Plasma Accelerator for Detection of Hidden Objects by Using Nanosecond Impulse Neutron Inspection System (NINIS)

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Abstract. Nanosecond Neutron Analysis method and Fast Neutron Scattering Analysis technique, which recently have been developed within the program of hidden objects interrogation by fast neutrons, noticeably improve the problem of signal-to-noise ratio in comparison with previous practice. However they leave difficulties connected with a high necessary fluence and relatively long investigation time to be practically unresolved. The reason for it is too low brightness of neutron sources used (isotopes or classical diode-like accelerators). We propose to bring into play a neutron source based on a *plasma accelerator*, which generates very powerful pulses of neutrons in the nanosecond (ns) range of its duration. New generation of powerful neutron sources of the Dense Plasma Focus type can generate neutron pulses not only short by its duration (in the *nano-second range*), but provides *a very high neutron yield* in these pulses. Our device PF-6, recently put into operation at the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland, has energy in its capacitor storage 7.4 kJ. Operated with the DPF chamber of a special design it is reckoned on a current maximum of the order of 800 kA with a quarter period of the discharge equal to 1 microsecond. It should generate in one pulse of ≅ 10-ns duration up to circa 10^9 D-D (2.5-MeV) neutrons or 10^{11} DT (14-MeV) neutrons. This feature gives a principal possibility to create a "single-shot detection system". It means that all necessary information will be received during a single very bright pulse of neutrons having duration in a nanosecond range by means of the time-of-flight technique with a short flight base. It might be a foundation for the creation of the Nanosecond Impulse Neutron Inspection System (NINIS). Because of these characteristics of the neutron source the signal-to-noise ratio will be increased just proportionally to the decreased number of shots (one instead of billions) whereas neutron fluence necessary to characterize hidden objects will be noticeably decreased. Due to these features this technique can be used in inspection of potential suicide bombers. An interrogation time in this case will now depend only on the data-processing system. In our report we present characteristics of the device as well as first results on its tests for the goals of NINIS method.

1. Introduction

Two important issues encountered in the non-intrusive inspection of buried materials by neutron methods with using isotopes or generators based on direct acceleration are low signal-to-background ratio and long duration of measurements at a detection procedure. Attempts to implement Nanosecond Neutron Analysis (NNA) method [1] and Fast Neutron Scattering Analysis (FNSA) technique [2] noticeably improve the first problem. However they leave the second one practically unresolved. The reason for it is too low brightness of both neutron sources used in these schemes. In the case of NNA it was a classical accelerator with direct diode-like acceleration of ions striking a target, which generates neutron pulses in the microsecond range with low intensity. In the FNSA method the Van de Graaff accelerator generating nanosecond neutron pulses of very low neutron yield was applied. That is why these methods demand to produce a huge number of shots (on the order of billions), and for each of them a "signal to noise" ratio is rather poor. It results in the above-mentioned problem even in spite of the nanosecond "gating" technique [1] used. We propose to bring into play a neutron source based on a *plasma accelerator*, which generates very powerful pulses of neutrons in the nanosecond (ns) duration range [3].

2. Apparatus

New generation of powerful neutron sources of the Dense Plasma Focus (DPF) type can generate neutron pulses not only short by its duration (in the nano-second range), but provides *a very high neutron yield* in these pulses. Our device PF-6 (Fig. 1), which has been recently put into operation at the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland, has maximal level of energy in its capacitor storage 7.4 kJ. Delivery of this amount of energy into DPF chamber of a special design at the charging voltage of the battery on the level of 23 kV will characterize as expected a current maximum of the order of 800 kA with a quarter period of the discharge equal to 1 microsecond. It might generate in one pulse of ≅ 10-ns duration up to circa 10^9 2.5-MeV neutrons or 10^{11} 14-MeV neutrons at operation of the device with pure deuterium or deuterium-tritium mixture correspondingly. Moreover being ecologically acceptable source (it becomes a neutron source "on demand" for a few nanoseconds and doesn't require special storage) this modern DPF because of recent improvements in high power technology has the following features:

- it may operate with sealed chambers, filled with a working gas (deuterium or DT mixture) from a special self-contained actuator (so it can be treated as "closed or sealed radiation source"),
- switching time and jitter of all its electrical elements are of the order of a few ns,
- life-time of the device is of the order of 10^7 "shots",
- modern technology of the device assembling and its up-to-date constituents ensure its operation perfect and reliable as in a real industrial product,
- it has relatively low size and weight (circa 1 m^3 and 400 kg), thus it is a transportable device,
- its cost is comparatively low,
- it may work with a high repetition rate – up to 10 pps and more [4].

