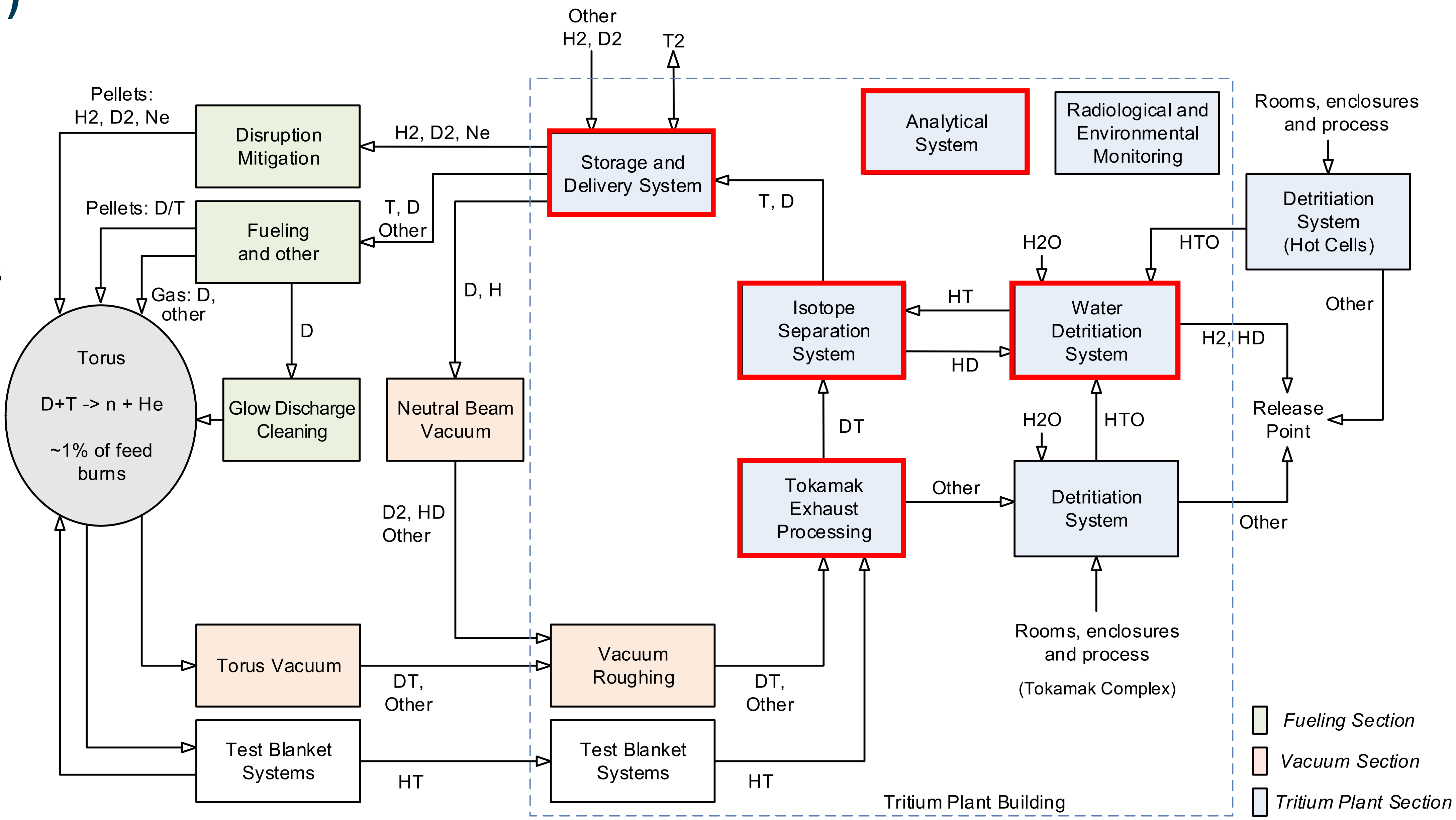
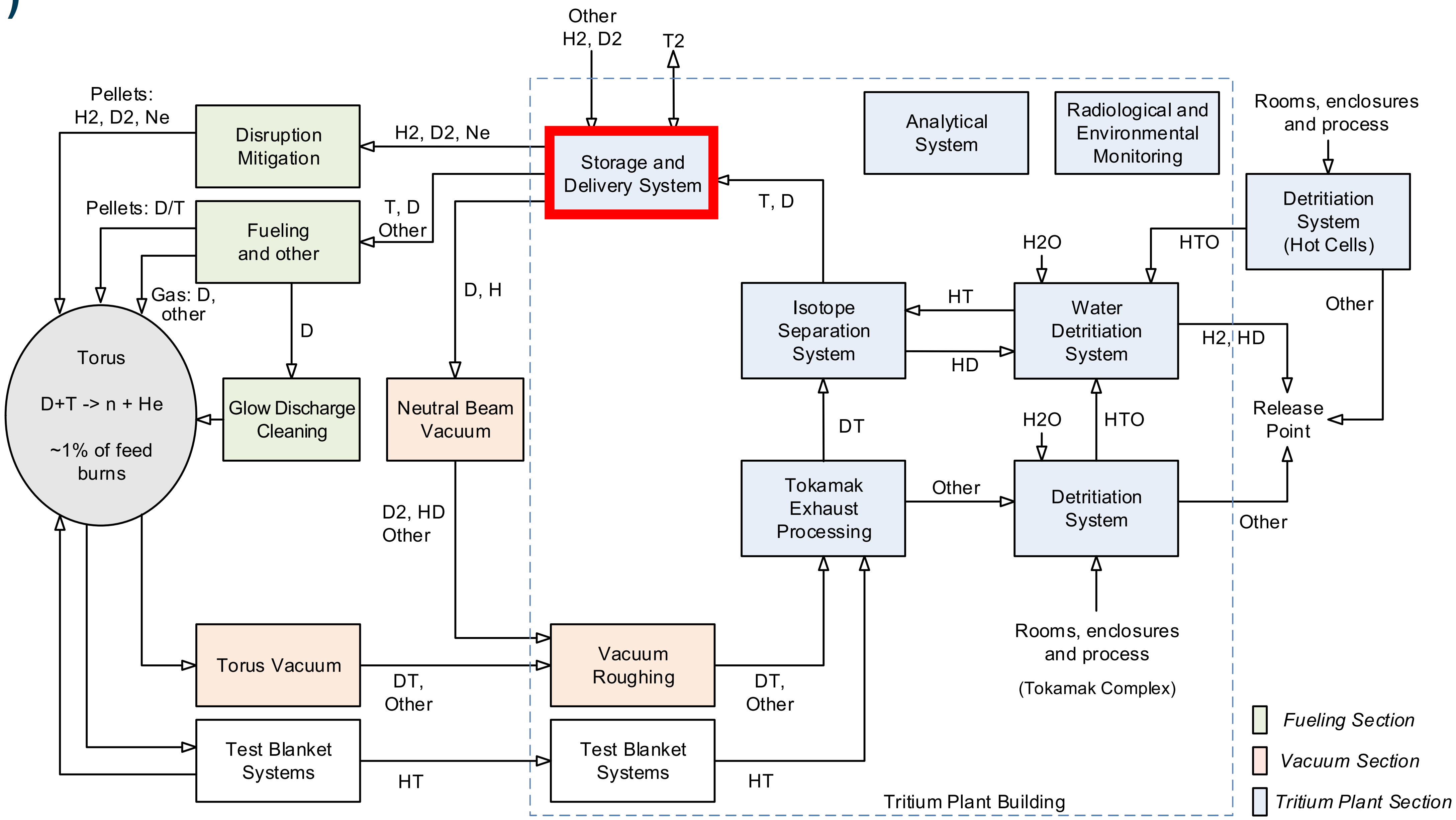


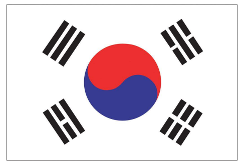
Detailed Fuel Cycle (2nd layer)

Fuel - Deuterium and Tritium .

- **Storage & Delivery**



Storage & Delivery System (SDS)



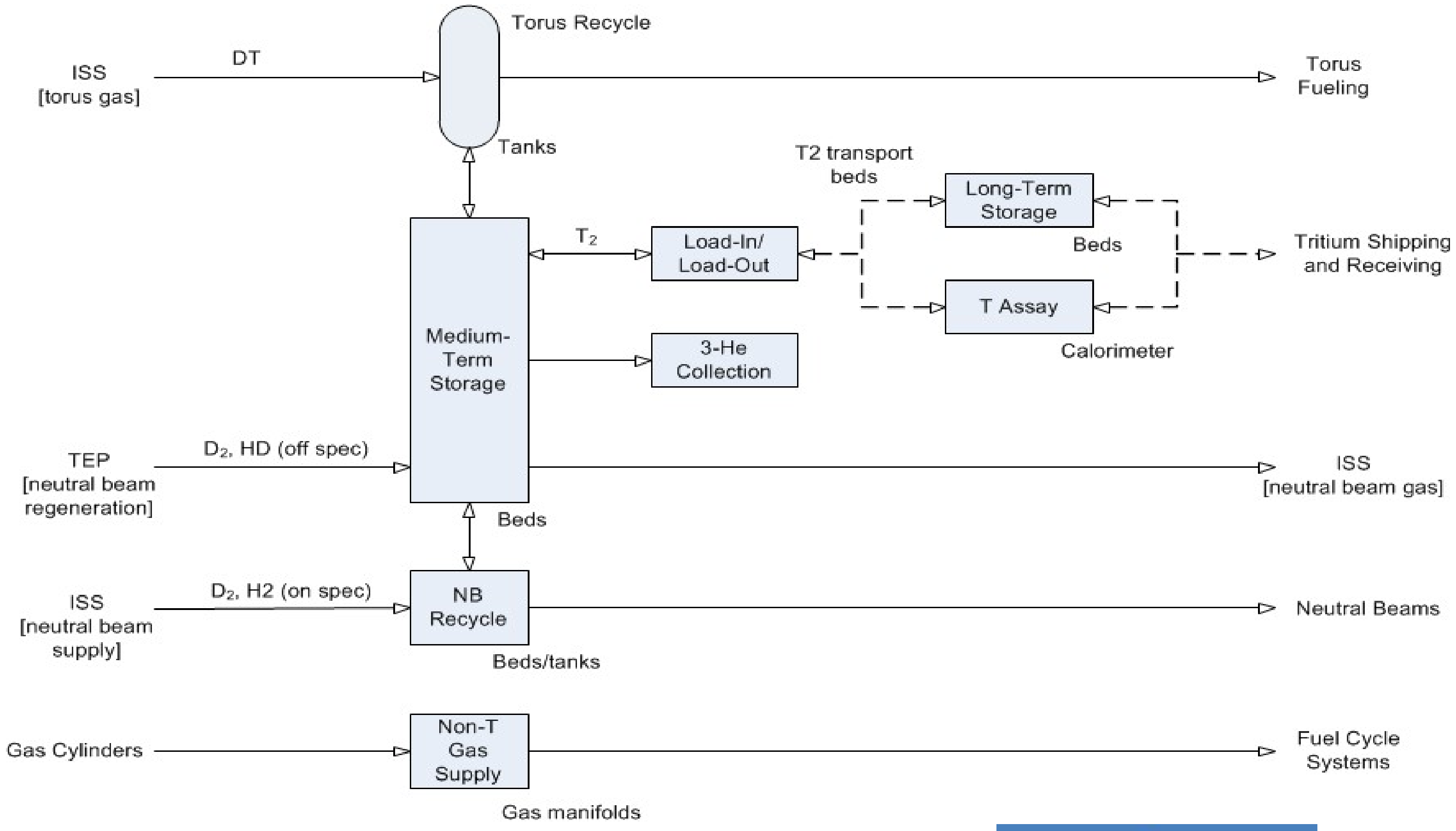
Unit operations of SDS for main functions:

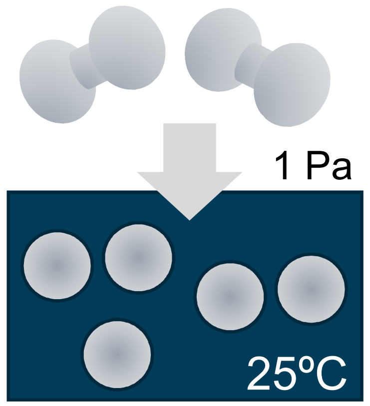
○ Storage of Deuterium and Tritium

- Uranium Hydride Beds
  - Safe storage of tritium/deuterium by formation of hydrides

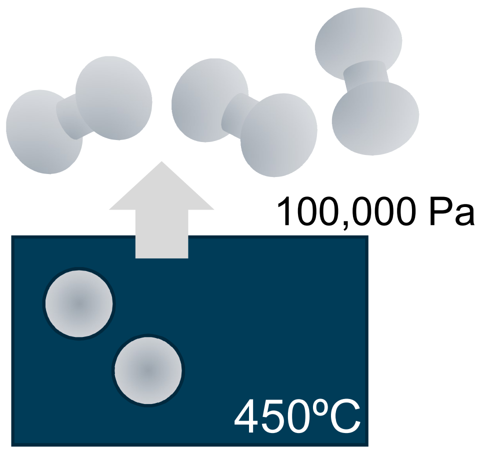
○ Delivery of fuelling gases

- Buffer tanks
  - Provision of fuelling gases (for torus and neutral beam units) within specifications
  - Transfer gases under defined supply conditions (composition, flow rates, pressure)
- Uranium Hydride Beds
  - Delivery of stored gases by heating U-beds
  - Direct supply to clients or to fill buffer tanks





$U + {}^{3}/_{2}\, Q_2 \rightarrow UQ_3$



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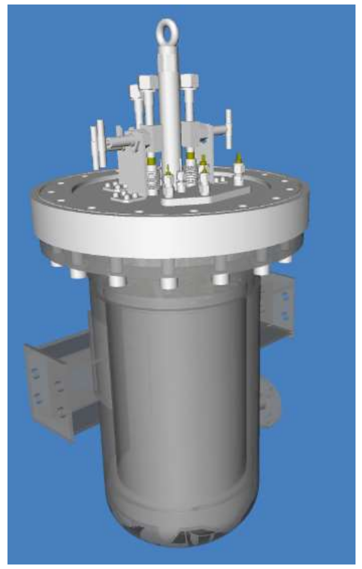
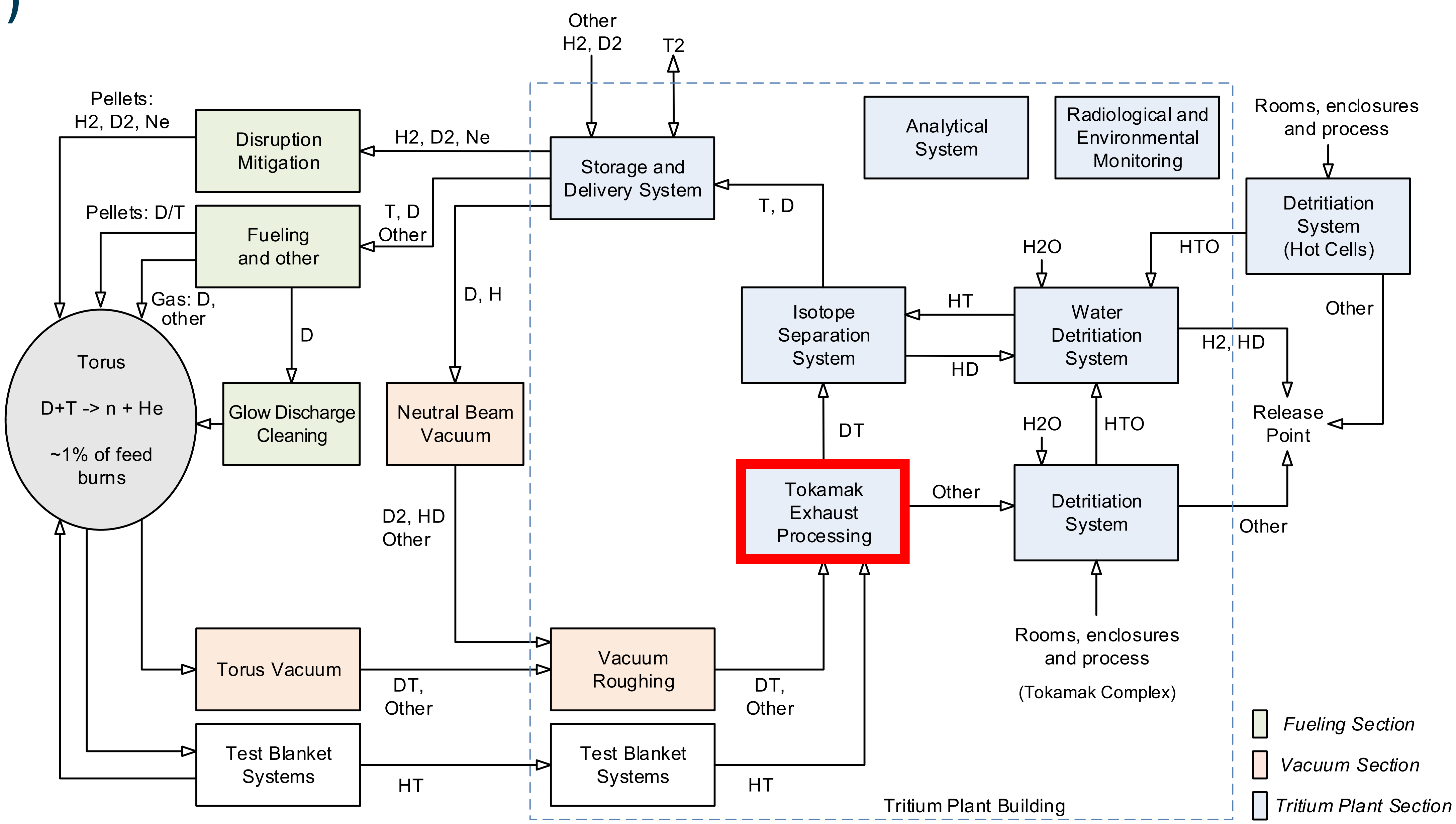


5x Ubed - prototype

Detailed Fuel Cycle (2nd layer)

Fuel - Deuterium and Tritium .

- **Tokamak Exhaust Processing**



Tokamak Exhaust Processing (TEP)

Unit operations of TEP for main functions:

○ Separate impurities from exhaust fuel gases

- Permeators – Permeation of Q_2 through a Pd/Ag membrane
  - Leaves impurities in the retentate stream
- Cryogenic Molecular Sieve Beds – Fractionation by Cryo-adsorption
  - Several fractions of gas species – He, Q_2, impurities

○ Recover Tritium from chemical species

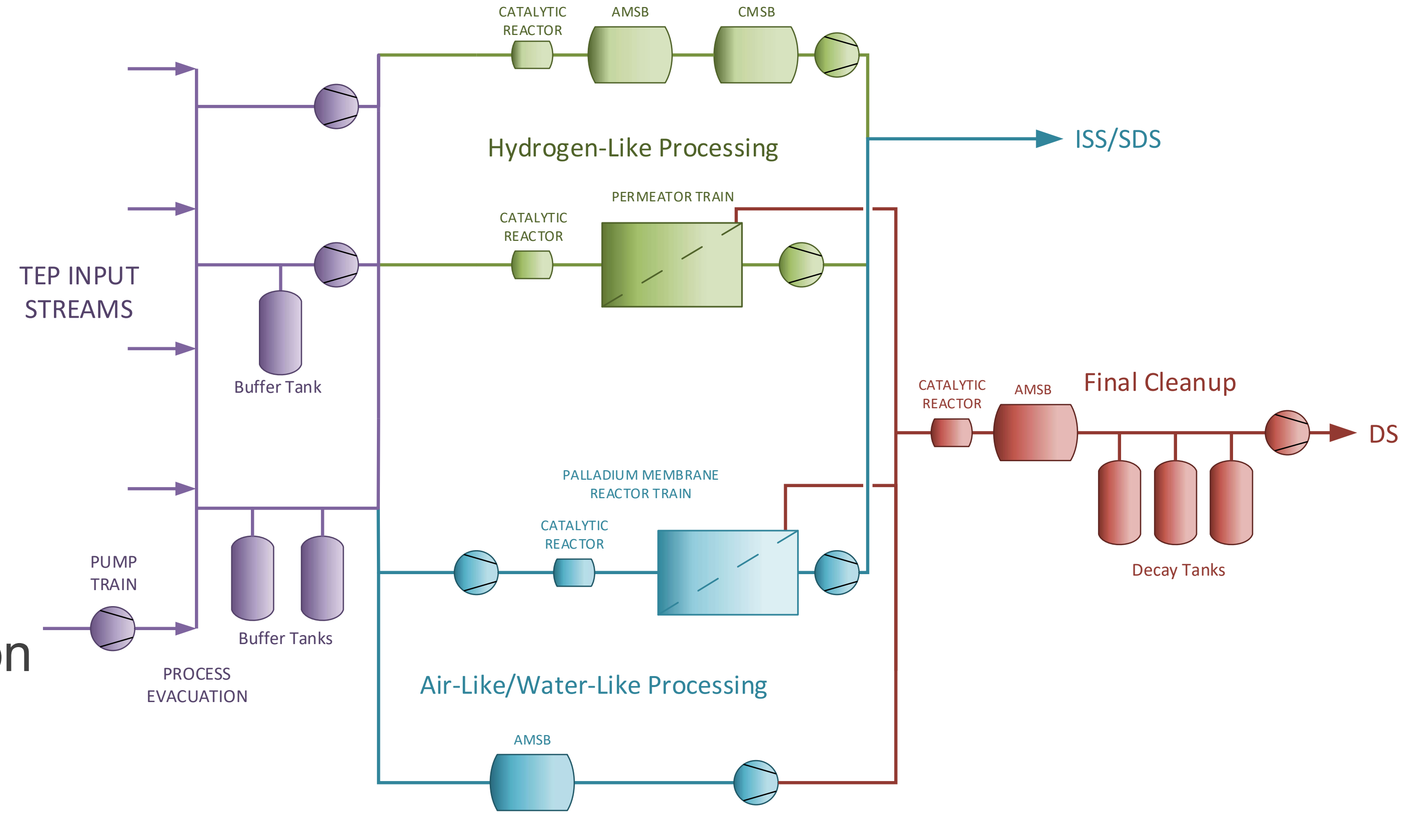
- Ambient Molecular Sieve Beds – Capture of tritiated water
  - Retain water from process gas streams
- Palladium Membrane Reactor – Tritium recovery by chemical reactions
  - Water-like and Air-like tritiated gas species are processed

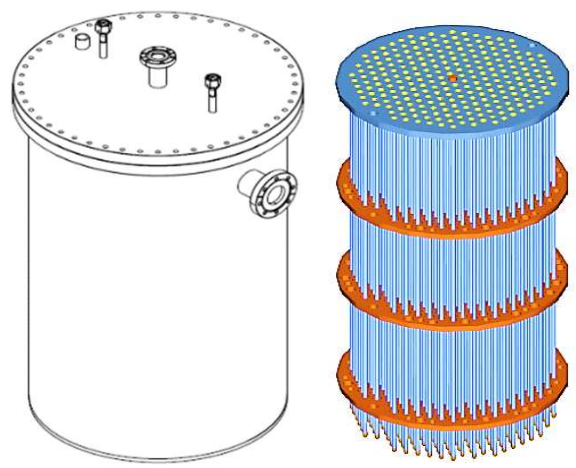
$$HTO + CO \leftrightarrow HT + CO_2$$

Water Gas Shift reaction

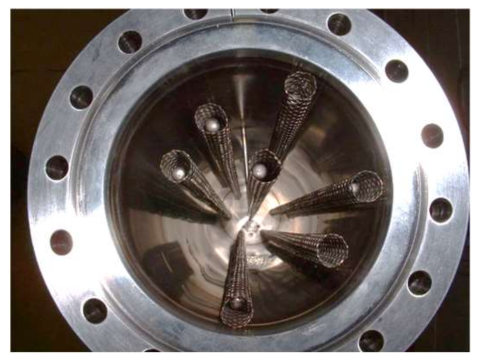
$$CTH_3 + H_2O \leftrightarrow 2\,H_2 + HT + CO$$

