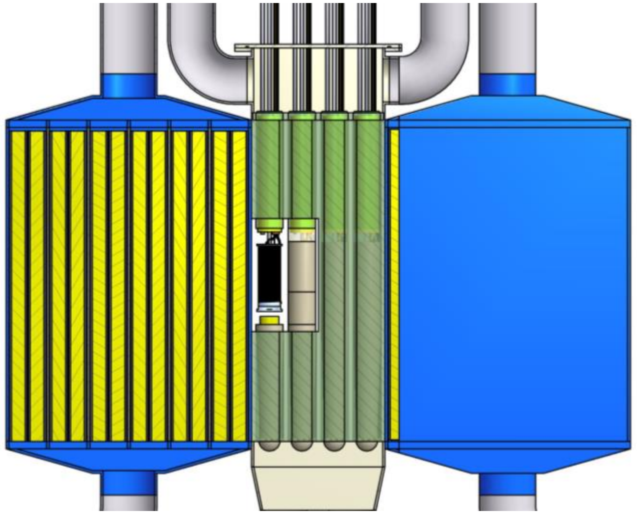
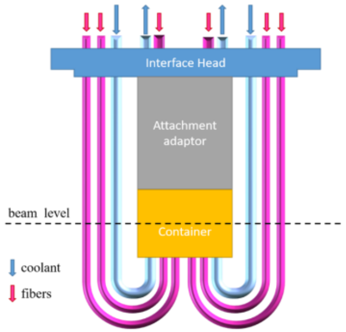
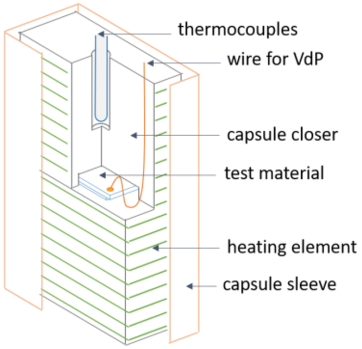
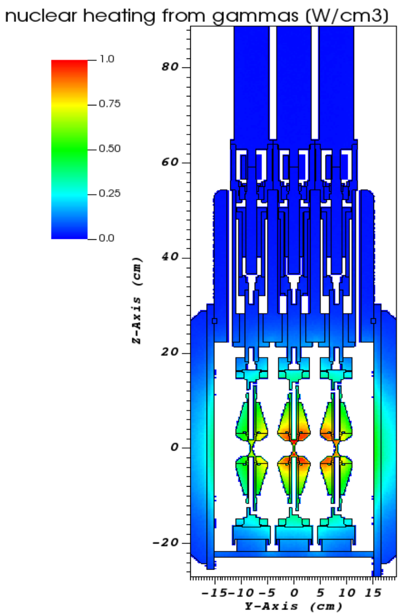
Oher irradiation modules proposals made in DONES PreP project





