Radiation measurements in reactor pulse mode at the JSI TRIGA reactor – Power meter based on Cherenkov light intensity measurements

Julijan Peric[1,*], Vladimir Radulović[1], Loïc Barbot[2] and Grégoire De Izarra[2]
[1]Jožef Stefan Institute, Reactor Physics Division, Slovenia
[2]CEA, DES, IRESNE, DER, Instrumentation Sensors and Dosimetry Laboratory, Cadarache, F-13108 Saint Paul-lez-Durance, France
(*) julijan.peric@ijs.si

Abstract—**The Cherenkov power meter developed at the Jožef Stefan Institute (JSI) is an independent, reliable and cost-effective measurement system based on Cherenkov radiation detection, used to measure fast power transients during pulse operation at the JSI TRIGA research reactor. It is based on a closed tube in order to avoid interference from external light sources and radiation damage experienced by optical fibers. The tube is placed in the reactor core periphery, the bottom part of the tube is filled with water, serving as the source of Cherenkov light. The measurements obtained in the framework of an extensive experimental campaign in collaboration with the French Atomic and Alternative Energy Commission (CEA) focused on reactor pulse operation using the Cherenkov power meter show excellent agreement with existing nuclear instrumentation (TRIGA pulse recorder), especially for high peak power pulses. However, the Cherenkov power meter outperforms the TRIGA pulse recorder in accurately recording low peak power pulses. The power vs. time behavior measured with the Cherenkov power meter is in accordance with measurements using miniature fission and ionization chambers developed at the CEA. The possibility of reactor pulse characterization based on measurements with the Cherenkov power meter combined with neutron dosimetry measurements sets the basis for enabling irradiation during pulse operation at JSI TRIGA research reactor in the future.**

Keywords — **Cherenkov radiation, Cherenkov power meter, Silicon photomultiplier, SiPM, Reactor pulse, Irradiation, Dosimetry, Miniature fission chamber, CEA, JSI, TRIGA research reactor.**

I. Introduction

The Jožef Stefan Institute (JSI) TRIGA research reactor is used to test electronic components and systems in a well-characterized radiation field during steady-state operation. It is known as a well-established irradiation facility. The reactor can produce a maximum neutron flux of about 2×10^{13} n cm^{-1}s^{-1} at a thermal power of 250 kW. However, the neutron flux level relevant for testing of instrumentation for use in material testing reactors (MTRs) or nuclear power plants (NPPs) is in the range between 10^{14} and 10^{15} n cm^{-1}s^{-1}. On the other hand, in the JSI TRIGA research reactor, such neutron flux levels are achievable in pulse operation mode, albeit only for short periods of time. The height and duration of the pulses depends on the inserted reactivity. Irradiations in pulse operation mode represent a possibility to extend the experimental capabilities of the JSI TRIGA research reactor.

Cherenkov radiation is present in most water-cooled nuclear reactors, with the exception of zero-power reactors. It is caused by energetic charged particles traveling faster than the speed of light in a dielectric medium. In open-pool reactors, Cherenkov radiation can be observed as a blue glow around the reactor core. Since the intensity of the Cherenkov light produced in the reactor cooling water is in principle proportional to the neutron flux during a reactor pulse, Cherenkov light intensity measurements as an alternative method for measuring the time dependence of reactor power were investigated, implemented, and tested at the JSI TRIGA research reactor.

II. Reactor pulse operation

The JSI TRIGA research reactor is equipped with a pneumatic system that enables pulse mode operation by allowing for the rapid ejection of the transient control rod. After a rapid ejection of the transient control rod, the reactor becomes prompt supercritical, and the power starts to increase exponentially. The change in power and consequently in the fuel temperature causes a decrease in reactivity, since the reactivity coefficient of the fuel is prompt negative, therefore the reactor rapidly and efficiently reaches a new equilibrium state. The decrease in reactivity slows or stops the chain reaction, resulting in a drop in power.

The peak power of the pulse is in the range between 1 MW and several 100 MW (depending on the core configuration), and the total energy released in the pulse is relatively small (usually a few MJ) due to the short pulse duration. In the TRIGA reactor, the temperature reactivity coefficient of the fuel is the strongest and most important feedback effect of the reactor state on reactivity. The temperature feedback mechanism of the TRIGA reactor is due to the unique composition of its fuel, which is a homogeneous mixture of 20 % enriched uranium and zirconium hydride with a Zr-H ratio of 1.6. In this design, the hydrogen in the zirconium hydride acts as a moderator, with most of the moderation occurring in the fuel elements themselves and only a small fraction in the surrounding water. As a result, changes in the fuel temperature are rapidly reflected on the moderator within the fuel, which results in an immediate effect on the reactivity of the core.

