The Fuel Cycle System

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The Fuel Cycle System for ITER

The ITER Fuel Cycle system

1. **Fuelling**
2. **Vacuum pumping**
3. **Tritium Plant**

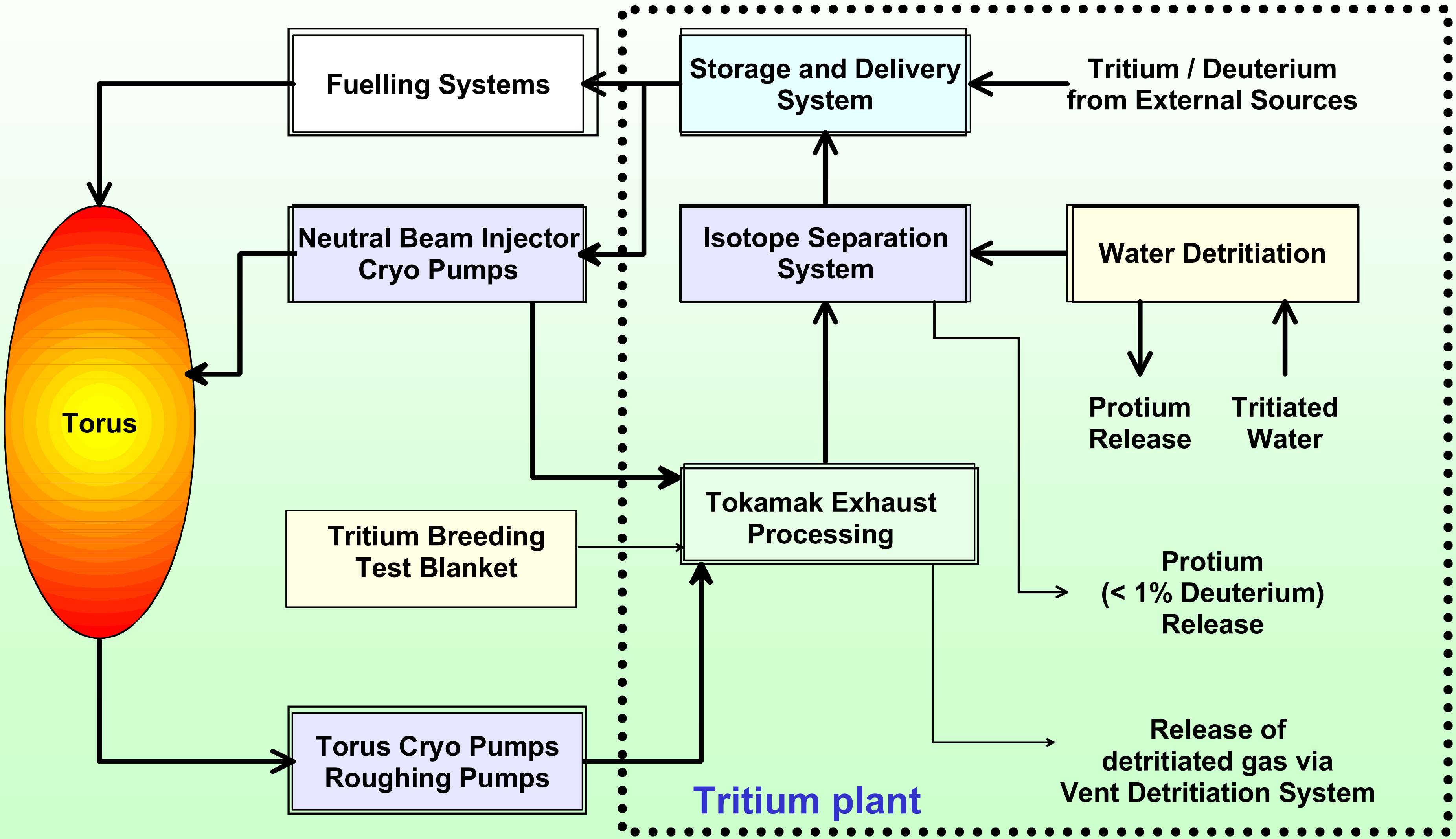
Requirements and constraints for each system.

Proposed solutions and on - going experimental investigations.

Major design criteria for the inner deuterium / tritium fuel cycle are:

- **Safe handling of tritium**
- **Minimization of tritium inventories and of tritium effluents and releases**

Simplified Block Diagram of the Inner ITER DT Fuel Cycle



ITER Fuelling Requirements

- **Fuelling rate: 200 Pam^3s^{-1} (2 liter (STP) per second) of D_2, DT, T_2**
- **Current design basis operation scenarios**

  - Short burn pulse of 450 s (repetition time 1800 s)

  - Long burn pulse of 3000 s (repetition time 12,000 s)

Deep Fuelling for short pulses

ITER fuelling system comprise :

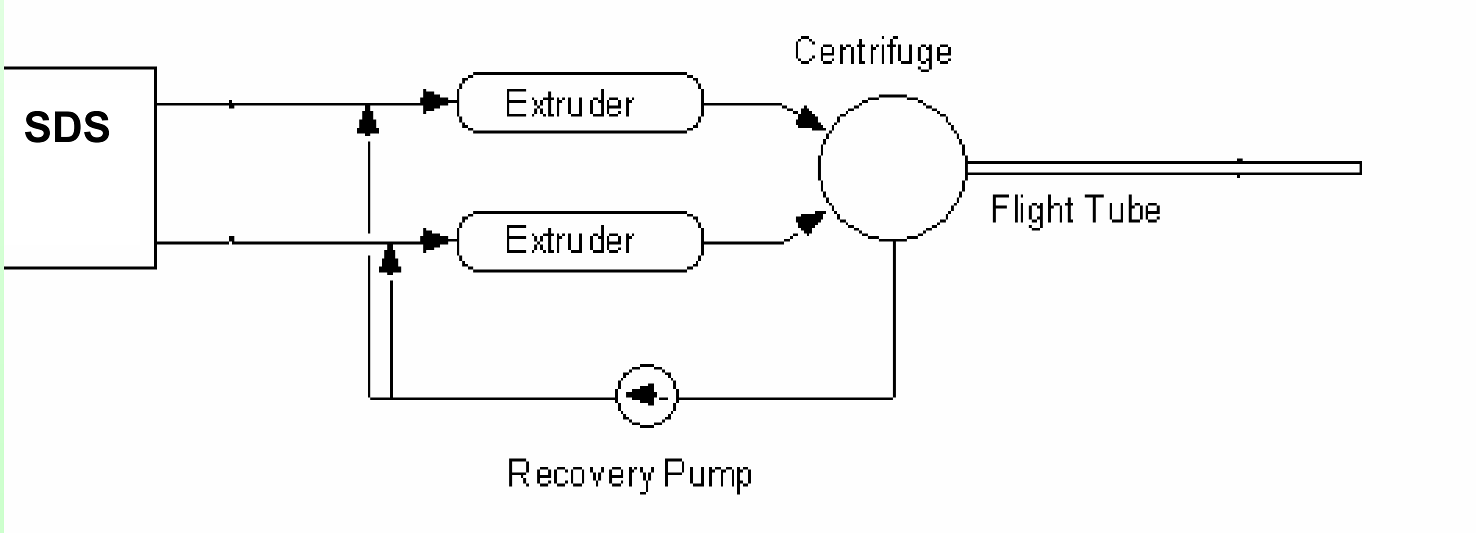
1. Gas fuelling system – for plasma operation
2. Pellet injector system
- High density in the hot central plasma gives higher rate of fusion reaction and reduce the interaction with the surrounding materials
- Solution : to fire high speed pellets of solid frozen hydrogen or deuterium

