Fast Scintillation Probes For Investigation Of Pulsed Neutron Radiation From Small Fusion Devices

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Abstract. This paper presents the design as well as laboratory/performance tests results taken by means of the fast scintillation probes. The design of each scintillation probe is based on photomultiplier tube hybrid assembly, which - besides photomultiplier itself - also includes high-voltage divider optimized for recording of fast radiation bursts. Plastic scintillators with short-time response are applied as hard X-ray and neutron radiation detectors. Heavy-duty probe's housing provides efficient shielding against electromagnetic interference and allows carrying out pulsed neutron measurements in a harsh electromagnetic environment. The crucial parameters of scintillation probes have been examined during laboratory tests in which our investigations have been aimed mainly to determine: a time response, an anode radiant sensitivity and an electron transit time dependence on high-voltage supply. During the performance tests, the relative calibration of probes set has been done. It allowed to carry out very accurate measurements of neutron emission anisotropy and investigations of neutron radiation scattering by different materials. The usefulness of presented scintillation probes – embedded in the neutron time-of-flight diagnostic system was proven during experimental campaigns conducted on the plasma-focus PF1000 device.

Keywords: Scintillation detectors, Photomultipliers in nuclear physics, Plasma focus devices, Sources of neutrons, Neutron elastic scattering, Neutron time-of-flight measurement.
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INTRODUCTION

The investigations of pulsed neutron radiation, originating in the final stages of dense *plasma-focus* (DPF) discharge are of great importance to understanding all the processes occurred in dense, hot deuterium (or deuterium-tritium) plasma and are most frequently sole source of experimental data applied for reconstruction of the time-resolved neutron energy spectra. The fast scintillation probes – presented in this paper, have been primarily dedicated for investigation of DPF PF1000 device – leading facility of the International Centre for Dense Magnetized Plasma (ICDMP) that has been established at the Institute of Plasma Physics and Laser Microfusion (IPP&LM, Warsaw, Poland).

Investigation carried out on the modified (new electrodes set) PF1000 device started in September 2000. Since this time, the PF1000 laboratory has been gradually equipping with new diagnostic tools, which enabled to perform more and more advanced investigations and to obtain reliable scientific results [1,2].

In the late of 2003, it has been decided that existing experimental arrangement of the PF1000 device should be further improved and equipped with quite new diagnostic system dedicated for neutron time-of-flight (NTOF) measurements. Almost all the tasks concerning the NTOF system development and its put into experimental investigations were entrusted to ACS Company.

At present, the NTOF system is practically completed and incorporates a few subsystems [3]:

- Ten scintillation probes FNSP-1 type located in heavy-shielding barrels;
- Ten mobile stands AS16U-8 type equipped with battery powered HV power supplies as well as digital oscilloscopes TDS305X type (*TEKTRONIX*);
- Synchronization system able to trigger individual diagnostic elements with accuracy better than 2 ns;
- Optical, laboratory INTRANET joins all the system elements in one web;
- A set of software enables to perform a control of system elements, data management and processing.

For obvious reasons, even abridged presentation of all the NTOF subsystems is unfeasible within the framework of this paper. Hence, the more or less detailed presentation of probes' design as well as laboratory/performance tests results will be given in the next paragraphs. However, before beginning detailed description of performed works, it seems to be necessary to list the main problems related to recording of pulsed neutron radiation by means of scintillation probes:

- Firstly, a scintillation associated with single (n,p) elastic collision within scintillator volume is most frequently overlapped by others scintillations. It is caused by a high density of colliding neutrons – for high-yield neutron emission ($\sim 10^{11}$) and scintillation probe located 8 m away from neutron source, a few hundreds of neutrons with energy of about 2.45 MeV arrive to scintillator volume in every single nanosecond. Hence, it is unfeasible to apply well-established scintillation counting methods in order to obtain a total number of neutrons collided within a scintillator volume;
- Secondly, intense, pulsed neutron generation is usually joined with strong emission of hard X-ray pulses. Such very bright flashes acquired by means of scintillation probe can usually cause overloading of a photomultiplier tube (PMT), which means, in turn, that amplification of the next parts of a signal can be expected to become nonlinear. For that reason – in order to attenuate hard X-ray radiation, an experimental arrangement should be additionally equipped with shielding wall (usually Pb bricks) located in front of a scintillation probe. Other solution of that problem (not so very popular like the former one) is based on decrease the irradiance of PMT photocathode. It is done by means of neutral density filters that are put between adjoining surfaces of a scintillator and a PMT photocathode. Furthermore, the separation of mutually overlapped hard X-ray/neutron signals can be done only by measurements carried out in time-of flight arrangement – none of pulse shape discrimination methods are applicable;
- Thirdly, the pulsed neutron generation is usually non-reproducible, which means that recording of X-ray/neutron signals from scintillation probes has to be carried out in single acquisition mode – an usage of average operation mode is impossible.

SCINTILLATION PROBES' DESIGN

All the internally mounted elements of the scintillation probe (SP) FNSP-1 type are located inside cylindrical housing of 172 mm diameter and 483 mm length, made from stainless steel (Fig. 1a). Its relatively large overall dimensions allow to apply scintillators of up to 120 mm diameter and 100 mm thickness. High-conductive contacts ensured between outside housing's elements, provide high immunity of internally mounted PMT against strong electromagnetic interference. The both electrical connectors – HV supply input (SHV female) and signal output (BNC female) are accessible at rear panel of the SP housing.

As the SP's photodetector we have applied the PMT hybrid assembly H1949-51 type (*HAMAMATSU*), which - besides photomultiplier itself - also includes high-voltage divider optimized for recording of fast radiation bursts. Its head-on PMT has 12 dynodes, arranged in linear structure and is characterized by fast time response and good temporal resolution. The useful diameter of the PMT photocathode is not smaller than 46 mm (51 mm nominal). The detailed technical data, concerning the mentioned PMT assembly can be found in HAMAMATSU website [4].

The BC-408 type organic scintillators (*BICRON*) are applied as hard X-ray and neutron radiation detectors. They also are characterized by fast time response (a pulse width of about 2.5 ns) and high efficiency detection of fast neutrons. Furthermore, their peak of emission (425 nm) is very good matched to PMT photocathode sensitivity. The scintillation effectiveness – the ratio of the number of created photons to energy absorbed within scintillator volume is equal about ten scintillation photons for each keV of proton deposited energy, whereas the estimated mean free path of 2.45 MeV neutrons is equal to 47.6 mm. Remaining technical data and parameters are published in BICRON website [5].

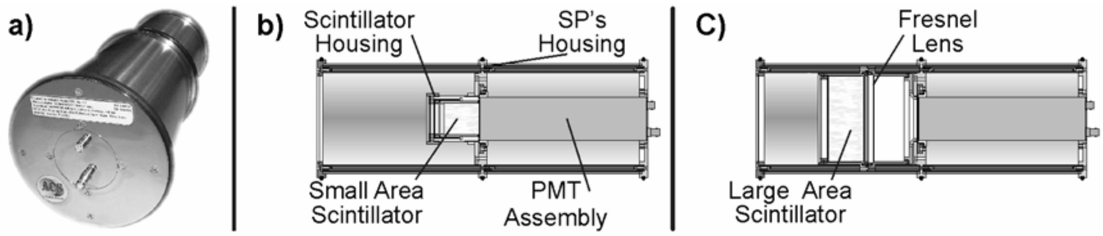

FIGURE 1. The scintillation probes FNSP-1 type.
1a) General view of the probe. 1b) The cross section of a probe equipped with smaller scintillator.
1c) The cross sections of probe equipped with large area scintillator.