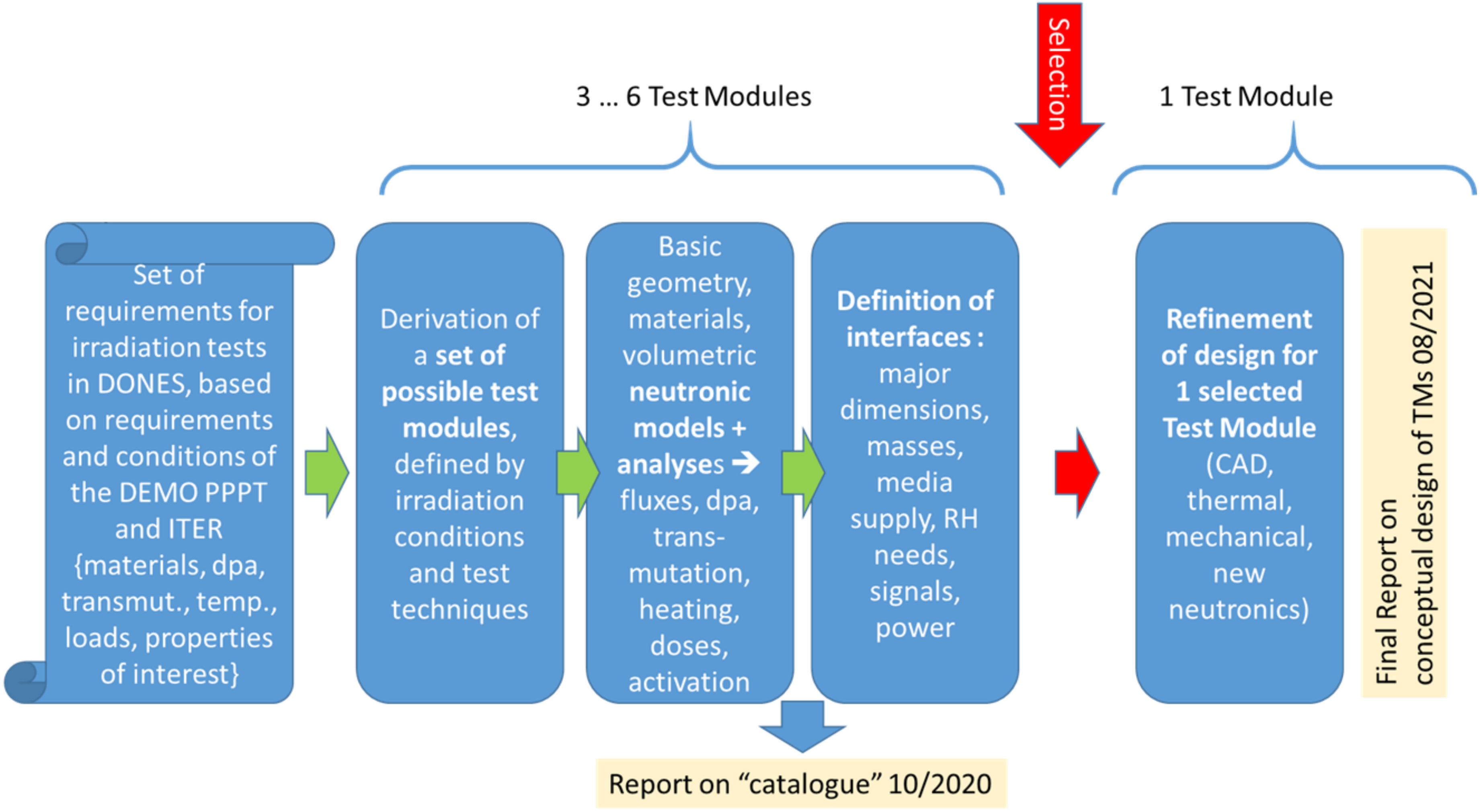




DONES PreP WP8.3 contributors

- WP8 leader Adam Maj (IFJ-PAN)
- WP8.3 coordinator Frederik Arbeiter (KIT)
- UKAEA (UK) technical contact Alex Valentine.
- IST/Uni Lisboa (Portugal) technical contact Norberto Catarino
- WUT/IPPLM (Poland) technical contact Lukas Ciupinski

WP 8.3 workflow



Review of top level documents on irradiation needs

- Documents that
  - Discuss the irradiation requirements of DEMO
  - Discuss the irradiation proposals for IFMIF, A-FNS etc.

[A1] P. Garin et al., **IFMIF specifications from the users point of view**, 2011 https://doi.org/10.1016/j.fusengdes.2011.01.109 or BA_D_224ERJ v1.1

[A2] D. Stork, **Materials R&D for a timely DEMO:** Key findings and recommendations of the EU Roadmap Materials Assessment Group, 2014 https://doi.org/10.1016/j.fusengdes.2013.11.007 or EFDA_D_2MJ5EU

[A3] G. Federici, **European DEMO design strategy and consequences for materials**, 2017, http://dx.doi.org/10.1088/1741-4326/57/9/092002

[A4] **IFMIF Intermediate Engineering Design Report** – Plant Design Document IIEDR Plant Design Description Document, BA_D_23NESY v1.0

[A5] Sato et al. 2020, Kwon et al. 2020, Ohta et al. 2020 :
Overview of test modules for Advanced Fusion Neutron Source A-FNS

Review of top level documents on irradiation needs

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- For each reference [A1] … [A5]
  - Discussion of **scope** of each contribution
  - Excerpt of **key statements** (referenced by ID numbers Ax-Sy)
  - Derived **consequences** for DONES

  were summarized.

- Key statements i.e. concerned
  - **Materials** (groups) of interest
  - **Applications** and significance (safety/non-safety) of materials
  - Envisaged **operation conditions** in DEMO (Temperature, load types and magnitudes, nuclear responses)

Classification of Irradiation experiments

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- <u>**Approach of measurement**</u>

- **PIE** : (Post Irradiation Examination) the quantities of interest are measured on the test objects after the objects have been irradiated (and extracted), usually in a dedicated facility. (Example: performing tensile tests on irradiated samples) . The samples are placed statically in the irradiation.
- **INS** : (In-Situ testing/measurements) some quantities of interest are measured during the irradiation in the irradiation position of the test objects (Example: applying cyclical loads and measuring load-deformation histories of creep-fatigue samples during irradiation)

- <u>**Class of measured properties**</u>

- **M** : mechanical properties (tensile, ductility)
- **P** : physical properties (thermal conductivity, electrical conductivity, hydrogen permeation/solubility, dielectric, optical, …)
- **S** : microstructure (TEM etc.)
- **N** : nuclear properties (activation, volumetric heating, shielding)

Classification of Irradiation experiments

- **Class of material / assemblies**

- **RAFM**: Reduced Activation Ferritic Martensitic steels (Eurofer, F82H)
- **VAN** : Vanadium alloys
- **ODS** : Oxide dispersion strengthened steels
- **CU** : Copper alloys (Glidcop, CuCrZr-IG, …)
- **W** : Tungsten materials and composites (W pure, laminates, fibres, gradings, …)
- **SIC** : Silicon Carbide materials and composites (SiC/SiC_f)
- **OPT** : optical materials or assemblies (windows, fibres, …)
- **INS** : electrical insulator materials or assemblies (ceramics, electrical feedthroughs, wires, heaters)
- **CB** : ceramic breeders (Lithium Orthosilicate, Lithium Metatitanate, …)
- **Be** : Berillium or beryllide neutron multipliers
- **LB** : liquid breeder (PbLi, FLiBe, …)
- **COAT** : coatings (anti permeation, flow channel inserts, …)
- **SC** : superconductors

