Karlsruher Institut für Technologie

Bundesministerium
für Bildung
und Forschung

Gefördert vom:

Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren

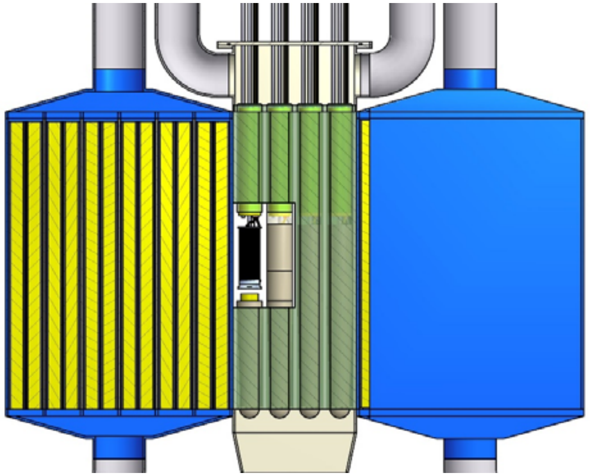
DONES
Preparatory
Phase

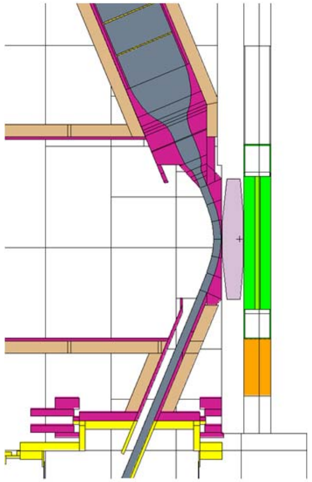
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

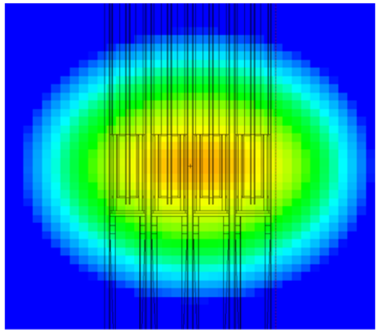
Tritium Release Test Module - design overview

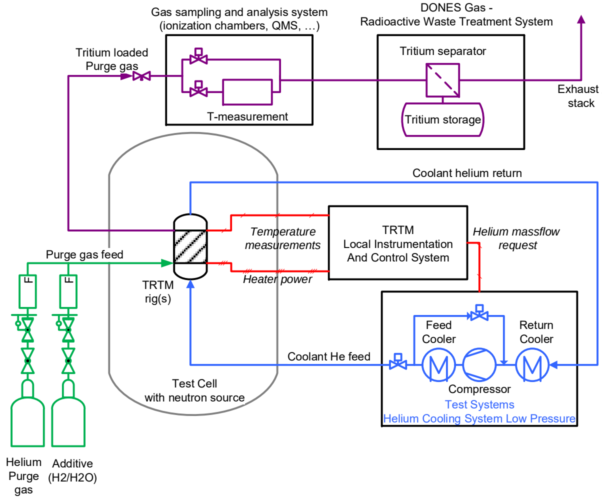
Frederik Arbeiter (KIT), A. Abou-Sena (KIT), Y. Qiu (KIT), A. Valentine (UKAEA), H. Chohan (UKAEA)

Second DONES User Workshop, 19.–20. Oct. 2023, Granada, Spain.









Scope of reported work on “TRTM”

- IFMIF/EVEDA 2011-2013 “Tritium Release Test Module”
  KIT , “DDD-III”
  - Conceptional design
  - Neutronics, thermal, mechanical, tritium transport analyses
  - Purge system, tritium analysis station
  - CAD model + production drawings (capsule prototype parts fabricated)

- DONES-PreP 2019-2021“In-Situ Ceramic Breeder Irradation Module”
  KIT, UKAEA, “Del.8.3.2” + attached ICBIM DDD
  - Update and detailing of neutronics (DONES specific)
  - Update of test requirements

TRTM mission statement

- The TRTM is the device dedicated for
  - irradiation of breeder ceramics or solid neutron multiplier materials,
  - at controlled temperatures (300 – 1100 °C) in bounded intervals,
  - in the high/medium flux region of the DONES neutron source,
  - for long term periods (months),
  - with the ability to monitor on-line the release of tritium species to a purge flow,
  - with the ability to retrieve the irradiated materials for PIE.

