Karlsruher Institut für Technologie

FUSION FOR ENERGY

EUROfusion

sck cen
Belgian Nuclear Research Centre

Dmitry Terentyev SEP/2025

Irradiation of Be- and Li-based materials for application in ITER TBM

D. Terentyev1, S. Fontanelli[1], R. Knitter[2], J. Leys[2], R. Gaisin[2], V. Chakin[2], M.Ionescu-Bujor[2], Salvatore D'Amico[3]

Qualification of materials: NEEDS & APPROACH

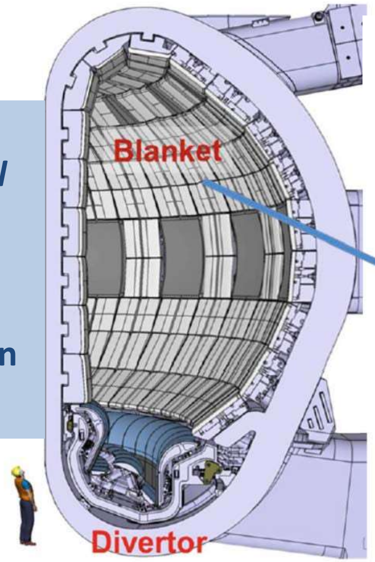
Component Design
- Loads
- Performance
- Safety

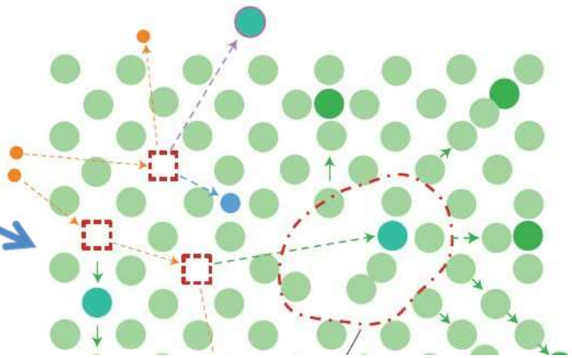
Operational conditions
- Temperature
- Stresses
- Displacement damage

Material Characterization
- Physical
- Chemical
- Functional (^3H)

Codification
- Property Handbook
- Design Rules
- Code Update

Ferritic-Martensitic *Steel (structural)*
Li-Ceramic (breeder)
Beryllide (neutron multiplier)

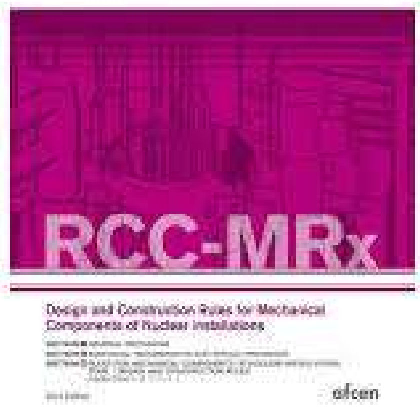




High temperature and irradiation damage

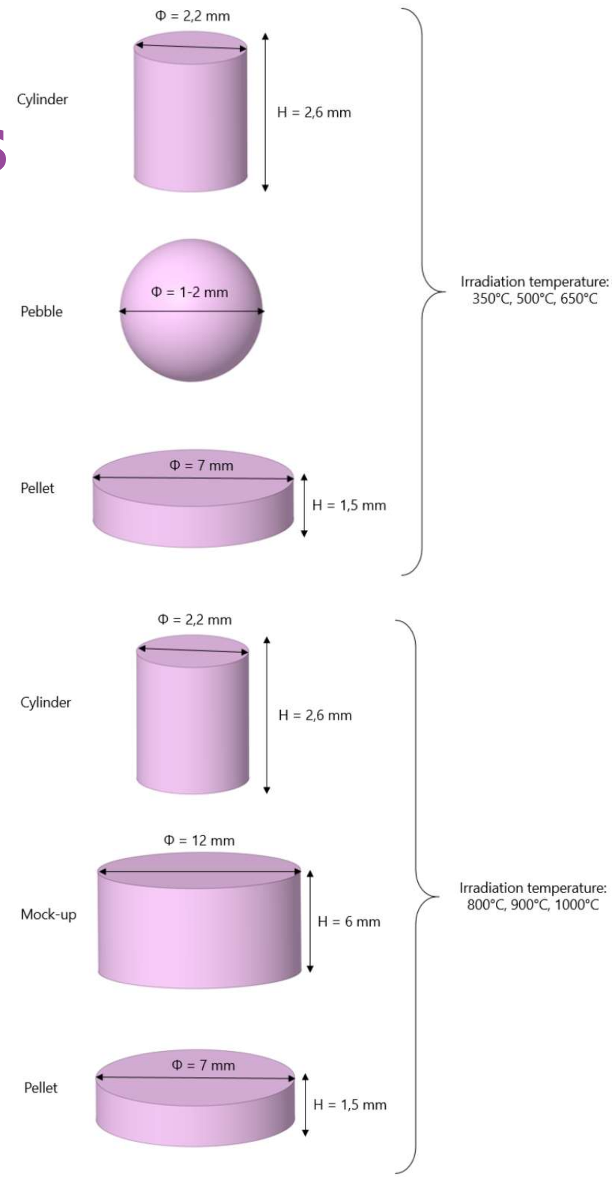
Damage in materials
- Embrittlement
- Thermal conductivity
- Swelling
- Tritium retention

Severity of irradiation damage measured by dpa
- **ITER ~0.035 - 3 dpa**
- **Pilot FPP 20-50 dpa**



Irradiation matrix: Be-based materials

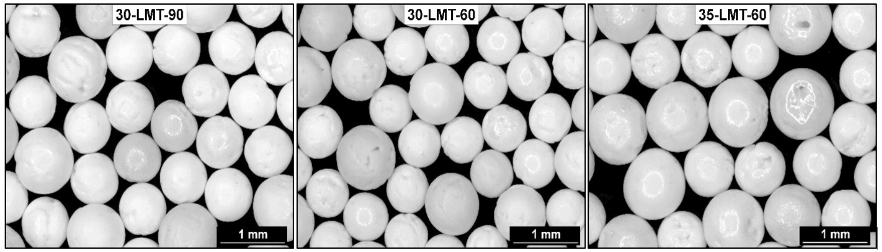
- Beryllium and Beryllides
  - Pure Be, $TiBe_{12}$ (69.3 % Be, 30.7 % Ti), $CrBe_{12}$ (67.5 % Be, 32.5 % Cr)
  - Pebbles, pellets and mock-ups
- Target temperatures → 350, 500, 650, 800, 900, 1000C °C
- Target fluence → 3 dpa in Fe
- Shielding from thermal neutrons is not required
- No exotic materials for the containment of Be during the irradiation are required



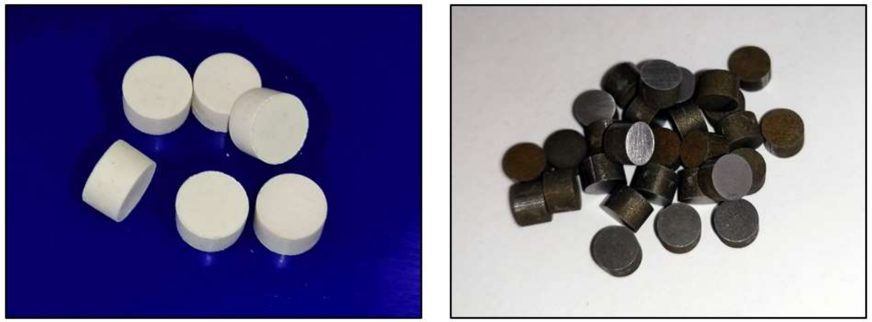
Irradiation matrix: Lithium-based materials

- Li-based ceramics
- biphasic materials consisting of *lithium orthisilicate* (Li_4SiO_4 = LOS) and additions of *lithium metatitanate* (Li_2TiO_3 = LMT)
- Target temperatures → 500, 600, 700, 800, 900°C
- Target fluence → 3 dpa in Li
- Shielding from thermal neutrons to achieve as close as possible ^3H/dpa ratio
- Platinum containment to prevent chemical reaction of Li samples with containment
- Priority: Li_2TiO_3 (LMT)
- Minimum Irradiation mass: 12 grams of LMT