A. Fuchs-Hansen theoretical model

The time dependence of a pulse can be calculated using the point kinetics equations by considering only the contribution of the prompt neutrons to the neutron population and assuming that the reactivity decrease during the pulse is proportional to the energy released - adiabatic process. The model derived by Fuchs and Hansen is also referred to as the "adiabatic model" because of the second assumption used in its derivation [1].

From the theoretical model, important dependencies of pulse parameters can be calculated. In particular, the pulse height is proportional to the square of the prompt reactivity ($P_{peak} \propto \rho'^2$), the energy released is proportional to the prompt reactivity ($E_{rel} \propto \rho'$), and the pulse width is inversely proportional to the prompt reactivity ($FWHM \propto 1/\rho'$). The prompt reactivity (ρ') is equal to the inserted reactivity (ρ_i) reduced by the delayed neutron fraction (β) [1-2].

III. CHERENKOV LIGHT

The electromagnetic radiation known as Cherenkov light is emitted when a charged particle moves in a dielectric medium at a speed greater than the speed of light in that medium [3]. From Einstein's special theory of relativity, we know that the speed of light in a vacuum is a universal physical constant c_0 = 299792458 m/s, and this is the upper limit on the speed at which conventional matter can move through space. On the other hand, when light travels through transparent material, its speed is lower. Using the refractive index, we can easily formulate the condition for the occurrence of Cherenkov light in a transparent medium:

$$\frac{v}{c_0} = \beta > \frac{1}{n}, \tag{1}$$

where v is the speed of charged particle, and β is the ratio between the speed of the particle v and the speed of light in vacuum, c_0 [3-4].

Any charged particle with a velocity in the range of $0.75 \cdot c0 < v < c0$ causes the emission of visible Cherenkov light in water. For pure water at 20ºC, the refractive index is $n = 1.33$, which results in a speed of light of $c = 0,75 \cdot c_0$ [5]. The threshold kinetic energy for electrons moving in water and emitting Cherenkov light is about 250 keV. Since most Cherenkov photons are emitted at lower wavelengths, it is important to note that water is not transparent at wavelengths in the UV range, and photons of these wavelengths are immediately absorbed. In nuclear reactors, there are several sources of ionizing radiation that cause the production of Cherenkov light. Heavier isotopes can undergo α-decay, but they are not expected to contribute significantly to the production of Cherenkov light, since α-particles are easily stopped within the fuel material or fuel cladding [6]. One important source of radiation are the electrons produced in the β-decay process. These electrons often have energies greater than 250 keV, therefore they can produce Cherenkov light in water. However, they are also effectively stopped in materials (e.g. fuel, cladding, reactor structural materials) and therefore their contribution to the overall Cherenkov light emission is low. During reactor operation, the fuel and other materials in the reactor are an intense source of prompt and delayed gamma radiation, which is not attenuated as strongly as alpha particles or electrons and can generate energetic electrons in the reactor cooling water.

The prompt γ-rays represent the largest contribution to the intensity of the Cherenkov light in a nuclear reactor during operation. A much smaller contribution is due to the γ-rays from the fission and activation products and the β-particles. When a nuclear reactor is operated at power (the fission power is dominant compared to the residual power), the intensity of the Cherenkov light is linear with the reactor power. When the fission power is no longer dominant in a nuclear reactor, linearity is no longer valid [6-7].

IV. EXPERIMENT AT THE JSI TRIGA REACTOR

An extensive experimental campaign was carried out at the JSI TRIGA reactor from 17 January 2022 to 28 January 2022 as part of the bilateral collaboration between the Jožef Stefan Institute and the French Atomic and Alternative Energy Commission (CEA). The aim of the campaign was to explore the feasibility of utilizing the high neutron flux that can be achieved during reactor pulse mode for testing nuclear instrumentation detectors at the JSI TRIGA research reactor. Additionally, the campaign sought to evaluate the performance of CEA miniature fission with ultra-low fissile coatings and ionization chambers, as well as the MONACO v2 data acquisition system [8-9] at high neutron flux levels.

In the campaign, a Cherenkov pulse recorder was used as an independent measurement technique in conjunction with miniature fission (FCs) and ionization chambers (ICs) operated by the CEA-developed MONACO v2 data acquisition system, and different dosimetry foils. During the campaign 128 pulses were recorded at the JSI TRIGA research reactor and 159 dosimetry foils were irradiated during different pulses.

