DEVELOPMENT OF OPTICAL NEUTRON DETECTORS AT CEA

Toward an innovative neutron detector for sodium fast reactors

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INTRODUCTION:

For more than 70 years, the CEA has been developing numerous neutron sensors for its own needs and for industry. A large number of fission chamber models have been developed for both thermal electronuclear reactors and sodium-cooled fast reactors. The need for distributed, miniature instrumentation that can withstand harsh conditions led the CEA's Dosimetry, Sensors and Instrumentation Laboratory (LDCI) to take an interest in optical neutron detectors. These sensors, first proposed in the 1950s, use the luminescence of a rare gas to measure neutron flux. The physics of this type of detector is far more complex than that of ionisation chambers: knowledge of nuclear plasmas and their emission spectra is limited, and radiation-induced luminescence or parasitic absorption in optical components can interfere with the measurement.

Since 2017, the LDCI has been carrying out theoretical and experimental work to develop this new type of sensor. Theoretical work, coupled with spectroscopic experiments carried out on nuclear plasmas, has led to a better understanding of the origin of noble gas scintillation. At the same time, prototypes of optical neutron detectors were built and then tested in various facilities to demonstrate their potential and evaluate existing technological solutions. Since 2022, work has been underway on using these sensors under SFR conditions.

The paper summarises the work conducted on optical neutron detectors. After a brief bibliography and a presentation of the sensor's operating principles, all the work carried out at the CEA is detailed.

1. PRINCIPLE OF OPERATION OF AN OPTICAL NEUTRON DETECTOR

An optical neutron detector consists of a gastight body containing at least a volume of noble gas and a thin active deposit, usually uranium oxide. When a neutron passes through the sensor, it may react with the deposit and produce a fission: two energetic fission fragments (100 and 68 MeV on average) are emitted. One of the two fragments may leave the deposit and slow down in the gas via a series of inelastic collisions. These collisions generate primary electrons, which in turn lose their energy, ionising and exciting the gas atoms. Excited atoms de-excite, emitting photons which are then collected and transported out of the reactor pile by means of a light well or an optical fibre (fig. 1). By measuring the photons produced over time, it is possible to estimate the neutron flux passing through the detector. The first mention of optical neutron detectors (OND) was made by Koch in 1959 [1]. At that time, they consisted of a glass cell containing a deposit of uranium oxide and argon. A light guide was used to transport the scintillation photons out of the reactor for analysis. Since then, several scientists have tested similar sensors with limited success [2].

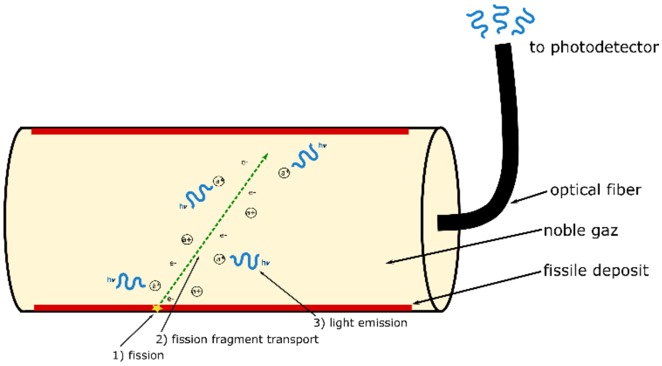

FIG. 1. Schema of an OND with an optical fiber used to collect and transport the signal. The steps involved in the signal generation are numbered.

This type of detector offers a number of potential advantages. The absence of polarisation voltage makes the sensor immune to space charges and also to partial discharges that occur in insulators at high temperatures. The use of optical fibres allows the design of multipoint detectors without crosstalk problems. Thanks to advances in optical fibres and in photonic, we decided to take a fresh look on this type of detectors.

Designing an optical detector is a challenge: the prediction of light spectrum emitted by the fission tracks i.e. nuclear plasmas is difficult due to the limited amount of models and experimental data in the literature. The light collection is far more complicated than electric charge collection. Additional physicals effects arise when irradiation of optical materials is considered: radiation induced absorption might decrease the signal intensity while radiation induced luminescence and Cherenkov effect generates parasitic signals. In SFR conditions, the ambient temperature may also lead to a parasitic black body radiation.