Pebbles → size range 500-1000 μm



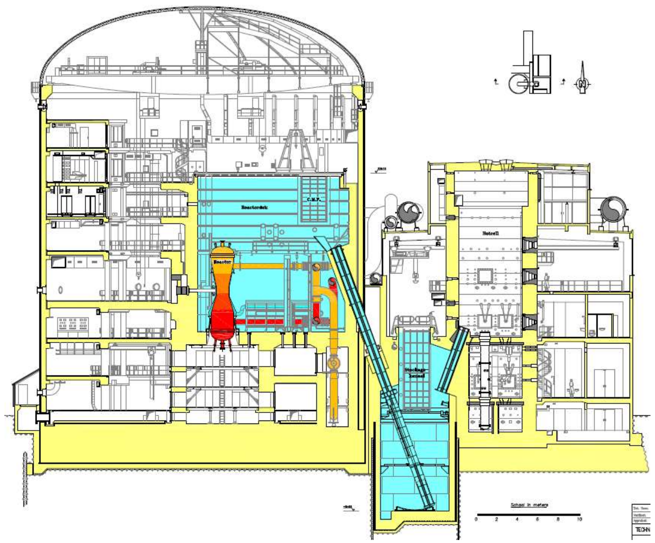
Disks → diameter = 5 mm and height = 3 mm

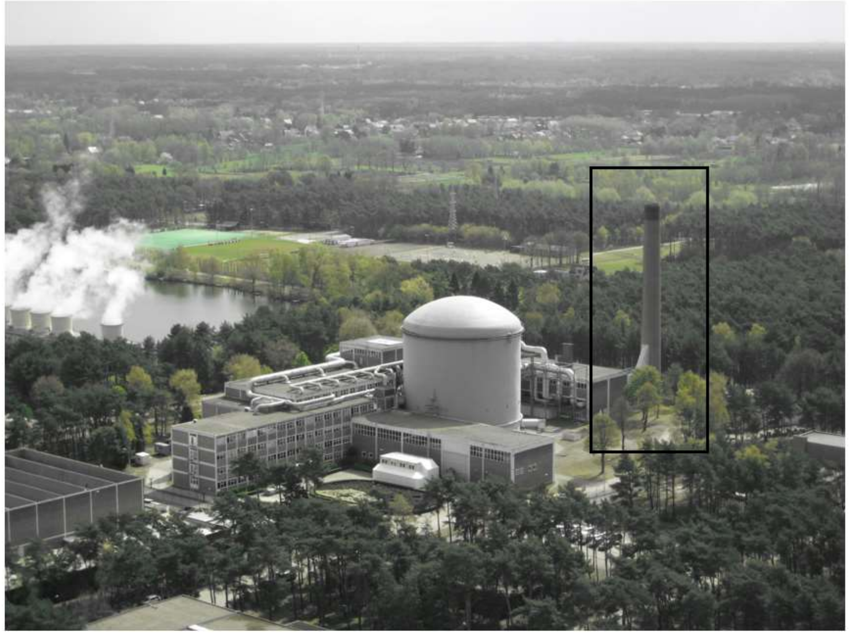


Setting irradiation experiment in BR2 reactor

Principal steps:

Conceptual Design
Safety analysis
Detailed Design
BR2 Safety approval
Rig Manufacture+Assembly
Safety Tests
Irradiation
Dismantling
Transportation to PIE location





Principal Safety Concerns:

- Contamination of BR2 primary circuit (with Be, ^{3}H, Gd, Li_2TiO_3)
- Corrosion of fuel cladding (due to Gd)
- Release of radioactive element in the BR2 building or BR2 hot cells/chimney

“if you government is generous – you can take a lots of risks © Hiro Tanigawa”

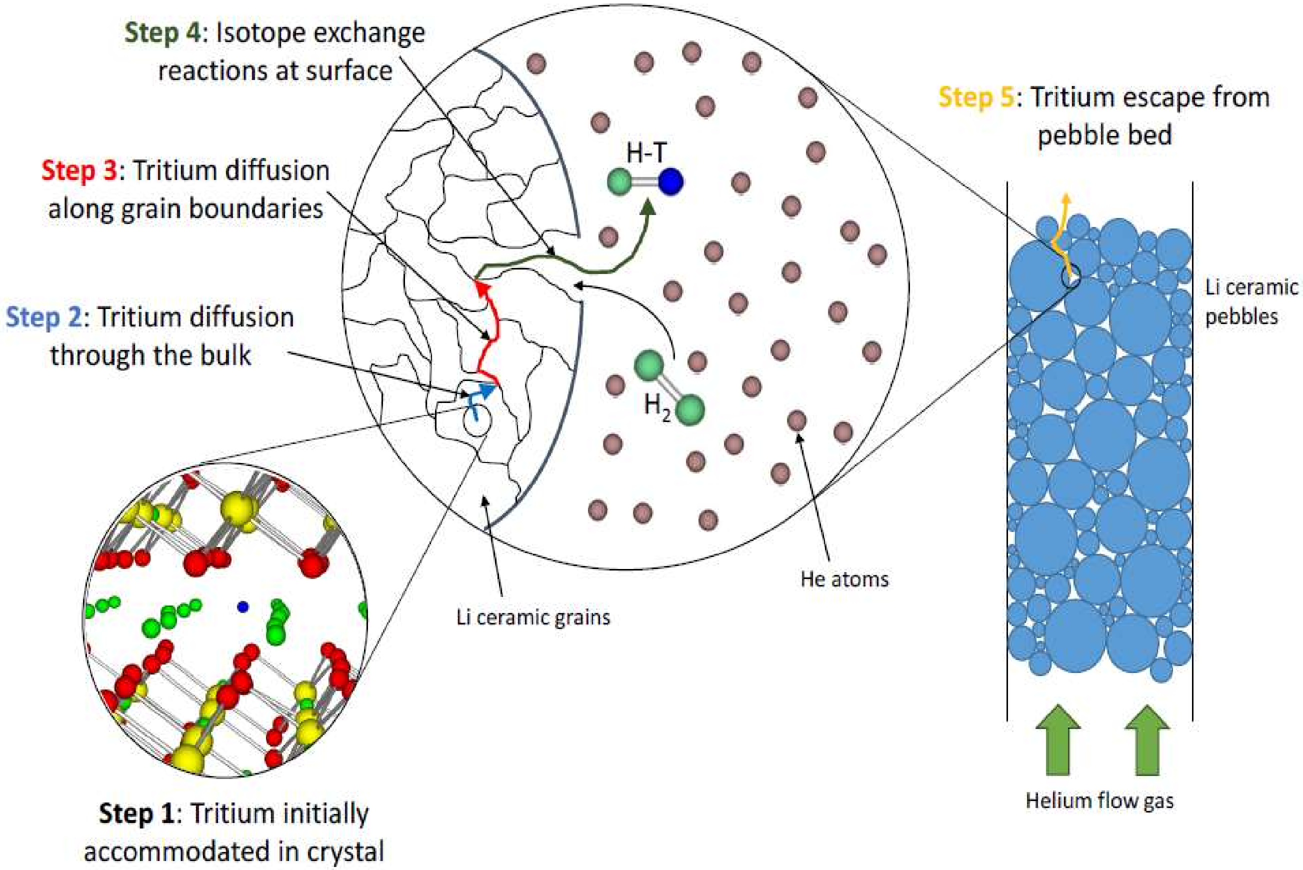
First of a kind high temperature irradiation of Pt