Methane Steam Reforming





Permeator unit

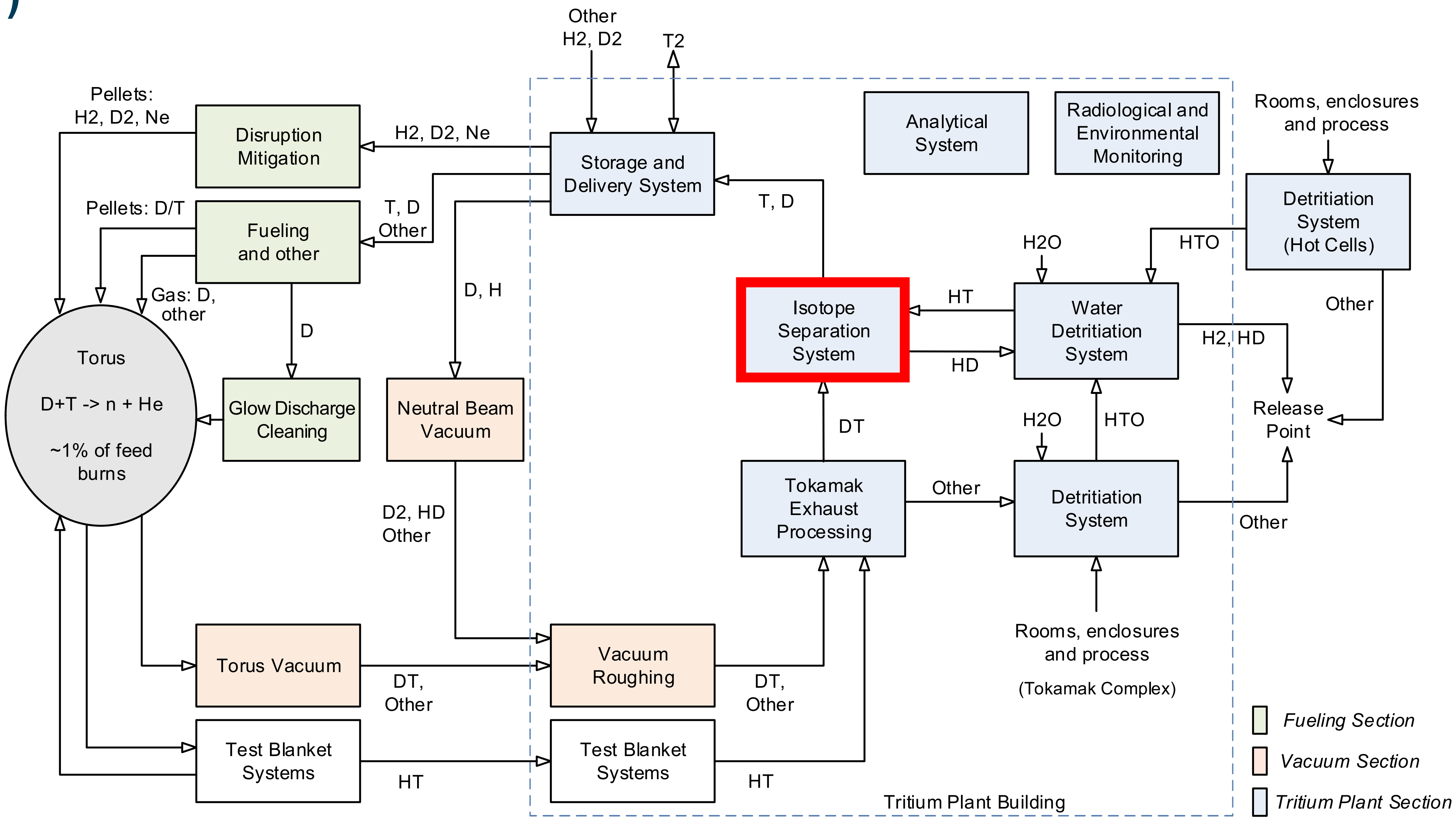


Palladium Membrane Reactor (unloaded)

Detailed Fuel Cycle (2nd layer)

Fuel - Deuterium and Tritium .

- **Isotope Separation System**



Isotope Separation System (ISS)

Unit operations of ISS for main function:

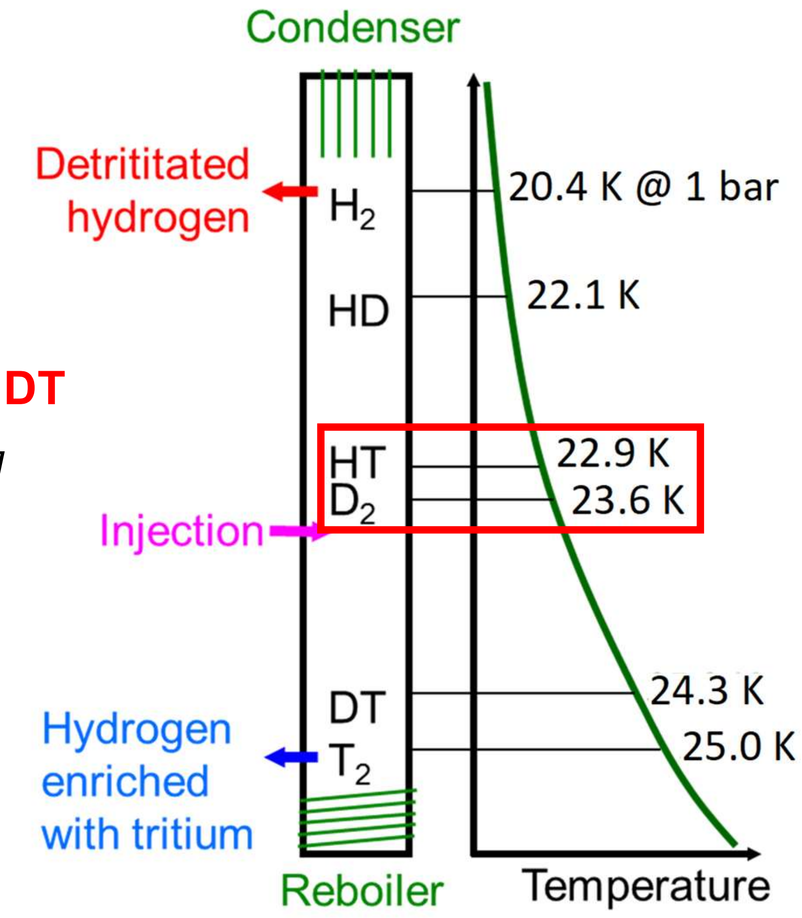
○ Separate hydrogen isotopes

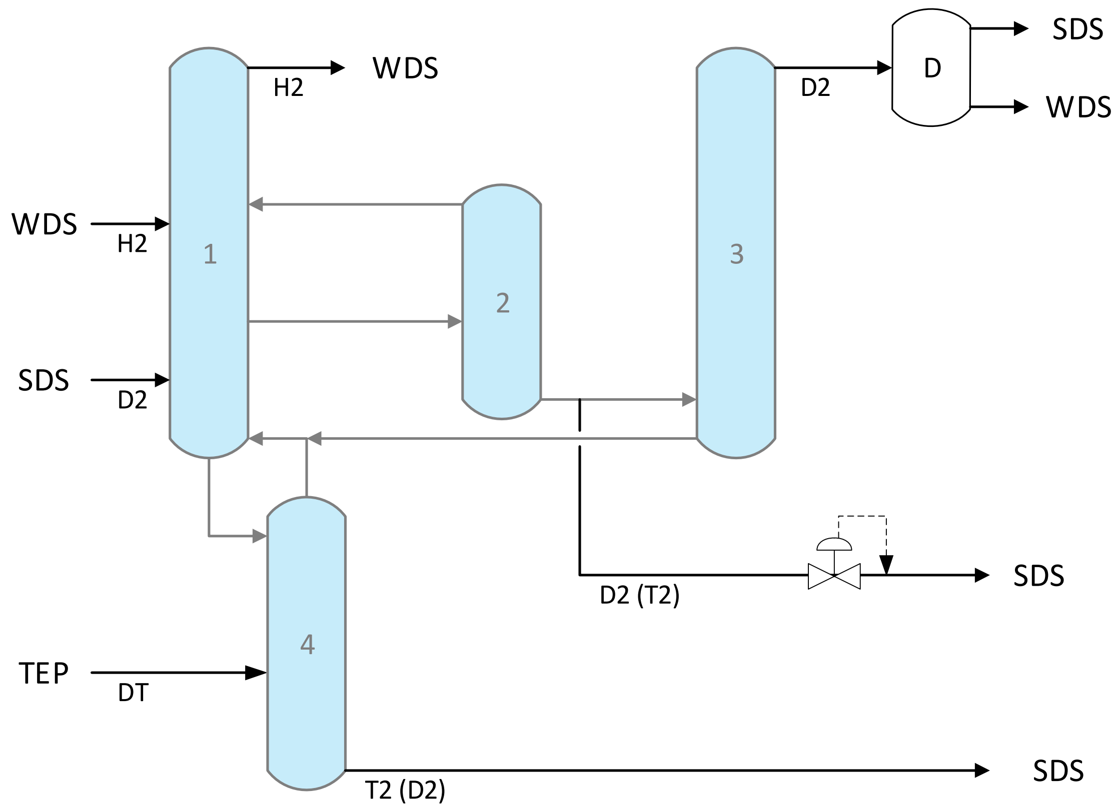
- Cryo-genic Distillation of hydrogen isotopologue mixtures
  - Generate H_2, D_2 and T_2 products within various specifications (compositions)
  - Utilization of slight differences of boiling points for the different isotopologues
- Dynamic operation and generation of different products on spec at different feed flows and compositions

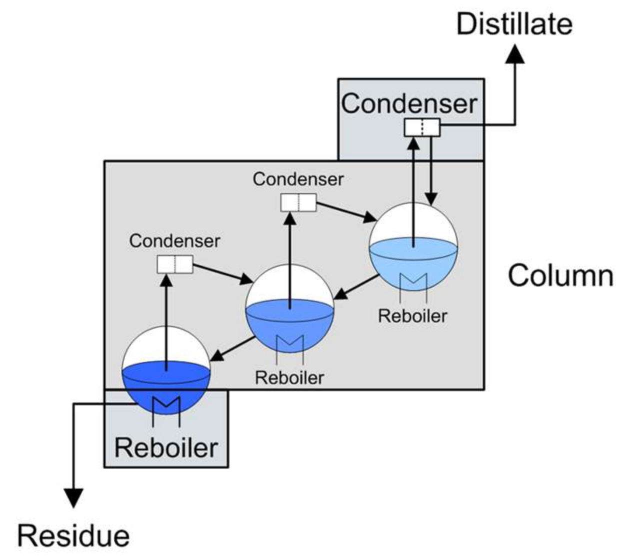
Catalyst

$HT + D_2 \rightarrow HD + DT$

[conversion of HT]