To build such a detector, we decided at LDCI to study extensively nuclear plasma experimentally and theoretically. In the same time, we designed simple and modular prototype of ODN to validate the proof of concept and test different components, from optical fibres to photodiodes. In the following section, we will briefly summarise all the research done on this topic. The main experimental results will be presented. We will try to evaluate the remaining steps that will lead to a SFR ready detector.

2. EXPERIMENTAL STUDIES OF NUCLEAR PLASMAS AND OPTICAL NEUTRON DETECTORS

2.1. Experiments on nuclear plasmas

Spectroscopic data on nuclear plasma is scares in the literature. To study nuclear plasmas spectra, it was decided to build a dedicated experimental device (called PSEG). To avoid technological constraint related to a neutron irradiation, we decided to select a Plutonium 238 deposit as a source of heavy ion [3]. Alpha particles from plutonium generates primary electrons with an energy spectrum similar to the one generated in gases by fission fragments. A schema of the device is shown in fig.2 as well as a picture of an argon nuclear plasma. The PSEG has two windows to perform emission and absorption spectroscopy and can be filled with different noble gases up to a pressure of 5 bars. Spectrum of Neon and Argon nuclear plasma were recorded with this device. Lines intensities were studied to verify if the Local Thermal Equilibrium (LTE) is reached, it appears that nuclear plasmas are not in LTE, a precise simulation of the plasma is needed to predict the emission spectrum. We also noticed that pressure line broadening is a good way to detect detector failures. Such tabletop experiments allowed us to select neon and single photon avalanche detector (SPAD) as an optimised emitter/detector couple for OND.

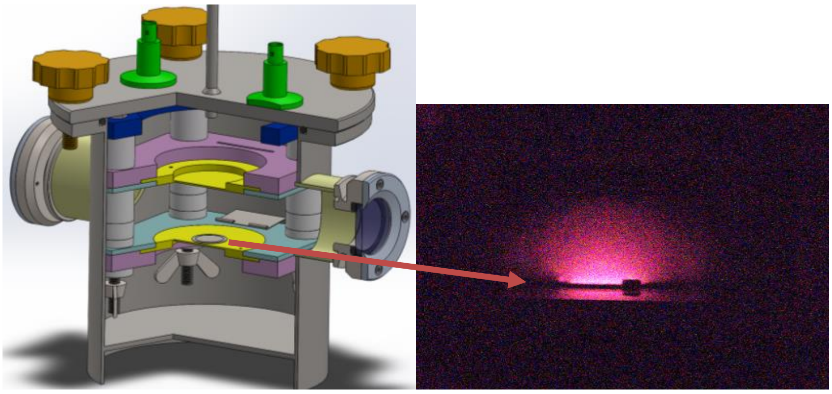

FIG. 2. Left: Schematic of the experimental device for spectroscopic study of nuclear plasmas. Right: a picture of the ^{38}Pu oxide deposit and a surrounding argon nuclear plasma.

2.2. Test of an optical neutron detector on a neutron beam

The validation of the proof of concept was performed step by step. Our first goal was to prove it is possible to detect neutrons in a pure neutron flux. To do so, a modular detector called CANOE was designed to test the concept on a neutron beam of ORPHEE facility [4]. The detector is long enough to avoid a direct irradiation of the window. A ^{235}U oxide deposit of 800 µg was used as a source of fission fragment. Because of the detector geometry, the light collection efficiency is quite low, and a SPAD is mandatory to monitor the neutron flux in real time. With CANOE, we were able to monitor the neutron beam shutter operation, the proof of concept was validated. The next step was to validate ODN in a mixed neutron/gamma field of a reactor.

2.3. Test of an optical neutron detector in CABRI reactor

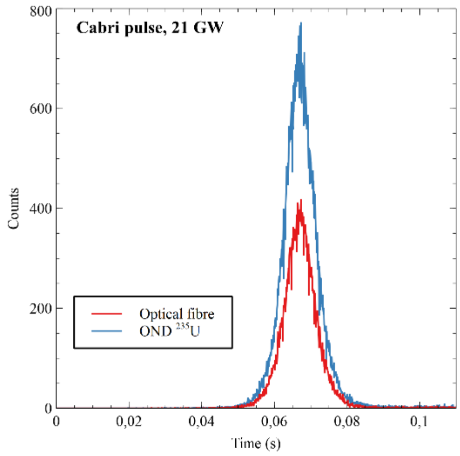

FIG. 3. Signal recorded with a OND connected to an Hamamatsu C13001-01 single photon detector. The Cherenkov contribution was also recorded on a transmission line without any detector.

CABRI reactor is dedicated to test the behaviour of reactor fuel in reactivity-initiated accident. To do so, the reactor is able to generate 10 ms long pulse with a maximum power up to 21 GW thank to the reactivity insertion obtained by a rapid draining of control rods containing high pressure Helium 3. Miniature fission chambers fails to monitor reactor pulses in its vicinity because of the space charge effect, so we had the opportunity to test OND to monitor pulses. During the pulse, maximum gamma flux is of the order of 2 10^{16} $cm^{-2}.s^{-1}$, Cherenkov radiation in optical fibres become really intense and saturates SPAD. A miniature CANOE was then designed to increase the light collection efficiency. The ^{235}U in the detector was increased to 10 mg to maximise the signal. To limit the Cherenkov effect, 3m long hollow fibers with reflective coating was used in the vicinity of the reactor core. An optical fibre line without any detector was set along the one use by OND to assess the Cherenkov contribution.

Signals recorded during a 21 GW pulse are shown in fig. 3. Cherenkov light is still a non-negligible part of the signal recorded by Hamamatsu C13001-01 photodetectors. Bandpass filters should be used to reject the continuous Cherenkov spectrum and keep interesting lines emitted by the OND.

3. SIMULATION OF OPTICAL NEUTRON DETECTORS

Two different kinds of simulations were set-up to understand how ODN works and to simulate their signal. First, simulation of single fission tracks was performed to estimate the line spectrum and the light yield of a detector. As the nuclear plasma is not under LTE, we decided to compute the primary electron source with CSDA approximation for heavy ions and HKS cross section. Then, Boltzmann equation was solved in time and space using a Monte-Carlo Method [5]. By tracking electron collisions, we are able to compute the excited levels populations. Assuming a corona model, line spectra of nuclear plasma are computed. With this model, we are also able to estimate the relaxation time of electrons.

Another simulation asset is used mainly to estimate the signal generated by OND in current mode, the light collection efficiency and the amount of Cherenkov light emitted. To do so, the geometry of the detector is cut in voxels. The energy deposition inside the detector is estimated using randomly generated fission fragments and moderation laws. Once the energy distribution is sampled properly inside the detector, a number of light rays is emitted from each voxel according to energy deposited in it, and propagated until the light rays are collected or absorbed. For this step, home-made ray tracing code or optic studio is used depending on the complexity of the detector geometry. Ultimately, the Cherenkov signal is estimated inside the optical fibre with a Monte-Carlo code that generate and propagate Compton electrons.

4. OPTICAL NEUTRON DETECTOR FOR SODIUM FAST REACTORS

A work is ongoing through a PhD thesis to adapt the OND to SFR conditions. Models are modified to take into account black body radiation and effect of temperature on optical fibre defect healing. From an experimental point of view, a high temperature OND was designed and should be tested in a furnace to validate its operation at 550 °C.

5. CONCLUSION

In few years, LDCI managed to validate the operation of Optical Neutron Detector in a mixed neutron gamma field of a nuclear reactor. The theoretical work allowed a better understanding of nuclear plasmas and a prediction of their emission spectra. Work is still needed to simulate the behaviour of gas mixture. The next step is to design a detector optimised for SFR conditions.

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