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New approach to the conceptual design of STUMM: A module dedicated to the monitoring of neutron and gamma radiation fields generated in IFMIF-DONES

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ABSTRACT

International Fusion Materials Irradiation Facility — DEMO—Oriented Neutron Source (IFMIF-DONES) is a planned powerful neutron source, which will generate an intense flux of neutrons (up to ~10^{15}n/s/cm^2) with a fusion-relevant energy spectrum. It will be an accelerator source based on deuteron beam - lithium target reactions. The engineering design of IFMIF-DONES is elaborated in the frame of the Early Neutron Source work package of the EUROfusion consortium. The facility will be dedicated to the irradiation of suitable structural materials planned for the construction of future fusion reactors such as DEMO (Demonstration Fusion Power Plant). Start-up Monitoring Module (STUMM) is designed to monitor radiation and thermal conditions during the commissioning phase of IFMIF-DONES, characterize the produced neutron flux and validate neutronic modeling of the facility. The conceptual design of STUMM is prepared by a team of physicists and engineers from the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) and the National Centre for Nuclear Research (NCBJ), Poland. This paper presents the concept of STUMM, the proposed design of the module, and selected measuring systems.

Introduction

In order to design and build future fusion reactors such as DEMO, suitable materials able to withstand extreme radiation and temperature conditions for a long time must be identified, tested, and certified. The facility planned for testing and certification of such materials is IFMIF-DONES [1, 2, 3]. The following radiation and thermal conditions are expected in the irradiation volume located behind the neutron source target: fast neutron flux density up to 10^{15} n/cm^{2}s and nuclear heating up to 3 W/g which can increase the temperature up to 550 °C. A dedicated High Flux Test Module (HFTM) [4] will be used for the irradiation of materials samples which will operate under nominal operating conditions of IFMIF-DONES. The STUMM is a module dedicated to the commissioning and testing phase of the facility. STUMM will be positioned at the same position as HFTM and will operate in the commissioning phase before the installation of HFTM [5]. Thus, STUMM will be located at a distance of 2 mm (+/−1 mm) to the IFMIF-DONES neutron source target, i.e. behind the lithium target backplate (BP) inside the Test Cell (TC) - the irradiation area (Fig. 1). This position will be assured by the dedicated positioning and fixing system developed by the WIGNER group (Fig. 2) [6].

The main mission of STUMM is to characterize the neutron flux and verify the radiation and thermal conditions adjacent to the neutron source. Additionally, STUMM shall validate the neutronic calculations and models used for the engineering design of the TC and HFTM. During the measurements also the strength of the construction materials of STUMM will be tested and validated, which is an important point since the same materials are used for the design of HFTM.

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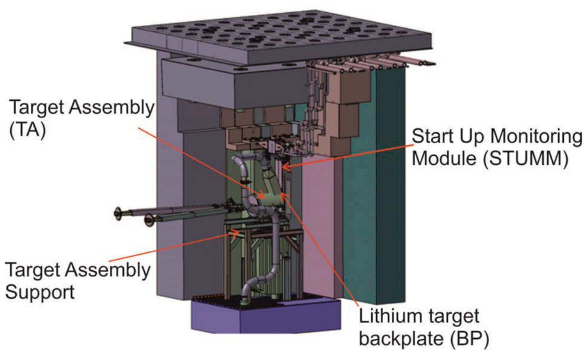


Fig 1. General view of STUMM in TC in working position.

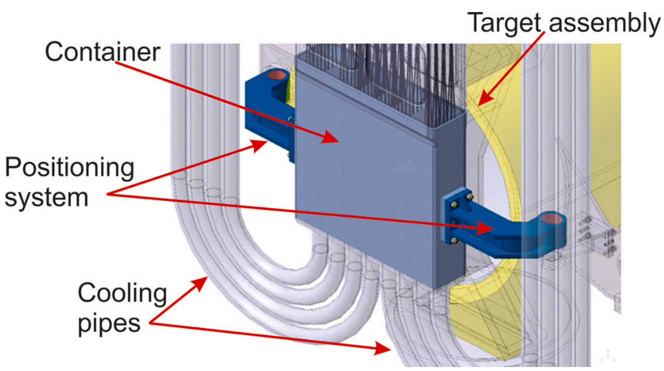


Fig. 2. View of the positioning and fixing system on Container level.

The external design of both STUMM and HFTM are similar in order to use the same remote handling (RH) equipment, nevertheless, the two modules have a very different interior design. To fulfill its mission STUMM will be composed of selected detection systems and sensors characterized by high radiation resistance and adequate radiation sensitivity.

At this stage of the STUMM conceptual design the following detection systems are foreseen: a Rabbit System, Micro Fission Chambers with U-235 (MFC-U235), Micro Fission Chambers with U-238 (MFC-U238), Self-Powered Neutron Detectors (SPND), Ionization Chambers (IC), and thermocouples.

Conceptual design of STUMM

An early version of the STUMM design was presented in [7]. The present design of STUMM is partly based on the design of HFTM. The casing structure of STUMM will be made of X2 CrNiMo 17–12–2 (AISI 316 L) austenitic steel defined in the RCC-MRx code [8]. The location of STUMM inside the Test Cell is presented in Fig. 1 and a general view of the module is shown in Fig 3. The external geometry of STUMM is similar to the HFTM. Both modules have the same the following main parts: the Container, the Attachment Adapter, the Support Trusses, and the Helium cooling system.