Specified test objectives [DONES-PreP Del8.3.2]

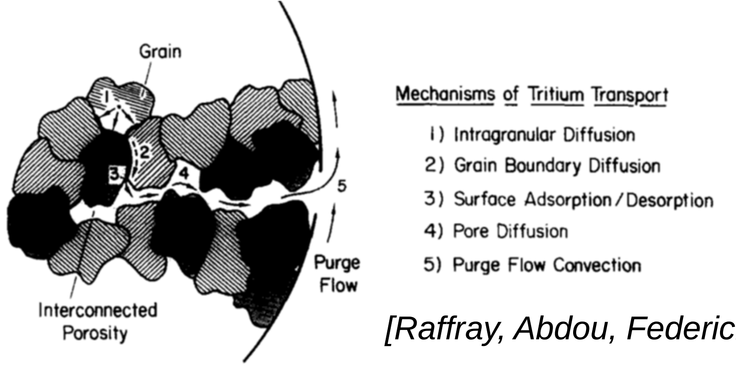
- 1. Determination of **time structure** (so called residence time) **of tritium release** from Li ceramics, **as reaction to transients** {n-flux, temperature, purge gas} and as function of age.

- 2. Determination of **chemistry of the purge gas and tritium / hydrogen species**, i.e. fractions of HT, HTO etc. during irradiation

- 3. Determination of **change of mechanical properties** {dimensional stability, microstructural evolution, crushing load} - **and physical properties** {thermophysical properties, density, tritium diffusivity} by PIE

Some underlying physics questions

- Transport mechanisms of tritium from “place of birth” into purge gas flow



[Raffray, Abdou, Federici]

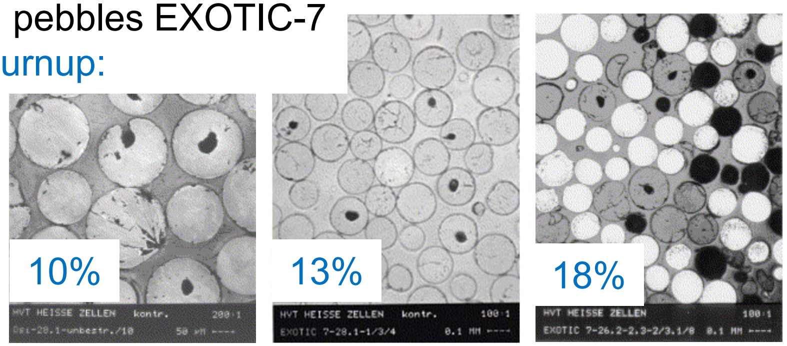
➔ Can only be studied with real breeding Li(n,T), otherwise T-source in volume can be achieved !

➔ Tritium release rate determines the reactors T-inventory /safety !

- Evolution of properties driven by progressing transmutation (Li-burnup), radiation damage and chemistry

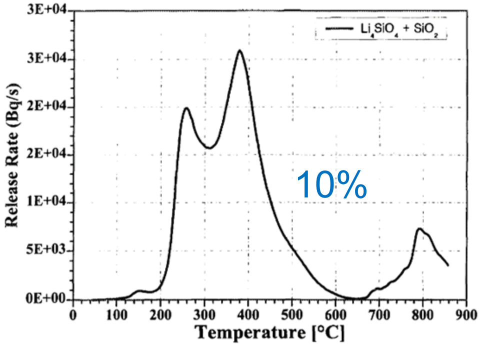
OSi pebbles EXOTIC-7

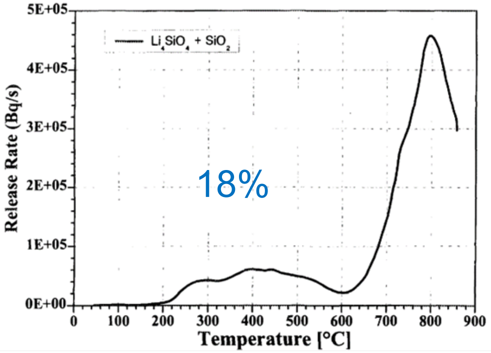
Li burnup:



[Scaffidi-Argentina, Werle]