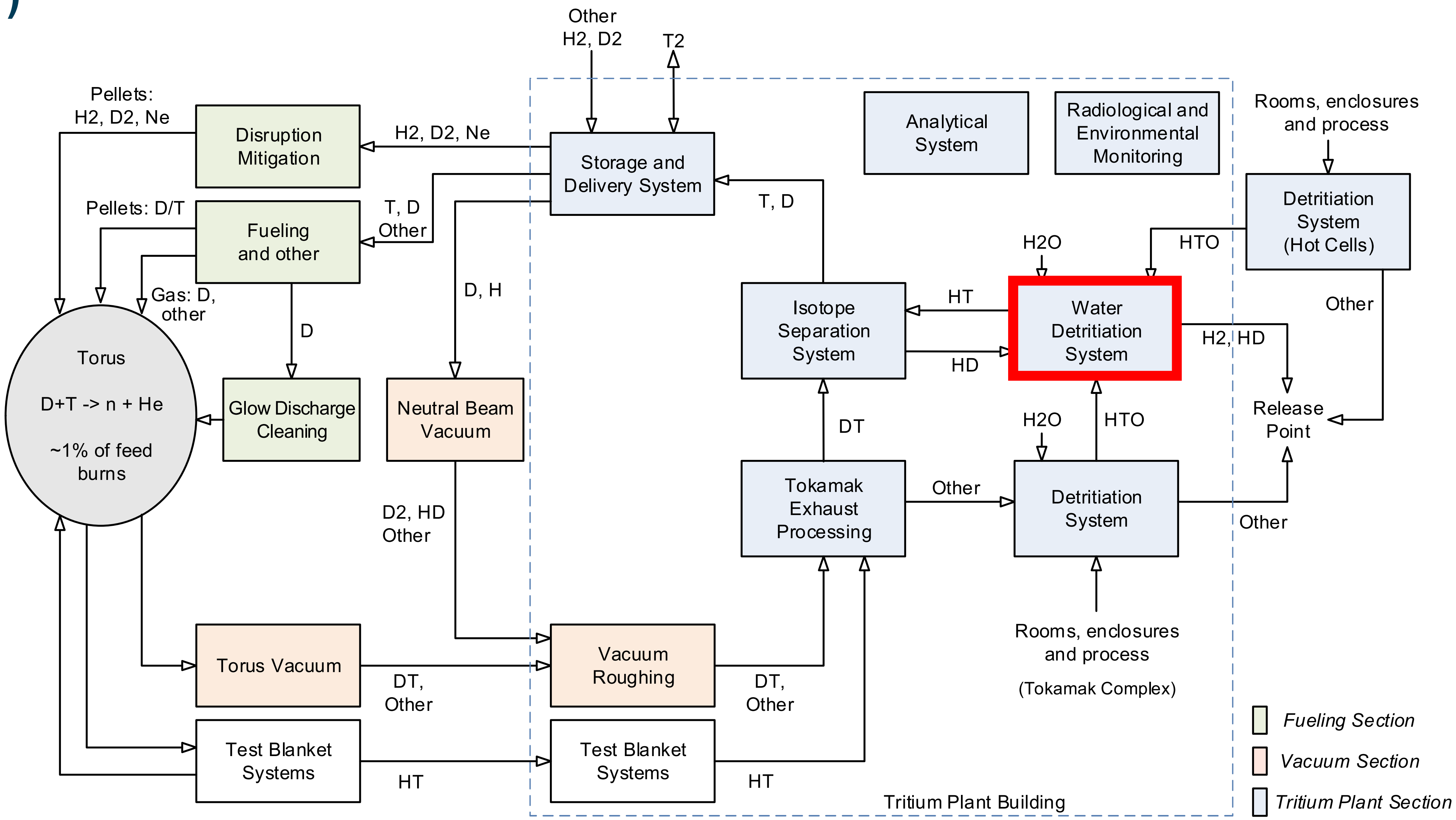




Detailed Fuel Cycle (2nd layer)

Fuel - Deuterium and Tritium

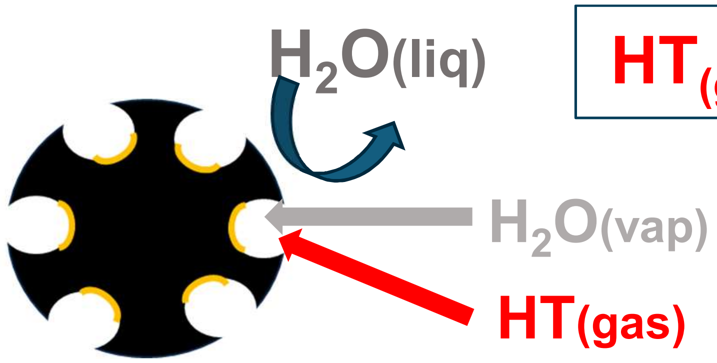
- **Water Detritiation System**



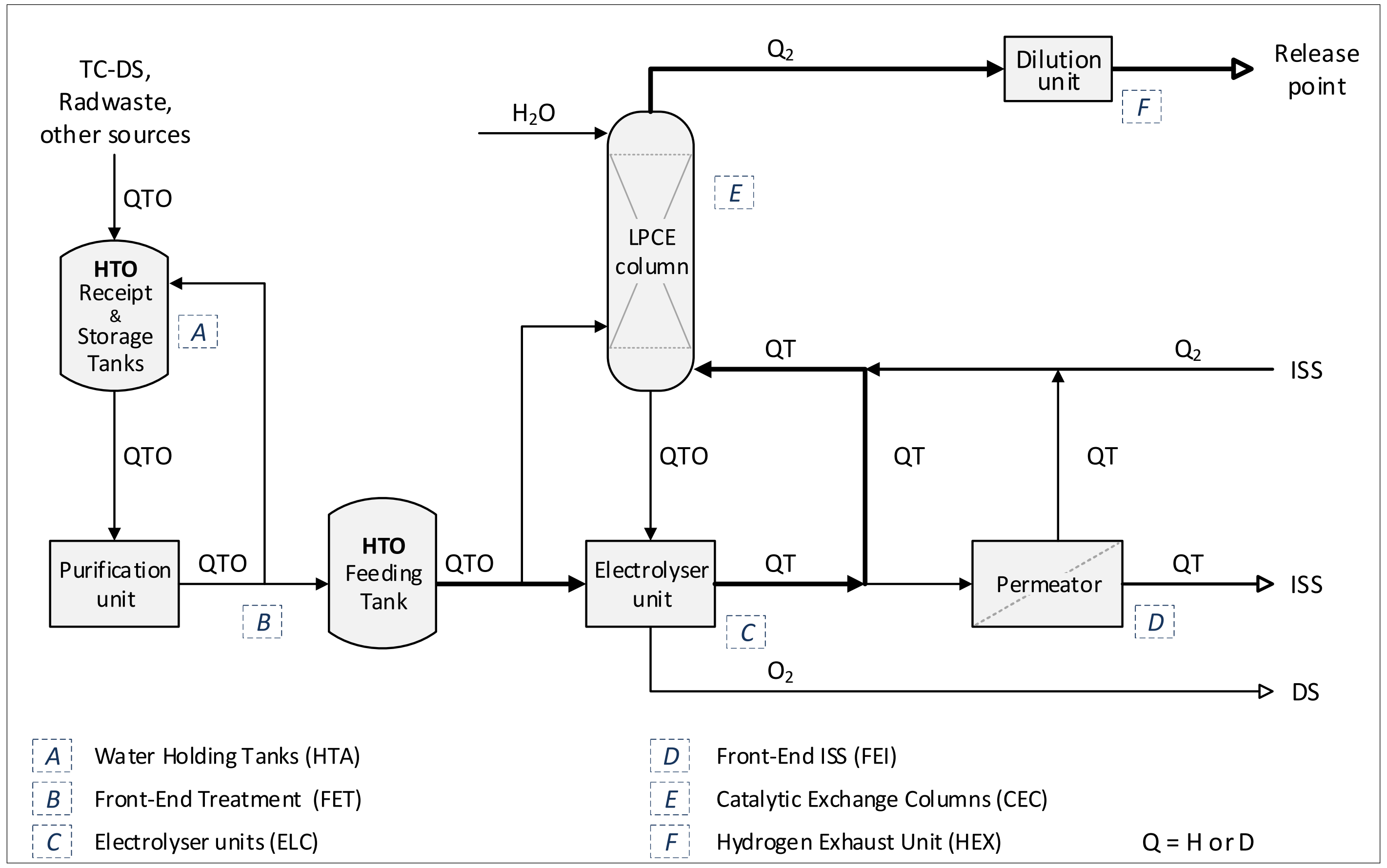
Water Detritiation System (WDS)

Unit operations of ISS for main functions:

- ○ Recover Tritium from water
  - Water Holding Tanks
    - Receive and store tritiated water (HTO) for final processing
  - Electrolyser unit
    - Generate tritiated hydrogen stream from HTO
  - Catalytic Isotope Exchange Column
    - Detritiate hydrogen stream for final discharge
  - Permeator
    - Supply pure enriched tritiated Q_2 stream to ISS
- ○ Receive water from (Air) Detritiation System
  - Emergency tanks
    - Safety important storage capacity for tritiated water from DS



$$HT_{(gas)} + H_2O_{(vap)} \rightarrow HTO_{(vap)} + H_{2(gas)}$$



Emergency tank (100 m^3)

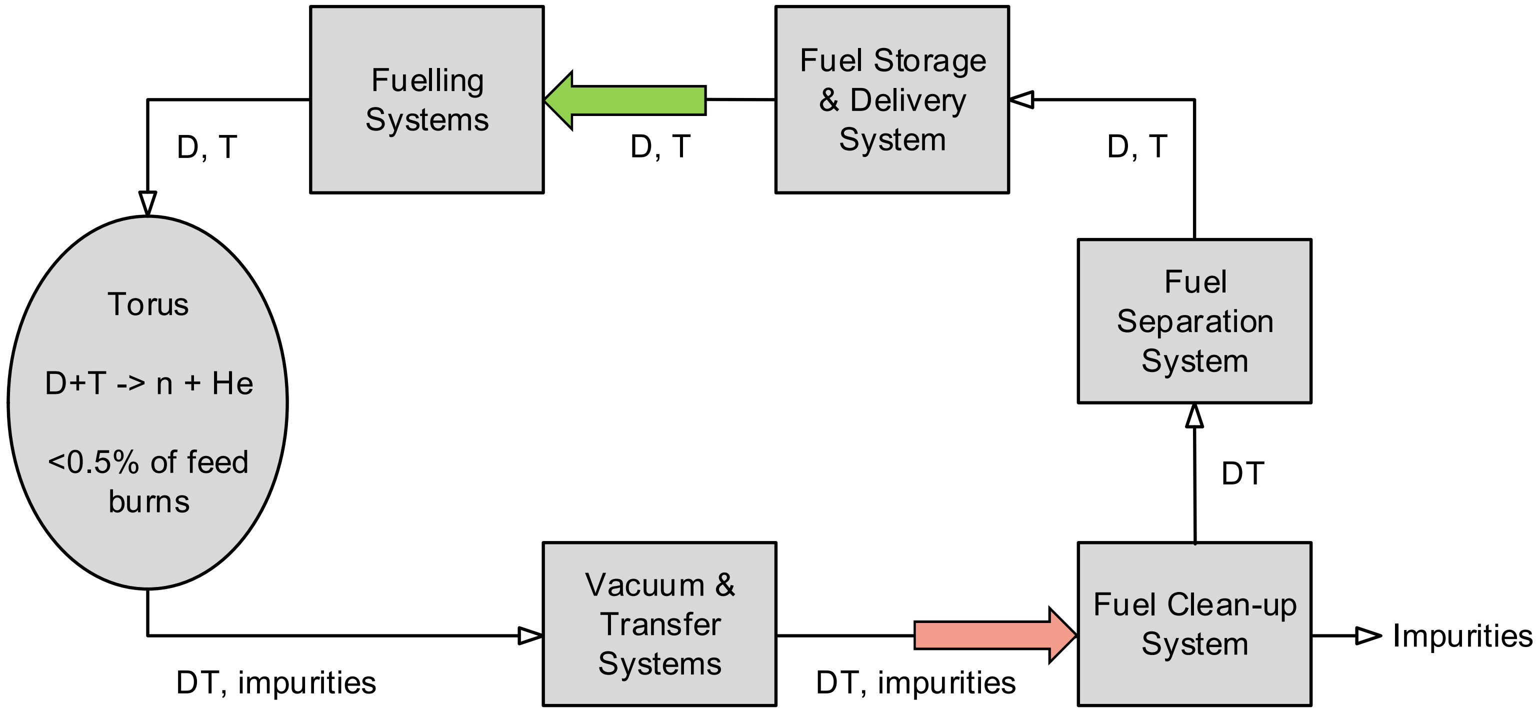
Holding tank (20 m^3)

