

Self Powered Neutron Detectors with High Energy Sensitivity

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THE Roadmap to Fusion Energy poses several technological challenges, many of them related to neutrons generated in the fusion reactions. Fusion reactions between deuterium and tritium will take place in tokamaks releasing a large amount of energy. The generated nuclear power is mainly transferred to the neutrons produced in the reactions, and then converted to thermal power and then to electricity. As a consequence, a high intensity fast neutron flux ($>10^{14}$ n/cm²s) is expected to hit the inner walls of the tokamak. ITER will be the first fusion reactor to be built in which neutron fluxes of the order of 10^{14} n/cm²s will be reached on the first wall surface, decreasing with depth. Monitoring this neutron flux is one of the key diagnostics to understand plasma burning conditions, and with such flux intensity this is a challenging task, also considering the environment conditions such as high temperatures above 200°C. Owing to the high neutron fluxes, radiation damage of structures and devices are one of the main challenges for future fusion reactors design. Several displacements per atoms (DPA) and up to tens of DPA are foreseen on the exposed materials and structures. DEMO is the ITER's successor, and it will be the first prototype of a fusion power plant. In order to evaluate the damage to structural materials in DEMO, the Roadmap to Fusion Energy has foreseen the construction of a dedicated test facility, IFMIF-DONES, which is planned to be built in Escuzar, 30 km far from Granada (Spain).

DONES is based on the acceleration of a deuteron beam up to 40 MeV, 125 mA current in continuous wave mode, with 5 MW beam average power. The rectangular beam (approximately 20 cm × 5 cm) hits a liquid lithium target flowing at 15 m/s to dissipate the beam power. A neutron flux of 10^{14} n/cm²s, with a broad peak at 14 MeV, is produced by stripping nuclear reactions, reproducing the expected conditions in DEMO [1]. The materials samples to be tested are positioned right behind the lithium target. The neutron flux in the test cell must be monitored. The detectors to be used to this purpose must withstand the high incident neutron flux at high temperatures (between 200°C and 500°C), working consecutively for almost one year without the possibility to access the irradiation cell. Almost any neutron detector currently available would not work in these conditions for such long time, therefore new ad-hoc detectors must be developed.

The DONES collaboration identified two possible candi-

dates for neutron flux monitoring in the test cell: micro fission chambers and Self Powered Neutron Detectors (SPNDs). Although micro fission chambers have the right sensitivity, have small dimensions and are radiation-resistant, they can't work at such high temperatures. On the contrary SPNDs, aside from their radiation hardness and reduced dimensions, are also capable of working at high temperatures, and seem therefore one of the most suitable option for the DONES sample irradiation cell.

SPNDs are electronic devices that exploit the neutron-induced activation of specific materials, which then decay through electron emission: in an SPND, the activated material acts as a first electrode called emitter. A second electrode (collector) placed at close distance from the emitter catches the beta electrons. These two electrodes, connected in a circuit, act as a current generator whose current is proportional to the emitter activation, which is in turn proportional to the incoming neutron flux (Fig.1). SPNDs are used for in-

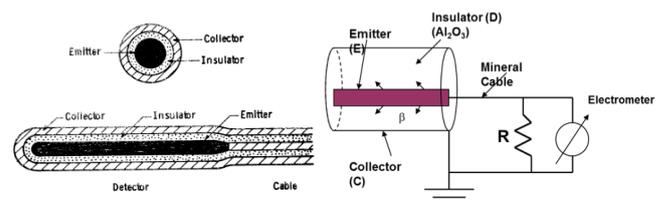


Fig. 1. Schematic view of an SPND (left) and simplified readout scheme (right)

core neutron flux measurements in fission reactors, exploiting thermal neutron induced activation. The typical time response ranges from milliseconds to seconds, and the sensitivity is around 10^{-21} A/(n/cm²s); the assembly is coaxial with an outer diameter of 3 mm and few cm length. Due to the low current over neutron flux ratio, SPNDs are used for the measurement of neutron fluxes above 10^{10} n/cm²s. Their use can be extended over several orders of magnitude above, where other kind of detectors fail due to radiation effects (NIEL, SEE, DDD) especially when exposed for long periods of time. As an SPND does not require bias voltage to work, these detectors are easy to operate.

Different types of reactions can take place in the electrodes and insulator, inducing a current through the emission of

electrons [2].

- (n,β) : after a neutron capture on an emitter nucleus, the nucleus is unstable and beta decays emitting an electron. The decay takes place after a time that depends on the half life of the activated isotope, producing a *delayed* signal. When the signal reaches its saturation value, the current is proportional to the incident neutron flux.
- (n,γ) : after a neutron capture the nucleus reaches a stable state through the instantaneous emission of gammas. The gammas interact with the medium through photoelectric effect, Compton effect and pair production, with the consequent emission of secondary electrons. This process produces a *prompt* signal that is proportional to the incident neutron flux.
- (γ,e^-) : those elements which are sensitive to radiative capture can also produce a signal through the direct interaction with external gammas, producing a *prompt* signal that is proportional to the incident gamma flux.

The polarity of the current produced by these processes depends on which electrode is involved in the primary interaction. Electrons coming from the emitter that stop in the collector produce a positive current signal, while electrons produced in the collector that stop in the emitter produce a negative current signal. The net current is the algebraic sum of all these contributions. Along with the main signal formation interactions, also charged particles such as electrons can induce a current in the SPND, whose contribution to the detector response must be taken into account.

In order to extend the use of SPNDs for high energy neutron flux measurement, a new set of emitter materials have been studied and proposed. The operation of SPNDs in fusion environments like DONES imposes some constraints on the choice of the materials. Low melting point materials must be avoided, since the temperatures can reach 500°C. There will not be the possibility of accessing the test cell for almost one year, therefore attention must be paid in order to avoid a sensitivity change over time. The value of the neutron capture cross section in the energy region of interest shouldn't be neither too high (to avoid the *burn-up* effect due to transmutation, that reduces the sensitivity) nor too low (so that the sensitivity to neutrons is high enough). The half life of the activated nucleus produced by the neutron capture must be small enough to obtain a fast response, with the signal reaching the saturation value within a maximum of few minutes. Also, the half lives of the daughter nuclei of the activated nuclei must be either very short (similar or less than that of the parent) or very long (at least equal to the duration of the measurement), otherwise the response of the detector would change during the time of the data taking. In light of these considerations two prototypes of SPNDs were produced: one with a rhodium emitter (a common material used in fission reactors neutron flux monitoring) and one with an aluminum alloy emitter. Also one dummy SPND with no emitter material was produced to study the electronic background noise. Rhodium has a neutron radiative capture cross section of $\sim 10^{-1}$ - 10^{-3} barn between 100 keV and 15 MeV, while the cross section for aluminum in the same energy region is roughly constant, with a value

of the order of 10^{-3} barn (Fig. 2) [3]. Both chosen elements would produce a delayed response in the SPNDs due to the beta decay of ^{104}Rh and ^{28}Al .

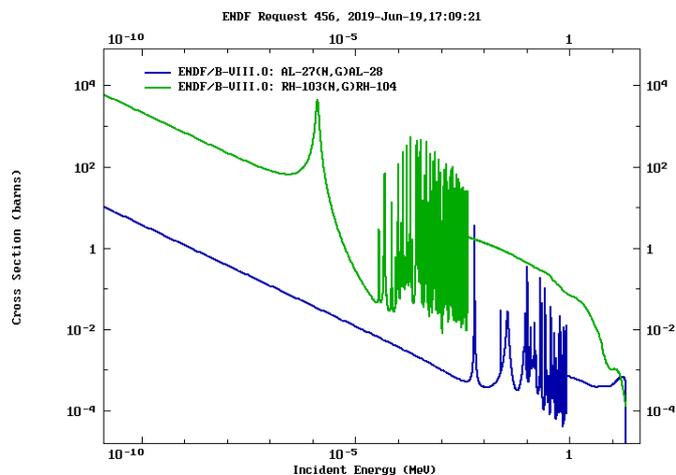


Fig. 2. Radiative capture cross section for ^{103}Rh and ^{27}Al , that constitute 100% of natural rhodium and aluminum, the chosen elements for the emitters of the SPNDs under test [3].

The SPNDs had to be tested in an environment similar to the one expected in DONES, that is a mixed neutron and gamma field, with a neutron spectrum up to 40 MeV, in an accelerator-driven neutron source with a similar background radiation conditions.

The two prototypes were firstly tested at the GELINA neutron time-of-flight facility of the JRC in Geel (Belgium). GELINA is a photoneutron source based on the acceleration of an electron beam on a rotating uranium target. The electron bunches are accelerated by a linac up to 140 MeV. The bunches are then compressed and exit the accelerator with a width of ~ 1 ns. The repetition rate of the bunches can be varied between 50 Hz and 800 Hz, leading to different average neutron production rate. The electrons interact with uranium producing bremsstrahlung and generate neutrons by photonuclear reactions. Each electron pulse produces 4.3×10^{10} neutrons (with an average production rate of 3.4×10^{13} n/s) with an energy distribution from subthermal up to about 20 MeV [4].

The SPNDs were placed 5 cm away from the target, on a support structure specially designed to hold the detectors as close as possible to the neutron production point (Fig. 3), substituting the moderator that is used for time-of-flight measurements. Two support structures of different materials were used in the test, one in lead and one in polyethylene.

A full MCNP simulation of the interaction between the beam and the target was made, considering the maximum repetition rate of 800 Hz. The resulting expected neutron flux is 6×10^{10} n/cm²s both with the lead and PE support, but with a different energy distribution due to the moderating effect of polyethylene. The expected gamma flux is 9×10^{11} γ /cm²s with the lead support, while it is 6×10^{12} γ /cm²s with the PE support. This difference is due to the higher interaction cross section of gammas in lead with respect to polyethylene. Also the Warren model [6], [7] for SPNDs current production was used to calculate the expected current produced by the



Fig. 3. GELINA experimental setup. The support structure for the SPNDs and the exit of the beam line are visible.

simulated incident neutron and gamma fluxes. The calculated current include the contributions from the prompt and delayed response of the detectors to the incident neutrons and the signal induced by the incident photons. The calculated current is of the order of 10 pA for the aluminum SPND, with a slight difference between the lead and PE case. The rhodium SPND calculated current was found to be of the order of hundreds of pA, more than 10 times greater than the aluminum SPND current, due to the much higher cross section.

Three Keithley picoammeters (models 6485, 6487 and 6517A) were used to measure the current of the three SPNDs. Different runs were made varying the repetition rate of electron pulses on the target, starting from 50 Hz and increasing it by a factor 2 up to 800 Hz, doubling each time the neutron yield. The neutron production was monitored with a calibrated neutron detector located in the target hall. Nickel activation foils were used to measure the flux on the support structure. The flux at the maximum beam intensity turned out to be 5.9×10^{10} n/cm²s, consistent with the simulated value 6×10^{10} n/cm²s.

The current from both the SPNDs was found to be proportional to the neutron rate over the full range of possible values obtained with the variation of the repetition rate.

The time response of the rhodium SPND with the polyethylene support structure was studied in the time window corresponding to the transition between a constant neutron flux and the beam switching off. As expected, the response is delayed, and the signal decays exponentially. The decay of the signal is consistent with the hypothesis of neutron activation of the ¹⁰³Rh nuclei of the emitter. Note that, while a prompt response is the sum of the contributions from the gammas of the radiative capture, the external gammas and background charged particles, a delayed response can only be due to neutron capture.

The measured signal amplitude differs partially from the expected values. Also the polarity of the current is different from what one would expect. If the dominant process in signal formation is neutron capture, the produced current should be positive under any condition, because it would be induced by the flowing of electrons from the emitter to the collector. The

aluminum SPND current is instead always negative without any delay in the response to a sudden change in the neutron flux (Fig. 4). This leads to the conclusion that some processes other than beta activation of the emitter contribute the most in the formation of the signal. The rhodium SPND produced a prompt and negative signal with the lead support, with a much smaller amplitude than the one measured with the polyethylene support. When the support structure was made of polyethylene, the rhodium SPND signal was instead delayed with a positive polarity. This observations may be explained by the presence of external electrons that interact with the detectors inducing a negative current, that in some cases dominates over the other components. This hypothesis could be confirmed by the results of a dedicated MCNP simulation, which gave as a result a current due to external electron fluxes of the order of 10^{-10} A with negative polarity.

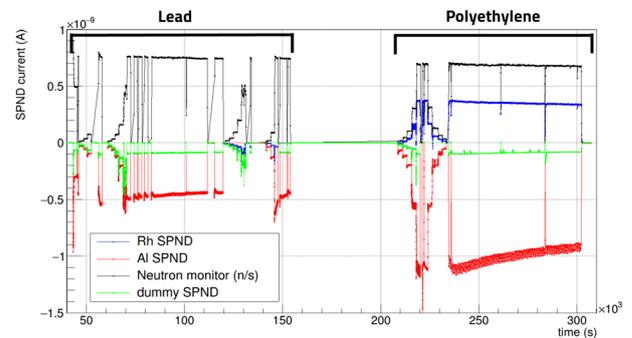


Fig. 4. Data taken at GELINA facility. The rhodium SPND current is shown in blue, the aluminum SPND current is shown in red, and the dummy SPND current is shown in green. The average neutron rate is shown in black. The first part of the data was taken with the lead support, while the last part was taken with the polyethylene support.

The time resolution of the neutron beam at GELINA didn't allow to disentangle the prompt and delayed components of the signal, because of the sampling time (3 s) being much higher than the spacing between neutron pulses (that was a maximum of 20 ms).

The SPNDs were then installed at the n_TOF facility at the European Laboratory for Particle Physics (CERN) for a new test. The n_TOF facility is part of the fixed target experimental program at the CERN accelerator complex. The neutrons are produced by the spallation of 20 GeV/c protons coming from the Proton Synchrotron (PS) on a pure lead target. The high intensity neutron pulses are produced by 7 ns (1 sigma) wide proton bunches of 7×10^{12} p every 1.2 seconds (or multiples of this interval). The neutrons have a wide energy spectrum ranging from 10 meV up to several GeV [5]. There are two experimental areas to perform measurements with the time of flight techniques, EAR1 and EAR2, placed at a distance of about 200 m and 20 m from the target respectively, in which the flux is of the order of 10^4 n/cm²s and 10^6 n/cm²s. In order to get a neutron flux of about $\sim 10^{11}$ n/cm²s with the main component in the energy range between 1 MeV and 10 MeV, it was decided to install the SPNDs in the area surrounding the target, inside the concrete shielding (Fig. 5).

The DAQ was installed far from the detectors, in a non-

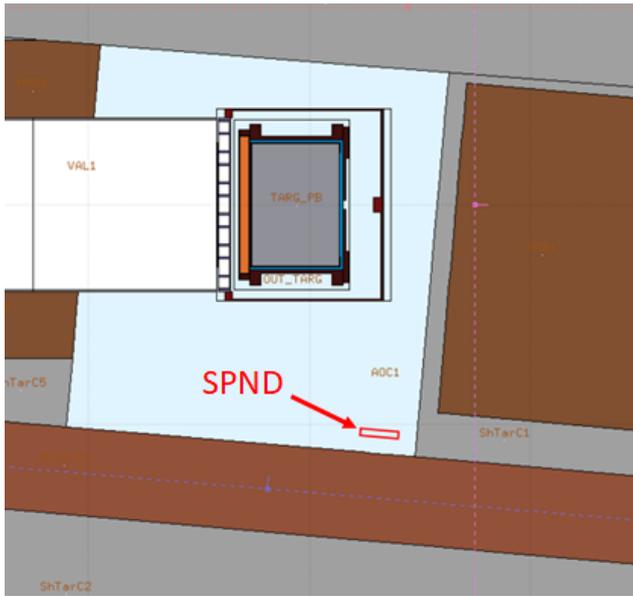


Fig. 5. FLUKA Monte Carlo model of the target area at n_TOF. The SPNDs were installed in the area showed in the red box.

radiation controlled area at the Intersecting Storage Rings (ISR). The SPNDs were connected to the readout system through three cables 100 m long. Since the target area is not directly accessible, the detectors were pushed through the concrete blocks chamfers, only sustained by the semi rigid mineral cables. Two readout systems were used: one with the Keithley picoammeters employed in the GELINA run, and one with a 4-channel CAENels picoammeter (model AH401D).

The test beam lasted over 50 days, between September and November 2018. During this time the detector response under different beam conditions were tested, including Machine Development stops, technical stops and short beam interruptions, as well as different proton pulse intensities, that have resulted in a wide range of average neutron production rates.

The 10 ms time resolution of the CAENels picoammeter allowed us to resolve the individual current peaks produced by the prompt emission of the target following the proton pulses. In such conditions it was possible to distinguish the prompt and the delayed components of the SPNDs signal.

The rhodium SPND showed a higher sensitivity than the aluminum SPND. The acquired signal is the superposition of a prompt and a delayed component (Fig. 6). The prompt component is represented by the sharp current peaks corresponding to a proton pulse hitting the target, which are produced by the prompt emission of photons and charged particles. The delayed component is visible as a slow variation of the baseline current with the change of the average neutron flux caused by the different sequence of proton pulses on the target. The delayed component is entirely due to neutron activation, and it was therefore isolated from the prompt current peaks in order to study the neutron response of the rhodium SPND.

The time response of the detectors was studied in the time windows in which the beam is switched off. The baseline current decays exponentially, consistently with the data from GELINA and the hypothesis of the beta activation of ^{103}Rh .

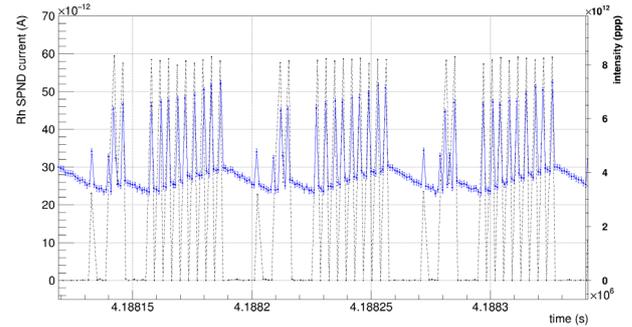


Fig. 6. Rhodium SPND signal shape at n_TOF. The proton pulse intensity is shown with black points connected by a dashed line, the Rh SPND current is shown with blue points. The superposition of a prompt and a delayed signal component is clearly visible.

Because of the particular position of the detectors (currently not employed for measurements), no reference value of the neutron flux was available. The only measurable quantity which is proportional to the neutron flux is the average proton current on the target. In order to study the linearity of the signal, the rhodium SPND baseline current was put in relation with the corresponding average proton current, and a linear relation was found. The measured current is also consistent with the analytical calculations based on the Warren model [6], [7], that predict a delayed component of the order of 10^{-11} A in the simulated flux conditions.

According to the Warren model the prompt component of the signal of the aluminum SPND is one order of magnitude lower than the rhodium SPND current, as it was confirmed by the data. Also, the expected delayed component is of the order of $\sim 10^{-15}$ A, much lower than the noise level. This is consistent with the measurements, that show sharp current peaks corresponding to the proton pulses, but no change in the baseline current is visible. This could be explained by the low cross section for neutron capture on aluminum in the energy region of the actual neutron spectrum at n_TOF, which was simulated with FLUKA, resulting softer than expected.

The performances of the SPNDs and the experience of the first on-target experiment at GELINA and n_TOF could open new scenarios. SPNDs are planned to be installed near the third generation n_TOF spallation target to monitor the neutron production independently from the detectors in the experimental areas. This installation could be interesting also for the fusion community, since it will give the chance to perform a long-term test of the detectors before the installation of SPNDs in the DONES test cell.

Before the installation of the SPNDs at n_TOF new Monte Carlo simulations are needed, in order to understand better the SPNDs response in neutron and gamma mixed fields. The development of a new Monte Carlo model of signal formation in the detectors will allow to design new SPND prototypes also for tests at research reactors and other neutron sources. Particular attention will be paid to the materials chosen for the emitter, which must work at high temperatures and produce a signal that is fast enough to monitor the changes in the neutron flux, along with being sensitive to high energy neutrons.

In addition to these considerations, also some methods to reduce the gamma component of the signal will be further investigated.

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