Pellet Injector

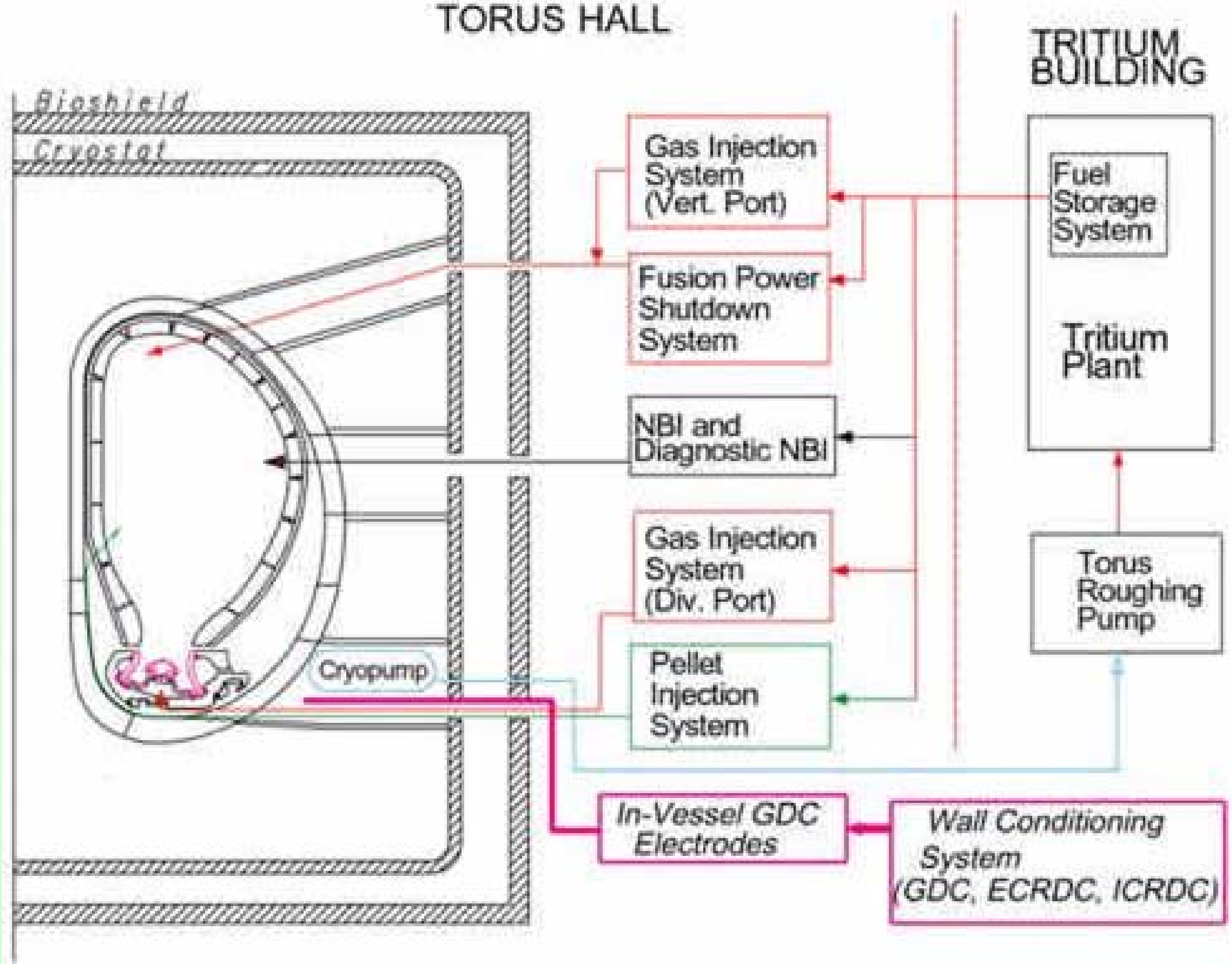
Extrusion cryostat – solid hydrogenic rod is pushed out from screw extruder continuously

Chopping unit cuts a piece and directs the pellet into centrifuge

Pellet is accelerated to the barrel periphery and ejected to the flight tube



ITER Fuelling system locations



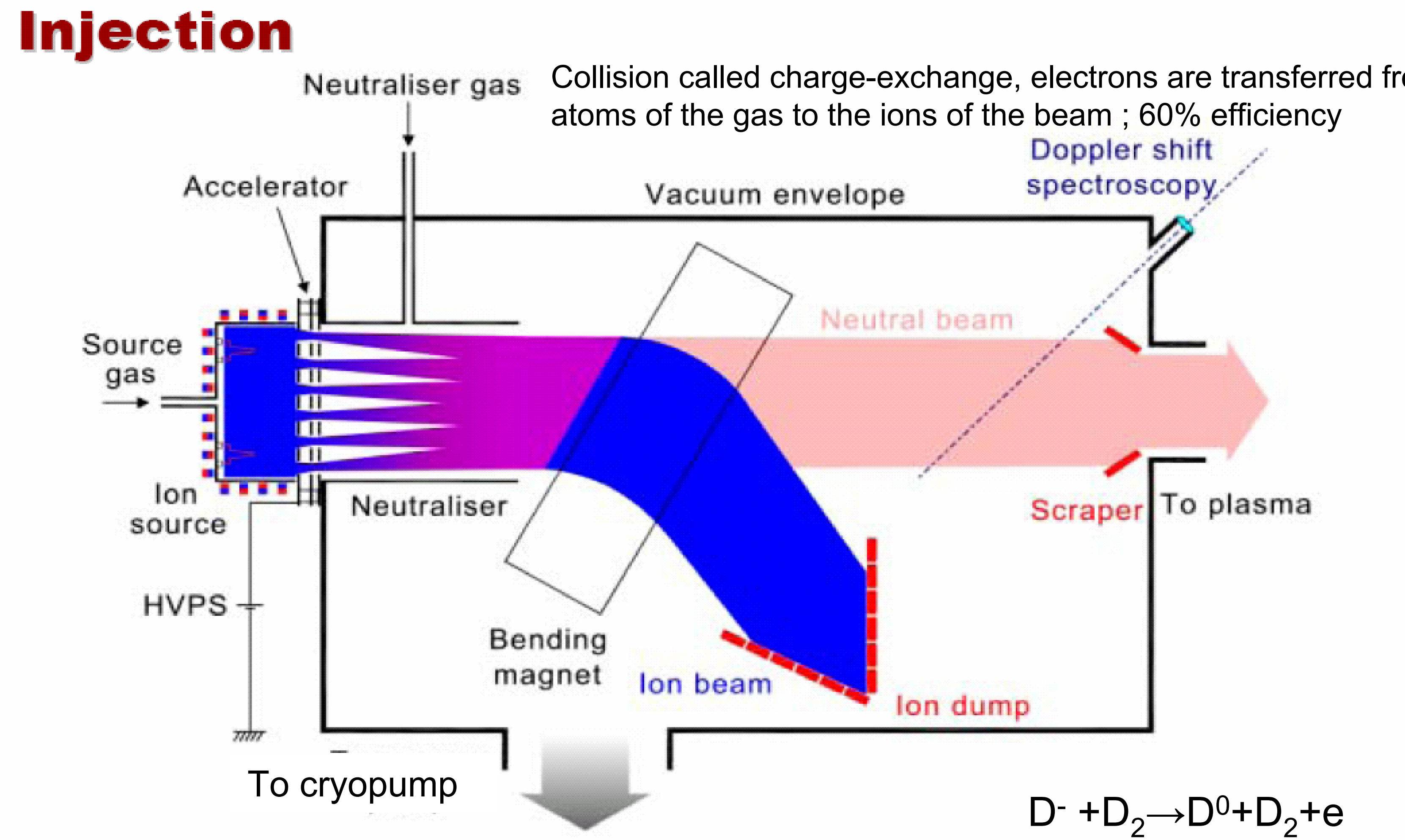
Neutral Beam system

- **In combination with other heating systems (ion cyclotron, electron cyclotron, lower hybrid) the Neutral Beam system assures the plasma heating**
- **Principle:**

  High energy beam particles (>80keV/nucleon) penetrate plasma; their energy is transferred by collisions to the plasma particles → plasma is heated, beam ions are slowed down

  When ion beams have the same energy as plasma ions, they join the plasma ions as part of the basic plasma

Neutral Beam Injection - principle

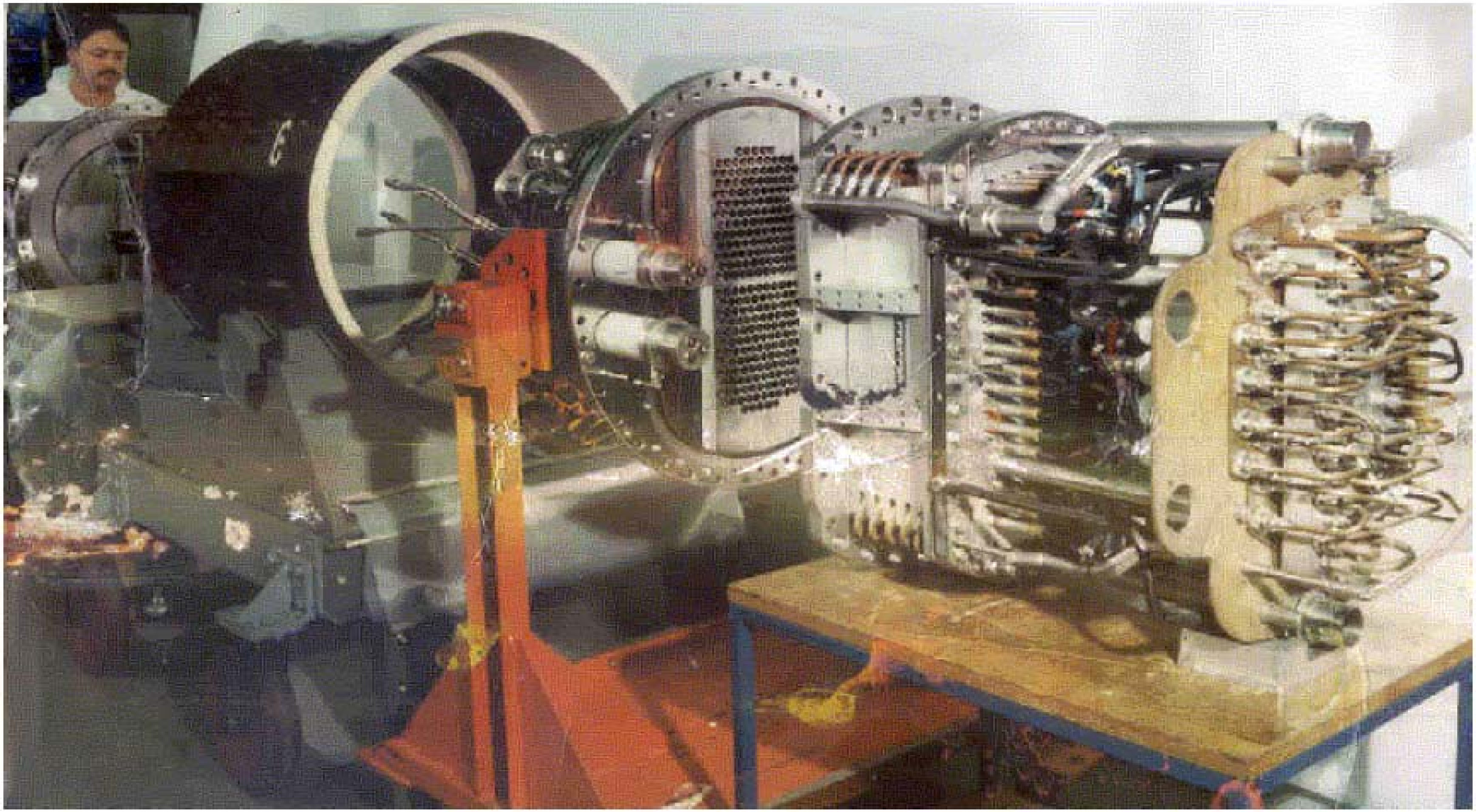


Collision called charge-exchange, electrons are transferred from neutral atoms of the gas to the ions of the beam ; 60% efficiency

