# Tritium Technologies of ITER and DEMO breeding blankets

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

A.Ciampichetti

**Current research topics in Nuclear Fusion Engineering**

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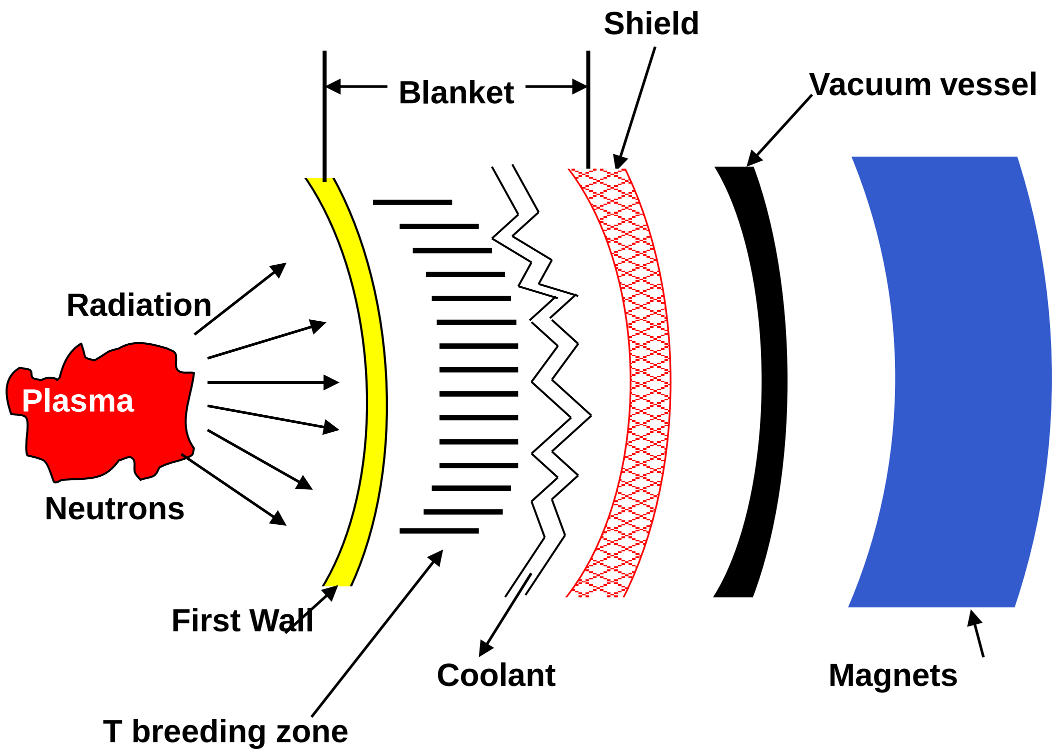
# Outline

- Introduction
- Some Tritium properties
- DT Fuel Cycle in ITER and DEMO
- Systems of the DT Fuel Cycle in ITER
- DEMO blanket Fuel Cycle
- Tritium Systems in TBMs
- Summary

# Introduction

## Functions of the Breeding Blanket

- Tritium breeding for tritium self-sufficiency
- Nuclear to thermal power conversion
- Neutron/γ-ray shielding



# Introduction

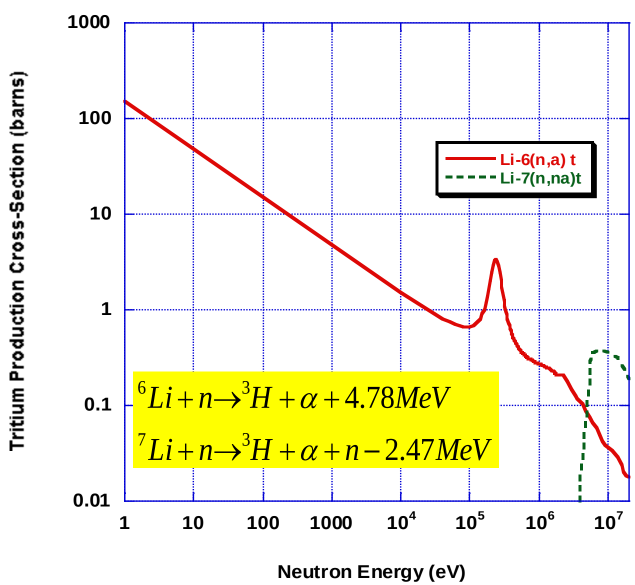
## Blanket: tritium breeding

**Important blanket performance parameter:** $TBR = \frac{\text{Tritium generated per unit time}}{\text{Tritium burnt per unit time}}$

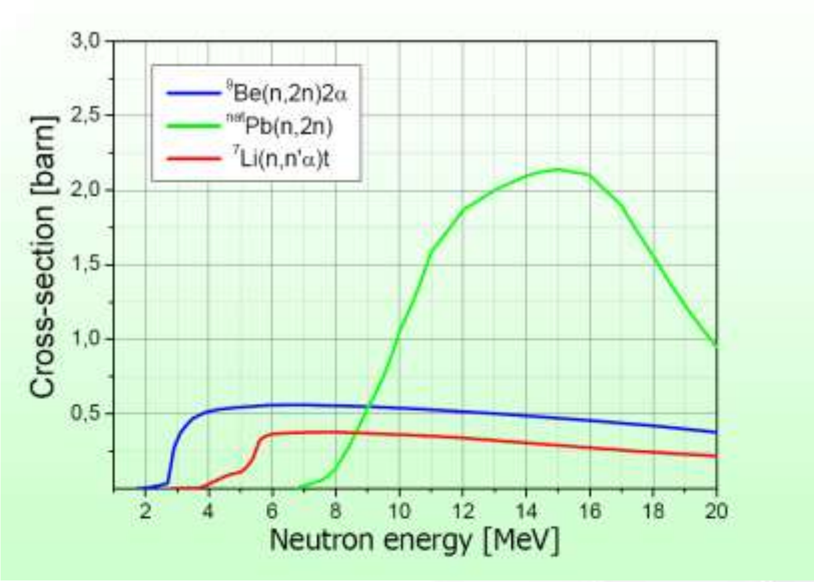
**How to reach a TBR> 1?**

a) by Li-n reactions
b) by neutron multiplication
c) by reducing the n-parasitic capture

**a) T breeding reactions by Li-n interaction**




**b) Neutron multiplication**

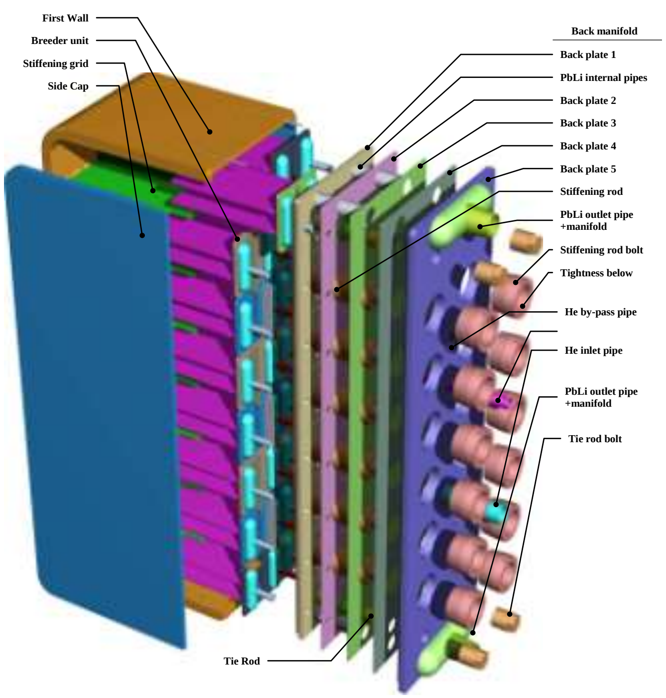


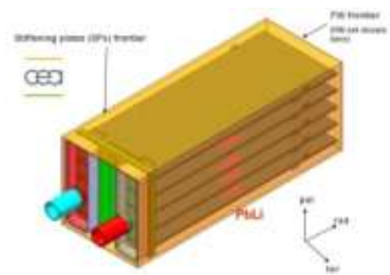

Natural lithium contains 7.42% $^{6}$Li and 92.58% $^{7}$Li

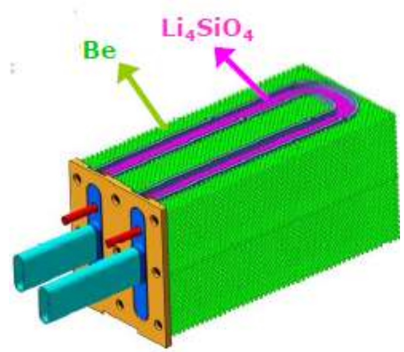
# Introduction

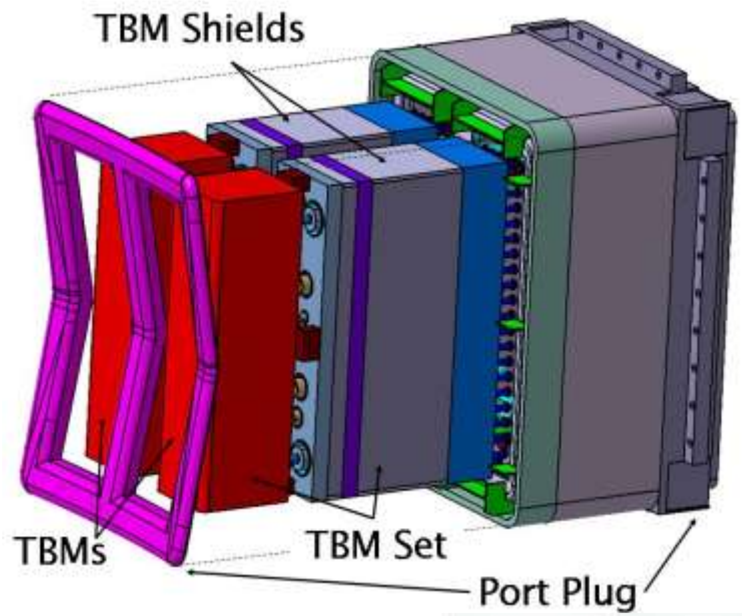
## Test Blanket Modules (TBMs) for ITER

Europe is developing two breeder blanket for DEMO reactor that will be tested in ITER as TBMs: the HCLL concept, where eutectic Pb-15.7Li acts as breeder and neutron multiplier, and the HCPB concept where lithiated ceramic pebbles ($Li_4SiO_4$ or $Li_2TiO_3$) are used as tritium breeding material and Be pebbles as neutron multiplier.