A. Experimental setup

The Cherenkov pulse recorder system consists of a measurement channel, Cherenkov light radiator, a light sensor, amplifier, and a data acquisition system. The measurement channel was an aluminum tube with an inner diameter of 36 mm and approximately 6 m in length. The bottom end of the tube was blanked off with an aluminum plate, making it watertight. The channel was designed to fit into the standard fuel element positions in the JSI TRIGA reactor core. The channel was inserted in the periphery of the reactor core, in position F-18. 0.65 l of water was poured into the channel (filling the height of 0.65 m in the tube), which served as the source of Cherenkov radiation. The top end of the channel reached the reactor platform level. The channel had a slight bend in order to limit radiation streaming from the reactor core to the reactor platform. Due to the bend, there was no direct line-of-sight from the top end of the channel to the water in the bottom end. However, the inner surface of the channel was sufficiently smooth to allow for some light reflection from the water in the bottom end to the top end.

The sensor consisted of a silicon photomultiplier - SiPM (KETEK PM3315- WB) selected for its peak photon detection efficiency at around 450 nm, a readout circuit (KETEK PEPCB-EVAL-MCX-RESP) and a plastic holder. The SiPM and the readout circuit are manufactured by the German company KETEK. The detector was connected to the data acquisition system with a BNC cable through a Thorlabs amplifier (AMP220) and lowered approximately 2.5 m inside the measurement channel. The top end of the measurement channel was taped up in order to minimize light interference from external sources.

A Red Pitaya [10] module was used as the data acquisition system and was controlled by a script implemented in Python language for pulse recording in the form of a GUI - Graphical User Interface. The script triggers data acquisition when the measured signal is above a threshold level ($U_{threshold} = 0.015$ V). The signal is measured at a sampling rate of 1.8737 kS/s for 8.59 s and stored in a csv file.

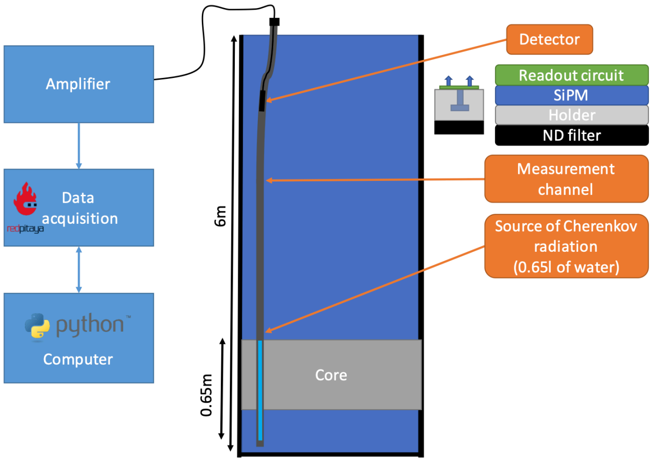

Fig. 1. Cherenkov pulse recorder experimental setup scheme [11].

In pulse operation mode, the power of the nuclear reactor can vary from low power levels (below 1 kW) to the GW range in a short amount of time. Therefore, the Cherenkov pulse recorder requires a large dynamic range, made possible by the Red Pitaya module. However, for high peak power pulses, neutral density filters (ND) were used in front of the SiPM to reduce the Cherenkov light intensity, as otherwise the signal generated by the sensors would have exceeded the Red Pitaya input range.

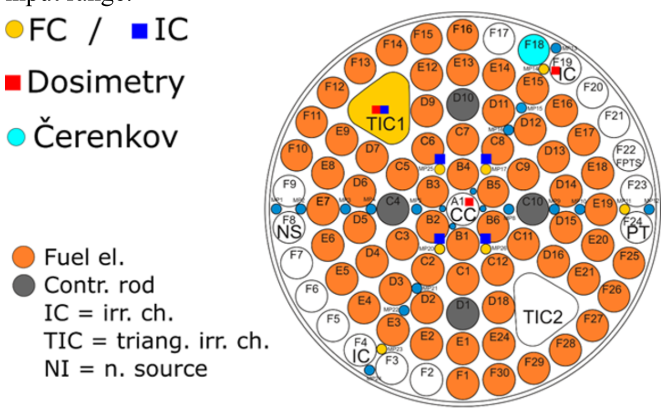

Fig. 2. Experimental reactor core arrangement scheme.