The SPs are manufactured in two basic versions (Fig. 1b, 1c). The first of them, incorporates scintillator of 45 mm diameter and 50 mm thickness, which is directly coupled to PMT input window. To minimize interface losses, a silicone grease is applied between adjoining surfaces. In the second solution, scintillators of 120 mm diameter can be applied. In such case, the light transmission from large area scintillators onto photocathode surface (smaller diameter) is ensured by the Fresnel lens with focal length equal to 76 mm. Such optical and non-imaging coupling has efficiency of about 8%. Regardless of overall scintillators dimensions, them housings are made from non-reflected, black-anodized aluminum. It decreases a PMT photocathode irradiance, but increases total temporal resolution of the SP.

LABORATORY TESTS

The final test sheet – usually delivered with a PMT, contains a very limited number of PMT parameters that could be a source of reliable information concerning PMT operation for a broad range of its working conditions. Hence, in order to get a much more detailed knowledge, it is necessary to carry out a set of laboratory tests, in which crucial parameters of PMT could be examined. To accomplish these tasks, we have arranged the test stand and prepared the set of measuring procedures. Some of them are presented in the next paragraphs.

Time Response Measurement – Usage of Neutron Background Radiation

The measurement of PMT time response (called also anode pulse response) is usually carried out in very well-known arrangement [6,7] in which a pulsed laser diode is used as the light source. The emitted light pulse width should be sufficiently short compared to the expected temporal characteristics (rise time and fall time) of a PMT itself, which can be found in manufacturers' catalogs. If mentioned condition is fulfilled, the incoming light pulse can be treated as a delta-function light source, which means, in turn, that an output signal acquired from an anode is equivalent to a PMT time response. According to this, we have applied the laser pulse of 610 ps width (Fig. 2a) as a light source. The typical result taken during the PMT time response measurement is shown on Fig. 2b. However, it should be realized that pulsed laser light sources can be found in limited number of labs. Furthermore, in order to avoid a PMT failure it is necessary to have an expertise to proper introduce laser beam onto photocathode surface.

Fortunately, there is another – a more safe manner to carry out a PMT time response measurement. It is based on detection of a neutron background radiation which originates either in nuclear interactions of high-energy cosmic ray particles with the Earth's atmosphere and neutron production in the Earth's crust.

It appears that a "nude" PMT (equipped with none scintillator) is sensitive to neutron radiation. Hence, single neutron collision at photocathode surface followed by electrons emission can be equivalent of a delta-function light pulse applied in typical arrangement. It means, in turn, that the neutron background radiation can be easily adopted to obtain a PMT time response, like it is shown on Fig. 2c.

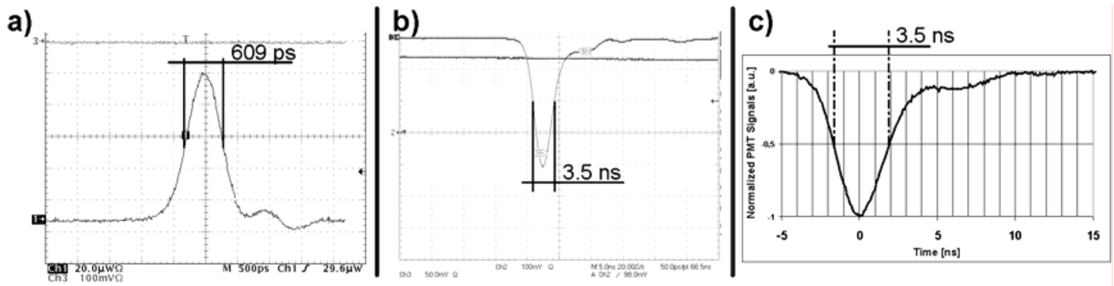

FIGURE 2. In search of the PMT time response.
Measurements carried out in typical arrangement; Incoming laser pulse shape (2a) and the PMT time response (2b). Neutron background radiation exploited to obtain the PMT time response (2c).