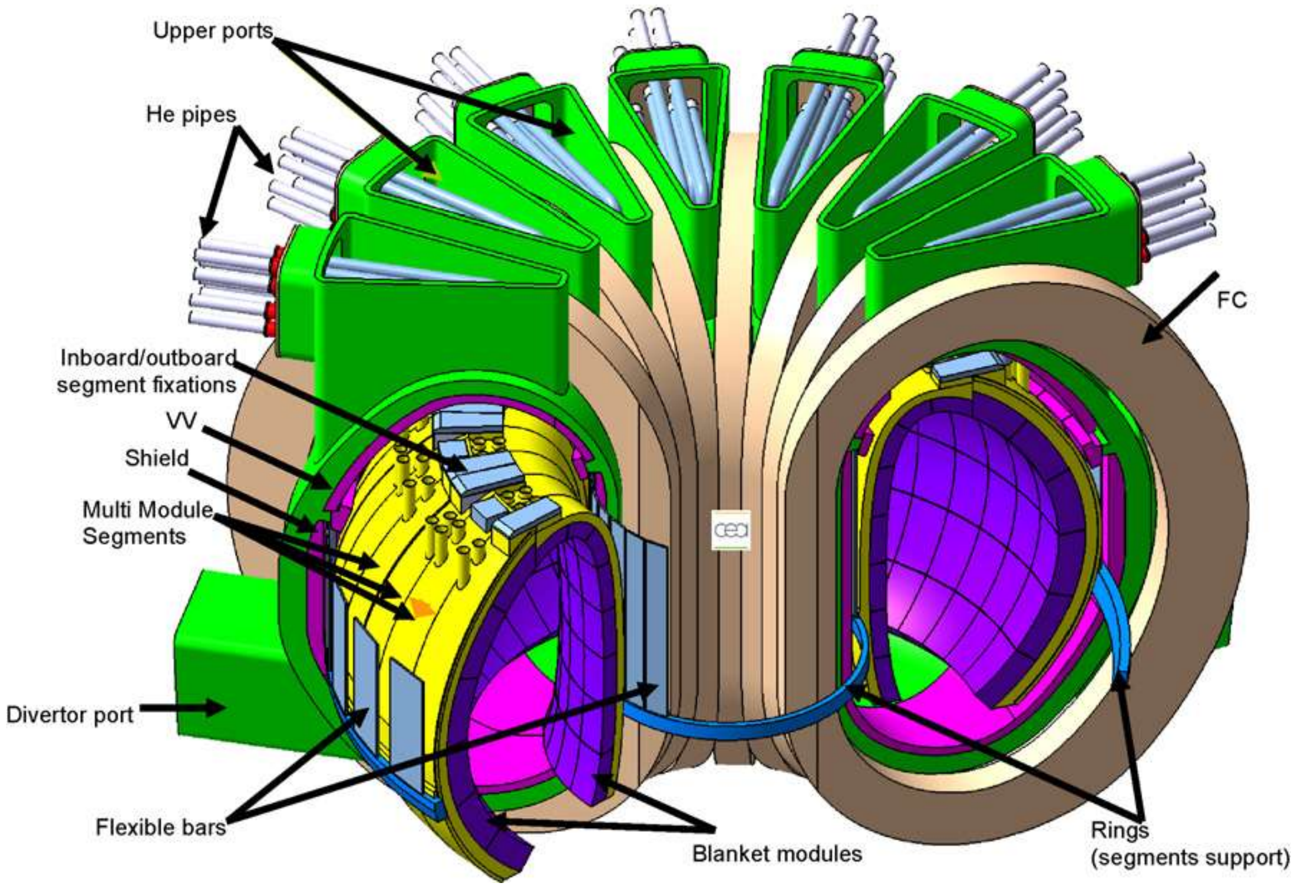



# Introduction

## Breeding Blanket in a Fusion Reactor

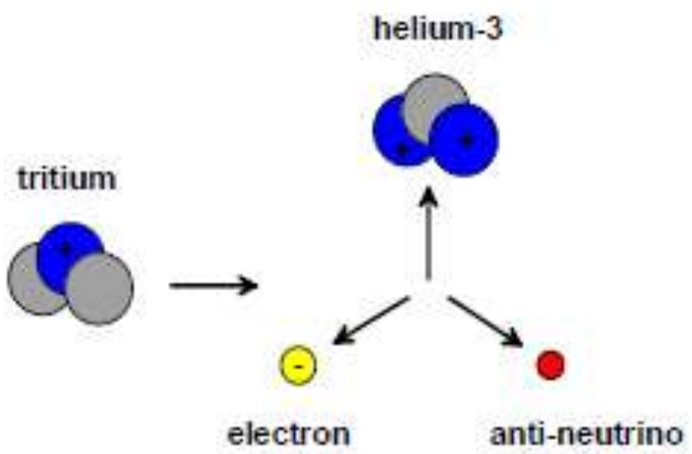


# Some Tritium properties

- Tritium is a weak β emitter ($E_{ave}$ = 5.7 keV)
- Its half life is 12.25 y
- The specific activity is about 10000 Ci/g

(1 Ci = 3.7 $10^{10}$ Bq)

- The decay heat is 324 mW/g




Tritium may be essentially found in the environment in two forms: HT (tritiated hydrogen) or HTO (tritiated water). HTO, in particular, is a dangerous compound, because of its high solubility into human body fluids. In fact, its Annual Limit of Intake (ALI) is about 10 µg for personnel and 1 µg for population (i.e., one microgram of HTO is sufficient to cause, in case of intake, an internal exposure sufficient for a dose equivalent commitment equal to the annual limit defined by law).

# Some Tritium properties

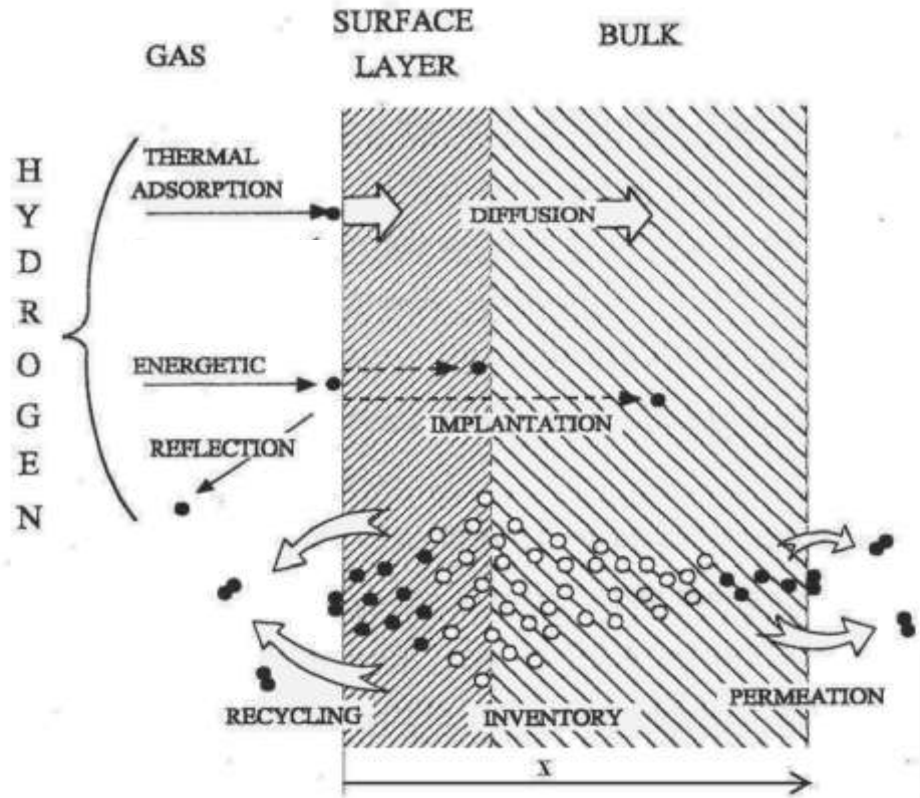
## Hydrogen-metals interaction

The thermal hydrogen molecules that are adsorbed by the metal surface dissociate into constituent atoms. These atoms can diffuse through the bulk of the solid or back towards the front surface. When hydrogen atoms reach the front surface (recycling) or the back surface (permeation), before leaving the solid, they must recombine into molecules (recombination).

Two kinds of processes:

Surface Processes: adsorption, dissociation recombination and desorption.

Bulk Processes: interstitial diffusion caused by concentration gradients, thermo-migration and trapping at defects.



# Some Tritium properties

## Diffusion-limited permeation

The permeation flux [mol m-2 s-1] can be expressed as:

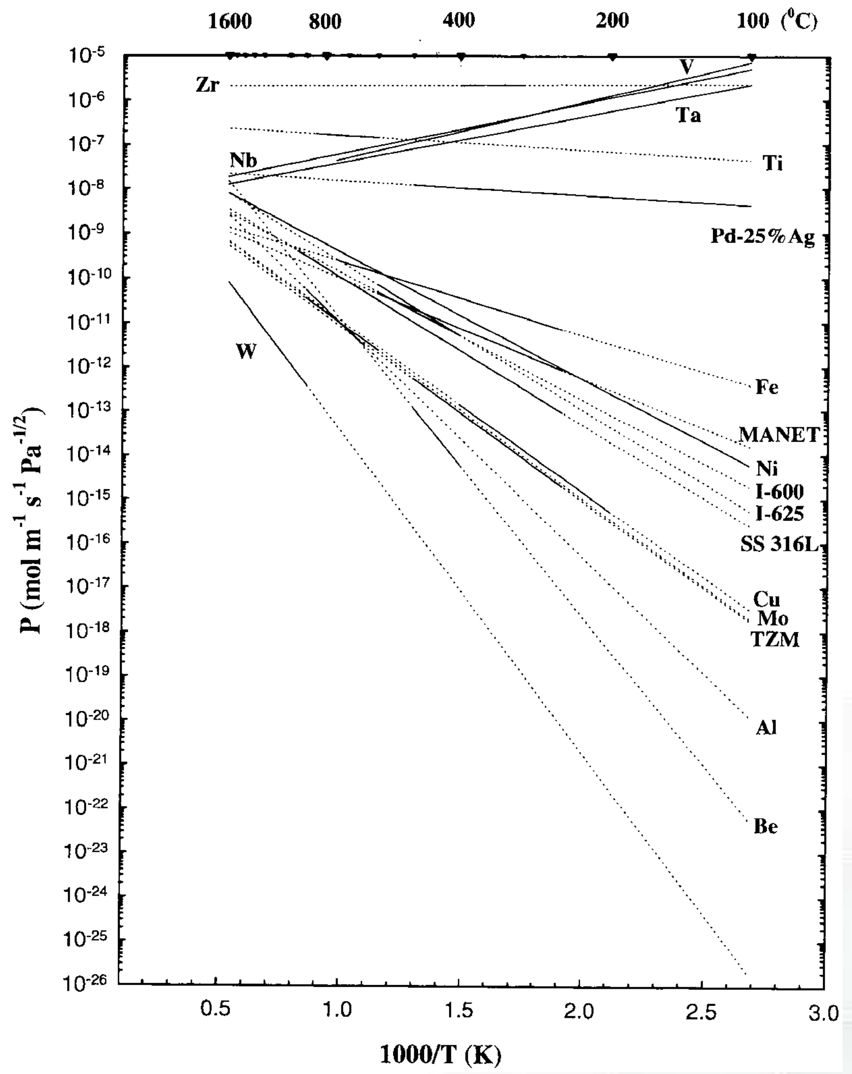
$$J = \frac{P}{d} \cdot (p_1^{0,5} - p_2^{0.5})$$

known as Richardson's Law, where:

P = $K_s$D [mol m-1 s-1 Pa-0.5] is defined as the permeability of the material;

d is the thickness of the membrane;

p1 and p2 are the hydrogen partial pressure in the front and back side of the membrane.



# Some Tritium properties

## Tritium in fusion reactors

Tritium represents one of the main radiological hazards of fusion reactors and its presence inside these machines constitutes a safety concern for personnel, population and the environment.

In ITER the main source of tritium accumulation will come from the adsorption on PFCs, while permeation phenomena through the structural materials represent a minor concern in terms of safety.

For DEMO the safety issues include both the tritium retention in the PFCs and the permeation phenomena. The latter ones may be divided into the tritium permeation through the first wall material and the permeation from the breeder to the coolant. During the normal operation of the reactor, they are the mains responsible of tritium release to the environment.
The minimisation of tritium releases in accordance to the ALARA (As Low As Reasonably Achievable) principle is one of the key safety issues for fusion reactors. In fact, for both safety and economic reasons, as much tritium as possible must be recovered inside the plant for reuse within the tritium fuel cycle.

