Karlsruhe Institute of Technology

Brennstoffkreislauf für Fusionsreaktoren und Entwicklungsarbeiten im Tritiumlabor Karlsruhe

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Outline

- Basis of nuclear fusion
  - Outer and inner fuel cycle of fusion reactors
  - Properties of tritium
- Processes of the inner and outer deuterium/tritium fuel cycle
  - Storage of tritium
  - Plasma Exhaust Processing
  - Processing of tritiated water
  - Isotope Separation
  - Fuelling
  - Pumping
  - Tritium breeding and blanket
- Introduction into the European Tritium Laboratory Karlsruhe (TLK)
- Summary

Fusion of Hydrogen in the Sun

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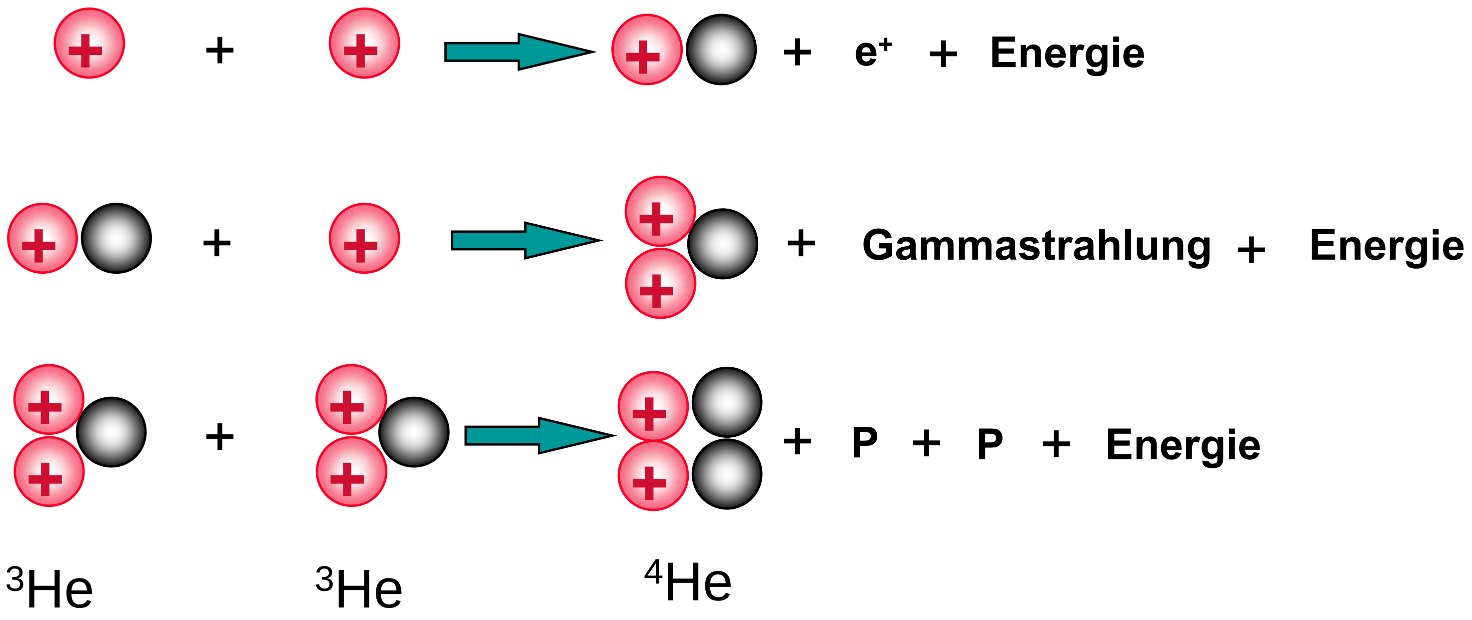
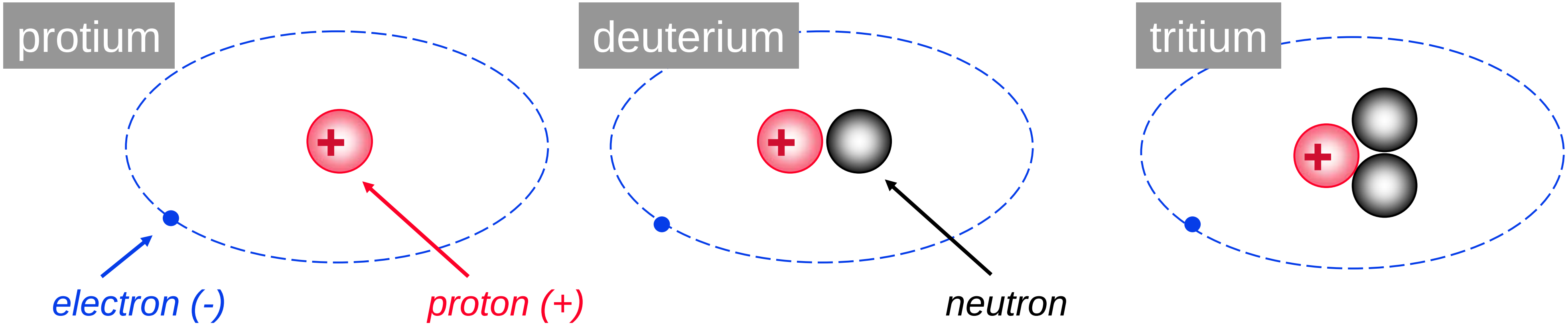
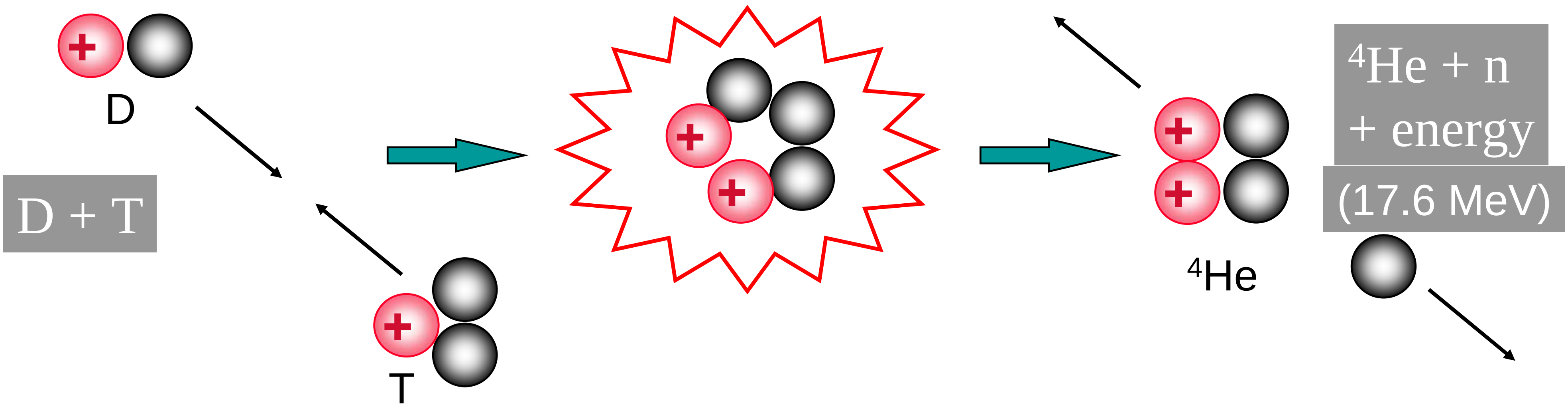
Proton-Proton-Cycle



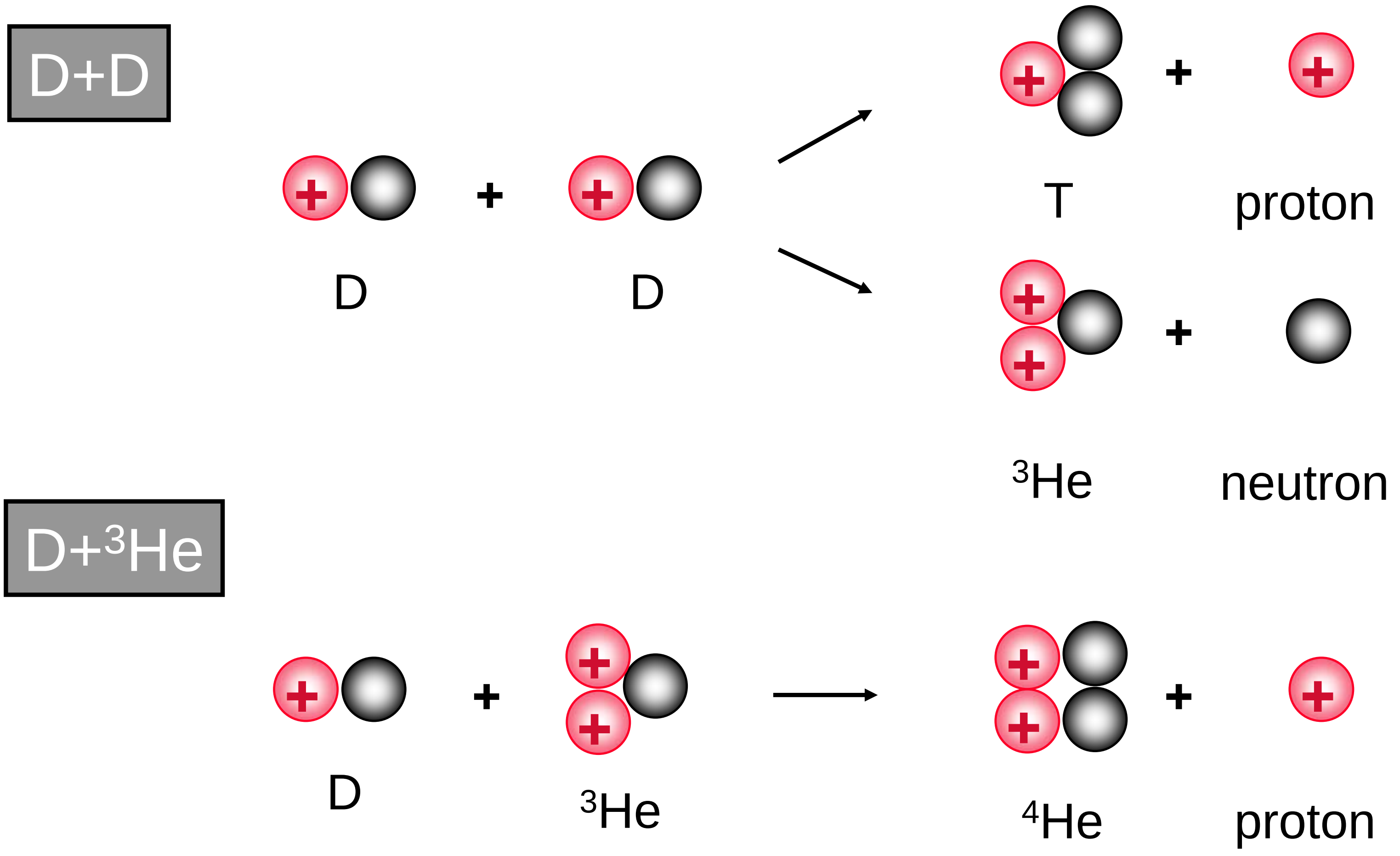
Fusion of Hydrogen Isotopes in Reactors



The D-T fusion reaction is the "easiest" to access

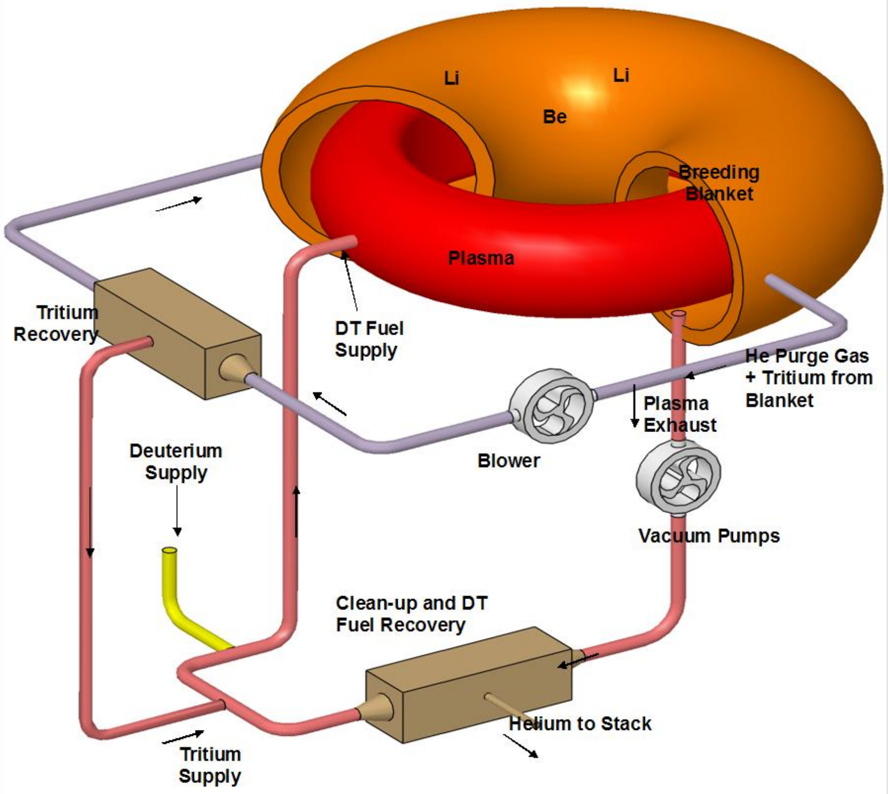


Fusion of other Hydrogen Isotopes



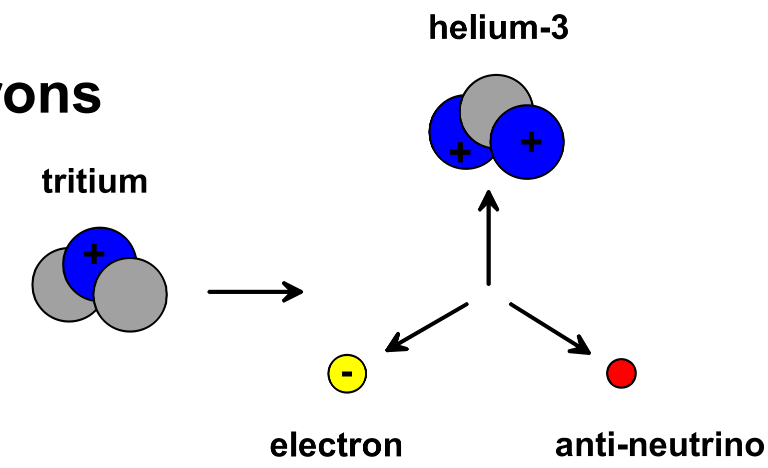
The Inner and Outer Fuel Cycle

- Among the potential fusion reactions technically most suitable is the reaction between deuterium and tritium
  - D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)
- Deuterium can be extracted from natural water (contains 0.016%)
- Tritium must be imported (very limited) or bred internally from lithium
  - Import from heavy water moderated fission reactors (CANDU type)
    - T from neutron capture by D
    - Waste product to be removed from D_2O
  - Breeding reactions in a fusion reactor
    - n + ^{6}Li → T + ^{4}He + 4.87 MeV
    - n + ^{7}Li → T + ^{4}He + n' - 2.47 MeV

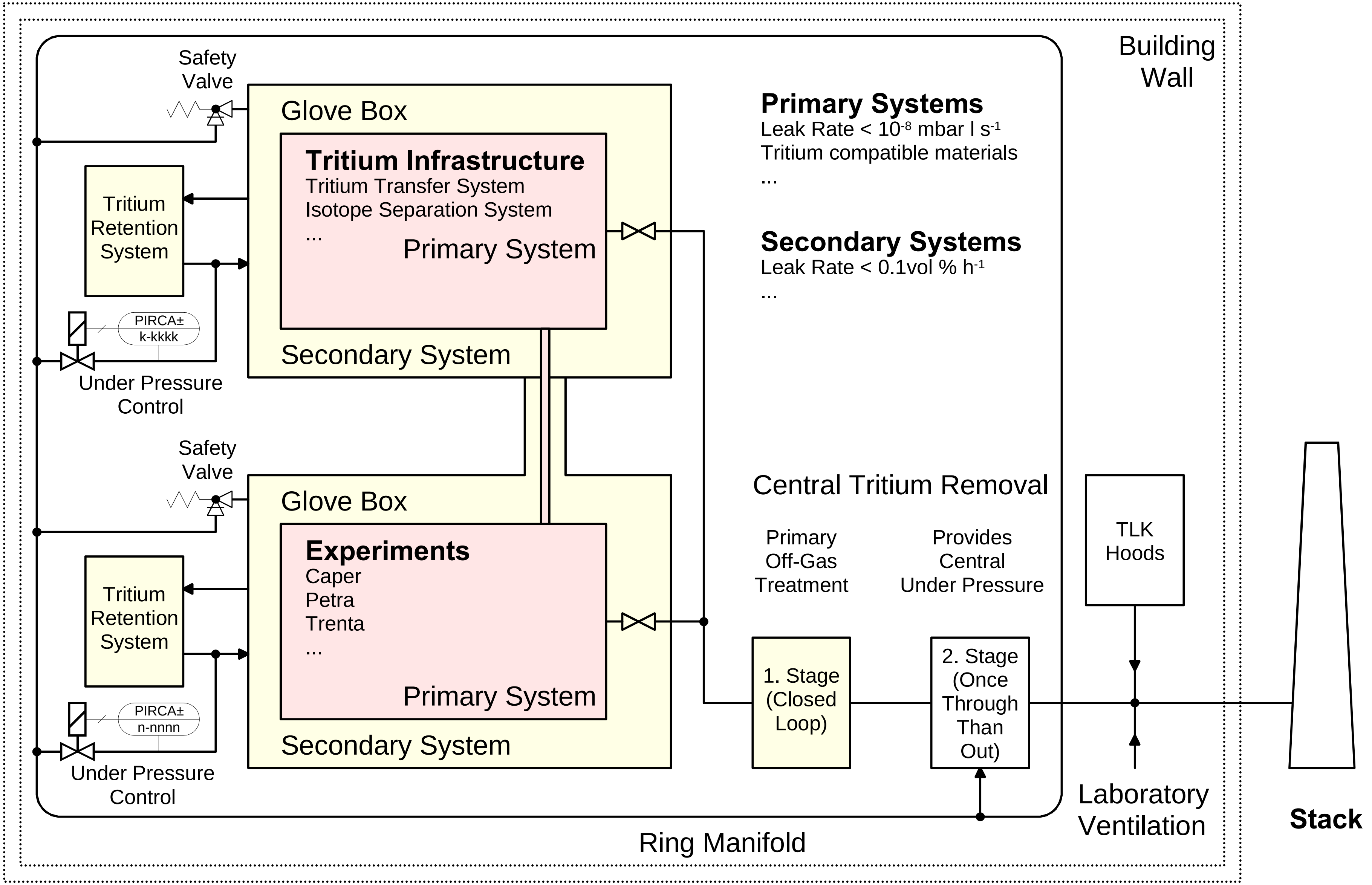


Some Particular Properties of Tritium

- Tritium is the heaviest hydrogen isotope and is radioactive (pure beta emitter, today's total tritium atmosphere inventory is estimated to be about 40 kg)
  - Half life $t_{1/2}$ = 12.323 ± 0.004 years
    - about 1 g tritium per year is lost at an inventory of 25 g
      - Tritium radiation is rather intense
  - Energetically almost weakest natural beta emitter E_{max} = 18.6 keV
    - ^{187}Re has E_{max} = 2.5 keV, however at $t_{1/2} = 5 * 10^{10}$ years is practically stable
  - Maximum range of tritium decay electrons
    - Air : 6 mm
    - Metals: < 1 µm
  - 1 g tritium
    - 324 mW decay heat
    - Activity 9.615 Ci or 3.557 * 10^{14} Bq
    - Volume 3.72 Liter (standard temperature / pressure)