Unlike in the previous case, a neutron background radiation is very frequently exploited to obtain a time response of a SP (including a PMT and a scintillator). Principle of measurement consists in acquisition of an anode pulse associated with single neutron collision occurring within scintillator volume. The SP time response is a convolution of the scintillator response, the PMT response and the response of acquisition system. However, the contribution of acquisition system can be neglected when, analog bandwidth and applied sample rate are sufficiently high – at least a few GHz and 20 GS/s (Giga samples per second). In general, the SP time response signal is always broadened in comparison with the time response signal of the PMT itself (Fig. 3a). The extraction of the scintillator time response from the SP time response can be done by means of deconvolution methods.

The measurement of a SP time response is usually treated as a base to perform considerations related to evaluation of limiting temporal resolution that can be achieved in diagnostic systems including SPs. There are a few definition of a limiting temporal resolution. However, from experimental viewpoint, the most adequate seems to be definition, according with, the limiting temporal resolution of a SP is its ability to distinguish two, identical delta-function neutron radiation peaks shifted in time. The evaluation consists in the replacement of delta function peaks by the SP time response signals and analysis of resulting signal shape, which should be similar to this one shown on Fig. 3b. The limiting temporal resolution is equivalent to the time shift for which the difference between amplitudes of lower peak and valley is equal to 5% (for normalized signal). It has been checked that the limiting temporal resolution of the SPs presented in this paper is equal to 5.5 ns.

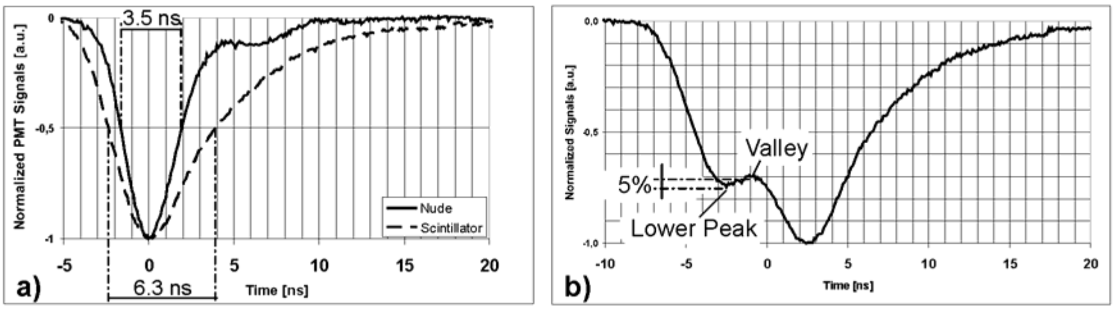

FIGURE 3. 3a) Comparison between the time response of the PMT itself (continuous line) and the time response of the scintillation probe (dashed line);
3b) Considerations concerning temporal resolution of the scintillation probe – expected pulse shape for two delta-function neutron radiation peaks shifted in time by 5.5 ns.

Anode Radiant Sensitivity and Electron Transit Time

Knowledge of the actual anode radiant sensitivity for each of the SP employed in NTOF system is crucial to obtaining reliable physical results. Generally, anode radiant sensitivity S_a is wavelength dependent and can be expressed as the ratio of the anode current I_a to the incident (photocathode surface) radiant power $\mathbf{\Phi}$:

$$S_a[A/W] = \frac{I_a}{\Phi} \tag{1}$$

Anode radiant sensitivity is frequently expressed in terms of cathode radiant sensitivity S_k (also wavelength dependent) and PMT gain G (HV supply dependent):

$$S_a[A/W] = S_k G \tag{2}$$

From experimental viewpoint, the most important is dependence of recorded signals amplitude A_S on incident radiant power that can be expressed as follows:

$$A_S[V] = 50 S_a \Phi \tag{3}$$

where the factor 50 relates to input resistance [50 Ω] of signals acquisition systems.

