Studies on Flat Sandwich-type Self-Powered Detectors for Flux Measurements in ITER Test Blanket Modules

Prasoon Raj, Maurizio Angelone, Toralf Döring, Klaus Eberhardt, Ulrich Fischer, Axel Klix, Ronald Schwengner

Abstract— **Measurement of neutron and gamma fluxes in designated positions in TBMs will be important during ITER campaigns. Experimental investigations on self-powered detectors (SPD) are undertaken in the framework of ongoing task on development of nuclear instrumentation for application in European ITER test blanket modules (TBM). This paper reports the findings of irradiation tests performed with a test SPD in flat sandwich-like geometry. Detector with vanadium emitter is chosen for preliminary studies. Its signal is measured in a thermal neutron field to present a proof of the principle of flat SPD. It is further irradiated in mixed neutron-gamma field of a 14 MeV neutron generator and a bremsstrahlung photon field. The detector signal is proportional to the incident flux, deeming it suitable for flux monitoring. Whereas both neutrons and gammas can be detected with appropriate optimization of geometries, materials and sizes of the components, the current design is more sensitive to gammas than fast neutrons. The measured sensitivities of SPD are extrapolated to TBM conditions to estimate the range of signals achievable in actual application.**

I. Introduction

THE breeding blanket will be a critical component of a power reactor based on nuclear fusion. Breeding of tritium for the fuel cycle of reactor, heat extraction and radiation shielding will be its main functions. To validate the performance of such a blanket under representative conditions, test blanket modules (TBM) based on different blanket concepts will be inserted in designated equatorial ports of ITER reactor. From the fusion neutronic point of view, nuclear measurement experiments in TBMs will be of great interest. In different phases of the machine's operation, responses like tritium production, nuclear heating, material activation etc. will be measured at different locations in TBMs. The results of these experiments will be compared with those obtained from calculations. ITER being a large tokamak device with physical characteristics like those of a fusion power reactor, these tests will be used for a validation of the computational tools (e.g. Monte-Carlo and activation/inventory codes) and nuclear data employed in neutronic design studies of fusion reactors.

Online measurements of neutron and gamma fluxes will be important tasks in the neutronic experiments, since the TBMs will not be accessible during ITER campaigns. With high radiation, high temperature, and electromagnetic interferences the operating conditions for nuclear detectors in TBM are detrimental. Development of suitable instrumentation for such harsh conditions is an ongoing project. Activation foils, diamond detectors and self-powered detectors (SPD) are among the detector classes chosen for further study.

Self-powered detectors are commonly utilized as flux monitors in fission power reactors. They have simple, compact and robust design fit for regions with less accessibility like reactor cores. They are often composed of standard metals, mineral oxides and alloys, making it desirable with respect to nuclear proliferation and export-control guidelines. Moreover, they are relatively inexpensive to manufacture. For these reasons, some regular SPDs, one commercially manufactured ad-hoc SPD [1] and several different variants in flat sandwich-like design [2] are under investigation. The aim is to check the adaptability of these detectors to fusion environment, identifying the challenges in detector design and manufacture, application and signal interpretation. Solutions are being explored to address these tasks and find a way to design and test prototype SPDs for neutron and/or gamma detection in TBM. In this paper, parts of the experimental studies with flat SPDs involving irradiation tests with thermal neutrons, 14 MeV fast neutrons and bremsstrahlung photons are reported. Preliminary conclusions regarding feasibility of an SPD for the TBM are presented.

II. Design and Test Methodology

A. Description of a Self-Powered Detector

An SPD is a multi-layered device [3] with two electrodes separated by a mineral oxide insulation layer. There is an *emitter* layer with high neutron or gamma interaction cross-section. Under these interactions, the material produces high energy electrons. These electrons move outwards and are stopped in the outer electrode layer called *collector*. The separation of charges forms the detector signal. The response is usually measured as a direct current (DC) signal. The rate of neutron/gamma interactions, thereby the rate of electron emission and magnitude of DC signal is proportional to the incident flux. *Sensitivity* of an SPD is defined as SPD current per unit of incident flux and is expressed in unit of A cm^2 s^1.

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Traditionally, SPDs [4] are made in coaxial cylindrical geometry. A wire (or rod) of emitter is placed in a closed tube of collector with a tube or beads of mineral oxide between them for electrical insulation. It can also be designed in a flat geometry with foils of insulator and collector sandwiching a foil of emitter. A schematic of this design is shown in Fig. 1 with the current measurement connections.