FIG. 1. PF-6 device (in the centre with red frame), its control unit behind the shadow shield on the right-hand side and the first fast photomultiplier-oscilloscope module on the left-hand side for time-of-flight neutron measurements

Electrical schematic diagram of the device in presented in Fig. 2.

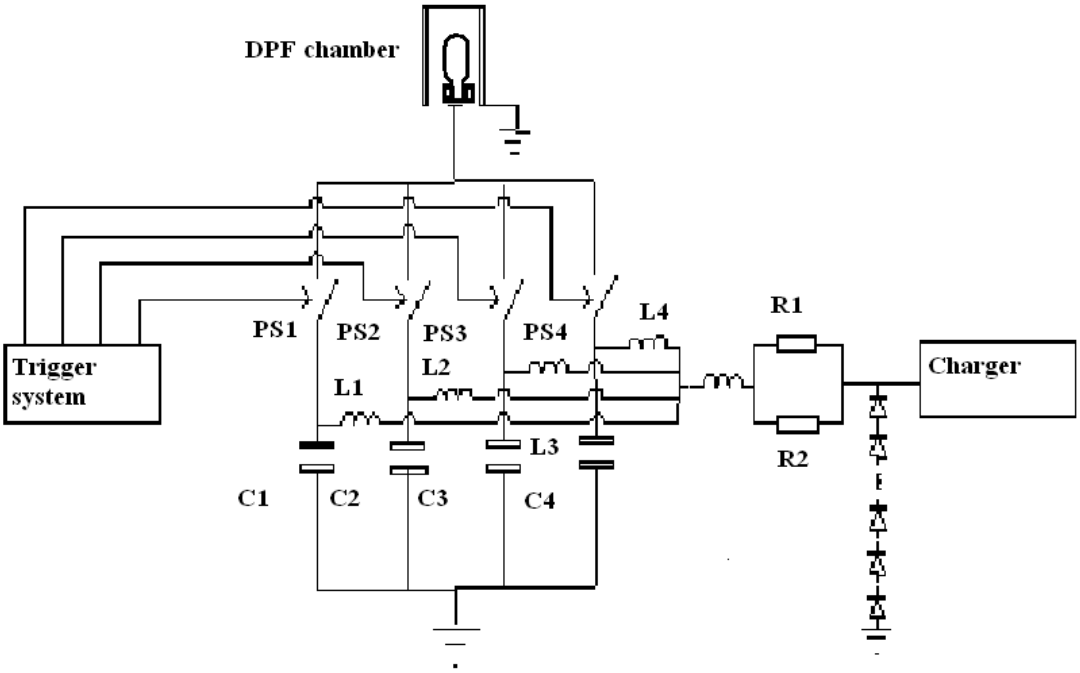


FIG. 2. Electrical schematic diagram of the PF-6 device (PS – pseudospark switches, C – capacitors, L and R – inductances and resistors)

This device has been tested on this stage with a small neutron chamber intended for the energy operational level not higher than 3.6 kJ with maximal charging voltage U = 16 kV (Fig. 3). In the upper part of the picture one may see cables connecting Rogowski coil and magnetic probe with an oscilloscope.