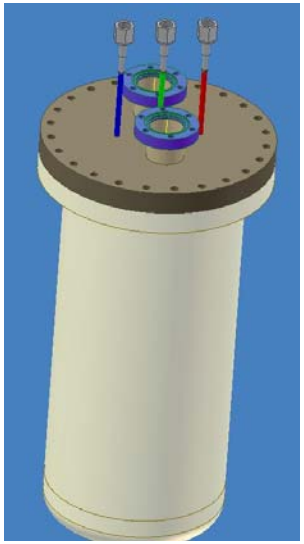


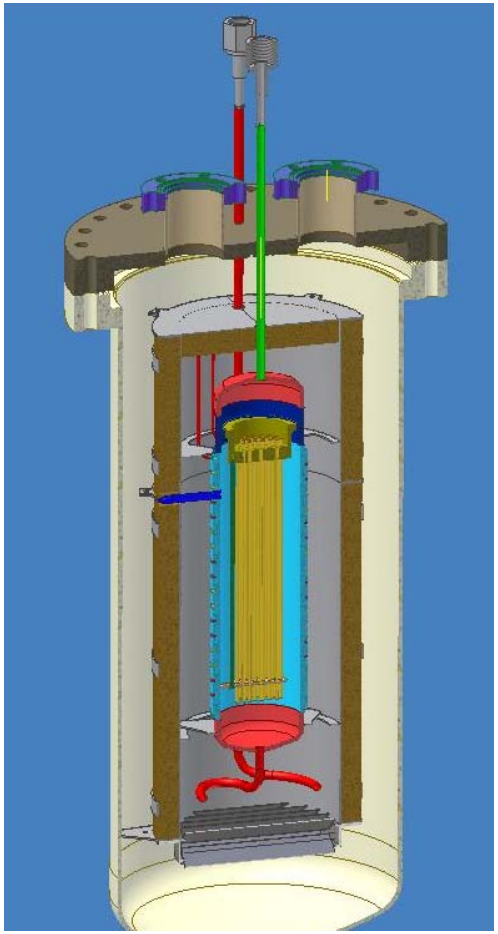
Safe Handling of Tritium (TLK) - Barriers



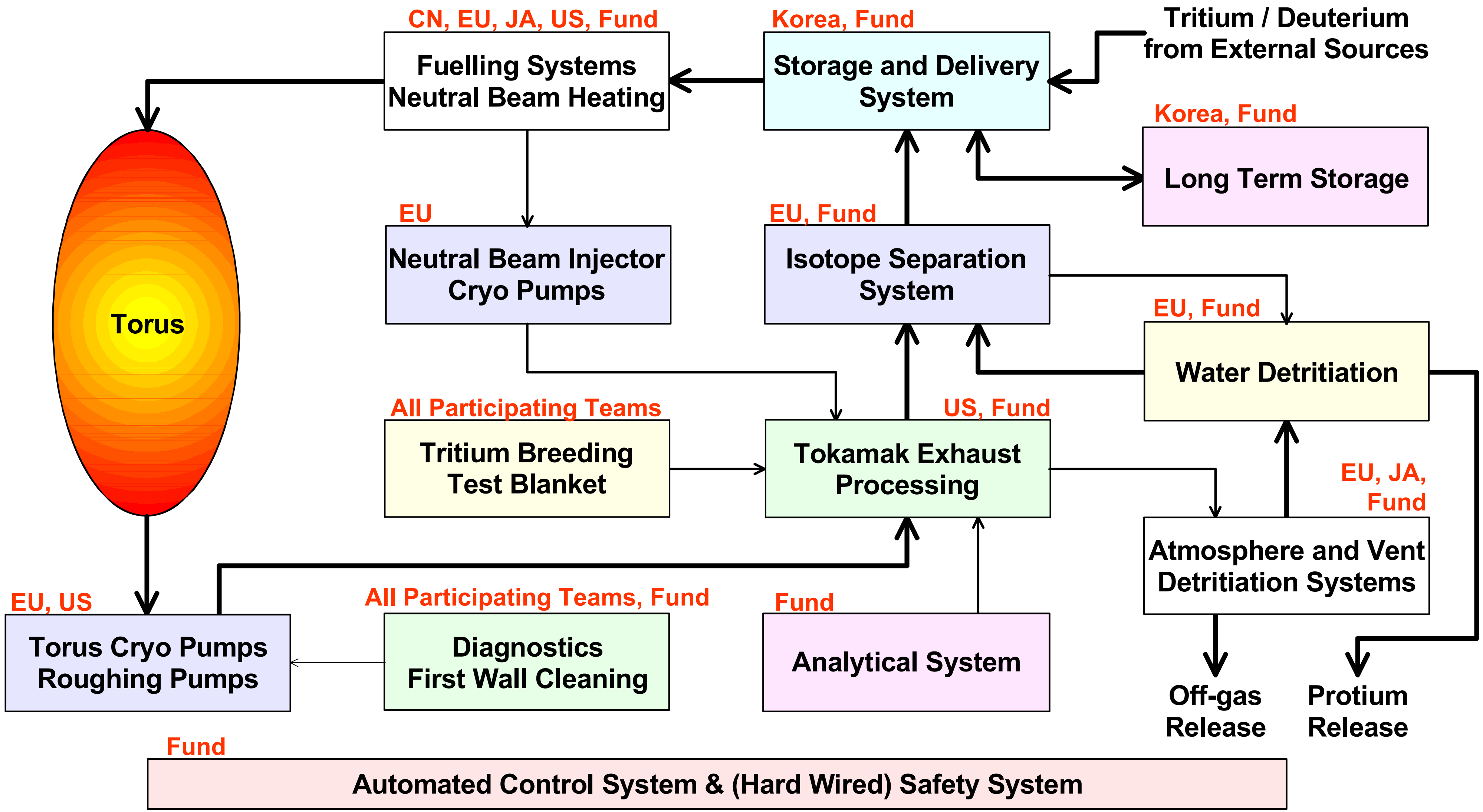
Review on Guidelines for Tritium Handling

- **Large quantity tritium handling involves a high integrity primary containment system**
  - **Primary containment shall be all metal sealed, leak tight and "tritium compatible"**
    - **Wetted materials should be metallic or ceramic**
    - **No organic materials such as pump oils**
    - **Organics unavoidably employed degrade**
      - **Polyimide ("Vespel) is used for valve seats**
        - **Life time of organics depends on tritium exposure (concentration and time)**
      - **Degradation shall not produce corrosive gases**
  - **Vessels are typically built against the European Pressure Vessel Directive**
  - **Tritium process components heated to temperatures above 150°C shall have an outer containment (inter-space evacuated)**
    - **Confinement of tritium permeating through hot structural materials**
    - **Recovery of permeated tritium by regular evacuation**



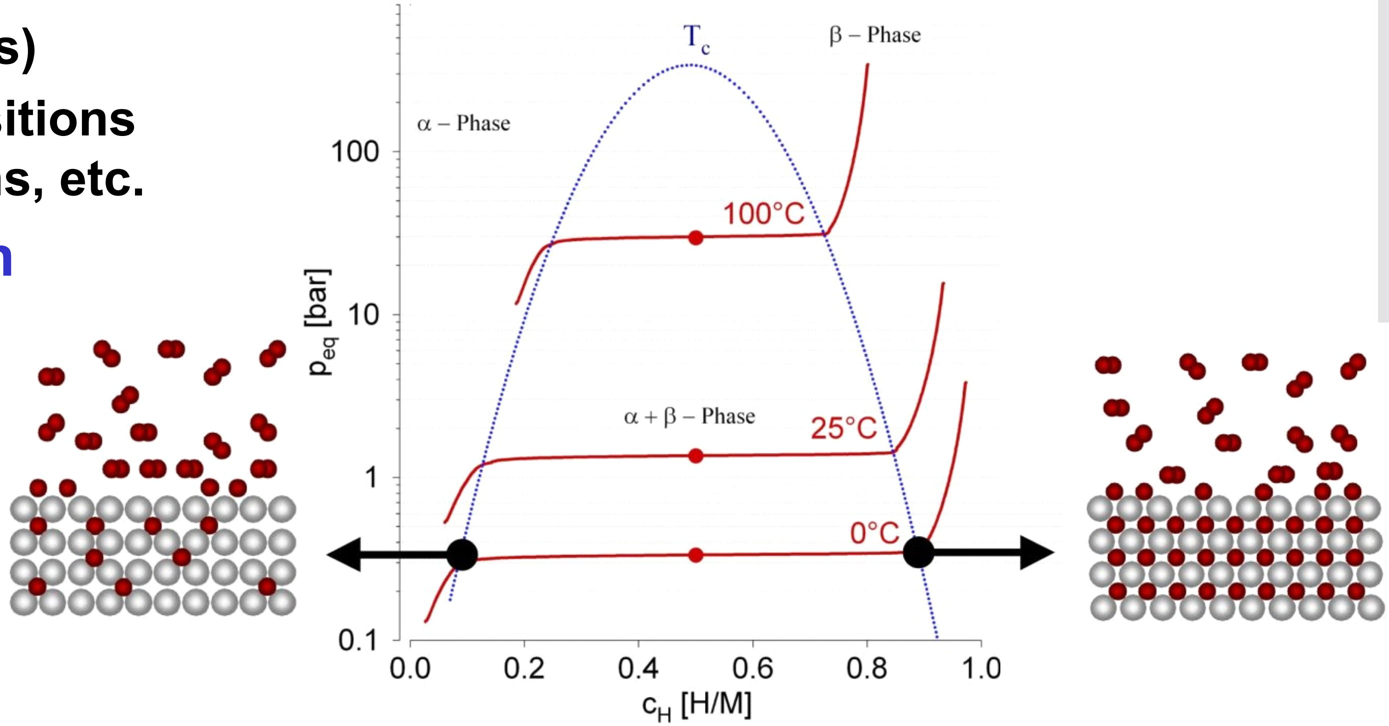


Block Diagram of the ITER DT Fuel Cycle developed at TLK 2001



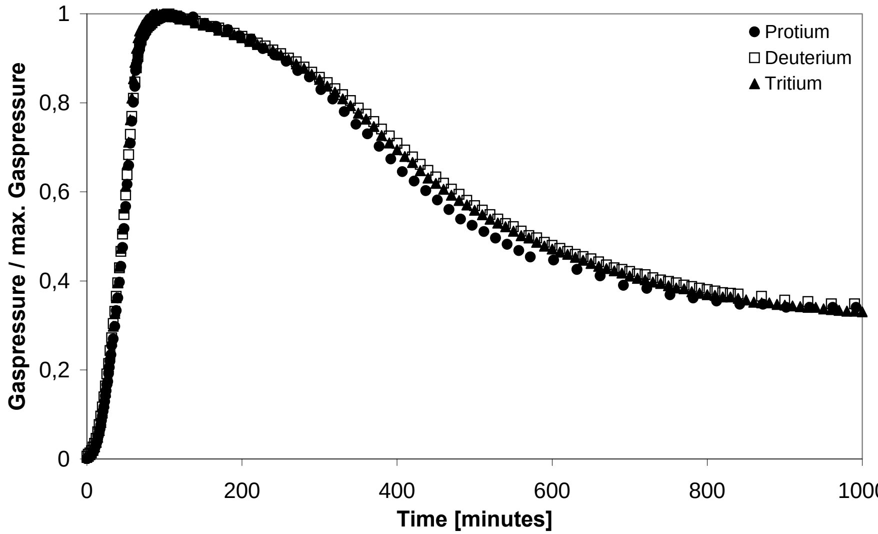
Hydrogen, Deuterium and Tritium in Metal Hydrides (1/2)

- Hydrogen isotopes are dissolved (α-phase) before hydride (β-phase) formation, MeH_x is formed above a certain hydrogen concentration
- Metal hydrides show very interesting physical properties
  - Superconductivity at relatively high temperatures (still cryogenic levels)
  - Order-disorder transitions and phase transitions, etc.
- Reversible absorption and desorption of hydrogen



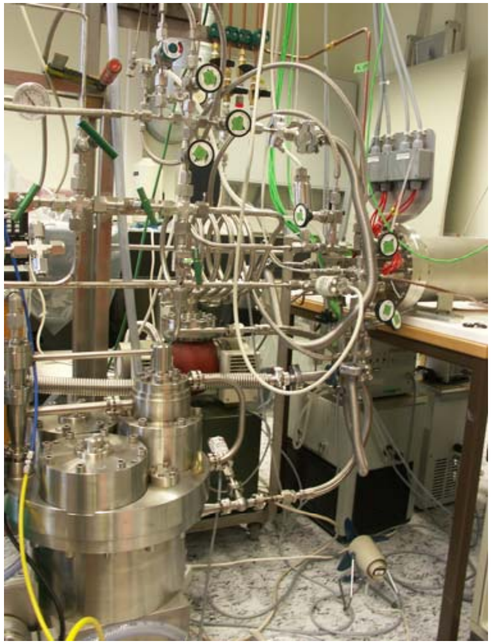
Storage (and Supply) of T (and D) in ITER

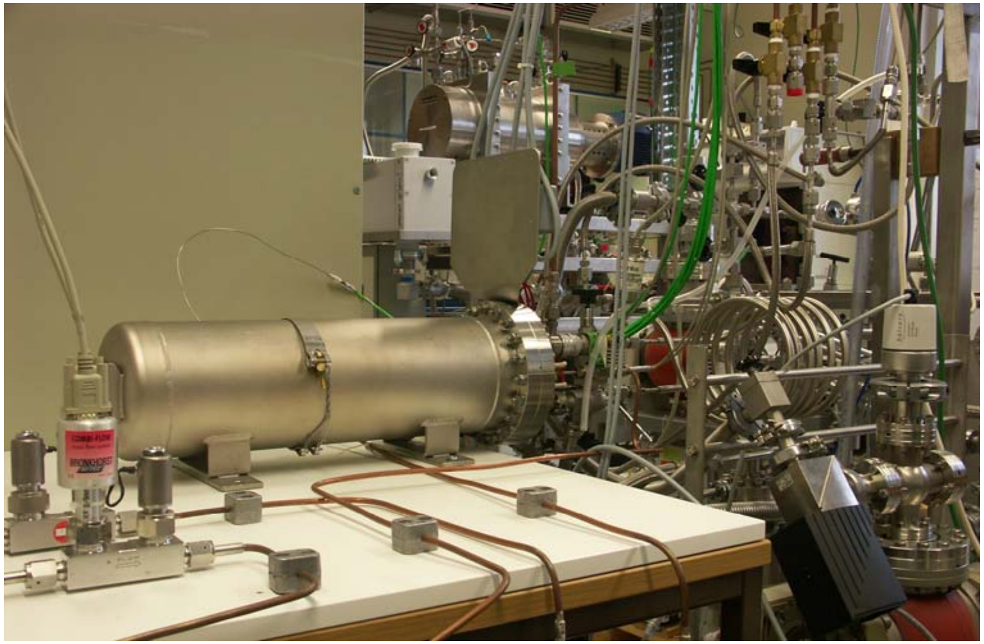
- **Criteria for technical applications of metal tritides**
  - **Low equilibrium pressure of hydrogen isotopes at room temperature**
    - **Metal hydride acts as a highly effective pump**
    - **Save storage of tritium in the gaseous phase**
  - **Low temperature for hydrogen equilibrium pressures around atmospheric**
    - **Liberation of hydrogen isotopes from the metal hydride under moderate conditions**
  - **Flat plateau for the α-phase (dissolution) to β-phase (metal hydride) transition**
    - **Hydrogen isotope pressure remains constant during release at constant temperature**
- **Metal hydride bed design**
  - **Effective heating and power dissipation to allow fast hydrogen release**
    - **Hydrogen release reaction is strongly endothermic**
    - **Thermal insulation to allow calorimetry**
      - **Decay heat is a measure for the tritium content of the bed**