In addition to the Cherenkov pulse recorder, in the campaign 10 miniature fission and ionization chambers were arranged in various measurement positions in the reactor core and 3 irradiation positions were used for dosimetry experiments. The arrangement of the measurement and irradiation positions during the experiment can be seen in Figure 2 and the positions are listed in Table 1.

TABLE I
MEASUREMENT AND IRRADIATION POSITIONS

Location	Detector	Dosimetry
MP17	FC	
MP20	FC	
MP25	IC	
MP26	IC	
MP23	FC	
MP11	FC	
MP14	IC	
TIC1	FC + IC	Dosimetry
CC		Dosimetry
F19		Dosimetry
F4		Dosimetry
F18	Cherenkov	
MP2	FC	

B. Reactor pulse shape measurements

To enable the use of the JSI TRIGA reactor in pulse operation mode and thus to achieve higher neutron flux levels than in steady-state operation, it is critical to characterize the time behavior of the reactor power during each individual pulse. Pulses with a low inserted reactivity have a longer duration and a lower peak power, whereas pulses with a high inserted reactivity have shorter duration and a high peak power. In practical terms, pulses with a peak power in the range between 2.5 MW and 25 MW correspond to a peak neutron flux range between 2×10^{14} n cm^{-1}s^{-1} and 2×10^{15} n cm^{-1}s^{-1}. The corresponding inserted reactivities are 1.3 \$ - 1.55 \$. Therefore, the primary focus is on lower and longer pulses with inserted reactivities from just over 1 \$ to around 1.55 \$. Higher peak power pulses are also of interest; however their quick duration may represent an important constraint for applications.

Pulse operation of the JSI TRIGA reactor is monitored by a dedicated instrumentation channel – the pulse channel, based on an uncompensated B-10 lined ionization chamber, the signal being acquired and processed by a pulse recorder. The pulse recorder calculates quantities of interest for each reactor pulse, i.e. the peak power, duration (FWHM) and energy released. It is designed to cover all the pulse range, up to peak power levels of 2 GW. The pulse recorder produces reliable results for high peak power pulses, however at the very low end of the range (ρ < 1.2\$) the results are unreliable as the pulse shape and characteristic times change significantly. This shortcoming was one of the main drivers in the development of the Cherenkov pulse recorder.

Since the Cherenkov pulse recorder is based on a different principle of reactor power measurement than the TRIGA pulse recorder, which uses an uncompensated ionization chamber as detector, a signal comparison is necessary. All measurements used in this analysis were taken during the first week of the campaign. Measurements were performed again in the second week with a different arrangement of fission and ionization chambers. Figures 3 and 4 display a representative set of pulse shapes obtained, respectively, with the Cherenkov pulse recorder (in units of voltage, proportional to the Cherenkov light intensity) and the TRIGA pulse recorder (in units of power). The comparison of the pulse shapes between Figure 3 and Figure 4 shows that the signals of the two systems are practically identical and confirms that the Cherenkov pulse recorder produces reliable pulse shapes.

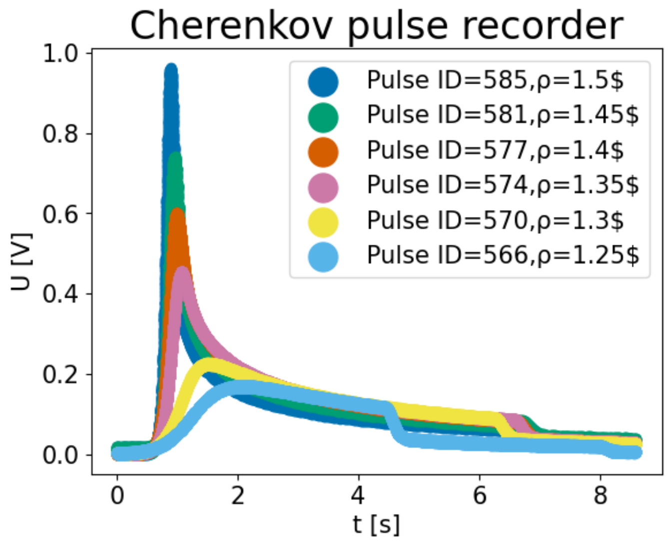

Fig. 3. Selected pulse signals measured with Cherenkov pulse recorder.