# DT Fuel cycle in ITER and DEMO

## Reactors Parameters impacting the fuel cycle

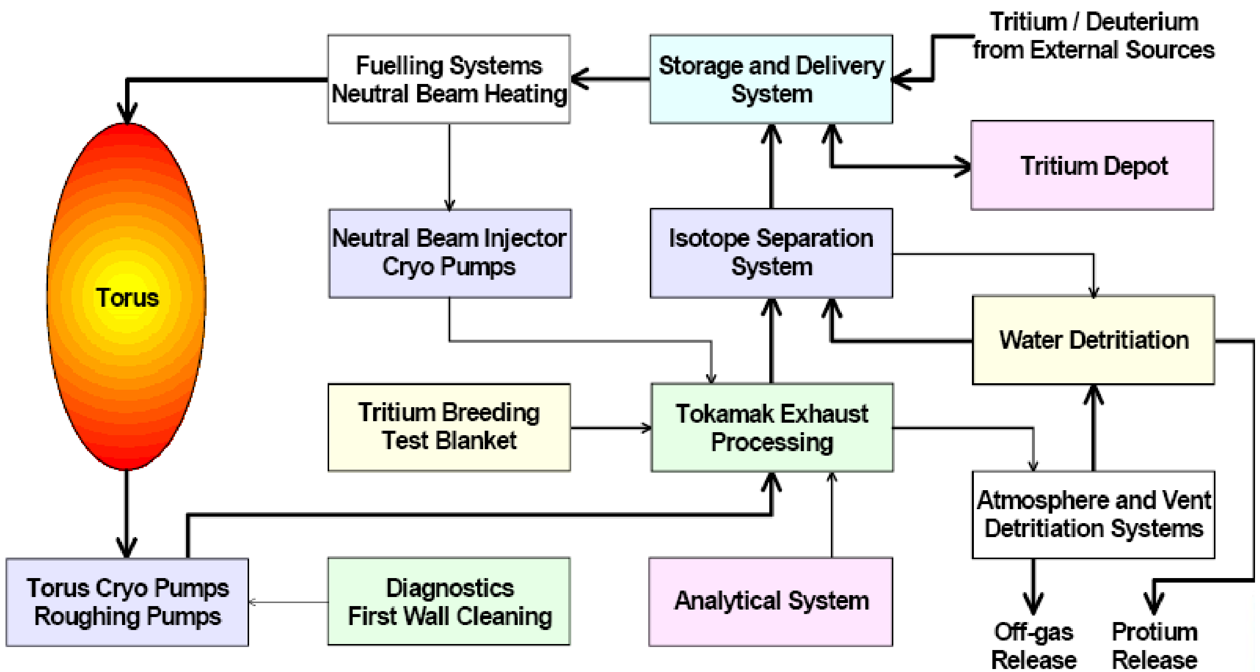
| | ITER | PPCS-B |
|---|---|---|
| Fusion Power | 0.5 GW | 3.6 GW |
| Electrical power | -- | 1.5 $GW_{el}$ |
| Tritium burn-up | 18 g/d* | 500 g/d |
| DT fueling rate | 120 $Pam^3/s$ | ~300 $Pam^3/s$ |
| Tritium breeding rate | ~ 1.2 µg/s<br>~ 25 mg/d* | ~6.4 mg/s<br>~550 g/d |

*continuous daily sequence of standard pulses (repetition time of 1800 s)

**Despite the 7 times larger fusion power than in ITER, only 2.5 times higher fueling rate was expected in PPCS-B due to higher burn-up efficiency.**

# DT Fuel cycle in ITER and DEMO

## Architecture of the Fuel Cycle in ITER

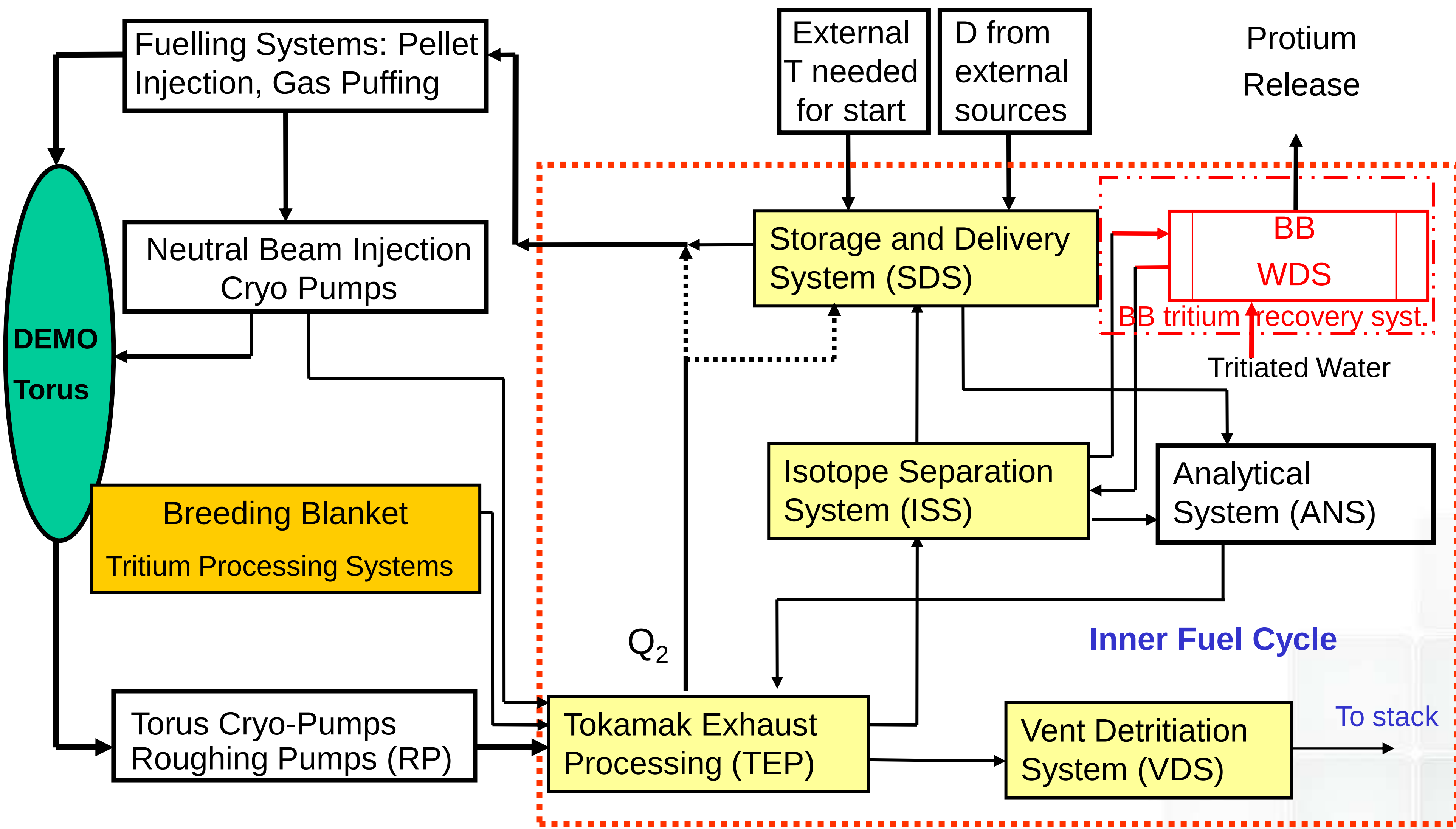



### MAIN FUNCTIONS

- Storage/delivery of tritium from/to tokamak device (SDS)
- Recovery of Q (H,D,T) from different gas streams (TEP)
- Separation of pure Q streams into Q streams of specified composition for refueling
- Final detritiation before gas release into environment

# DT Fuel cycle in ITER and DEMO

## Architecture of the Fuel Cycle in DEMO



# DT Fuel cycle in ITER and DEMO

## Comparison between fuel cycle in ITER and DEMO

**Tokamak Exhaust Processing System (TEP):**

**The DEMO TEP will be moderately bigger in size than ITER TEP. The contribution from Breeding Blanket in terms of T load becomes important.**

**Isotope Separation System (ISS):**

**DEMO ISS will be similar/smaller than in ITER ISS as most of the recycled $Q_2$ will bypass ISS.**

**Storage and Delivery System:**

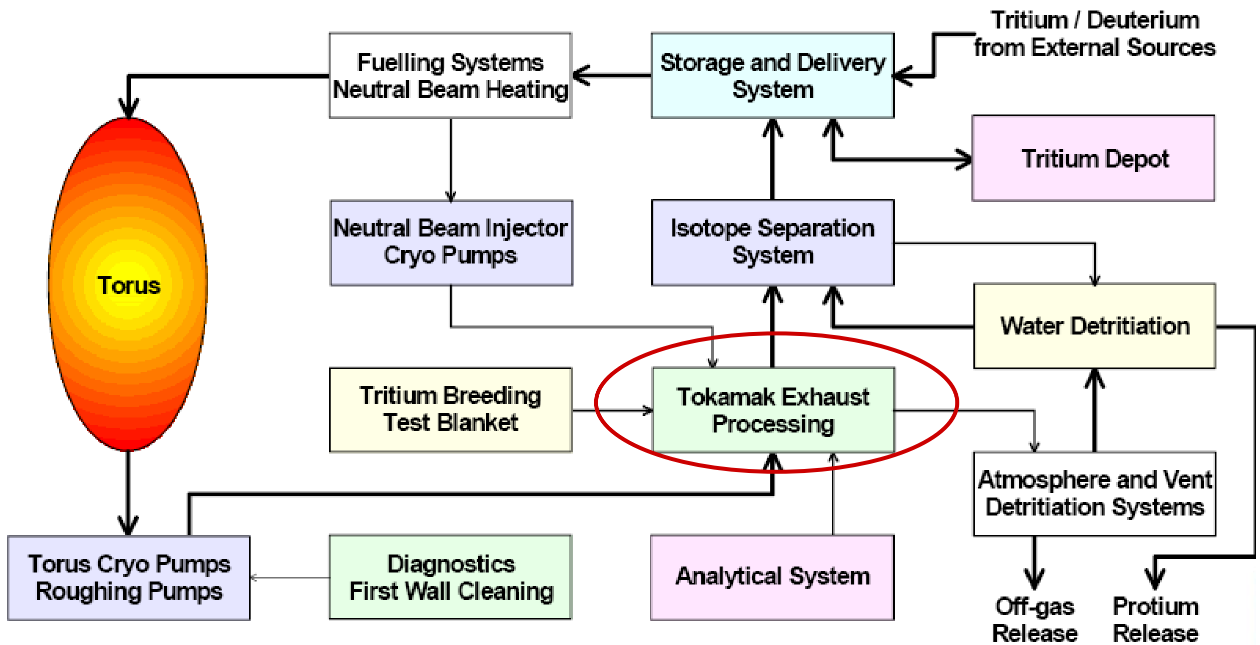
**The tritium and deuterium storage beds could be very similar to the ones of ITER (designed for in-situ calorimetry and high supply rates).**

- **The continuous regime in DEMO will make the inner fuel cycle design and operation simplified compared to ITER**
- **Tritium inventory in the DEMO Fuel Cycle will become more critical**

# Systems of the DT Fuel Cycle in ITER

ENEA AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

## Tokamak Exhaust Processing (TEP), *1/2*



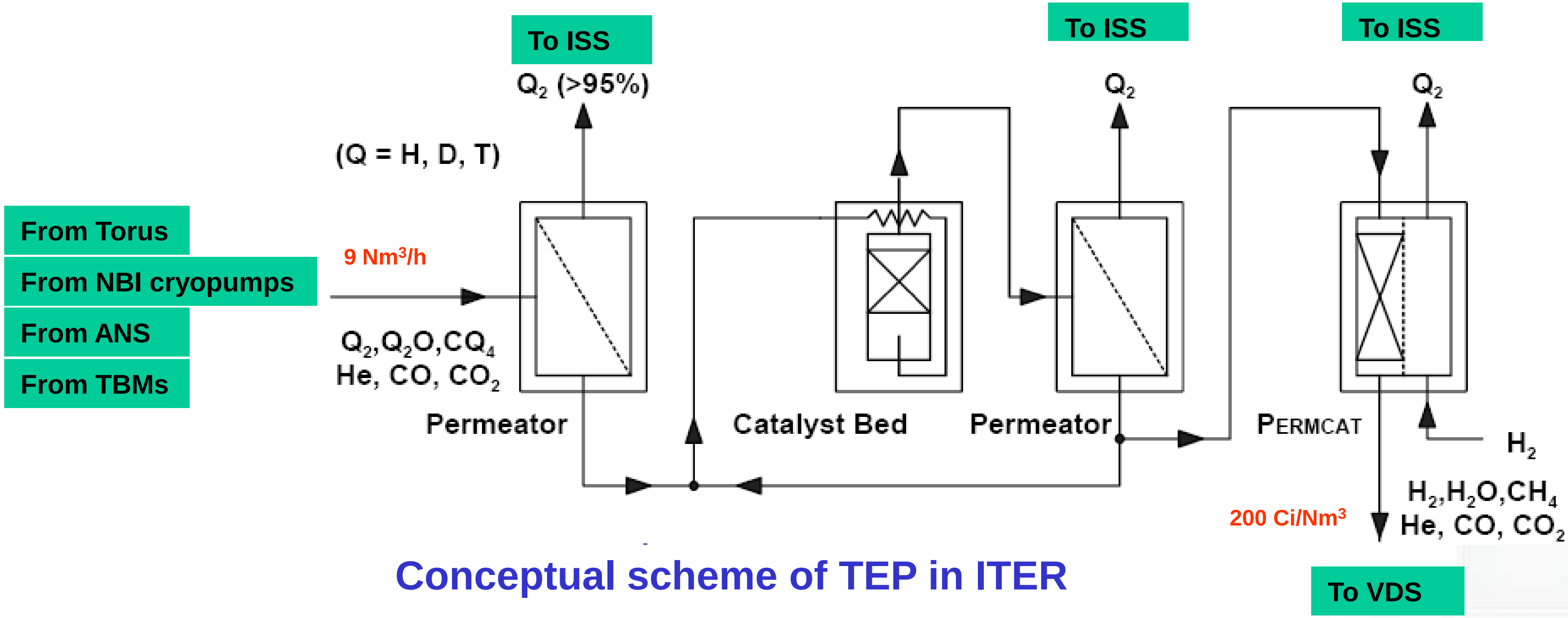

### *Functions*

- To purify Q from impurities
- To extract tritium from tritiated impurities (mainly $Q_2O$ and $C_xQ_y$)
- To discharge into environment the detritiated impurity stream via Vent Detritiation

