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A real-sized start-up monitoring module prototype for comprehensive test and irradiation campaigns of miniaturized neutron detectors according to the IFMIF-DONES baseline

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ABSTRACT

The key system to know the neutron and gamma fields during the commissioning at IFMIF-DONES facility will be the STart-Up Monitoring Module (STUMM), which will include tens of very sophisticated and miniaturised detectors providing crucial information about the radiation fields. In particular, there will be MFCs (micro-fission chambers), ICs (Ionisation Chambers), SPNDs (Self-Powered Neutron Devices) and GTs (Gamma Thermometers).

The current state-of-the-art does not provide answers about the performance of the detectors in the very specific working conditions inside the IFMIF-DONES Test Cell, as a very high spatial density of detectors inside the STUMM vessel, an extremely harsh environment with neutron flux up to $5\cdot10^{14}$n/cm^2/s and the need of long mineral cables (>30 m) to drive the very weak current signals from the irradiation area to the closest electronics cubicles available in the facility.

Except for the extremely high neutron flux provided by IFMIF-DONES, all the other very critical conditions can be replicated by means of a 1:1 scaled prototype of the STUMM (STUMM-PROTO), which will be subjected to comprehensive testing and irradiation campaigns in order to increase the knowledge about the performance of the detectors above mentioned.

The present work shows the wide range of capabilities offered by STUMM-PROTO as well as the current status of its construction and some first notions about the experimental campaigns to be implemented.

Previous section about the present work's structure

Through the present work a consistent line is drawn from the IFMIF-DONES top-level description to the need of the STUMM-PROTO and its technical overview in the different disciplines such that a solid notion of the main objectives and the current status of the prototype is given to the reader.

In particular, the first section provides an introduction about the IFMIF-DONES project and a description of the role of the STUMM in the facility to end up with the characterization needs to be covered by the STUMM-PROTO.

The second section, "the STUMM in a nutshell", describes the main features of the STUMM system according to the present baseline design, while the following section introduces the main requirements and boundary conditions applicable to the STUMM-PROTO coming from the characterization needs and the geometric constraints propagated from the STUMM system to the prototype.

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The section called “main guidelines of the STUMM-PROTO experimental programme” explains the main test campaigns foreseen for the STUMM-PROTO to cover the characterization needs mentioned in the previous sections. Some guidelines are also included for the future selection of irradiation sources for the different campaigns.

All the sections so far mentioned allow the reader to have a thorough idea about the context and the main objectives of the STUMM-PROTO. The following sections provide an overview of the main technical features of the prototype, both from mechanical point of view (“Mechanical design and manufacturing status”) and from electronics point of view (“Electronic engineering status and first mockup results”.

Finally, the conclusions section summarizes the main highlights provided by this work about the STUMM-PROTO.

1 Introduction and motivation of the STUMM-PROTO

IFMIF-DONES (International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source) is a single-sited research infrastructure [6] for testing, validation and qualification of the materials to be used in future fusion power plants like DEMO (DEMOnstration Power Plant). This facility is included in the European Roadmap for fusion and will be based on a high-current deuteron accelerator (40 MeV, 125 mA) that will produce a stripping reaction with the high-speed (15 m/s) liquid Li target. As a result, high-energy neutrons (up to 55 MeV) with intense fluxes (maximum $5{\cdot}10^{14}$ n/cm2/s) will be produced, with predominance in the range between 2 and 20 MeV. These spectral characteristics fit very well with the characteristic neutron energy (14 MeV) produced in the fusion reaction between deuterium and tritium.

It will be in the last phase of the commissioning [1] that the stripping reaction between the D + beam and the lithium target will occur for the first time in the lifetime of the facility. During this phase, it will be absolutely crucial to characterize the neutronic and gamma fields downstream to the lithium target. This is, in fact, the main aim of the STUMM system (Start-Up Monitoring Module) [2], which will be the first module ever irradiated at the facility. This module will be located at the same position foreseen for the High-Flux Irradiation Module (HFTM), which will be the first module housing materials specimens during the operation phase of the facility [6]. Thus, both the STUMM [2] and the HFTM will be located inside the Test Cell (TC) behind the lithium target backplate (see Fig. 2) at a distance of 2 mm (+/ 1 mm). Fig. 1 shows the position of the Target Assembly and the STUMM inside the IFMIF-DONES Test Cell.

Together with the characterization of the neutronic and gamma fields just behind the target, the STUMM shall play a key role for the benchmarking of the neutronics models used to predict for the HFTM and other irradiation modules important parameters as neutron and gamma fluxes, dpaNRT distributions, He production, etc. Furthermore, it shall provide reliable feedback of the beam position and size during all the commissioning phase with beam. The beam position monitoring also includes an eventual MPS (Machine Protection System) functionality such that a sudden beam position shift is detected in less than 30 μs.

In order to provide these functionalities and according to the current baseline design, STUMM will house around 240 miniaturized detectors and sensors: a Rabbit system (8 channels, one per rig), around 60 microfFission chambers (MFC), some with U-235 (MFC-U5) and the rest with U-238 (MFC-U8), around 40 self-powered neutron detectors (SPND), around 60 ionization chambers (IC), around 40 gamma thermometers (GT) and 40 thermocouples type-K (TK). Benchmarking of the irradiation fields will be possible by cross-check and appropriate correction of the theoretical models with the real data provided by the detectors. Fig. 3 shows the theoretical neutron flux distribution at the front of the STUMM container.

The most common types of detectors in the STUMM are the MFCs and the ICs, which will provide integrated signals as a result of its interaction with the neutron and gamma fields throughout the whole spectra. Fig. 4 includes the neutron spectra in several positions at the front inside the STUMM container.