Dynamic Conditions

Sequential batch-wise torus pumps regeneration of various compositions

Buffering and controlled flow regimes within TP systems to calm the conditions during plasma operation

Simultaneous separation and control return/supply of process gases to various systems



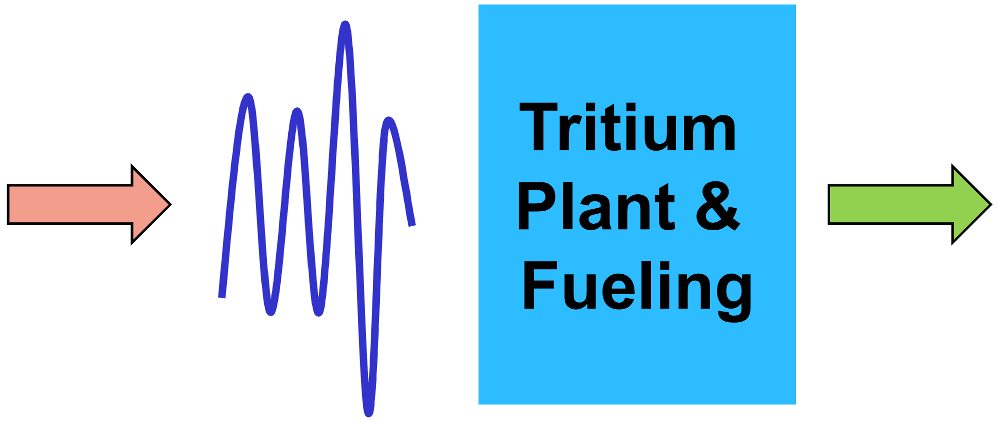
Flow & composition from vacuum pumps

He with trace DT (CVC)

DT with Ne

Argon/N2 with trace DT & impurities e.g. CQ4

HTO with trace DT & impurities e.g. NQ3, QI

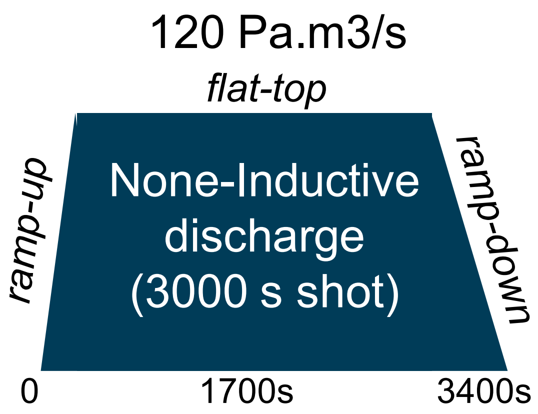


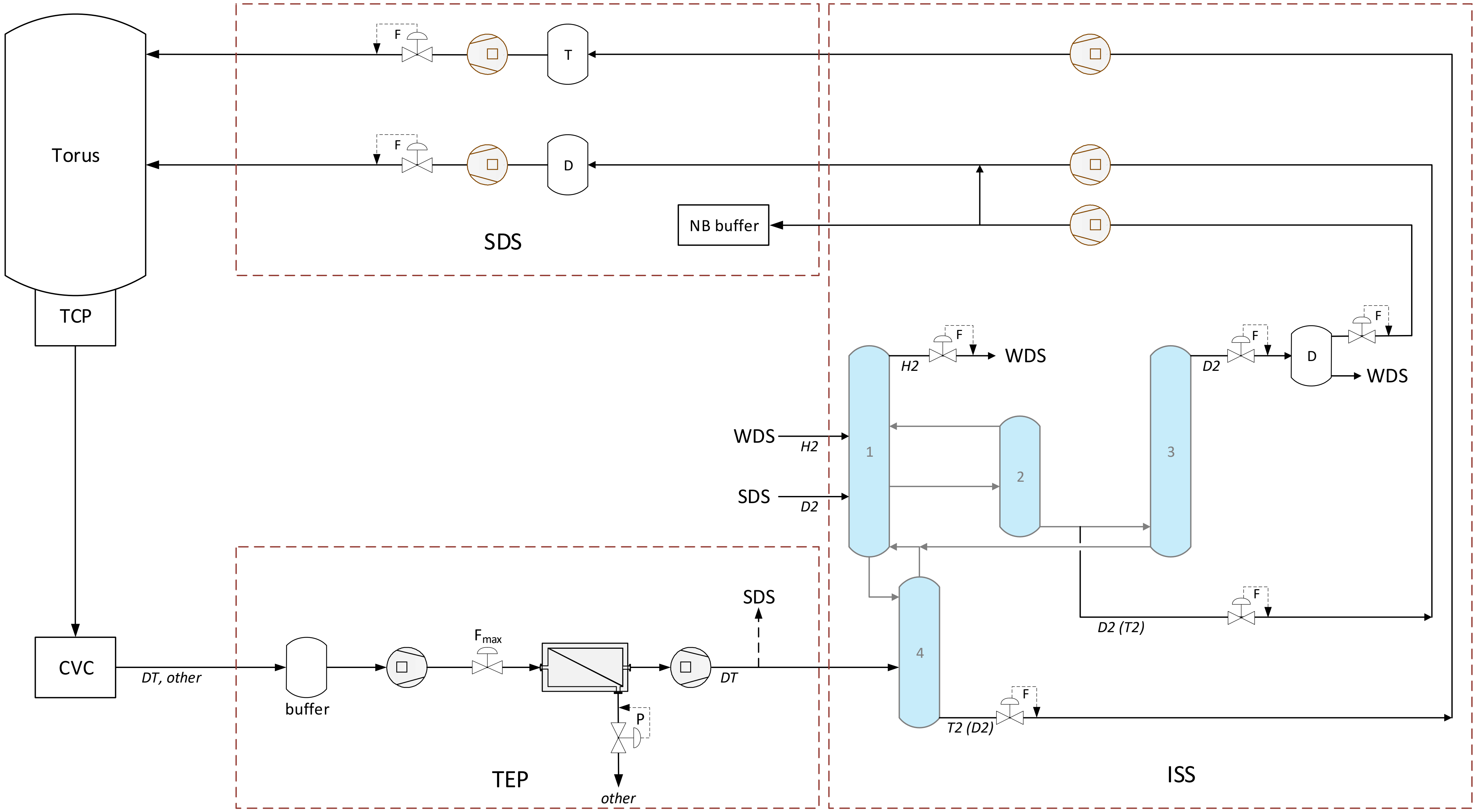
Flow & composition to clients

Pellet injection/gas puffing	>85% **T**, <15% D pellet >85% **D**, <15% T pellet >85% **D**, <15% T gas
Neutral Beam neutralizer	<1% T, >99% **D** gas
Neutral Beam Ion Source	<200ppm T in **D** gas <200ppm T in **H** gas
Effluent H2 to Water Detritiation	**H** with <5ppm T gas

Operation and control of Fuel Cycle

- "3000 s plasma shot day"





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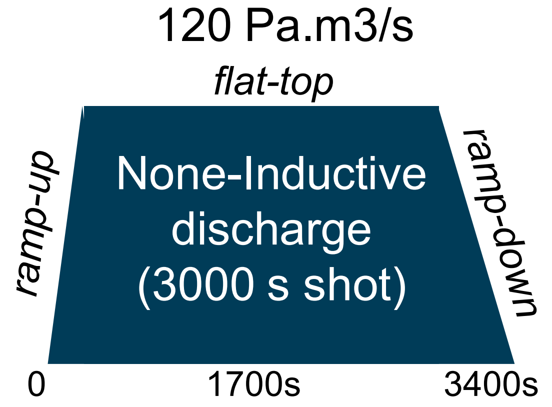