To cryopump

$$D^- + D_2 \rightarrow D^0 + D_2 + e$$

JET NB Injector



Vacuum pumping system tasks

- **To evacuate the Torus from atmospheric pressure down to <10^{-5} and 10^{-7} Pa prior to plasma pulse**
- **To provide high vacuum pumping during all modes of operation (burn, dwell, cleaning), divertor pressure 1-10Pa**

↓

- **High pumping speed and throughput at low pressure ⏩ pump location should be close to the Torus**
- **High magnetic fields and highly mobile dust particles ⏩ pumps without moving parts**

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Cryopumps backed by roughing pumps

Vacuum pumping system for ITER

Cryogenic pumps :

'pumping mode'

cryopanels (activated charcoal coated panels) are cooled down to 5K, cryosorbent is loaded with gas molecules

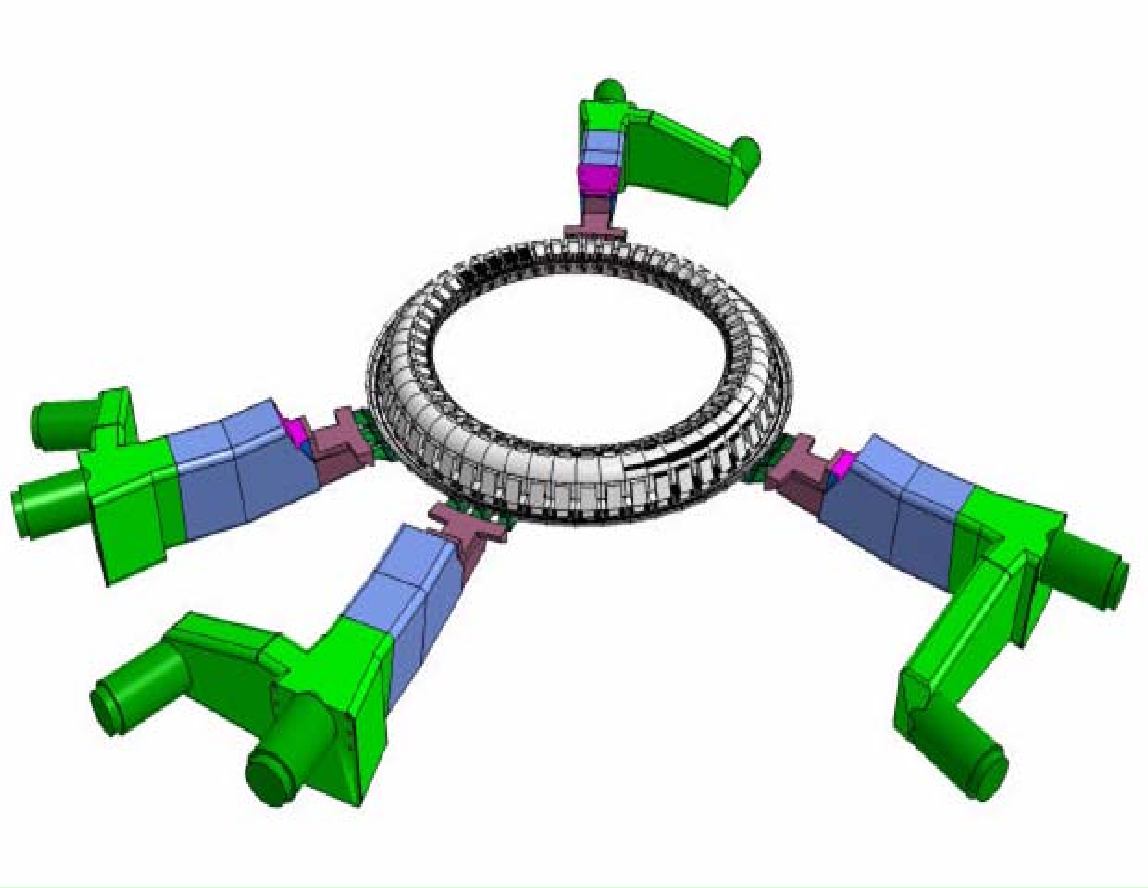
'regeneration mode' (partial regeneration)

cryopanels are heated up to ~90 K, hydrogenic gas molecules are desorbed from the panels, pressure inside the pump increase, pump housing is evacuated by torus roughing pumps

'high temperature regeneration' (total regeneration)

cryopanels are heated up at 300K, impurities (Ar, N_2, CH_4, CO, CO_2) are desorbed from the panels; water vapours and polytritiated carbons are desorbed at higher temperatures (>450K)

3D Torus Pumping arrangement



Test facility for ITER Model vacuum pump (TIMO)

The cryopump is a 1:2 scale model (pumping speed of 50 m³/s for DT) of the ITER 1998

Pump performances have been tested:
- Pumping speed
- Ultimate pressure
- Regeneration mode (warm-up time, evacuation time, cooling time)

The Tritium Plant Requirements

Tritium Plant has the following major functions:

- **Receiving of tritium shipments and loading into fuel cycle.**
- **Storage of tritium and deuterium.**
- **Processing of tokamak exhaust and NB exhaust for recycling of tritium and deuterium:**
  - **- separation of hydrogen from all other exhaust gases;**
  - **- separation of hydrogen into specific isotopic species for refuelling;**
  - **- detritiation of impurities for controlled release into environment.**
- **Detritiation of water to allow release into environment.**
- **Extraction of tritium from breeding blanket modules (if required) and processing of tritium from test blanket modules**

Storage and Delivery System for ITER

T_2 and DT are stored in metal hydride getter beds, ZrCo hydride current reference material

– **2 ZrCo + $3T_2 \rightarrow$ 2 $ZrCoT_3$ + Heat** **tritium absorbtion**

(low absorbtion pressure at room temperature)

– **2 $ZrCoT_3$ + Heat $\rightarrow$ 2 ZrCo + $3T_2$** **tritium delivery**

(dissociation pressure >1 bar at 300-400°C)

Storage and Delivery System comprises about 20 metal hydride getter beds

Nominal storage capacity 100 g tritium per bed

Tritium inventory measurements by in-bed calorimetry

- **accuracy about 1% of the full bed capacity (100 g) within a measuring time of 24 hours**

10 additionally getter beds are used in Long Term Storage System

1:1 Prototype Tritium Storage Getter Bed at TLK

- Full size ITER getter bed has been designed, manufactured and is ready for tritium testing
  - Disproportionation: $2\ ZrCoQ_3 \rightarrow ZrCo_2 + ZrQ_2 + 2Q_2$
  - Reproportionation possible under certain conditions

- On-going experimental program
  - Isotope effects as function of hydride composition and supply flow rates
  - Validation of maximum deuterium / tritium delivery rate