STUMM differs from HFTM in its interior parts. Due to the mission of STUMM, its main components are the measuring systems located inside the Container. The interior design of the Container was made to ensure the possibility of housing an appropriate number of sensors and at the same time not to have a significant impact on the flow of the cooling gas for the detectors. The internal STUMM structure is based on eight rigs. In the active area (area with detectors inside Container) each rig is divided into 5 levels (Fig. 4), so the whole active area of STUMM is divided into 40 rectangular segments (Fig. 5). The central region of the Container (four middle segments on the third level) is situated centrally in front of the beam and is called the beam footprint area. It is planned to be a

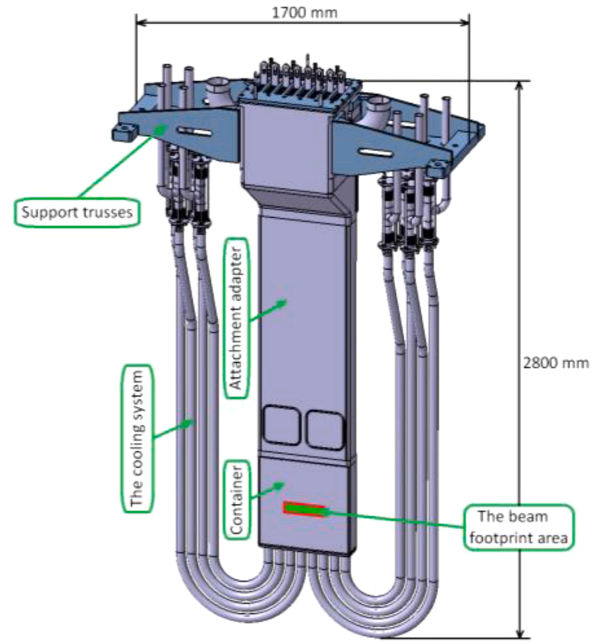


Fig. 3.. The general view of STUMM.

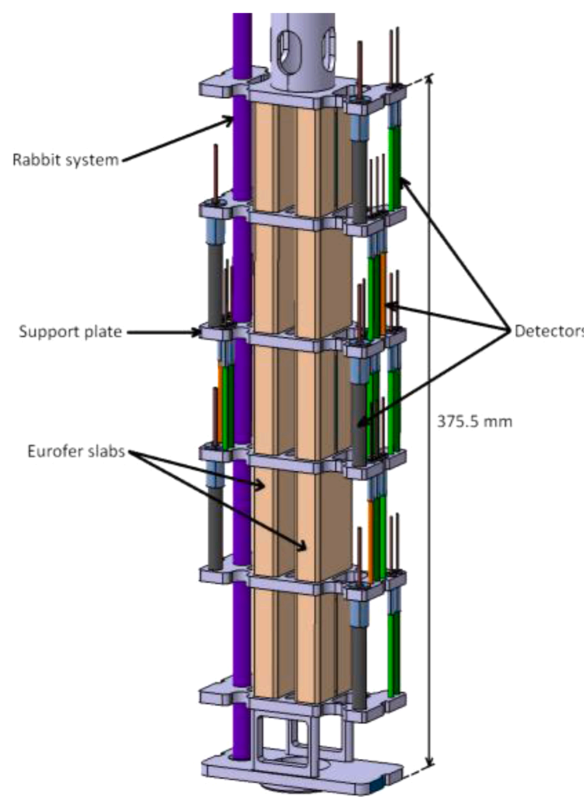


Fig. 4. The view of an active part of single rig.

rectangular area of 20 × 5 cm^2 for the reference design that could be potentially reduced down to 10 × 5 cm^2. Such an approach allows to map the area of interest and obtain the necessary information about the neutron source.

The active part of a single rig presented in detail in Fig. 4 consists of the following main elements: the supporting plates, the connecting elements (lower and upper), and the Eurofer slabs. Apart from these elements the following measuring systems: the Rabbit System (RS), pairs of

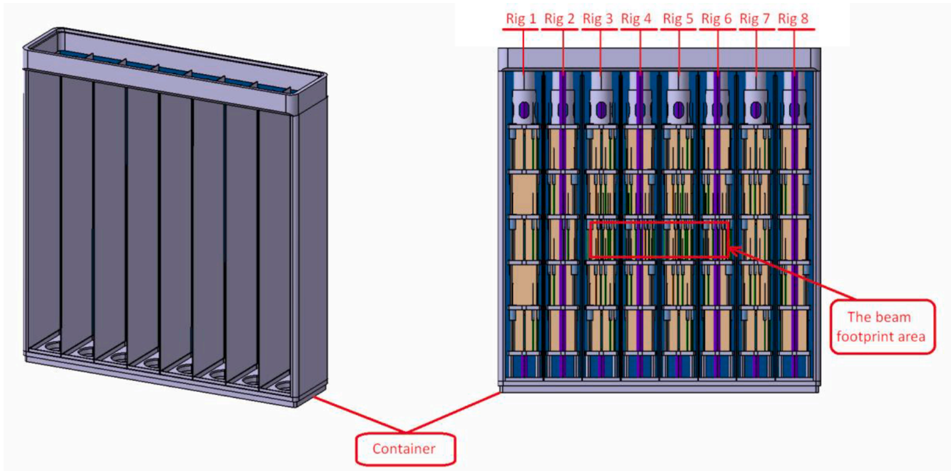


Fig. 5. The view of container and active area of STUMM.

Micro Fission Chambers (U235 and U238) and Ionization Chamber, the gamma thermometers, thermocouples will be installed.

The space between two supporting plates forms a segment, in which one can distinguish the front, the central, and the rear area. The instrumentation installed in the front area will deliver information about the distribution of neutron and gamma fluxes coming from the IFMIF-DONES source. For testing the behavior of steel elements to be installed in the HFTM two Eurofer slabs (material planned as structural elements of HFTM) will be installed in the central area of each rig. As a consequence, the instrumentation installed behind the Eurofer slabs, in the rear area, will collect information about the radiation conditions similar to the ones inside the HFTM. The Attachment Adapter located in the middle part of STUMM is designed to guide cables from the lower to the upper part of STUMM and for transporting the cooling gas. Support Trusses provide handles for transport and are used to properly position STUMM in the TC.