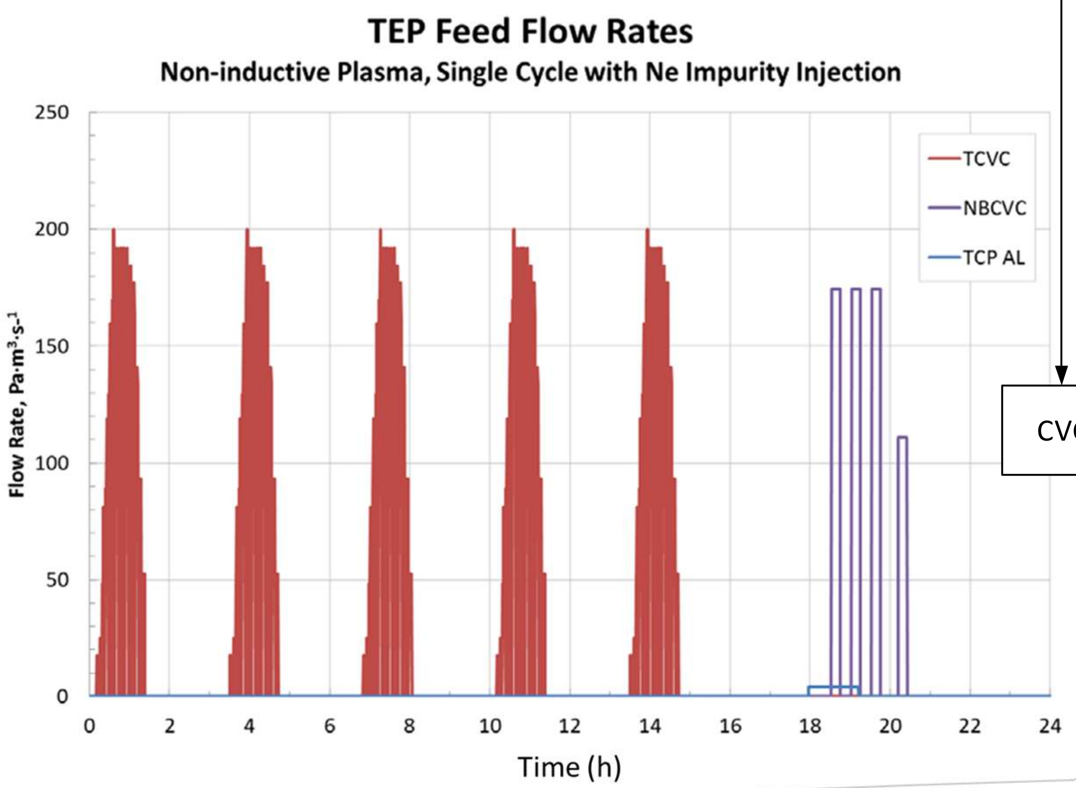

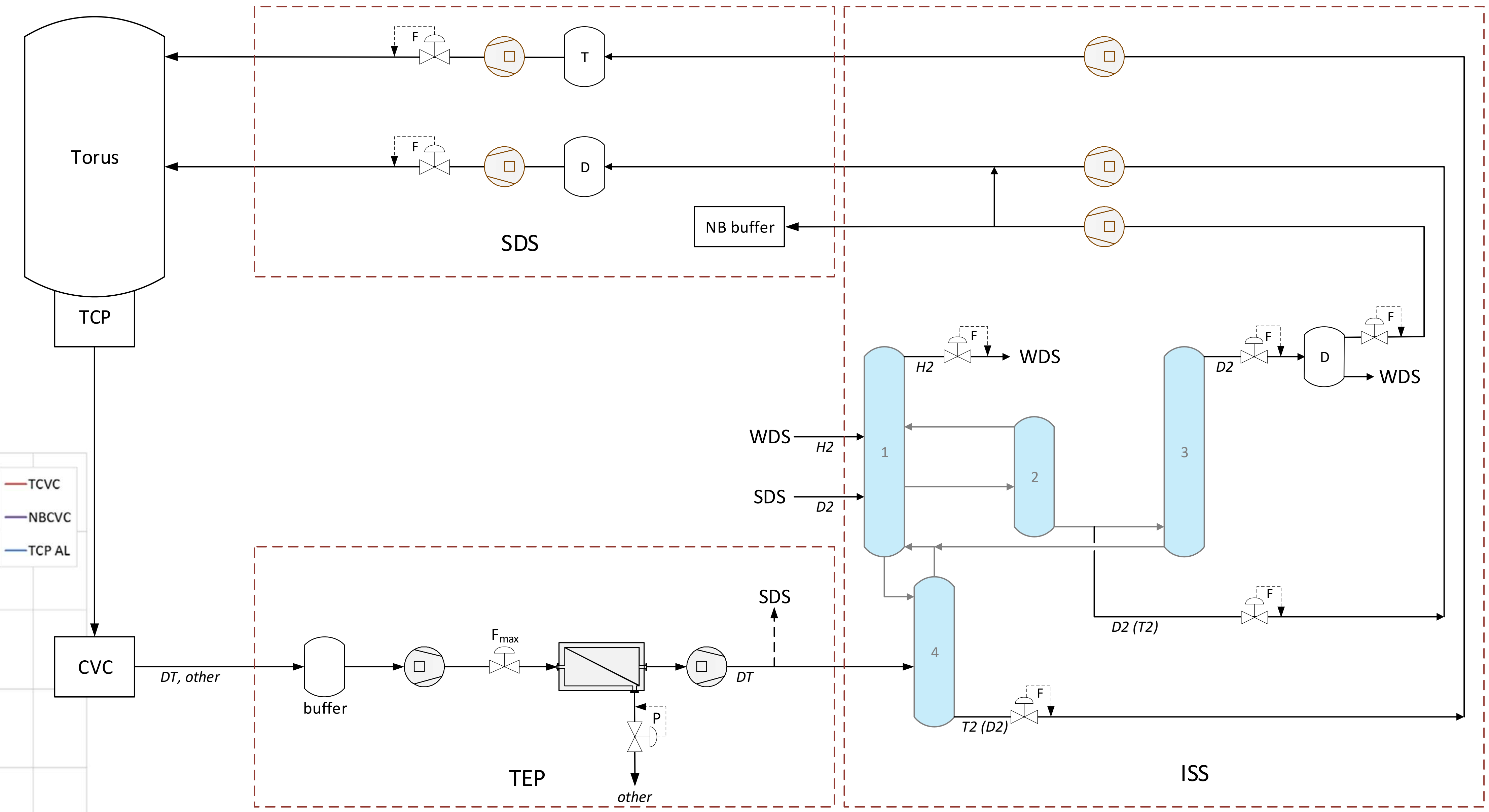

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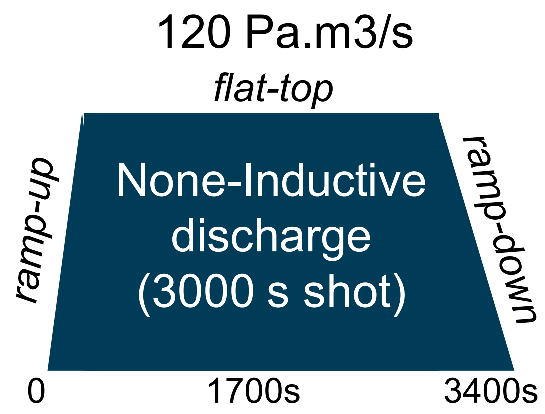
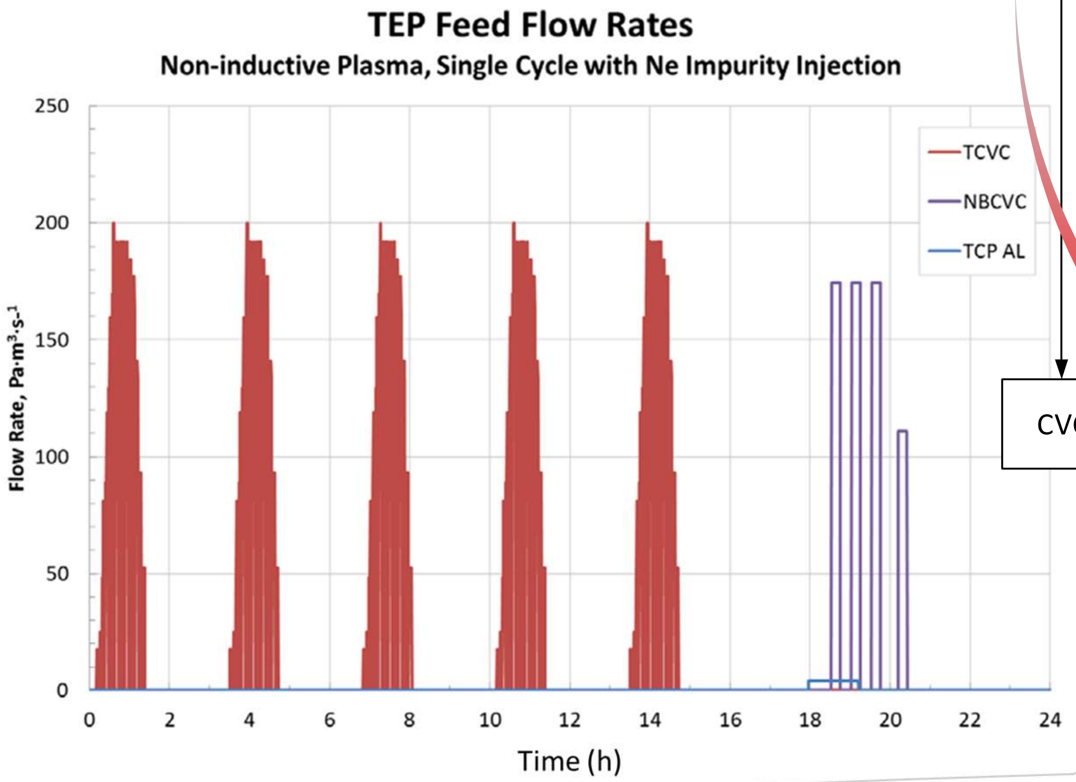
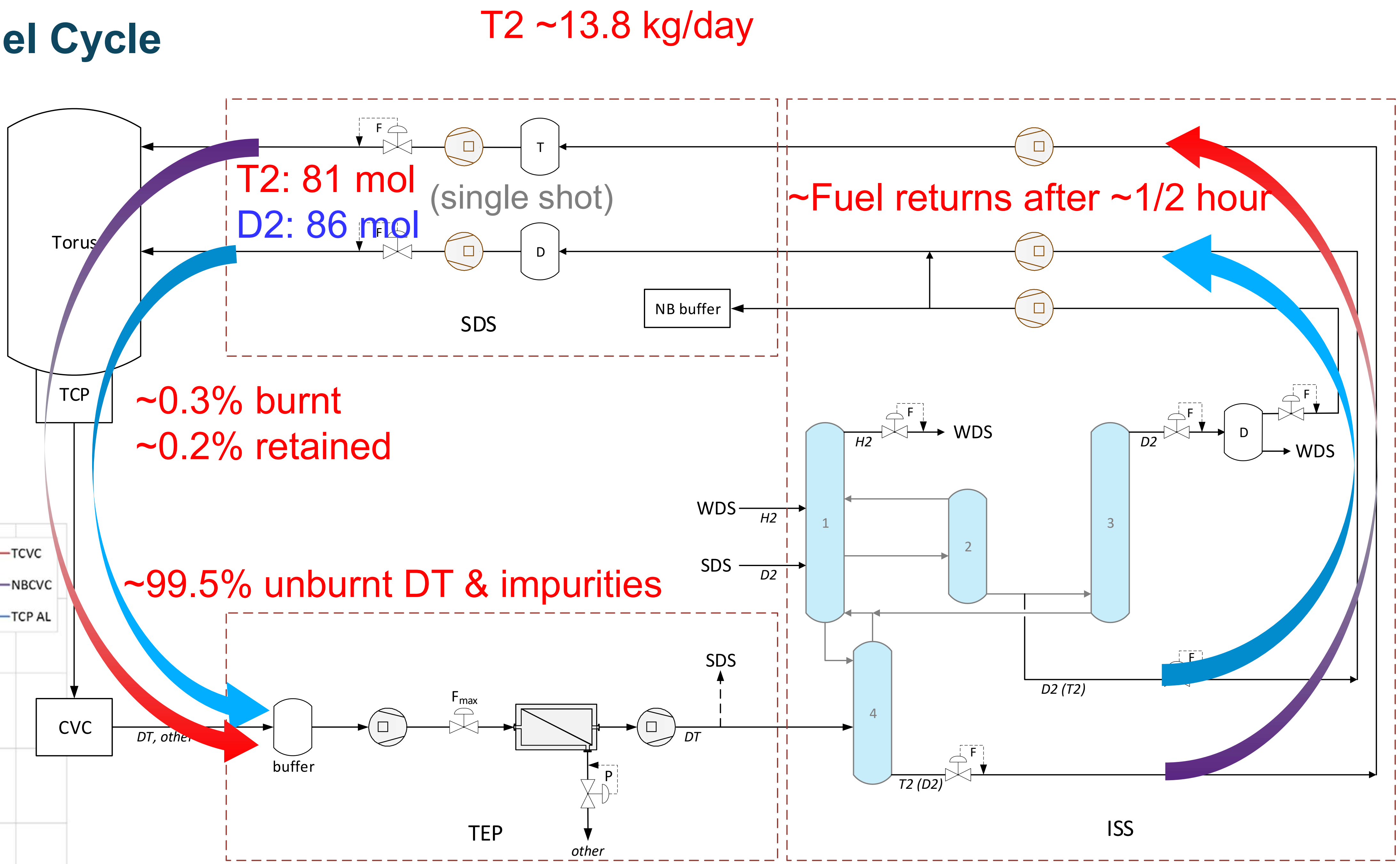


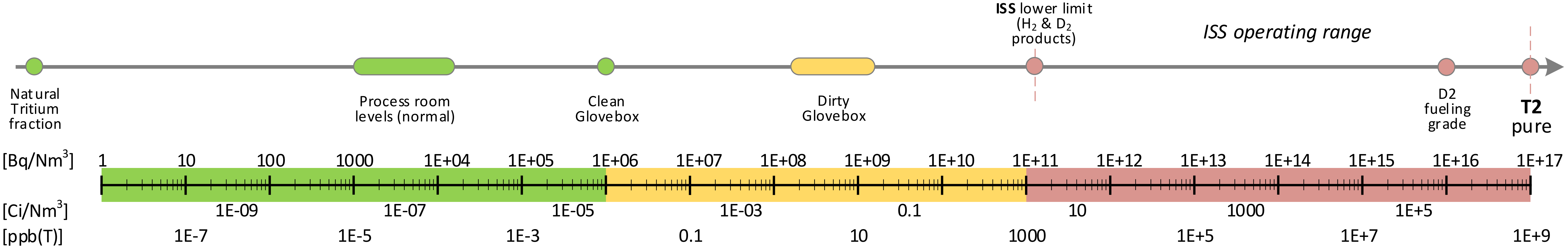




Tritium Plant Operating Conditions

Hydrogen gas mixtures (fuel cycle):

- Pressures ranges between 0.5 – 2.0 bara
- Temperatures from 20 – 25 K via ambient up to 700 – 800 K
- Flow rates between 15 – 320 mol/h (10 - 200 Pam³/s; 0.35 – 7.3 m³/h)
- Compositions (Q_2) from pure down to traces