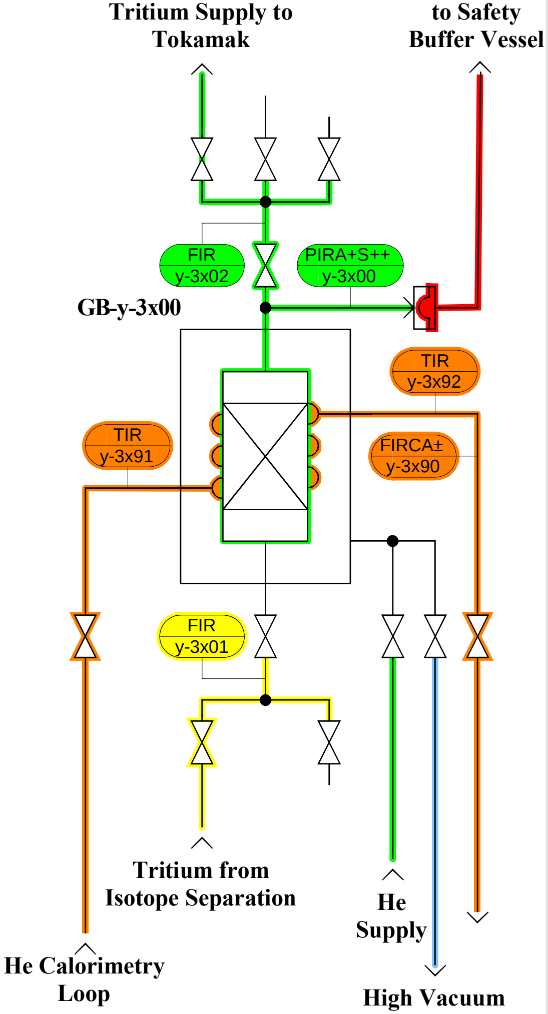


Prototypical ITER 1:1 Metal Hydride Storage Bed at TLK

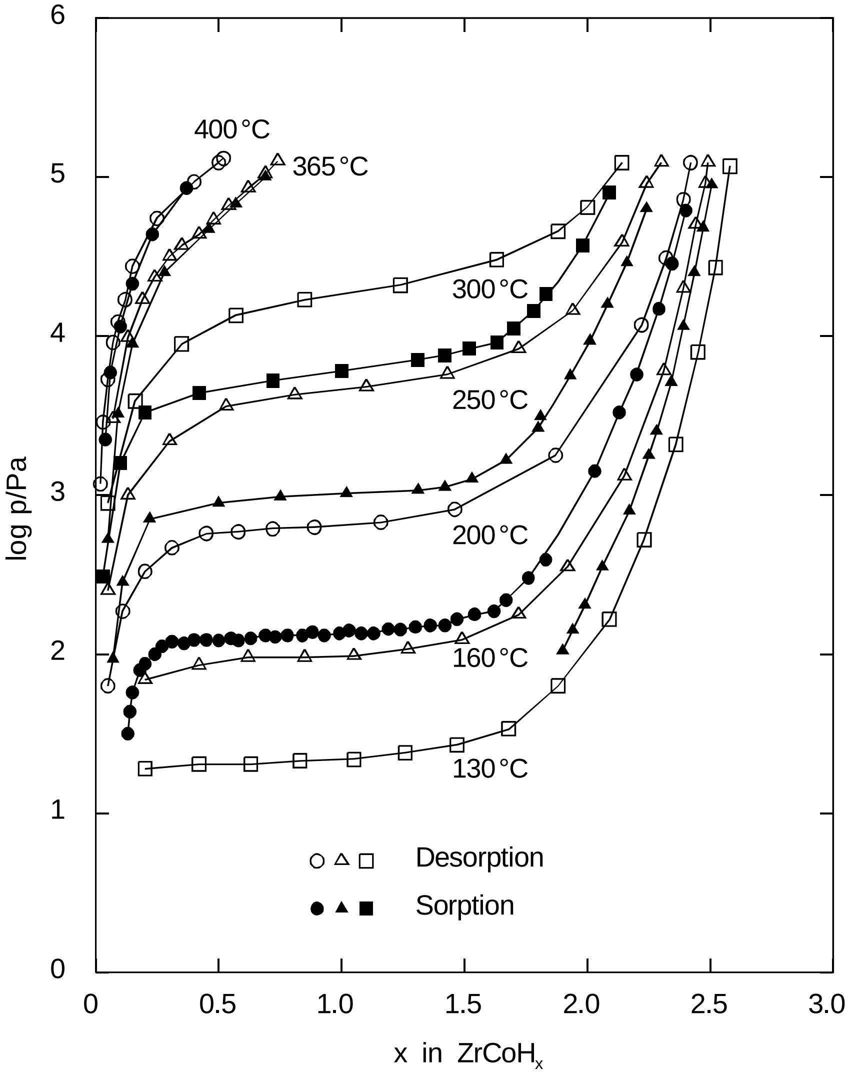
- Essential ITER requirements
  - Safe storage of tritium (ZrCo or U as hydride?)
  - Inventory measurement by calorimetry
  - Inherent limitation to 70 g tritium / bed
  - Fast tritium delivery (200 Pa*m^3*s^{-1})
    - Dissipation of about 8 kW into powder packing (V ~ 1 liter)

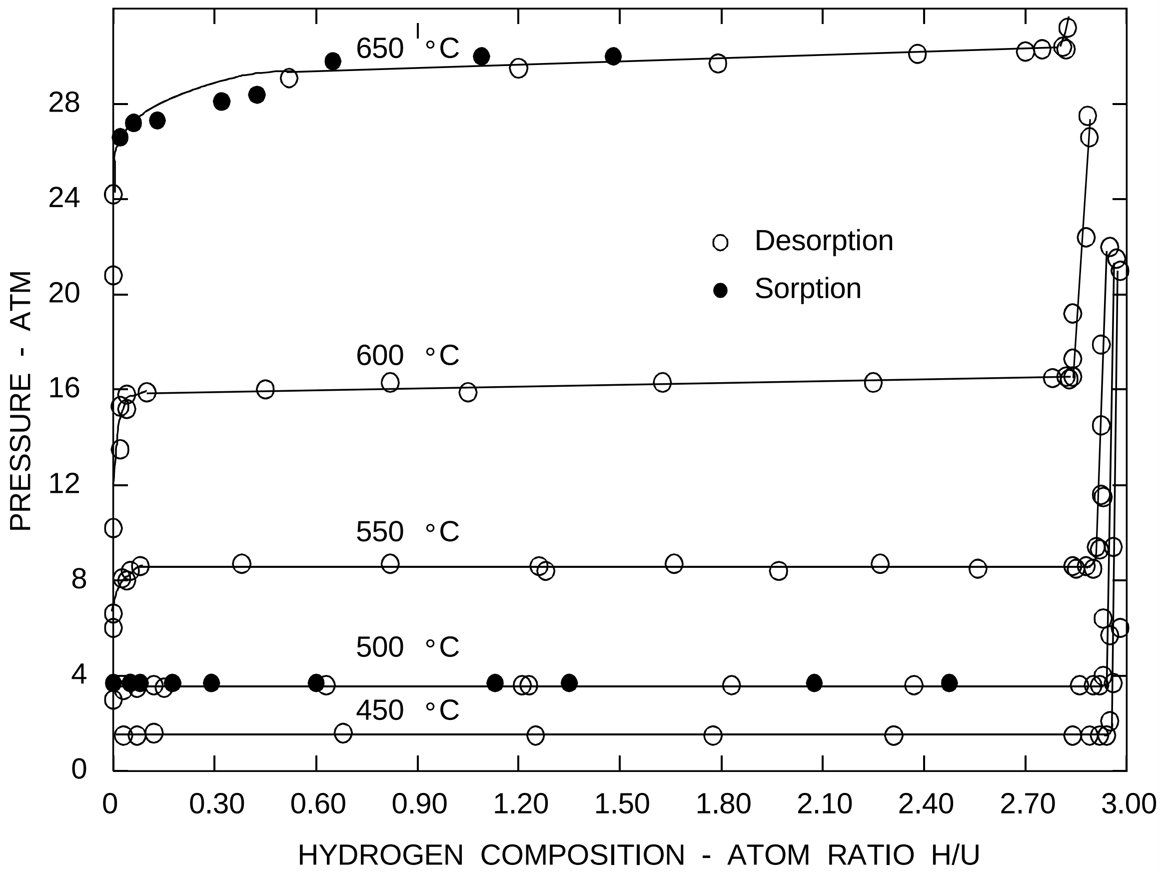






Comparison of $ZrCoH_x$ (log scale) and UH_x (linear scale) Isotherms





The "Ash" of Fusion Reactors

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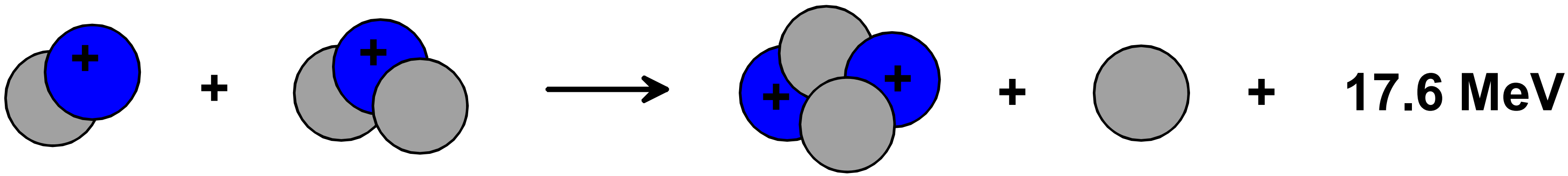
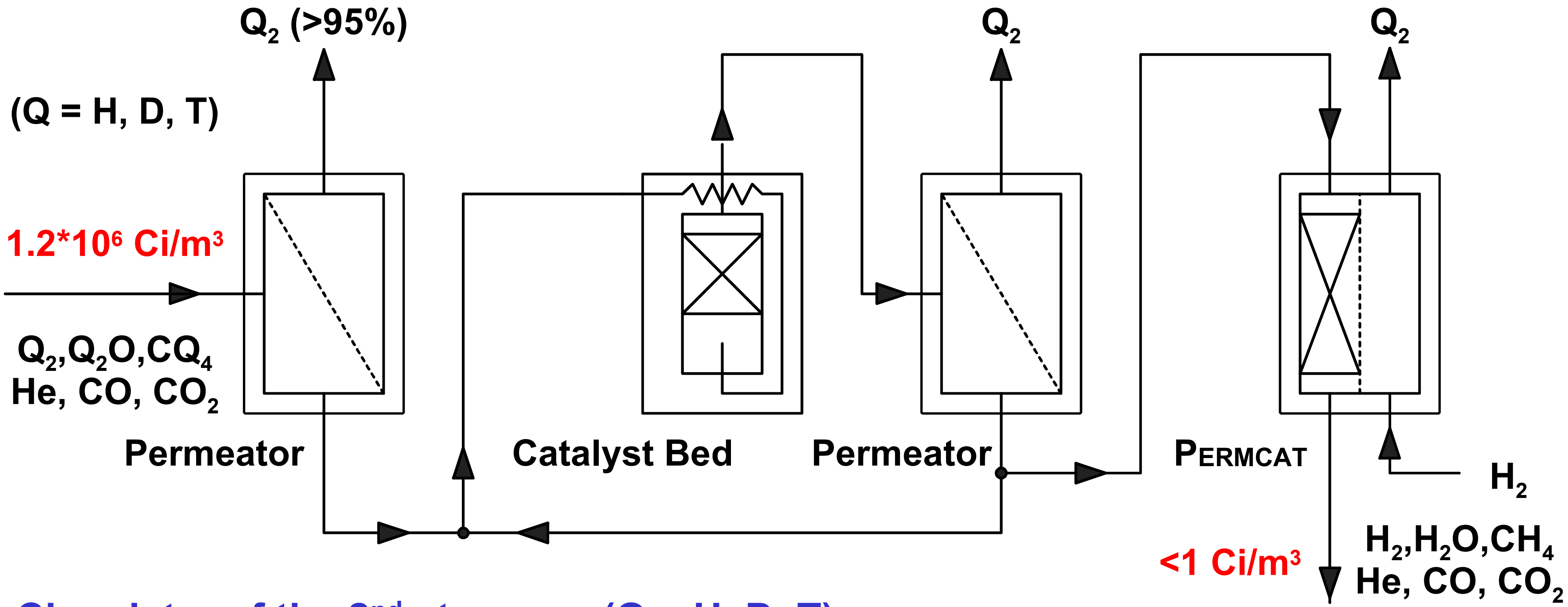


Deuterium Tritium Helium

- Gases from interactions of the plasma with the first wall (carbon, beryllium, tungsten)
  - Carbon oxides (CO, CO_2)
  - Water (Q_2O with Q=H,D,T; 6 isotopically different species)
  - Hydrocarbons (CQ_4 (15 isotopically different species), C_xQ_y with $x < 8$)
- Helium and other gases need to be continuously removed
  - Plasma confinement strongly dependent upon "impurity" content

A closed deuterium tritium fuel cycle is necessary

The Three Steps for Processing of Tritium Containing Gases



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

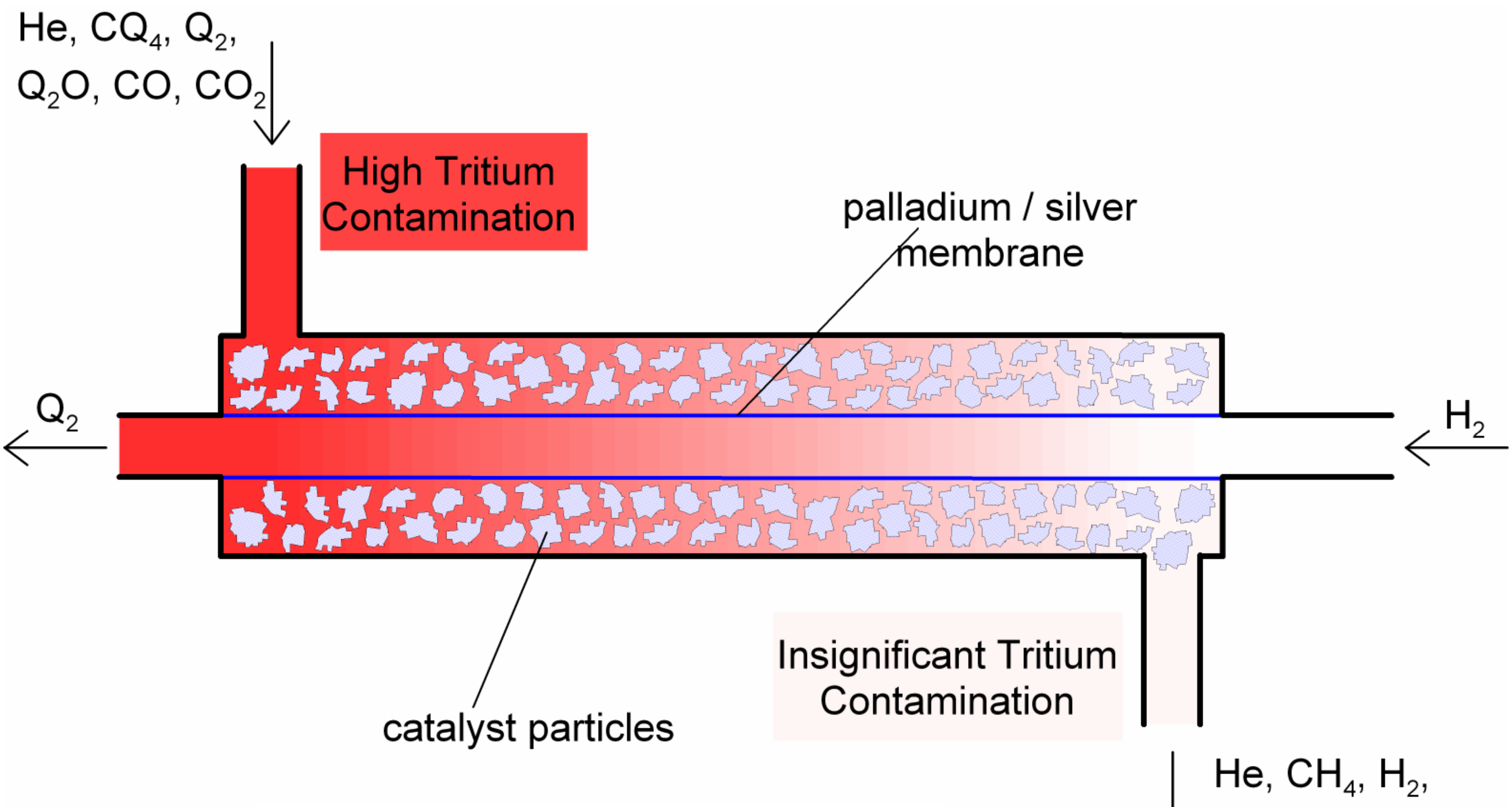
CQ_4	$\leftrightarrow$	$C + 2\ Q_2$	(decomposition)
$C + CO_2$	$\leftrightarrow$	$2\ CO$	(Boudouard reaction)
$CO + Q_2O$	$\leftrightarrow$	$CO_2 + Q_2$	(water gas shift)
$CO + 3\ Q_2$	$\leftrightarrow$	$CQ_4 + Q_2O$	(methanation reaction)

Chemistry of the PERMCAT:

$$2\ H_2 + CQ_4 \leftrightarrow CH_4 + 2Q_2$$

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

PERMCAT (Permeator/Catalyst) Principle



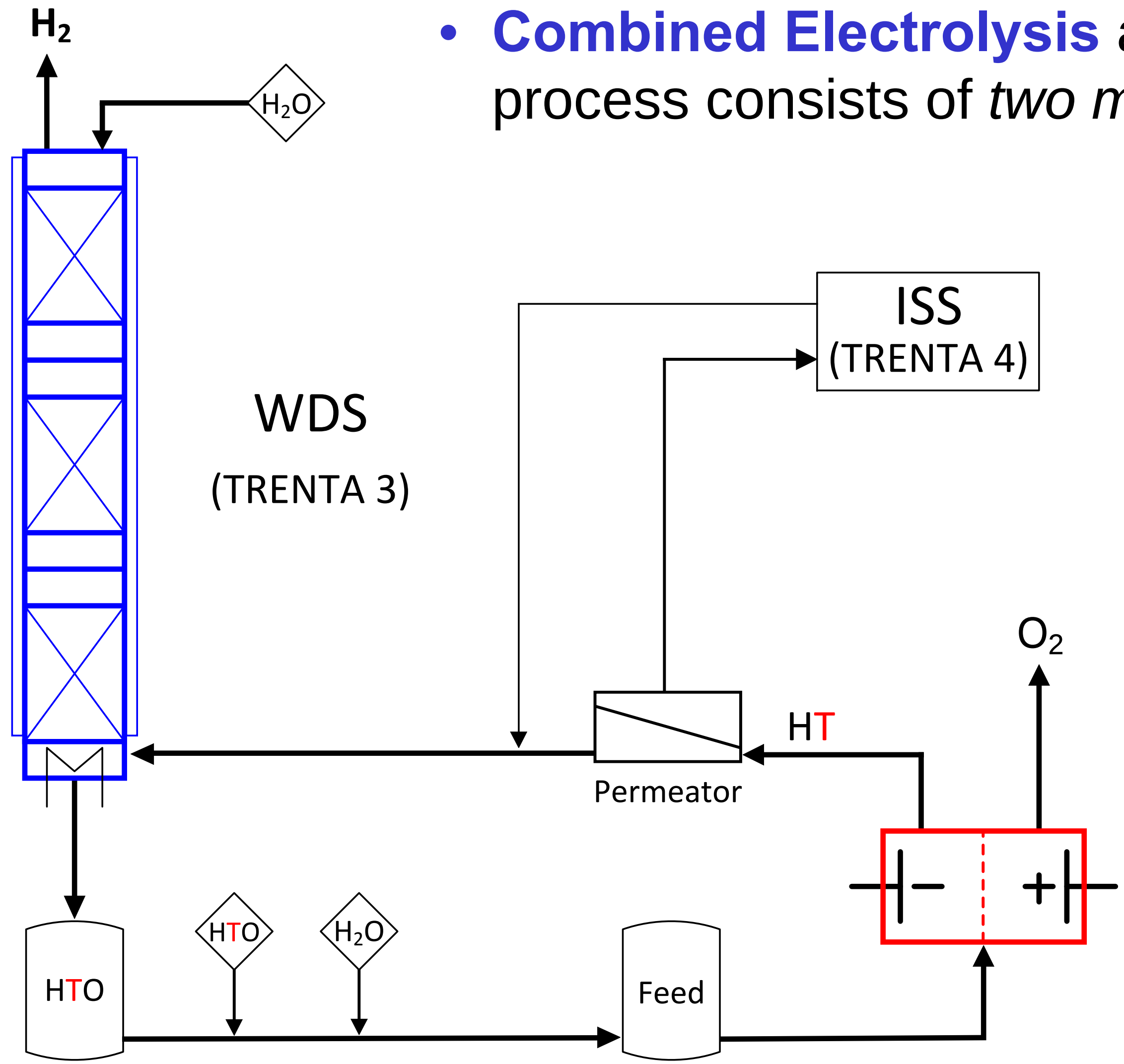
Decontamination factor up to 10^5

CECE Process for Processing of Tritiated Water (WDS)