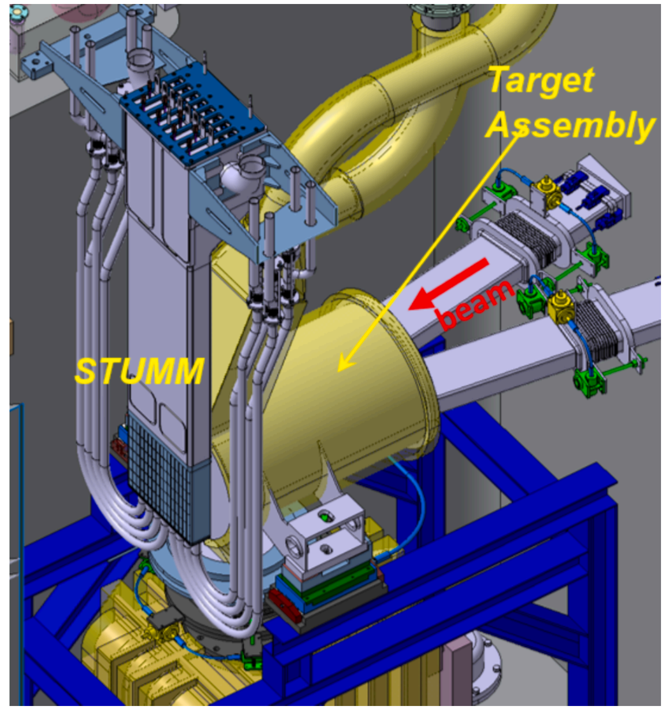

Fig. 1. The STUMM inside the IFMIF-DONES Test Cell (TC) just behind the Target Assembly, which houses the liquid Li target flowing through.

According to the current baseline design, the spatial resolution in the characterization of the irradiation maps is aimed to be in the order of few centimeters. Therefore, the size of the MFCs and the ICs foreseen for the STUMM is specified within the millimetric range (3 mm diameter). The neutron and gamma fields can be monitored in a small region (around 1 cm diameter) by locating a pair of one MFC and one IC very close to each other: the MFC will provide the integrated signal from neutron (fast in case of U238, thermal in case of U235) and gamma fields while the IC will provide the integrated signal from the gamma field. Therefore, by subtraction of the IC signal from the MFC signal, the discrimination of the gamma and neutron integrated signals can be achieved locally.

SPNDs are another kind of detector also present in the STUMM, their main role being also the characterization of the neutron field. One of the contributors to its signal comes from the (n, beta) reaction [4]. Once a neutron is captured by the emitter’s material, the nucleus becomes unstable and beta decays emitting an electron. The decay time depends on the half-life of the isotope, thus a delayed signal being produced. In this case, the main interest lies on the fact that the SPNDs are in general more robust detectors than the MFCs and ICs so they are the main current candidates to monitor the neutron field in the container of the HFTM, which, in turn will be subjected to much higher temperatures than the STUMM container. Therefore, even if they are not crucial for the characterization of the neutron fields during the commissioning of the facility, they need to be present in the STUMM for testing its performance in the high-flux region inside the TC before the start-up of the operation phase.

The GTs will be used for measuring the nuclear heating so they will be the only detectors providing the overall amount of deposited energy locally.

To conclude, a Rabbit composed by 8 channels will be the only diagnostic able to characterize the neutron field spectrum. Each channel will expose a stack of activation balls of various materials to the neutron beam. Those materials have been selected to produce specific and well known isotopes by the interaction with the neutron field, the formation

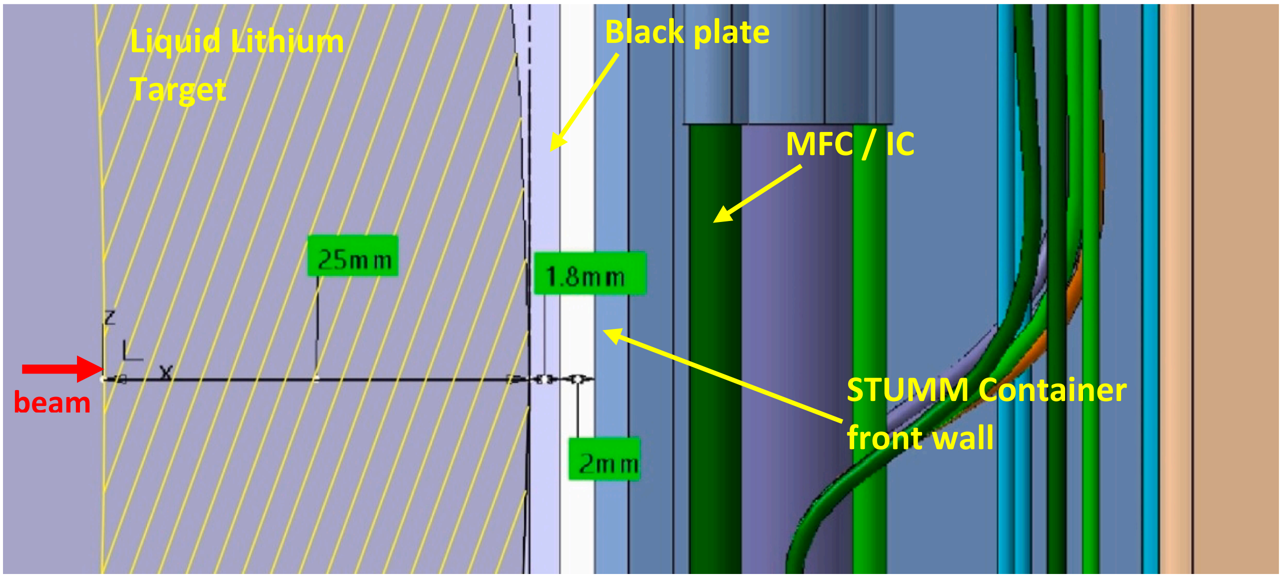

Fig. 2. Detailed side cut view sketch of the position of the STUMM detectors with respect to the liquid target (yellow hatching). The Back Plate end of the Target Assembly is concave with a minimal thickness of 1.8 mm. The gap between the STUMM Container and the Back Plate is 2 mm (white gap) while the front wall of the STUMM container is only 2 mm thick to enable as high neutron streaming as possible to the detectors inside the STUMM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