## Tokamak Exhaust Processing (TEP), *2/2*

### *Adopted Technology*

- selective Pd-Ag permeators
- catalysts to crack hydrogen containing molecules

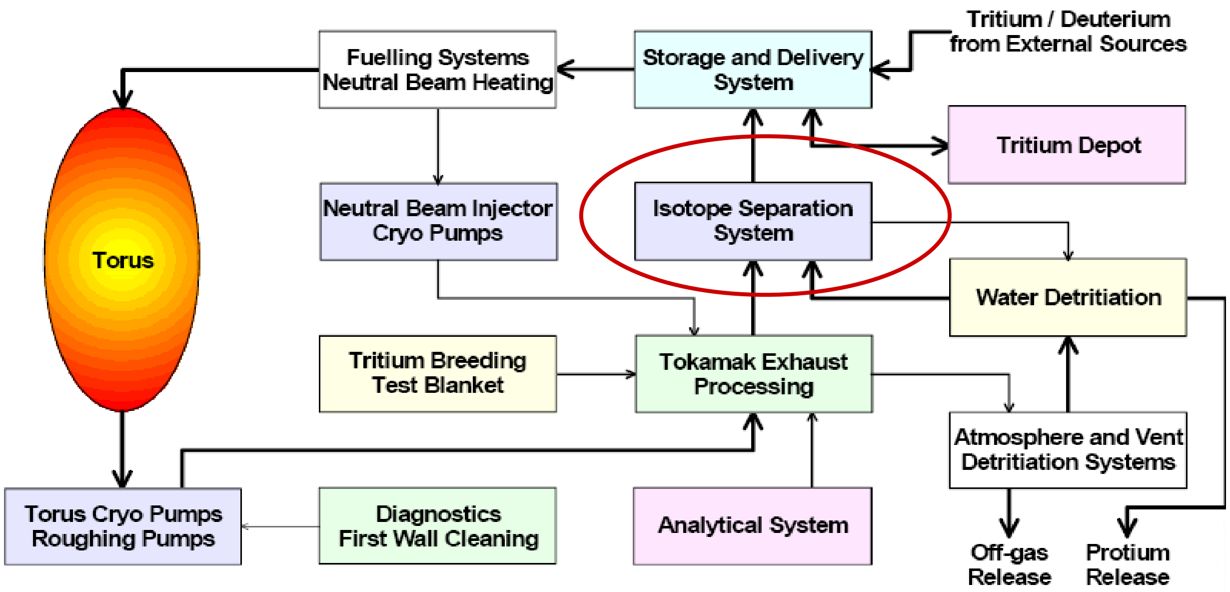



Conceptual scheme of TEP in ITER

**baseline 2001: *currently under modification***

# Systems of the DT Fuel Cycle in ITER

## Isotope Separation System (ISS), 1/2



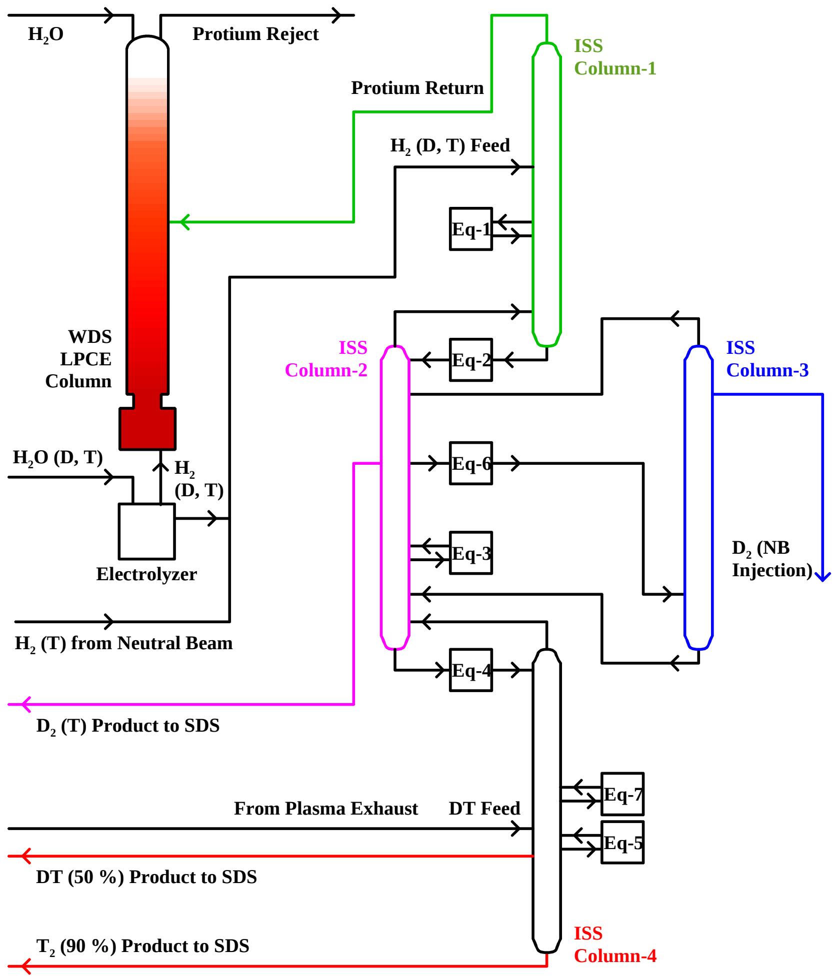

### Function

To produce hydrogen isotope streams with a fixed isotopic composition

# Systems of the DT Fuel Cycle in ITER

## Isotope Separation System (ISS), 2/2

### Adopted Technology: *Cryogenic Distillation*




**ISS utilizes four cryogenic distillation columns to process two feed streams**:

- from WDS and NBI feeding the column 1 (around 8 Nm$^3$/h)
- from TEP (around 7 Nm$^3$/h)

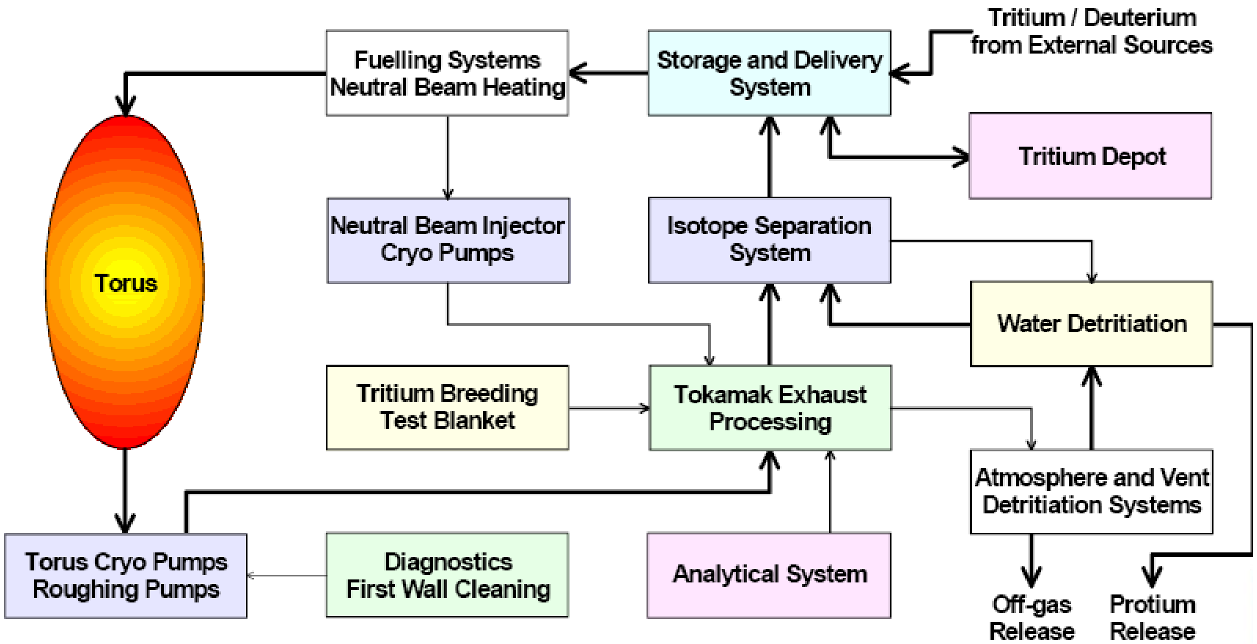
**ISS produces five product streams**

- T (90% of purity) for refueling
- DT (50%) mixture T for refueling
- D contaminated with T for refueling
- D at high purity for NBI
- Pure H to Water Detritiation System

**baseline 2001:** *currently under modification*

# Systems of the DT Fuel Cycle in ITER

## Storage and Delivery Systems (SDS), 1/2




### Functions

- Storage of Isotope Separation System product streams from ISS
- Release of Isotope Separation Systems for Fuelling
- Tritium accountancy by pVT-c measurements & calorimetry

## Storage and Delivery Systems (SDS), 2/2

### Technology adopted: *Metal Hydride Bed*

- **Zirconium-cobalt, although very promising, was found to suffer the problem of dis-proportionation with consequent tritium trapping**

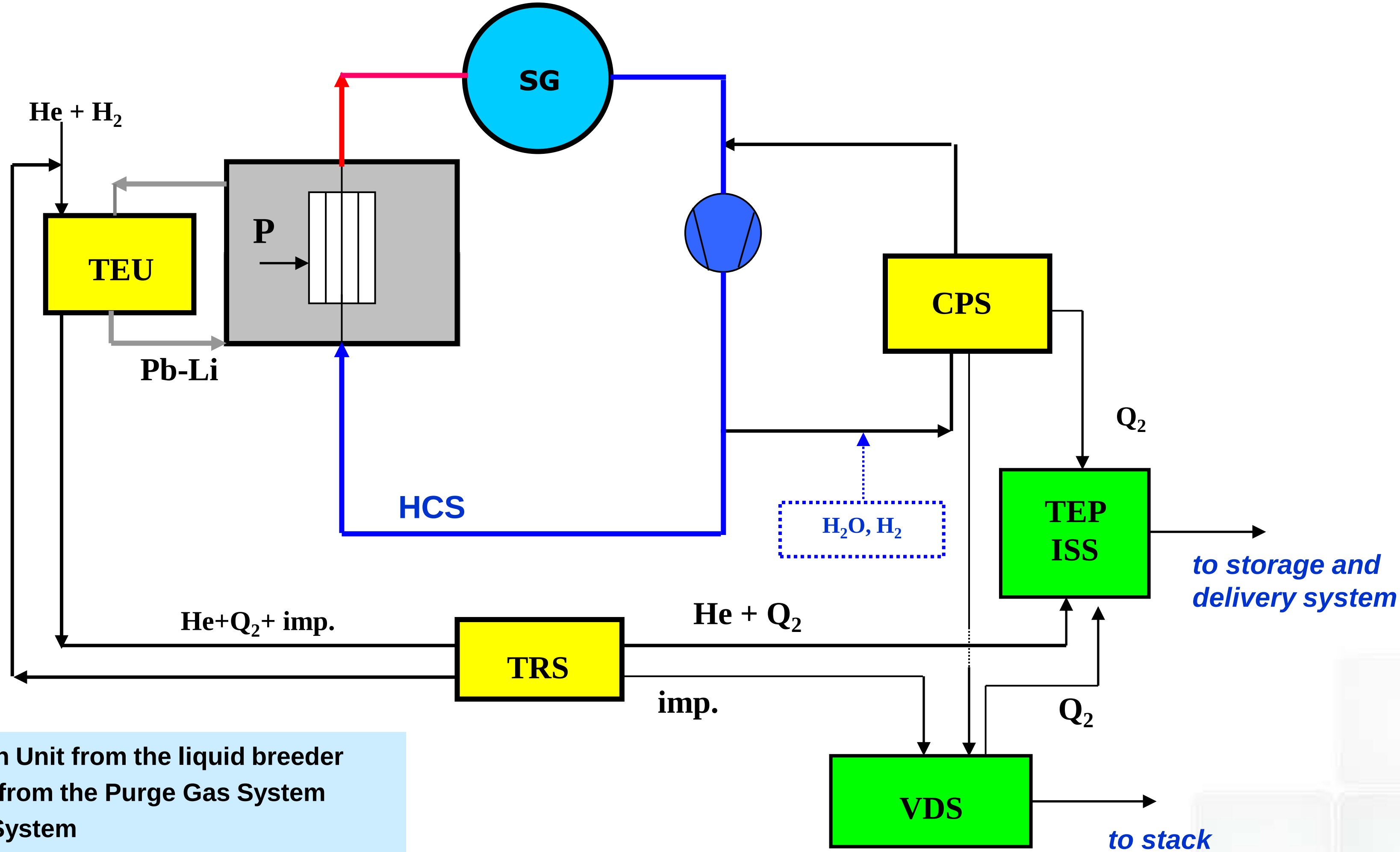
$$2\ ZrCoT_x \rightarrow ZrCo_2 + ZrT_2 + (x - 1)\ T_2$$