Besides anode radiant sensitivity, it is necessary to know the electron transit time (ETT) dependence on HV supply applied to the PMT HV divider. The ETT is the time interval between arrival of a light pulse at the photocathode and the appearance of the output pulse at anode. This parameter is crucial to determining the total delay time in acquisition system.

The test stand shown on Fig. 4a has been arranged to measure both above-mentioned parameters. The pulsed laser of 30 ns width (FWHM) and 415 nm wavelength is applied as the light source. The actual laser power is measured by means of optical-to-electrical converter. The measurements idea (Fig. 4b) consists in recording the dependence of the pulse amplitude and the delay time on the HV supply applied to tested probe. The exemplary results taken in presented test stand are shown on fig. 4c and 4d. It should be added that the computation of the anode radiant sensitivity has been done according with formula (4).

$$S_{a\,415nm}[A/W] = \frac{A_s^{TEST}[V]}{50\Phi^{LASER}[W]} \tag{4}$$

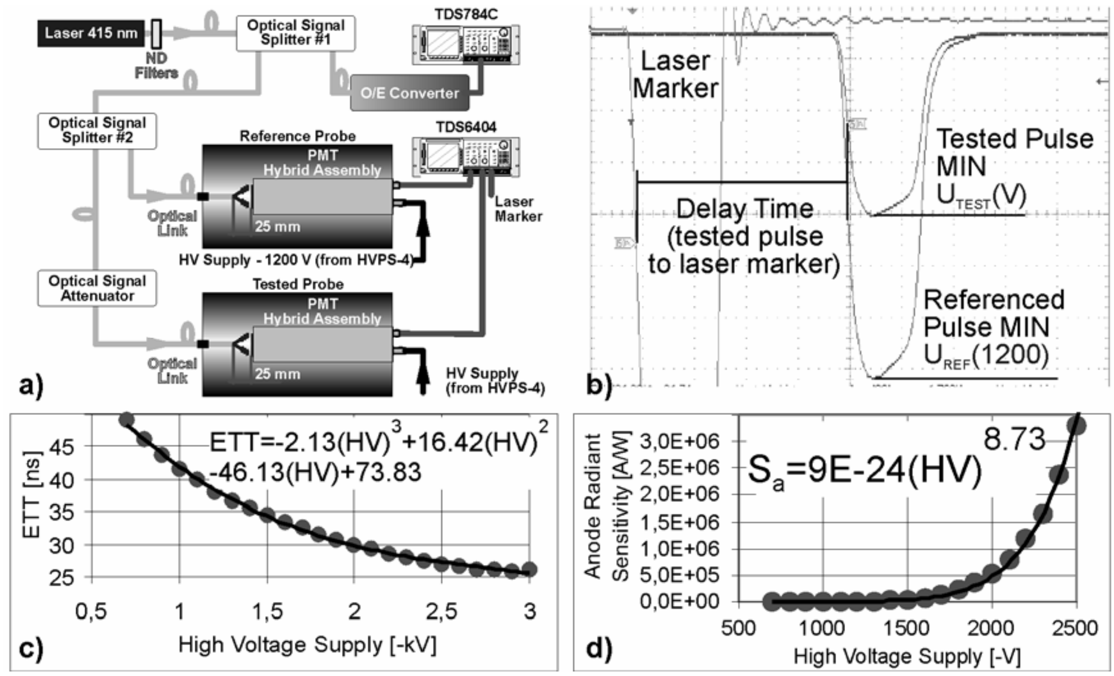

FIGURE 4. The investigations of the anode radiant sensitivity
and delay time dependence on HV supply applied to the SP:
The test stand block diagram (4a), The measurement principle (4b);
The exemplary results taken during the investigations are shown with related approximate functions:
The delay time (4c), The anode radiant sensitivity (4d).