Safety concerns for Be/Li irradiation

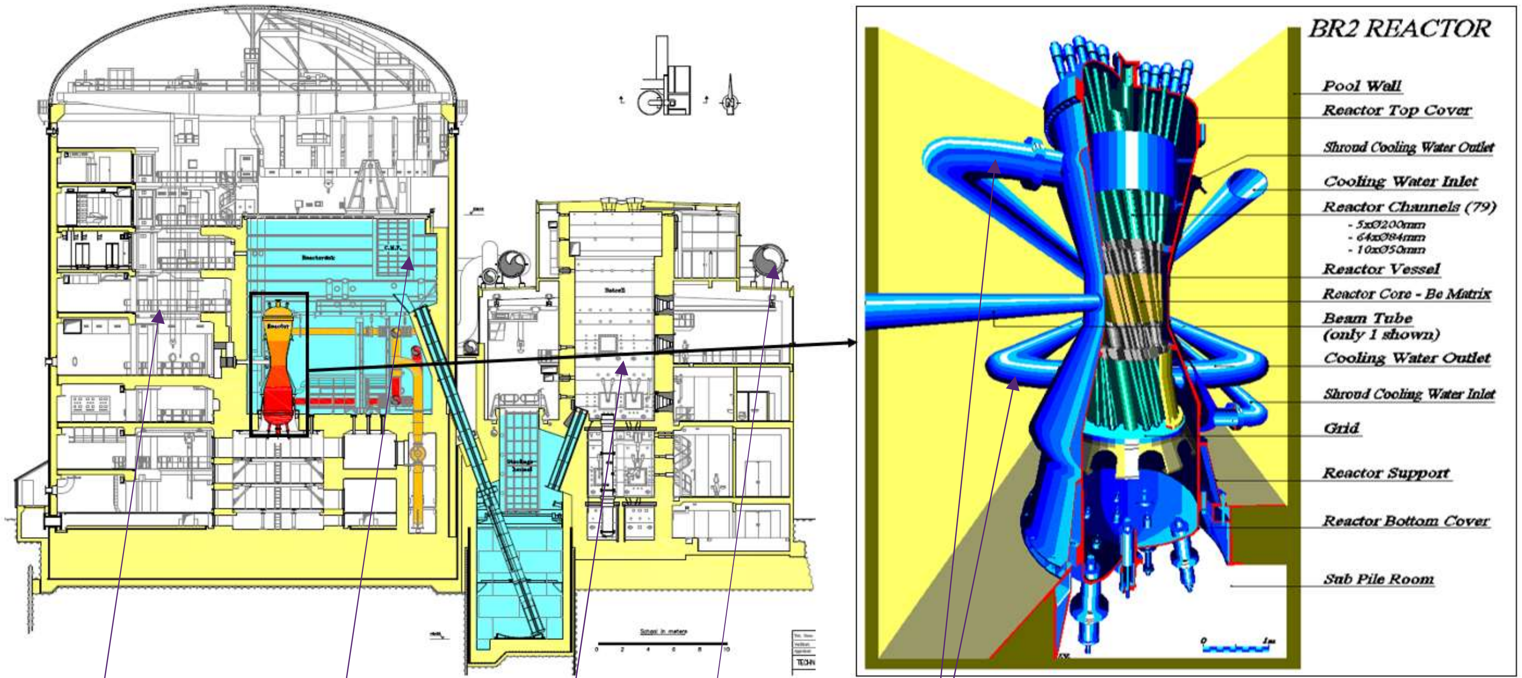
Issue	Response
Tritium (^3H) release during and after irradiation, during transportation	See further slides
Be-contamination before and after irradiation	All operation must be done in fume hood or glove box. Decontamination procedures.
Li-/Be- oxidation (assembly and post irradiation treatment)	Minimize exposure to air, control humidity if exposed to air, operation in glove box
Li chemical interaction with steel (for containment of the samples)	Apply Platinum for the containment of Li samples
Gas pressure build-up during irradiation due to production of ^3H and He	Estimation of the maximum possible pressure and qualification of the weld for this pressure level

Risk due to ^{3}H generation: physics

- Upon irradiation at elevated temperature, ^{3}H release from the samples is unavoidable
- Diffusion of ^{3}H through the welds/brazing joints is postulated by the safety, because opposite cannot be proven
- Continuous and Sudden ^{3}H release to various **Reactor Systems** is postulated by the safety => assessment is needed



Risk due to ^{3}H generation: Reactor Systems



BR2 containment atmosphere

BR2 pool water

BR2 hot cell

BR2 chimney

BR2 coolant loop

1. *BR2 primary water coolant loop*
2. *BR2 pool water*
3. *BR2 containment atmosphere*
4. *BR2 hot cell/BR2 chimney*

Each System has its own upper release limit

Exceeding the limit leads to different response such as:
- *Stop of Reactor operation*
- *Evacuation of the building*
- *Site emergency and evacuation of SCK CEN personnel*

Operation of Reactor and Safety approach

Tritium release

The main accident scenarios are:

1. ***BR2 primary water*** → *during the irradiation all the capsules fail and all the tritium gas is supposed to be absorbed in the BR2 primary water.*

2. ***BR2 pool water*** → *during capsule manipulation inside the BR2 pool water (after irradiation), all the capsules fail and all tritium generated during the irradiation will be absorbed inside the BR2 pool water.*

3. ***BR2 containment atmosphere*** → *during the manipulation of the capsules inside the BR2 pool water, all the capsules fail and all tritium generated during the irradiation migrates in the BR2 containment atmosphere.*

4. ***BR2 hot cell/BR2 chimney*** → *during the manipulation of the capsules inside the BR2 hot cell, all the capsules fail and all tritium generated during the irradiation migrates in the hot cell atmosphere. After the tritium has migrated into the atmosphere of the BR2 hot cell it is sent to the BR2 chimney to be dispersed into the environment.*

*(**conservative assumptions: NO ventilation and all the capsules fail simultaneously**)*

Risk due to ^{3}H generation: Be-based samples

- The total activity (33g beryllium) due to the Tritium is equal to:

$$A_{tritium} = 7{,}18 \cdot 10^{8} \left[\frac{Bq}{g}\right] \cdot 33[g] = \mathbf{2{,}37 \cdot 10^{10}[Bq]} \approx \mathbf{2{,}4 \cdot 10^{4}[MBq]}$$

- Activation of pure Be is driven by ^{3}H
- Activation of $Be_{12}V$/$Be_{12}Ti$ is driven by ^{46}Sc ($T_{1/2}$=83.79 d), ^{47}Sc ($T_{1/2}$=3.351 d), ^{48}Sc ($T_{1/2}$=1.82 d) , ^{49}Sc ($T_{1/2}$=57.2 min), ^{51}Ti ($T_{1/2}$=5.80 min) and ^{52}V ($T_{1/2}$=3.745 min)

$$Be_9 + n \rightarrow He_6 + H_3$$
$$He_6 \rightarrow Li_6 + \beta^- + \nu$$
$$Li_6 + n \rightarrow He_4 + H_3$$

Safety limits are respected

Environment of the accidental release	Calculated expected values		Limits	
Tritium release in the BR2 primary water	160	MBq/m^3	400	MBq/m^3
Tritium release in the BR2 pool water	27,6	MBq/m^3	3360	MBq/m^3
Tritium release in the BR2 containment atmosphere	1	MBq/m^3	4	MBq/m^3
Tritium release in the BR2 hot cell	2,4e4	MBq/m^3	2,22e9	MBq/m^3
Tritium release in the BR2 chimney	2,4e4	MBq/m^3	1,19e9	MBq/m^3

Risk due to ^{3}H generation: Li-based samples

$$Li^6 + n \rightarrow He^4 + H^3 + 4.8\ MeV$$

- The total activity (12g LMT @ 3 dpa) due to the Tritium is equal to:

$$A_{tritium} = 0{,}3\left[\frac{TB}{g}\right] \cdot 30[g] = \mathbf{9[TBq] \approx 25\ mg\ of\ {}^3H}$$ => ITER_TBM end of DT1 is 30-50 mg of ^{3}H

- Given violation of the limits, additional safety measures must be taken:
  - Double barrier encapsulation of the specimens during irradiation and transportation
  - Continuous monitoring of ^{3}H in each Reactor System

Safety limits are violated

Environment of the accidental release	Calculated expected values		Limits		Dose
Tritium release in the BR2 primary water	60	GBq/m³	4	GBq/m³	
Tritium release in the BR2 pool water	10,6	GBq/m³	4	GBq/m³	
Tritium release in the BR2 containment atmosphere	383	MBq/m³	4* 100**	MBq/m³ MBq/m³	4 µSv
Tritium release in the BR2 hot cell and BR2 chimney	9	TBq	43,6*** 1190****	TBq TBq	

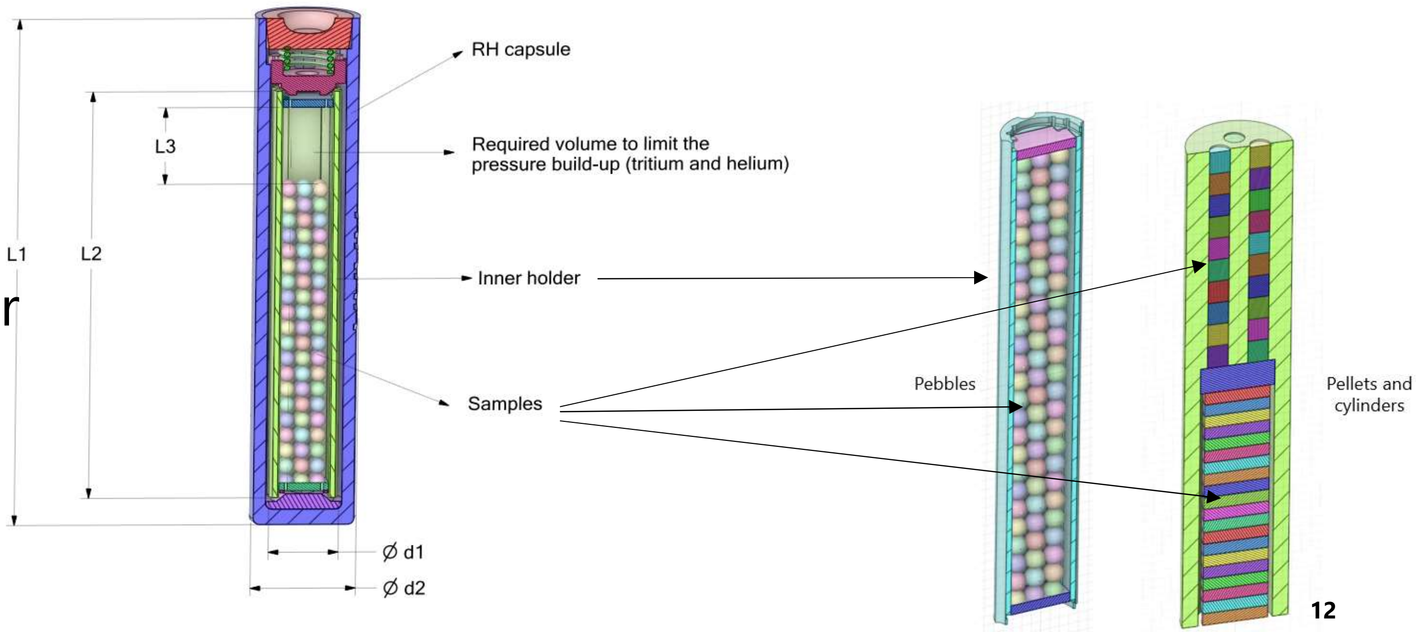
* H alarm
** HH alarm
*** monthly release limit
**** annual release limit