- **Although pyrophoric, Uranium still appears a suitable material:**
  - defined stoichiometry ($UT_3$): no problems of tritium trapping
  - equilibrium pressure < 1 Pa at RT: safe storage
  - equilibrium atmospheric pressure at only about 430 ºC: liberation of hydrogen isotopes under moderate conditions

# DEMO blanket Fuel Cycle

## ***HCLL blanket fuel cycle***

Q= H,D,T




**TEU**: Tritium Extraction Unit from the liquid breeder
**TRS**: Tritium Removal from the Purge Gas System
**HCS**: Helium Cooling System
**CPS**: Coolant Purification System
**ISS**: Isotope Separation System
**TEP**: Tokamak Exhaust Processing
**VDS**: Vent Detritiation System
**SG**: Steam Generator

# DEMO blanket Fuel Cycle

**Different problems associated to the tritium cycle in PbLi based blankets**

1) **Low tritium solubility in Pb-15.7Li → high tritium partial pressure in the breeder → high T permeation rate into HCS → need of a high capacity CPS → feasibility problems**

$$\Gamma_{CPS} = \frac{P}{C_{T,O}\,(1 - \frac{1}{DF})}$$

**where $\Gamma_{cps}$ is the feed flow-rate to be processed by CPS to keep the $c_{TO}$ tritium concentration in He coolant when P is the tritium permeation rate from the breeder into the coolant and DF is the CPS tritium decontamination factor (ratio between the tritium concentration at CPS inlet and outlet)**

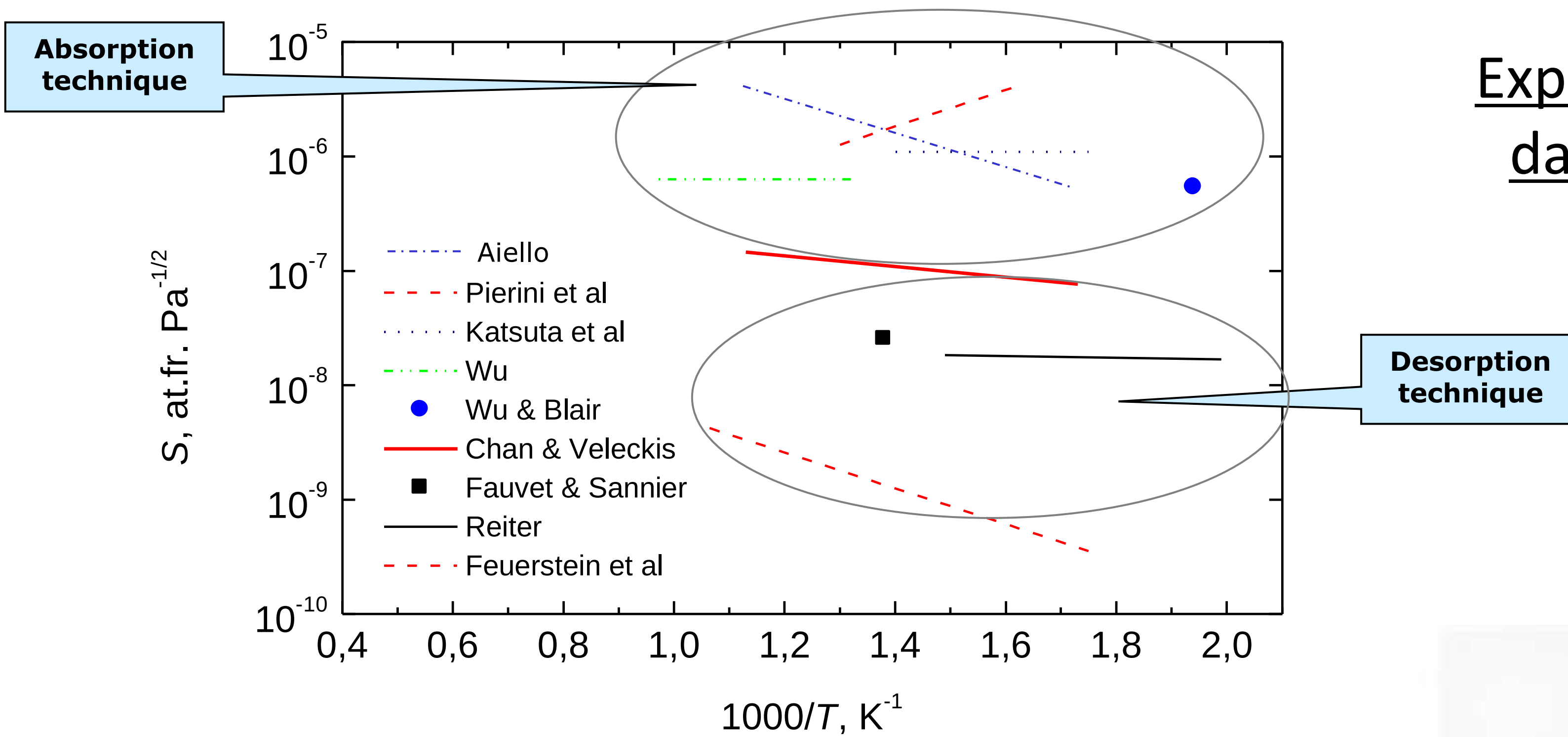
2) **Need to extract tritium from Pb-15.7Li with high efficiency (> 70%) to decrease the load on CPS because of the less tritium permeation rate: problems in technology development for the tritium extractors**

3) **The low tritium solubility can produce also high tritium permeation from the pipes/components of the ancillary systems towards environment: possible safety and tritium mass balance issues**

# DEMO blanket Fuel Cycle

## The Sieverts' constant for the system tritium/PbLi

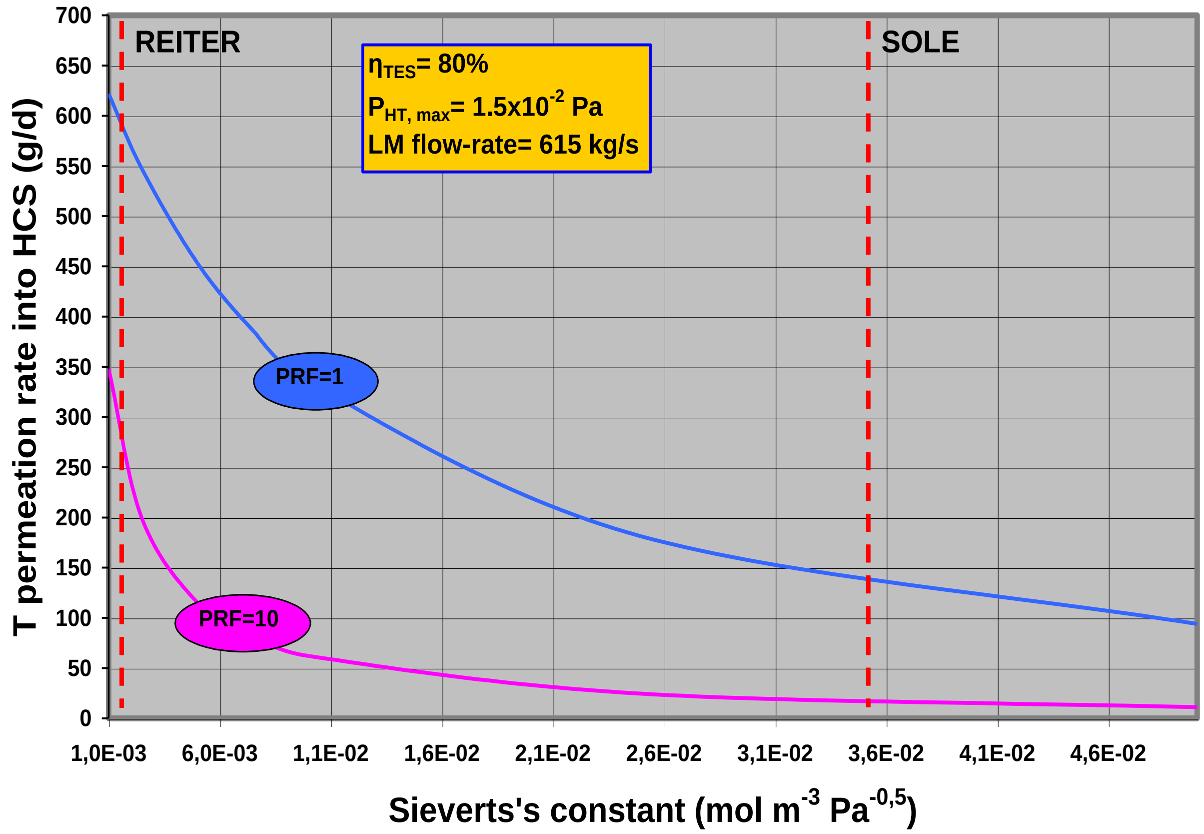
**The knowledge of the function linking the tritium concentration solubilised in LM with the corresponding tritium partial pressure at equilibrium, $C_T=f(P_T)$, is of basic importance for the LM breeder blanket concepts due to its strong impact on the tritium permeation rate and on the whole bred tritium recovery cycle.**
**In the low tritium pressure region the concentration in the liquid metal phase is linear with the square root of tritium partial pressure: $C = K_s p^{1/2}$**




Experimental data for Ks

# DEMO blanket Fuel Cycle

## Tritium permeation into HCS




**T permeation for a 4.2 GW Fusion Reactor**

**The T Sieverts' constant in Pb-Li strongly impacts the tritium permeation rate from the liquid metal into the main cooling circuit: higher is the Sieverts' constant, lower is the tritium permeation rate.**

# DEMO blanket Fuel Cycle

## Tritium extraction from Liquid Metal

**Need to maximize the tritium extraction efficiency from LM in order to:**

1) Increase the fraction of tritium generated which is extracted directly from the LM
2) Decrease the tritium permeation rate into the primary blanket coolant (possible need of **tritium permeation barriers**)

**Different technologies have been studied and proposed**

- ✓ **GAS LIQUID CONTACTORS (GLC)**
  - **spray columns**
  - **plate columns**
  - **bubble columns**
  - **packed columns**
- ✓ **V GETTERS**
- ✓ **VACUUM PERMEATOR (PAV)**

# DEMO blanket Fuel Cycle

## Tritium permeation barriers

**Tritium is highly soluble in and permeable through metallic high temperature blanket structural materials**

↓

**Need to find suitable technologies to contain tritium in the breeder**

↓

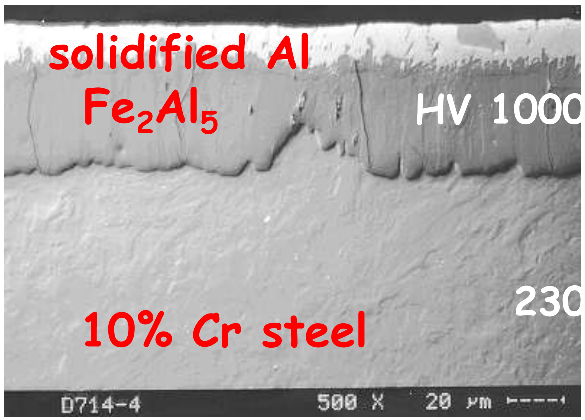
**Development of Tritium Permeation Barriers**