- **Combined Electrolysis** and **Catalytic Exchange** process consists of *two main systems*

⇒ ***Exchange column***

⇒ ***Electrolyser Unit***



CECE Process (Combined Electrolysis Catalytic Exchange)

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Water electrolysis (SPM)

$2\ HTO \rightarrow 2\ HT + O_2$

H_2 ← | ↓ H_2O

HTO ← | ↑ HT

$HT + H_2O \rightarrow H_2 + HTO$

Catalytic isotopic exchange (LPCE column)

LPCE Column

Catalyst

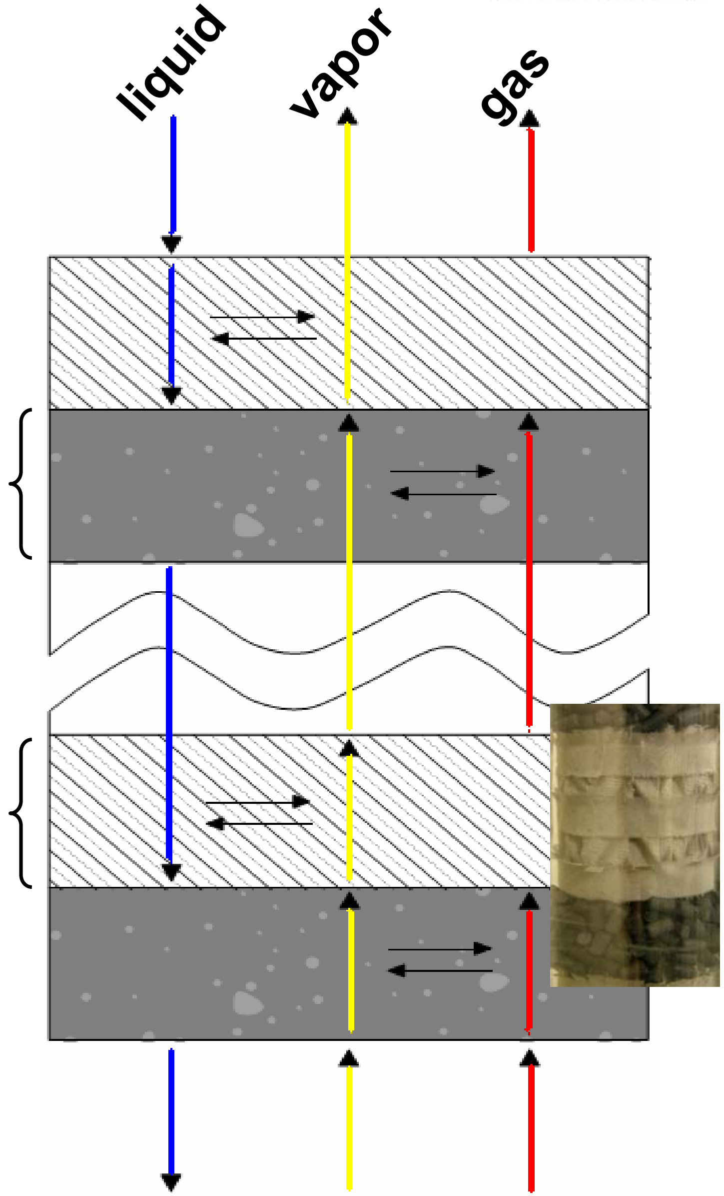
- Isotopic exchange between gaseous phases
- Hydrophobic / large (inner) surface
- PTFE (Teflon) / charcoal / platinum

$$HT^{(gas)} + H_2O^{(vapor)} \rightarrow H_2^{(gas)} + HTO^{(vapor)}$$

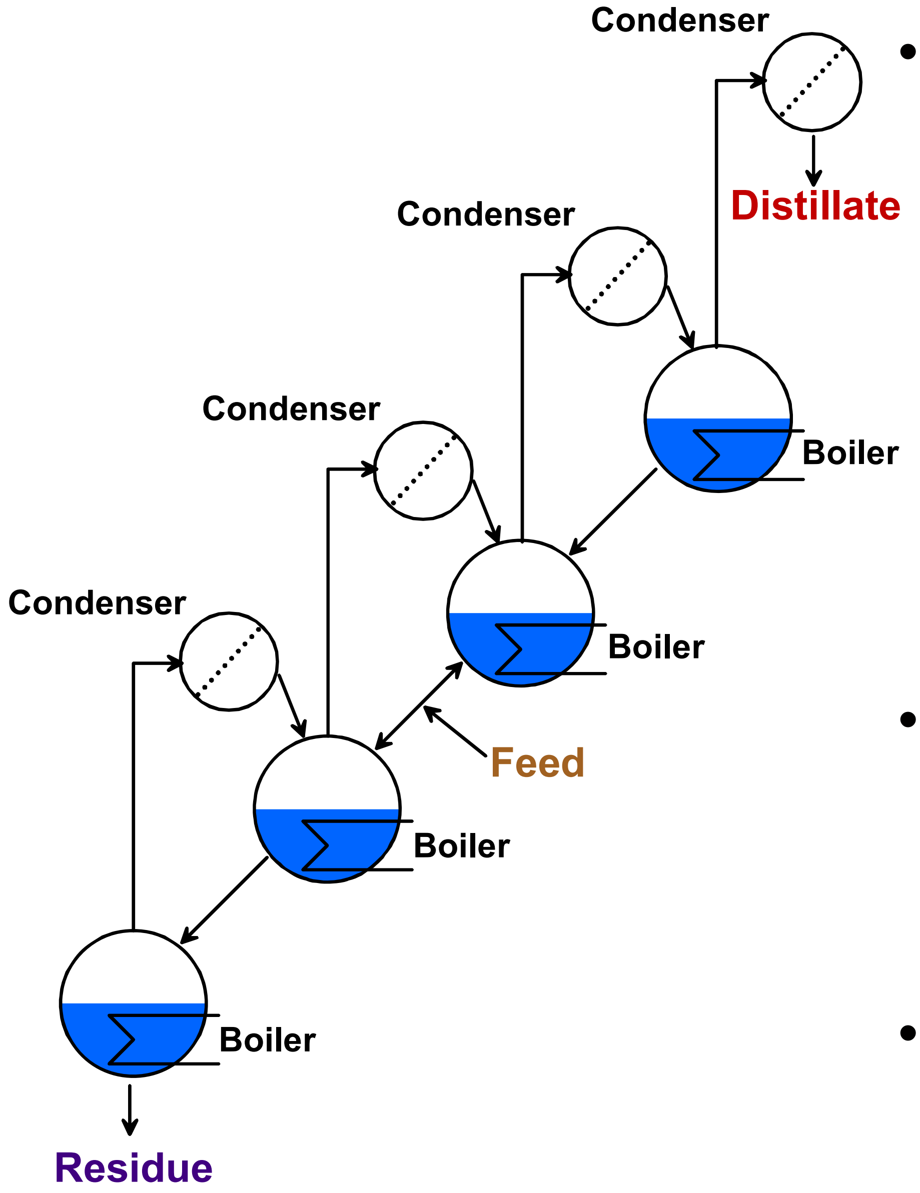
$$HTO^{(vapor)} + H_2O^{(liquid)} \rightarrow HTO^{(liquid)} + H_2O^{(vapor)}$$

Packing

- Different boiling points of HTO and H_2O (distillation)
- Large surface
- Structured metal grids



Separation by Multi Stage Distillation



- Mixtures of liquids with different volatility can be separated by distillation
  - Distillate is enriched in the more volatile component
  - Residue is depleted in the more volatile component
  - Composition of the distillate and residue obviously changes with time
- Process can be made continuous in a multi stage arrangement
  - Feed at a certain stage
  - Withdrawal of distillate and residue
- Counter current vapor-liquid contacting column instead of multiple boilers

Cryogenic Separation of Hydrogen Isotopomers

- **Six molecular hydrogen isotopomers with different boiling points**

Isotopomer	H_2	HD	HT	D_2	DT	T_2
Boiling Point [K]	20.7	22.1	23.5	23.8	25.0	25.5

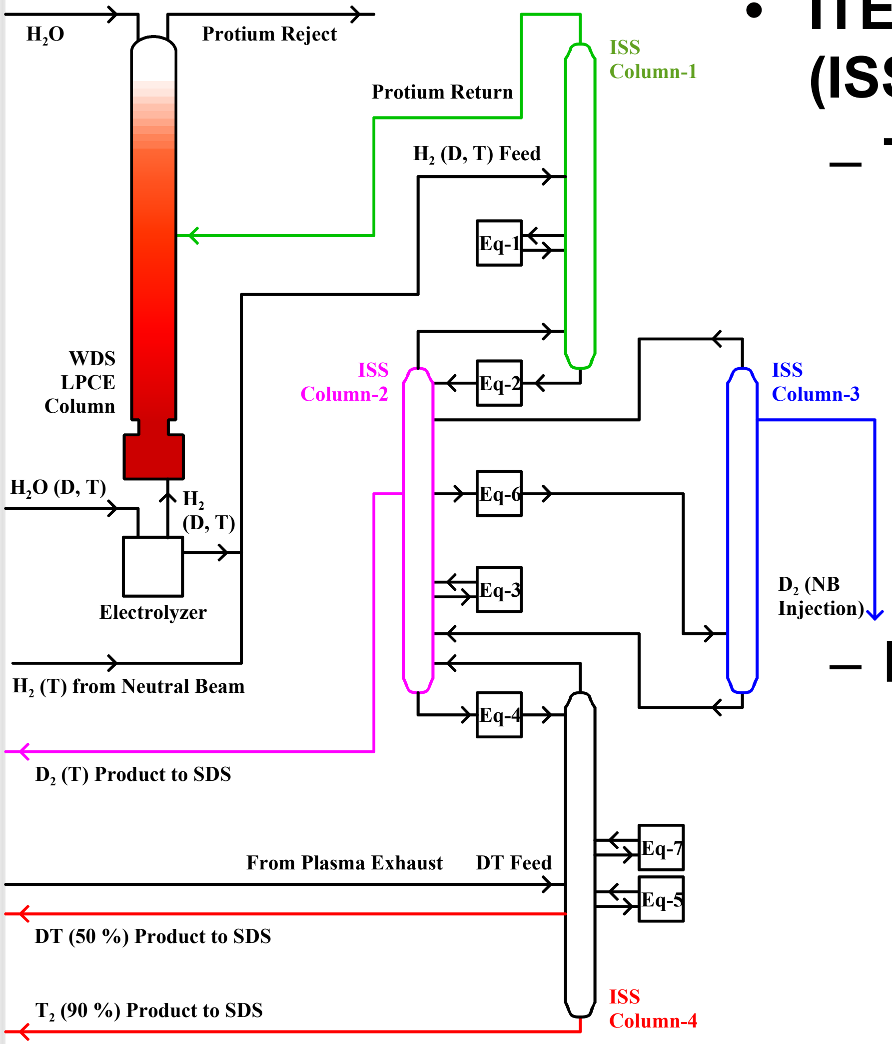
- **Hydrogen isotopomer separation requires distillation at cryogenic temperatures**
- **Separation between HT and D_2 is particularly difficult**
- **Side streams must be withdrawn, heated, equilibrated on a catalyst to split the heterogeneous isotopomers and returned into the column**

$$2\,HD \longleftrightarrow H_2 + D_2$$

$$2\,HT \longleftrightarrow H_2 + T_2$$

$$2\,DT \longleftrightarrow D_2 + T_2$$

Isotope Separation (ISS)



- ITER cryogenic Isotope Separation System (ISS) comprises 4 interlinked columns (2001)
  - Two feed streams
    - About 8 m^3h^{-1} of tritiated hydrogen and deuterium from the Water Detritiation System (WDS) mixed with tritiated deuterium from Neutral Beam injection and fed into column (1)
    - Deuterium Tritium design feed flow rate into column (4) from Tokamak Exhaust Processing (TEP) system is about 7 m^3h^{-1}
  - Four product streams
    - Tritium (90% purity) or alternatively DT (50%)
    - Deuterium contaminated with tritium (refueling)
    - Deuterium at high purity (Neutral Beam injection)
    - Hydrogen (protium) for rejection
      - This would be the largest source for tritium releases into the environment

Combination of Water Detritiation and Cryogenic Destillation

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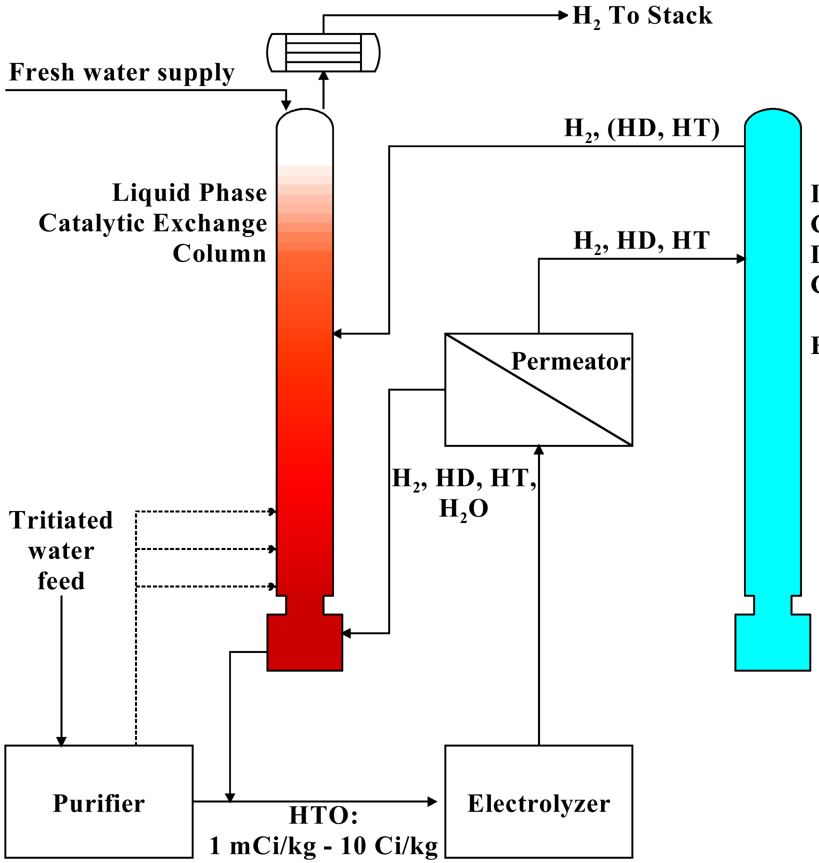


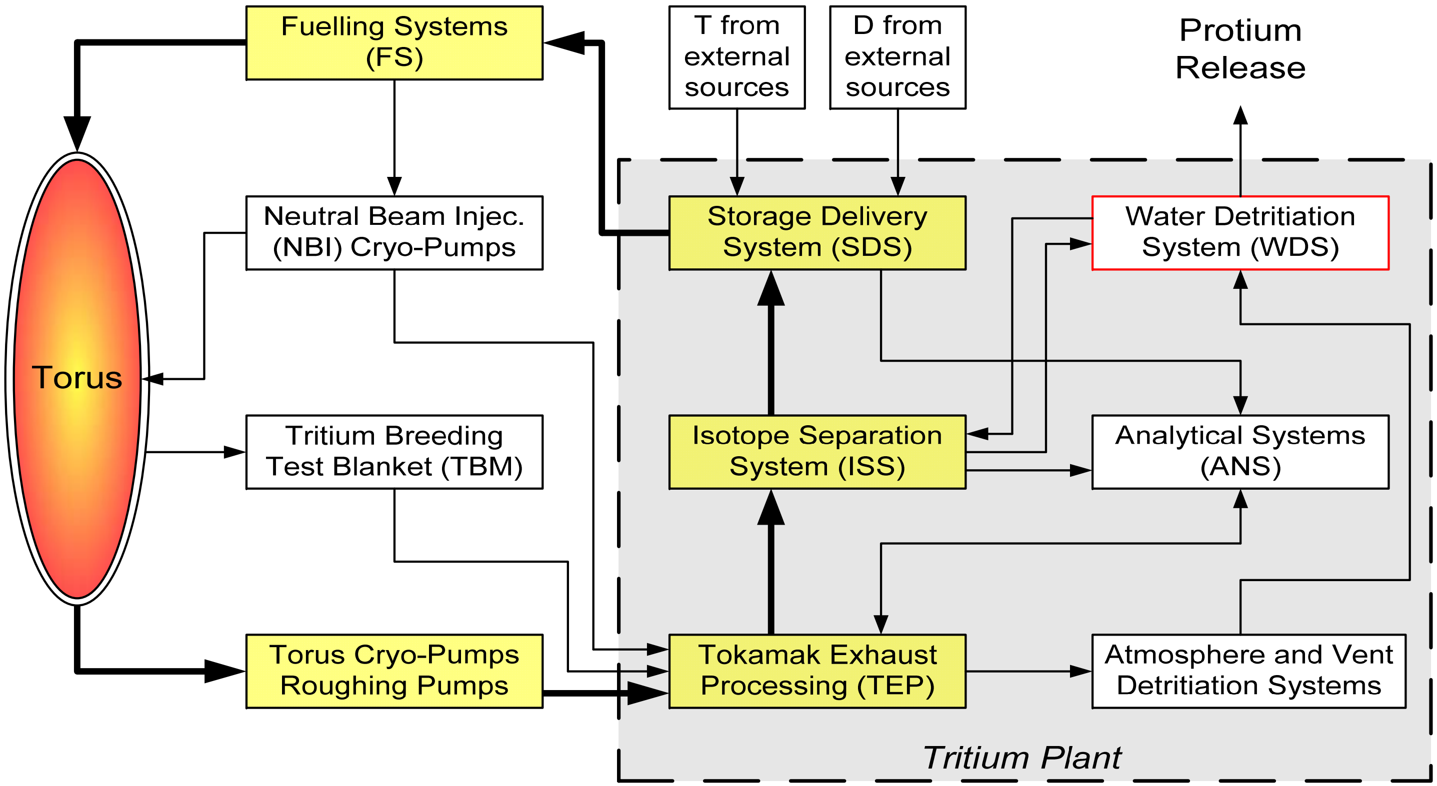
- ITER Isotope Separation System (ISS) based on cryogenic distillation of hydrogen isotopomers
- ISS protium stream (1% deuterium) contains traces of tritium and returned to Water Detritiation System (WDS)
  - Concept is about to be experimentally proven at TLK
  - ISS protium flow rate is only about 10% of the LPCE hydrogen flow rate
- No liquid effluents from WDS