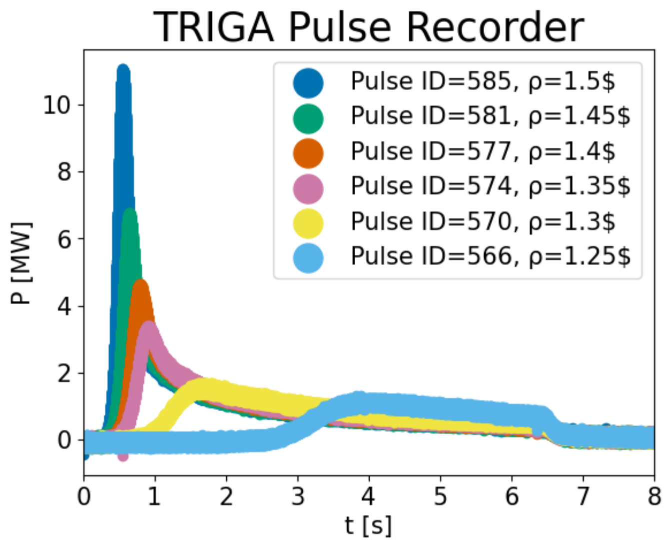

Fig. 4. Selected pulse signals measured with TRIGA pulse recorder.

It should be noted that between the two systems the trigger signal is different, because, as mentioned earlier, signal acquisition in the Cherenkov pulse recorder is triggered by the magnitude of the signal, whereas in the TRIGA pulse recorder signal acquisition is triggered by the "fire" signal, which initiates the pulse. Each time a pulse is initiated, an automatic reactor "scram" (shutdown by rapid insertion control rods) occurs after a pre-programmed time interval. This is why in Figure 4 the scram point is common to all the pulses at time 6.5 s after the "fire" signal. The width of the measured signal is similar for both systems at higher pulses ($\rho > 1.4\$$), but at the smaller pulses, the advantage of the Cherenkov pulse recorder is evident, providing a more accurate measurement because it is optimized for the entire pulse range.

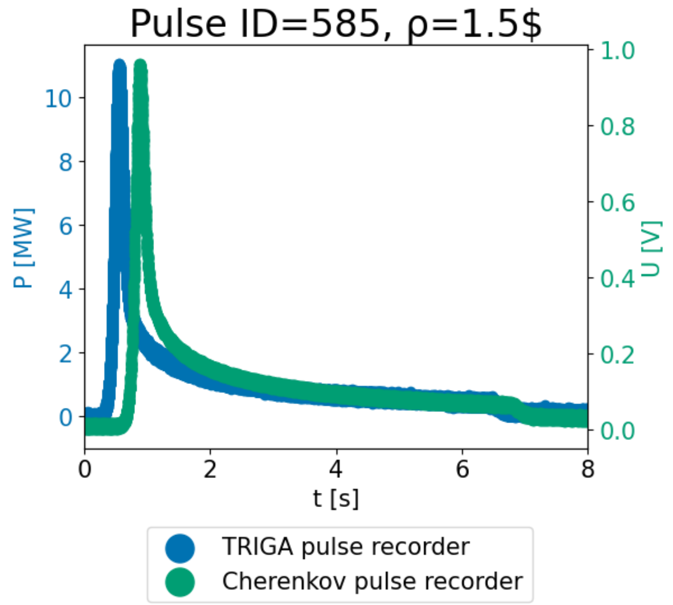

Fig. 5. Combined pulse (ID =585) signals measured with TRIGA and Cherenkov pulse recorder.

Figure 5 shows combined measured pulse signals with both systems for one specific 1.5 $ pulse, and the qualitative agreement is excellent. The shape of the pulse is the same for both systems, indicating that the Cherenkov pulse recorder operates as well as commonly used nuclear instrumentation.

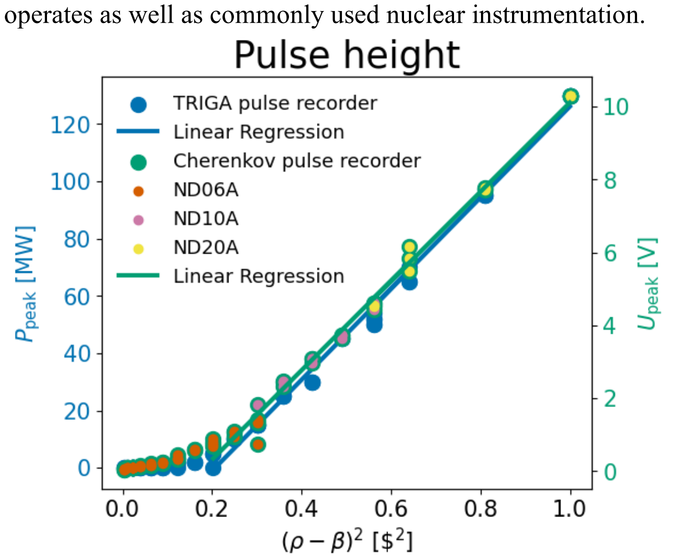

Fig. 6. Pulse height vs. the square of the prompt reactivity.