Thermal desorption tests

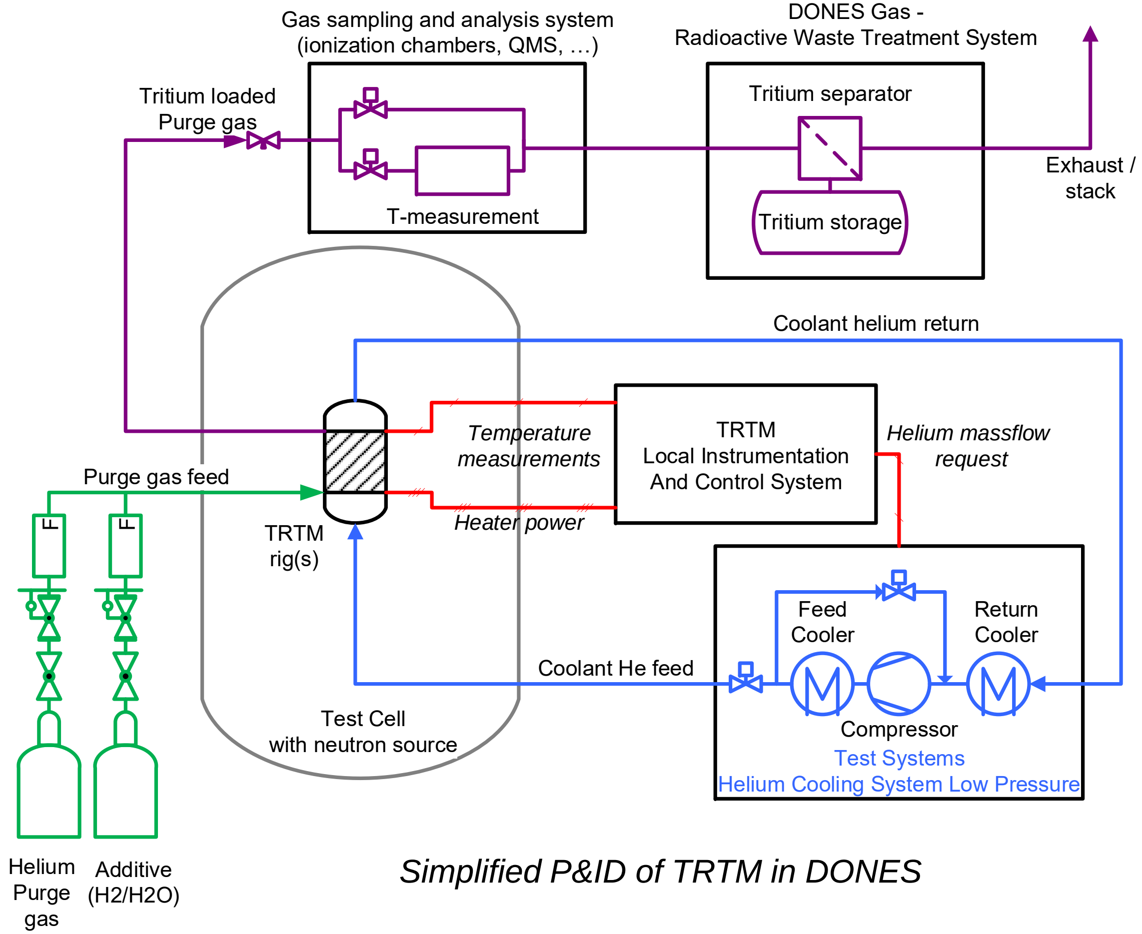




Example irradiation conditions (DEMO HCPB 2021)

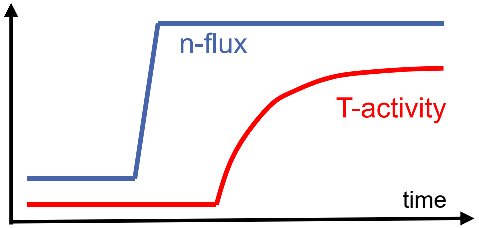
- Breeder material: **KALOS-ACB** pebbles : Li_4SiO_4 with 30 mol-% of Li_2TiO_3
- Polydisperse **pebble bed** 250 – 1250 µm (typical diameter **625 µm**), packing fraction 63-64%
- Purge gas: **helium with 0.1-wt% of H_2** at 0.2 MPa abs. (Changed to 8MPa!), superficial velocity **29 to 46.3 mm/s**
- Temperatures in the pebble bed are predicted at
  - **320** - 360°C minimum, given by the coolant helium outlet temperature from the FW
  - around **600 - 800 °C** in large bulk regions
  - **1055** °C peak
- Neutron flux in BZ : **5×10^{13} to 7×10^{14} n/cm²/s**
- Tritium production : **0.5 – 1.7 $\times10^{19}$ atoms(T)/m^3/s** in the breeder material
- Volumetric heating in BZ : **4 – 20 W/cm³**