Water Detritiation employed for detritiation

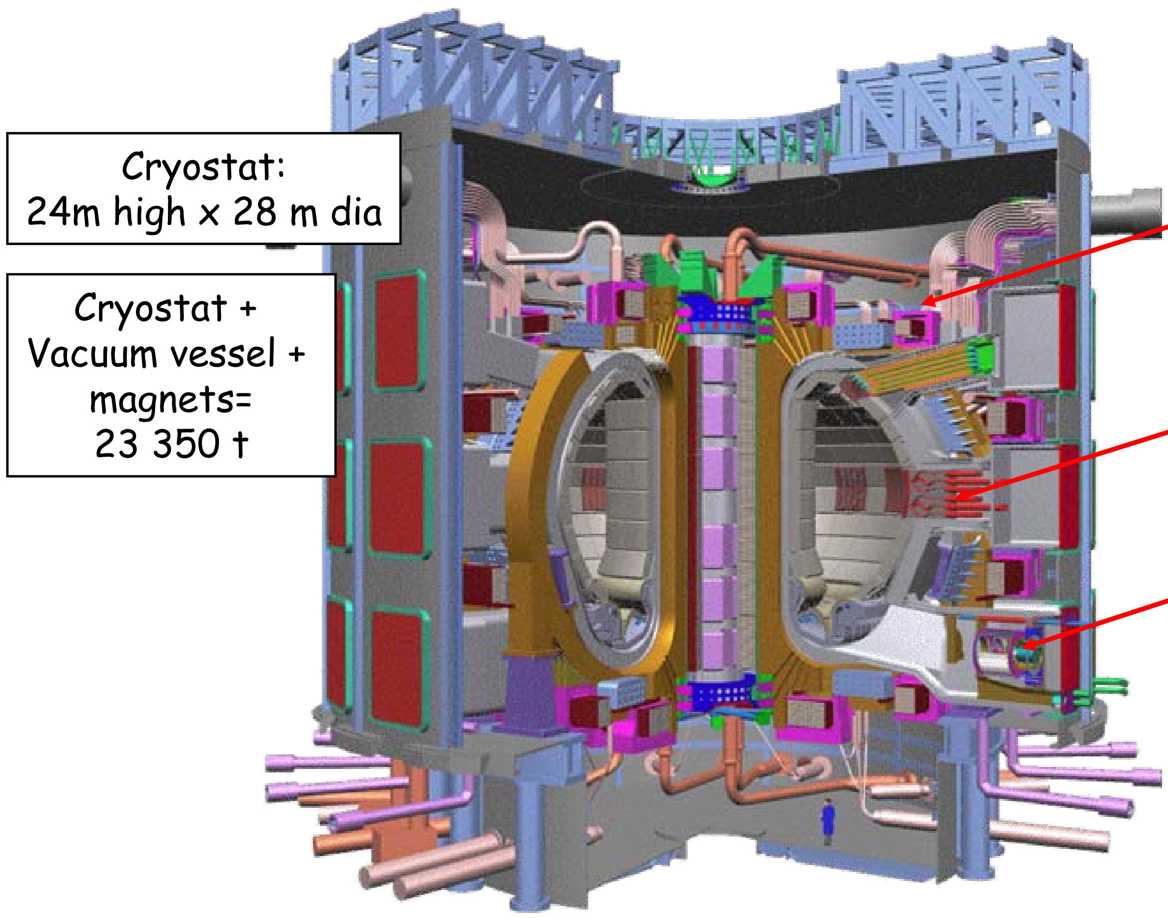
Isotope Separation employed for tritium recovery

Fuelling System

- General duty: Injection of fuel gases (H2, D2, DT T2) for the fusion reaction and to control the plasma.
- Fuelling requirements
  - Short pulses (450 s) and long pulses (3000 s)
  - Fuelling rates in the order of 120 Pam^3s^{-1} DT - 200 Pam^3s^{-1} DT for ITER
- Systems
  - Gas Injection (gas)
  - Pellet Injection (frozen pellets)
  - NBI and Diagnostic NBI (gas)



ITER and its main vacuum systems



3 Large Cryopump systems

Cryostat HV pumping system

Neutral Beam HV pumping system

Torus exhaust HV pumping system

\+ **Mechanical forepump trains** (identical for each of the three high vacuum systems)

Major plasma radius 6.2 m	Plasma Volume: 840 m^3
Plasma Current: 15 MA	Typical Density: 10^{20} m^{-3}
Typical Temperature: 20 keV	Fusion Power: 500 MW

Cryo-mech cross-over pressure is 10 Pa

ITER large cryopump systems

	Torus	Heating (NBI)	Cryostat
# Pumps	8	2 (3) +1	2
Pumping mode	Dynamic = maintain the pressure (1-10 Pa) inside the vacuum vessel volume (1350 m³) at a total gas throughput of (120 Pa·m³/s (fuelling rate) or 60 Pa·m³/s (He case))+ (33 Pa·m³/s (impurities)); Base pressure for hydrogens: 10^{-5} Pa.	Dynamic = maintain the pressure (0.01 Pa) inside the NBI volume (150 m³/H-NBI) at a throughput of 36 Pa·m³/s/H-NBI (protium operation)	Transient pump-down (closed cryostat volume of 8400 m³) to 10^{-4} Pa and steady-state pumping of magnet coolant leak helium and outgassing gas
Gases	Hydrogen (all six isotopomers), helium, impurities Depending strongly on the operation mode (burn& dwell, conditioning, leak detection..)	Hydrogen (H_2, D_2)	Nitrogen, outgassing and leaking gas

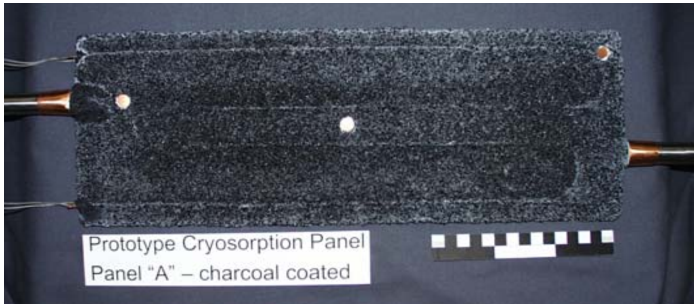
Cryosorption to Pump H_2 and He @ 4.2 K

- Pumping of the gas via physisorption at the cold cryosorbent.
  The pumping effect is given by the porosity of the material (pore size distribution rather than BET surface).

- Activated charcoal is the method of choice.

- In the ITER design, micro porous granular activated coconut charcoal is bonded to the cooled cryopanels by means of a glue (inorganic cement, tritium compatible).

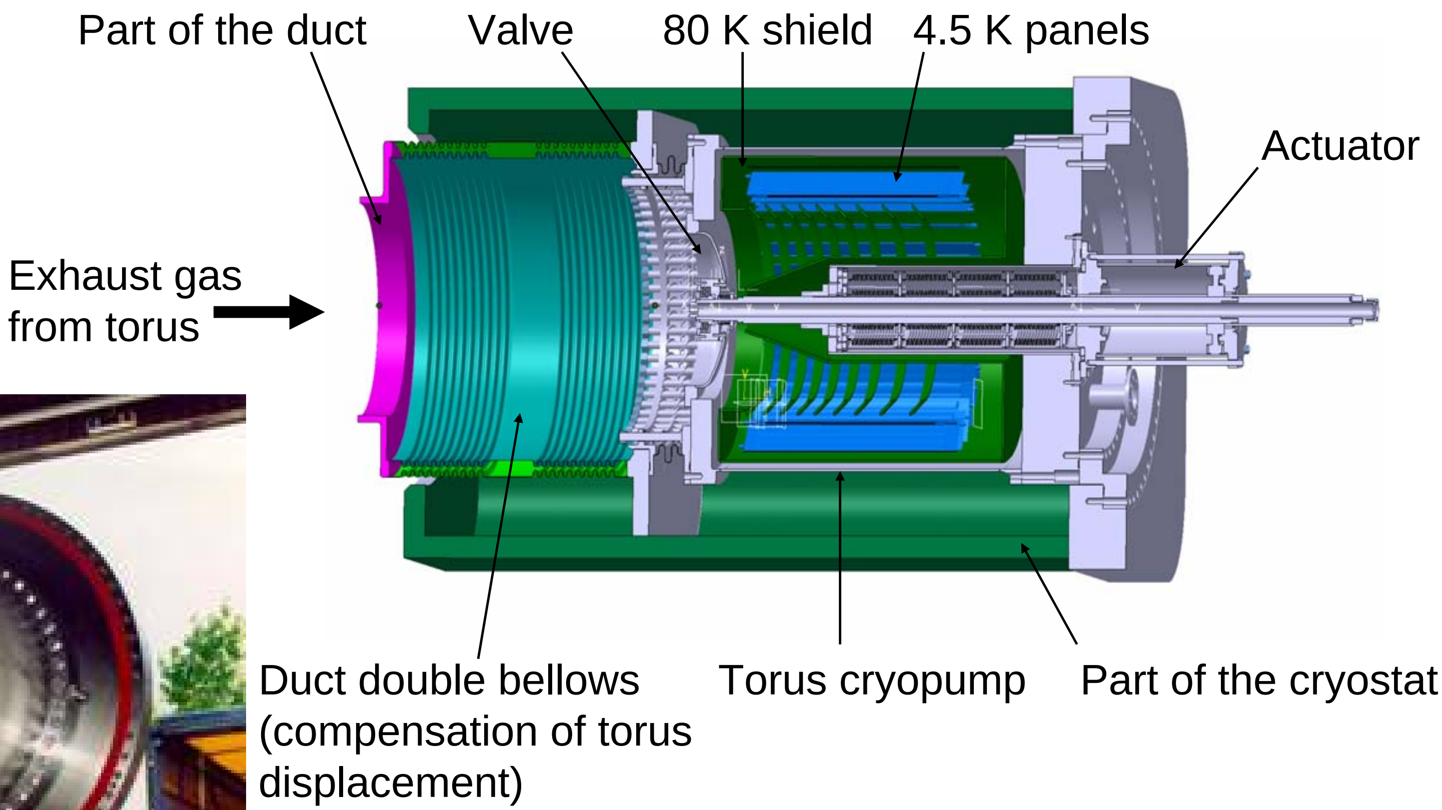
- Additional design parameter: Not only pressure and temperature, but also the gas load → saturation effects.



Panel charcoal coated

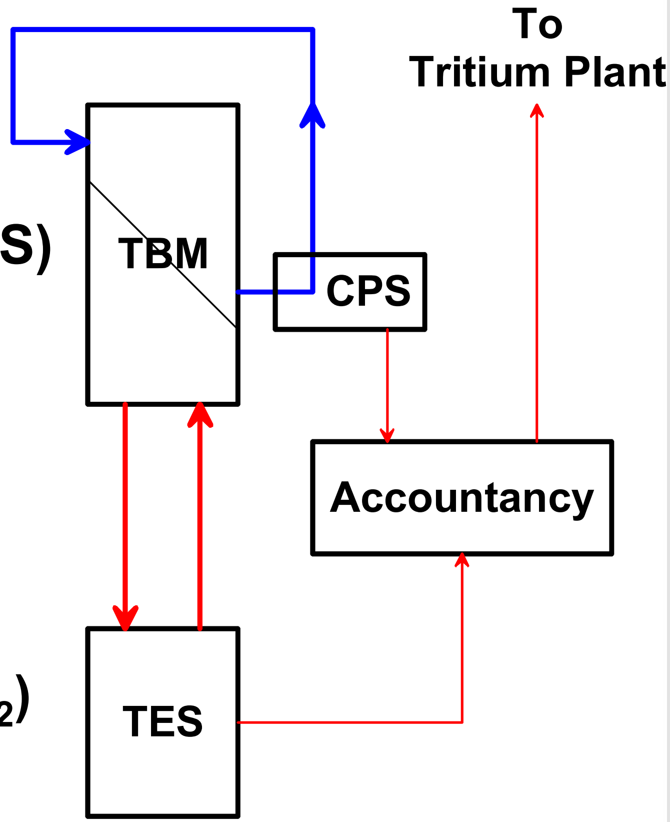
All three ITER cryopump systems are tailor-made and share the common approach of charcoal-coated modular cryosorption panels.

ITER 1.1 Scale Prototype Torus Pump

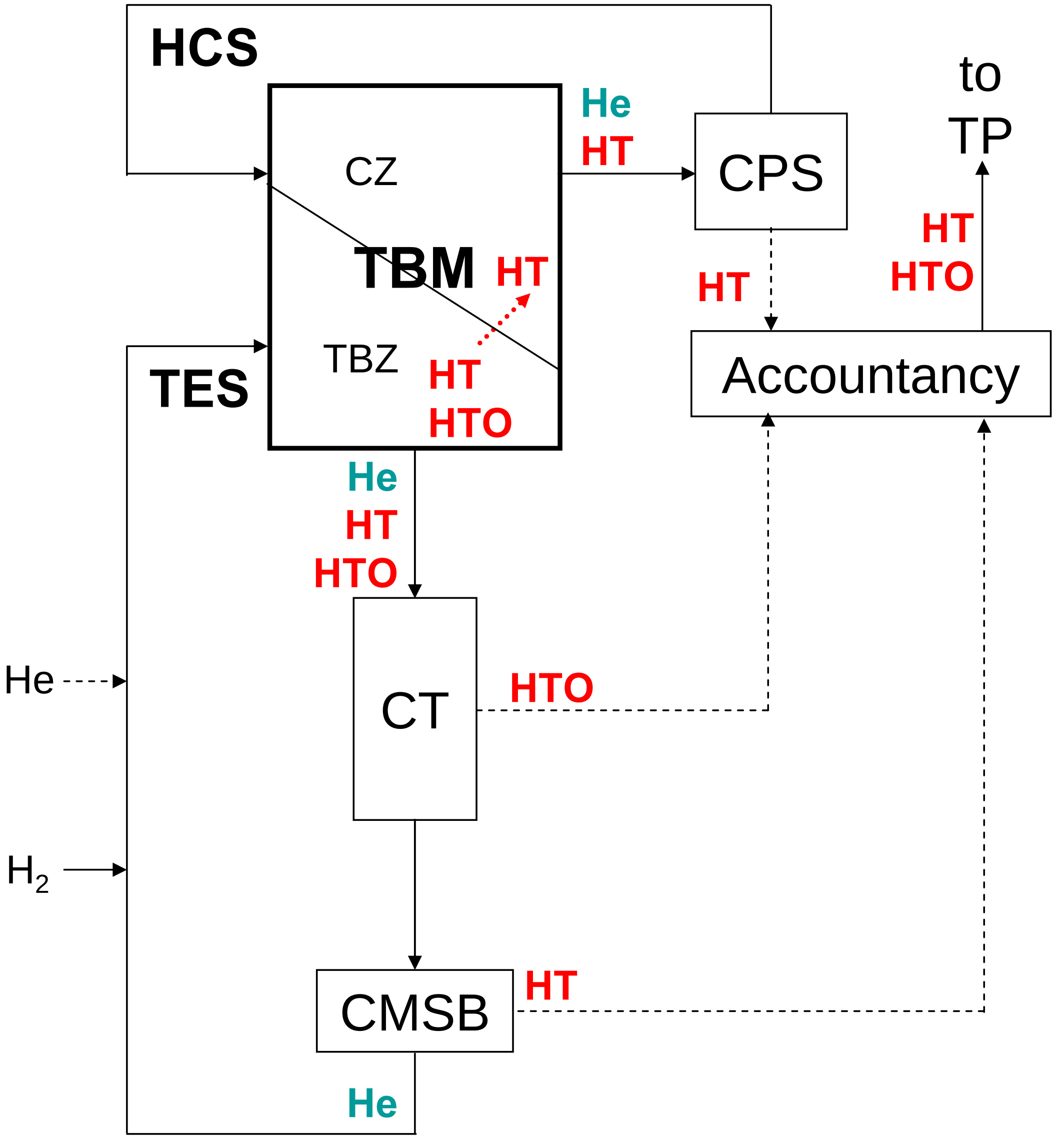


General Issues on Tritium Breeding in ITER

- **ITER will not have a full breeding blanket but only Test Blanket Modules (TBM) installed on port plugs (T production 25 mg/d (module))**
  - **TBMs are based on lithium ceramics or lithium alloys**
    - **$n + {}^{6}Li \rightarrow T + {}^{4}He$ + 4.87 MeV**
    - **$n + {}^{7}Li \rightarrow T + {}^{4}He + n$ - 2.47 MeV**
  - **Currently 42 different TBMs are foreseen**
- **Each TBM will have a Tritium Extraction System (TES)**
  - **Purging of the breeder module with e.g. helium**
    - **Hydrogen (protium) is added (0.1%) to helium to support tritium release as HT by isotopic exchange (swamping)**
    - **The tritium content in HT is estimated to be only 0.1%**
    - **Tritium can also be released as tritiated water**
    - **Tritium content in helium will be only about 1 ppm**
  - **The almost only way to remove HT (together with H_2) from the helium purge gas stream is by trapping (in the widest meaning of the word)**
    - **Molecular sieve beds at room and/or cryogenic temperatures**



TLK – First Concept for TES in HCPB



Albrecht, FZK-TLK (1997)

TBM: Test Blanket Module

TBZ: Tritium Breeding Zone

CZ: Cooling Zone

TP: Tritium Plant

HCS: Helium Cooling System

CPS: Coolant Purification System

TES: Tritium Extraction System

CT: Cold Trap

CMSB: Cryogenic Molecular Sieve Bed

dotted line = intermittent stream

continuous line = continuous stream

red = tritiated stream

ITER (2001): He 12 m^3/h + 0.1% H_2

TLK – R&D on CT & CMSB

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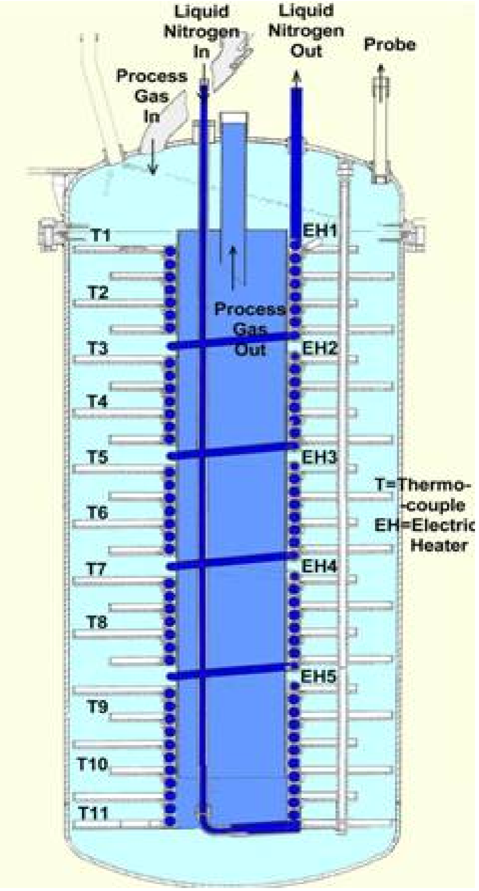