Figure 6 shows the measured pulse height as a function of the square of the prompt reactivity for both systems. It is evident that both measurements follow a linear trend resulting from the Fuchs-Hansen model, as described in the previous section. It can be seen that linearity holds for pulses with inserted reactivity greater than $\rho = 1.4\$$. The Fuchs-Hansen model is not suitable for describing smaller pulses because the assumptions used for its derivation do not hold in this range.

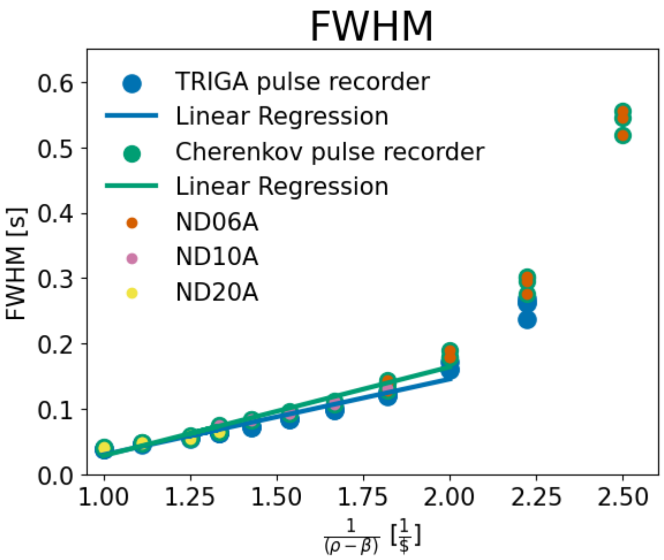

Fig. 7. Pulse full width at half maximum vs. the inverse prompt reactivity.

The full width at half maximum (FWHM) of the pulses is an important pulse parameter that allows us to assess whether the measured pulse is consistent with the assumptions used in deriving the theoretical model. Figure 7 shows the measured FWHM values vs. the inverse of the prompt reactivity. For higher pulses ($\rho > 1.4\$$) the FWHM dependency agrees with the theoretical model. On the other hand, the FWHM for lower pulses begins to increase nonlinearly as the lengthening pulse tail is included in the determination of the FWHM. In the tail of the pulse, the assumption of adiabatic heating is no longer valid. The alignment of FWHM measurements for both systems means that the shape of the measured pulses is in excellent agreement, although the measurement principle is completely different. This shows that the Cherenkov pulse recorder is more than suitable for this kind of application.

The energy released during the pulse can be calculated using various methods. For this analysis, the pulse shape was integrated in an interval corresponding to 1000 measurement points before and 1000 measurement points after the pulse peak. In terms of the integration time this selection is consistent with the theoretical model assumptions. However, these values do not correspond to the actual energy released during the pulse, which is crucial for TRIGA pulse operation for irradiation of different samples. Figure 8 displays the energy released versus prompt reactivity from both systems and shows that both systems produce results in accordance with the Fuchs-Hansen theoretical model. Figure 8 also shows that the TRIGA pulse recorder did not perform as well as the Cherenkov pulse recorder in measuring the energy released at lower pulses ($\rho < 1.3\$$) due to the low signal-to-noise ratio at its operating limit.

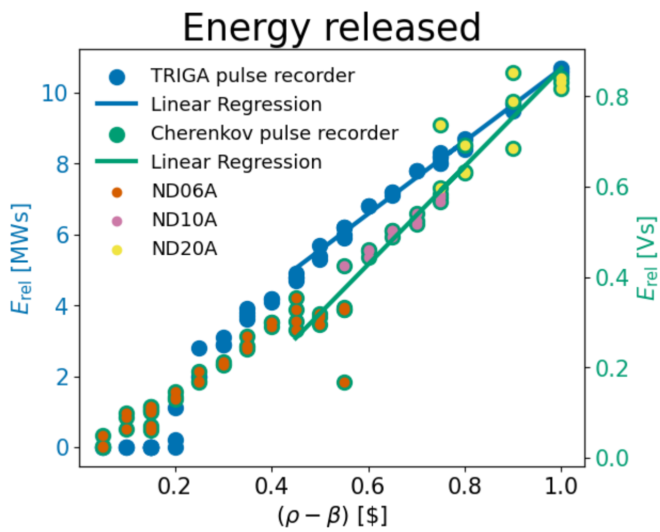

Fig. 8. Pulse energy released vs. the prompt reactivity.