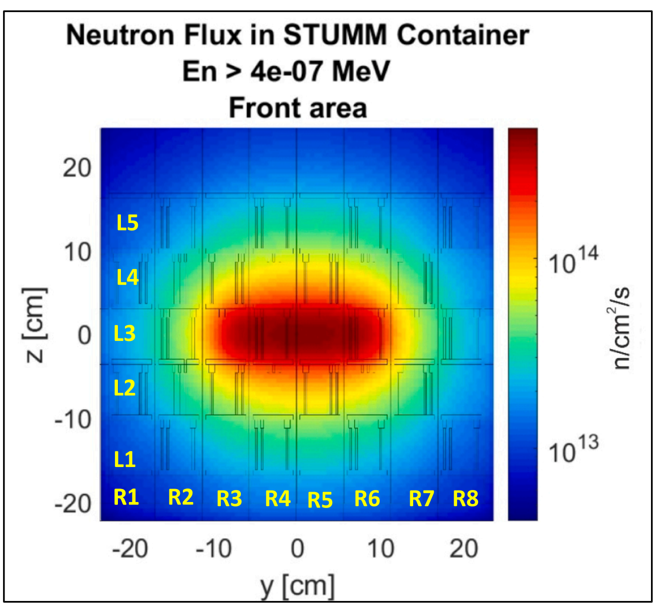

Fig. 3. Front view of the integrated neutron flux map at the front of the STUMM container for an energy range over 4E-7 MeV. The STUMM container is divided into 8 vertical compartments, each of them housing one instrumented rig. Rigs are numbered from R1 to R8 from left to right, each rig including 5 levels from L1 to L5.

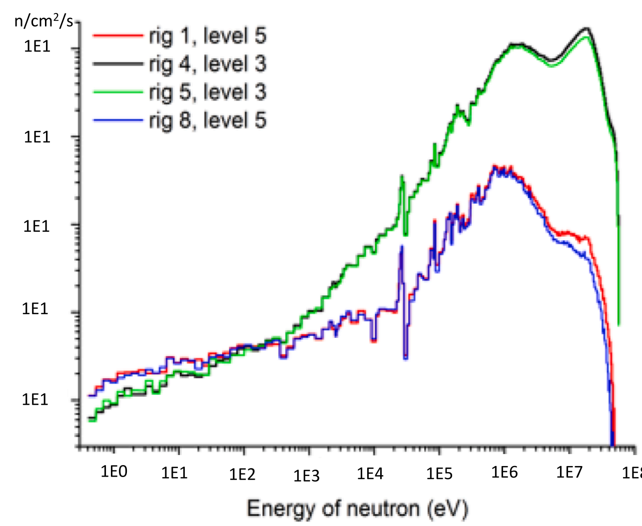

Fig. 4. Neutron spectrum in DONES at the front of several rigs of the STUMM. The STUMM container will include 8 rigs, each of them inserted in a single compartment. On the other side, each rig is divided into 5 levels (see Fig. 3).

of each isotope being sensitive to specific energy bands of the spectrum.

The detailed procedure for achieving the characterization of the neutron and gamma fields by appropriate processing of data coming from these different kinds of detectors has not been detailed yet.

- The STUMM-PROTO objective is to cover present knowledge gaps, in particular concerning miniaturized MFCs, ICs and SPNDs. Customised detectors have been developed by Photonis and Thermocoax for the specific space constraints and the mapping resolution aimed in the STUMM. This already justifies the need of particular characterization research works.
- Fast neutron fields in the STUMM container: The MFCs, ICs and SPNDs have been traditionally developed and used for fission nuclear reactors, where the neutron spectra is substantially different from the one in IFMIF-DONES (Fig. 4). Dedicated irradiation campaigns have been implemented in the past for the characterization of such miniaturized MFCs and ICs at the Belgian reactor BR2 (fast neutron and gamma fields) and in NAYADE Co-60 gamma source at CIEMAT [3]. Nevertheless, these experimental works were implemented with experimental rigs housing just one pair MFC/IC and at room temperature, which are quite dissimilar conditions as compared to the ones existing in the STUMM and the HFTM in DONES TC. Likewise, the SPNDs are currently beyond the state of the art regarding applications to fast neutron fields. Quite recently, some research activities have been started [4] to find emitter's material with good performance under fast neutron fields.

- Wide range of working temperature: Both the STUMM and the HFTM will be subjected to a very significant nuclear heating. In addition, the HFTM shall include heaters make the material specimens increase its temperature as much as 550 °C.
- Very high spatial density population of the detectors inside the STUMM container: Cross-talk effects, specially for the SPNDs, induced to the detectors due to the closeness to the neighbours are an uncertainty that needs to be experimentally addressed.
- Long mineral-insulated (MI) cables: The distance from the detectors location inside the STUMM and the first feasible acquisition electronics outside the TC will be around 30 m, all this distance being covered by MI cables, which has to be taken into account to preserve the integrity of the very low signals.

Except for the first two bullets, all the remaining points have not been addressed so far for the specific working conditions expected at IFMIF-DONES. This is the main reason why a prototype of the STUMM, the so called STUMM-PROTO, and its corresponding experimental campaigns are necessary.

2. The STUMM in a nutshell

From constructive point of view (Fig. 5), the STUMM consists of a long vertical, leaktight vessel at 3.5 bar (He), its lower section (container) housing all the sensors and detectors necessary for the characterization of the neutron and gamma fields. The container is the part directly exposed to the high flux neutron field. All the MI cables from the detectors are driven through the attachment adapter up to the upper section where a leaktight feedthrough connection panel is placed. The long distance between the container and the panel connection allows for much lower dose rate affecting at the leaktight feedthroughs, its reliability being this way increased.

The detectors and sensors are mounted in 8 rigs, each of them inserted in one of the 8 compartments of the container (Figs. 3 and 5). Each rig is divided into 5 levels highwise; therefore, the so-called cells are named by the combination of a rig number (1 to 8) and a level number (1 to 5) and provide the volume for the placement of the detectors. In turn, the cellhas two different regions: the frontand the back, both of them being separated by a slab all along the vertical extent of the container. The aim of this slab is to lower the neutron flux in the rear part of the cell so that the theoretical models of interaction of neutrons with materials can be validated.

The STUMM vessel is cooled down by helium gas flow since conventional water-based cooling is forbidden inside the Test Cell asthe highly exothermal reaction produced in case of incidental spillage between lithium and water shall be avoided at all means. Helium gas flows into the STUMM vessel through the two elbowed pipes (Fig. 5) at the top and goes downwards through the vessel to the container where the flow is split into eight compartments, thus going out from the vessel though eight thinner pipes at the bottom.