TRTM mode of operation



Simplified P&ID of TRTM in DONES

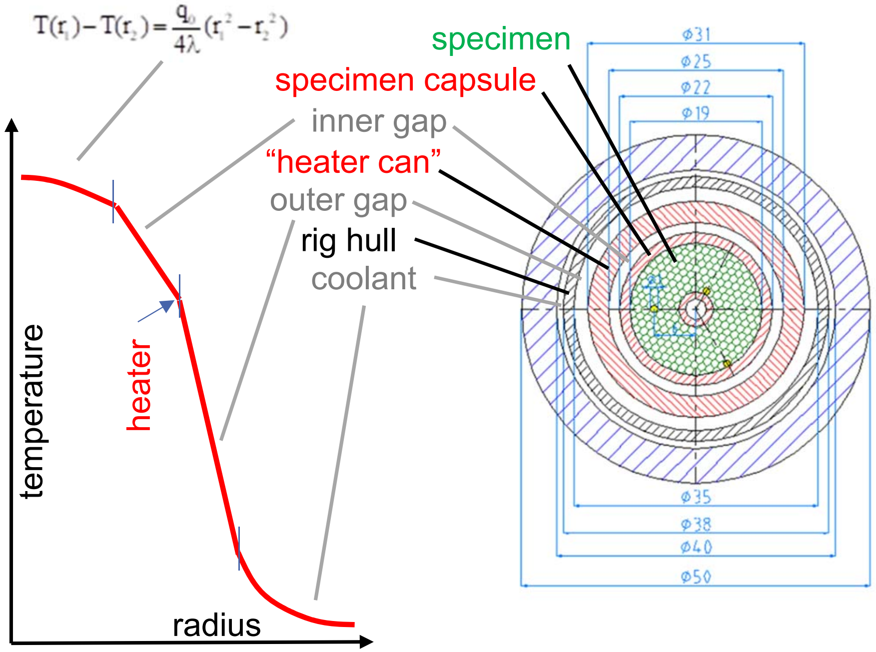
1. Loading capsules with unirradiated specimen material
2. Inserting TRTM into DONES TC
3. During irradiation:
    - Controlled setpoint changes {Temperature, purge gas, neutron flux} OR: observe long-term changes
    - Registering time dependent {T-activity, Temperature, purge flow conditions etc.}
4. Retrieve TRTM, Extract specimens
5. Perform PIE on irradiated specimens {microstructure, mechanical, T-desorption}



Example of transient measurements with TRTM

Design challenges (1) : Temperature management

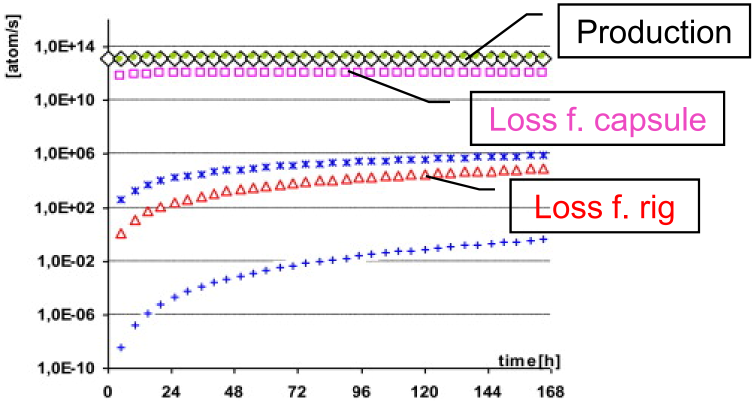
- Achieve high temperatures as in BZ (1100 °C)
  - Electrical heater limits 600 – 1000 °C, worse under irradiation (RIC, RIED)
  - Mechanical limits of materials (creep etc.)
- Limit temperature spread within specimen region

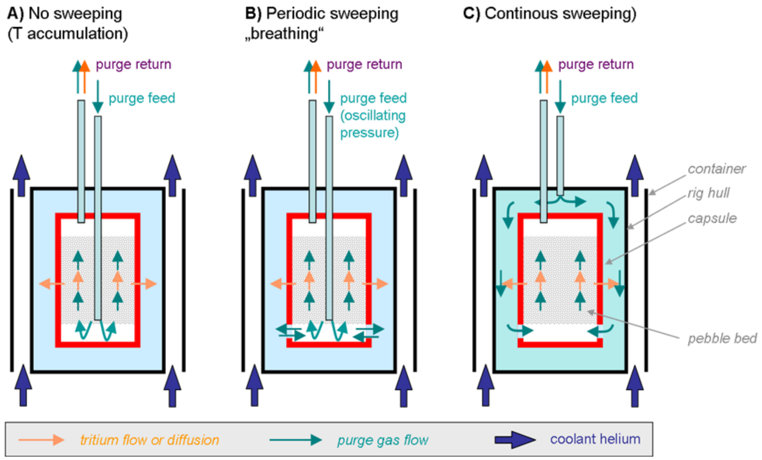


- Inner cylinder "specimen bin" contains specimens,
  high-temp. alloy, no pressure-diff. effective
- Two concentric gaps (stagnant gas) achieve thermal isolation, $T_{heater} < T_{specimens}$
- Pressure bearing wall and final tritium diffusuion barrier "rig hull" is cold
- Temperature difference within specimen stack is limited so that diffusivity varies by max. 10%