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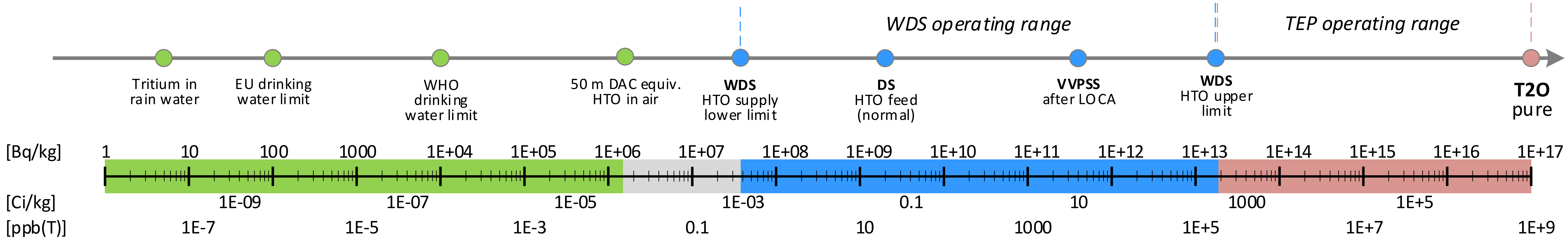
Tritiated water (plant operation):

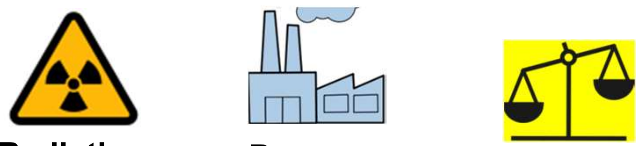
- Pressure atmospheric up to 4 bar
- Temperatures from ambient to 400 K
- Throughputs between 400 – 6700 mol/h (7 – 120 kg/h)
- Compositions (Q_2O) from 1E+6 – 1E+16 Bq/kg



Tritium specific analytics

18 orders of magnitude from environmental level to pure Tritium

Different applications



Radiation protection **Process control** **Accountancy**

Tritium in different states

Gas

Liquid

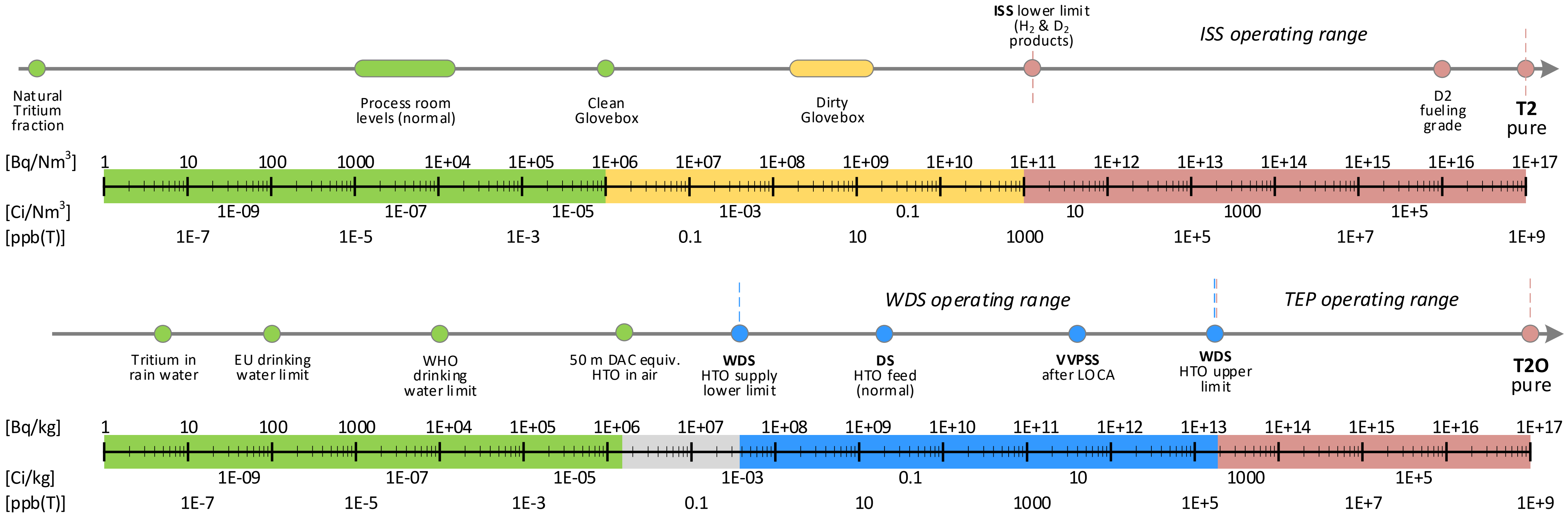
Solid

Tritium in different forms

Molecular

Oxidised

In compounds



Operation and control of Fuel Cycle

Controlled fuelling of known D & T grade gas streams

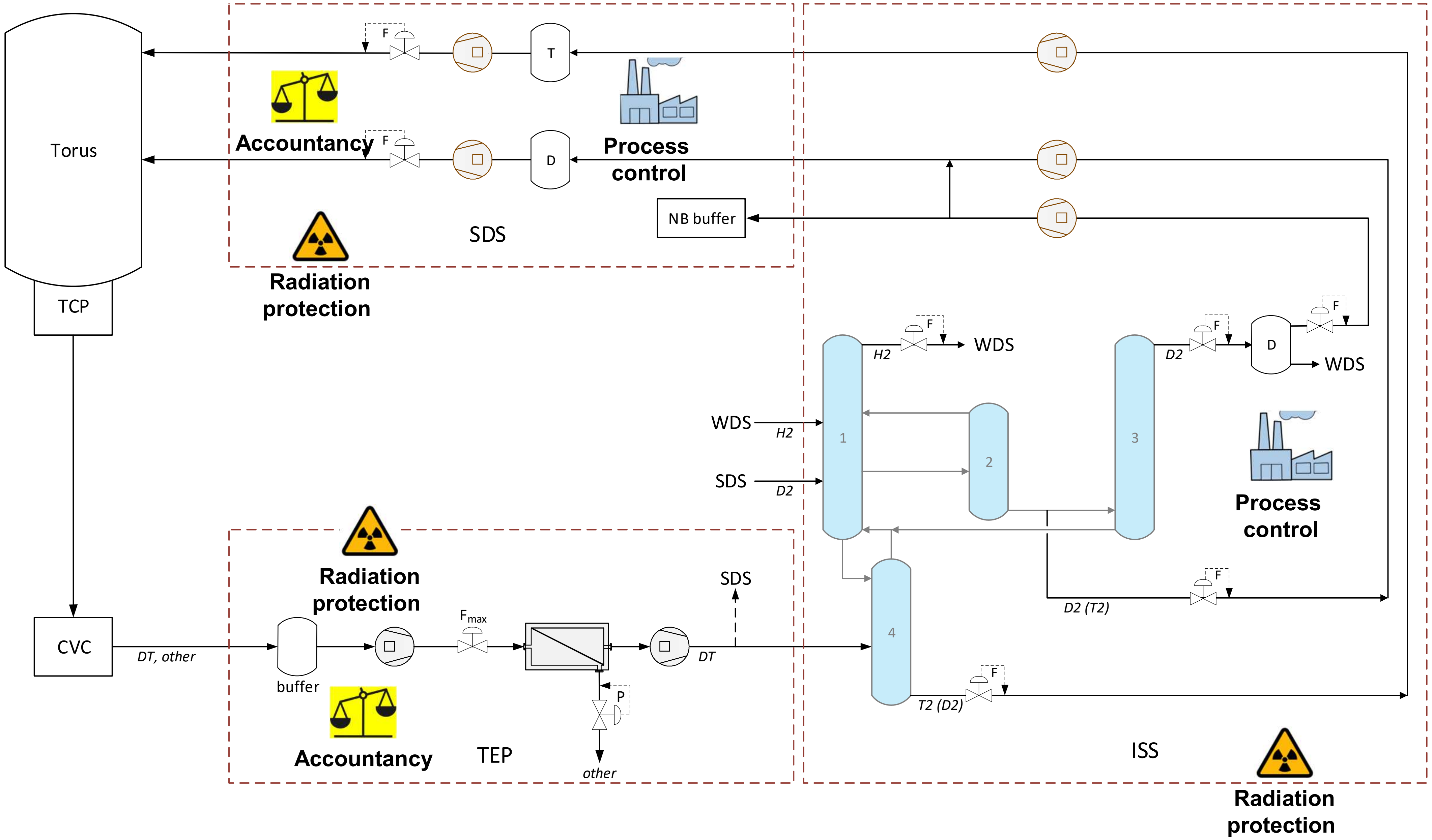
- Analytical point for Q2 fractions (control & accountancy)

Pumped exhaust gases returned to TP process systems

- Analytical point for Q2 fractions and impurities (accountancy)

Purification, separation and product supplies of fuel gases on spec

- Analytical point for Q2 fractions (control)



Analytical Techniques

Accountancy | **Radiation protection** | **Process control (routine)**

Liquid Scintillation Counting
Property: Radioactive Ionisation
Benefits: Sensitivity, price
Drawbacks: Waste, Sampling, Offline

Calorimetry
Property: Decay Heat
Benefits: Absolute Activity
Drawbacks: Measuring Time, Offline

Ionization Counting
Property: Radioactive Ionisation
Benefits: modular, in/online
Drawbacks: Gas conditions dependent

Laser Raman Spectroscopy
Property: Polarization
Benefits: Resolution, inline and sensitivity

IR Absorption Spectroscopy
Property: Induced Di-pole Moments
Benefits: Inline and sensitivity
Drawbacks: Waste water/gas

Gas Chromatography
Property: Adsorptivity
Benefits: Multispecies
Drawbacks: Waste Gas, Sampling Time

Mass Spectroscopy
Property: Mass to charge ratio
Benefits: online
Drawbacks: Cost, low pressures

Analytical Needs

Hydrogen isotope gas mixture:

- ○ Absolute Q_2 composition (accountancy)
- ○ Relative Q_2 composition changes (process control)
- ○ Impurities in Q_2 mixtures (process control and safety)
- ○ Long-term stable analysis equipment

Tritiated water mixture:

- ○ Absolute Q_2 composition (accountancy)
- ○ Relative Q_2 composition changes (process control)
- ○ Impurities in Q_2 mixtures (process control and safety
- ○ Inline measurements

Ion-chamber – Tritium measurement
http://www.tyne-engineering.com/Tritium%20Controller.html [2022]

RGA – Q2 & impurity analysis
https://www.mks.com/#mz-expanded-view-1110841570607 [2023]

Hydrogen isotopes & Tritium specific Analytical Techniques Development

KIT – TLK selected as expert for Tritium Analytics

○ IO contract with KIT in place for Analytical Techniques development (started 2022; min. 4 years)

○ Identification of potential techniques for the different areas of *Process Control*, *Accountancy* and *Radiation Protection*

○ Specification of potential techniques suitable for defined analytical requirements

○ Demonstration / qualification of selected analytical techniques

○ Development of analytical processes and calibration procedures adopted for the Tritium Plant systems