The STUMM will not include any heater, the temperature distribution inside the container thus resulting from the interaction between the

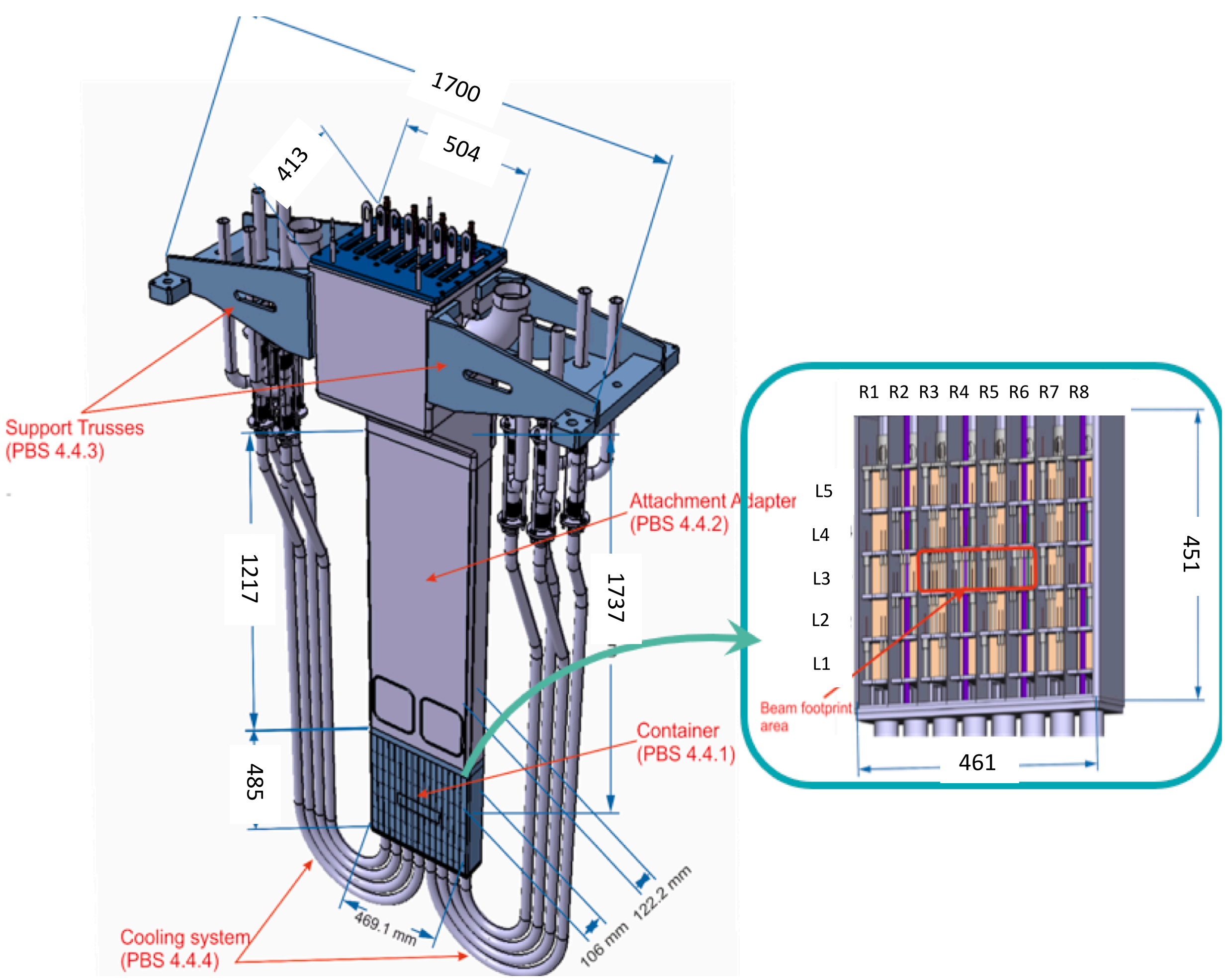

Fig. 5. General view of the STUMM and a detail view of the container's inside. On the detail view, the orange-coloured parts in the rigs are the slabs separating the front from the back. Diagnostics are placed both at the front and at the back of the slabs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

helium cooling flow (190 g/s) and the nuclear heating induced by the irradiation fields. The maximal temperature expected in the container is around 200 °C [2], in particular, in the slabs of the central rigs.

3. Stumm-Proto main requirements and specifications

According to the context presented so far, the main requirements and boundary conditions for the STUMM-PROTO is as follows:

The STUMM-PROTO will be built at a 1:1 scale relative to the STUMM, although it will house one quarter as many detectors as the STUMM, specifically 15 MFCs, 15 ICs, 6 SPNDs, 11 GTs, and at least 10 TKs. No Rabbit System will be included.

The system must comply with RCC-MRx standards [8] as Class NRx3, including significant improvements from NRx2 and NRx1:

- Design by analysis according to rules described on RB 3200 (N1Rx), i.e. mechanical limit Sm reduced to S according to the RD 3800.
- Acceptable welding configurations according to RC 3834.32 (N2Rx).100 % volumetric examination in all pressure retaining weldings.

This requirement has been defined to provide a high quality assurance to the prototype, even if it is not fully necessary from safety point of view because the STUMM vessel is not a safety-important component.

The system must fulfill specific electrical requirements, including signal ranges to be measured, bias voltage (polarization) and acquisition rates as specified in Table 1 for the different types of detectors. The bias voltage should be adjustable from + 150 VDC to + 250 VDC for MFCs and ICs. Notably, SPNDs do not require any bias voltage.

As a noticeable fact, reference [5] includes an estimate around 16 – 20 μA for the signal expected signal from a MFC/IC subjected to a neutron flux of 5E14 n/cm2/s. For the MFCs and ICs, the minimal signals specified in Table 1 are around three orders of magnitude lower because the neutron facilities where the STUMM-PROTO may be irradiated do have much lower fluxes than IFMIF-DONES.

Concerning the fast trigger signals, this challenging requirement comes from the eventual use of few MFC/ICs as Machine Protection System (MPS) components such that, given a sudden shift of the D + beam, those could trigger an alarm in less than 30 μs. With respect to the expected signals for the SPNDs, reference [4] includes real measurements of SPND signals at NEAR/nTOF (CERN), which are in the order of few tens of pA. So the requirement below follows those figures.