# DEMO blanket Fuel Cycle

## Tritium permeation barriers /1

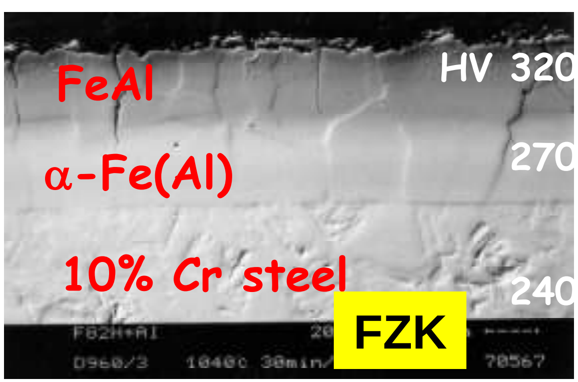
**Hot-Dip aluminizing process (HDA)**
Parameters for hot dipping: 700° C, dipping time 30 s

**Microstructure of hot dipped surface**

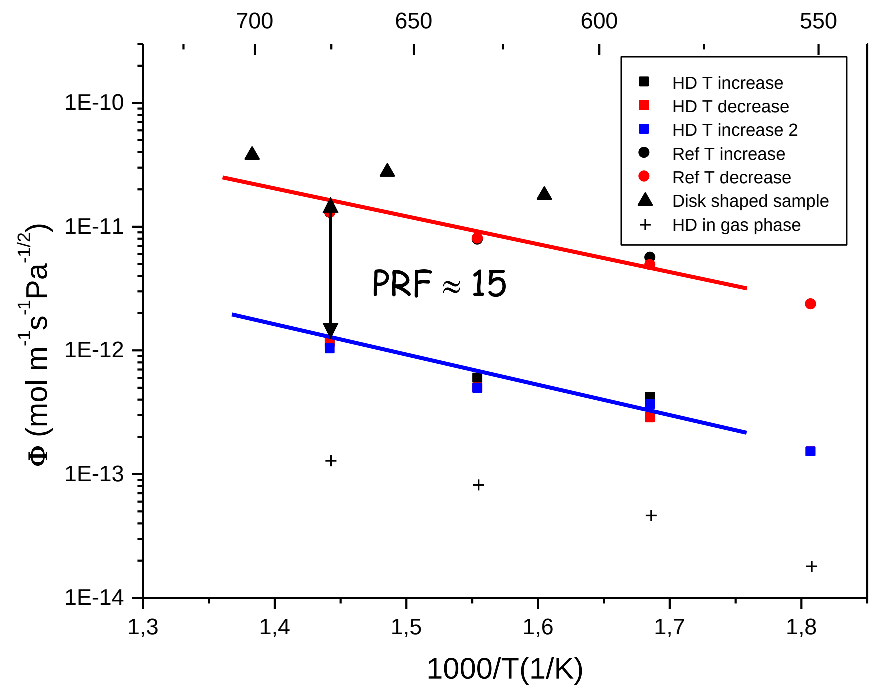



The alloyed surface layer consists of brittle $Fe_2Al_5$, covered by solidified Al

**Microstructure after heat treatment**




**Measurement of Permeability of HDA-coated tubes in $H_2$-gas and Pb-17Li**




**From ENEA-Brasimone**

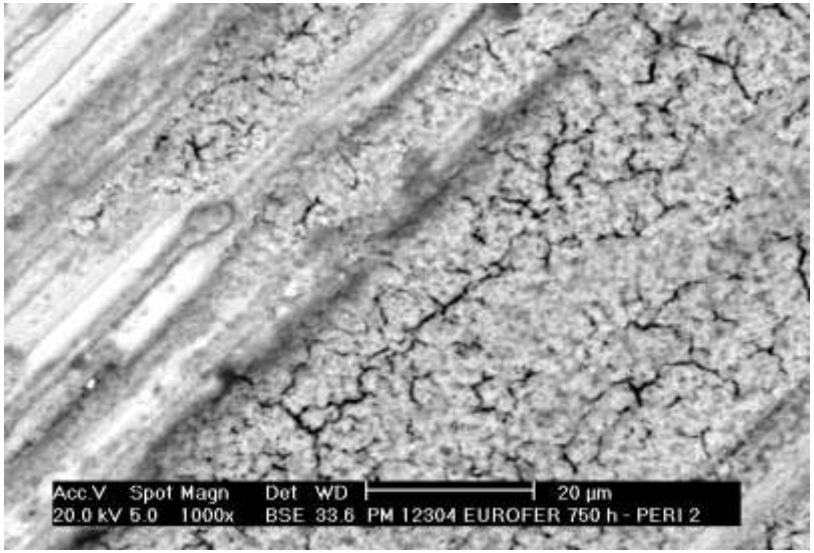
Heat treatment at 1040° C/0.5 h + 750° C/1 h and an applied pressure of >250 bar (HIPing) reduces porosity and transforms the brittle $Fe_2Al_5$-phase into the more ductile phases FeAl α-Fe(Al)

# DEMO blanket Fuel Cycle

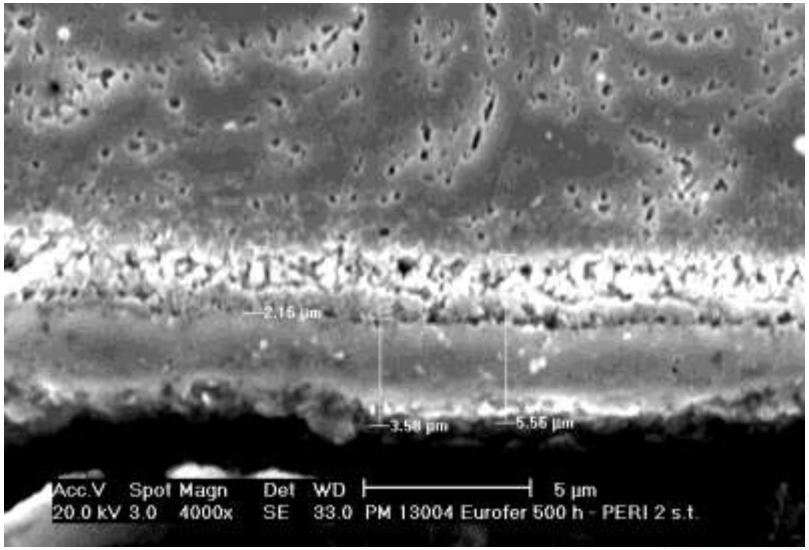
## Tritium permeation barriers /2

The performance of aluminium coatings on Eurofer steel were tested during an extended experimental campaign in ENEA Brasimone. The obtained results showed PRF values one order of magnitude lower than those obtained in gas phase on simple specimen geometry → **permeation barriers based on natural oxides**

**Pre-oxidised sample**




**Sample after self-healing**




The results of the permeation tests carried out with an online oxidation proved the effectiveness of the self healing to preserve or improve the initial performances. PRF in the range 10 – 20 have been obtained.

# DEMO blanket Fuel Cycle

*Environmental tritium release*

***T activity in HCS***

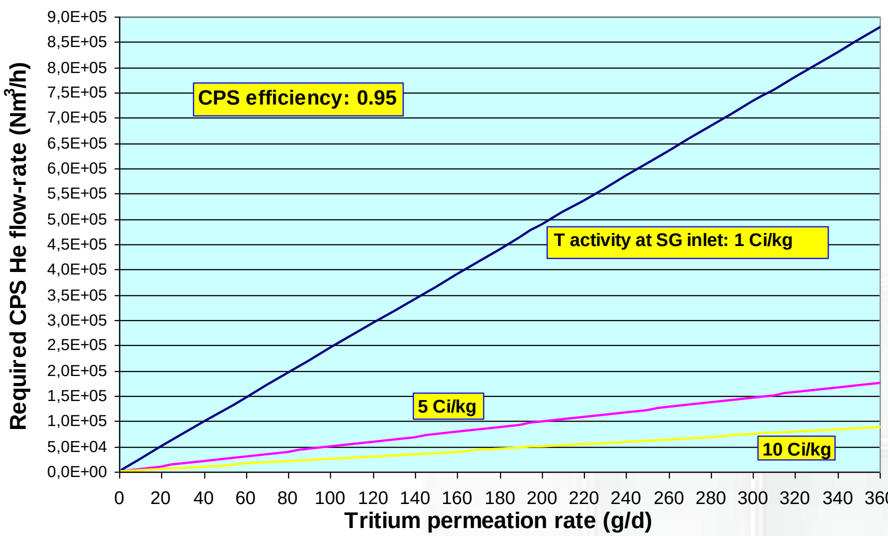
*SGs characteristics*

***T permeation into HCS***

***required TES performance***

***required CPS performance***

***required TPB efficiency***



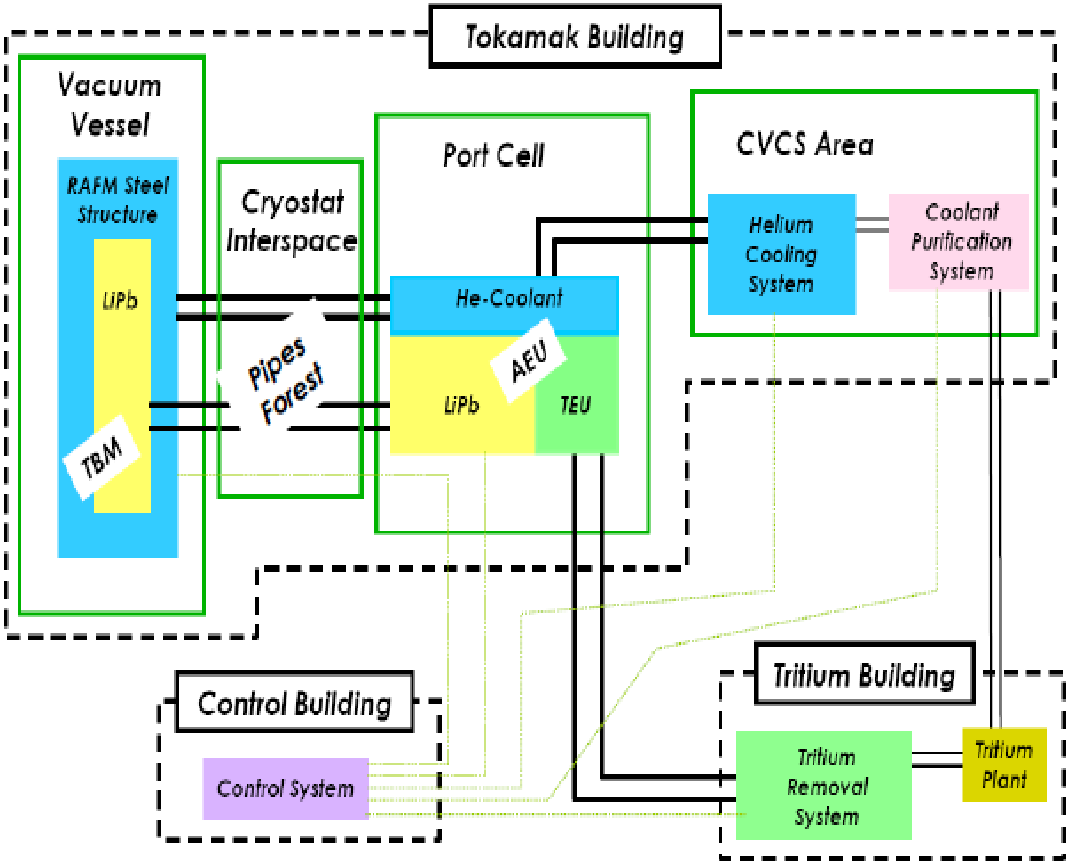

**Critical is the size of the CPS which depends on**:

- tritium permeation rate into the primary cooling circuit
- maximum allowed tritium partial pressure in the primary cooling circuit

## TBMs auxiliary systems in ITER

The auxiliary systems are mainly circuits devoted to the removal of thermal power and tritium recovery from the blanket modules.

- The Helium Cooling System (HCS);
- The Coolant Purification System (CPS);
- The Tritium Extraction System (TES);
- The lead lithium loop (for HCLL-TBM).