The next important element of STUMM is the cooling system. Its function is to assure appropriate thermal conditions inside the module to ensure that all the installed detectors are operating within their operating conditions. The cooling system is based on ten pipes: eight small pipes running outwards on the sides of the STUMM and two large pipes on the top of the Attachment Adapter. The flow of helium gas will be possible in both directions: in the first case start from the eight outside pipes to the bottom part of the Container (1st flow direction) and in the second case from the two larger pipes downwards to the container (2nd flow direction).

Thermo–hydraulic and mechanical analysis

Thermo-hydraulic analysis has been performed for STUMM assuming the maximum allowed inlet helium temperature of 60 °C (allowed temperature range 15–60 °C) and maximum allowed helium mass flow rate of 180 g/s. Both helium flow directions have been considered.

The distribution of nuclear heating values was obtained from the Monte Carlo N-particle Transport Code (MCNP) [9, 10]. The thermo-hydraulic analysis was based on a numeric model similar to [11] where hydraulic analysis only was performed. The mesh was created in Ansys Fluent Meshing 2020 R2 resulting in 42.3 mln cells. The helium density was modelled with incompressible ideal gas law and the thermal conductivity and dynamic viscosity temperature dependent properties were used according to the NIST database. Temperature dependent thermal conductivities were defined as well for the solids. The cooling to the Test Cell environment (at 50 °C) was modelled via natural convection with a heat transfer coefficient of 5 W/m^{2}K. The SST (Shear Stress Transport) k-ω turbulent model was used for helium.

The influence of the boundary conditions was studied within two models: a conservative model with a stagnant helium layer between the front side of the Container and BP and a second analysis with convective cooling of the front panel of the Container and radiative heating from BP. Full details on the thermo-hydraulic analysis of STUMM will be given in a dedicated paper. However, the most important conclusions are summarized herein:

1. The pressure drop in the STUMM computed with CFD models without and with heat transfer was in the range of 2.6÷3.2 kPa for both flow directions, therefore well below the acceptable range of 60÷80 kPa.

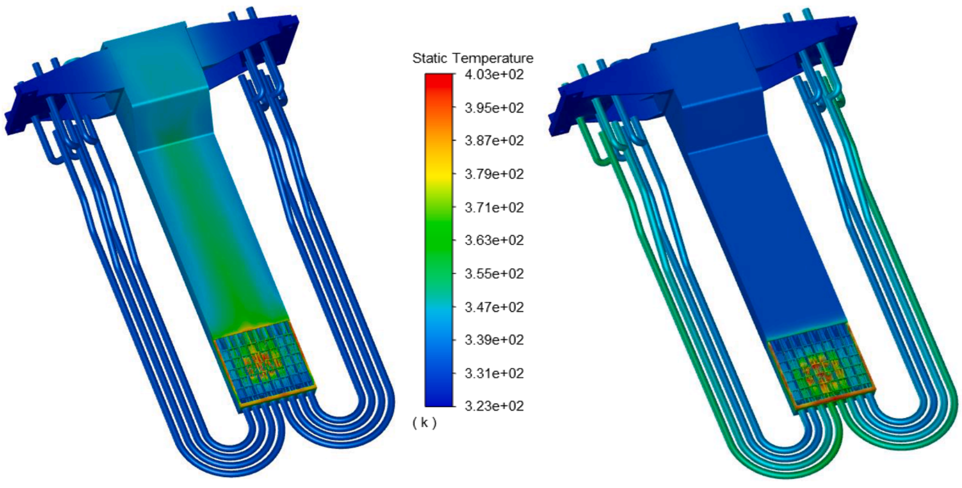
2. The model with a stagnant helium layer predicted considerably higher temperatures of the Container especially near the front panel which is directly in contact with the stagnant helium layer heated by BP. Maximum detectors temperature in the 1st flow direction reached 127 °C, whereas for the 2nd one it was 101 °C. For the 2nd flow direction, the maximum temperature of detectors was 133 °C for the conservative model

3. The average temperature of the helium at the outlet equals 72 °C (ΔT=12 °C), which is well below the outlet temperature limit of 150 °C.

4. The maximum temperature of the structure (front panel of the Container) in the conservative model was up to 241 °C regardless of the flow direction (Fig. 6). The most heated elements where the Eurofer slabs located in the center of the beam's footprint area. Their maximum temperature was 207 °C (2nd flow direction) and 182 °C, (1st flow direction) so considerably larger than the temperature calculated for the detectors. Due to Eurofer's bulky shape and intense nuclear heating, its cooling is difficult, resulting in such high temperatures.