The electrical cabling configuration must accommodate significant distances, with 35-meter-long coaxial mineral-insulated (MI) cables from the upper section of the STUMM to the nearest signal acquisition cabinet. Different coaxial mineral-insulated cables will be available for wider testing and characterization capabilities.

The current signal range must be configurable by inserting ad-hoc feedback capacitors (Cf) and feedback resistances (Rf) in the analog stage of the signal acquisition electronics, according to the expected responses during the different irradiation campaigns. This requirement will allow tuning the acquisition electronics to the expected responses of the detectors in selected neutron and gamma source facilities once the experimental program of the STUMM-PROTO is further described.

Table 1
Required signal ranges and acquisition rates for the different detectors in STUMM-PROTO.

Detector [amount]	Bias Voltage (V)	Expected signal range	Acquisition rate (kHz)
Monitoring MFC/IC [26]	150–250	10–1000 nA	2–5
Fast trigger signals (MFC/IC) [4]	150–250	4000 nA step signal detection threshold = 1000 nA	200–1000
SPND [6]	N/A	20–500 pA	0.1
GT [11]	N/A	In the order of few mV	1
TK [10]	N/A	In the order of few mV	1

Configurable sets of polarized MFC/IC will be provided, allowing each MFC/IC to be independently fed with bias voltage. This requirement will enable high versatility in the amount and selection of polarized MFC/IC in the different groups of detectors.

The system will offer both floating and grounded electrical configurations for the rigs. Since the signal response expected from some neutron detectors (mainly SPNDs, but also MFCs and ICs) will be very weak, this requirement will allow different electrical configurations to be tested and compared in terms of background noise and signal integrity.

The working temperature range for the system will be from 20 °C to 350 °C, allowing for reaching the upper limit according to the manufacturer's specifications for the MFCs and ICs. The survival temperature range will extend up to 500 °C. Additionally, the system will feature a leaktight mechano-welded vessel capable of operating under vacuum (10^{-3} mbar) and under helium pressure (3.5 bar). This requirement aims to replicate the same mechanical concept as the STUMM.

Finally, the system will maintain a low temperature gradient (few Kelvins) between detectors in a densely instrumented cell, as shown in Fig. 8. This small gradient is very convenient because it will allow reducing the amount of TKs so most of the cell's volume will be used for neutron and gamma field diagnostics.

4. Main guidelines of the Stumm-Proto experimental programme

The experimental programme for STUMM will include three main phases:

- Cold test campaign, where basic performance parameters of the MFC, IC and SPNDs will be characterized in an industrial EMC (electromagnetic compatibility) environment. These tests will be crucial to understand the lowest detection threshold for each kind of nuclear detector and will feedback the detailed definition of the following testing campaigns.

In summary, the leakage current and the background signal will be the main parameters to be measured in different conditions of: (a) population of detectors, to see parasitic cross-talks; (b) temperature; (c) electric configuration (floating/grounded) with different MI transmission lines.

By the possibility of activating/polarizing individually the selected detectors, the population of detectors can be configured as to reproduce the STUMM worst conditions.

- Gamma irradiation campaign, where typical parameters from the MFC and ICs will be measured: bias voltage calibration curves, signal response linearity, signal response repeatability, signal-to-noise ratio, correlation between MFC and IC responses. In reference [3] a very interesting work can be found about the characterization of these miniaturized detectors under fast-neutron fields at room temperature.

For SPNDs prompt signal measurements will be of great interest, too. According to [4], SPNDs may be sensitive to a (γ, e^-) reaction, thus a prompt signal being produced, which might give interesting outputs about the possibility of using SPNDs as a MPS component.

The free variables will be the same as in the previous phase: working temperature range, spatial density of detectors and floating/grounded electric configuration.

- Fast neutron irradiation campaign, where the same features as the previous campaign will be measured for MFC and ICs. Furthermore, the SPNDs will be characterized in terms of signal response linearity and signal-to-noise ratio. Finally, correlations between MFC, IC and SPND responses will be possible in this final campaign. The free variables will be the same as in the previous phases.

The STUMM-PROTO experimental programme is not yet defined so no specific facilities have been explored so far. Nevertheless, few of the guidelines driving the eventual selection of the irradiation sources are defined as follows:

- Energy spectra: Both for the gamma and neutron campaigns, the energy spectra need to be similar to the ones expected at IFMIF-DONES. Regarding the gamma spectrum, Co-60 sources match quite well this need. For neutron irradiation, energies above 1 MeV reaching more than 10 MeV are necessary.
- Neutron and gamma flux: The irradiation sources have to ensure enough flux to provide a signal high enough in MFCs, ICs and SPNDs. Therefore, the background noise characterization of these low-signal detectors is crucial to define the minimal signal to be produced and, hence, the minimal flux required from the gamma/neutron source. A very sensitive and low-noise acquisition electronics will play a key role here, this topic being one of the most challenging in the development of the STUMM-PROTO.
- As an example that might be explored, according to the supplier, the measuring range in fast neutron fields for the MFCs and the ICs is between 1E10 and 1E14 n/cm^2/s. Therefore, a facility like U-120 M at NPI [7], which provides fast neutron fluxes as high as 1E11 n/cm^2/s could be an option.
- The gamma irradiation campaign will be the longest one because it does not lead to the activation of the materials while the neutron irradiation campaign would likely make the STUMM-PROTO non-usable further in the short and mid term.

5. Mechanical design and manufacturing status

The prototype (Fig. 6) will be made of AISI316L. Thermo-mechanical analyses have been implemented according to the RCC-MRx class N3Rx.

The mechanical manufacturing is currently ongoing (Fig. 7), the most critical component from constructive point of view, the container, being already finished. For its manufacturing a very high portion of material needs to be removed by proper machining, both the front and the inner walls being as thin as 2 mm. Therefore, the machining process has been planned very carefully to minimize internal stresses and further deformation of the piece. The very thin front wall of the container will allow the detectors to be placde at the front as close as possible to the irradiation source, which is crucial to get detector signals over the background noise [2].