# Tritium Systems in TBMs

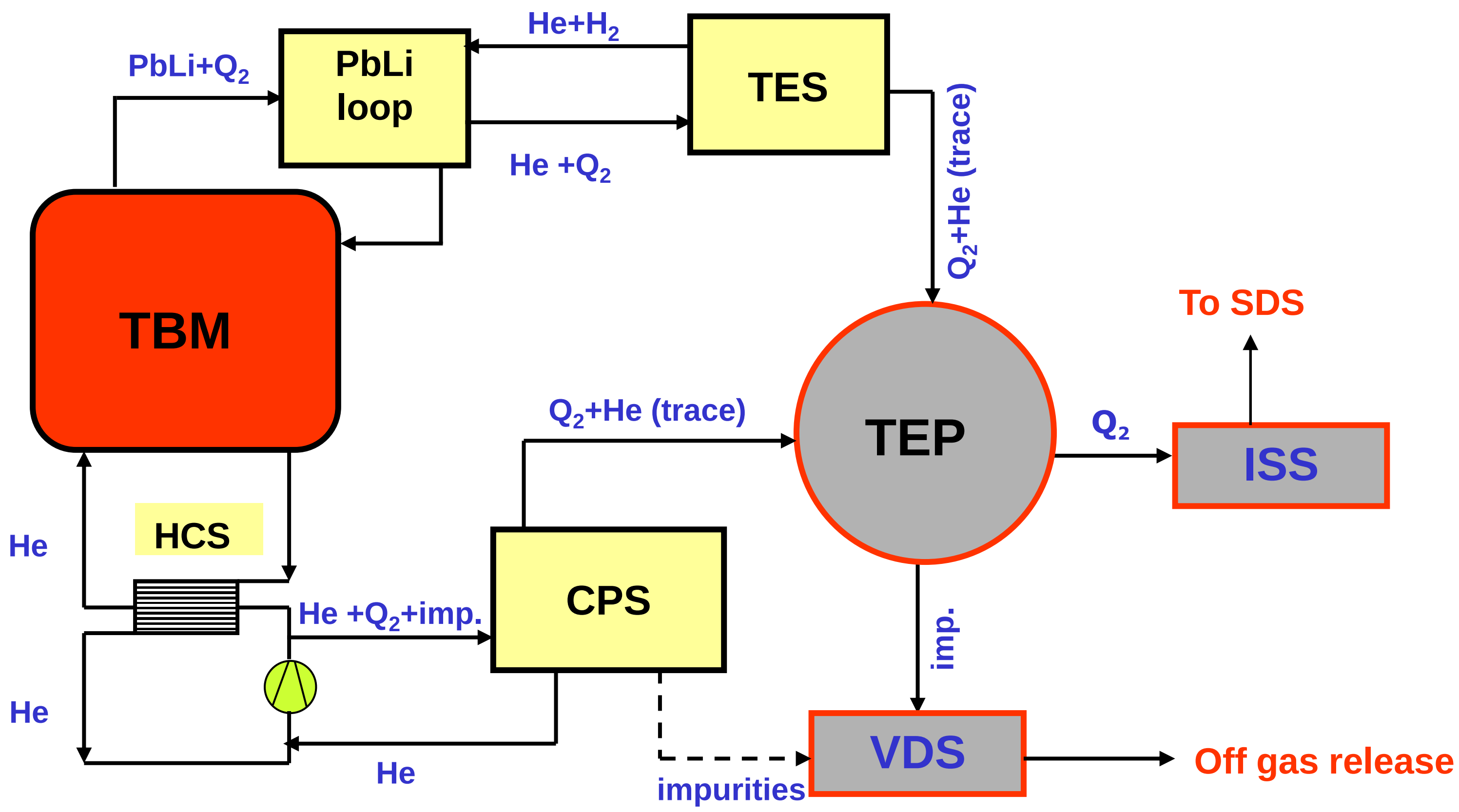
**Objectives of ITER campaign for tritium processing systems**

**Although of very small amount, in the order of magnitude of some tens mg/day, tritium bred in TBMs needs to be extracted and accounted for, with the main aim of:**

- **validating theoretical predictions on tritium breeding**
- **validating modelling tools on tritium recovery performance and inventory in structural and functional materials**
- **getting experience in technologies and components for tritium processing**

# Tritium Systems in TBMs

## Integration of HCLL-TBM in the ITER Fuel Cycle



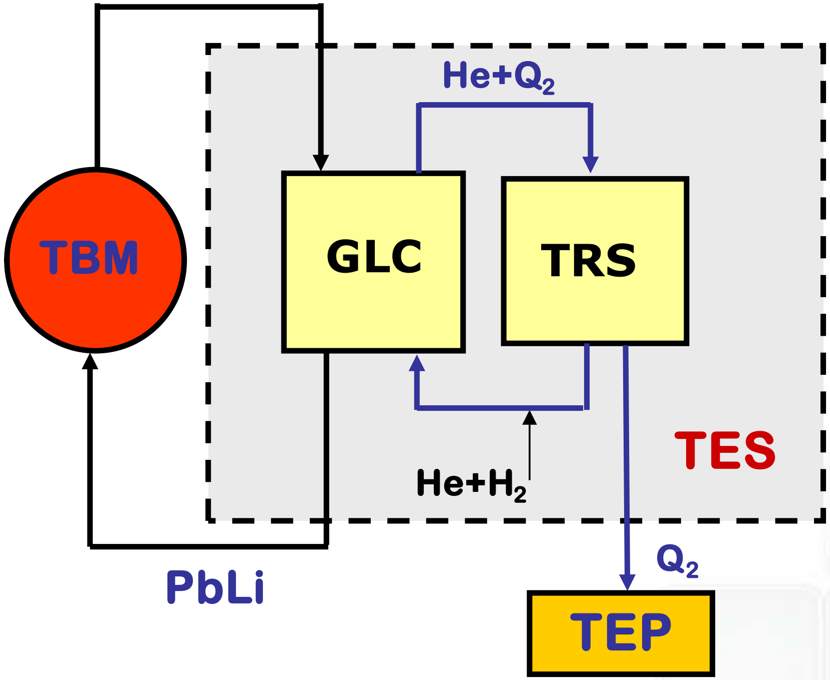

**TEP**: Tokamak Exhaust Processing
**HCS**: Helium Cooling System
**TES**: Tritium Extraction System
**CPS**: Coolant Purification System
**VDS**: Vent Detritiation System

## Tritium Extraction System for HCLL-TBM

In HCLL (Helium Cooled Lithium Lead)-TBM the main functions of TES are to extract tritium from the flowing lead lithium alloy in a dedicated subsystem, to remove it from the resulting gas stream and to route it to the ITER Tritium Plant for final processing.

The reference solution foreseen two steps:

- first tritium is extracted from the lead-lithium by a tritium extraction unit (TEU) based on a gas-liquid contactor (GLC) with He doped with $H_2$ as stripping gas.
- in the second step, He containing $Q_2$ ($HT+H_2$) stripped in the gas-liquid contactor, is processed by TRS (Tritium Removal from Purge Gas System). Purified He is then routed back to GLC.

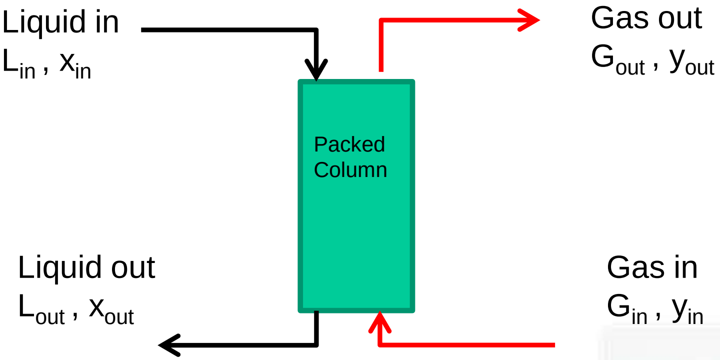


## Tritium Extraction Unit

Among the different possible technologies proposed for TES, a gas liquid contactor (GLC) is the reference solution for the tritium extraction unit. However, also the option of the permeator is considered.

The packed columns are vertical columns filled with packing or other device providing a large interfacial surface between liquid and gas phase in both counter-current and co-current flow.

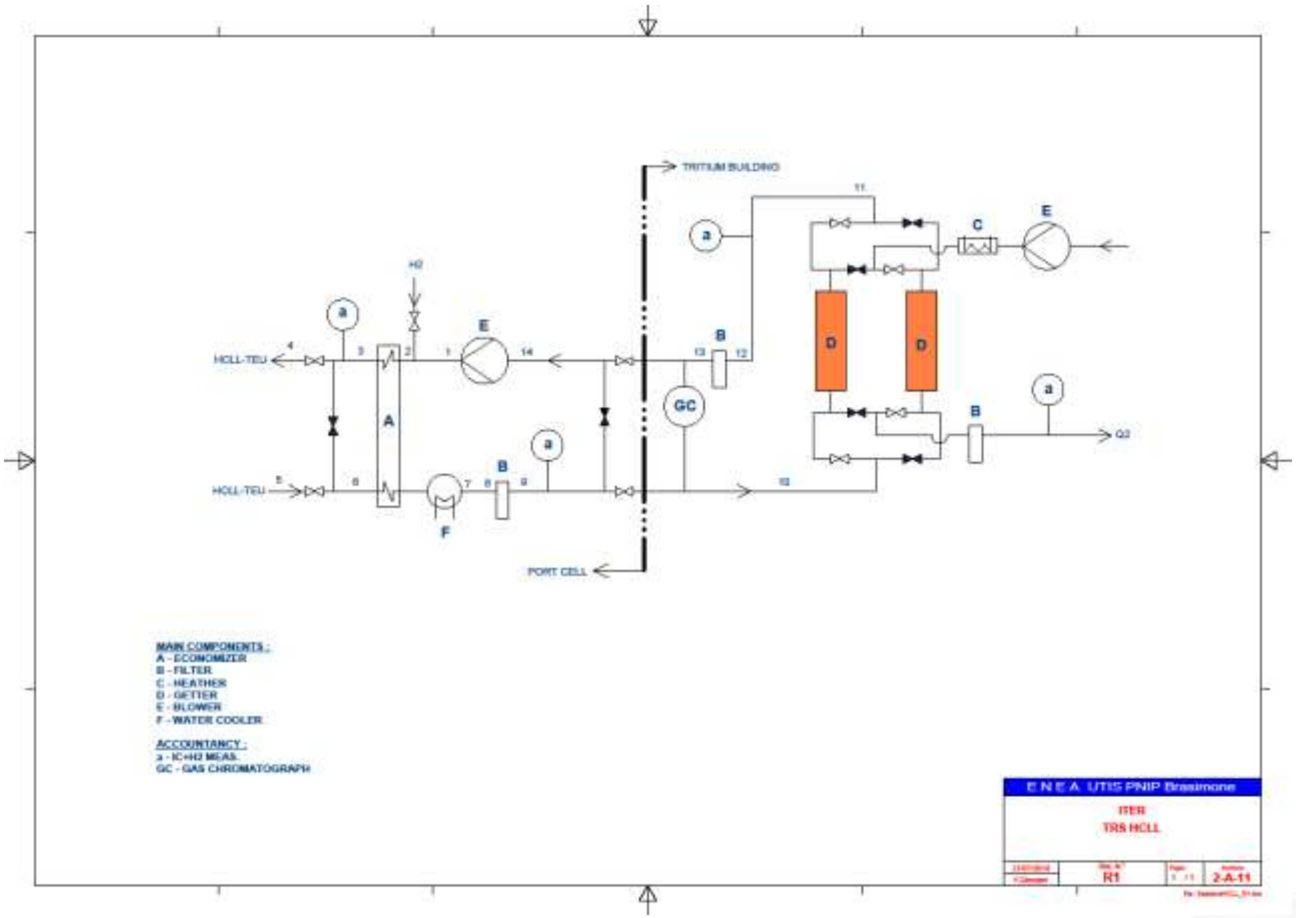
Packed columns for HCLL TEU contain the metal filler Mellapak 750Y. TEU has variable operational temperature up to 450° C.