- **Temperature levels of interest :** (Cryogenic up to 1200°C)

Building a calatogue of irradiation experiments

Systematic naming <Type-Measurements-Materials-Temperatures>

Name and short description of function

Tracing of the advocating reference statements

ID	Function	Req. statements	Comments
1	<PIE-MPS-RAFM-250-550C> : Test Module (TM) for the (unloaded) irradiation of RAFM SSTT specimens in the temperature range 250 – **550 °C** in the high flux zone, for PIE testing (HFTM) Options: (a) enable periodic temperature elevation for annealing (b) enable inclusion of creep tubes	A1-S1/2 A2-S1/2/3/5/6/12/(13)/19 A3-S1/2/3/6 A4-S1 A5-S1	Design exists
2	<PIE-MPS-Cu-100-3500C> : Test Module (TM) for the (unloaded) irradiation of copper alloy SSTT specimens in the temperature range **100** – 350 °C in the high flux zone, for PIE testing (HFTM-Cu) Note: largely identical to <PIE-MPS-RAFM-250-550C> low temperature to be explored, no immersion in Na.	A2-S1/4/5/6/17 A3-S1/4/	
3	<PIE-MPS-VAN+ODS-250-800C>: TM for the (unloaded) irradiation of ODS-RAFM or Vanadium SSTT specimens in the temperature range 200/400 – **750/800 °C** in the high flux zone, for PIE testing (HFTM-ET) Options: (a) enable periodic temperature elevation for annealing (b) enable inclusion of creep tubes	A1-S1/2 A2-S14 A5-S3	V/ODS are no EU baseline materials

Catalogue of Irradiation Experiments

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ID	Function	Req. statements	Comments
1	<PIE-MPS-RAFM-250-550C> : Test Module (TM) for the (unloaded) irradiation of RAFM SSTT specimens in the temperature range 250 – **550 °C** in the high flux zone, for PIE testing (HFTM) Options: (a) enable periodic temperature elevation for annealing (b) enable inclusion of creep tubes	A1-S1/2 A2-S1/2/3/5/6/12/(13)/19 A3-S1/2/3/6 A4-S1 A5-S1	Design exists
2	<PIE-MPS-Cu-100-3500C> : Test Module (TM) for the (unloaded) irradiation of copper alloy SSTT specimens in the temperature range **100** – 350 °C in the high flux zone, for PIE testing (HFTM-Cu) Note: largely identical to <PIE-MPS-RAFM-250-550C> low temperature to be explored, no immersion in Na.	A2-S1/4/5/6/17 A3-S1/4/	
3	<PIE-MPS-VAN+ODS-250-800C>: TM for the (unloaded) irradiation of ODS-RAFM or Vanadium SSTT specimens in the temperature range 200/400 – **750/800 °C** in the high flux zone, for PIE testing (HFTM-ET) Options: (a) enable periodic temperature elevation for annealing (b) enable inclusion of creep tubes	A1-S1/2 A2-S14 A5-S3	V/ODS are no EU baseline materials
4	<PIE-MPS-W+SIC-1200C> : TM for the (unloaded) irradiation of SiC/SiC or Tungsten SSTT specimens in the temperature range up to **1100/1200 °C** in the high flux zone, for PIE testing (HFTM-HT)	A1-S1/2 A2-S4/5/6/(16) A3-S1/2/(5)/(10) A5-S3	Concept exists (analog TRTM)
5	<INS-M-RAFM-550C> : TM for the **in-situ** creep/fatigue/crack-growth loading & measurement of RAFM specimens in the temperature range 250 – **550 °C** in the high flux zone, for PIE testing (ICFTM) (base materials, welds, dissimilar welds ; optionally multiaxial loads)	A1-S3/1 A2-S1/2/8/(9)/12 A3-S1/2/3/6 A4-S3 A5-S5	IFMIF/ EVEDA CFTM concept exists
6	<INS-M-VAN+ODS-800C> TM for the **in-situ** creep/fatigue/crack-growth loading & measurement of RAFM-ODS or Vanadium specimens in the temperature range 300/400 – **750/800 °C** in the high flux zone, for PIE testing (ICFTM-ET) (base materials, welds, dissimilar welds ; optionally multiaxial loads)	A1-S3/1 A2-S1/2/8/(9)/14	IFMIF/ EVEDA CFTM concept exists
7	<INS-M-W+SIC-1200C> TM for the **in-situ** creep/fatigue/crack-growth loading & measurement of tungsten and SiC specimens in the temperature range up to **1100/1200 °C** in the high flux zone, for PIE testing (ICFTM-HT) (base materials, welds, dissimilar welds ; optionally multiaxial loads)	A1-S3/1 A2-S1/2/8/(9)/4 (*) not sure if the mechanical fatigue of W must be studied	
8	"Model blanket module" addressing material compatibility (coolant/structure/breeder/purge gas), welds, multiaxial loading, dimensional stability (MBM)	A1-S3 A2-S1/2/6/7/8/9/10/11/ A3-S6/11	
9	"Model blanket module" addressing hydrogen permeation (MBM-Perm)	A1-S3 A2-S15	
10	<PIE-MP-CB+Be+INS+COAT-1000C> TM for the irradiation of ceramic breeder materials or Be, Insulators, coatings, diagnostics in the temperature range 300 – 1000 °C in the high flux zone, for PIE of dim.stability, microstruct.stabil., therm.cond., tritium diffusivity, fracture toughness(+other mechanical), chem.composition (CBIM)	A1-S4/5/7/9/11/13 (A3-S8)	Concept exists (TRTM)
11	<INS-P-CB+Be+INS-1100C> TM for the in-situ irradiation and testing of ceramic breeder materials or Be in the temperature range 300 – 1000 °C in the high flux zone, measuring (time resolved) tritium release (ICBIM)	A1-S4/6/12 A4-S4 A5-S4	Concept exists (TRTM)
12	<INS-P-LB-1000C> TM for the in-situ irradiation and testing of liquid breeder materials and coatings (tritium release/recovery/permeation (ILBIM)	A1-S8/10 A4-S5	IFMIF/ EVEDA LBVM concept exists
13	<INS-P-INS-Diagnostics-20-500C> TM for the in-situ irradiation and test of electrical conductivity, optical transmission, radioluminescence, permeation (IIDIM) Note: realistic lower temperature is 60-100°C in DONES without special arrangements.	A1-S11/14 A3-S8 A5-S6	
14	<PIE-PM-SC-Cryogenic> TM for the irradiation of superconductors irradiated at cryogenic temperatures, at low nuclear heating and low damage (0.01dpa), for PIE measurement of superconducting parameters and mechanics (SCIM)	A1-S15	Not yet investigated
15	<INS-PM-RAFM+Cu-100-500C> TM to test corrosion of structural/heat sink materials in the presence of flowing media (water, helium, liquid metal), irradiation and (cyclic) loads (SCC, IASCC) (See also #8)	A1-S3 A2-S6/10/11 A3-S11 A5-S4	Water should be avoided in TC
16	A device to load armor materials (W) with Plasma (erosion) and heat flux under neutron irradiation	A2-S16	Not yet investigated
17	<INS-P-RAFM+Cu-300-550C> TM to measure Tritium retention and permeation through/in structures touched by purge gas or coolant during neutron irradiation	A3-S9	
18	<INS-P-W-500-1200C> TM to measure Tritium retention and permeation through/in armor material	A2-S15	
19	TM to perform irradiation of Vacuum vessel materials (presumably 316L stainless steel) under low fluence and low temperatures	A2-S18 A3-S7	installation in low flux region
20	A Radioisotope production device, i.e. for Mo-99	A5-7	