Maximum temperature achieved (by analysis) ~ 900 °C

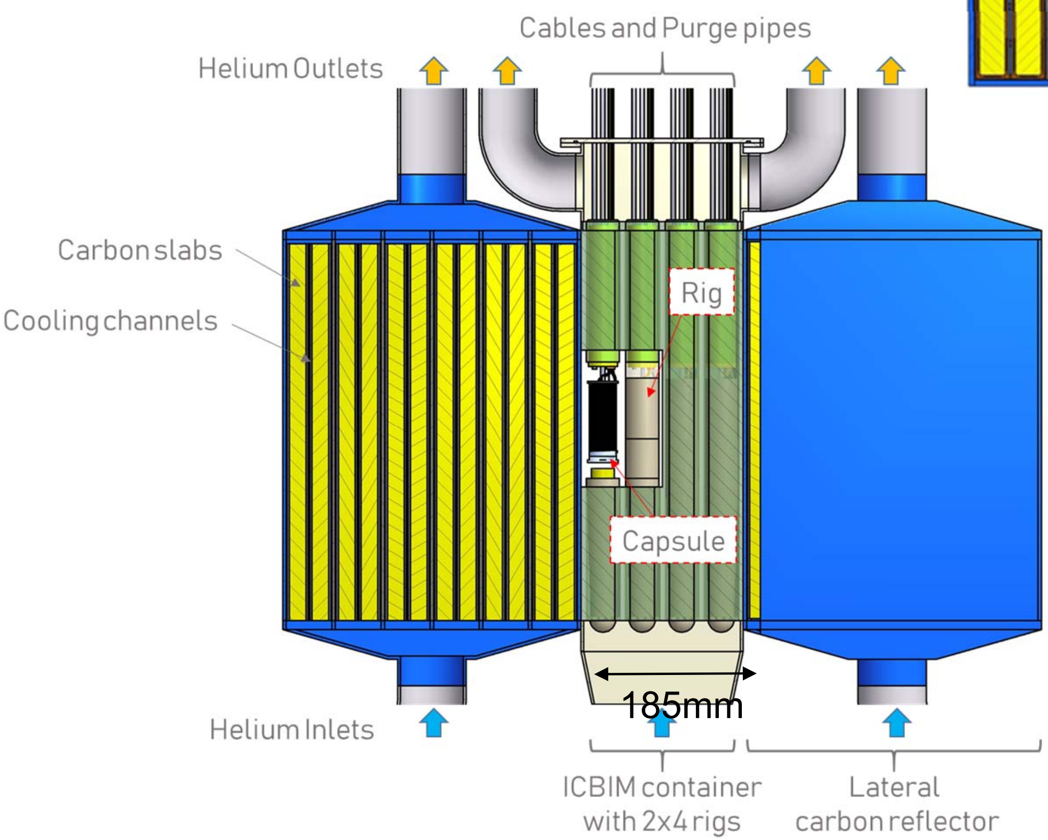
Design challenges (2) : tritium containment