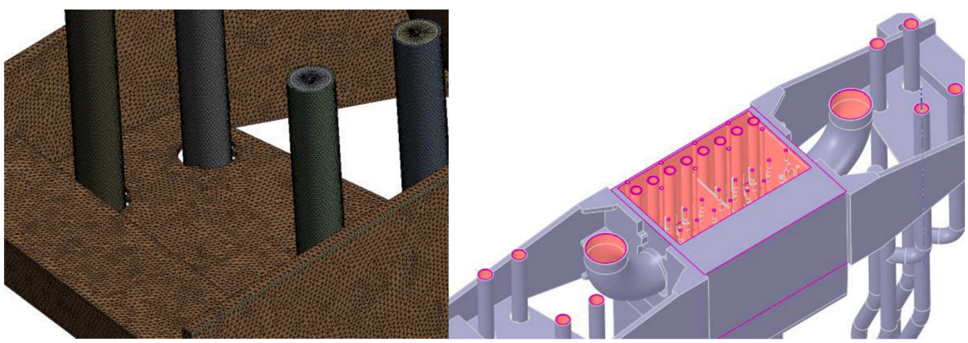
After obtaining the temperature maps, the mechanical analysis was performed in Ansys Mechanical 2020 R2. The model was meshed with 2nd order tetrahedral elements (Fig. 7a). The full mesh counted 9 mln elements and 18.4 mln nodes. The ends of the 8 tubes were closed with thin caps (Fig. 6a) in order to apply the internal pressure in a self-equilibrated manner – satisfying the condition $\int^{p} dA = 0$ (Fig. 7b). Temperature dependent Young moduli were used for the solid materials: Eurofer, 316 LN stainless steel, Aluminum for RS. The model was supported only on the 4 holes on the support truss (Fig. 8).

In the analysis including all the loads: temperature distribution in the structural elements, the internal pressure of 4.235 bar (safety valve pressure), and gravity a considerable difference in the deformation away from BP were found between the 1st and the 2nd flow directions. For the 1st flow direction by up to 3.41 mm (Fig. 9a) and much less – max. 1.37 mm (Fig. 9b) for the 2nd flow direction. Such deformations are unacceptable and show the need for additional support to keep the position of the Container fixed, ensuring the same distances between the detectors and the radiation source in the MCNP model and in reality. The design of



a) b)

Fig. 6. Temperature distribution of STUMM for the conservative model, values are limited to 130 °C (403 K) for better visibility for: a) 1st flow direction; b) 2nd flow direction.



a) b)

Fig. 7. a) Local view on the mechanical mesh of STUMM; b) Internal surfaces where the pressure was applied coloured. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

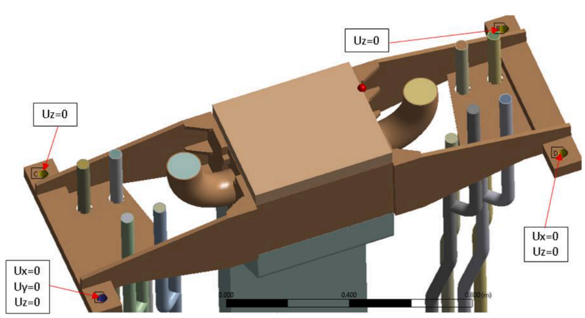


Fig. 8. Boundary conditions used for the mechanical model.

such supports will be done in the next update of the STUMM design.

The mechanical analysis showed that stresses are below the yield limit in most of the STUMM components: the inlet and outlet tubes, all the inside parts of the Container and the Attachment Assembly as well as the supporting frame. Very similar von Mises stress distributions were obtained for the normal operating conditions (loads: gravity, temperature field, the pressure of 4.235 bar) for both flow directions (Fig. 10). Stresses in the Attachment Adapter and the top part were similar due to the dominant effect of the pressure (same for both cases) with a very small impact on the temperature field and weight. The difference in the stresses between the two flow directions was visible only in the Container part, as the temperature fields were considerably different there - especially on the front panel (Fig. 10).

The von Mises stress on the front panel of the Container was slightly above the yield limit due to the high temperature of the front panel (Fig. 10) resulting from the conservative assumption in the CFD model: the helium layer between BP and front panel is stagnant and all heat is transferred via conduction. Full elasto-plastic analysis was performed in order to check the extent of possible yielding. The same mechanical model was used as for the normal operating conditions and pressure test, but multilinear stress-plastic strain curves at 3 temperatures: 20 °C, 100 °C, and 250 °C were defined for the 316LN stainless steel of the front panel, according to the data in the RCC-MRx norm. The analysis showed that the yielding of the front panel was almost negligible with the maximum plastic strain below 0.5% for both flow directions, indicating the safety of the structure even for the conservative thermal assumptions. The model used for the mechanical analysis, its assumptions, and detailed results will be presented in a dedicated paper.

A separate analysis only with the pressure load was performed to simulate a pressure test of 6.1 bar, showing that the Container and the Attachment Assembly support fully that pressure (Fig. 11). The pressure value of 6.1 bar was calculated based on the RCC-MRx norm by multiplying the pressure of the safety valve 4.235 bar by a safety coefficient of 1.43.

Due to the almost exact design of the outer structures of STUMM and HFTM – differing by the Container and the inside elements, based on the

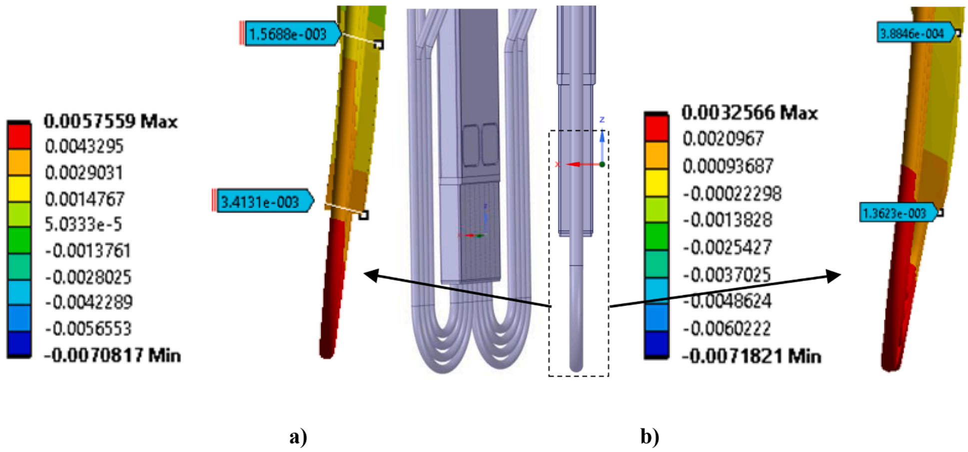


Fig. 9. Deformation in the x direction (in m) for the combined loads (gravity, pressure, temperature); a) 1st flow direction; b) 2nd flow direction.