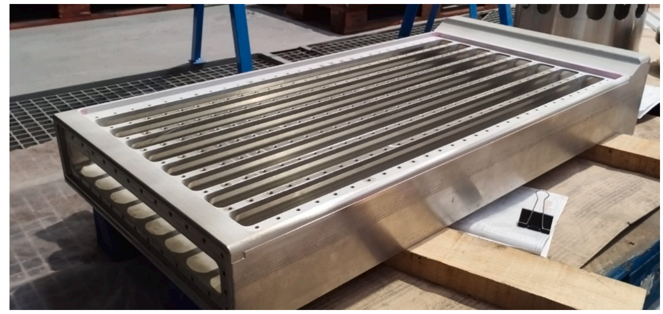

Fig. 7. Left: General view of the STUMM-PROTO container after one of its main stages of manufacturing.

Although the STUMM-PROTO replicates the main dimensional features of the STUMM, its upper section (Fig. 6) with the feedthrough connection panel will probably differ from that of the STUMM as the design of the latter is not yet consolidated.

A wide temperature range inside the container is provided through a heating system composed by 8 internal heaters, independently controlled, and one external heater (Fig. 8). The external heater and the external thermal insulation are easily removable. The internal heaters are placed inside the rig slabs, which make the role of heat radiators. The external heater will be placed in front of the container to achieve thermal gradients in the range of few degrees in each cell. This configuration will only be valid for the cold test campaign. For the radiation test campaigns, nothing can be placed in between the front face of the container and the irradiation source.

Fig. 8 shows a horizontal cut sketch at the level 3 of the container,

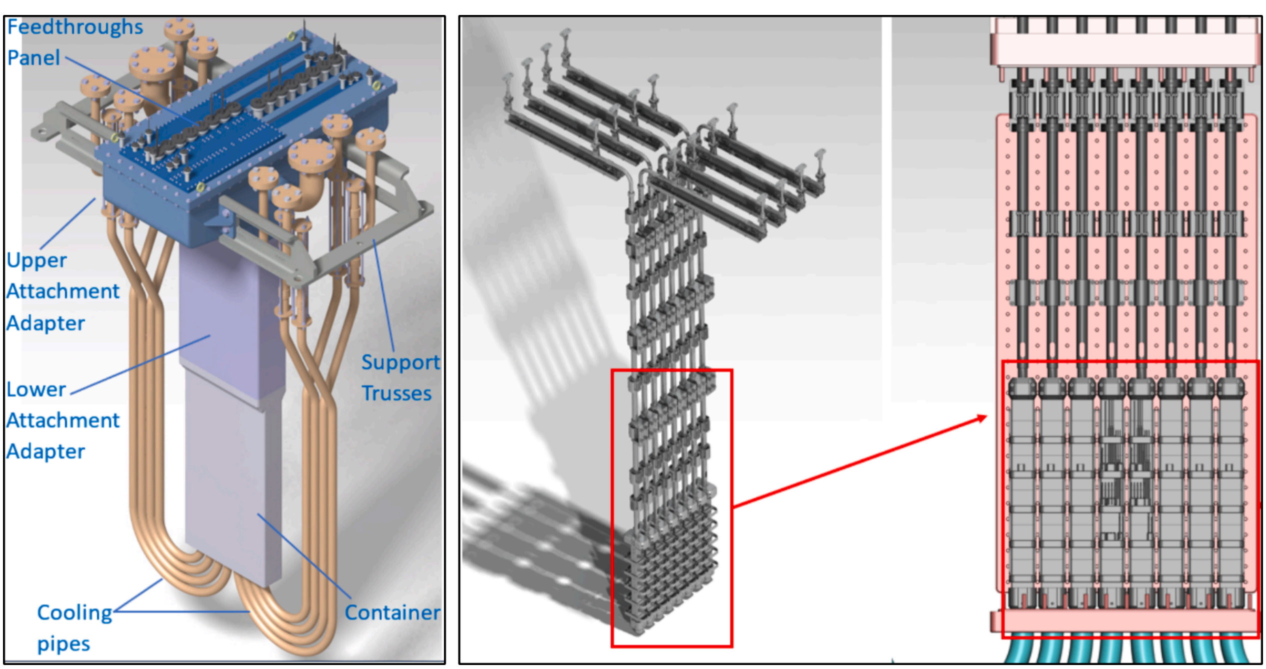

Fig. 6. Left: General view of the mechanical design of the STUMM-PROTO vessel. Right:Composed image showing an overall view of the set of 8 rigs and an specific image of the rigs sections corresponding to the container region.

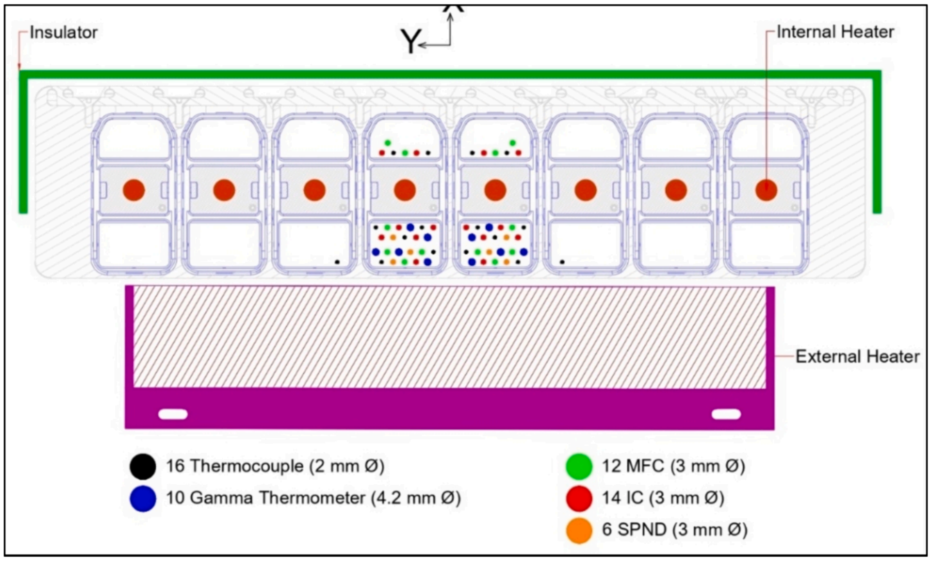

Fig. 8. Horizontal cut sketch showing the container with its 8 rigs, each of them with an internal heater. The external heater and insulation are also included. Last but not least, for the sake of example the densest configuration that can be achieved inside a front cell of the STUMM-PROTO is shown in rigs 4 and 5.

where the densest population of detectors will be placed, as well as all the heaters and the the thermal insulator behind the container. This concentrated configuration of detectors is specially well suited for point sources for the gamma and neutron irradiation campaigns.