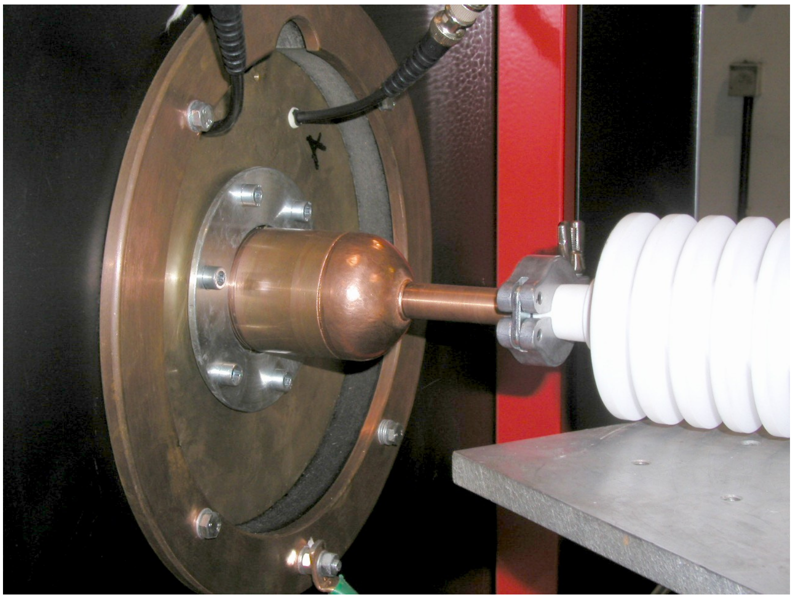


FIG. 3. Small DPF chamber with current collector

Typical current derivative waveform registered with the above-mentioned technique at this device is presented in Fig. 4 with current value I = 575 kA at U = 16 kV.

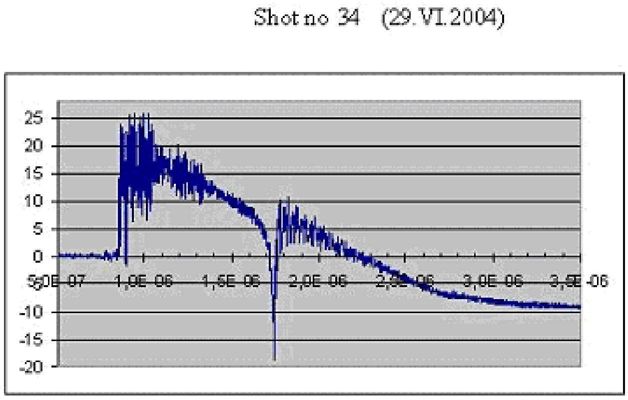
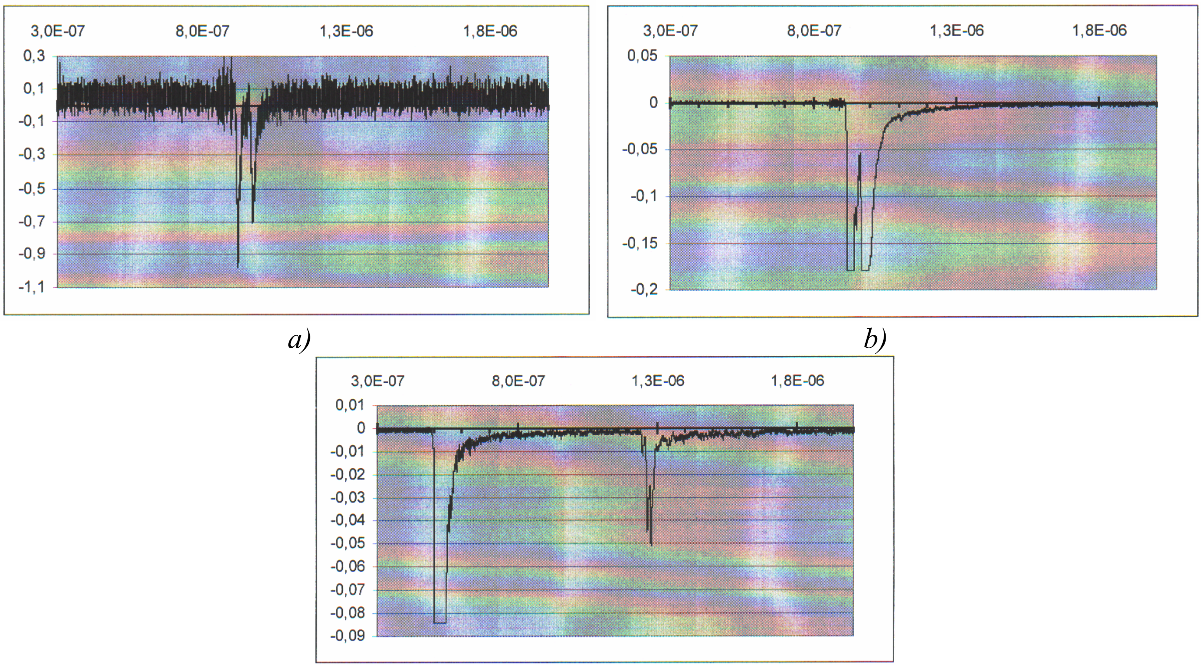