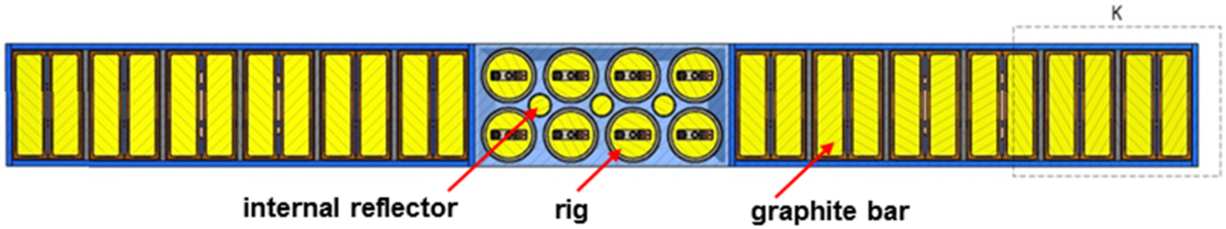


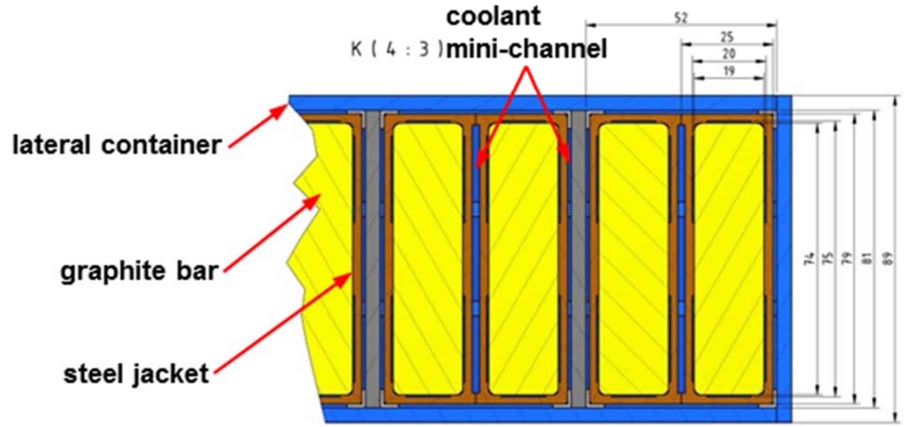


- Without recovery, 94% of bred T reaches the analysis station (losses over hot capsule wall)
- “Periodic sweeping” can be implemented by oscillating the purge gas pressure
(part of the 6% losses are recovered)
- Losses from rig are “negligible”