Design or irradiation devices: Be-based samples

- Single encapsulation inside stainless steel capsule
- Use tungsten as holders for Be samples (to ensure sufficient heating)
- Be-W chemical compatibility study (to avoid risk of galvanic corrosion)
- Assembly in fume hood
- Welding in glove box (He)
- After irradiation:

opening of capsules in dry air

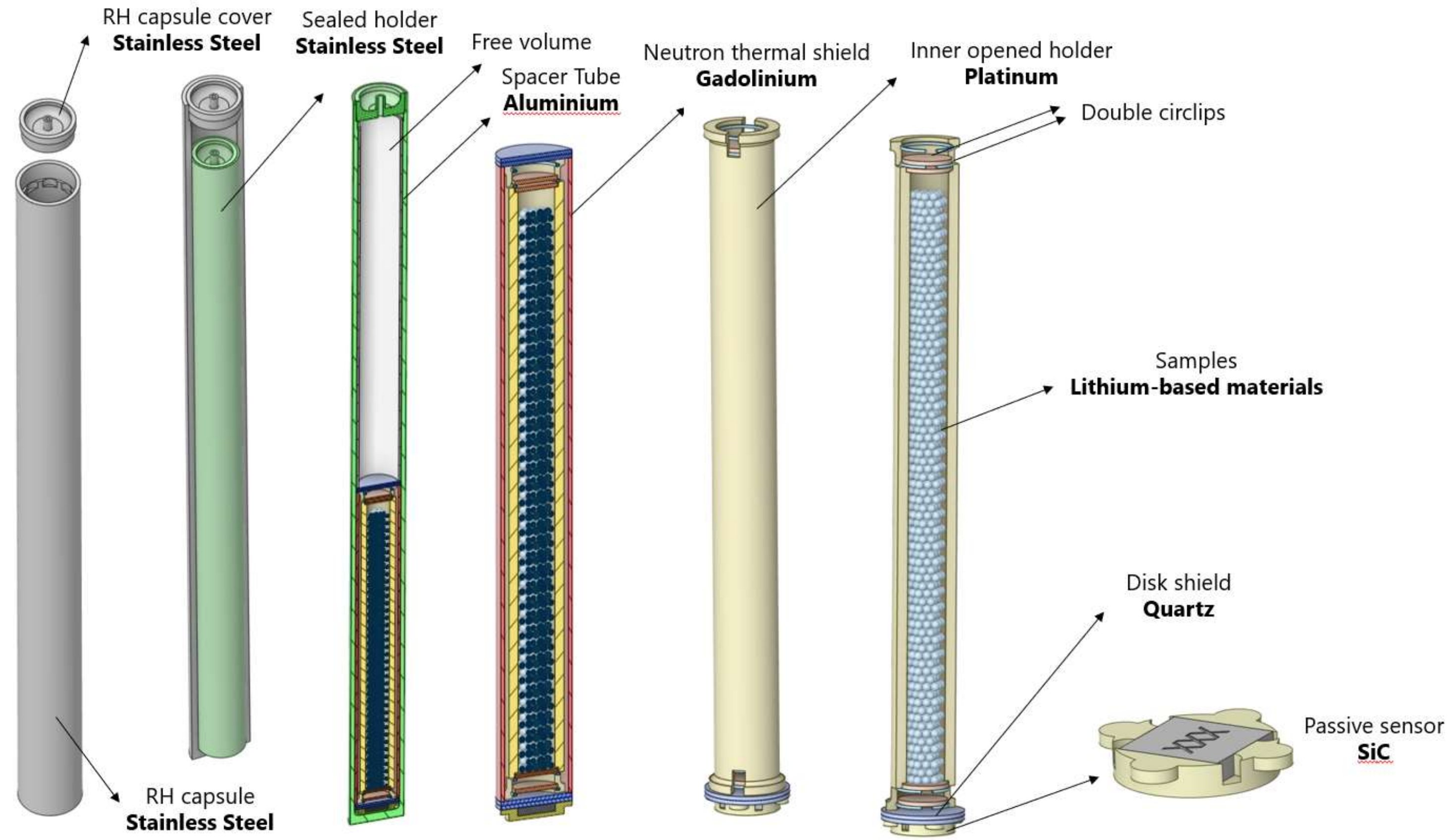
Transfer of Be inside holders



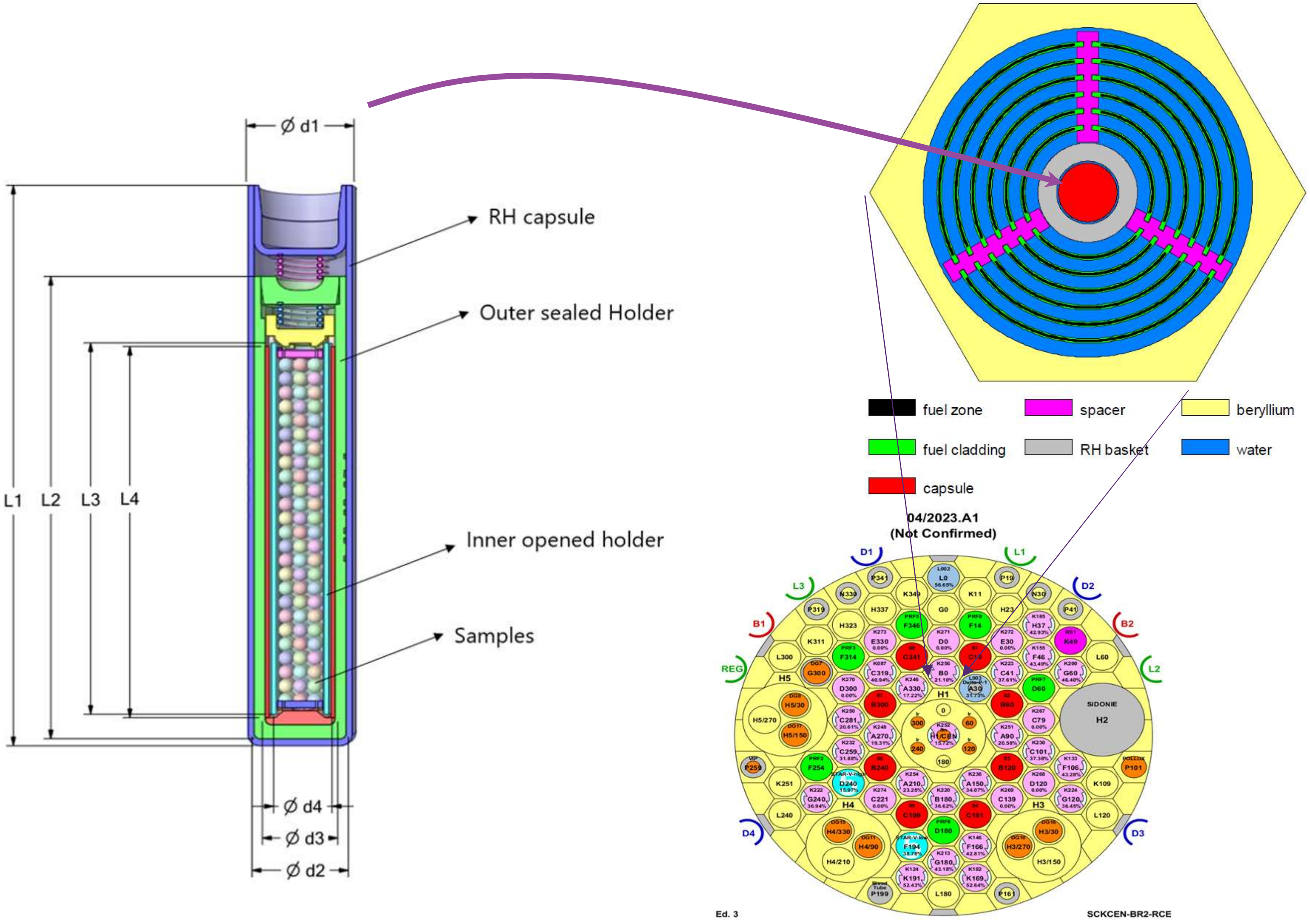
Design or irradiation devices: Li-based samples