20 entries

Irradiation Experiments advanced during DONES-PreP

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- Adaptation to DONES conditions of the design of the **<INS-M-RAFM-550C>** basing on the Creep Fatigue Test Module CFTM already developed for IFMIF during the IFMIF/EVEDA phase, by Polytechnika Warszawa, with support in neutronics by IPPLM

  “In-Situ Creep Fatigue Test Module” (CFTM)

- Adaptation to DONES conditions of the design of the **<INS-P-CB+Be+INS-1100C>** basing on the Tritium Release Test Module already developed for IFMIF during the IFMIF/EVEDA phase, by KIT Germany, with support in neutronics by UKAEA United Kingdom.

  “In-Situ Ceramic Breeder Irradiation Module” (ICBIM)

- New conceptual design of the **<INS-P-INS-Diagnostics-20-500C>** by IST / Uni Lisboa Portugal.

  “In-Situ Irradiation Module for Diagnostics” (IIMD)

Table of contents for the Concept DDDs

In-Situ Creep Fatigue Test Module (ICFTM)

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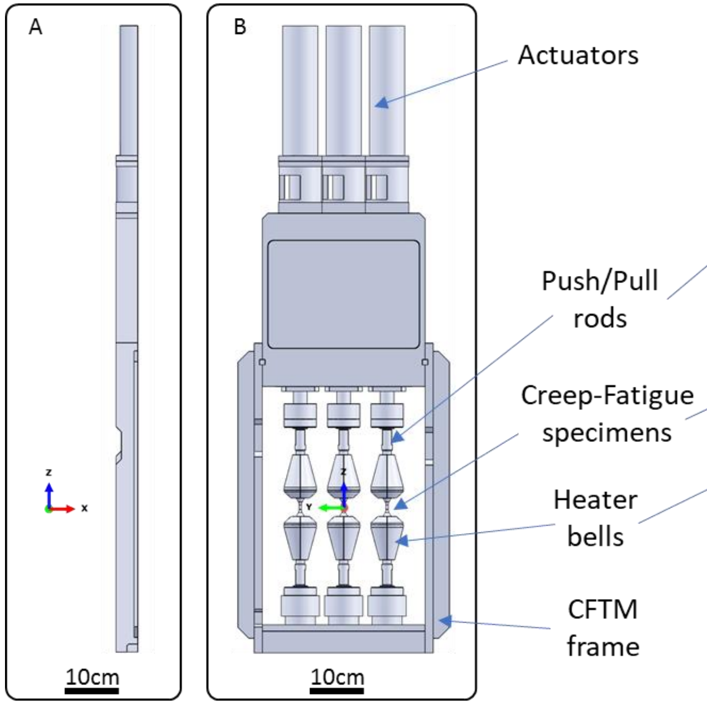
Mode of operation