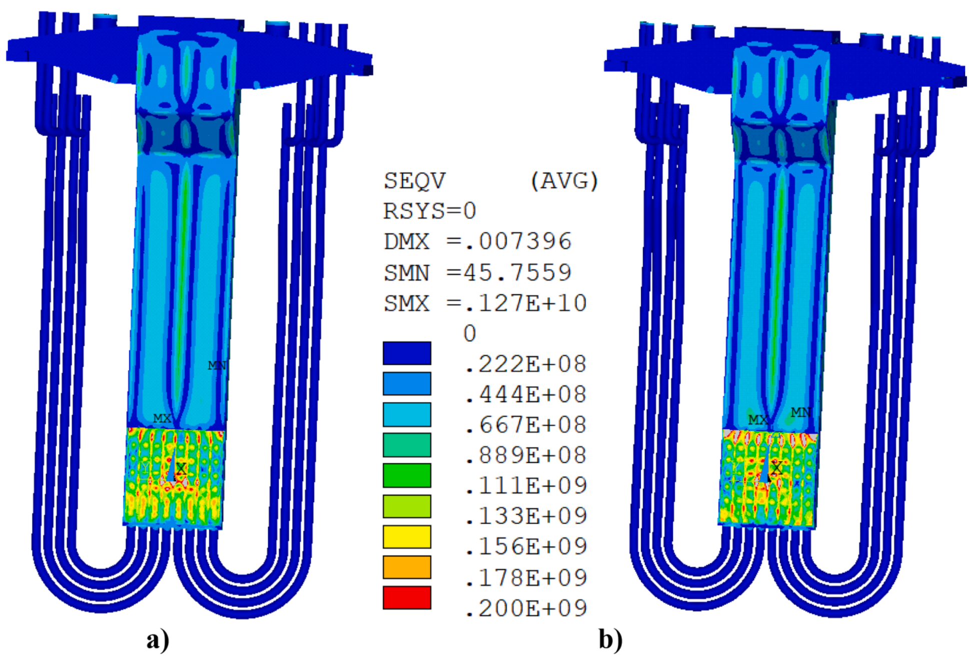


Fig. 10. Von Mises stress maps for the normal operating conditions of STUMM, values limited to 200 MPa for better visibility: a) 1st flow direction; b) 2nd flow direction.

experimental analysis of HFTM prototype under pressure [12], it is expected that the mechanical design of STUMM is valid as well. The 2nd flow direction looks more favourable from the mechanical point of view – due to smaller deformations of the Container, but the final decision of the flow direction will be made after analysing the complete design including the front supports for the Container.

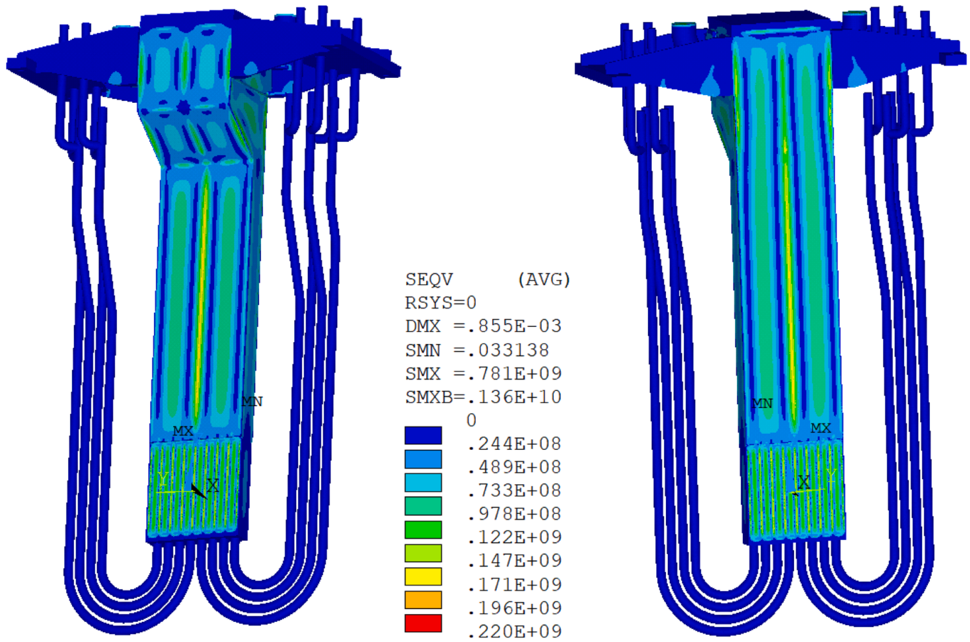
Detection systems foreseen for STUMM

The needs for the sensors to be used in STUMM are determined by the operating conditions of the module. The sensors have to be characterized by radiation resistance and a relatively small radiation sensitivity (to avoid detector saturation). Most of the systems proposed for STUMM are commercially available, however, some new solutions, purpose-prepared for IFMIF-DONES, need to be considered. For STUMM needs, the following detection systems are proposed:

- A Rabbit System (RS) for measuring the thermal, epithermal, and fast neutron flux density.
- Pairs of Micro-Fission Chambers (MFC with U238) and Ionization Chamber for fast neutron flux density.
- Micro-Fission Chambers (MFC with U235) or Self-Powered Neutron Detectors (SPND) for thermal and epithermal neutron flux density.
- Gamma Thermometers (GT) for nuclear heating measurements.
- Thermocouples (TC) for temperature measurements.