- Double encapsulation in S
- Gd shield to reduce ^3H tra
- Pt holder for specimens
- Gd/SS and Gd/Pt compati
- Assembly in dry air fume
- Welding in glove box (He)
- After irradiation:

Capsules will be transportec is to avoid possible release

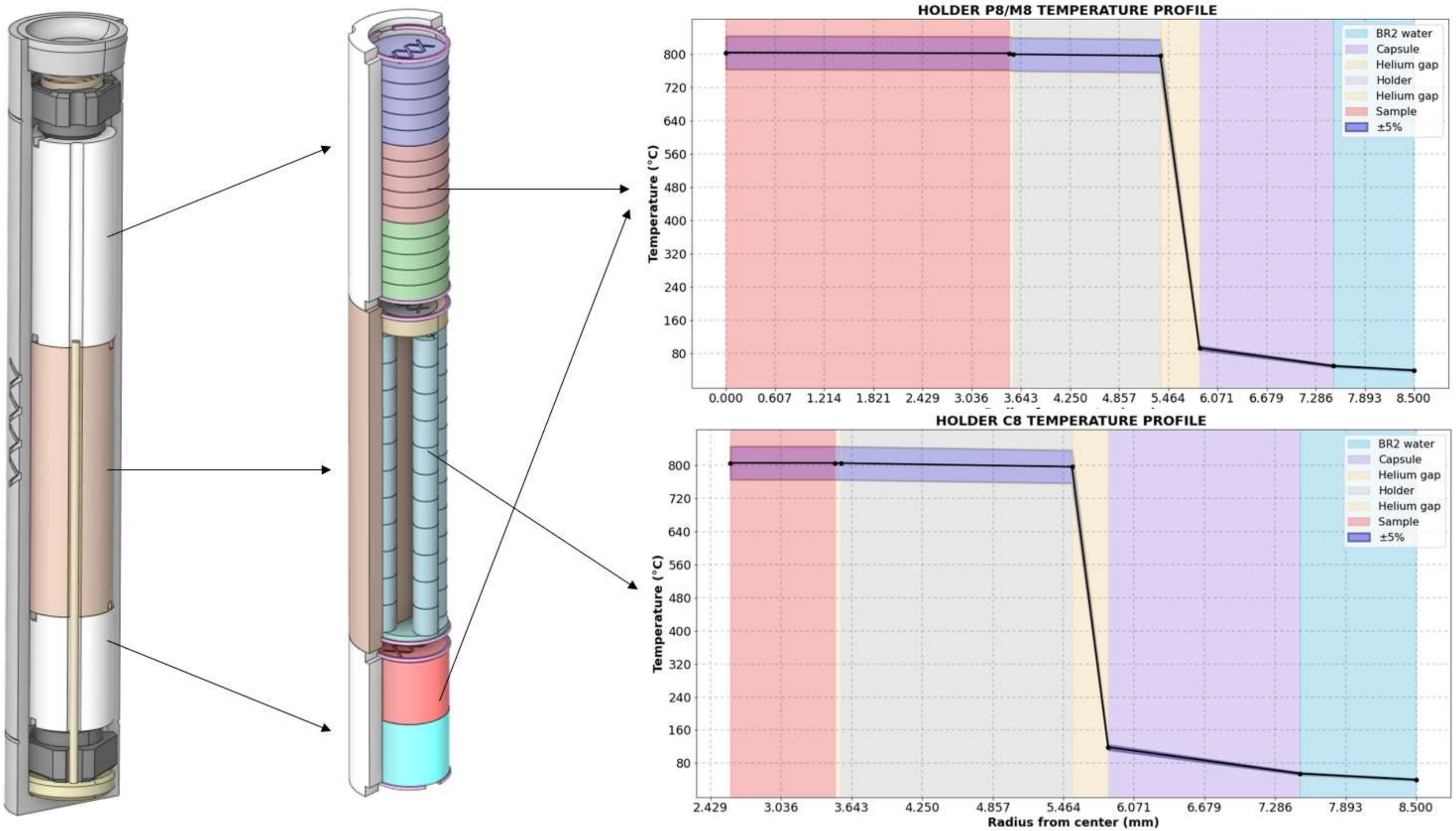


Selection of irradiation channel



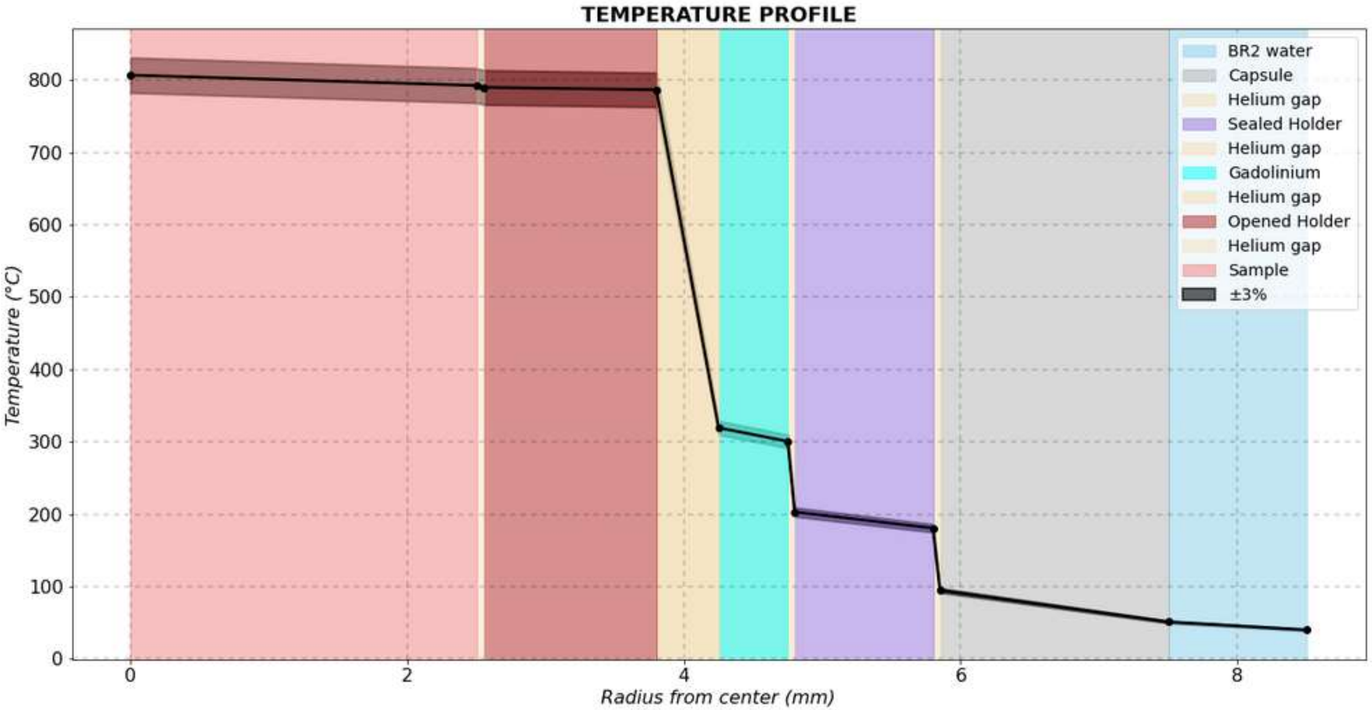
Expected irradiation temperature: Be

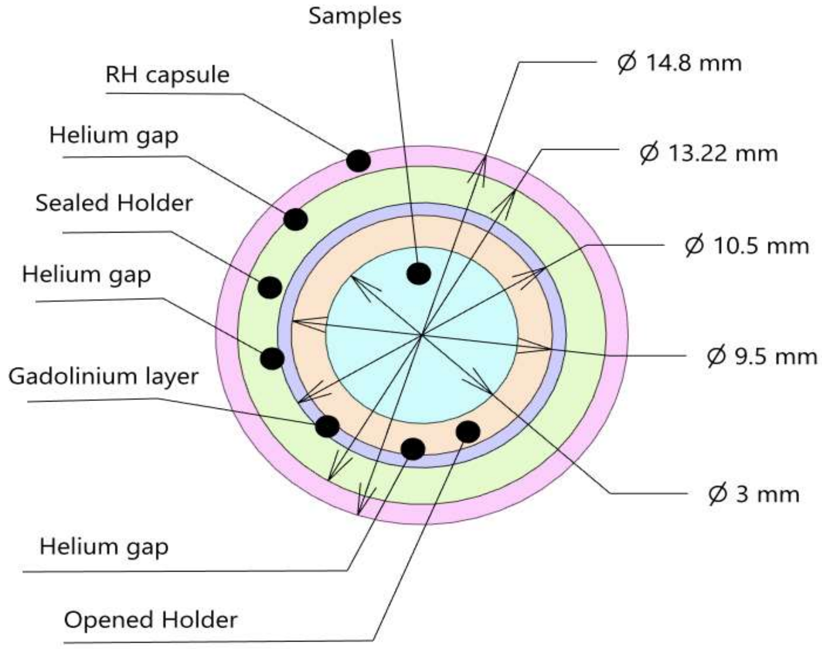
- in-cycle temperature variation is ~5% of the absolute temperature
- Inter-cycle temperature variation is ~5% of the absolute temperature