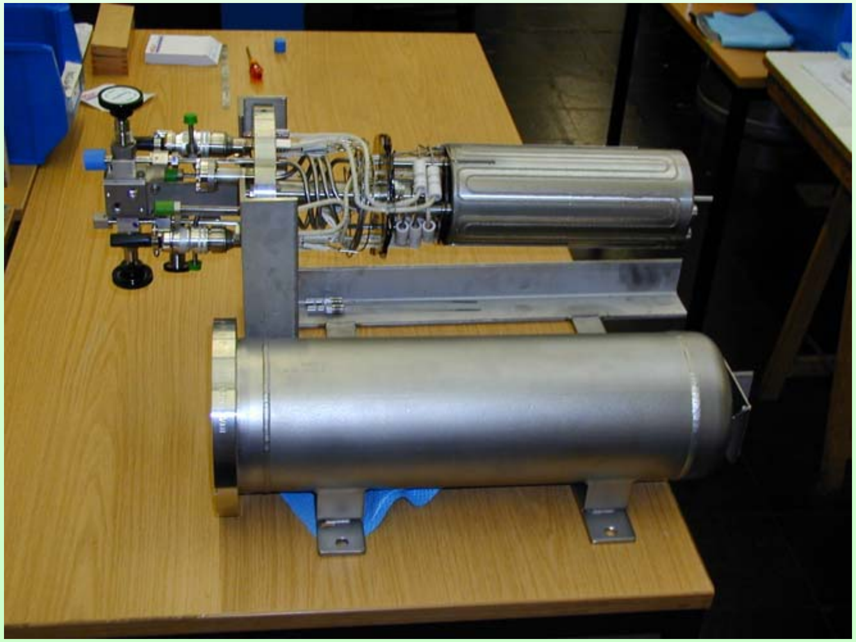
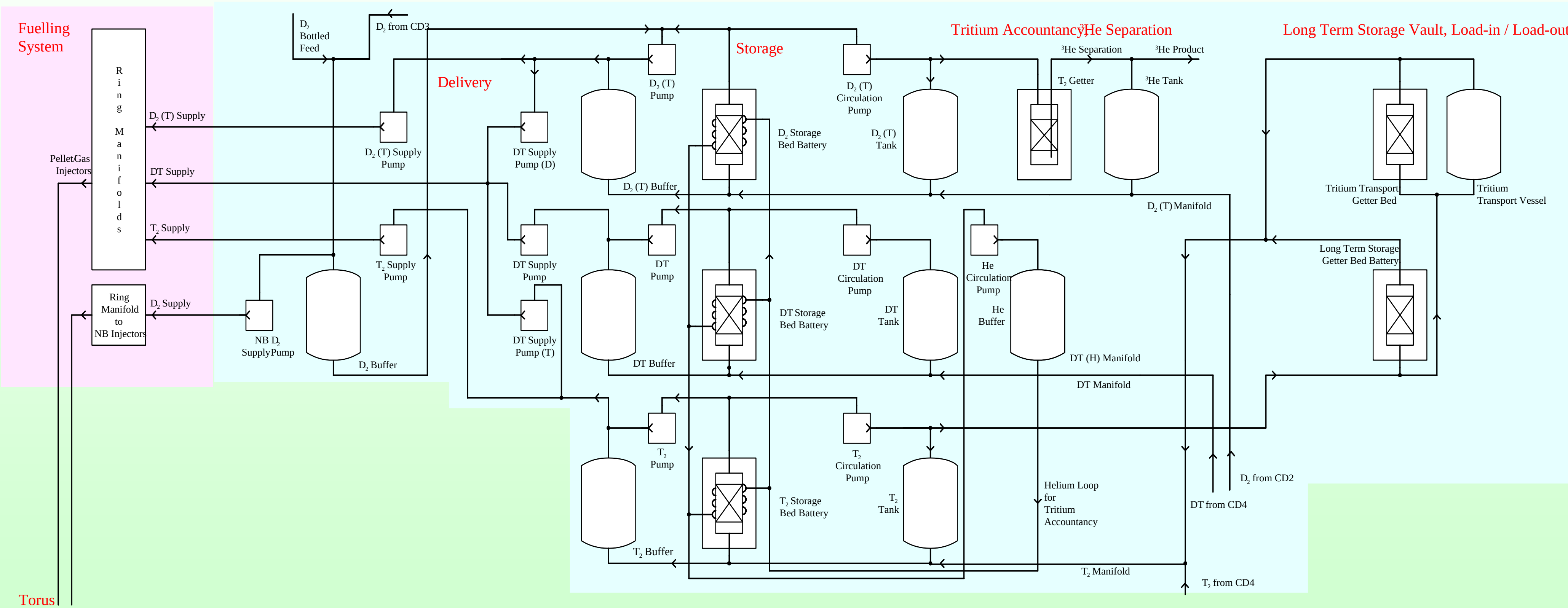


Diagram of Storage and Delivery System for ITER



Tokamak Exhaust Processing system

TEP receives the following process streams:

-exhaust gas from the tokamak during normal operation, later stages of pumpdown, wall conditioning (baking and glow discharge cleaning) and codeposited tritium recovery gas and tritiated process gas, purge gas and process vacuum pump exhaust from various tritium systems such as ISS, SDS, and ANS.

TEP is composed by 3 sub-systems:

Front-end permeator - separates hydrogen isotopes from impurities by permeation

Impurity processing - recovery of elemental tritium from impurities by heterogenously catalyzed cracking or conversion

Final clean-up - final detritiation of waste after impurity processing

The Three Step Process for Tokamak Exhaust Processing

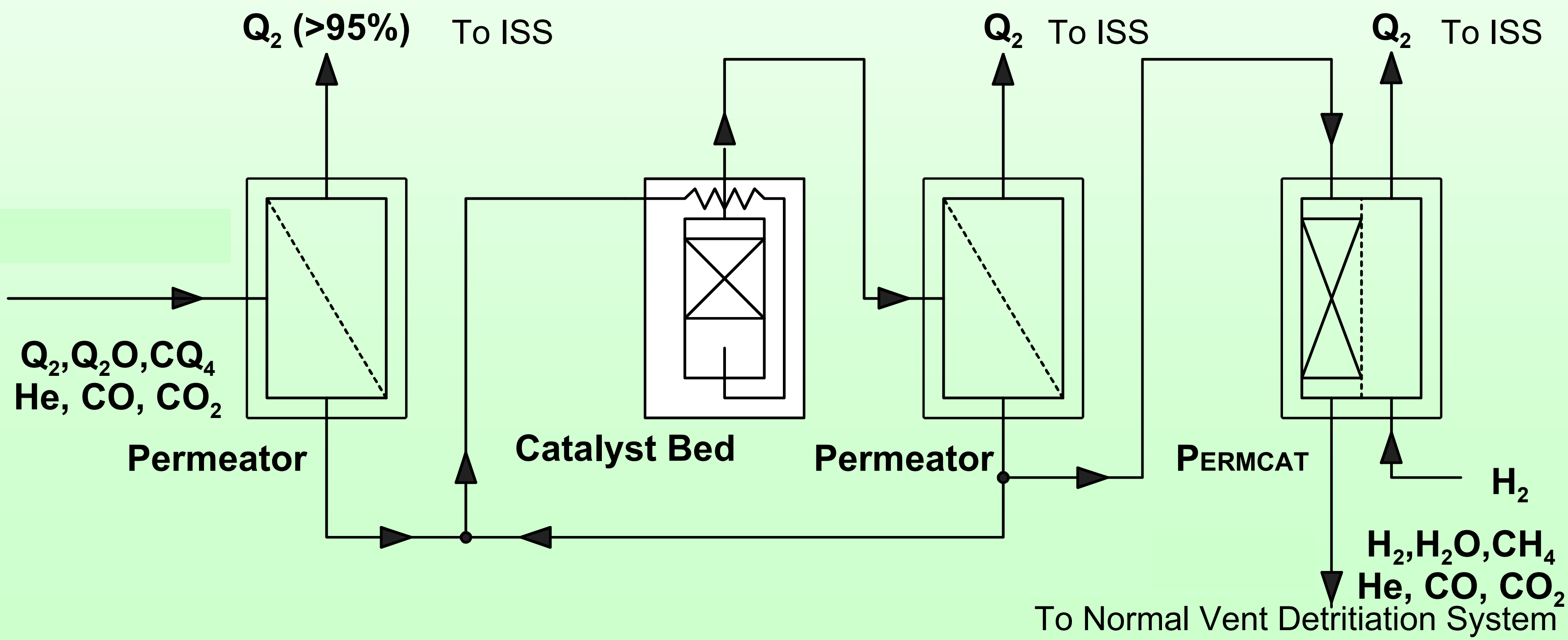
Chemistry of the 2nd step: (Q = H, D, T)

$CQ_4 \leftrightarrow C + 2\,Q_2$

$C + CO_2 \leftrightarrow 2\,CO$

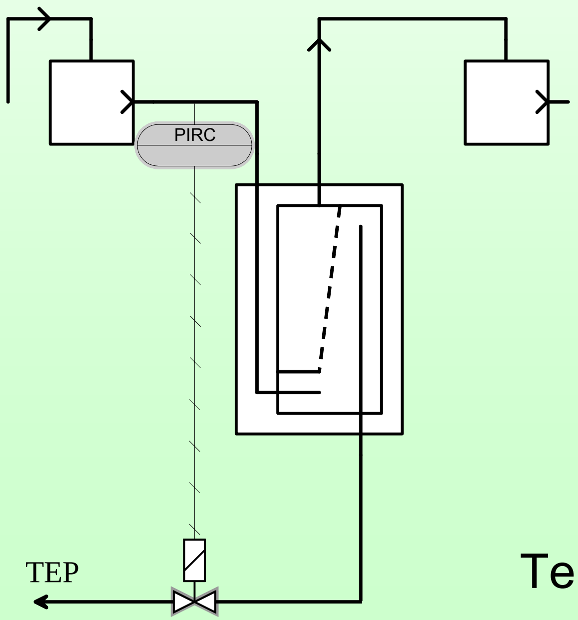
$CO + Q_2O \leftrightarrow CO_2 + Q_2$

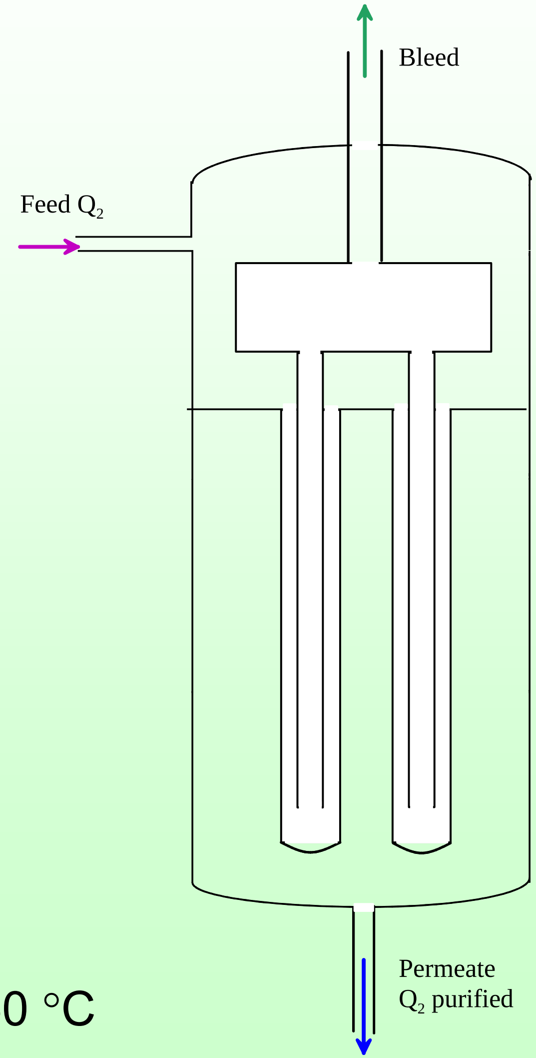
$CO + 3\,Q_2 \leftrightarrow CQ_4 + Q_2O$