TRTM configuration

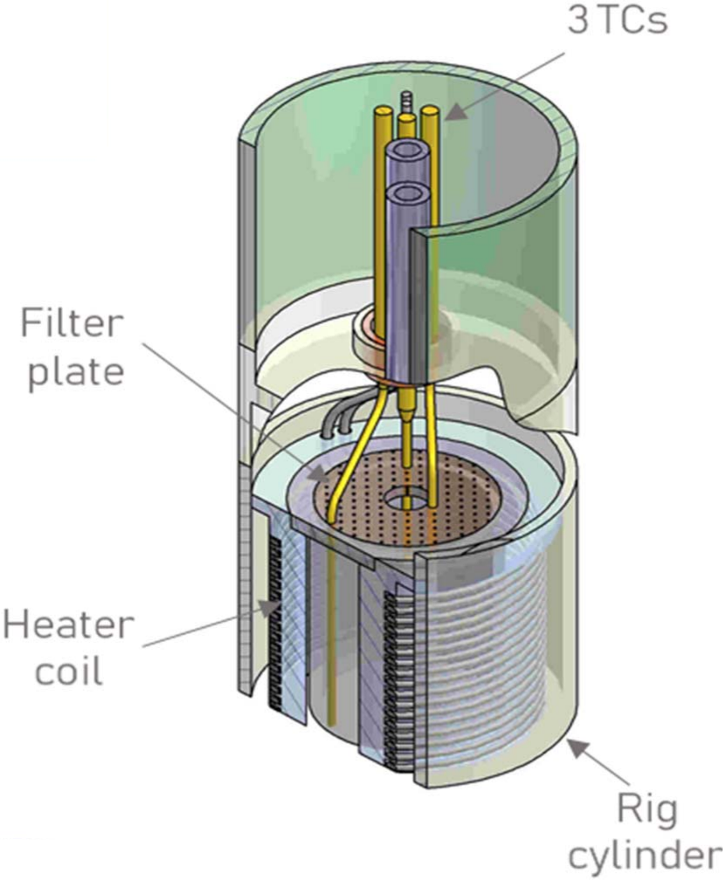


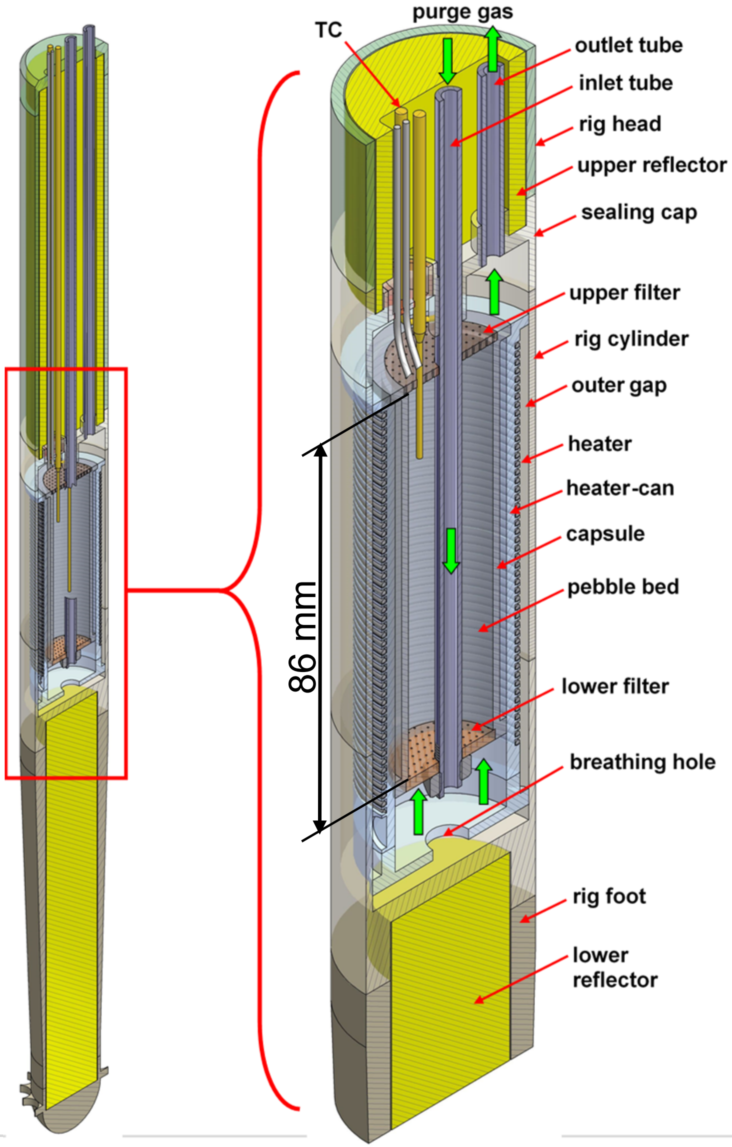




- Container: 316L(N) stainless steel
- Nuclear grade graphite
- Mass ~350 kg

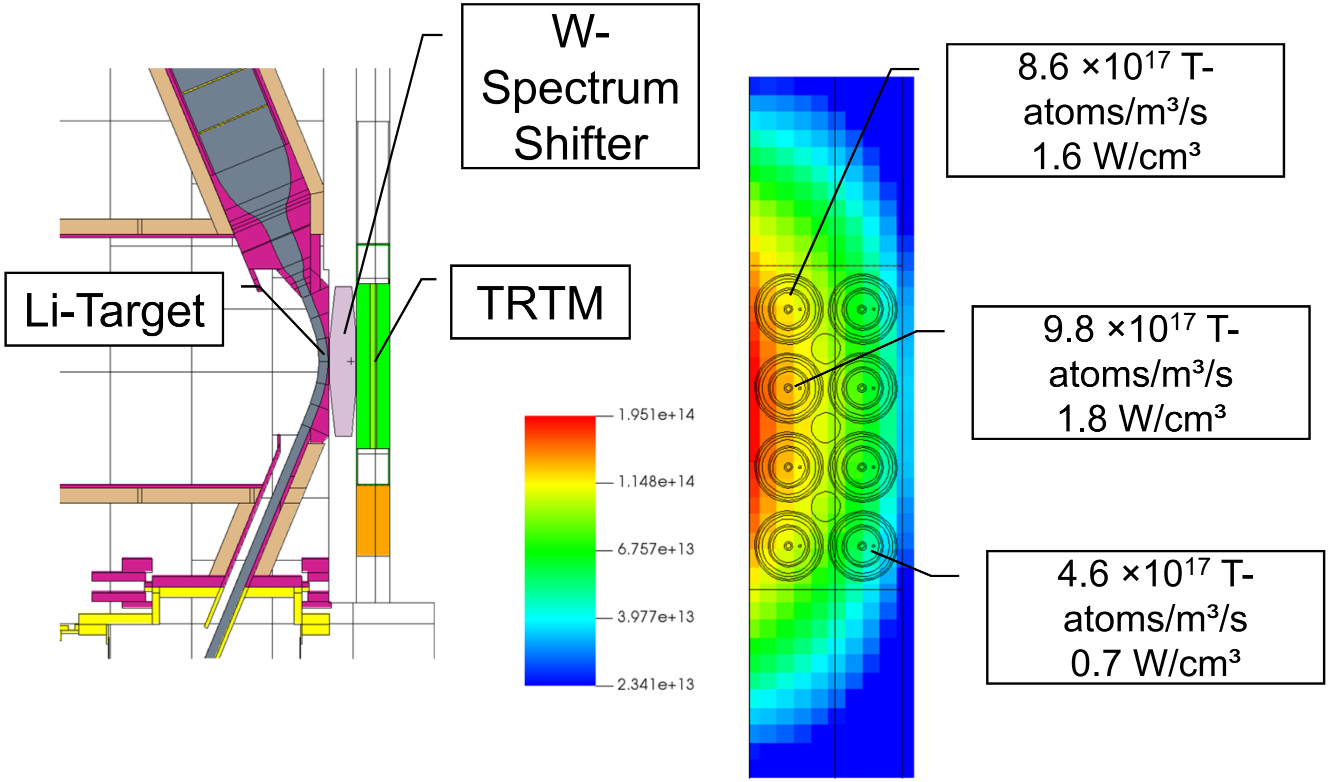
TRTM capsule





- Specimen capsule made of High-Cr stainless steel X15CrNiSi25-21
- Specimen volume D=19mm L=86mm 33 cm^3
- 3 Thermocouples
- Thermocoax heater (Inconel)
- OD 5mm purge tubes