PERFORMANCE TESTS

This part of the presented work has been executed at the PF1000 device laboratory. At first, we have made an attempt to perform a very precise – relative calibration of the four scintillation probes equipped with small area scintillators. As these probes have been expected to be located on the distance of a few meters from ground zero, the PMT overloading by the very bright – hard X-ray flashes has been most likely. To prevent it, each of employed probes has been additionally equipped with neutral density filter of 10% transmission that has been put between adjoining surfaces of the scintillator and the photocathode.

The scintillation probes prepared in such manner, have been then located in the single mobile stand as is shown on Fig. 5a and 5b. At that moment, it is necessary to explain what does it mean the concept “the relative calibration”. The proper relative calibration for the scintillation probes set, consists in the achievement of such working conditions (the level of applied HV supply), for which the mutual differences between integrals taken over neutron signals should be not higher than 2%. In considered case, all the scintillation probes have observed neutron source within identical solid angles, although, each of angles has been variously oriented in the space.

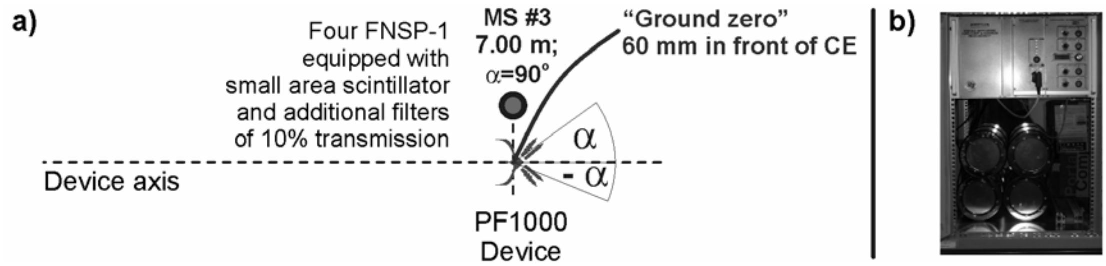

FIGURE 5. The relative calibration of the probes set: The location of the mobile stand in reference to the ground zero (5a), The general view of the four scintillation probes put into the mobile stand (5b).

At first, the level of HV supply applied to each of individual probe has been drawn from responded approximate curves of the anode radiant sensitivity (obtained during the laboratory tests). As it turned out, the fine (in the range of a few volts) adjustment of HV supply has been necessary to achieve the SPs’ working parameters, at which the above-mentioned condition for relative calibration has been fulfilled. All the relative calibrated probes have been then located inside them own mobile stands that have been distributed over the experimental area of the PF1000 device (Fig. 6a, 6b).

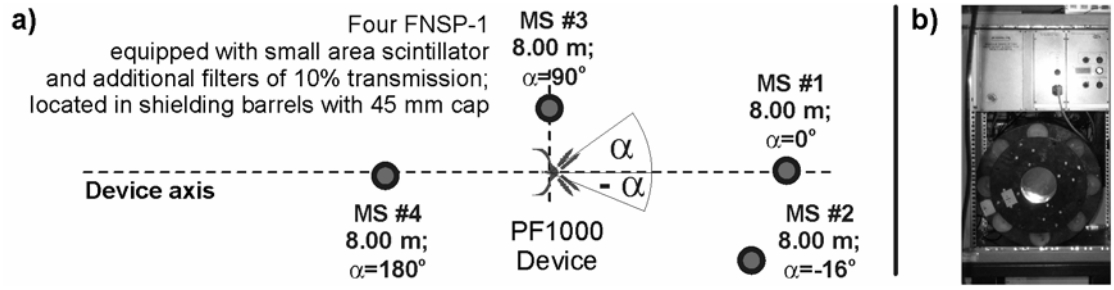

FIGURE 6. The four mobile stands arranged to carry out measurements of time-resolved neutron emission anisotropy: The simplified scheme of the mobile stands location at the experimental area (6a), The general view of the shielding barrel put into the mobile stand (6b).