Q2 separation by permeation

- Separates Q2 from impurities by membrane permeation
- The driving force is the partial pressure of Q2 from the two sides of the membrane
- Isotopic effect on the permeation process occurs as well





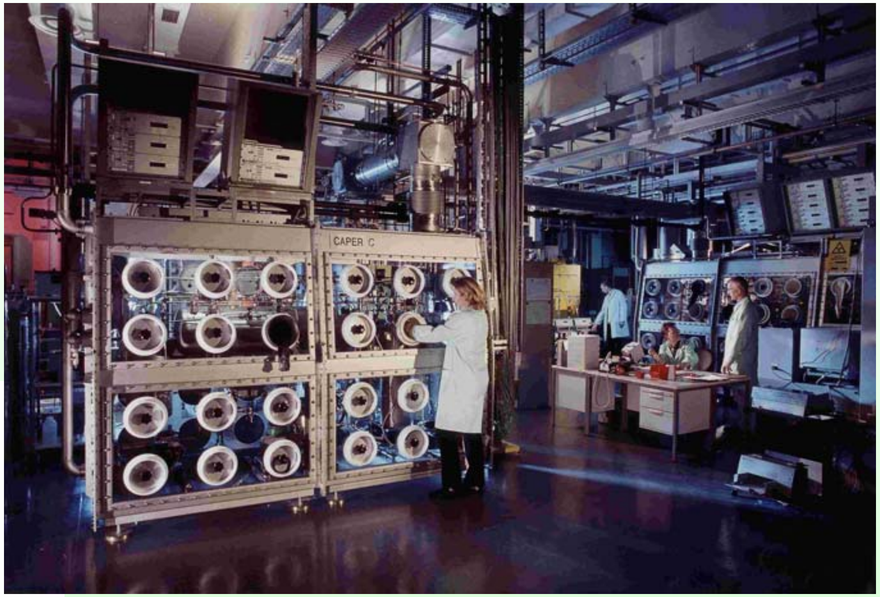
Temperature 350-450 °C

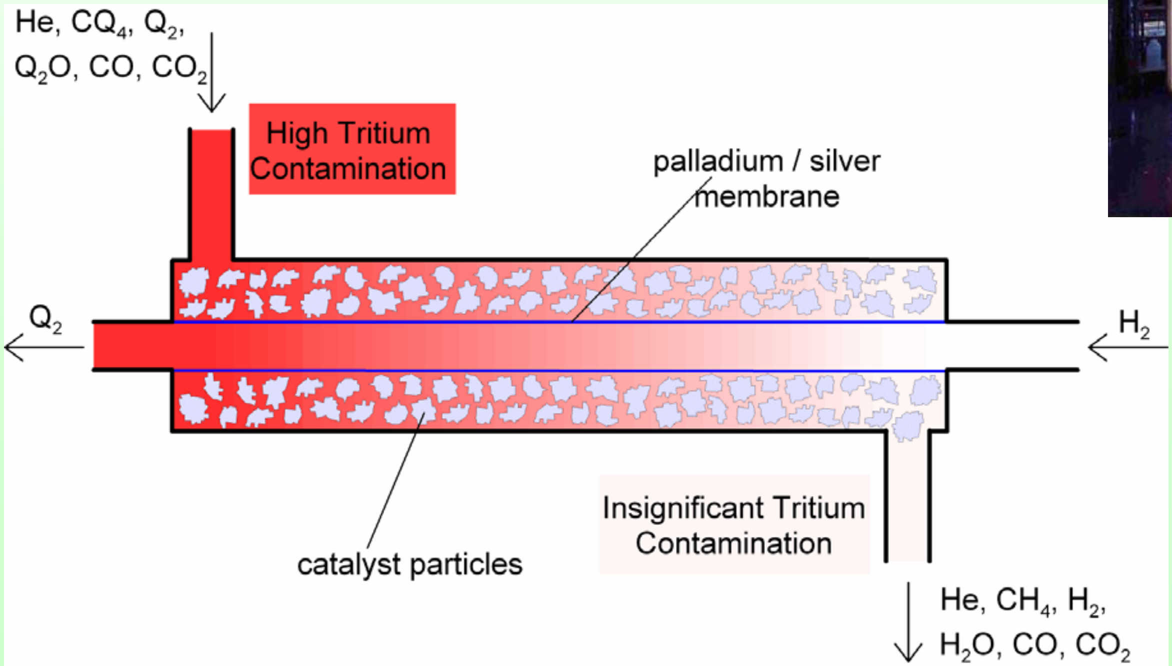
PERMCAT (Permeator/Catalyst) Principle for Final Clean-up

Chemistry of the PERMCAT:

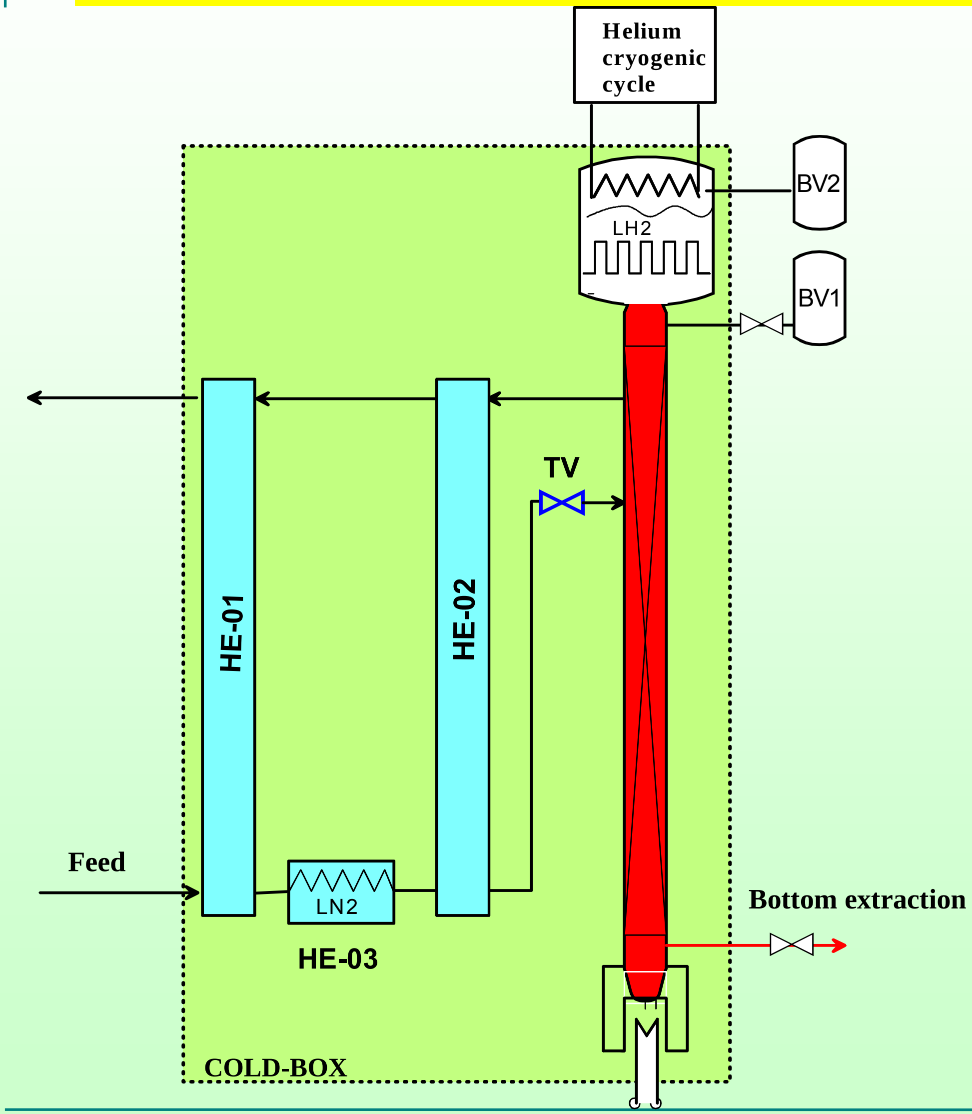
$$H_2 + CQ_4 \leftrightarrow CH_4 + Q_2$$