Fig. 9 shows the temperature gradient of one half of the container with special interest in the levels 2 to 4 – foreseen to be densely instrumented with detectors- of the rig 5. The front of the cells of those three levels in rig 5 have an overall temperature gradient lower than 20 °C. Nevertheless, it decreases to 5 °C for level 3, fitting the needs of the irradiation with point irradiation sources where a highly dense population of detectors will be advisable.

6. Electronic engineering status and first mockup results

In order to fulfil the diverse requirements of electronics packages, three types of DAQ (Data acquisition) devices are under development, as illustrated in Fig. 10: (a) Input stage based on TIAs (Trans-Impedance Amplifiers) for analog acquisition complemented with configurable ADCs (analog–digital converters) and FPGAs (Field-Programmable Gate Arrays) for fast processing; (b) Dedicated assemblies for physical and electrical segregation depending on the sensor type and electronics function, such as precise monitoring or alarm triggering; (c) integration with LCS (Local Control System) with varied funcionalities such as, post-mortem capabilities, digital filtering, industrial COMM, local/remote operation, interlocking, monitoring, etc. (d) Advanced electronics engineering approaches for power and signal integrity, adhering to relevant standards and leveraging prior experience (IEC61000, MIL-HDBK, and IEEE) in analogous facilities.

The electronics development status has nowadays already reached a good maturity where the main concepts for each of the packages managing with low-current signals have been frozen. From these validation activities, some relevant technical specifications already achieved are the following:

- **SPND DAQ**: Current-mode signal for monitoring purposes. Gain: 10^{10}. Bandwidth (BW): 100 Hz. Foreseen up to 200 Hz. Non-polarized. Successfully tested range: [+50,+500] pA.
- **Slow MFC/IC DAQ**: Current-mode signal for monitoring purposes. Gain: 10^{7}. Bandwidth: [1, 2.5] kHz. Foreseen up to 3 kHz. Polarized [0, 250] VDC. Successfully tested range: [+3, +600] nA.
- **Fast MFC/IC DAQ**: Current-mode signal for monitoring purposes currently understudy. Trigger interlocks in case of beam

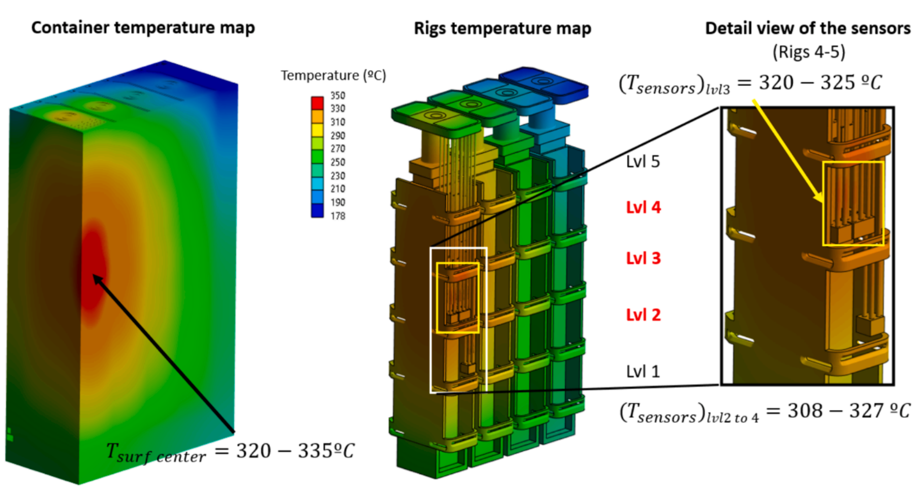

Fig. 9. Results from thermal analyses showing the temperature gradients in the front cell of levels 2 to 4 of an instrumented rig and on the nearby region of the container's walls. The model under study is one half of the container.

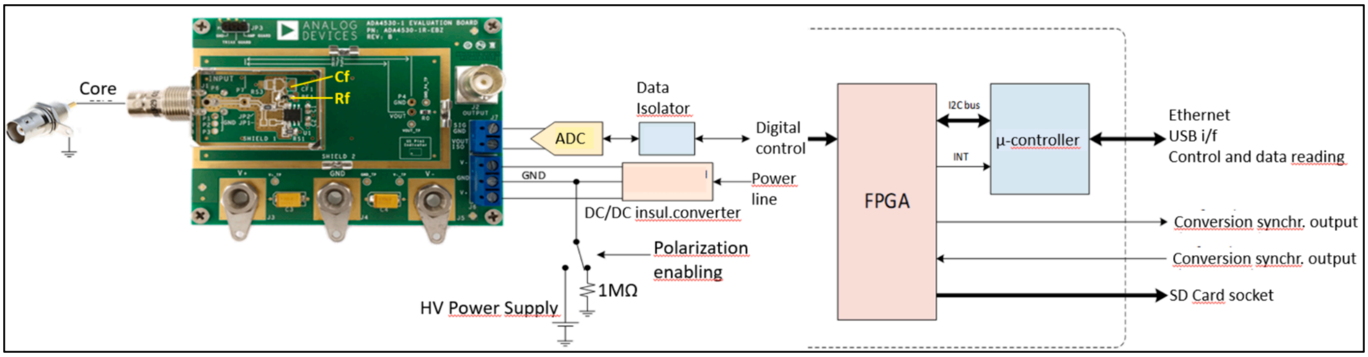

Fig. 10. Block Diagram of the neutron detectors signal acquisition electronics.

displacement, time response point-to-point < 10us. Configurable threshold levels. Gain: 10^6. Bandwidth: [50, 100] kHz. Foreseen above 100 kHz. Polarized [0, 250] VDC. Successfully tested range: [+10, +6000] nA.

Other important electronics aspects include the optimization of chipset-loop components, specifically Rf and Cf, both crucial for achieving an optimal balance between bandwidth and gain while ensuring the system stability. The system has the capability for fine tuning these components via soldering pads allowing for adaptation to multiple operational conditions and requirements.