Expected irradiation temperature: Li

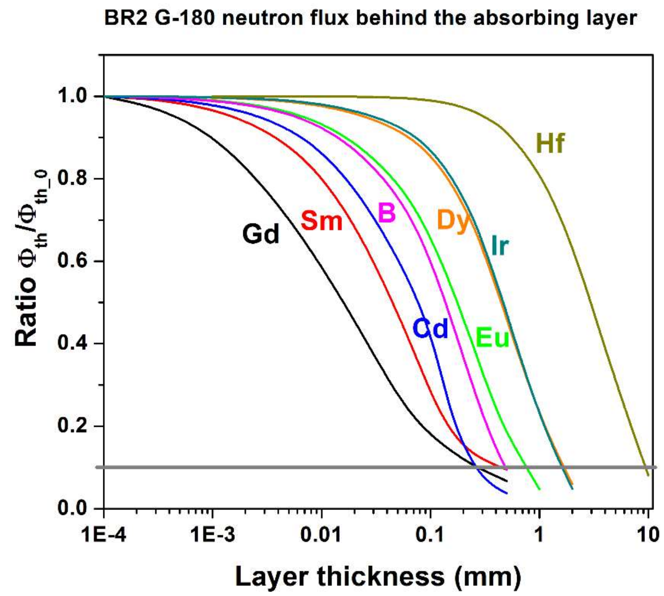
- in-cycle temperature variation is ~8% of the absolute temperature
- Inter-cycle temperature variation is ~5% of the absolute temperature





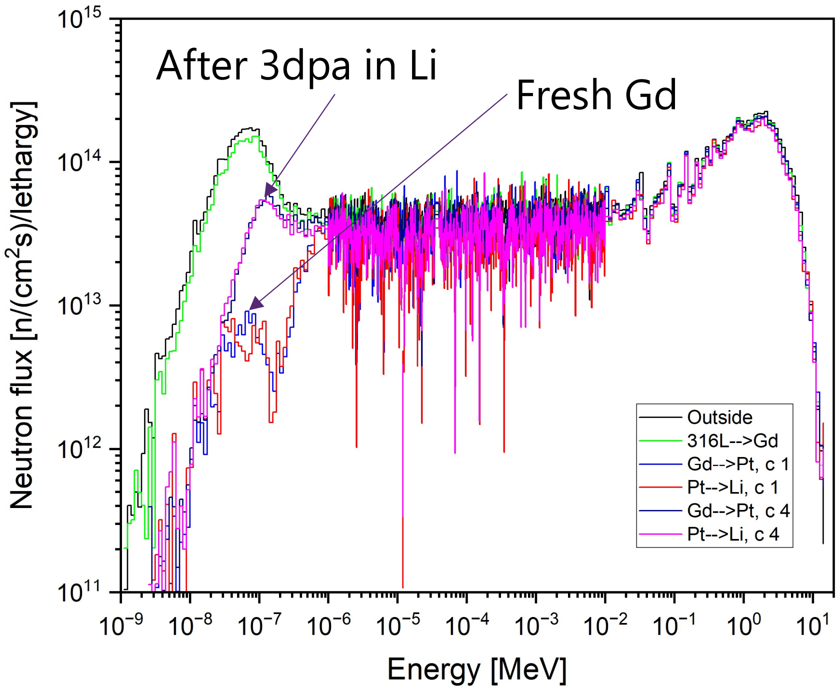
Thermal neutron shielding

- Objective is to reduce ^{6}Li/dpa burn-up rate down to 1.5%^{6}Li/dpa (dpa in ACB)
- Gd is selected based on compromise (safety, efficiency, cost, nuclear waste)
- 0.5 mm Gd shield reduces Li/dpa from 6.5 down to 2.8 in LMT (90% enrichment) at 2.5 dpa, thus respecting the requirement 1.5%^{6}Li/dpa

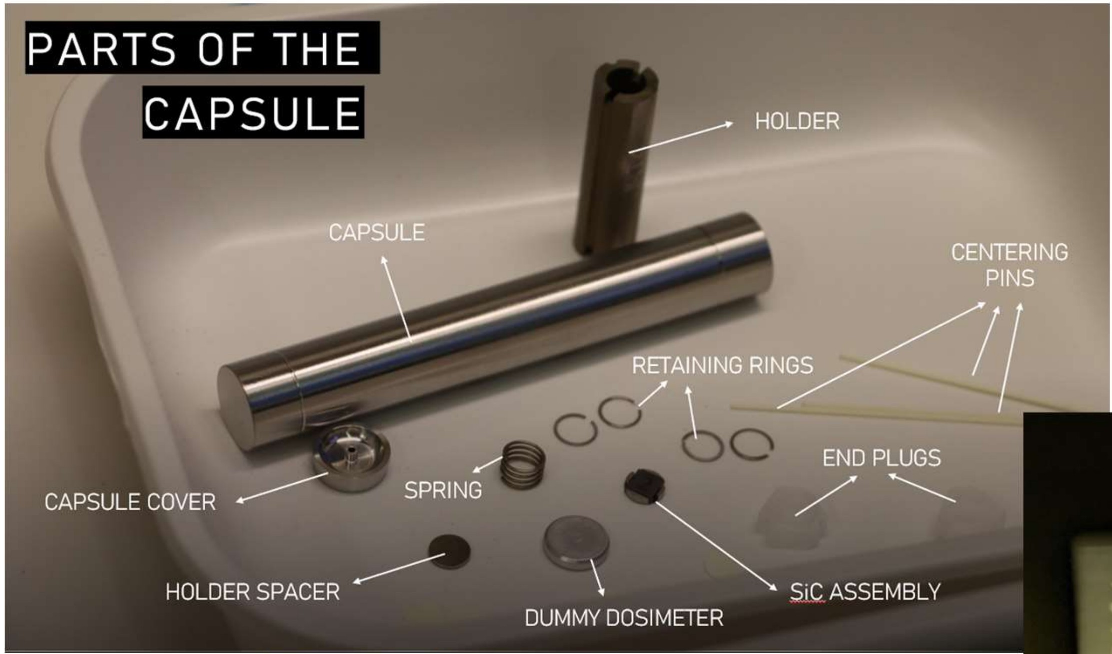


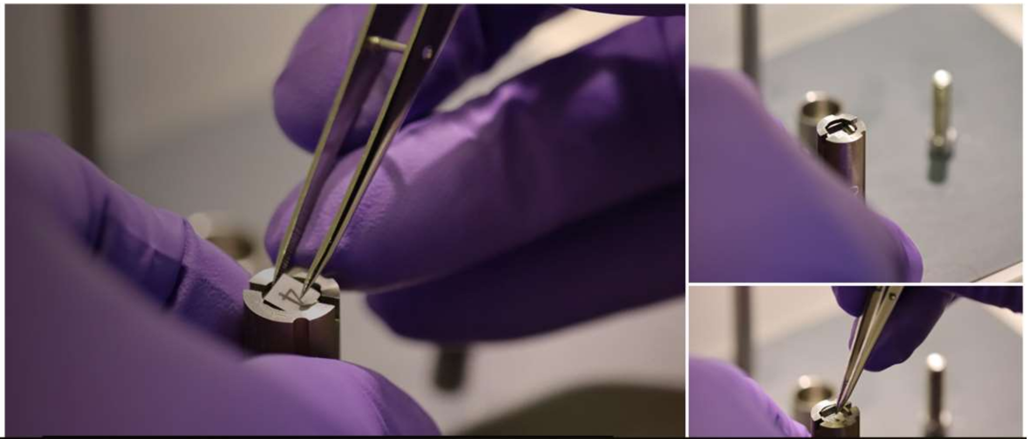
Materials with highest thermal capture cross section:

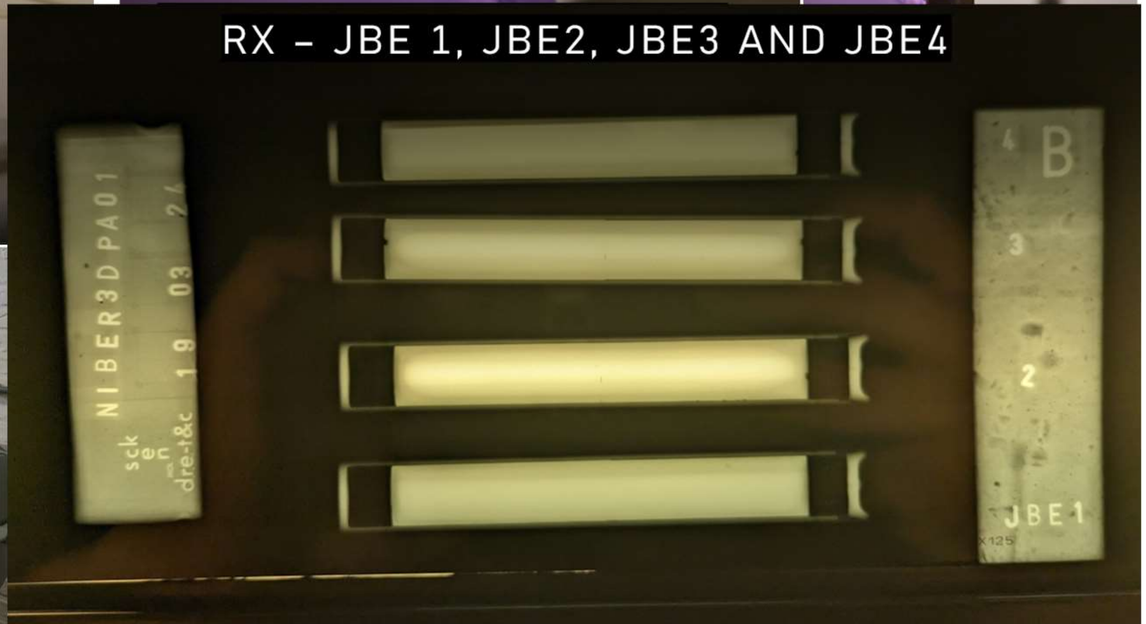
Elm.	σ_{th} (b)	Melting pt (°C)
Gd	49000	1312
Sm	5922	1074
Eu	4600	826
Cd	2450	321
Dy	920	1412
B	767	2076
Ir	425	2447
......		
Hf	104	2231