$$H_2 + Q_2O \leftrightarrow H_2O + Q_2$$



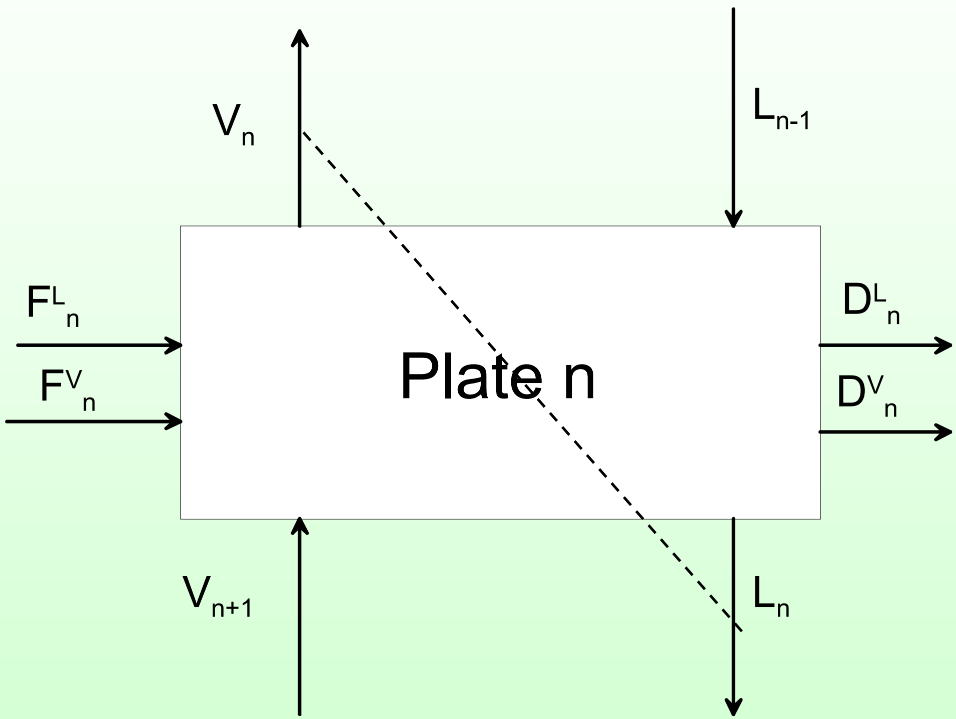


Separation of Hydrogen Isotopes – Cryogenic distillation



- Temperature: 21K-25K corresponding to 1 -3 bar working pressure
- Based on the difference in the saturation pressure of the hydrogen isotopes
- Counter-current mass transfer between the vapour and the liquid phase
- 'Lighter' isotopes are separated at the top, 'heavier' isotopes at the bottom of the column

Cryogenic distillation process



The CD column is filled with random or structured packing, characterized by a separation efficiency: Height Equivalent of Theoretical Plate (HETP)

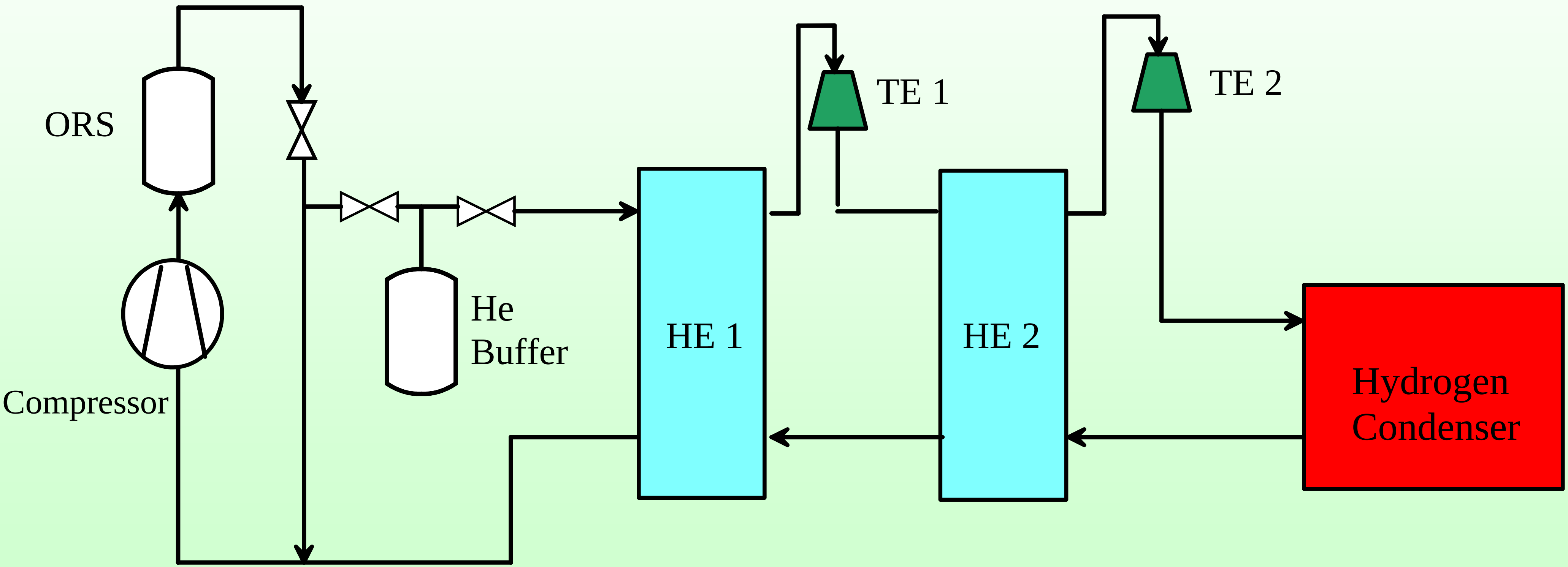
Actual value for HETP for CD columns ~ 5cm

Height of the column to achieve a required decontamination factor:
necessary number of theoretical plates x HETP

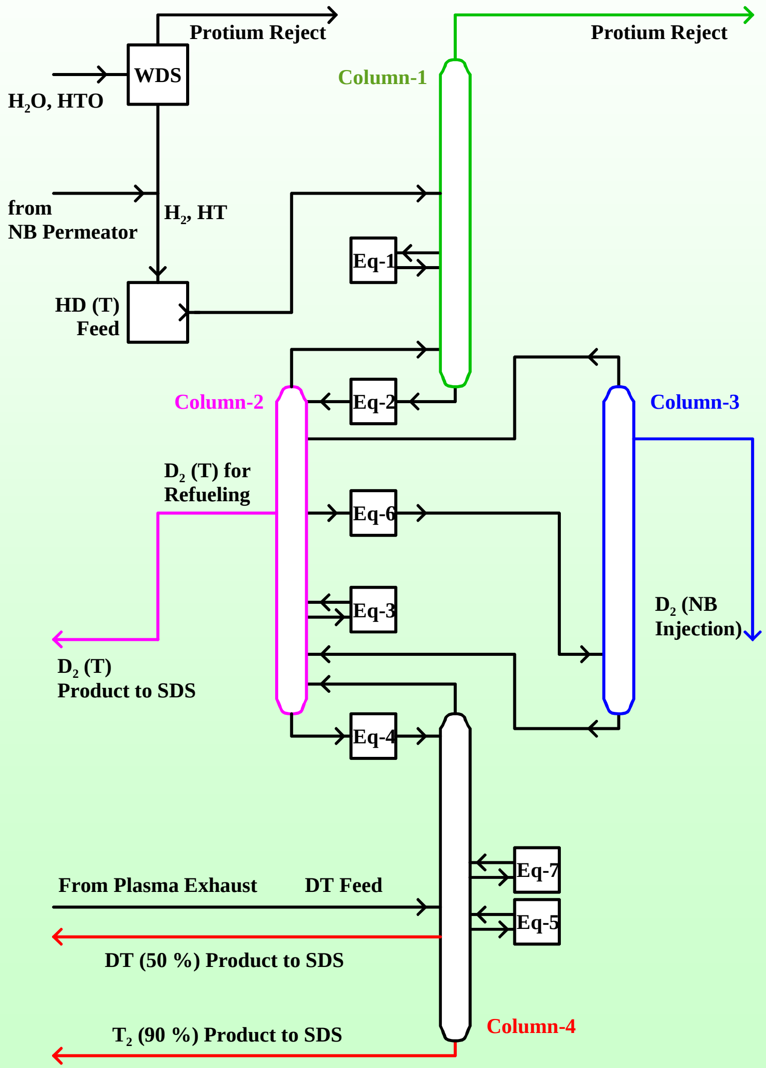
Necessary number of theoretical plates is computed by numerically modeling the CD column separation

The numerical model for CD column is based on mass and energy balance around each plate

Typical refrigeration unit for CD



Isotope Separation System of ITER



The requirements of ISS are to produce 4 streams:

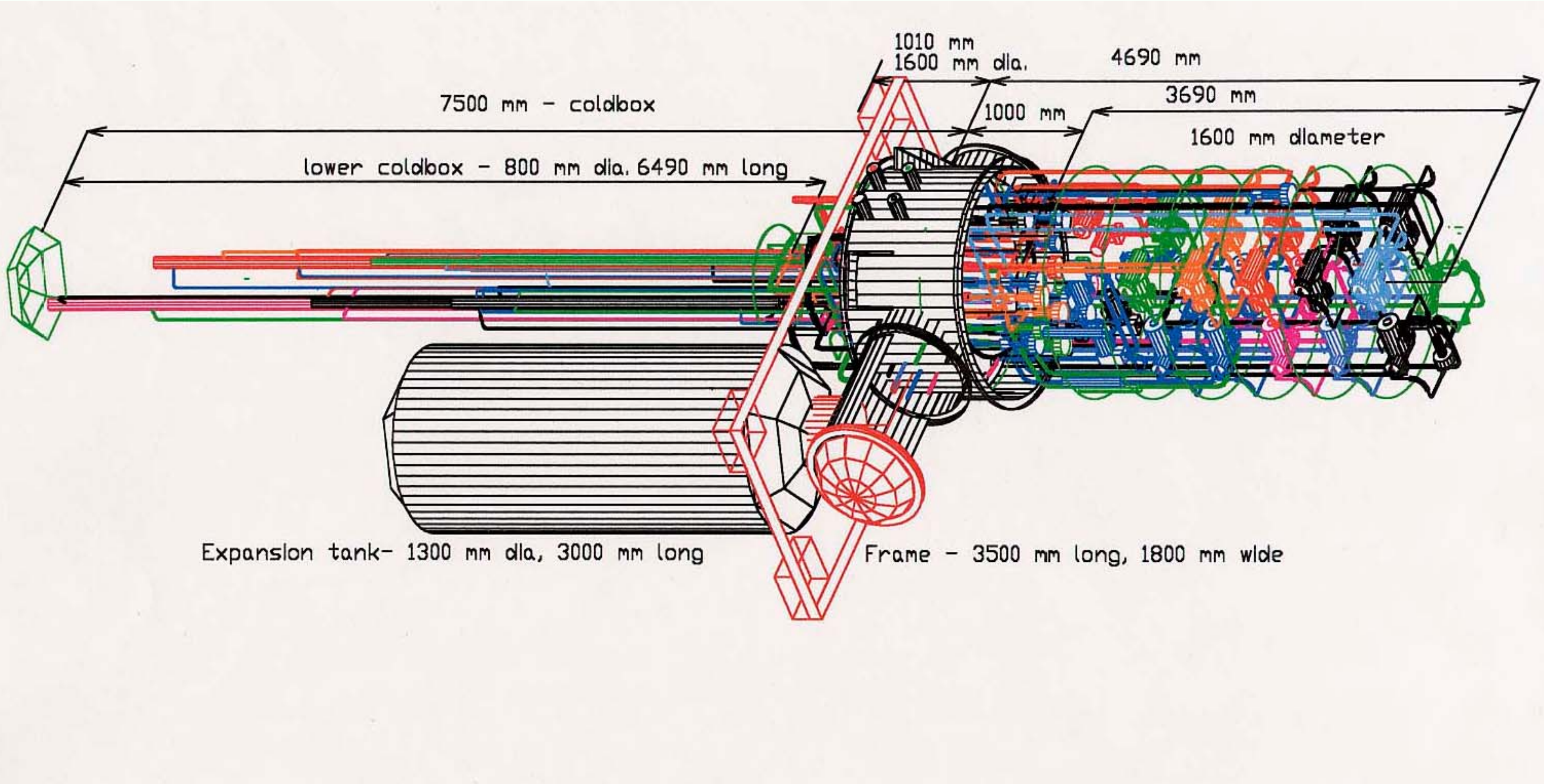
T_2 (T> 90%)
D_2 for Neutral Beam Injectors (T<200 ppm, H<0.5%)
D_2 for fuelling (H<0.5%)
H_2 ($T<10^{-7}$)

4 inter-linked distillation columns are necessary

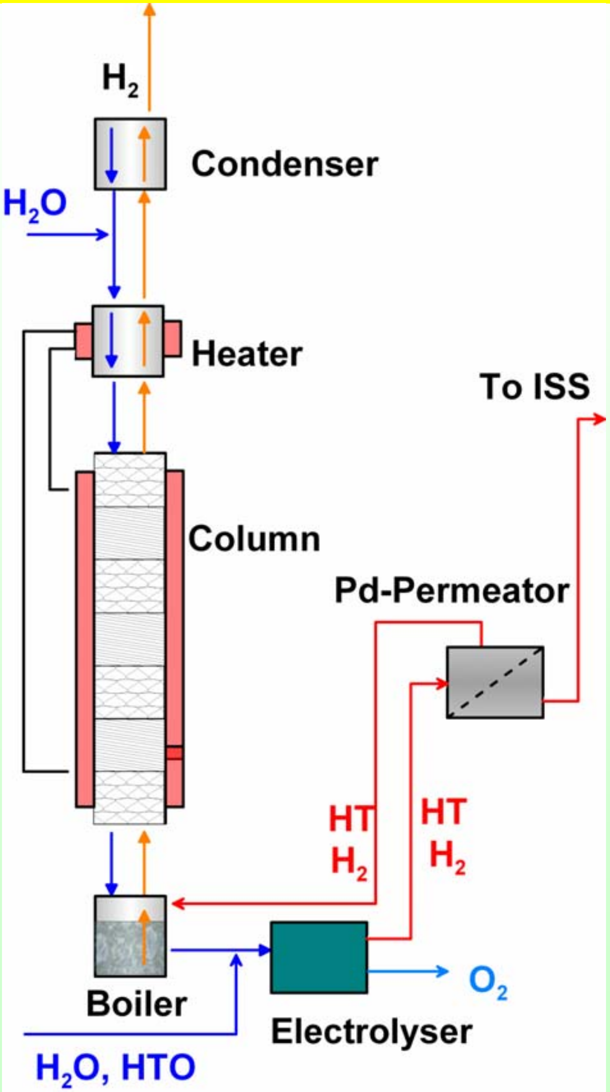
ISS will have to handle rapid fluctuations in feed compositions and flowrates

Accurate dynamic modeling is compulsory

3D layout of ISS

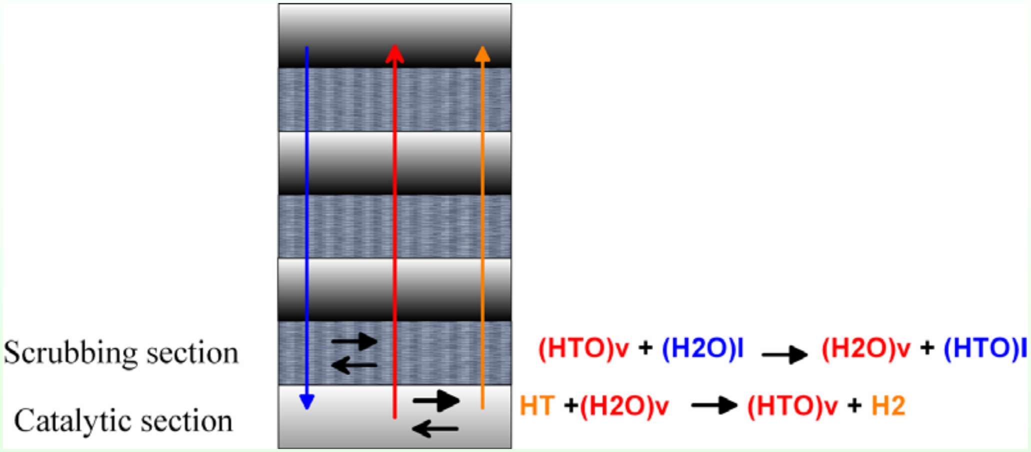


Water Detritiation - Combined Electrolysis Catalytic Exchange Process



- **Tritiated water will be produced in all ITER atmosphere detritiation systems (ADS)**
- **ITER will operate a Water Detritiation System (WDS) with a capacity of $\leq$ 20 kgh^{-1}**
- **Requires a decontamination factor of about 10^8**
- **Tritium feed concentration typically 10^{11} $Bqkg^{-1}$**
- **Tritium depleted hydrogen will be stacked**