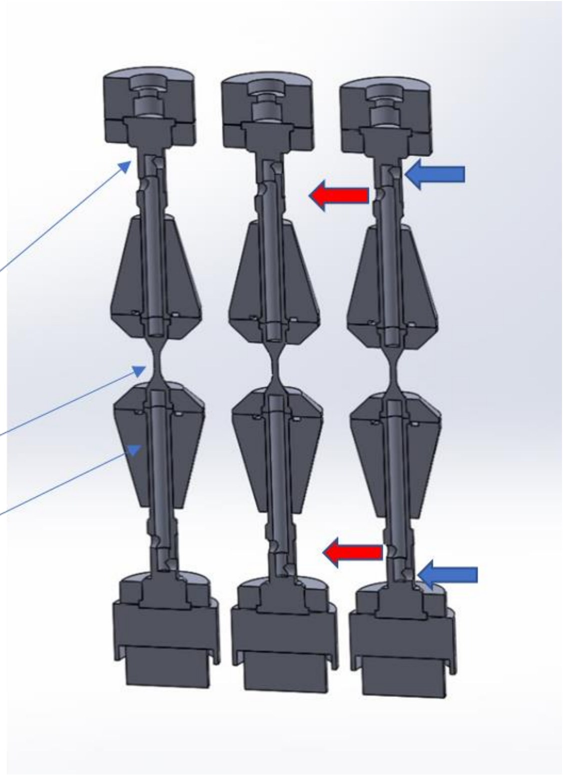
<INS-M-RAFM-550C> : TM for the in-situ creep/fatigue/crack-growth loading & measurement of RAFM specimens in the temperature range 250 – 550 °C in the high flux zone (ICFTM) (base materials, welds, dissimilar welds ; optionally multiaxial loads)

Speciemens are installed in the CFTM and are loaded and measured during neutron irradiation until break or end of test. The results are the recorded forces and elongations over time.

- To impress and measure controlled load cycles (force, displacement) on the specimens
- To maintain predefined temperatures (250 – 550 °C)

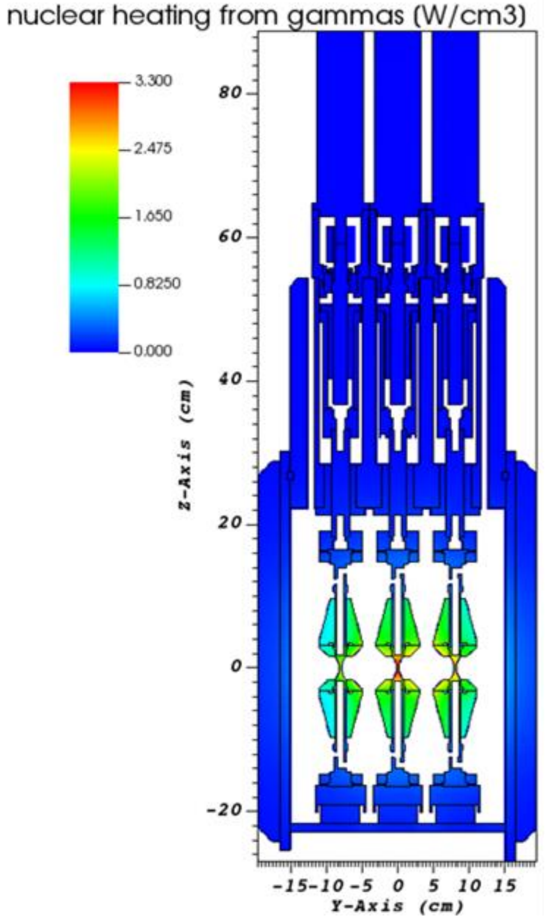
ICFTM design overview

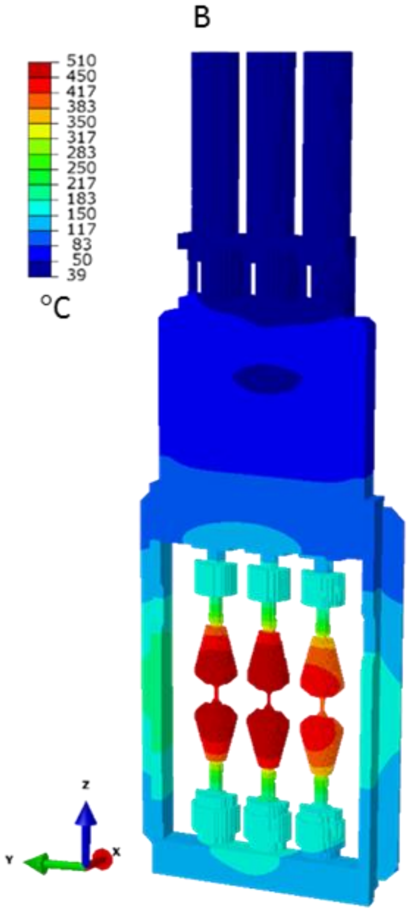




- Helium cooled frame
- 3 actuators, push/pull rods and specimen holders
- Nuclear-heated tungsten bells for passive heating
- Possibility of He cooling of specimen end surfaces