The radiation conditions in STUMM will be very similar to the ones in nuclear fission reactors, so before installing in STUMM, both already existing and newly-proposed sensors should be tested in DONES-like radiation conditions (such as e.g. the 14 MeV neutron converter in MARIA reactor [13].

The detection systems of STUMM will be used to verify the numerical calculations of neutron (and gamma) transport and, in this way, the modeling of the neutron source from the lithium target – deuterium beam reaction. Therefore, the signals recorded by the detectors must be accurately interpreted and compared with the results of neutron and gamma transport calculations performed by MCNP.



a) b)

Fig. 11. Von Mises stress distribution for the pressure test at 6.1 bars with the thickened rear walls, values limited to the minimum yield strength of 220 MPa: a) front side, b) rear side.

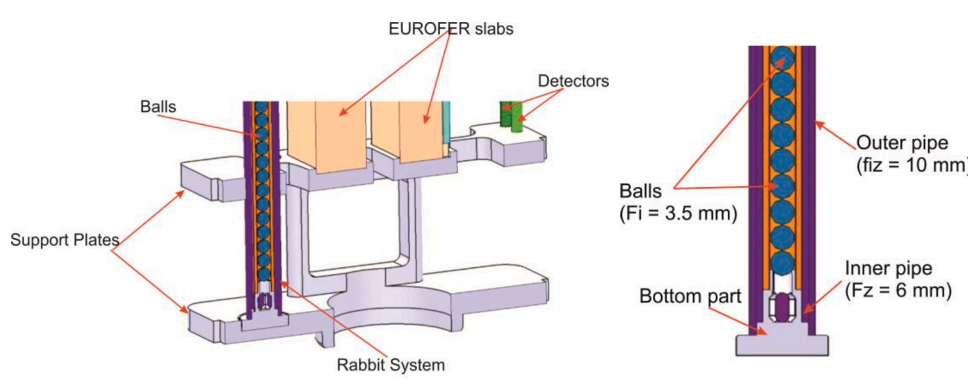
The rabbit system (RS)

The first of the proposed systems is the Rabbit System (RS) which can be described as an activation based detection system. It is planned to install eight RS units (one RS per rig). The RS system proposed for STUMM is based on a set of movable balls with dedicated activation materials inside and a set of two tubes, one inside the second – the so called Field's tubes. Both tubes in the cross-section are a circle (Fig. 12). The basis of the operation of this system is the transport of the balls by a flowing gas (helium), inside the STUMM and after the dedicated time (adapted to the selected materials) from the STUMM to the measuring station. Transport of the balls to the STUMM means that the gas with balls in it flows through the inner pipe, all balls are placed at fixed positions and gas leaves the system through the area between the outer and inner pipe. Transport to the measuring station means that the gas will flow through the space between the outer and inner pipe and push the balls out of the STUMM and will leave the STUMM through the inner pipe. The balls can be exchanged in a quasi continuous way, the frequency of it depends on the parameters of materials selected for the balls. This approach is different from the one adopted for the High Flux Test Module (HFTM). In the HFTM foils are to be used in the cassettes. The cassettes are to be dismantled in a hot cell in order to withdraw the samples and foils. According to the design assumptions, dismantling of the STUMM internal parts is not planned. Thus it is necessary to install a rabbit system.

The RS is the most important system for the verification of the modeling - the measured samples activity can be directly compared with the results of neutron transport calculations. This is the only available detection system able to estimate the neutron energy spectrum. The activation samples (balls, in this case, see Fig. 12) assure the highest spatial resolution, thereupon RS seems to be the best system to observe high neutron flux density and gamma dose rate. The most straightforward solution is to use one of the commercially available systems designed for nuclear power plants, for example systems made by Framatome (formerly Areva NP) [14].

Pair of micro-fission chambers (with U-238) and ionization chamber (MFC and IC)

The micro-fission chamber (with U-238) could be used as an online



a) b)

Fig. 12. Rabbit system proposed for STUMM: a) inside Rig, b) section along with the system (Fi – diameter of the balls, fiz = outer diameter of the outer pipe, Fz – outer diameter of the inner pipe).

monitor to determine the density of the fast neutron flux. The fission chamber with ^{238}U coating is suitable for both source and power ranges of IFMIF-DONES operation. In the source range, it is used in pulse counting mode. In the power range, it is typically used in a current mode. However, even a very small content of ^{235}U in uranium coating causes problems in the signal analysis. It is necessary to perform a precise determination of the ^{235}U impurity content.

The ionization chamber of a similar type as a fission chamber should be used in parallel (in pair) to assure the proper interpretation of fission chamber recordings. It allows not only the discriminating the neutron signals but also determining the gamma-ray dose rate.

The ionization chambers considered for STUMM are commercially available but manufactured only on demand [15].

Micro-Fission chambers (with U-235) or self-powered neutron detectors (MFC or SPND)

Beside of fast neutrons, the thermal neutron flux density in the Test Cell should be monitored as well. Thermal neutron flux density must be determined due to the activation induced mostly by thermal neutrons. It is proposed to use the Self-Powered Neutron Detectors (SPND) or Micro Fission Chambers with U-235.

The Self-Powered Neutron Detectors (SPND) are the detection system used in all nuclear reactors. They are small, robust, and easy to operate. They do not need additional external supply, thus limiting the number of cable connections). Only the direct current is measured. The signals of SPND are easy to read and interpret, they are slightly delayed; the delay depends on a chosen SPND's emitter. A time-deconvolution of the signal is easy and accurate and can be done in real time. The output signal of SPND has a very low current of the order of 10^{-14} – 10^{-7} A which can be problematic if the signals are to be transmitted at long distances. Professional pico-amperometers are therefore needed. All of the commercially available SPNDs are available on demand.