The power supply architecture incorporates isolated DC/DC converters, digital isolators for differential noise mitigation, and a bespoke high-voltage linear power supply, providing a robust, low voltage ripple, low noise DC bus and a wide polarization voltage range. This setup ensures efficient operation under a broad range of environmental conditions, minimizing the risk of power-related electrical emissions.

Regarding the DAQ digital capabilities is the use of a 16-bit ADC and an dedicated Artix 7 FPGA, 1 per electronics assembly. This combination facilitates fast time response and high-resolution data capture required for the high-precision applications.

Fast self-protection electronics for both low-voltage (LV) and high-voltage (HV) circuits has been integrated into the system. This mechanism is designed to identify and mitigate potential electrical failures in a active way, safeguarding the system against electrical damages, such as transmission line short-circuit or catastrophic chipset failure, mitigating and controlling the damage to the rest of the electronics subsystems.

Furthermore, the 'grounding' and 'earthing' concepts are engineered based on modeling of expected signal return path. Key aspects include the transmission lines, such as coaxial mineral insulated cables, system structures (vessel and cable trays), chassis assemblies, power lines, etc. Each of these components has been rigorously studied to significantly reduce interference across a wide noise spectrum by applying preventive design techniques. These techniques include galvanic isolation, digital isolators, active filtering, shielding, capacitive coupling among others. This approach to grounding ensures the system delivers unparalleled accuracy in challenging environments expected in IFMIF-DONES. Fig. 10 presents a comprehensive block diagram illustrating the prototyping activities and electronics design accomplishments up to the current date.

Several setups and test benches have been built to validate the electronics concept in order to carry out the development of subsequents assembly stages. The results obtained are very promising:

- Fast MFC/IC signal acquisition electronics response in ≈6 µs to a step current pulse of 4 µA once the detection threshold of 500 nA is reached (Fig. 11, left). Further validation have included the long MI transmission line plus organic extension cables, critically damped output and faster time response.
- SPND signal acquisition (only analogic stage)
  - o Systematic LF background noise of ± 40 pA at 50 Hz plus some spurious peaks due to domestic environment (typically switched-mode power supplies) shown (Fig. 11, centre/right). Further results are showing better signal integrity under ± 40 pA.
  - o A Low-Pass filter and FIR (Finite Impulse Response) is being included in each assembly via FPGA to cancel the low frequency noise component and stabilize the analog response along the BW.
- Slow MFC/IC signal acquisition electronics provide a noise background level as low as ± 3nA.

7. Conclusions

The present work has provided a complete overview of the STUMM-PROTO and the context within the IFMIF-DONES project. As the most

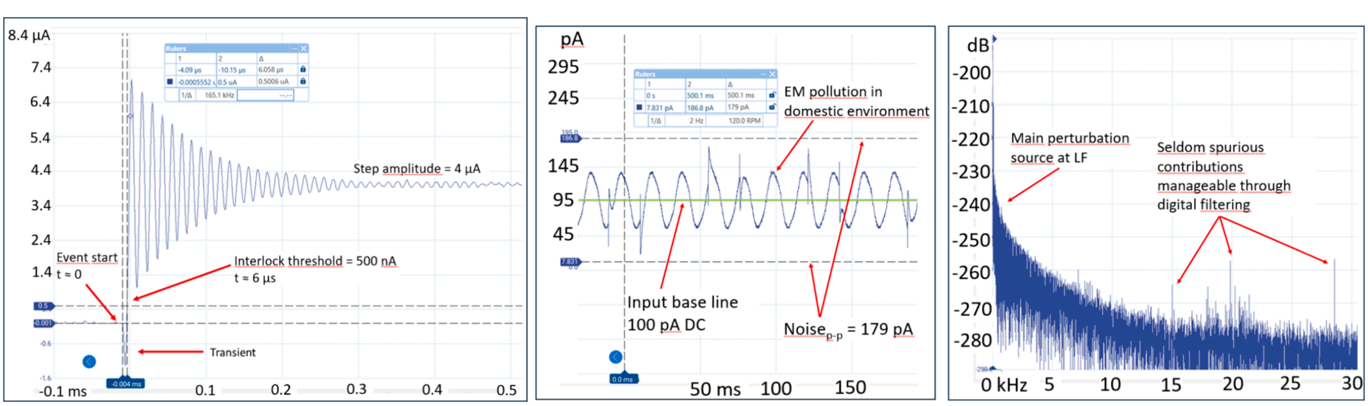

Fig. 11. Left: Fast MFC/IC signal acquisition response to a step change signal input (undamped). Centre/Right (FFT): Noise profile characterisation for a 100 pA DC input signal in SPND signal acquisition electronics.

significant features, the prototype replicates the STUMM at a 1:1 scale and will include as many as one quarter of the neutron and gamma detectors of the latter, its main purpose being the characterization of those detectors in the final conditions in terms of spatial density, temperature and electrical configuration. Testing campaigns will include cold tests, gamma irradiation tests and neutron irradiation tests,

Concerning the mechanical manufacturing, STUMM-PROTO will follow the RCC-MRx standards to assure a high quality of the component.

Eventually, from electronics point of view, some very promising results have been already obtained in terms of noise background level: 3nA for the MFC/IC acquisition and 40 pA for the SPND acquisition. For the fast MFC/IC a time response of ≈6 μs has been achieved. All those figures fit very well with the very low expected signals in fast-neutron sources (neutron irradiation campaigns), several orders of magnitude lower as compared to the IFMIF-DONES facility.

CRediT authorship contribution statement

Santiago Becerril-Jarque: Writing – review & editing, Writing – original draft. **Álvaro Marchena:** Investigation. **Andrés Roldán Aranda:** Investigation. **Pablo Araya:** Investigation. **Roberto García Baonza:** Investigation. **Agustín García:** Investigation. **Jorge Aguilar:** Investigation. **Luis Fernández:** Investigation. **Urszula Wiacek:** Investigation. **Rafal Prokopowicz:** Investigation. **Jesús Castellanos:** Investigation. **David Rapisarda:** Investigation.

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.

Data availability

No data was used for the research described in the article.

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