Such arrangement of the scintillation probes has been applied to carry out measurements of the time-resolved neutron emission anisotropy, being the ratio between number of neutrons emitted along any line-of-sight and number of neutrons emitted at right angle (in reference to PF device axis). The exemplary results taken during this phase of the performance tests are shown on Fig. 7.

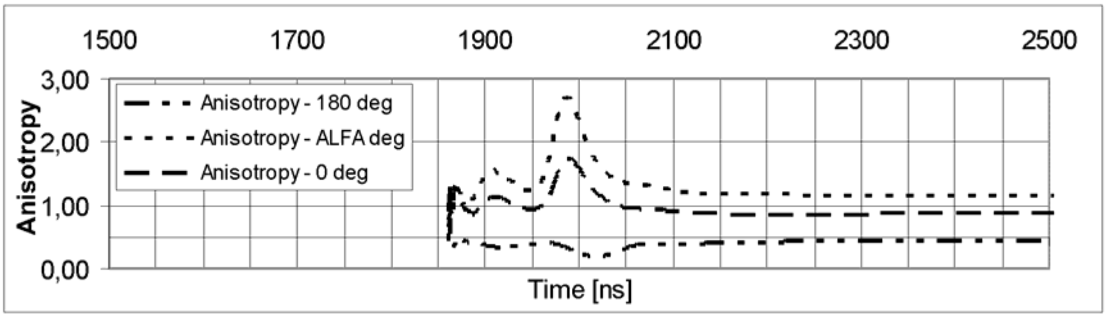

FIGURE 7. The exemplary results obtained during the measurements of the time-resolved neutron emission anisotropy.

The satisfactory results that were obtained in measurements of the time-resolved neutron emission anisotropy, confirmed us in a conviction that the relatively calibrated scintillation probes can also be applied to investigations of the neutron radiation scattering. To accomplish this task, we have repeated the relative calibration procedure for the next two scintillation probes. These probes have been then put in the next mobile stand that has been located 8 m away from ground zero, whereas its line-of-sight angle was equal to 80 degrees. During the measurements, the one probe was covered by different material specimens (aluminum, stainless steel, glass, etc.).

The principle of these measurements consists in examination of the ratio between signal integrals taken for test and reference (uncovered) probe. The obtained results (Fig. 8), were in good agreement with MCNP computations.

FIGURE 8. The investigations of neutron radiation scattering; The signals recorded from the reference as well as tested probe (covered by glass slab of 30 mm thickness) and the view of the arrangement.

Besides above-presented performance tests, the full set (10 pieces) of the scintillation probes FNSP-1 type has been obviously applied (as the part of the NTOF systems) during the main experimental campaigns conducted on PF1000 device. There are a lot of very interesting experimental data that were obtained during these campaigns. The part of them became a base to perform advanced physical analysis, the results of which have been already published and can be found in [8].

SUMMARY

This paper presents the scintillation probes FNSP-1 type, being the crucial element of the neutron time-of-flight system delivered to the dense plasma-focus PF1000 laboratory by ACS company.

The basic version of presented probe incorporates the PMT assembly and the small area organic scintillator. Other version can be equipped with large area scintillators and, as such, can be applied for neutron radiation recording carried out in separated measuring stands located up to 80 m away from radiation source. The construction of the probe's housing provides effective shielding against electromagnetic interference, which enables to carry out radiation recording in the harsh electromagnetic environment.

The specially prepared: test stand and the set of measuring procedures, allowed us to obtain the detailed information concerning: the limiting temporal resolution of the probes, which value has been evaluated on 5.5 ns, the electron transit time and the anode radiant sensitivity dependence on HV supply applied to each of the tested probe.

During the performance tests, the very precise – relative calibration of employed scintillation probes has been done. Thanks to that, it became feasible to conduct measurements of neutron emission anisotropy and to investigate the neutron radiation scattering by different materials.

The usefulness of presented scintillation probes – embedded in the neutron time-of-flight diagnostic system was proven during experimental campaigns conducted on the plasma-focus PF1000 device.

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