FIG. 4. Oscilloscope traces of current derivative taken under the charging voltage 16 kV for the shot of PF-6 No. 34 operated with deuterium as a working gas

Neutron radiation has been investigated by two activation counters, four bubble detectors and two fast photomultipliers with scintillators (S+PM). The last technique was used simultaneously for hard X-Ray monitoring. Typical oscilloscope traces taken by photomultipliers positioned at different distances from the DPF chamber are presented on the Fig. 5. From measurements provided with these traces (taking into consideration time-of-flight – TOF – of both types of radiation – X-Rays and neutrons) it was found that neutron pulse (NP) starts inside the chamber 8 ns later in relation to beginning of the hard X-Ray pulse (HXRP) whereas mean neutron energy irradiated within the angle of both S+PM locations is equal to 2.5 MeV. Absolute neutron yield at 16 kV was circa 2×10^8 neutrons per 10-ns pulse.



a)

b)

c)

FIG. 5. Oscilloscope traces of HXRP and NP taken at two distances – 1 m (a, b) and 18.5 m (c)

Comparative analysis of about 100 oscilloscope traces of such a kind demonstrates us that the time interval between HXRP and NP varies from shot to shot within the limits of less than 4%. We intend to present more detailed results on the NP and HXRP investigations together with absolute yield measurements elsewhere.

It should be mentioned here that we have also *a portable* modification of the DPF of this new generation [5] weighing only 15 kg. But its neutron yield being irradiated within the pulse of the 2-ns time duration is 3 orders of magnitude lower than that expected for the PF-6 at its full energy storage (7.4 kJ).

3. NINIS Tests

With the above-described device we have made some preliminary tests of its possible use within the frame of the Nanosecond Impulse Neutron Inspection System scheme.

In principal the described PF-6 device that can produce very short and at the same time very bright pulses of neutrons may be used in various neutron probing techniques, but in particular in Nanosecond Impulse Neutron Inspection System (NINIS) exploiting time-of-flight (TOF) method. It is so because the flight base may be short (10-ns pulse of D-D neutrons is 20 cm long whereas the same length for 14-MeV neutrons pulse is about 50 cm). It is important because it means that *in a distance of just a few meters* and during *only a single pulse* we may separate (and consequently distinguish) several groups of neutrons (direct beam, elastically and inelastically scattered neutrons) as well as prompt γ-rays, which are exited both by inelastic neutron scattering and by the neutron capture in the interrogated material and which are appeared within the time intervals between the neutron pulses.

It should be marked that this technique is inapplicable in the case of the contemporary classical accelerators (neutron generators with the diode-like acceleration principle) because of microsecond duration of their pulses. This feature implies the transit-time region of the order of several hundred meters. Yet the neutron yield of these generators is too small for this very case (besides of the evident inconvenience of long transit-time bases).

Another very important advantage of NINIS, which uses high-brightness neutron generators, is that we expect to execute all the measurements during just a *single* nanosecond pulse of the DPF. That increases *signal-to-noise ratio* even in comparison with the NNA technique as well as with the FNSA method almost in a proportion of the necessary statistics of those two methods, which are collected by a *high number* of nanosecond pulses (or time gates). At the same time the *duration* of the detection procedure will be limited in our methods mainly by the time of the data handling.

The last but not the least benefit of the DPF use for inspection of hidden objects results from its possibility to generate a nanosecond pulse of hard X-rays (of ~100-keV photon energy) in the same moment as its neutron pulse irradiation. In certain schemes it gives an opportunity to visualize high-density or high-effective charge objects within an interrogated compartment.