ICFTM irradiation conditions in DONES





[L. Ciupinski (WUT), B. Bienkowska (IPPLM)]

- Installation *behind* HFTM
- Allows controlled actuation (load/displacement) of specimens inside the neutron flux
- Maximum nuclear heating
  - 3.3 W/cm³ in specimen
  - 0.8 – 2.5 W/cm³ in tungsten bells
- Maximum achievable temperature ~ 500 °C (passive)

Eurofer	Specimen 1	Specimen 2	Specimen 3
Displacement damage rate [dpa/fpy]	1.467 ± 0.001	1.670 ± 0.001	0.9463 ± 0.0009
Helium production [appm/fpy]	0.0873 ± 0.0002	0.0992 ± 0.0003	0.0524 ± 0.0002
Hydrogen production [appm/fpy]	88.87 ± 0.09	100.0 ± 0.1	47.59 ± 0.07

In-Situ Ceramic Breeder Irradiation Module

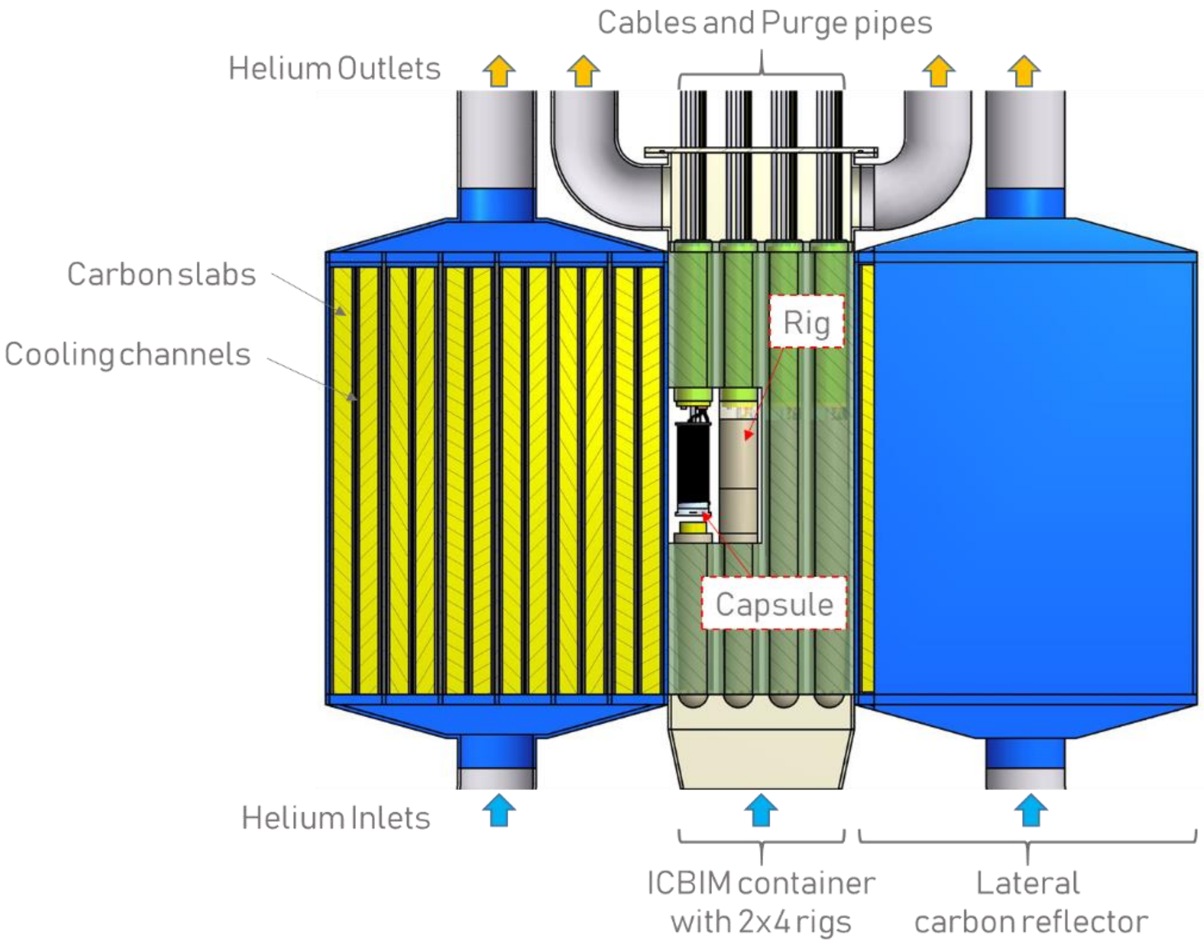
Mode of operation

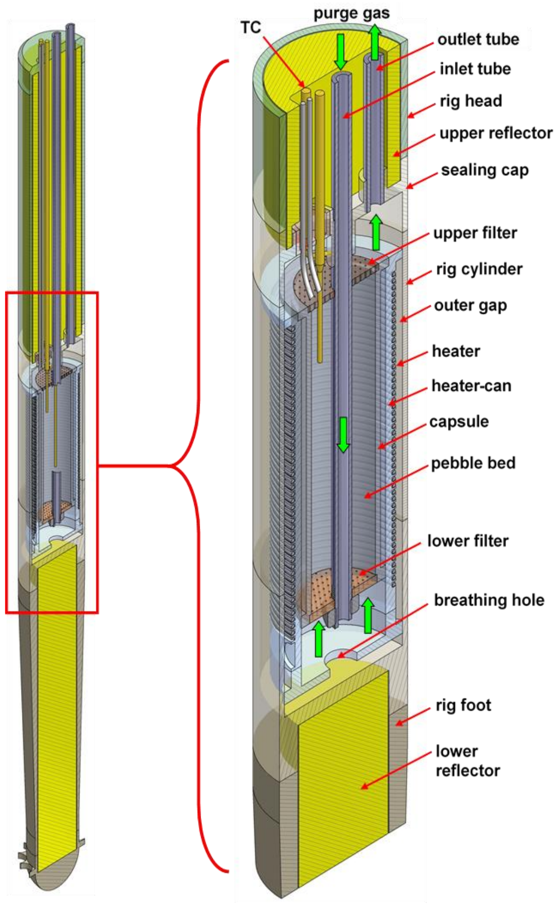
<INS-P-CB+Be+INS-1100C> TM for the in-situ irradiation and testing of ceramic breeder materials or Be in the temperature range 300 – 1000 °C in the high flux zone, measuring (time resolved) tritium release (ICBIM)