With the exception of the FWHM comparison, all other comparisons were performed in a relative sense, since the Cherenkov pulse recorder is not absolutely calibrated. There are several options for calibration. The most promising are calibration to the peak power of the TRIGA pulse recorder or calibration to the total energy released during the pulse, since it has been shown in this article that the shape of the measured pulse is the same as in the nuclear instrumentation commonly used to measure reactor flux. For calibration of the total energy released, dosimetry measurements can be used to evaluate the total neutron fluence during the pulse in the irradiation channel where the dosimetry foils are irradiated. Once the Cherenkov pulse recorder is calibrated, the total neutron fluence delivered to irradiated samples can be derived from the measured signal.

TABLE II
LINEAR REGRESSIONS – PULSE PARAMETERS

Pulse parameter (Measurement system)	k	y_0
Peak power (TRIGA)	$159.0 \cdot (1 \pm 0.01) MW/\$^2$	$-32.9 \cdot (1 \pm 0.04)\ MW$
Peak power (Cherenkov)	$12.2 \cdot (1 \pm 0.02) V/\$^2$	$-2.1 \cdot (1 \pm 0.05)\ V$
FWHM (TRIGA)	$0.1 \cdot (1 \pm 0.04)\ s\$$	$0.1 \cdot (1 \pm 0.08)\ s$
FWHM (Cherenkov)	$0.1 \cdot (1 \pm 0.04)\ s\$$	$0.1 \cdot (1 \pm 0.1)\ s$
Energy released (TRIGA)	$10.3 \cdot (1 \pm 0.02)\ MWs/\$$	$0.4 \cdot (1 \pm 0.27)\ Vs$
Energy released (Cherenkov)	$1.1 \cdot (1 \pm 0.06)\ Vs/\$$	$0.1 \cdot (1 \pm 0.19)\ Vs$

The linear regression parameters for peak power and released energy cannot be compared between the two systems because they are calibrated differently. However, the comparison of their computational errors shows that the calculated linear regression parameters for both systems are consistent with the proposed theoretical adiabatic model described previously. On the other hand, the FWHM linear regression parameters are the same with similar uncertainties, which means that the measured signals have a pronounced similarity in their waveform properties.

C. Reactor pulse dosimetry measurements

Neutron activation dosimetry is the reference method in the determination of the neutron flux or fluence, and are included in the present work as a reliable experimental technique to obtain measurements of the total neutron fluence which can be delivered in pulse operation mode to samples of interest (e.g. neutron detectors, etc.). A series of test irradiations was performed in reactor pulse mode in which samples of certified reference materials Al-0.1%Au, Al-0.1%Co and pure Ni were irradiated within polyethylene capsules in the Central Channel (CC), F-19 Irradiation Channel (F19) and Triangular Irradiation Channel 1 (TIC1) of the JSI TRIGA reactor. The induced activities in the samples were subsequently measured using two absolutely calibrated High-Purity Germanium (HPGe) detectors [12].

Fig. 9 displays the measured specific end-of-irradiation (EOI) activities (in Bq per mg of sample material) vs. the pulse prompt reactivity. The induced activities are proportional to the total neutron fluence received during the irradiations, which is in turn proportional to the released energy in the pulse. According to the Fuchs Hansen model [11] for reactor pulse operation, the energy released in a pulse is proportional to the prompt reactivity. The observed dependencies clearly exhibit a linear behavior, taking into consideration the experimental uncertainties. In this work, these are relatively low (of the order of 1.5-1.8 %) in the context of reactor dosimetry measurements [9]. It is evident that the measured specific activity of the samples irradiated during pulse No. 629 with inserted reactivity ρ_i=1.15$ is lower than expected. The comparison of the measured power versus time signals for pulses with the same inserted reactivity shows that the pulse was interrupted earlier (scram), consequently the samples were activated less and are removed from the calculation of the linear regression parameters.

TABLE III

LINEAR REGRESSIONS – DOSIMETRY PARAMETERS

Position	k $[Bq/mg\$]$	y_0 $[Bq/mg]$
CC	$5.15 \cdot 10^5 \cdot (1 \pm 0.05)$	$9.20 \cdot 10^4 \cdot (1 \pm 0.15)$
F-19	$2.65 \cdot 10^5 \cdot (1 \pm 0.06)$	$5.19 \cdot 10^4 \cdot (1 \pm 0.16)$
TIC 1	$3.20 \cdot 10^5 \cdot (1 \pm 0.05)$	$5.28 \cdot 10^4 \cdot (1 \pm 0.15)$

The dosimetry measurements serve as a reference for the absolute normalization of the time-dependent signals measured with the Cherenkov power meter and thus enable sample irradiation during pulse operation at the JSI TRIGA research reactor.