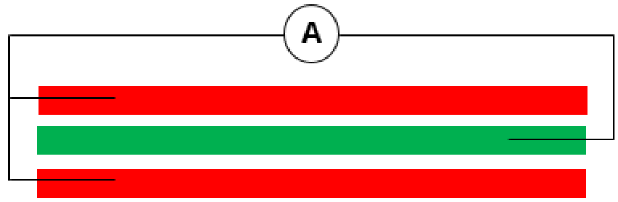

Fig. 1. Schematic of an SPD showing emitter layer in green, insulation in white and collector layers in red. An ammeter across emitter and collector (grounded) can be used to see the DC signal from the detector.

The variation of SPD signal under dynamic reactor conditions has a profile in time. This is based on the half-life corresponding to the exact atomic or nuclear process which creates most of the fast electrons. Following are the common processes which can give rise to a signal:

1. (n, β^-) process: in this, neutron absorption reaction leads to formation of a radioactive daughter nuclide in the emitter that undergoes beta minus decay. Due to the half-life of beta decay, the signal does not vary promptly with variation in incident flux. It must be interpreted accordingly [5]. Materials like Rh, V, Ag etc. have high cross-sections of neutron capture reactions, with half-lives from seconds to minutes. With high level of confidence in these cross-sections, these detectors are highly reliable. Known as *Delayed Self-Powered Neutron Detector (SPND)*, this is one of the most common SPDs in fission reactor cores.
2. (n, γ, e^-) process: in this, neutron activation leads to emission of high-energy gamma in the emitter material. The gamma interacts through photoelectric effects, Compton scattering and pair-production routes to produce fast secondary electrons, which form the detector signal. This is a two-step emission process unlike (n, β^-), making the detector relatively less sensitive. However, the detector responds to flux variations without delay because the process is prompt. This makes *Prompt SPND* a good choice for reactor power-level monitoring. Cobalt is a common emitter for such an SPND, wherein capture gammas make most of the signal.
3. (γ, e^-) process: is the principle at the heart of a *Self-Powered Gamma Detector (SPGD)*. In this, external gammas from the surrounding of the detector are detected through secondary electron emission in the emitter. A high-Z material like Bi [6] is suited for a gamma detector.

The radiation field in which an SPD is applied is mixed with both neutrons and gammas. Whereas a detector is optimized for high response with one of the preferred processes, the output signals are mixed with contribution from most of them. Therefore, when describing a signal, one uses terms like "delayed current", "prompt current" and "gamma current" to specify these components. The latter two are usually difficult to separate and computational models with particle transport calculations are required to know their ratio.

B. *SPD Design Studies for ITER-TBM*

Test blanket modules (TBM) of ITER have neutrons and gammas over a wide energy range [7]. Using A-lite MCNP [8] model of ITER with HCLL and HCPB TBMs, the energy spectra are calculated in relevant positions for integration of flux monitors. Figures 2 and 3 respectively, show calculated neutron and gamma spectra near the centers of the front walls of the two TBMs. The neutrons range from thermal energy to 14 MeV D-T neutron energy. Majority of them have intermediate energies. Total neutron flux intensity can go up to the order of 1.9 x 10^{14} n cm^{-2} s^{-1}. No available neutron sources provide comparable field characteristics.

Based on a set of criteria several materials were chosen for emitter of a delayed SPND for TBM [1]. These criteria included high saturation activity, short half-life of product nuclides and high beta energy.

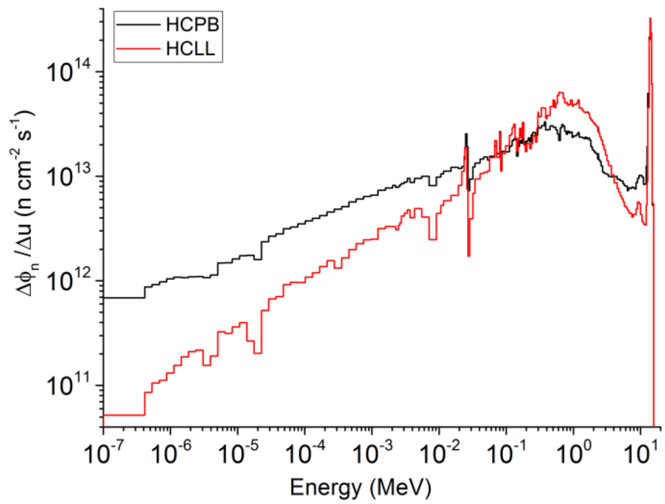

Fig. 2. Energy-spectrum of neutrons near the front wall of ITER TBMs; ordinates show group neutron fluxes ($\Delta\varphi_n$) per lethargy interval (Δu)

In Table 1, effective cross-sections of reactions of interest are shown for three neutron spectra: thermal reactor, HCPB TBM of ITER and DT neutron source (approx. 14 MeV). For the latter two cases, FISPACT EASY-2007 [9] calculations were performed to collapse EAF-2007 data library with relevant spectra. The cross-sections in TBM and DT neutron cases are multiple orders of magnitude lower than the thermal case. It can be noted that designing a pure delayed SPND for TBM neutrons is challenging because of relatively lower reaction cross-sections. Moreover, the probability of photon production is higher than that of beta emission for fast neutrons. Prompt current due to neutron-induced gammas in detector dominates the signal. This is unlike the case of thermal neutrons, where both the processes have similar cross-sections, and the delayed current dominates for short half-life beta decays. Overall sensitivity of SPND for fast neutrons is therefore, reduced. Another important difference is that possibility of threshold reactions gives a way to exclusively measure fast neutron contribution in TBM.

In TBM, especially near to the first wall there is a strong gamma field also (Figure 3). Corresponding to 500 MW operation of ITER in reference D-T phase, the total intensity of gammas at positions relevant to SPDs will be of the order of 7 x 10^{13} γ cm^{-2} s^{-1}. Dedicated detectors for measurement of TBM gammas (SPGD) are vital. Theoretical and experimental investigations are underway in European laboratories to realize SPDs for neutron and gamma measurement in European ITER TBMs [1], [2].

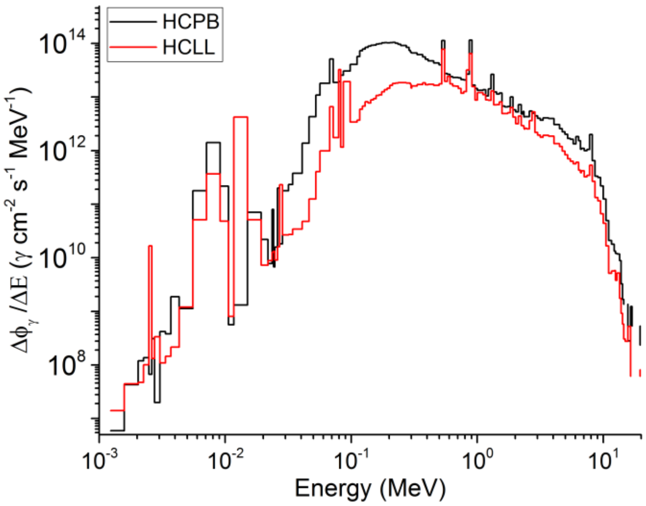

Fig. 3. Energy-spectrum of gamma near the front wall of ITER TBMs; ordinates show group fluxes ($\Delta\phi_\gamma$) per unit of the energy bin size (ΔE)

Table I

Effective cross-section of reactions of interest for SPNDs, in three different cases: thermal reactor, HCPB TBM and 14 MeV DT neutrons

Reaction	Thermal	TBM	DT
^{103}Rh (n, γ) $^{104m/g}$Rh	150.00 b	1.983 b	0.0008 b
^{51}V (n, γ) ^{52}V	4.9400 b	0.0316 b	0.0006 b
^{51}V (n, p) ^{51}Ti	$<E_{threshold}$	0.0046 b	0.0294 b
^{9}Be (n, α) ^{6}He	$<E_{threshold}$	0.0084 b	0.0090 b
^{52}Cr (n, p) ^{52}V	$<E_{threshold}$	0.0114 b	0.0738 b

Beryllium, vanadium, chromium and a few other materials are chosen for investigation as emitter of SPDs for TBM. For insulation alumina and for collector Inconel-600 alloy are used in these studies.

C. Motivation for Flat Sandwich-type SPD

Cylindrical coaxial-type SPNDs have been in use since decades. They provide for an optimum design giving high sensitivity in thermal reactors and are well-suited for insertion in the instrumentation channels of the reactor cores. One of the ways of combatting the low sensitivity of SPDs is to increase the reaction rate by increasing the active emitter surface facing the neutron/gamma field. Increasing wire or rod thickness in cylindrical design leads to increase of self-shielding of particles limiting the sensitivity again. In principle, this limitation can be avoided by using the emitter in a flat geometry. This is specifically of interest for TBM. A foil of emitter can be encapsulated in a case made from collector material with insulation material filling the gap. For application in TBM, one can think of a multi-layer strip-like detector or a chip-like compact detector which can be integrated with minimal invasion.

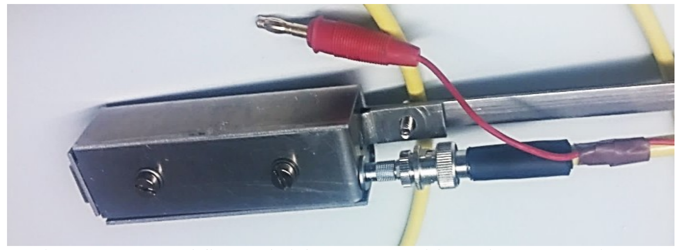

Fig. 4. Constructed flat sandwich-type SPD with an electromagnetic case made from aluminum and coaxial cable connection for signal

A test detector (Figure 4) in flat geometry was designed with foils of collector and insulator sandwiching a foil of emitter. High-purity foils with dimensions 25 mm by 25 mm by 0.5-2 mm were used in different experiments. The model is flexible with openable parts to tests different material combinations in different thicknesses. The assembled detector is packaged in a case of aluminum which also works as an electromagnetic shield.

D. Test Sources

A proof of the working of flat sandwich-type SPD is achieved by irradiating it in the TRIGA Mark II reactor of the Johannes-Gutenberg University Mainz. Experimental position is near the hot end of the graphite thermal column (GTC) of the reactor with total thermal neutron flux of the order of 10^{10} n cm^{-2} s^{-1} [10]. The detector is mounted on a plastic frame and positioned close to this end of the column.

For fast neutron irradiation, 14 MeV Neutron Generator of Technical University of Dresden (TUD-NG) is utilized. TUD-NG is an accelerator based intense D-T neutron source situated in Dresden-Rossendorf. It provides a neutron spectrum with peak around 14 MeV and flux going up to 10^{10} n cm^{-2} s^{-1} near the tritium target. A calibrated silicon diode detector measuring the alpha particles from the D-T reaction is used as the flux monitor. The detector is mounted in front of the cooling cup of the tritium target assembly.

The TUD-NG is characterized by a mixed neutron-gamma field. Estimation has been made in an MCNP calculation with model of the tritium target assembly of the generator and DT neutron source. At the experimental position, total gamma flux intensity is approx. 19% of the total neutron flux intensity. To obtain the neutron to gamma signal ratio for the tests at TUD-NG, a comparable test in a pure gamma field is required. Whereas radioisotope based line gamma sources are frequently used for such tests, a photon source is used in this work. At the beam dump of the ELBE [11] accelerator of Helmholtz-Zentrum Dresden-Rossendorf, there is a high intensity high-energy bremsstrahlung photon source created which is used for photo-activation experiments. The ELBE photon source has a continuous energy spectrum ending close to the energy of the electron beam. This is closer to the wide gamma spectra of mixed neutron-gamma fields encountered in fast neutron setups, e.g. TUD-NG. The detector is installed through a hole to the position, which is situated at the center of the graphite block which serves as the beam dump. Tests were performed at different electron beam energies and currents.

III. RESULTS

In irradiation tests performed with neutrons and photons, small DC current signals in the range of 50 fA to 500 pA have been measured. At these levels, there are chances of disturbance due to various currents produced because of mechanical, electromagnetic, thermal and radiation induced effects in detector components, cables etc. The measurements have been performed with care, reducing these sources as far as possible and ensuring the stability of the electrical connections. The flat SPD currents are proportional to the incident neutron [2] and gamma flux, as required for a flux monitor. It has been established in tests with multiple material combinations and flux levels varying over orders of magnitude.

A detector (V-SPD) with 1 mm thick layers of vanadium emitter (>99.8% purity) and Inconel-600 collector, separated by 0.5 mm thick alumina (Al_2O_3, >99.9% pure) insulator is used to obtain the results shown henceforth. There are three main reasons for the use of vanadium. Firstly, it is widely used as emitter in fission reactor SPNDs. Its response is well-understood and therefore, it makes for a good reference material to understand the newly designed detectors in flat geometry. Secondly, vanadium is a candidate emitter material for fast neutron SPNDs [1]. In the TBMs, especially HCPB TBM, V-SPND signal would have notable contribution from thermal neutrons. Information on thermal neutron flux is also valuable. For application in TBM, it is essential to acquire a good understanding of the behavior of vanadium as emitter. And finally, it is relatively easier material to handle in laboratories than the other main choices. For example, beryllium is highly toxic, chromium is brittle and silver tends to oxidize very quickly under laboratory conditions.

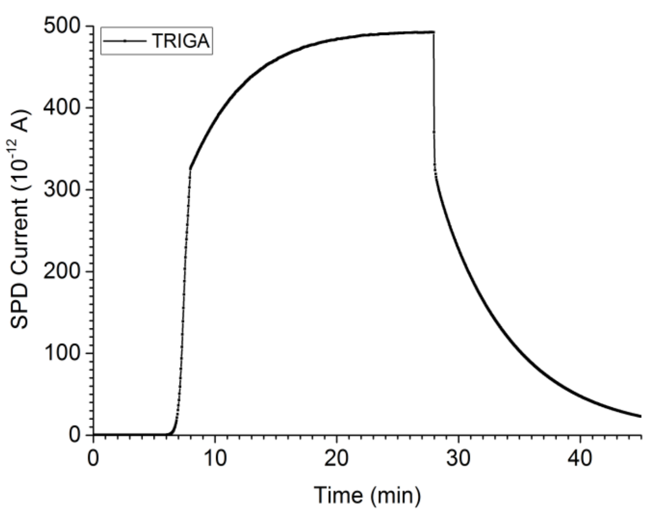

Figure 5: Flat V-SPD signal from neutron irradiation at TRIGA Mainz

In Figure 5, signal obtained with 20 minutes' irradiation of V-SPD in graphite thermal column (GTC) of TRIGA reactor Mainz (operated at 100 kW) is shown. Using activation foil measurements average neutron flux near the position of the detector is obtained as 2.63 x 10^{10} n cm^{-2} s^{-1}. The signal rises rapidly in first 2 minutes, approaching >67% of the total saturated current. During this time, the detector sees rapid variation of gamma and neutron fluxes as the reactor is brought to power. High prompt response is due to the reactor gamma field and gammas produced in the detector components including the aluminum case. During this time and in the rest of the irradiation period, a saturation curve is seen. This corresponds to the main beta emitter ^{52}V ($T_{1/2}$ = 3.75 min) produced in ^{51}V (n, γ) ^{52}V reaction. The curve saturates to enter a flat regime with a current of around 4.92 x 10^{-10} A. On immediate shutdown of the reactor, the current drops to 75% of its value in less than 0.05 min. A portion of the current is lost as prompt gammas from the surrounding and those induced in detector materials disappear with the neutrons. An exponential decay of current is observed afterwards, from which a half-life of approx. 4 min ($T_{1/2}$ [^{52}V] = 3.75 min) is obtained by fitting. Sensitivity of V-SPD calculated at saturation current value in case of TRIGA is 1.87 x 10^{-20} A cm^2 s^1 with a relative uncertainty of approx. 16%. This value is of the same order as the commonly reported sensitivities of cylindrical SPNDs in thermal reactor.

The response of V-SPD to fast neutrons is measured with TUD-NG. A high deuterium beam current is used to get an estimated flux intensity of around 1.82 x 10^9 n cm^{-2} s^{-1} incident on the detector. In this case, the detector signal rises and disappears almost instantaneously with the neutron flux as shown in Figure 6. Due to technical reasons, the incident neutron flux changed (by 1-2%) during irradiation, which is visible in the flat part of the signal between 1 to 15 min. The delayed current component is negligibly small (approx. 6.3% of the total). It is a sum of contributions from ^{51}Ti and ^{52}V beta electrons, betas from aluminum case, collector and insulator materials and decay gamma from activated detector and surrounding materials.

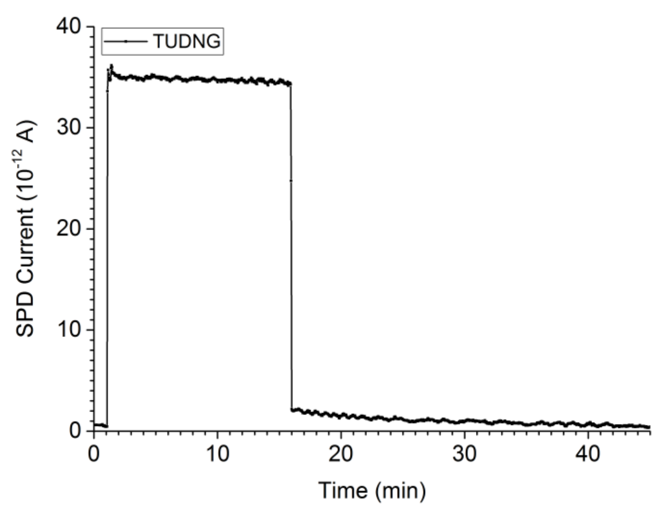

Figure 6: Flat V-SPD signal from irradiation in the mixed field of TUD-NG

To decide the electron beam parameters for photon irradiation of V-SPD in ELBE beam dump, an MCNP calculation was performed to have an energy spectrum close to the one in TUD-NG. Highest flux intensity in this experiment (I_{beam} = 0.5 μA) is estimated around 6.46 x 10^7 n cm^{-2} s^{-1}. In Figure 7, signal from the test with 10 MeV beam at various current points (0.1-0.5 μA) is shown. SPD current is proportional to the photon flux, showing again that the detector has high sensitivity to photons.

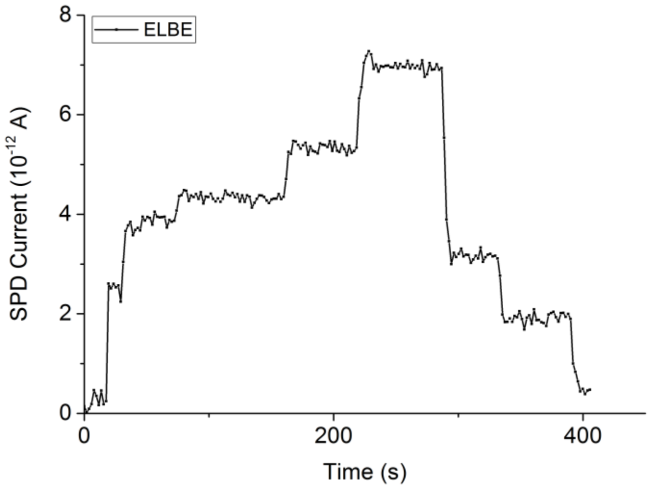

Figure 7: Flat V-SPD signal on irradiation with ELBE photons

The pure gamma sensitivity measured in ELBE irradiation of V-SPD is approx. 9.60 x 10^{-20} A cm^2 s^1. This is substantially higher than the optimistic thermal neutron sensitivity assessed in case of TRIGA irradiation. This means that V-SPD is essentially an SPGD. On multiplying this with the calculated total gamma flux at the experimental position in TUD-NG (2.95 x 10^8 n cm^{-2} s^{-1}), one obtains that about 81% of the signal is due to detection of gamma. With the rest 19% of the signal, the 14 MeV neutron sensitivity of V-SPD is determined to be approx. 4.15 x 10^{-21} A cm^2 s^{-1}. There are relative errors of 10-25% in these estimations mainly incurred in measurement or calculation of flux intensities.

Based on the reported experiments, one can say that SPGDs can be applied for gamma measurements in TBM. Signals in the range of nA to µA can be expected with the present design. This can be increased by changing emitter material to a high-Z metal and optimizing the detector's geometry and size. On the other hand, neutron detection is tricky. Thermal neutron detection using delayed SPND is feasible. But for fast neutrons as expected in TBM, an indirect mechanism is required in which neutron-induced gammas are detected in a prompt SPND. Further optimization of materials and geometries is underway. To determine the prompt, delayed, neutron and gamma sensitivities of an SPD in each irradiation condition, a Monte-Carlo model of detector is being developed and compared with the experiments.

IV. Conclusions

As part of the ongoing task on development of neutronic instrumentation for European test blanket modules of ITER, self-powered detectors in flat geometry have been constructed. The present sandwich-like vanadium SPD in aluminium casing is responsive to neutrons and gammas. The currents expected with this detector in TBM environment can be reliably measured. Gammas can be measured directly with such a detector, while neutrons need to be measured indirectly through neutron-induced prompt gammas. Essential design improvements and further tests are required before optimized prototype SPDs for application in TBM can be realized.

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