Micro-Fission Chambers with U-235 are commercially available and manufactured for example by PHOTONIS [16]. The company offers MFC's filled with a sensitive layer of uranium enriched in U-235 to more than 90%.

Gamma thermometers (GT)

Gamma thermometer measurements are performed to determine the nuclear heating in stainless steel materials [17]. The measurement is based on the temperature difference between the core of the sensor and the cooling environment - without absolute temperature measurement. This is performed by the K-type differential thermocouple with Al_2O_3 insulation. This kind of thermocouple has a linear response between 0 and 450 °C and its response up to 1400 °C can be suitably reproduced by a polynomial fit. Furthermore, this type of thermocouple has a good resistance under irradiation conditions. Among a variety of types of gamma thermometers, special attention should be given to the one designed and manufactured by the Belgian Nuclear Research center SCK-CEN. Standard gamma thermometers have been designed for typical applications in fission research reactors in a cooling water environment. SCK CEN indeed has designed, manufactured, and tested a modified gamma thermometer suitable for the measurement of high heating rates in the presence of gas cooling. The gamma thermometer detectors considered for STUMM application are not commercially available. They are manufactured on demand according to expected nuclear heating parameters and cooling conditions.

Main parameters of the measuring systems foreseen for STUMM

The main parameters of the instrumentation foreseen for STUMM are presented in Table 1. The number of active sensors foreseen for the installation inside STUMM's active area is 242.

Table 1
The main parameters of the diagnostics foreseen for STUMM.

	Detectors				
	Rabbit System	**MFC (U238) + IC**	**TC**	**GT**	**MFC (U235) / SPND**
Diameter	⌀10 mm	⌀3 mm	⌀2 mm	⌀8 mm	⌀3 mm
Length		50 mm	50 mm	50 mm	50 mm
Diameter of the cable		1 mm	1 mm	1 mm	1 mm
Output		pulse counting or current mode μA	Voltage: mV	Voltage mV	Current: MFC: μA SPND: pA
Number of detectors	8 (1 per rig)	132 (2 × 66)	44	44	22
Total number of detectors			**242**		

Electronic support for STUMM sensors

If the performed measurements do not have a special time requirement (half-life, decay intensity), a single set of tools can be used to support many measurements. In the case of short time measurement, where the time after irradiation for performing measurements is limited, and multiple simultaneous measurements have to be done at the same time, multiple sets of laboratory equipment may be needed.

For online sensors, industrial form-shaping electronics will be required. The measurements will be performed during machine operation, next to the Test Cell, with limited personnel access. All measurements performed online during machine operation are performed in parallel, and each sensor must have its own readout electronic device.

Due to the wide power range during IFMIF-DONES commissioning phase the ionization and fission chambers are to be operated in high count rate in current mode, and in low count rate, in which pulse or Campbel mode may be suitable. For high event rates picoammeters can be used (e.g. picoammeters offered by Keithley [18]).

The Self-Powered Neutron Detectors generate small current by themselves, and in their case, precise picoammeters will be needed. Measurements using nuclear heating calorimeters, gamma thermometers, and regular thermocouples are based on the temperature measurements, and thus dedicated temperature measurement controllers (e.g. PLC) shall be used.

The thermocouples and gamma thermometers require voltage measurements, whereas the SPNDs require current measurements.

Arrangement of measuring systems inside STUMM

To obtain the information expected during the commissioning phase of IFMIF-DONES proper arrangement of measuring systems inside STUMM is essential. The simplified horizontal cross section of measuring systems is shown in Fig. 13 and the vertical arrangement of measuring systems is shown in Fig. 14. The presented arrangement was proposed based on the results of neutronic calculations of the distribution of radiation flux in TC [19]. They showed a high symmetry of radiation distribution between the rigs. Therefore, many of the detectors are arranged in a given layer in odd or even rigs only. In each rig one rabbit system will be installed in alternate positions: in even Rigs (number 2, 4, 6, and 8), RS will be installed in the front area of the Rigs and in odd Rigs (number 1, 3, 5, and 7), RS will be installed in the rear part (behind the Eurofer slabs). In the central part of the active area (3-rd level in Rigs 3–6), the number of detectors is much greater than in the outer segments. Due to the limited space, it was decided to limit the number of detectors inside STUMM up to 250. In Fig. 13. and Fig. 14 an arrangement of the sensors in the particular segments of the STUMM