⇒ **Demonstrated at the 1:6 scale of ITER flow rate**

CMSB: 20 kg of Zeolite 5A

- Adsorption isotherms
- Isotopic effect
- Breakthrough curves

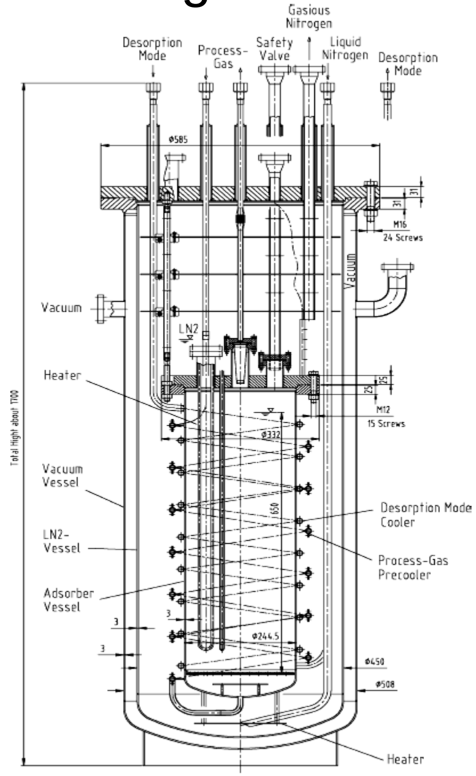
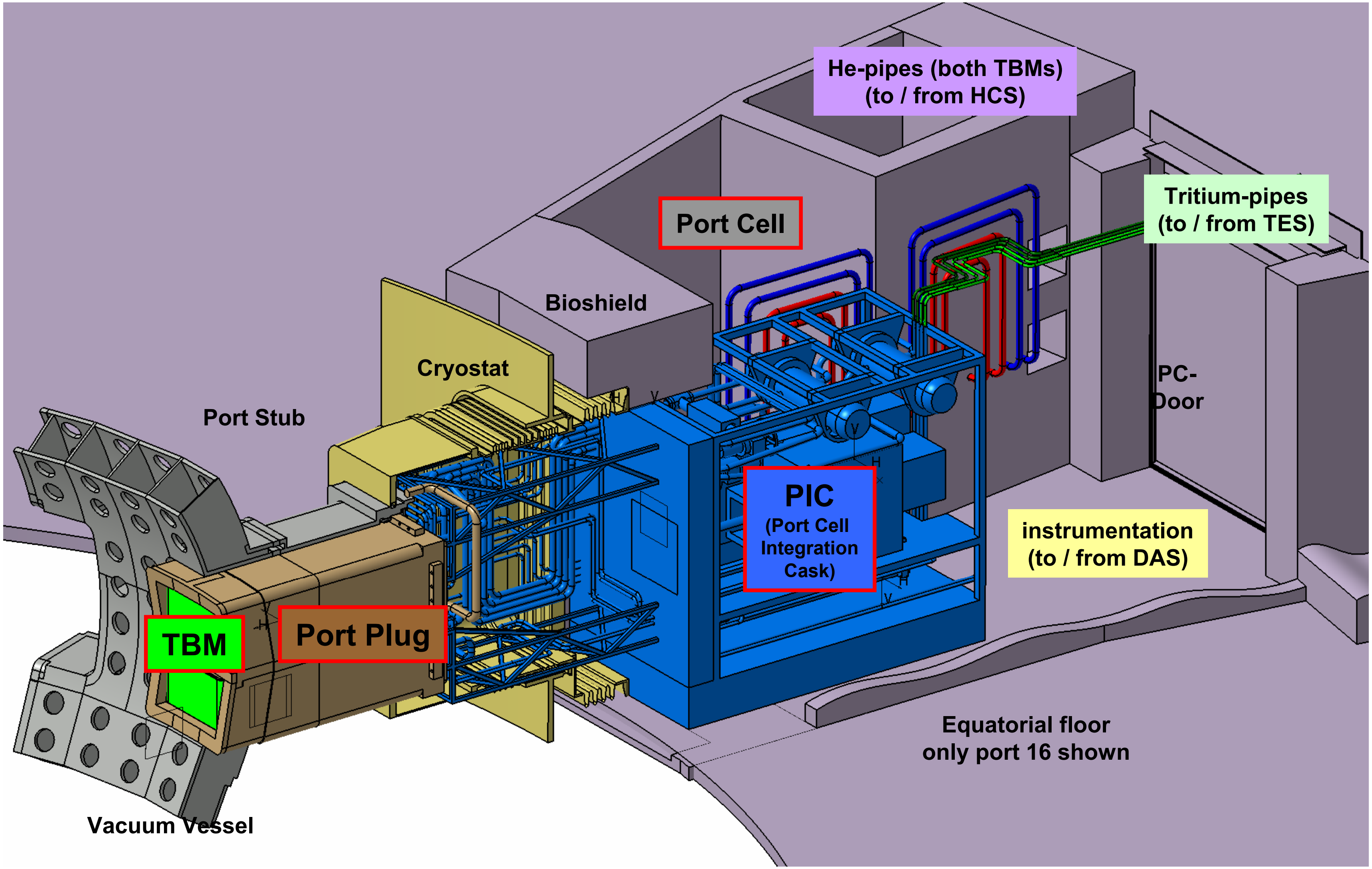


Fig. 4. Molecular sieve adsorber.

CT: from FZ Jülich

- 22 copper plates with temperature profile
- Low velocity to avoid turbulences

ITER Test Blanket



Tritium production in DEMO about 550 g/d (machine)

TLK Fields of Research

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- Foundation task of the TLK at Forschungszentrum Karlsruhe in 1983, programme fusion

  - Development of the technologies for the fuel cycle of fusion reactors

    → Processing technologies for deuterium, tritium and relevant compounds

    → Conduct technical and laboratory experiments with realistic concentrations of T_2

- Additional R&D activity, programme "Structure of Matter" since 2001

  - TLK hosts the international Karlsruhe Tritium Neutrino experiment (KATRIN) to measure the neutrino mass

    → Precise spectroscopic measurement of the electron spectrum from tritium ß-decay close the endpoint at 18.6 keV

    → Improving the sensitivity of electron neutrino mass measurement from its current value of 2.0 eVc^{-2} by one order of magnitude to 0.2 eVc^{-2}.

Key Data of TLK

- **The TLK is an almost unique, semi-technical facility**

  - Long experience in handling tritium

  - Licensed for handling up to 10 g tritium in April 1993

  - First delivery of 3.5 g tritium in October 1993

  - Commissioned with tritium in 1994

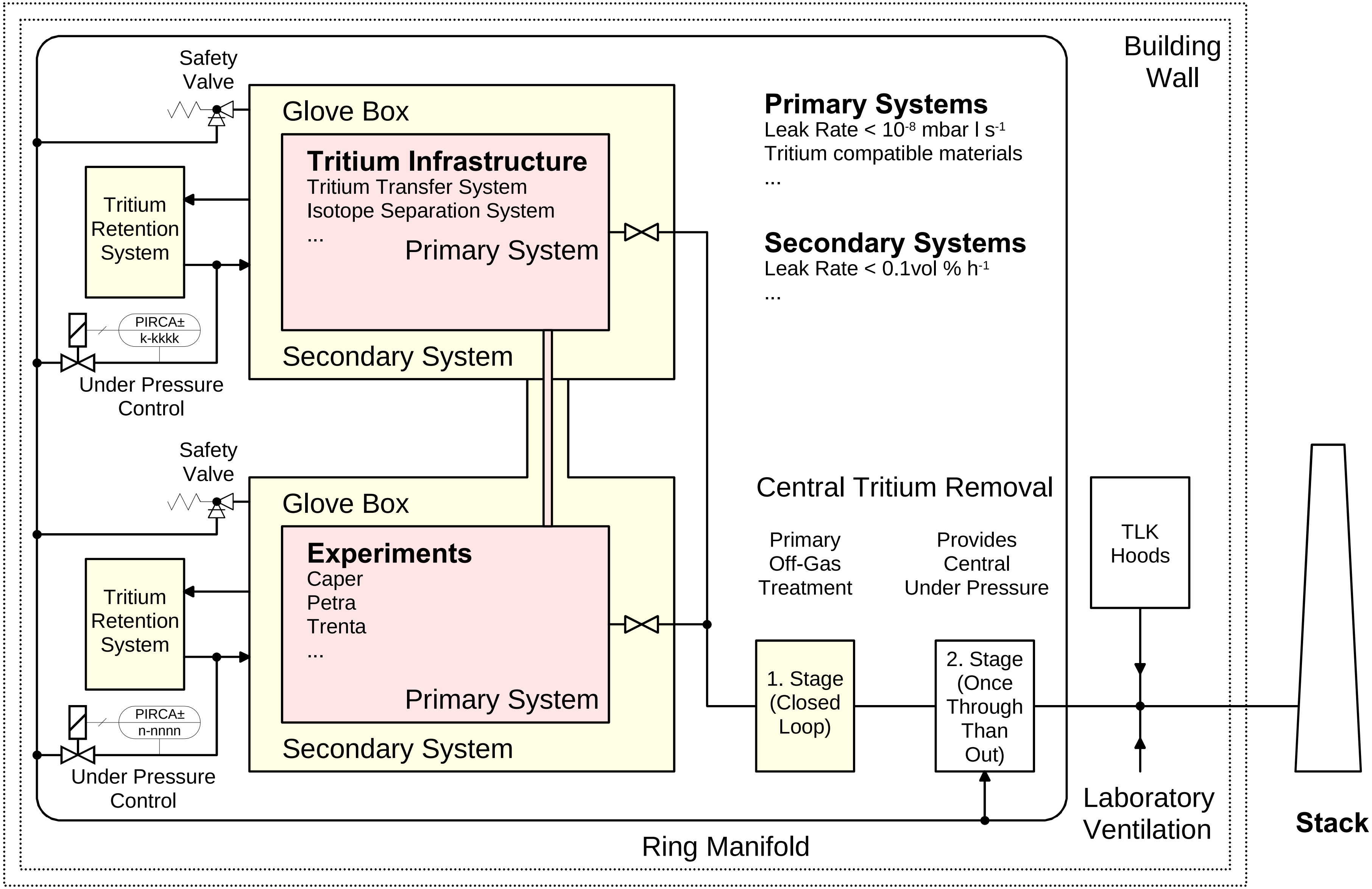
  - Licensed for handling up to 40 g tritium in February 1996 (new license since September 2007, includes operation of KATRIN)

  - Currently 24 g of tritium on site

  - Operates more than 10 glove box systems (total volume of about 125 m³) on an area of 841 m² for experiments and 615 m² for infrastructure

  - Operates a closed tritium loop

Confinement Concept at TLK



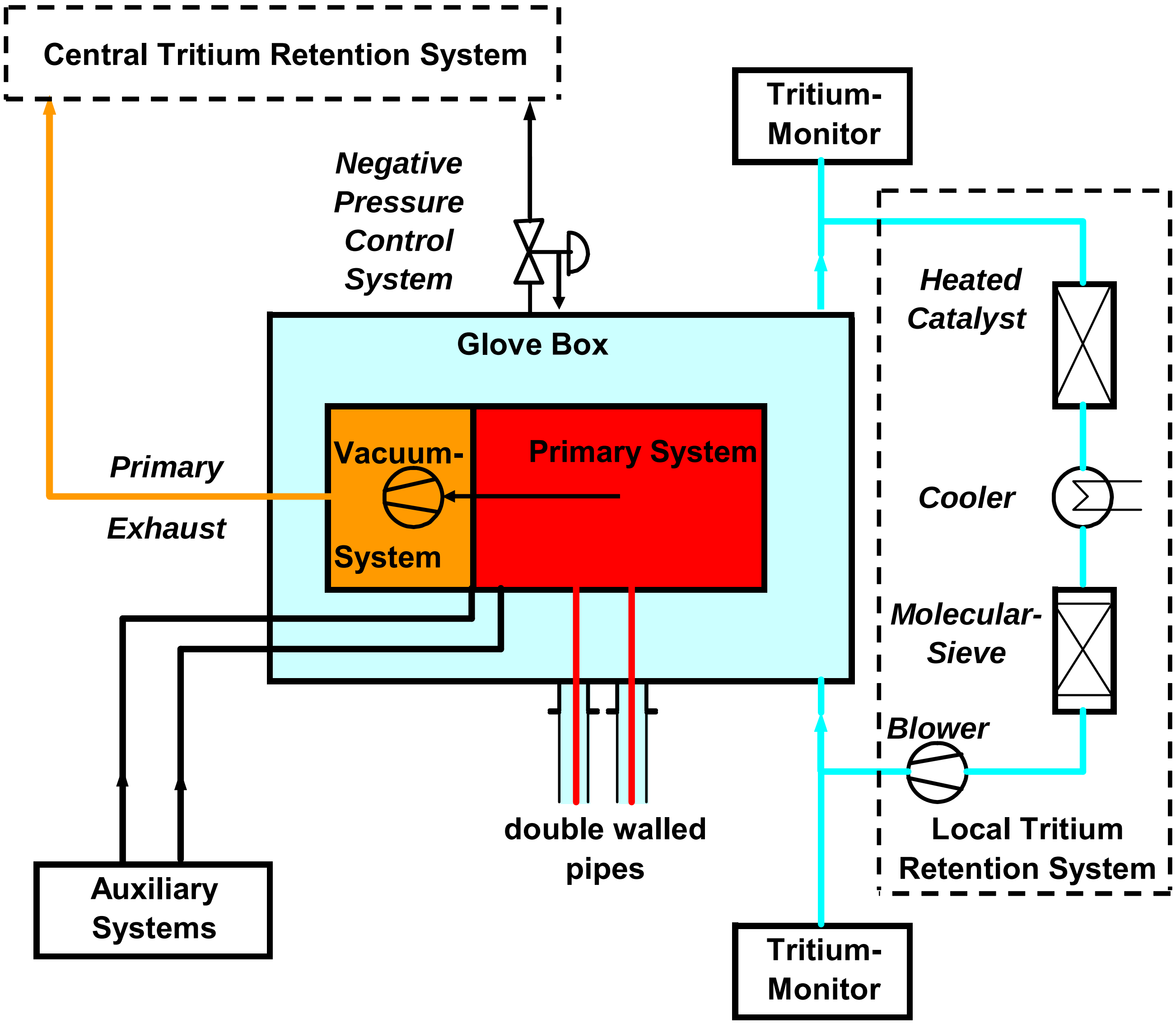
Primary and Secondary Confinement

- **Primary System**
  - Single leak rate

  $\leq 10^{-10}$ Pam^{3}s^{-1}

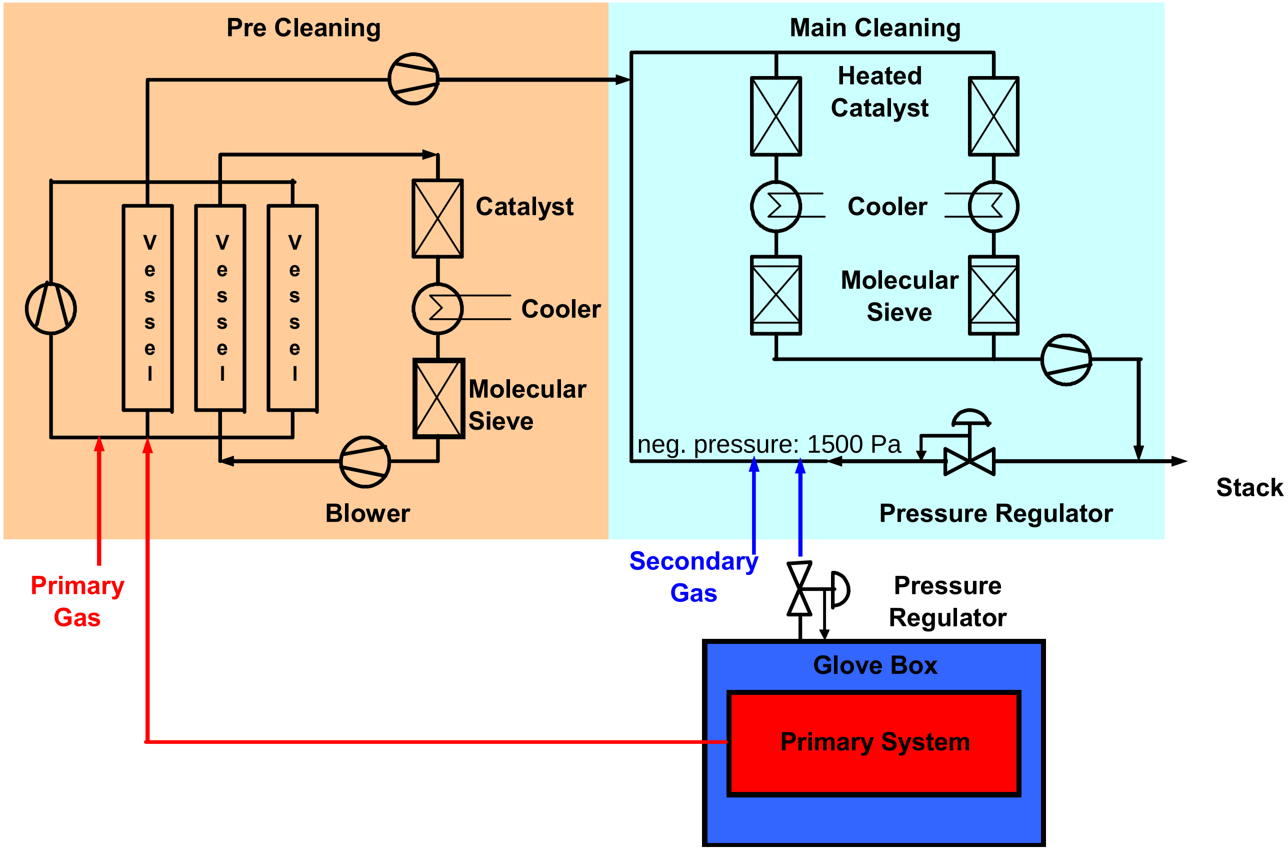
- **Secondary System**
  - Leak rate (glove box)