Between methods, which will be tested in a full-scale experiment with this device (23 kV of charging voltage, 7.4 kJ of stored energy, D-T filling of the DPF chamber thus producing circa 10^{11} neutrons of 14-MeV energy), are such as:

- FNSA as in the case of [2] (in fact there is a complex of methods here including elastic and inelastic scattering)
- Pulsed neutron-gamma method based on registration of gamma-photons radiated as a result of inelastic scattering or capture of fast neutrons in various materials (e.g. H, C, N, O, Na for explosives and narcotics); under certain conditions these ns gamma-ray pulses may give information on localization of suspicious objects by time delay of the pulses;

- Neutron Activation Analysis (NAA) based on the detection of hidden materials by a reaction (n, 2n) with a registration of 2 gamma-photons of 0.511-MeV energy (appeared due to positron annihilation).

But contrary to the contemporary used means all these methods will be checked for their applicability to a single-shot (or at the most to several high repetition rate shots) technique. The most important modification of them will be a usage of an array of S+PM for the prompt-gamma registration as we have to work in this scheme with a load of less than 1 gamma photon per PM. However for our main instrument – neutron TOF method – we need just the only one S+PM.

In our present preliminary tests we used the above-mentioned small DPF chamber, charging voltage not higher than 16 kV, deuterium as a working gas, a glass bottle with methanol (1 litre) as a sample for neutron scattering with its positioning either close to the DPF chamber or in the middle between the chamber and S+PM, and two S+PM at the distances of L1 = 1 m and L2 = 18.5 m apart from the chamber. Our shadow shield can be moved to open or to close the second S+PM-2 probe to check whether a signal seen on the trace is not an artefact. Schematic diagram of the experiment is presented in Fig. 6.