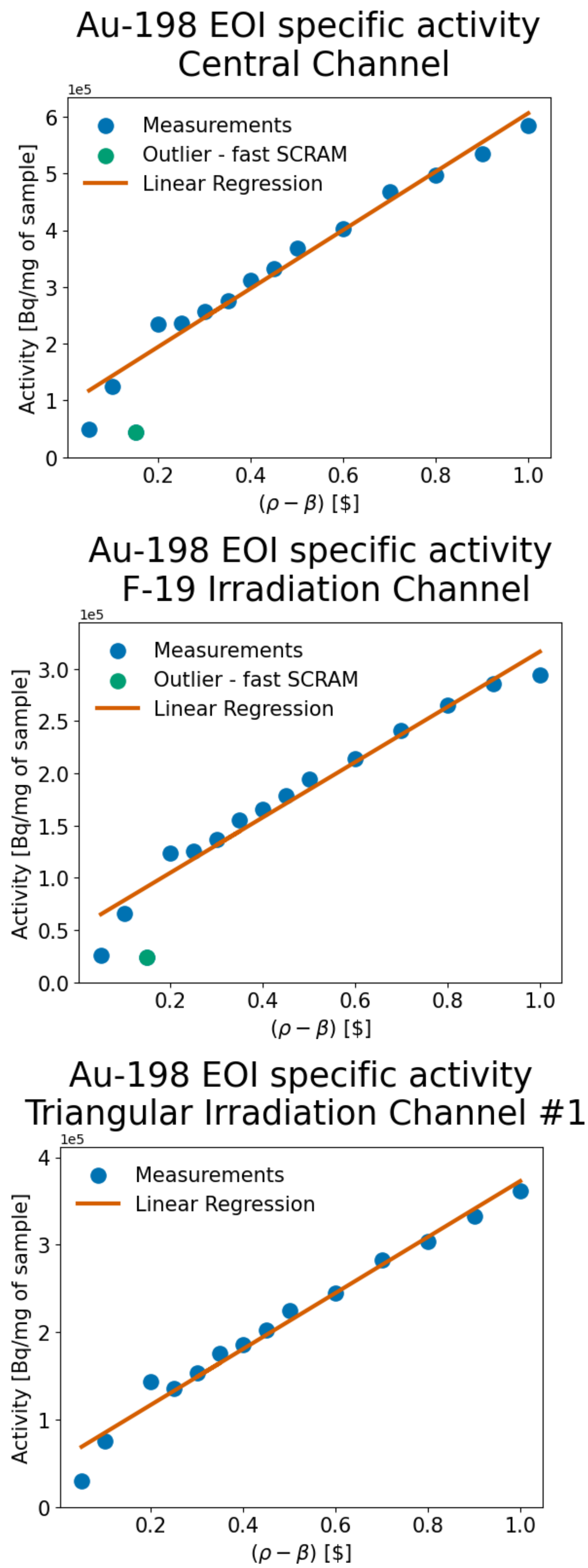

Fig. 9. Measured specific end-of-irradiation activities [Bq per mg of sample material] for Au-198, originating from the Au-197(n,γ) reactions, as a function of the pulse prompt reactivity.

V. Conclusions

This work demonstrates the use of the Cherenkov power meter for irradiation measurements during TRIGA pulse operation. The presented results clearly demonstrate that the Cherenkov power is a capable experimental technique for measurements of rapid transients in nuclear reactors. The present research is aimed at extending the experimental capabilities of the JSI TRIGA research reactor, making use of the high neutron flux levels achievable in reactor pulse operation. Cherenkov detector could be envisaged to complement the online nuclear instrumentation fleet such as fission and ionization chambers and SPNDs. It is shown that Cherenkov power meter in conjunction with dosimetry measurements enables sample irradiation during pulse operation at the JSI TRIGA research reactor. Nuclear reactor power meters based on Cherenkov radiation detection offer great potential for increased redundancy, adaptability, and diversity of instrumentation and control in modern nuclear applications. It should be taken into account that the developed Cherenkov power meter at the research reactor JSI TRIGA is more than a hundred times cheaper than the implemented instrumentation, which provides the same results and, in some cases, exceeds the performance of the implemented solution.

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