Nuclear analyses



8.6×10^{17} T-atoms/m^3/s
1.6 W/cm^3

9.8×10^{17} T-atoms/m^3/s
1.8 W/cm^3

4.6×10^{17} T-atoms/m^3/s
0.7 W/cm^3

- Neutron flux comparable to DEMO
- T-production rate and heating about 1 order of magnitude < DEMO

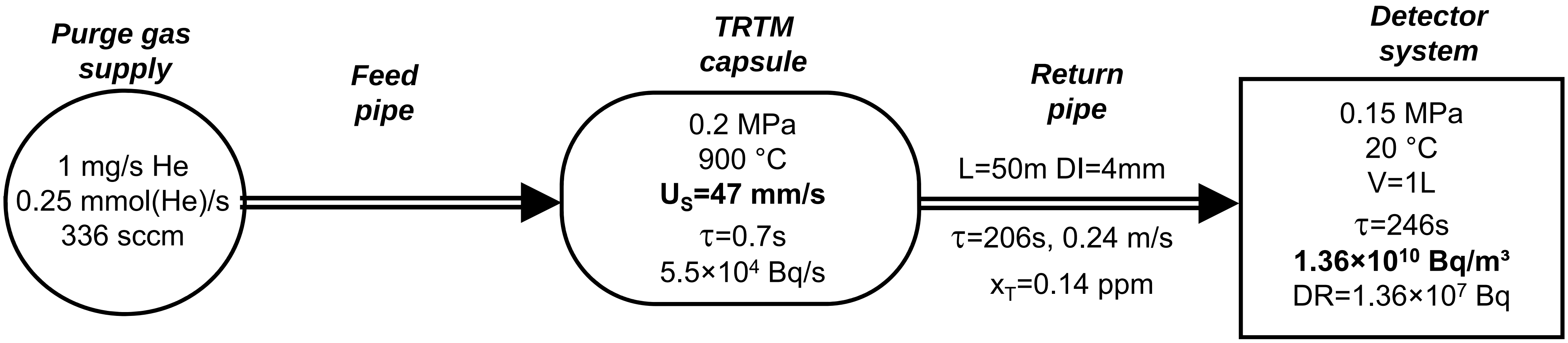
➔ Further optimization of neutron spectrum advisable (higher flux in low energy range required for Li-6 breeding)

HCPB DEMO BZ:

5×10^{13} to 7×10^{14} n/cm^2/s
0.5 – 1.7×10^{19} T-atoms/m^3/s
4 – 20 W/cm^3

Nuclear analyses completed with activation, decay-heat and dose-rates after shutdown

Purge gas system, tritium measurements



Purge gas supply

1 mg/s He
0.25 mmol(He)/s
336 sccm

Feed pipe

TRTM capsule

0.2 MPa
900 °C
U_S=47 mm/s
τ=0.7s
5.5×10^4 Bq/s

Return pipe

L=50m DI=4mm
τ=206s, 0.24 m/s
x_T=0.14 ppm

Detector system

0.15 MPa
20 °C
V=1L
τ=246s
1.36×10^{10} Bq/m³
DR=1.36×10^7 Bq

- Antagonistic effect detection rate vs. time resolution as function of flow rate
- Expected residence times in pebbles : O(hours)
- Detectors: Ionisation Chambers (IC), Liquid scintillation counting, Beta induced X-Ray spectrometry (BIXS)
- Typical detector properties:

Volume	1 – 3 L
Resolution	37 - 37×10^3 Bq/m³
Range	2×10^6 - 8×10^{14} Bq/m³

Conclusions

- Functions, requirements, mode of operation defined to 2021 HCPB needs
- The TRTM is in an advanced conceptual status:
  - CAD design + production drawings
  - Neutronic, thermal, mechanical, tritium transport analyses
- Design promises temperature range up to 900°C, requirements go up to 1100°C
- Neutron spectrum could be improved to match DEMO T breeding rate
- Effective tritium containment concept acc. to analyses
- Achievable Purge gas- and Tritium measurement parameters (purge gas velocity, activity resolution, time resolution) are compatible with mission

R&D needs up to deployment

- Interfaces definitions vs. DONES plant
- Optimization on neutron flux / spectrum →DEMO by NSS and NR

} WPENS ‘24+’25

- Detailed development of purge gas analytics
- Improvement of high-temperature capability
- Development of RH-compatible interface head vs. Test Cell
- Transient temperature steps analyses / control strategy
- Detailed material grades selection and fabrication planning
- Prototype fabrication (from capsule to module)
- Thermal-hydraulic validation (both: coolant & purge loops)
- Long-term (lifetime) test of heater at high temperatures

Fabricated TRTM capsule items

Limitation of temperature spread