Assembly of irradiation devices: Be

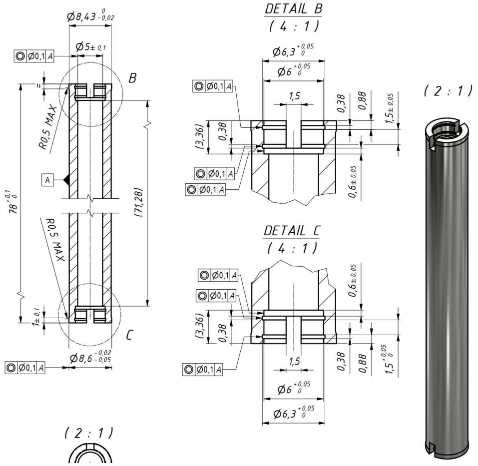


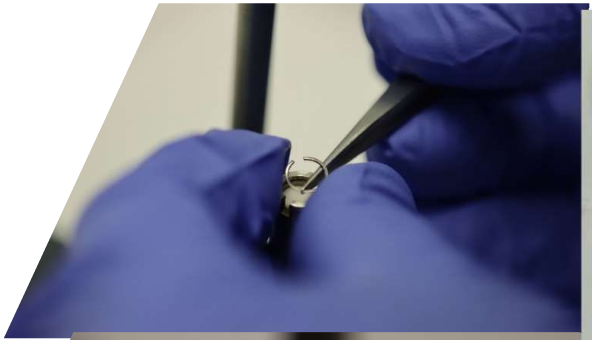


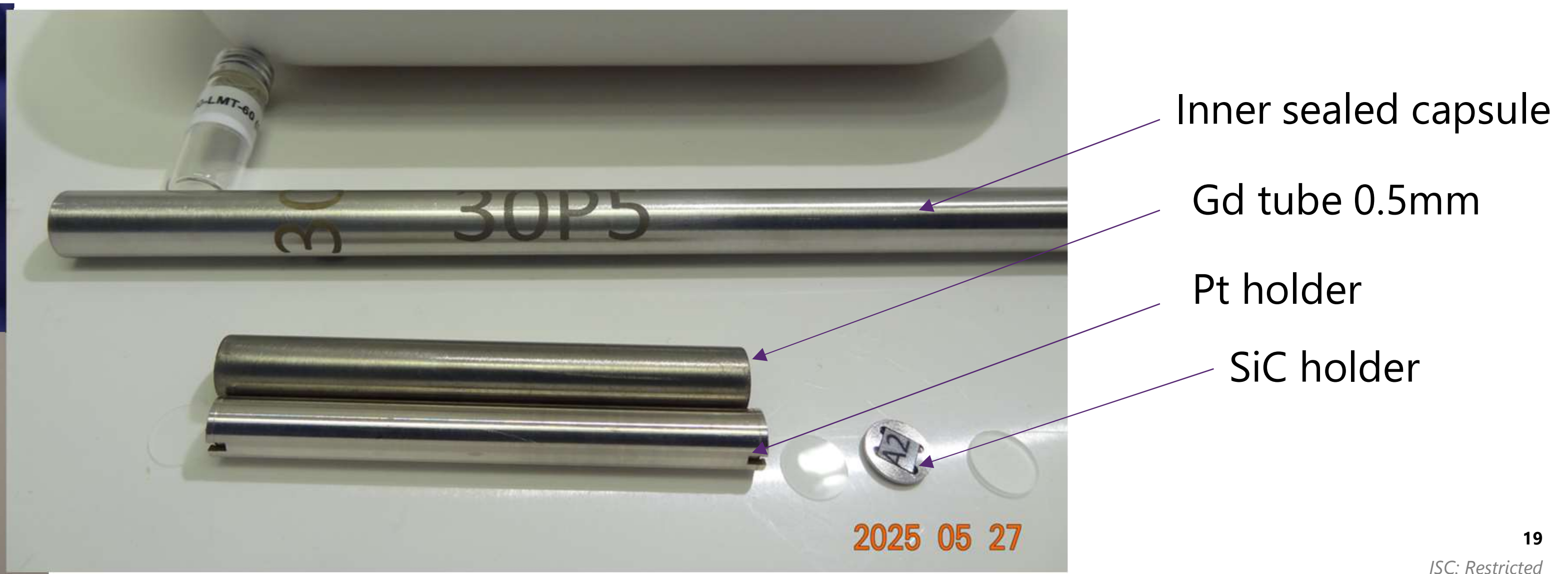


TIG – CIRCULAR WELDINGS

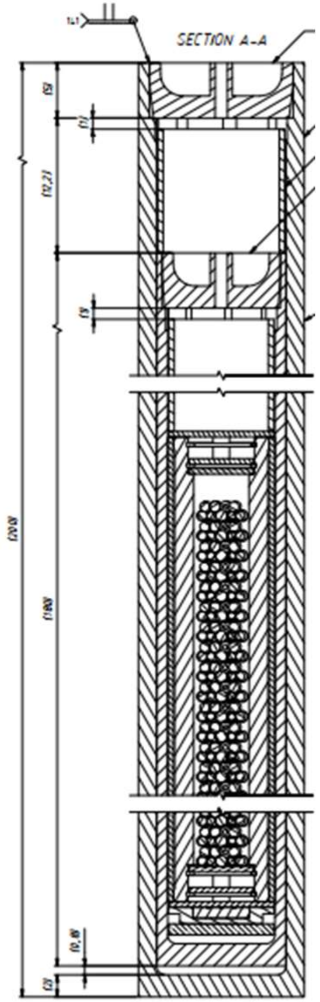
Assembly of irradiation devices: Li

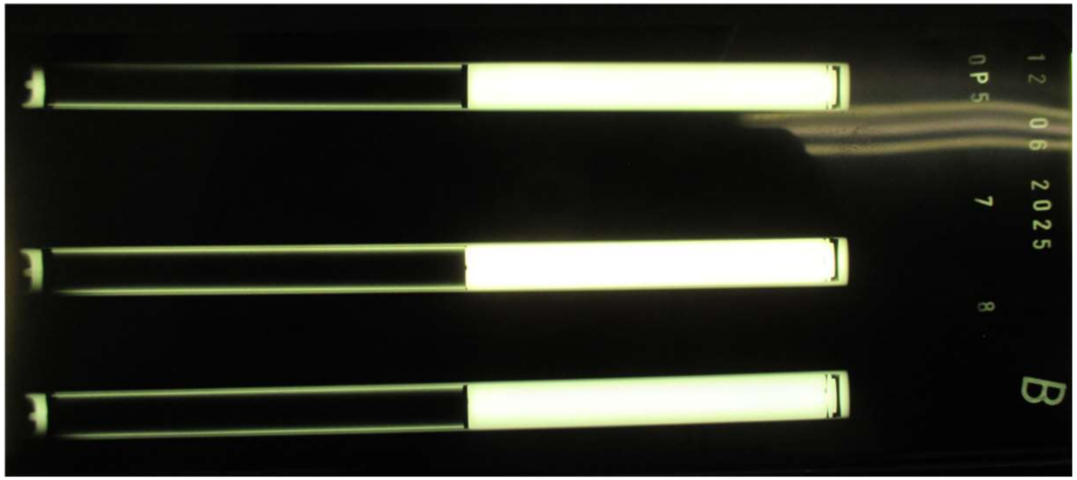






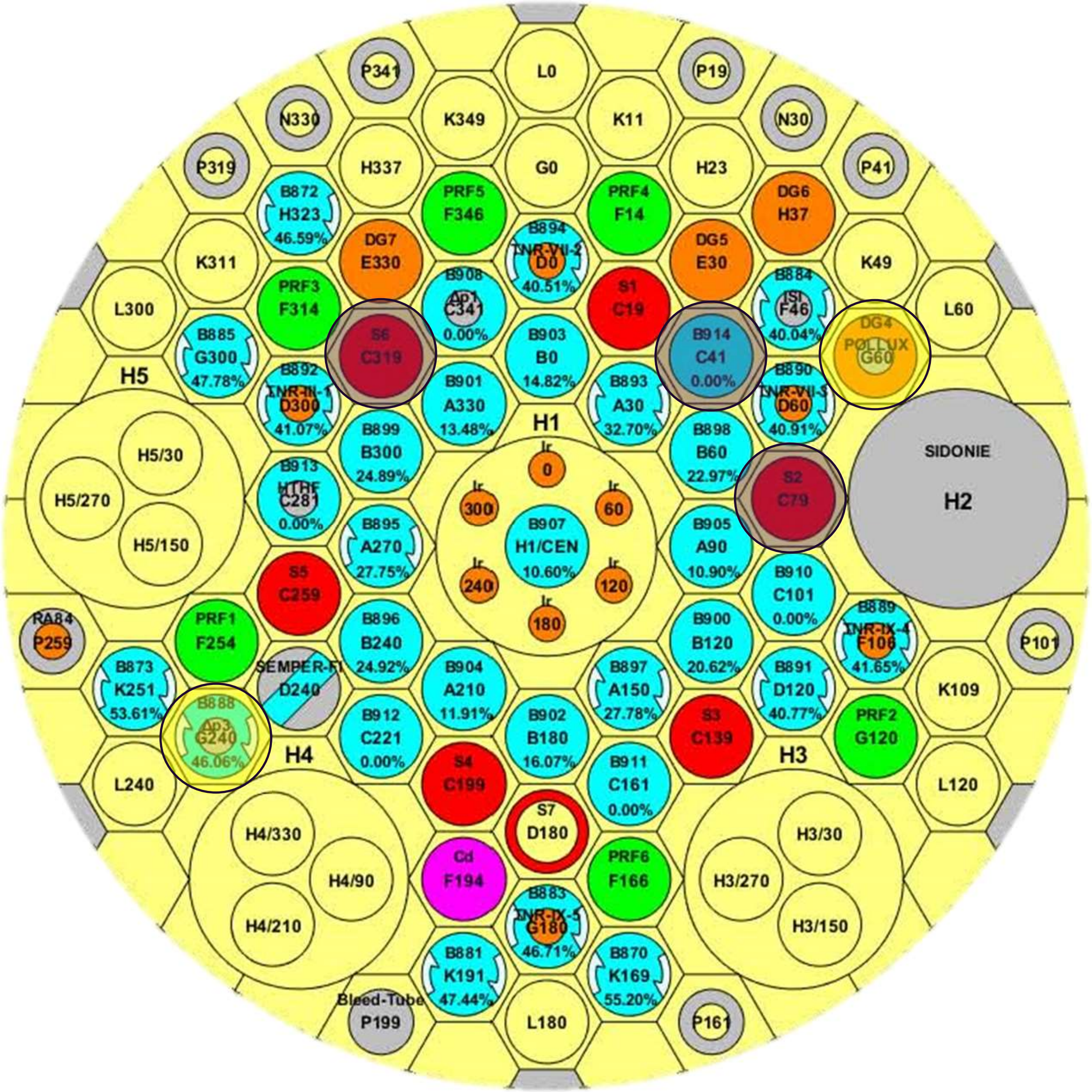
Assembly of irradiation devices: Li





Irradiation programme:

- Be samples: 9 irradiation capsules (3 rigs)
  - Channel 1 (C319)
  - Channel 2 (C79)
  - Channel 3 (C41)
- Li samples: 12 irradiation capsules (3 rigs)
  - Run 1
    - Channel 1 (G60)
    - Channel 2 (G240)
    - Channel 3 (C79)
  - Run 2
    - Copy of Run 1



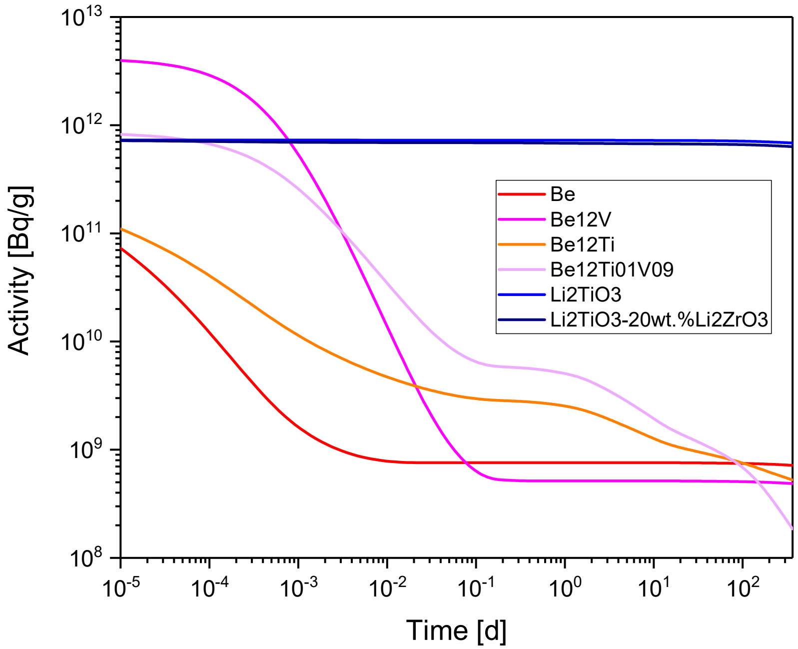
Overview of the Implementation

Irradiation of Be materials	2022	2023	2024	2025	2026
Conceptual Design					
Safety Analysis					
Detailed Design					
BR2 Safety Approval					
Procurement, Rig Manufacture, Assembly, Safety Tests					
Irradiation					
Dismantling and Transportation					

Irradiation of Li materials	2022	2023	2024	2025	2026
Conceptual Design					
Safety Analysis					
Detailed Design					
BR2 Safety Approval					
Procurement, Rig Manufacture, Assembly, Safety Tests					
Irradiation (Run 1)					
Dismantling and Transportation (Run 1)					

Transportation SCK CEN -> KIT

- For Be specimens:
  - Transportation inside W holders
  - Usage of B(U) container from KIT
  - Back-up1: A-type from SCK after 12 months cooling, transportation for 2026
  - Back-up2: extract samples from holders and use A-type from SCK by end of 2025
- For Li specimens:
  - Transportation of the whole capsule
  - Option 1: use B(U) or B-type container with sufficiently large cavity
  - Option 2: use A-type from SCK after sufficiently long cooling (for 2.5 dpa, cooling time is about 16 months, depending on cleanness of the capsule steel material)
  - Cooling time will be driven by ^{60}Co content in stainless steel



Conclusions

- Irradiation of Beryllides
  - No safety showstoppers
  - No exotic/safety sensitive materials are involved in rig construction
  - No ^{3}H safety concerns
  - Irradiation time to reach 3 dpa (in Fe) is 8 months (4-5 cycles of BR2), completed in July 2025
  - Transportation procedure yet to be proven
- Irradiation of Advanced Ceramic Breeder material
  - ^{3}H release to BR2 containment and through chimney is a risk, whose mitigation requires a number of technical solutions and its formal approval
  - Irradiation time to reach 2.5 dpa (in LMT) is 10 months (5-6 cycles of BR2), started in August 2025
  - Solution for transportation yet to be defined
  - Time drivers: ^{3}H safety file, qualification of weld (He pressure), tender for procurement (Pt and Gd)
  - Cost drivers: irradiation cost (high neutron absorption, 2 capsules per channel), ^{3}H safety file – onetime cost, Pt procurement

SCK CEN
Belgian Nuclear Research Centre

Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL