In-core measurement methodology with optical fibers using Cherenkov radiation for transient induced power measurement in the CABRI experimental reactor

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Abstract— **This paper presents our experimental work to assess the capability to estimate the transient-induced power distribution in the CABRI experimental reactor using Cherenkov radiation. The CABRI reactor is designed to produce a power transient up to 21 GW within a time less than 100 ms in order to irradiate a test fuel pin in condition representative of a Reactivity insertion Accident in pressurized water reactors. The large response range and short response time required to follow the flux evolution during a complete transient makes classical means of detection, such as ionization or fission chamber, inoperative. For that purpose, we suggest to measure Cherenkov light produced within optical fibers. Indeed, Cherenkov light emission is linked to the local electron production, which is proportional to the local gamma flux through the Compton or pair production cross-section, the intensity of Cherenkov radiation is related to the photon flux intensity. The knowledge of the fission photons emitted by the reactor gives direct insight on the fission rate, hence a spatial power density distribution could be reconstructed thanks to the measure of the Cherenkov light at different point in the reactor.**

Keywords **— CABRI, power Pulse, transient, Detector, Cherenkov, Optical fibers.**

I. Introduction

THE purpose of this document is to show the main results obtained by measuring the Cherenkov light in optical fibres during a CABRI power transient. The CABRI reactor is designed to produce pulses to irradiate a fuel pin at the center of the core. The short duration and the high amplitudes of the CABRI transient poses a particular problematic regarding the mean of detection available to follow 5 decades of variation in less than 100 ms with a size allowing in-core measurement. In order to detect how the spatial fission distribution evolves during a reactor transient. Indeed, the evolution of the fission distribution has a direct impact on the variation of the coupling factor [1] during the transient which quantify the energy released in the experimental fuel pin.

The mean of measurement such as ionization or fission chamber are not appropriate due to their overall size and the presence of static space charged in the detector due to the high neutron and photon flux. Another option would be the Optical Neutron Detector [2], which is still under development.

As optical fibers have the right size to allow in core measurement, we decided to explore the possibility to use them in order to monitor the reactor power during the CABRI power transient.

II. Presentation of CABRI

The CABRI facility at CEA Cadarache is a “pool reactor” with the core at the bottom of an 8m-deep water pool. The core is made up of 1,487 UO2 fuel rods, enriched to 6% and clad in stainless steel.

The reactor is equipped with 138 hafnium control rods divided into 6 groups of 23 elements symmetrically arranged in the core. Reactivity is injected by depressurizing 96 helium-3 rods, divided into 4 groups of 24 elements in the core. The speed at which the helium valves open and the number of valves open (1 or 2) will determine the shape and amplitude of the pulse. The reactivity insertion can be up to 4 \$ at a rate of 40 \$/s.

In stationary regime, the reactor has a power of between 100 kW and 25 MW. During the power transients, the power can reach 21 GW. The main detectors used to monitor CABRI’s reactor power is given in TABLE I.

TABLE I
DETECTORS FOR CABRI’S CORE POWER MONITORING

Chamber	type	Power range
BN1/BN2	*Fission chamber (^{235}U)*	*0-200 W*
HN1/HN2	*Ionization chamber (^{10}B)*	*0.2-100 kW*
G2-1/G2-2	*Ionization chamber (^{10}B)*	*0.100-450 MW*
G311/G312/G34	*Ionization chamber (^{10}B)*	*0.450-21 GW*

CABRI pulses are used to irradiate a test rod located in a pressurised water loop that passes through the centre of the reactor. The rod is in PWR condition and is subjected to a pressure of 155 bar and a temperature of 300°C.

III. Cherenkov Effect In Optical Fibers

The Cherenkov effect is due to charged particles which velocity are faster than the phase velocity of light in a given transparent media [3]. In the case of optical fibers, Cherenkov light is generated in the core and cladding of a fibers and propagates all along the fibers. The particle detected by the mean of Cherenkov effect in a nuclear reactor are mainly electrons produced by Compton interaction of gamma-rays with matter [4]. Unlike most of the detectors, optical fibers play the roles of both particle detectors and signal transmitters.

IV. Description of the Experiments

A. *Irradiated materials*

The material irradiated during the experiments consisted in an optical fiber from artPhotonics with the following characteristics:

- *Core diameter :* 400 µm
- *Cladding outer diameter :* 440 µm
- *Coating outer diameter :* 560 µm
- *OH content :* Low
- *Numerical aperture :* 0.22
- *Coating material :* Aluminum

The fiber is set up in a waterproof container next to CABRI's reactor core as it is shown in Fig. 1. A waterproof pipe is connecting the tank to the reactor hall so that the pipe and tank are in air.

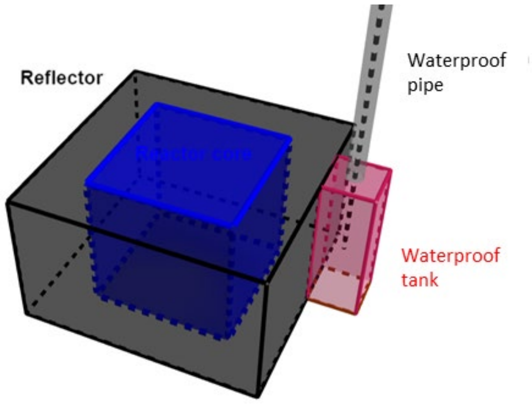

Fig. 1. Schematic view of the optical fiber position next to the reactor core (not to scale). The dashed line represents the optical fiber.

B. *Optical system and electronics*

The optical system aims at filtering the Cherenkov light intensity so that the photodetectors does not saturate during the transient. To do so, we mounted a band-pass optical filter centered at 800 nm with a bandwidth of 40 nm as it is shown in Fig. 2.

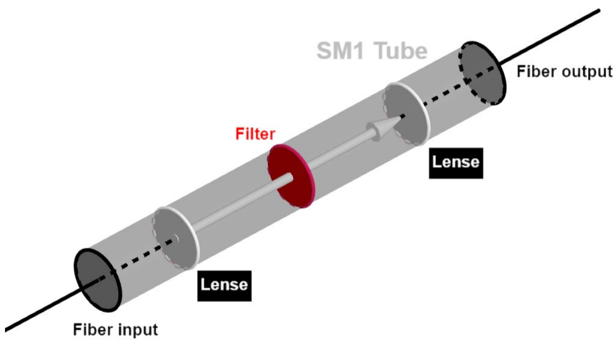

Fig. 2. Schematic view of the optical system (not to scale). The optical filter and the lenses are inserted in a SM1 optical tube. The white arrow represents the direction of light through the system.

The filter is placed between two lenses which focal lengths are 2 cm. The first lense makes the light beam from the optical fiber parallel to the optical axis, for it to be filtered, and the second lenses focuses the light on the output optical fiber. The SM1 lens tube and optical filter are designed by ThorLabs ®.

The filtered light is measured by a Single Photon Avalanche Detector (SPAD C1300-01 from Hamamatsu ®) which linearity and quantum efficiency are given in Fig. 3.

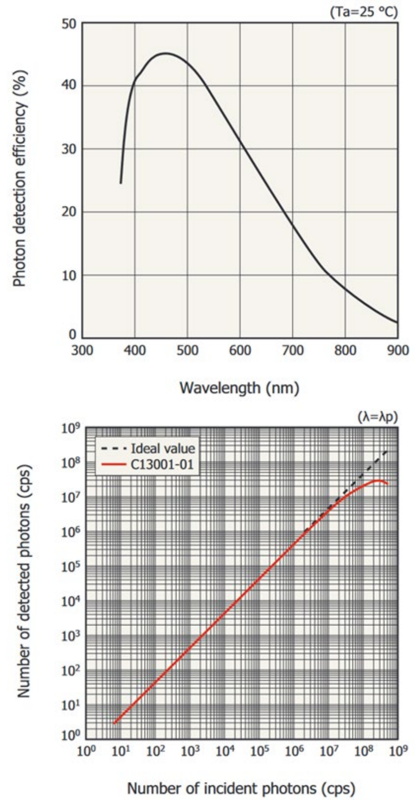

Fig. 3. (a) Quantum efficiency of the photosensitive surface and (b) linearity of the SPAD (C13001-01) at 450 nm [5].

The SPAD generates TTL pulses with 20 ns width. The TTL are counted by the mean of oscilloscopes (Agilent ®) and a FPGA (raspberry pi ®). The oscilloscopes record the full signal generated by the SPAD as the raspberry pi counts the TTL pulses on a 100 µs time interval. Both devices are triggered by an external signal controlled by the reactor operators.

V. Results of the Experiments

The results of the experiments were obtained during two reactor transients. Due to reactor maintenance, the waterproof tanks had to be replaced for each transients so that the same fiber has been placed differently in the tank from one transient to the other. The shape of the power transient is described on Fig. 4. We notice the steep increase in power next to the helium depressurization followed by a rapid drop due to the Doppler feedback, the control rods are then dropped to shutdown the reactor.

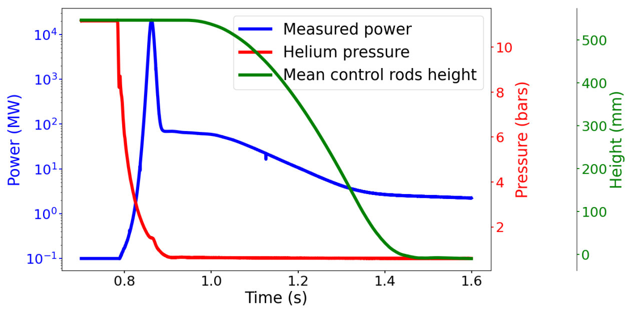

Fig. 4. The different phases of the reactor transient, helium release, power increase and control rods drop.

A. *First Transient Experiment*

For the first transient we counted the TTL with the FPGA only, the results is shown on Fig. 5. The high deviation of the counting rate at low power is due to the short time interval (100µs) over which the low counting rate is calculated.

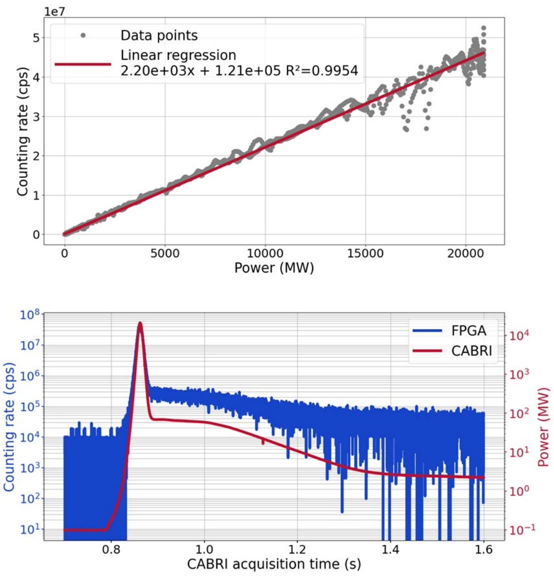

Fig. 5. (a) Linear regression between the counting rate measured by the FPGA and the reactor power and (b) the time evolution of the counting rate and the CABRI monitoring system.

B. *Second Transient Experiment*

For the second transient we counted the TTL with the FPGA and the oscilloscope with the raw data displayed on Fig. 6.

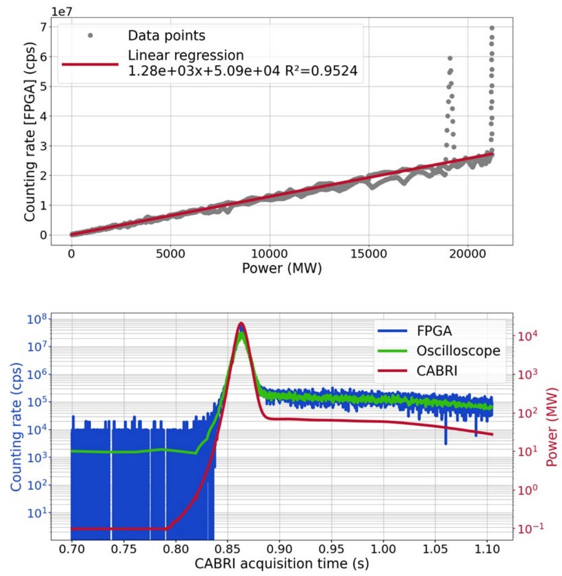

Fig. 6. (a) Linear regression between the counting rate measured with the FPGA and the reactor power and (b) the time evolution of the signals from the oscilloscope and the FPGA.

The measurement with the oscilloscope gives us an estimation of the counting rate at low power of 1 10^3 cps (Fig. 6 (b)). The correlation between the counting rate from the oscilloscope and the FPGA is given on Fig. 7. We can see that the slope is close to unity, with some overshoot on the FPGA, which confirm the reliability of the measurement with the FPGA.

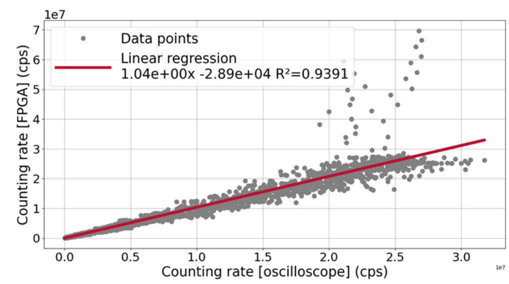

Fig. 7. Linear regression between the counting rate of the oscilloscope and the FPGA.

The comparison between the FPGA measurement from the first and second transient is shown in Fig. 8.

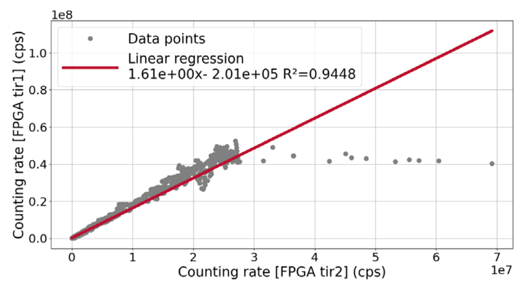

Fig. 8. Linear regression of the counting rate on the FPGAs between the first and second transient.

In this case, the slope is different from unity due to the change of the fiber position in the waterproof container from the first to the second transient.

In each transients we notice that the Cherenkov signal, unlike the measured power on CABRI is not varying through 5 decades.

Indeed the counting rate is varying between 1 10^3 cps up to 3-4 10^7 cps as the signal from CABRI is varying from 100 kW to 21 GW. In addition, the estimated WHM from the raw data shows that there is relative deviation of 6-9% from the WHM of each transient. This lead us to think that the linearity of the SPAD at high counting rate is not exactly described by Fig. 3.

TABLE II
WHM estimated on both transient

Transient	WHM	Deviation from the WHM on CABRI[a]
1st Transient	*9.55 ms*	*9%*
2nd Transient	*9.28 ms*	*6%*

[a]CABRI's WHM is 8.75 ms for each transient.

VI. Conclusions

The measurement of the Cherenkov light filtered at 800 nm allows us to measure the counting rate variation on a Single Photon Avalanche Detector over 4 decades. The measurement on both the oscilloscope and FPGA gives us insight of the counting rate for the reactor at low power and at maximum power. However The 5 decades covering of the CABRI's transient with a SPAD would require further work on the optical system to set the counting rate at a given value before the transient. Further more, the position of the fiber in the waterproof tank is not strictly defined which leads to fairly different counting rate from one transient to the other.

Finally, the use of other kind of photodetector, such as Avalanche Photodiode, could be more suitable for our experiments especially for in-core measurements.

Acknowledgment

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