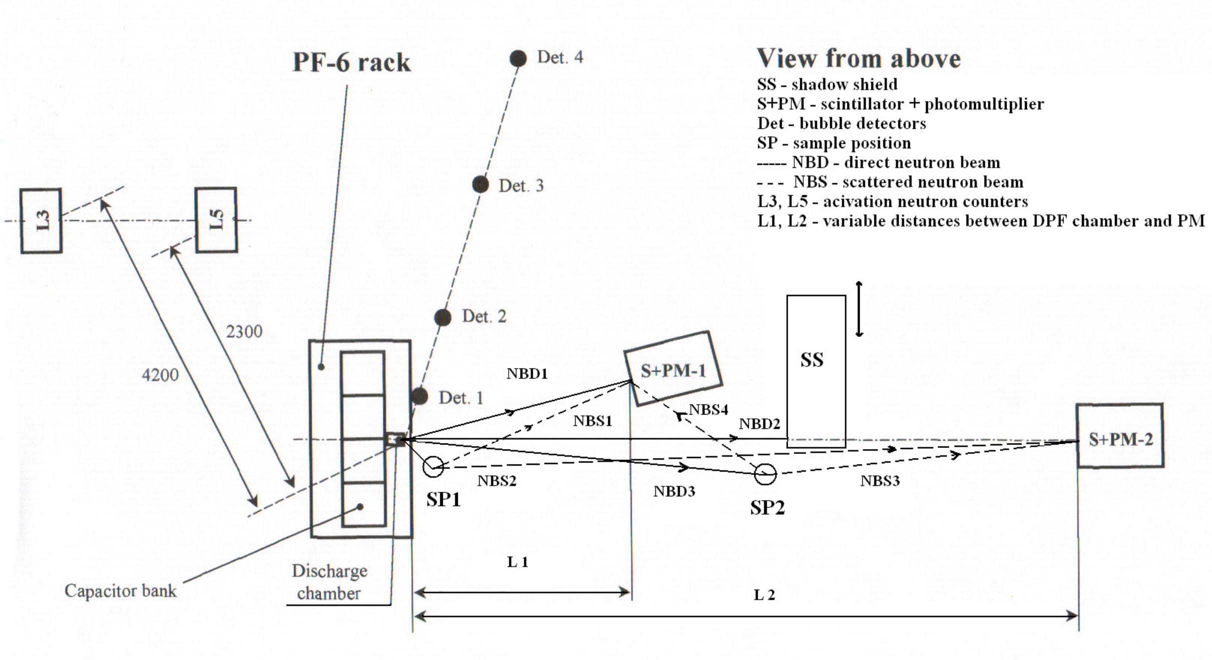
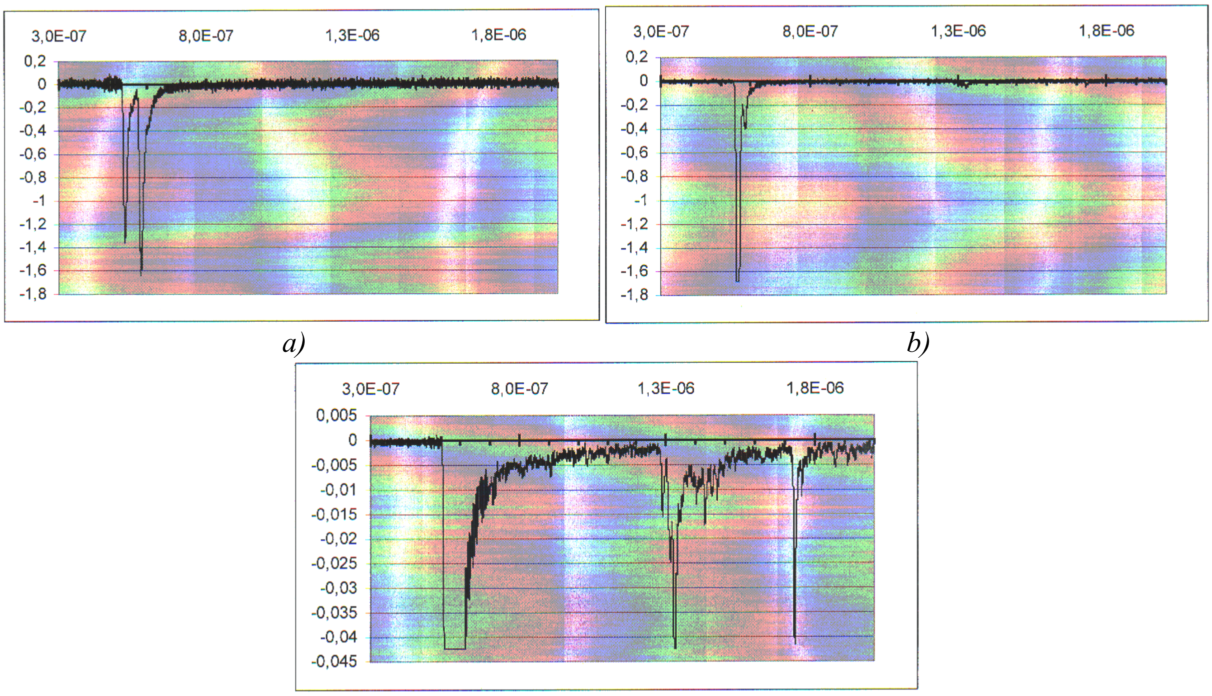


FIG. 6. Layout chart of equipment during the NINIS tests

We shall present here some preliminary results on these tests. Fig. 5 (see above) presents signals received by two probes (*a* and *b* corresponds to different sensitivities of the S+PM-1 probe, *c* – S+PM-2) taken for the same shot No. 153 (14 kV, 4 Torr of deuterium pressure) with removed the shadow shielding (SS) and without a sample. Traces on Fig. 7 are taken for almost the same conditions of the DPF operation (shot No. 164, 15 kV, 4.48 Torr) and without SS but with the sample installed in a close vicinity to the chamber (SP1) at an angle to the directions NBD1 and NBD2. One may see a clear additional peak at the trace of S+PM-2 delayed to the main neutron pulse by 415 ns whereas the main (direct) pulse of neutrons arrived to the S+PM-2 with the same delay as in Fig. 5. We believe that this peak is a pulse of neutrons elastically scattered by the bottle with methanol. The delay-time is correlated with the angles between NBD2 and NBS2 directions. The signal from the probe