Specimens are placed in high-temperature capsules with inlet/outlet of a purge flow. Time resolved tritium release (possibly species) is measured at the outlet, as reaction on purge gas composition, temperature, neutron flux (variations).

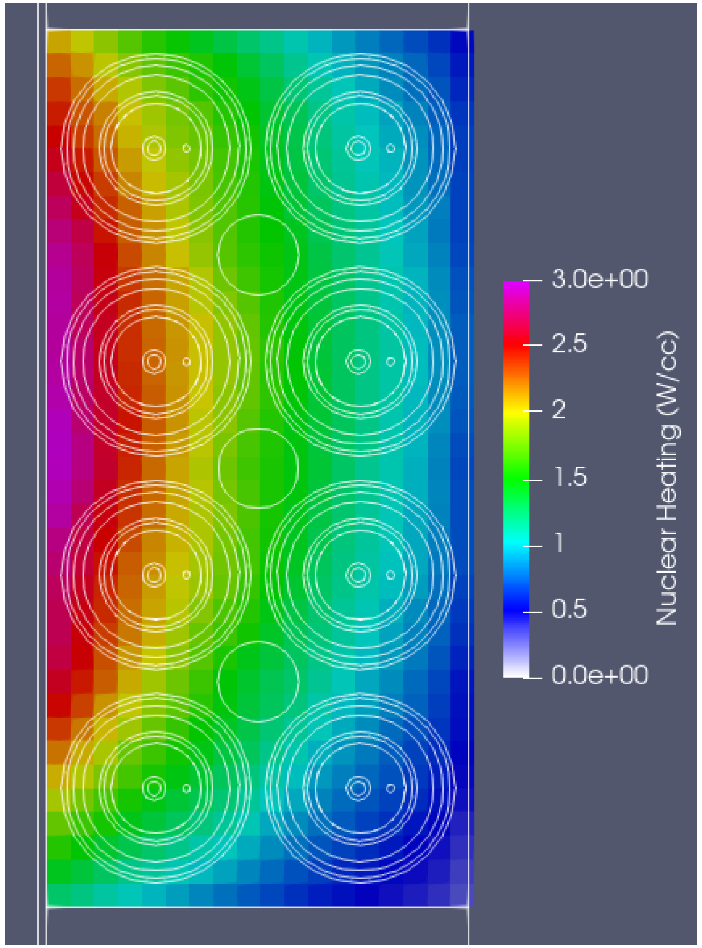
- Providing a purge flow to tritium analysis station (outside of test cell)
- Enable a consistent tritium budget and good time resolution
- Maintain temperatures of the specimens 300 – 1000 °C

ICBIM design overview





ICBIM irradiation conditions



- Installation behind neutron source and *tungsten spectrum shifter* module *instead of* HFTM

- Tritium production in Li4SiO4 specimen material is **2.8E11 – 6.35E11 atoms-T/g-CB/s** (66 – 100% of IFMIF/EVEDA)

- Volumetric heating is 0.45 – 1.2 W/g in the CB (80 – 120% of IFMIF-EVEDA)

➔ Tritium transport and thermal analyses of IFMIF-EVEDA are still applicable to the DONES conditions

- Achievable temperature range is **350 – 880 °C** (approximately) reached by electrical heated assisted by self-heating (2 insulation gaps used)

In-Situ Irradiation Module for Diagnostics” (IIMD)