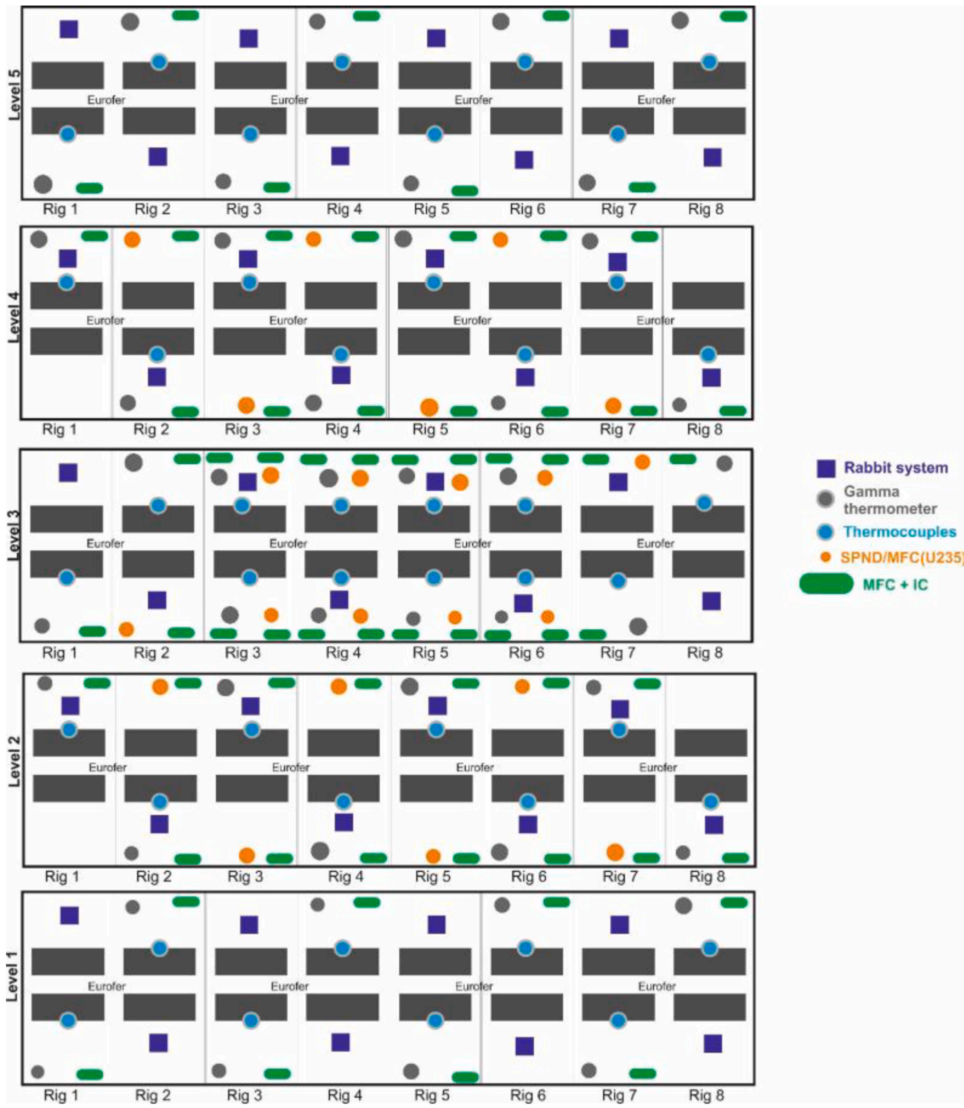


Fig. 13. The arrangement of the sensors in the particular layer of the STUMM active area – horizontal cross section.

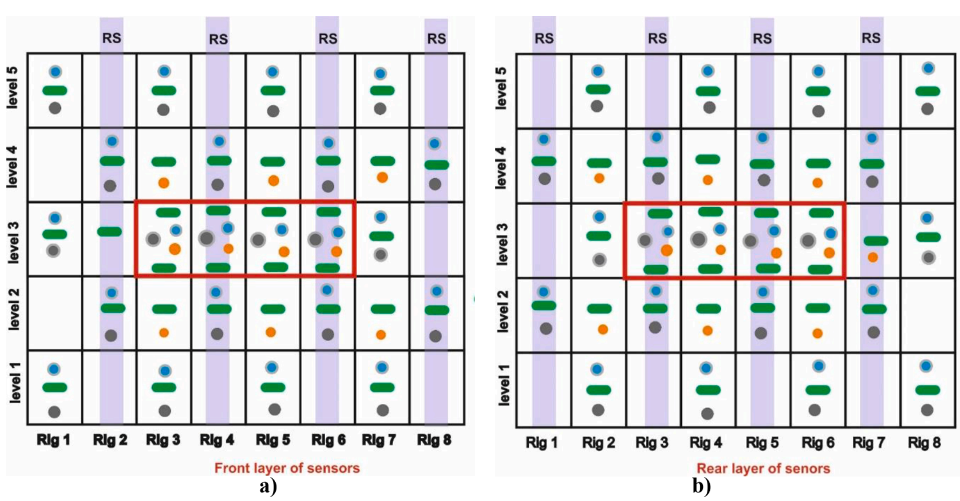


Fig. 14. The arrangement of the measuring systems inside STUMM – vertical cross section: a) front view of the front layer, b) front view of the rear layer.

active area is presented.

Summary

This paper presents the concept of the STUMM module designed for the IFMIF-DONES neutron irradiation facility. The design of this module is based on the design of HFTM, with the necessary changes and adjustments required by the needs of STUMM. The main mission of this module is to characterize the radiation conditions in a region adjacent to the neutron source. This mission defines the sensors and equipment of the module. Dedicated detection systems have been proposed which are known to operate well and are tested in reactor conditions, such as MFC, IC, SPND, gamma thermometers, thermocouples, and Rabbit Systems. Thermo-hydraulic analysis has shown that the considered cooling system based on helium flow, is able to provide appropriate thermal conditions for the proper operation (up to 250 °C) of the proposed number and arrangement of detectors. The STUMM design is still under development and works on the detailed engineering design will be continued.

CRediT authorship contribution statement

U. Wiącek: Conceptualization, Methodology, Writing – original draft, Visualization, Supervision. **F. Arbeiter:** Conceptualization, Writing – review & editing. **B. Bieńkowska:** Software, Formal analysis, Visualization. **D. Bocian:** Supervision. **J. Castellanos:** Writing – review & editing, Supervision. **A. Igielski:** Conceptualization, Methodology. **J. Kotuła:** Methodology, Visualization. **W. Królas:** Writing – review & editing, Supervision. **A. Kurowski:** Conceptualization, Methodology, Writing – review & editing. **G. Madejowski:** Conceptualization. **R. Prokopowicz:** Conceptualization, Writing – review & editing. **R Ortwein:** Methodology, Software, Formal analysis, Writing – review & editing, Visualization. **J Świerblewski:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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