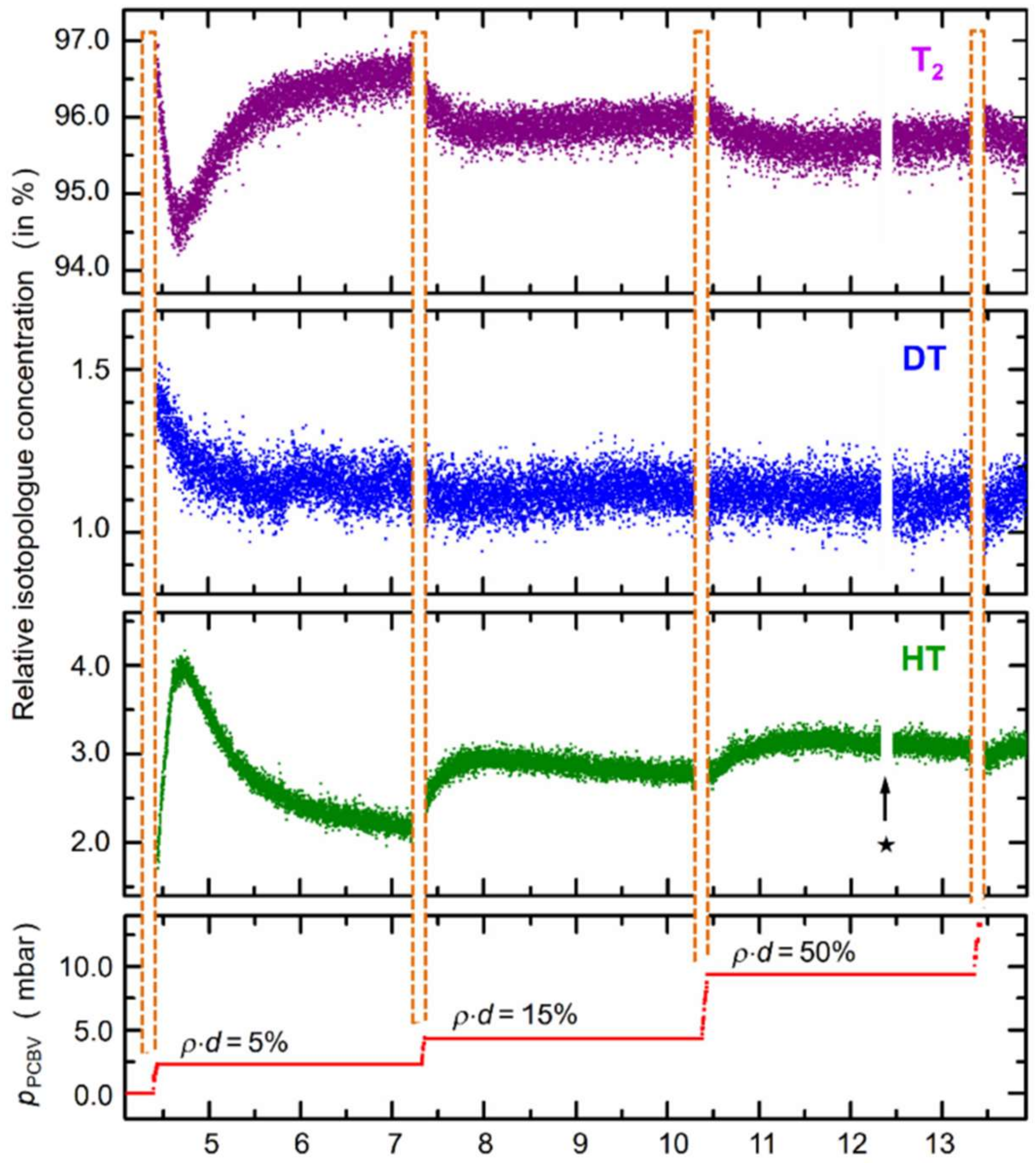


Figure – Long-term Q2 measurement during KATRIN experiments at KIT-TLK (M. Schloesser et al., Sensors 2020, 20, 4827; doi:10.3390/s20174827)

Example: Laser Raman

Identified as analytical technique for fast online measurement of Q_2 mixtures for process control

- suitable for absolute composition measurement
- precise relative measurements of composition changes
- tritium compatible

Adaptation / upgrade required in view of IO requirements

- high pressure operation (2 – 10 bar)
- fast measurement cycles for Q_2 product monitoring and process control feedback (1 min range)
- enhancement of accuracy/sensitivity for trace hydrogen isotopologues (reliable, stable)
- component qualification for nuclear operation (confinement, safety aspects)

Figure – micro-Laser Raman system (F. Priester et al., Sensors 2022, 22, 3952; https://doi.org/10.3390/s22103952)

Unresolved Analytical topics

Specification and upgrade of existing techniques or identification and development of new techniques

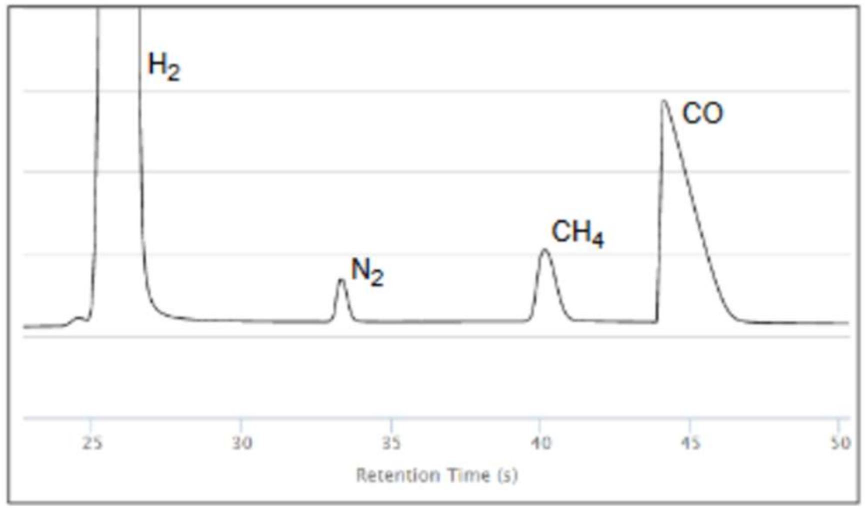
Q_2 mixtures

- ○ detection of ***impurities in Q_2*** gas
  - • He in Q_2 (fuel ash) / O_2 in Q_2
- ○ discrimination of impurities in Q_2
- ○ detection of ***trace Q_2 in inert gas***
- ○ lower detection limit of Q_2 species

Q_2O mixtures

- ○ online measurement of tritiated water
  - • deuterium and tritium detection
  - • decision to process or to discharge

Missing areas to be solved with the support of KIT - TLK



Micro-GC – Analysis of Q2 and impurities mixtures
https://www.chemlys.com/en/portfolio/rapid-syngas-biogas-analysis-by-micro-gc-fusion/ [2023]

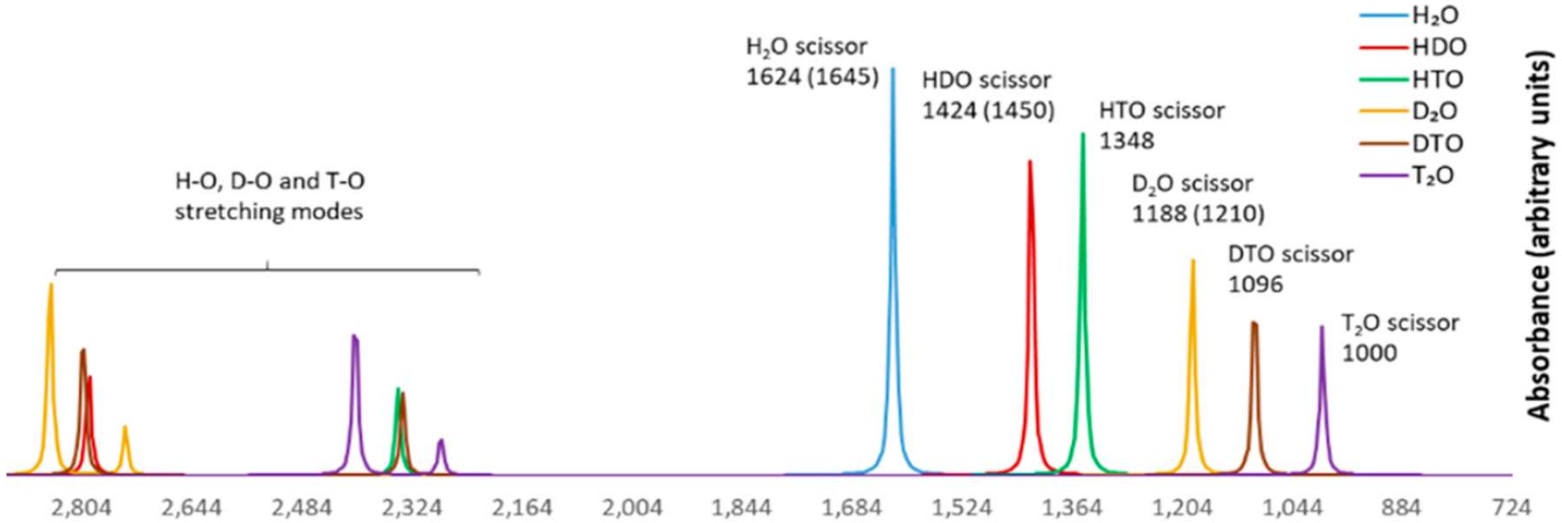


Figure – Simulated IR spectrum of water isotopologues
(R.L. Webster et al.; Anal. Chem. 2020, 92, 7500−7507 https://dx.doi.org/10.1021/acs.analchem.9b05635)

Summary

Main fuel cycle functions of Tritium Plant process systems

○ Storage and supply of fuel (DT)
○ Purification of fuel exhaust gases
○ Separation and recycle of fuel gas D & T

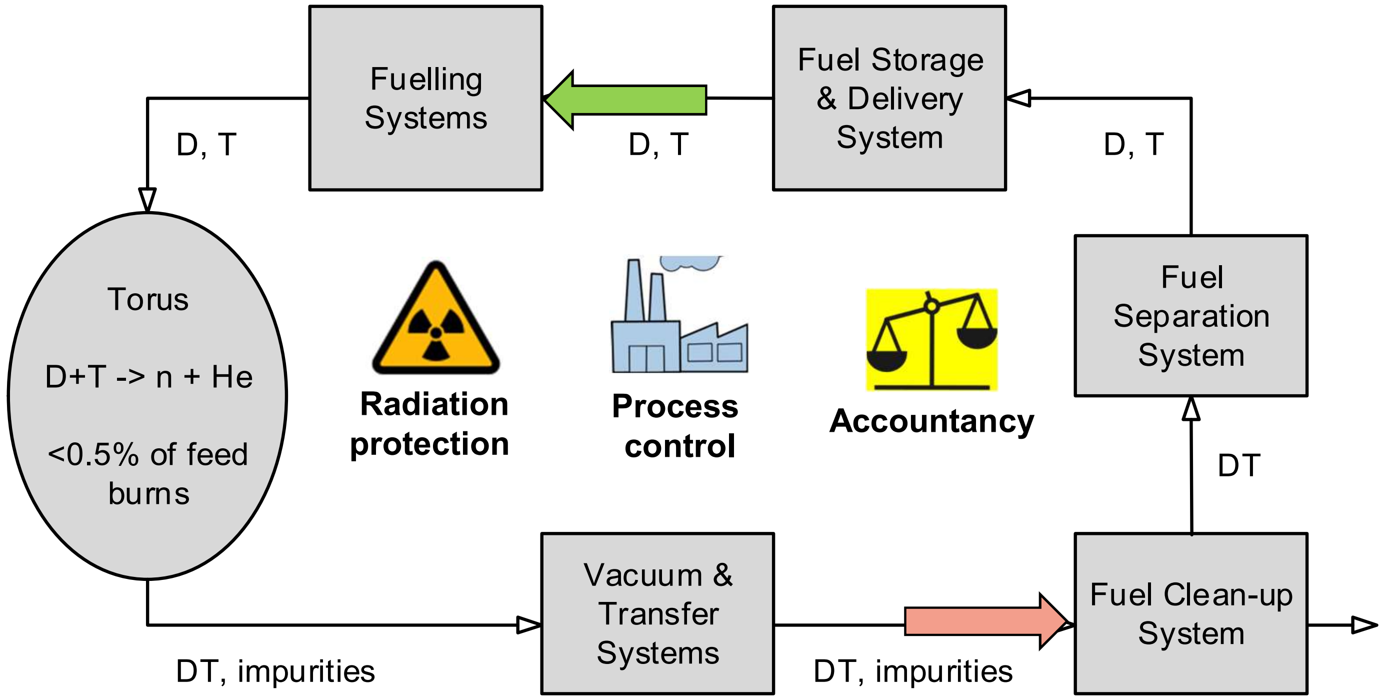
Main process systems in preliminary/final design stage

○ Prototypes to demonstrate performance requirements

Analytical requirements

○ Q_2 composition measurement
- for process control (fast, relative)
- accountancy (slow, precise)
- safety (reliable)

○ Tritium and Q_2 Analytics - Development program initiated with the expertise of KIT - TLK



Thank you!

Robert Michling, Group Leader Process,
Tritium Plant Section
2023-05-25

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