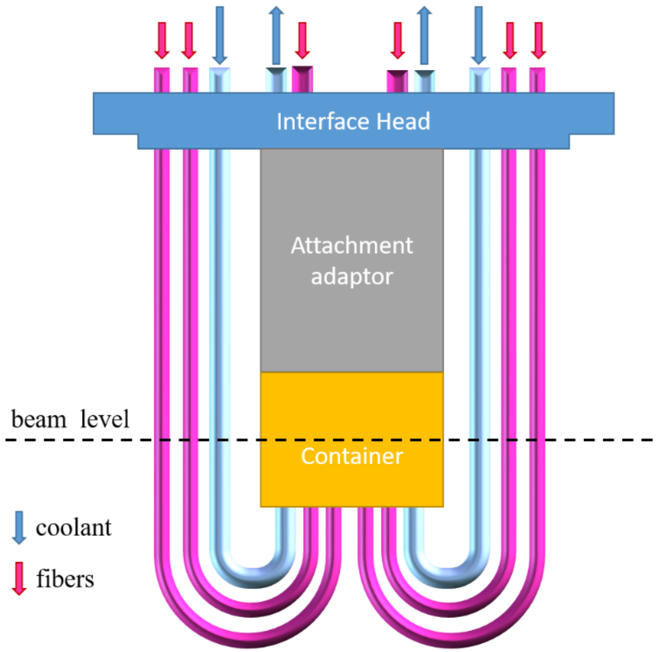
Mode of operation

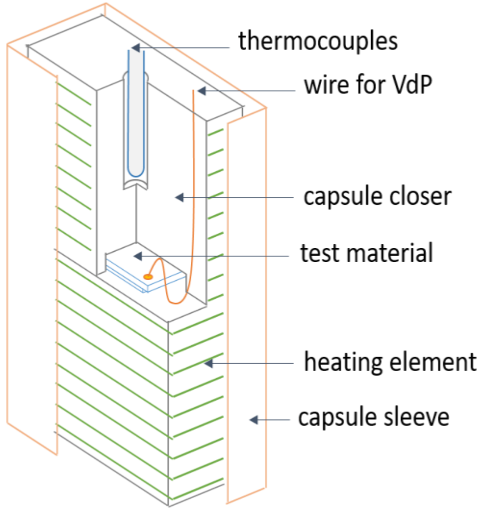
<INS-P-INS-Diagnostics-20-500C> TM for the in-situ irradiation and test of electrical conductivity, optical transmission, radioluminescence, permeation .

Materials or components of diagnostic systems are placed into the irradiation field in appropriate measurement configurations (electrical, optical, …). Key properties’ time evolution over time/dose can be measured with equipment outside of the test cell.

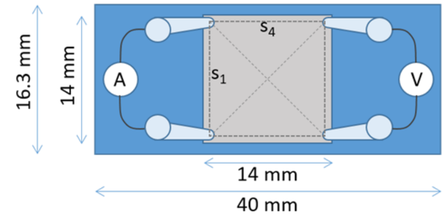
- Transmit interfaces for measurement of electrical properties
- Transmit interfaces for measurement of optical properties
- Maintain the specified irradiation temperatures (RT – 550 °C)

IIMD design overview



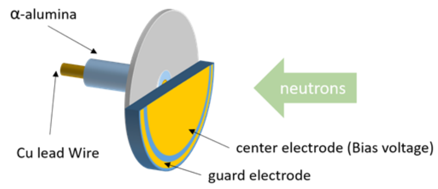


a)



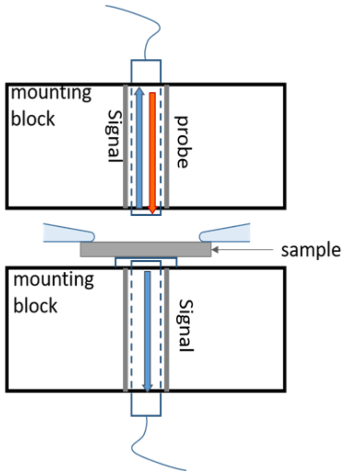
Van der Pauw Measurement of electrical conductivity

b)



Conductivity measurement of thick samples

c)



Measurement of optical reflectivity / transmission

- Design derived from HFTM
- Nuclear/Thermal analyses not available

Conclusions

- A catalogue of 20 irradiation experiments was derived from top level documents on DEMO material requirements
- Conceptual designs for 3 irradiation experiments were adapted/advanced for the DONES conditions in the frame of DONES-PreP :
  - In-Situ Creep Fatigue Test Module
  - In-Situ Ceramic Breeder Irradiation Module
  - In-Situ Diagnostics Irradiation Module
- Further experiments from the catalogue can be derived in a straight-forward manner from existing designs
  - Irradiation of Cu alloys for PIE possible in low-temp. Version of HFTM
  - Irradiation of W for PIE possible in high-temp. setup derived from ICBIM
- Further design concepts were evaluated already in the IFMIF/EVEDA phase
  - Liquid Breeder Validation Module
  - Low Flux Test Module (similar mission as Diagnostics Module)
- Some of the concepts in the catalogue have not yet been explored
  - “Model Blanket Module” (realistic load ensembles)
  - Corrosion module (IASCC
  - …