  ≤ 0.1 Vol%h^{-1}

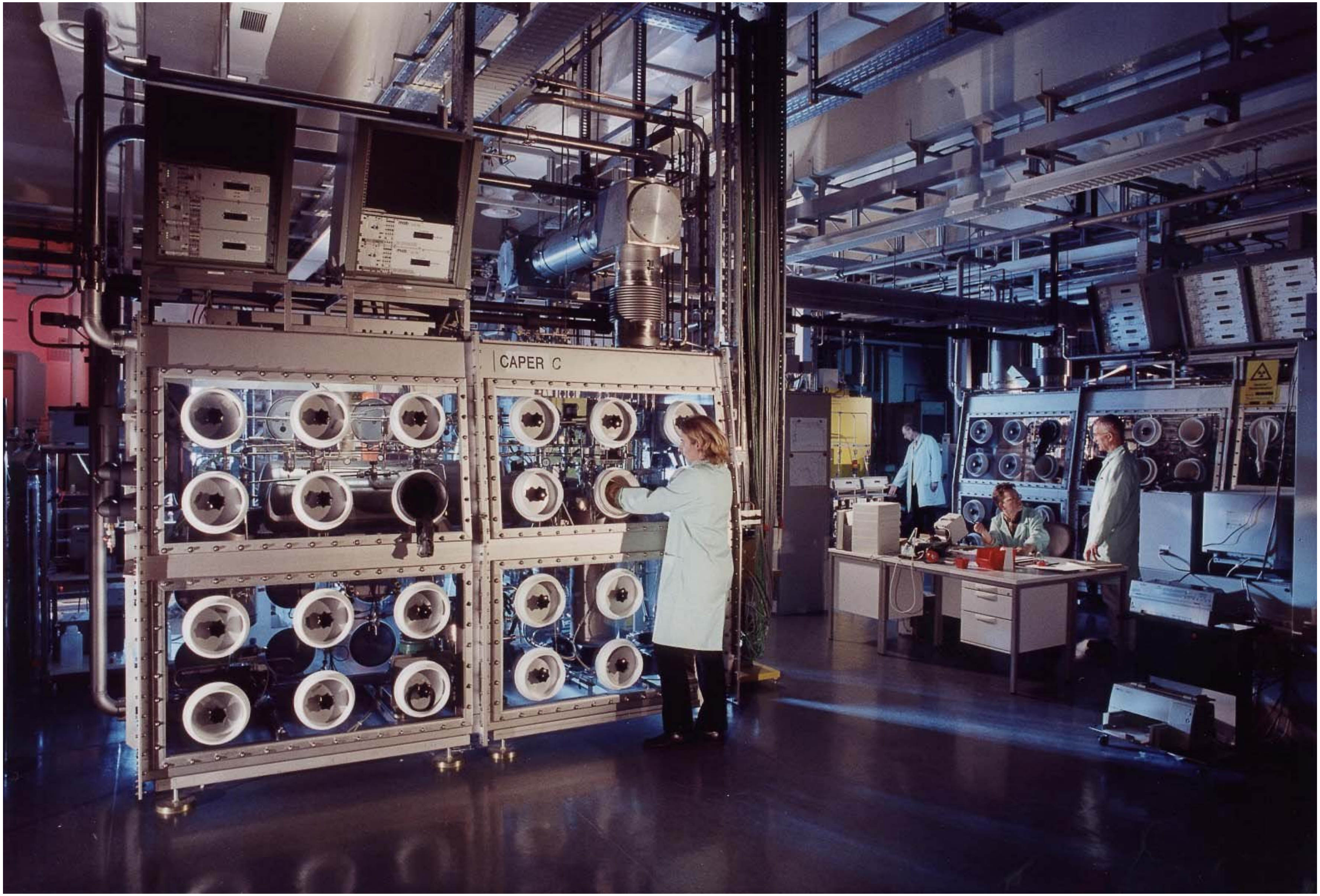


Central Tritium Retention

- Tritium from primary systems (potentially higher tritium concentration) collected in vessels and pre-treated
- Tritium from secondary systems (low tritium concentration) cleaned in once-through
- Tritium burned to water and water collected in molecular sieve beds (molecular sieve beds need to be regenerated)
- Catalyst: CuO, Pd



TLK: Experimental Hall



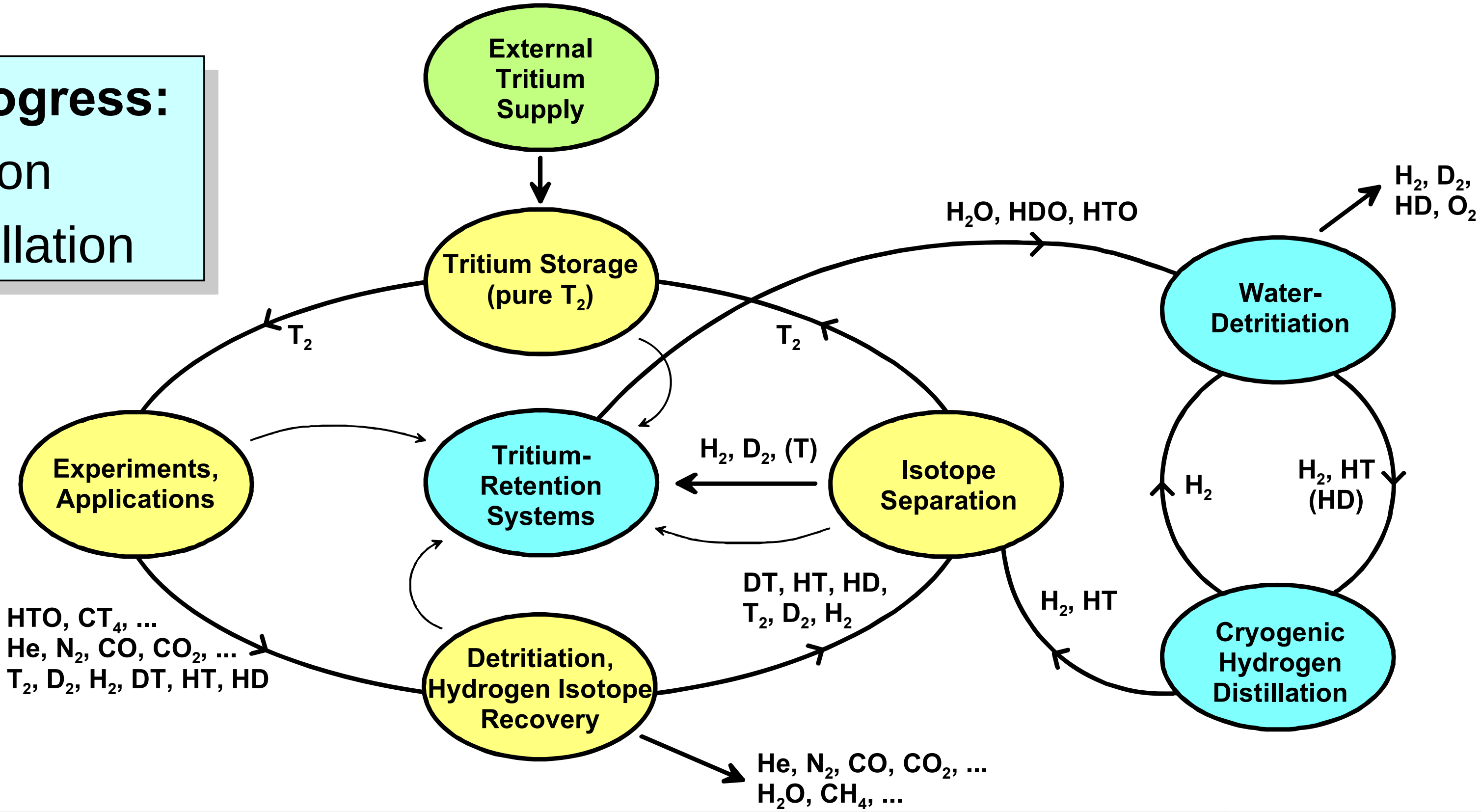
Closed Tritium Cycle at TLK

Existing closed tritium cycle at TLK:

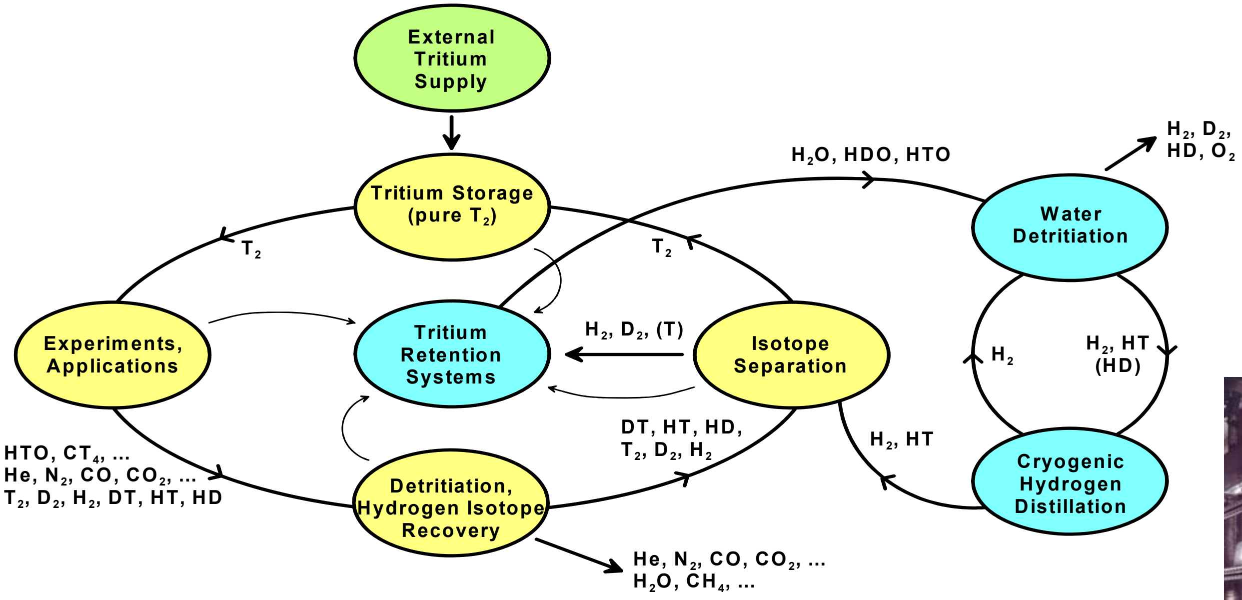
- Tritium storage (10 metal getter beds)
- Plasma exhaust processing (CAPER, detritiation factor 10^6 in T-concentration)
- Isotope separation (enrichment up to >99% tritium purity)
- Analytics (e.g. 3 Calorimeters, 3 GCs, 2 Quadrupoles, Omegatron, IR-spectrometer)

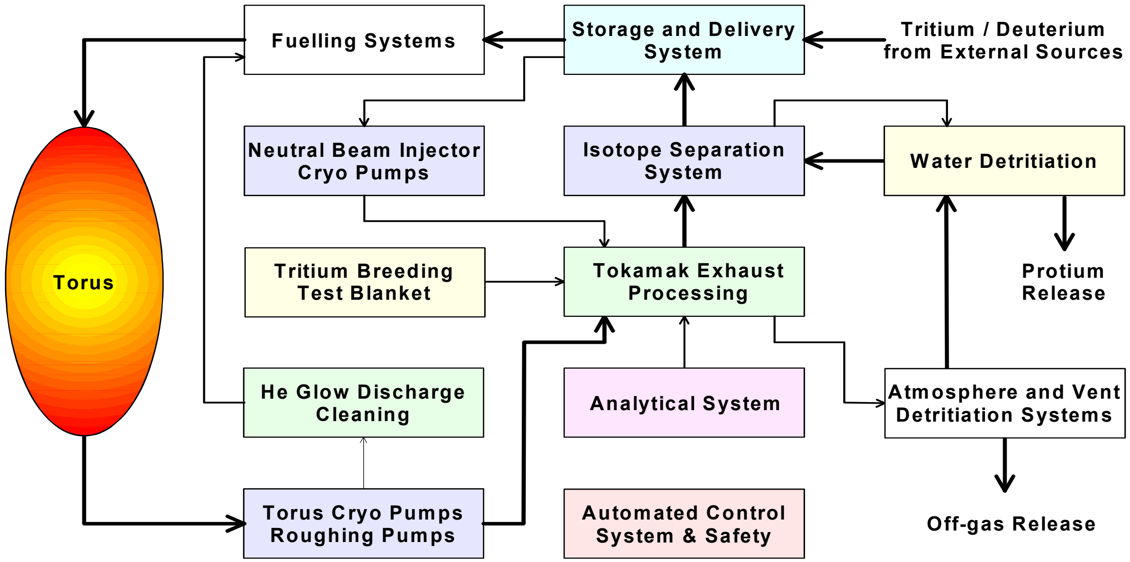
Extension in progress:

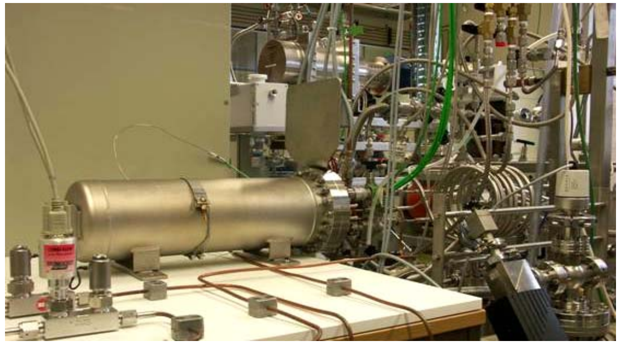
- Water detritiation
- Cryogenic distillation



TLK – Closed Tritium Loop & DT Fuel Cycle





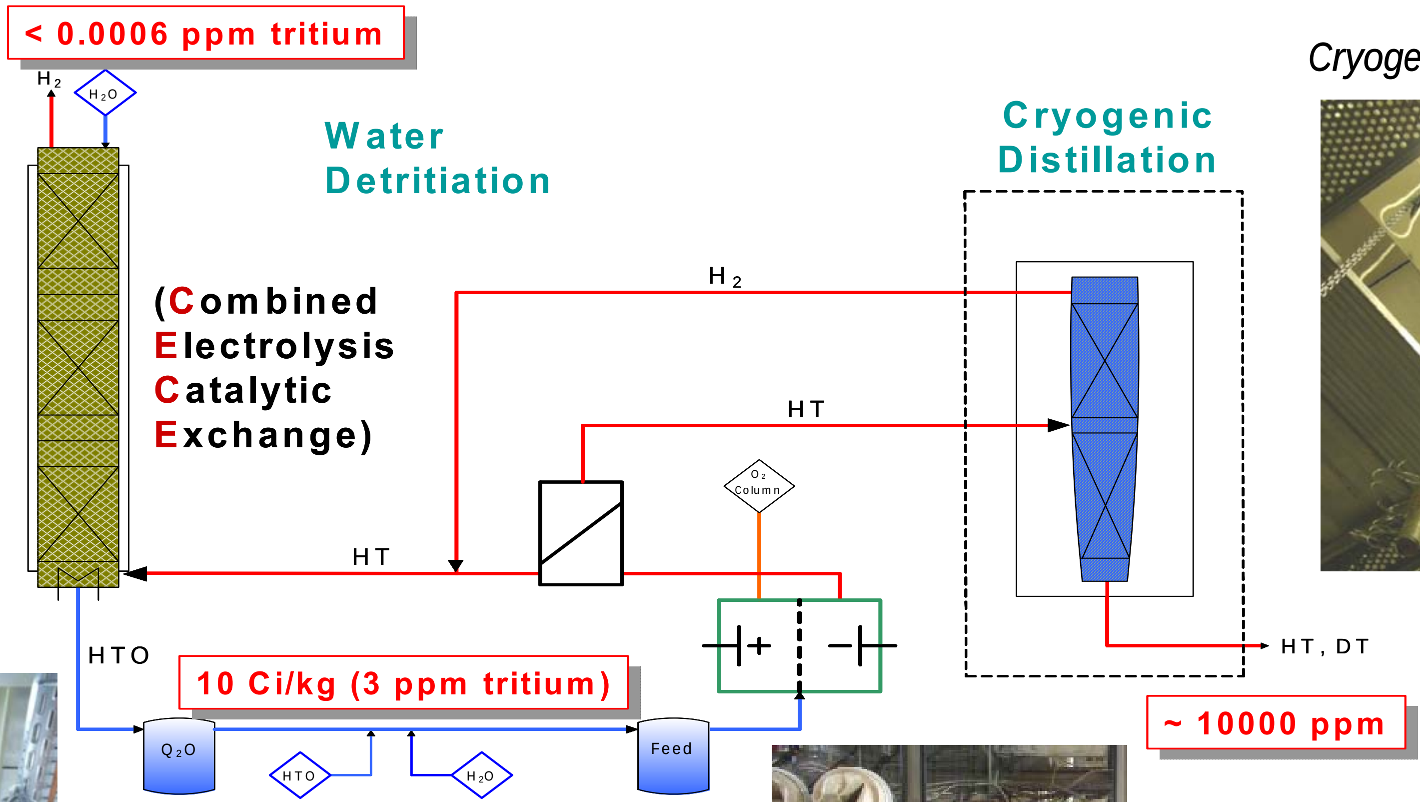


1:1 scale ITER getter bed fast delivery

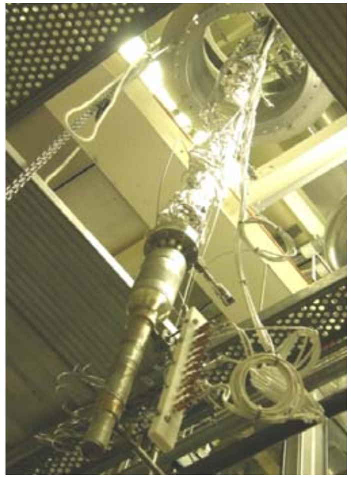
Isotope separation (enrichment up to >99%)

Plasma exhaust processing (CAPRICE / PERMCAT DF > 10^6 in concentration)

TLK – TRENTA for WDS / ISS in ITER (1)



Cryogenic distillation



Liquid Phase Catalytic Exchange column

Electrolyser

EU procurement package for ITER

TLK - Experimental Facility TRENTA at (2)