S+PM1 have no distinct change in its shape as we believe because of strong overlapping of both direct and scattered neutron pulses.



a) *b)*

c)

FIG. 7. Oscilloscope traces of HXRP and NP taken without SS and with the bottle of ethanol at two distances – 1 m (a) and 18.5 m (b, c)

To analyse in more details spectral distribution of the second (scattered) pulse we install our methanol bottle in the middle between the chamber and the probe S+PM-2 at small angle to the NBD2 (thus organizing a low-angle scattering geometry) and install the SS. One example of the results of the experiments is presented in Fig. 8 with correlative calculations of neutron energies corresponding to each peak of the trace. In these computations we supposed the mean neutron energy to be 2.5 MeV (previously checked – see above) and took into consideration HXRP TOF (our SS was partly transparent for the hard X-Rays). We intend to undertake an identification of these peaks with element contents of the sample and amplitude calibration of the signals in the nearest future. Traces from S+PM-1 probe was not processed to the moment of the paper preparation.

After these experiments we took away the sample and this scattered neutron pulse disappeared.

4. Conclusion

Our preliminary experiments have shown that Dense Plasma Focus device PF-6 is fitted to the demands of NINIS technique in its main part – TOF measurements of elastically scattered neutrons. Our next steps in the frame of elaboration of the method according to the program described above will be done successively.

5. Acknowledgements

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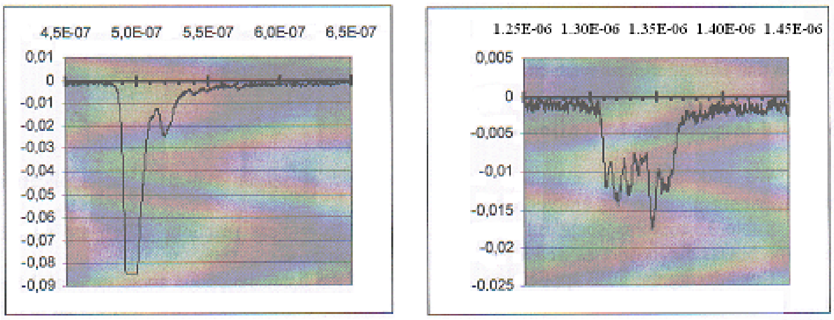
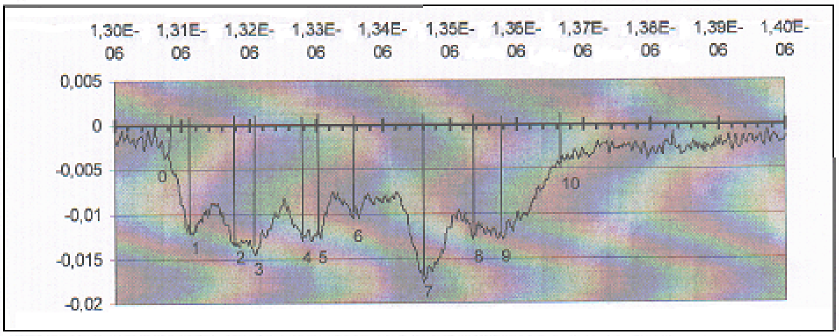


X-ray signal from 18.5m probe shifted back

neutron signal from 18.5m probe

Start of neutron emission is at 4.86E-07



Neutron energies corresponding to the reference points:

0.	T - 1.308 E-06	E - 2.64 MeV
1.	T - 1.311 E-06	E - 2.63 MeV
2.	T - 1.318 E-06	E - 2.59 MeV
3.	T - 1.321 E-06	E - 2.57 MeV
4.	T - 1.328 E-06	E - 2.52 MeV
5.	T - 1.330 E-06	E - 2.51 MeV
6.	T - 1.336 E-06	E - 2.48 MeV
7.	T - 1.346 E-06	E - 2.42 MeV
8.	T - 1.354 E-06	E - 2.38 MeV
9.	T - 1.358 E-06	E - 2.36 MeV
10.	T - 1.366 E-06	E - 2.31 MeV

FIG. 8. Computed spectrum of scattered neutrons taken at a distance 18.5 m from a neutron source

5. References

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