# Tritium Systems in TBMs

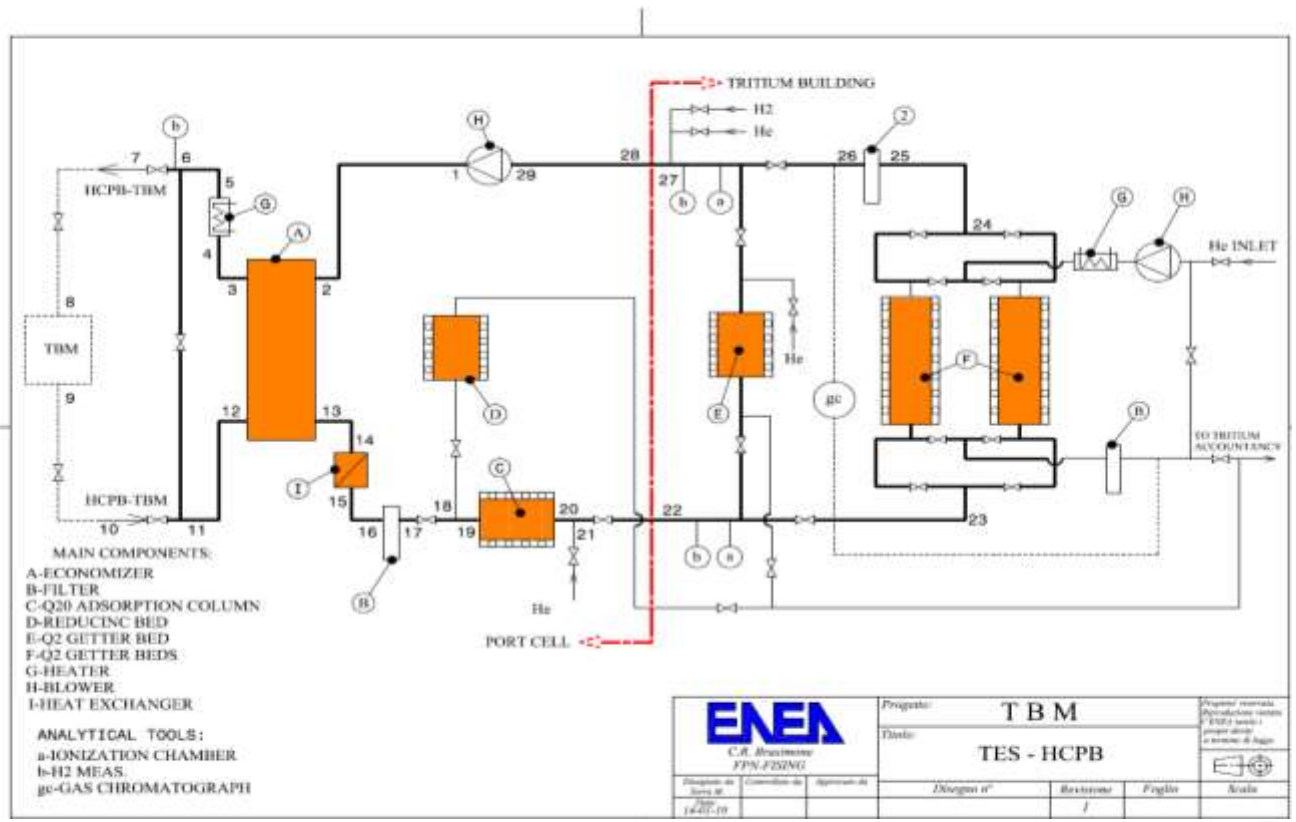
## Tritium Removal System (TRS)

HCLL TRS has a similar configuration with respect HCPB TES. Also in this case a ZrCo getter bed is adopted for $Q_2$ removal. An adsorption step for $Q_2O$ removal is not necessary because the stripping gas used in the gas liquid contactor does not contain water.



## Tritium Extraction System for HCPB TBM

In HCPB (Helium Cooled Pebble Bed)-TBM the main functions of TES are to extract tritium from the lithiated ceramic breeder by gas purging (He + 0.1% $H_2$), to remove it from the purge gas and to route it to the ITER Tritium Plant for final processing.



## Coolant Purification System /1

The functions of CPS are:

- to remove tritium permeated from the TBM into HCS routing it in a suitable form to the downstream tritium processing systems;
- to control the chemistry of He primary coolant in HCS by removing gas impurities coming from the different parts of HCS and adjusting the oxidation potential of the coolant by proper addition of chemical agents (normally $H_2O/H_2$).

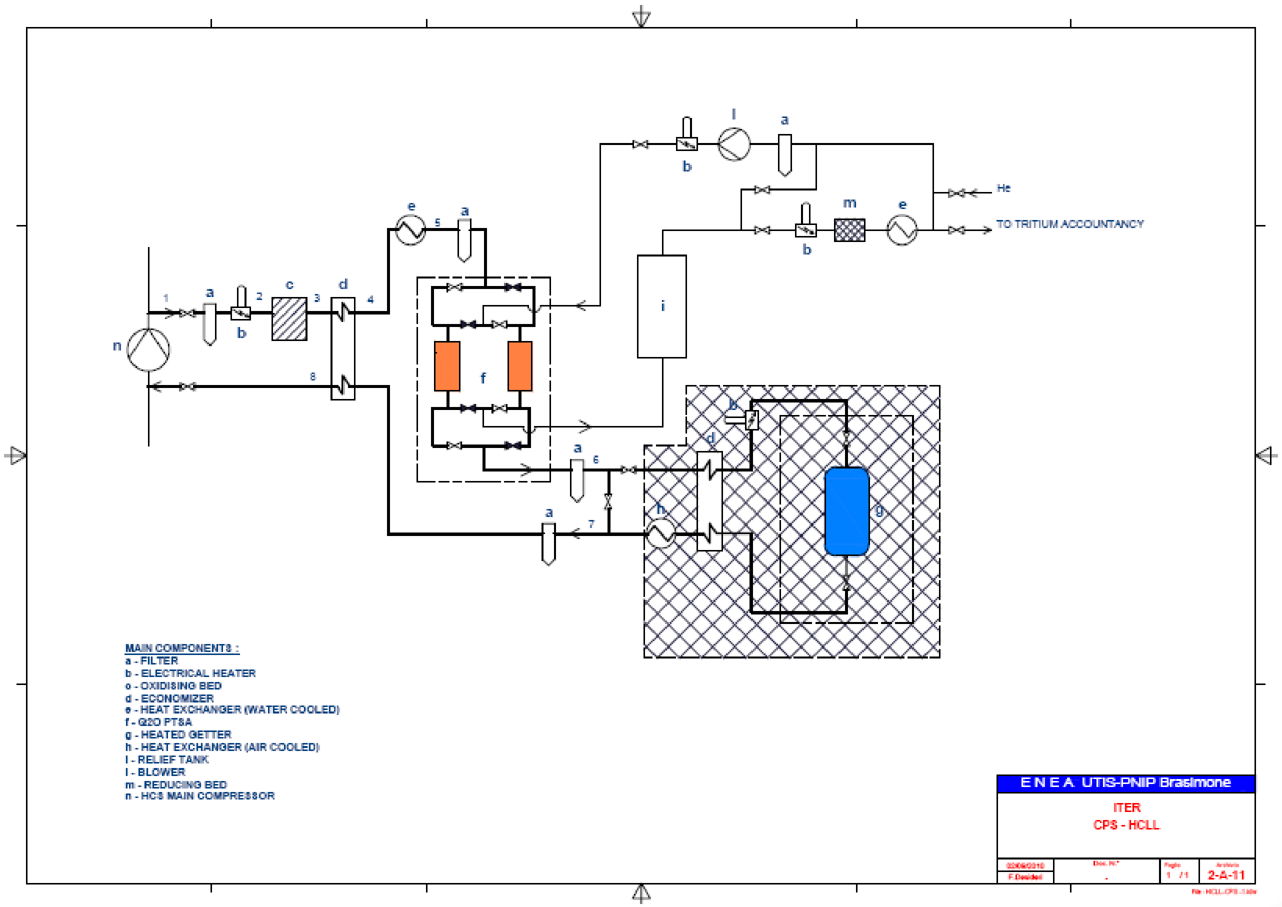
| INLET to | CPS | |
|---|---|---|
| Feed flow-rate ($Nm^3/h$) | **75** | |
| Inlet Temperature (°C) | **70** | |
| Pressure (MPa) | **8.2** | |
| | **Scenario 1** | **Scenario 2** |
| HT partial pressure (Pa) | **0.08 - 0.43** | **0.08 - 0.43** |
| $H_2$ partial pressure (Pa) | **5.5 – 19.3** | **1000** |
| $H_2O$ + HTO (Pa) | **8** | **30** |
| Maximum concentration of impurities expected (CO, $CO_2$, $N_2$, $CQ_4$, $O_2$) (vppm) | **10** | **10** |

The considered solution is a three stage process constituted by the following steps:

- Oxidation of $Q_2$ and CO to $Q_2O$ and $CO_2$ using a metal oxide (CuO) at 300°C;
- Adsorption of $Q_2O$ and $CO_2$ by an adsorption column based on molecular sieves;
- Adsorption of residual impurities by a heated getter.

## Coolant Purification System /2

The PFD of CPS: the feed stream is taken downstream the HCS main compressor and, after being purified, is routed to the main coolant upstream the compressor.



# Tritium Systems in TBMs

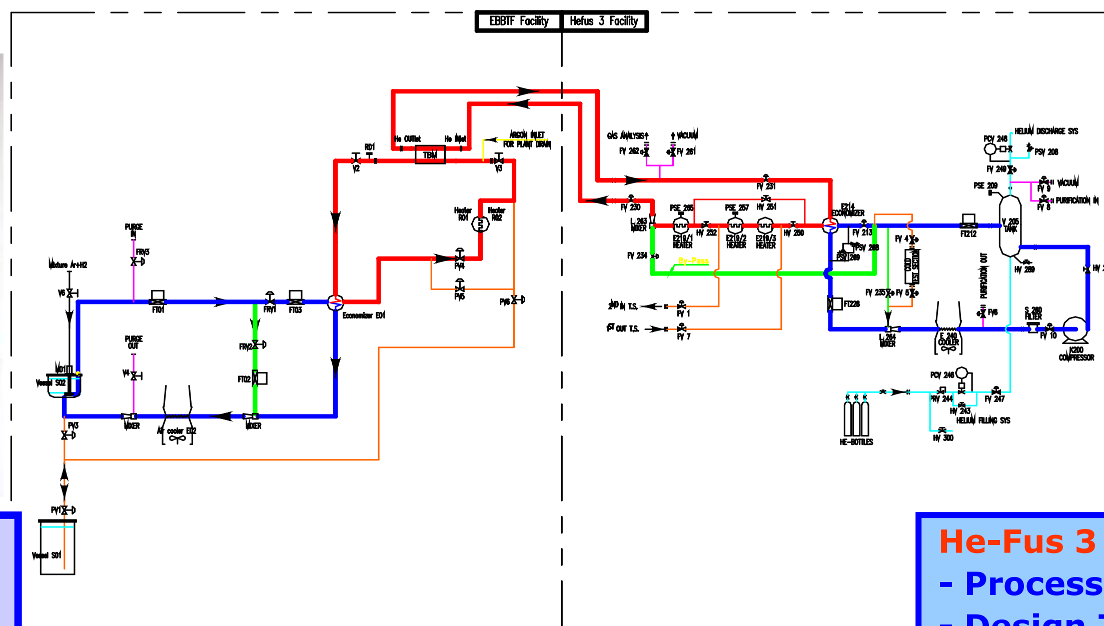
ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

## EBBTF (ENEA CR Brasimone)

**Mission:**

- ❖ testing of relevant components of the HCPB/HCLL blanket concepts
- ❖ operation of TBMs mock-ups in ITER relevant conditions
- ❖ testing of auxiliary systems (TES, CPS)

**EBBTF (European Breeding Blanket Test Facility) consists of the He loop He-Fus 3 coupled with the PbLi loop IELLLO**




**IELLLO Operative Conditions**
- Processed fluid: Pb-16Li
- Design Temperature: 550°C
- Design Pressure: 0.5 MPa
- Max LM flow rate: 3.0 kg/s
- LM Inventory: 500 l
- Max Heating Power: 60 kW

**He-Fus 3 Operative Conditions**
- Processed fluid: He
- Design Temperature: 530 ° C
- Design Pressure: 8 MPa
- Max He mass flow-rate: 1.4 kg/s
- Max heating power: 210 kW

# Summary

- **Functions of the Breeding Blanket**
- **Breeding Blanket for ITER and DEMO reactors**
- **Safety issues related with tritium interactions with materials**
- **The general structure of ITER Fuel Cycle is similar to what is foreseen for DEMO. The tritium technologies developed for ITER (for TEP, ISS, SDS) are based on DEMO relevant technologies.**
- **Issues related to the tritium cycle in PbLi based blankets for DEMO (T permeation, determination of Ks, TPB, high performances needed for TES and CPS)**
- **Tritium Systems in TBMs: objectives of ITER campaigns, technologies adopted for TES, TEU for HCLL, CPS**