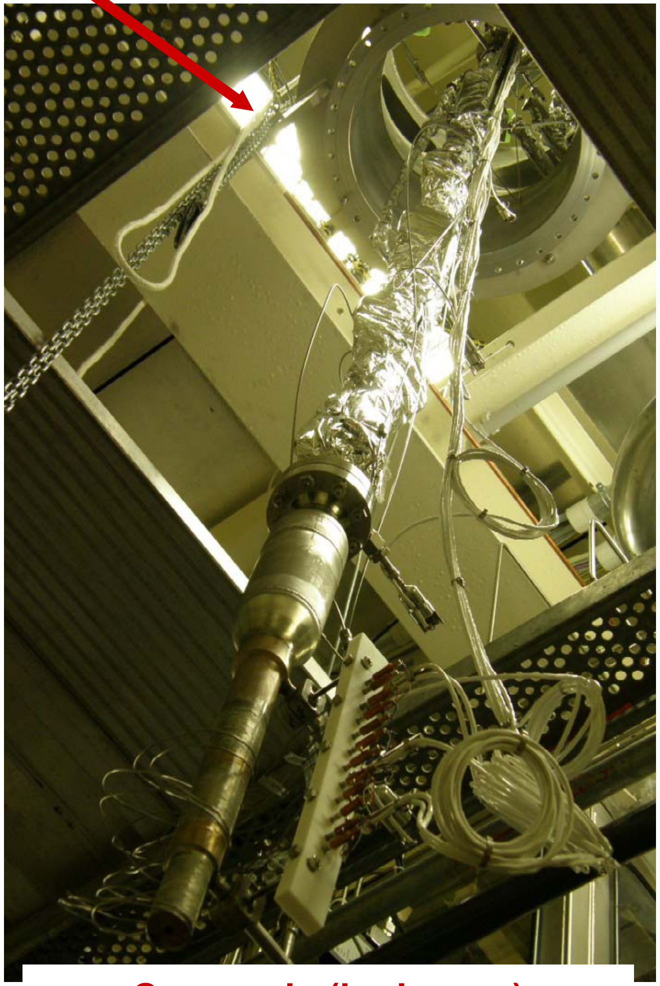
KIT Karlsruhe Institute of Technology

TRENTA: Water Detritiation and Cryo-Distillation

8 m long LPCE Column

2x Electrolyser each 1 m^3/h

CECE-Prozess

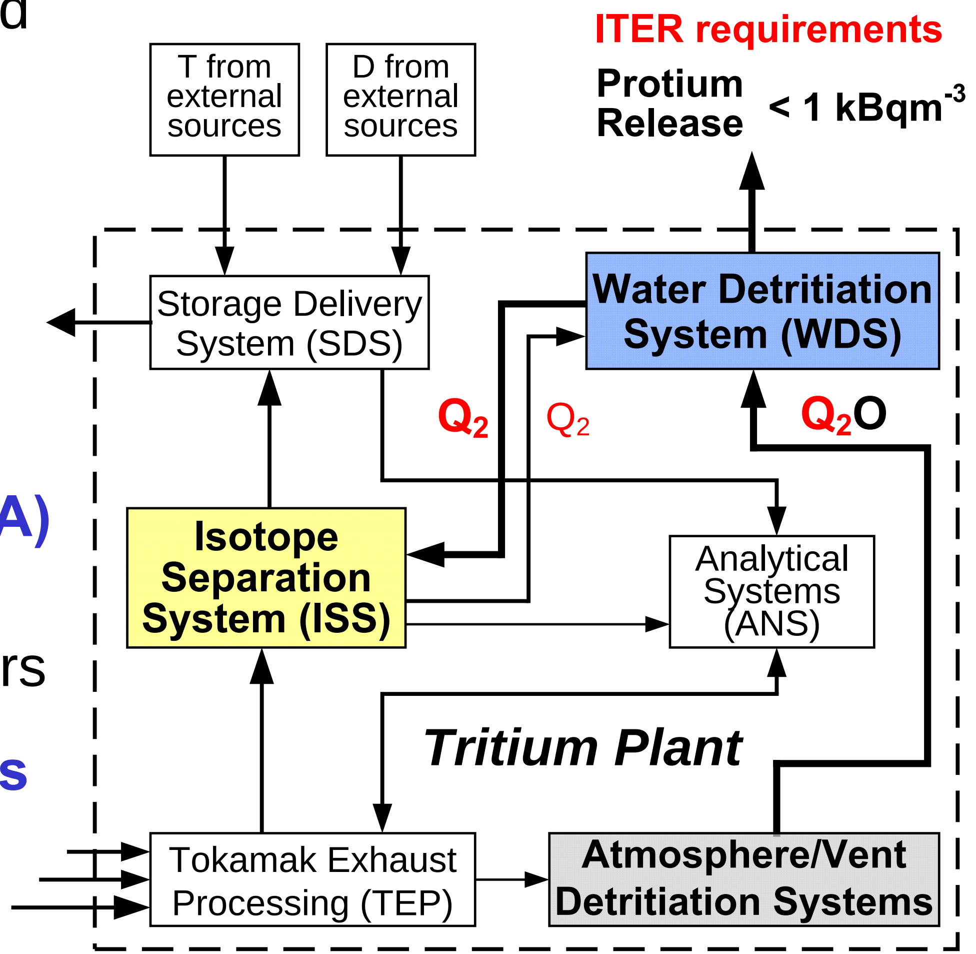


Cryogenic (hydrogen) Distillation Column with 2,7 m separation length

Work at TLK: ITER Planning WDS-ISS

- Procurement Packages of **Water Detritiation System (WDS)** and **Isotope Separation System (ISS)** for ITER given to **EU**
- TLK capable to process tritium in a technical scale and in closed loop as foreseen for ITER
- TLK is setting up a **WDS/ISS (TRENTA)** to demonstrate feasibility and to determine optimum process parameters
- **Design specifications and proposals** in progress

➢ **Final design proposal** for both ITER **WDS** and **ISS**

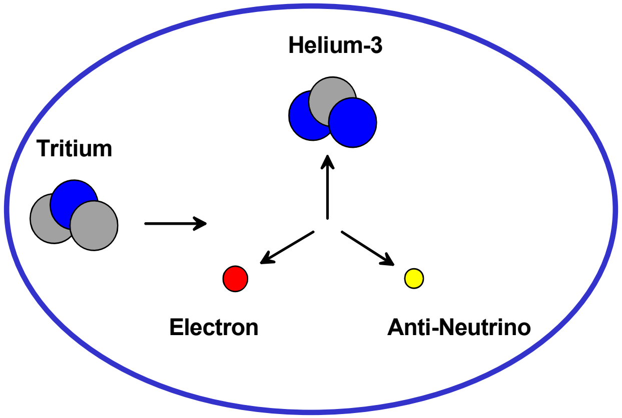


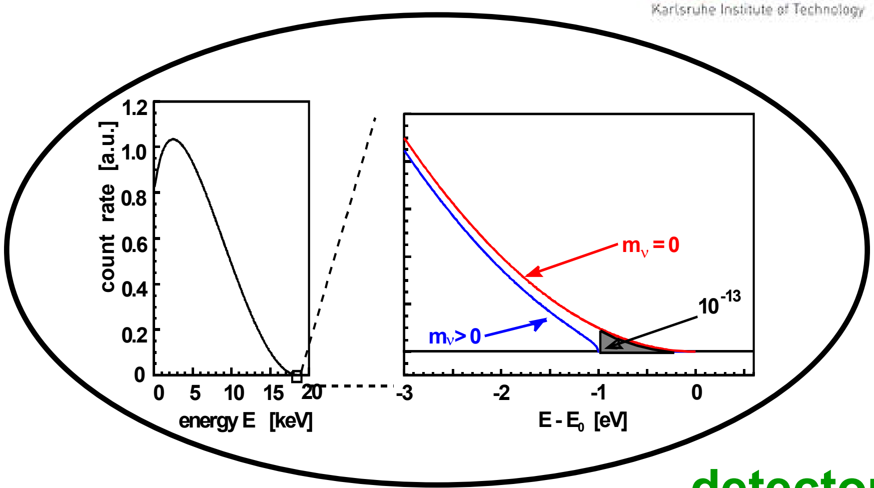
The KATRIN Experiment

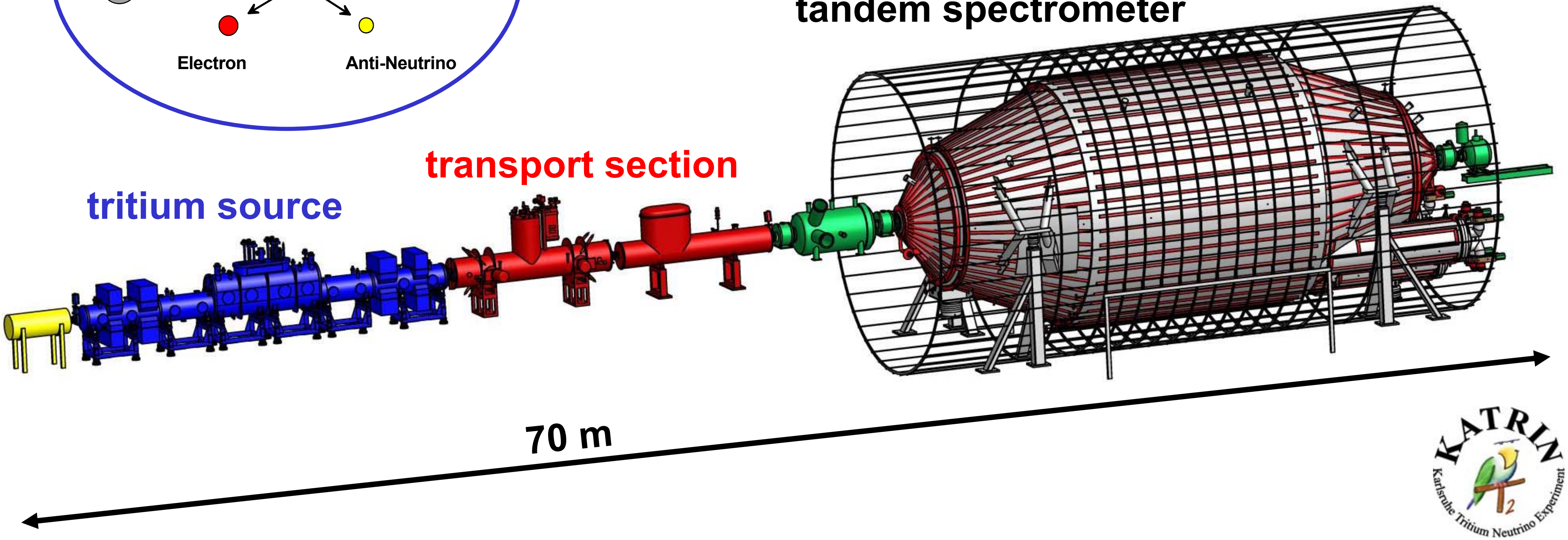
Karlsruhe Tritium Neutrino experiment

Sensitivity on electron neutrino mass 0.2 eV/c²

Measurement of electron energy spectra from tritium ß-decay

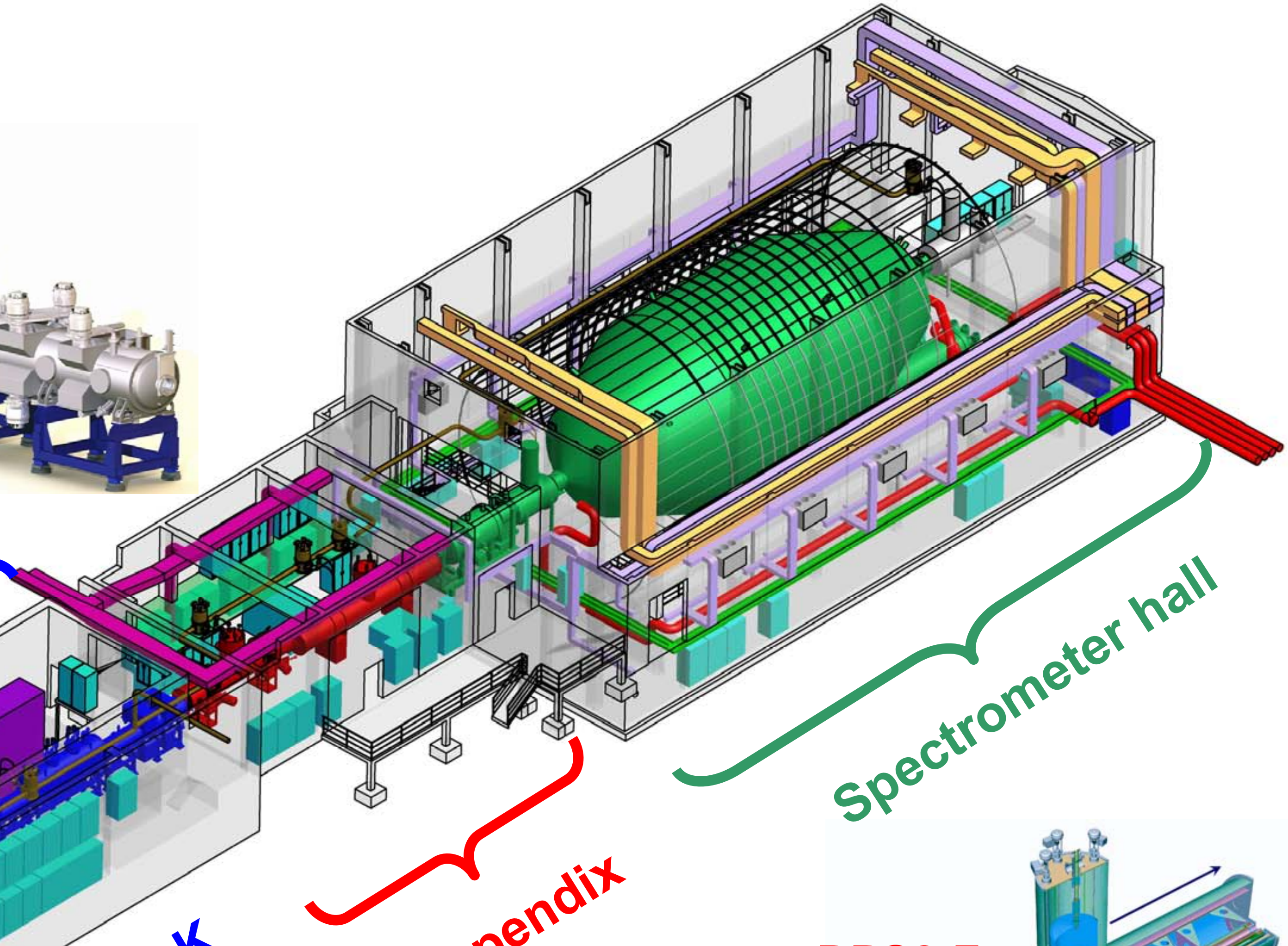




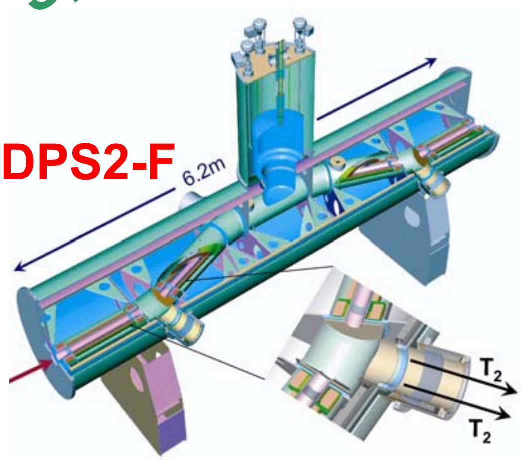


Katrin at TLK

WGTS: Windowless gaseous Tritium Source

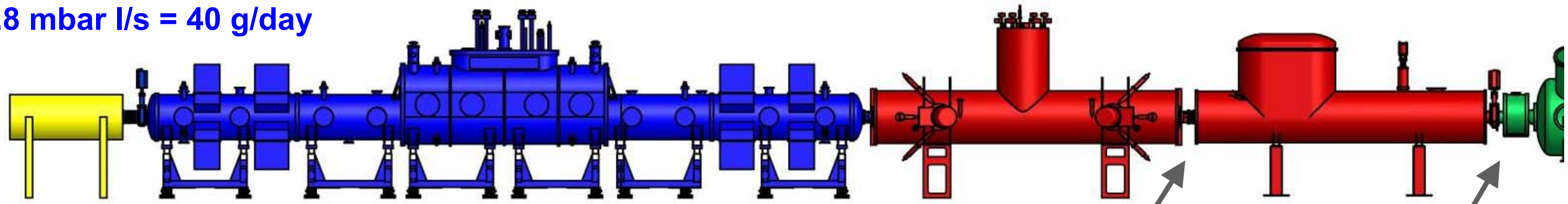


DPS2-F: Differential Pumping Section
CPS: Cryogenic Pumping Section



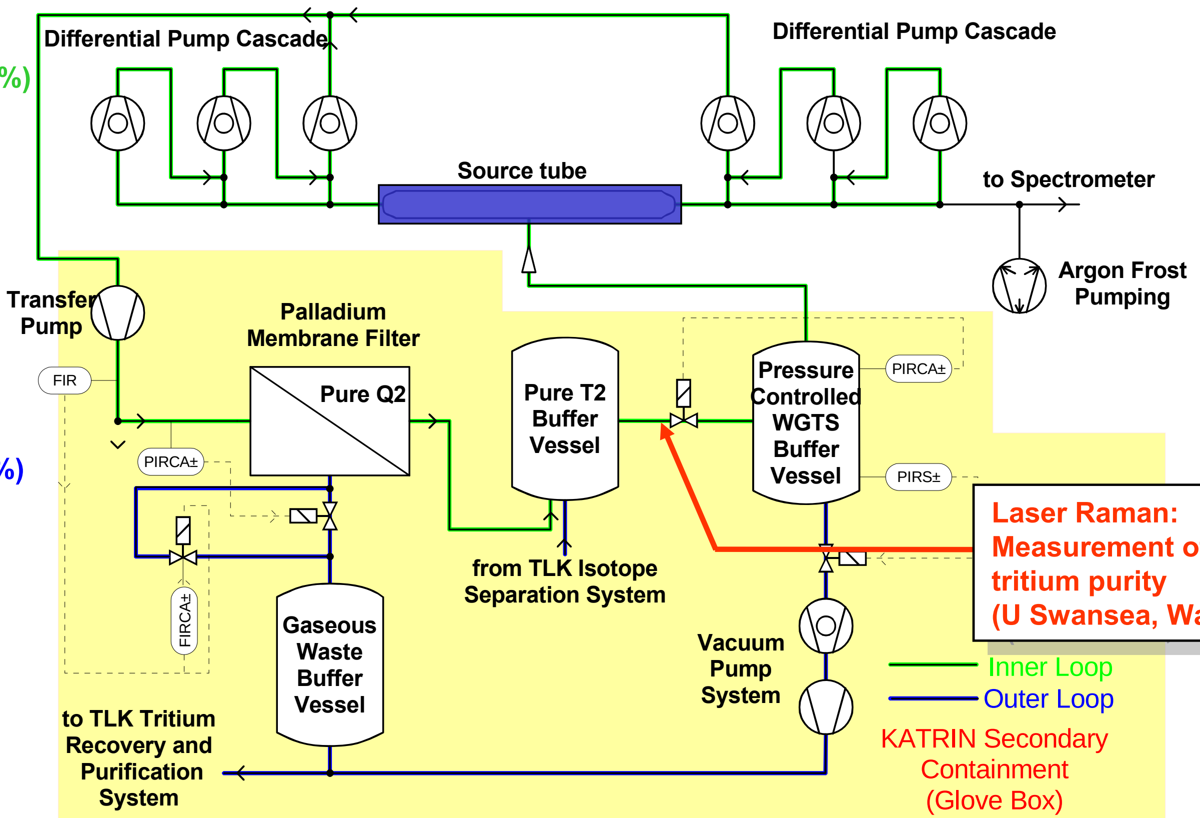
STS = Source & Transport System

required tritium gas injection:
1.8 mbar l/s = 40 g/day

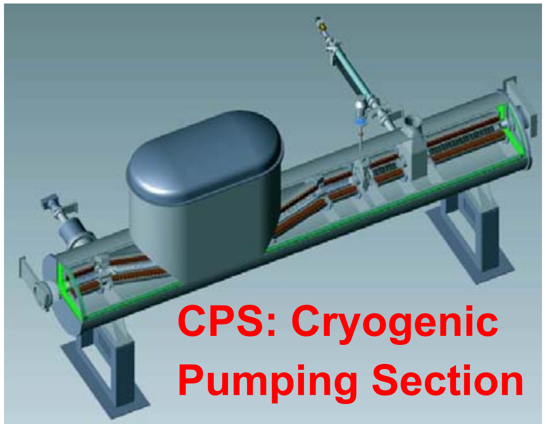


Inner loop:
stable (±0.1%)
tritium
injection

Outer loop:
high (>95%)
and
stable (±0.1%)
tritium
purity



➡ **reduction > 10^{14} by differential pumping and cryopumping**



Summary

- The Fuel Cycle for ITER is well prepared

- The European Tritium Laboratory Karlsruhe has contributed very much to the development of the fuel cycle of a fusion reactor