Liquid Phase Catalytic Exchange Column

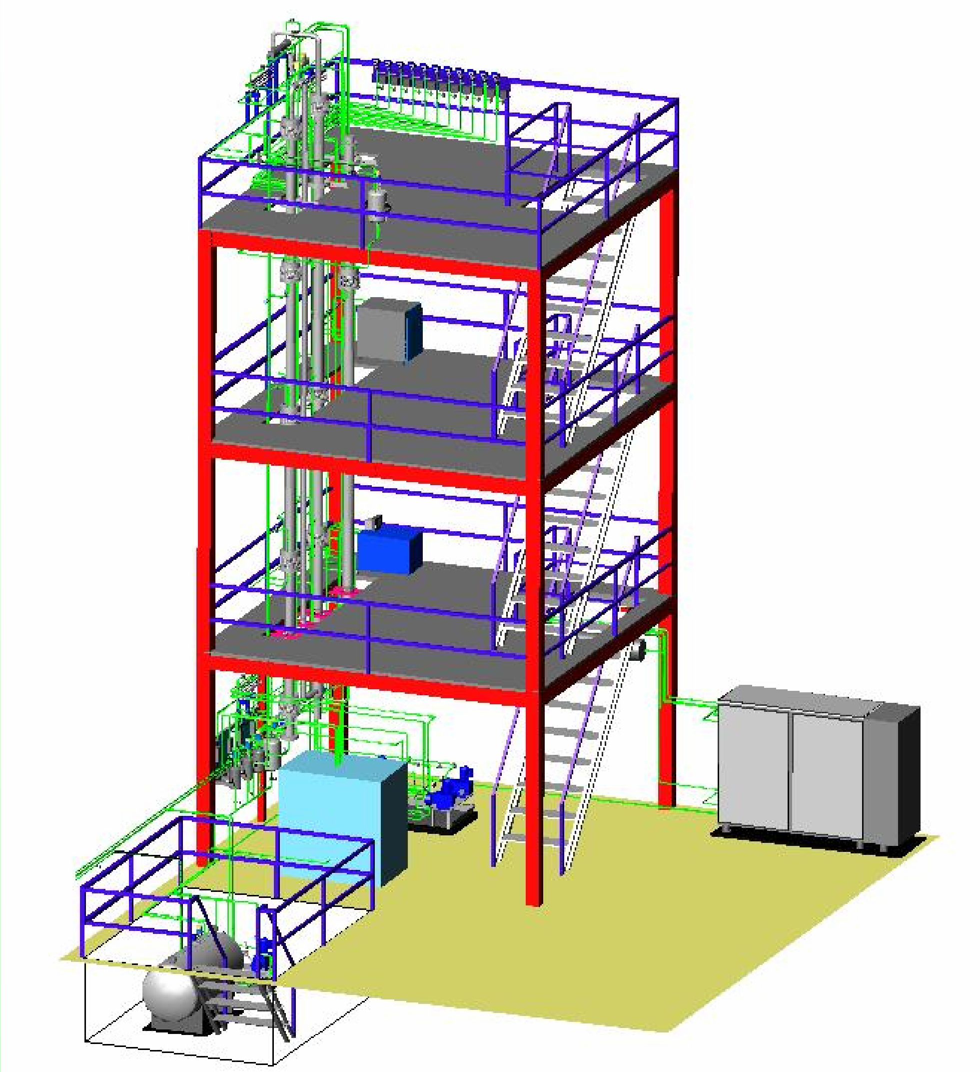


Temperature of the column: ~ 60°C

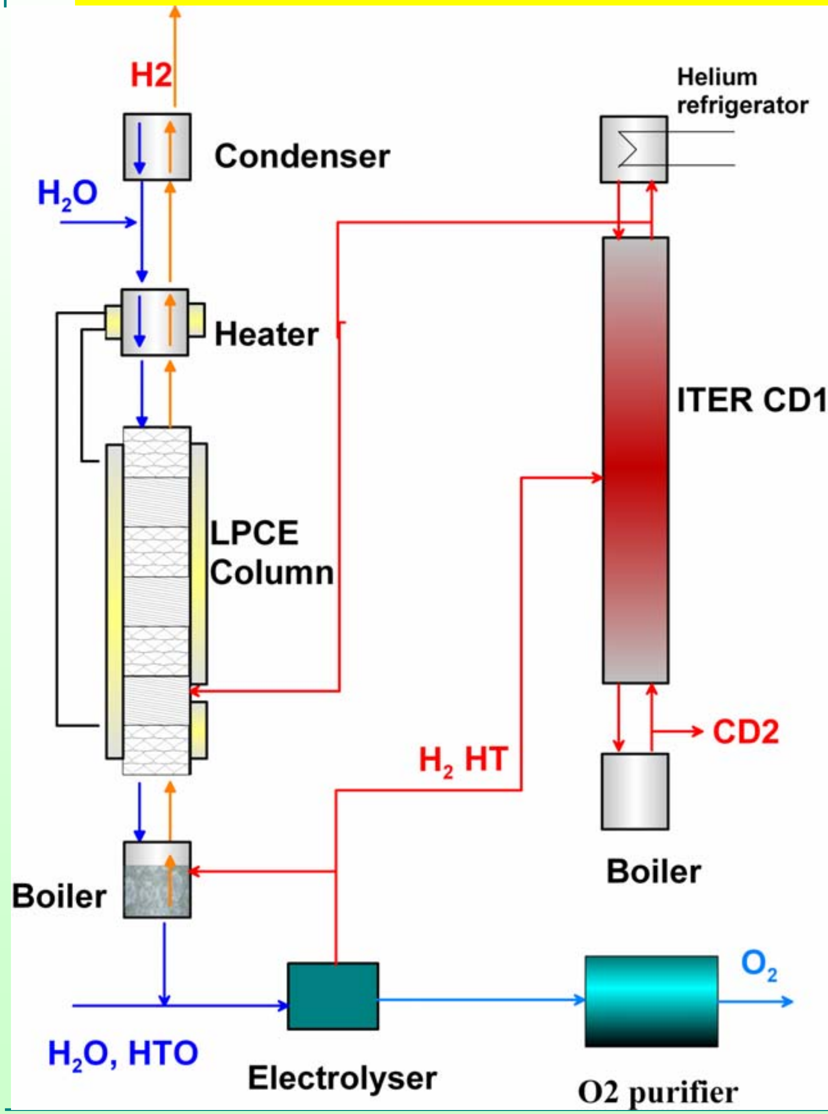
LPCE column is filled with mixtures of catalyst and packing

Achievable decontamination factor is given by the catalyst and packing separation efficiency

WDS 3D layout for JET



Potential combination of WDS and ISS at ITER



- **ISS protium stream from CD1 can be returned to WDS**
- **ISS protium flow rate is 20% of the LPCE hydrogen flow rate**

Trade – off between WDS-ISS

- **Rapid fluctuations in the ISS feed, may lead to unexpected and undesired tritium concentration in the CD1 top product**

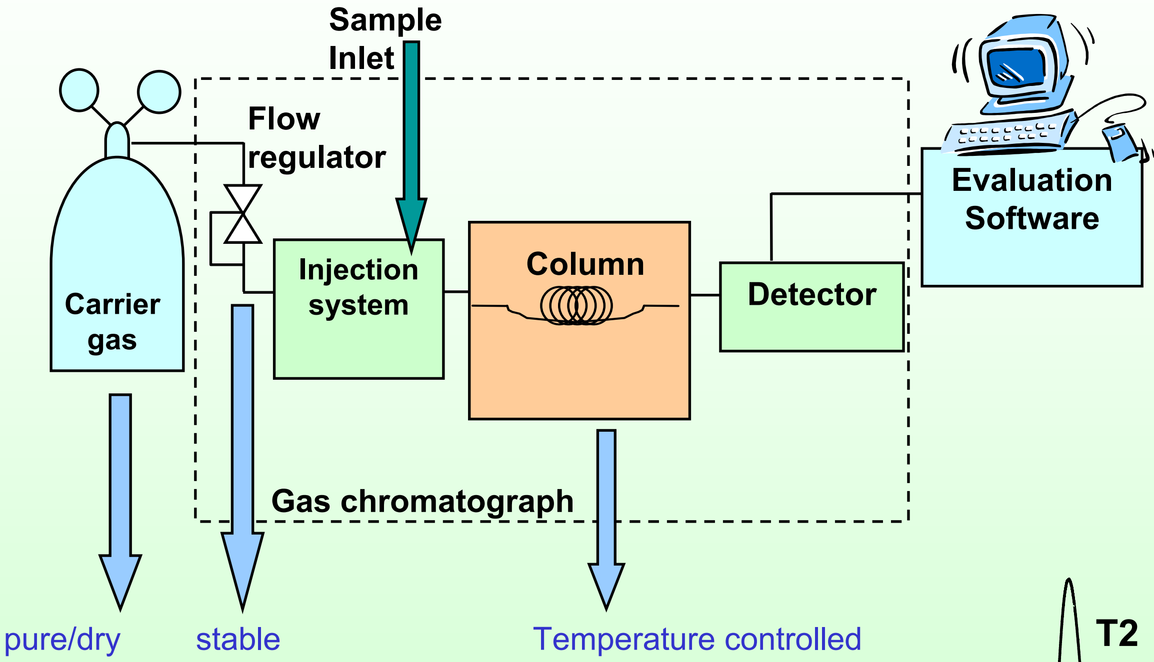
- **To prove experimentally that WDS is capable to detritiate the top product from the CD1 column and achieve the required decontamination factor along the LPCE column**

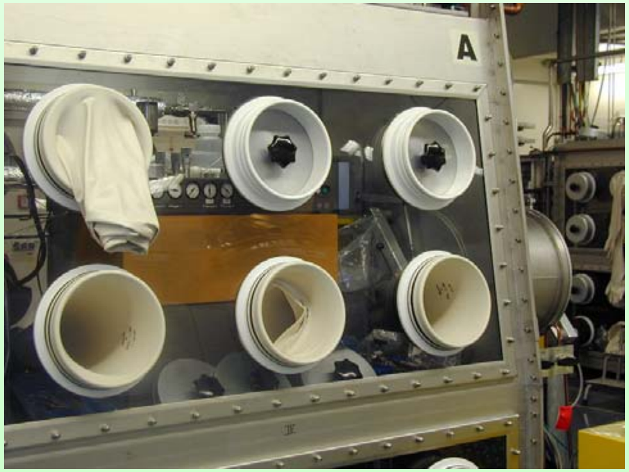
- **To improve and validate a dynamic modeling software for combination WDS-ISS**

Analytics - calorimetry

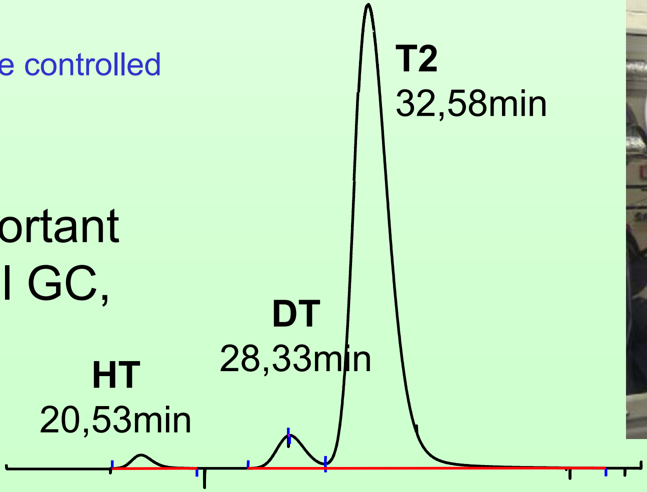
- Calorimetry is a technique of measuring the thermal power of heat producing samples
- The decay heat of tritium is reported to be 324.0 ± 0.9 J/s kg, an accuracy of 0.3%.
- Calorimeter are usually designed to accept directly getter beds in measuring chambers
- Calorimetry is independent of sample pressure, chemical composition
- Typical detection limit of about 3 mg ($1.1*10^{12}$ Bq or 30 Ci) of tritium. (The nominal capacity of Amersham uranium getter beds is 5 g **)**.
- Typical errors of shipper / receiver comparisons are unexpectedly low (~ 1%)

Analytics – gas chromatography





Future developments :
The Micro GC has all the important components of a conventional GC, different separation column
Very small retention times !
(<3 min)



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