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

## Cooperation

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## 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 Fast Neutron Scattering Analysis (FNSA) technique, where *elastically and inelastically* scattered neutrons are measured, and Nanosecond Neutron Analysis (NNA) method, where spectrum of promptgamma rays are measured noticeably improve the first problem However they leave the second one practically unresolved



#### NNA



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 low intensity neutron pulses in the microsecond range

In the FNSA *Van de Graaff accelerator* was applied, which generates nanosecond neutron pulses but having very low neutron yield

That is why these methods demand to produce *a* huge number of shots and for each of them a "signal to noise" ratio is still rather poor even in spite of the nanosecond "gating" technique applied together with  $\alpha$ -particle-based APT As a result in order to *collect relevant statistics* the reciprocal time is increased We propose to bring into play a neutron source based on a *plasma accelerator*, which generates very *powerful pulses* of neutrons of the nanosecond (ns) duration and can convert the procedure into "a single-shot interrogation"

### **Apparatus**

New generation of *powerful neutron sources* of the **Dense Plasma Focus (DPF)** type can produce neutron pulses not only short by its duration (in the nano-second range), but ensures a very high neutron yield in these pulses Our devices **PF-6** (Institute of Plasma Physics and Laser Microfusion, Poland) and PF-10 (Institute for Theoretical and Experimental Physics, Russia), have maximal level of energy in its banks 7.4 kJ and 13.2 kJ correspondingly

## **PF-6 (IPPiLM, Poland)**



## **PF-10 (ITEP, Russia)**



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 results in a generation of a current having maximum of the order of **800 kA** with a quarter period of the discharge equal to **1 microsecond** 

These devices generate in one pulse of  $\cong$  15-ns duration the yield up to circa 10 <sup>9</sup> of 2.5-MeV neutrons or 10<sup>11</sup> of 14-MeV neutrons at operation of the device with pure deuterium or deuterium-tritium mixture correspondingly



Moreover being *ecologically acceptable* (it becomes a neutron source "on demand" for a few nanoseconds and doesn't require special storage) this modern DPF source 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 gas generator (so it can be treated as "closed 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<sup>7</sup> "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* (~1 m<sup>3</sup> 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



#### **Small DPF chamber**

PF-6 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

In the upper part of the previous picture one may see cables connecting Rogowski coil and magnetic probe with an oscilloscope

Typical current derivative waveform registered with the above-mentioned technique at this device shows current value I = 575 kA at U = 16 kV Shot no 34 (29.VI.2004)



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 and two fast photomultipliers with scintillators (S+PM)

The last technique was used simultaneously for hard X-Ray monitoring

Absolute neutron yield at 16 kV was circa  $2 \times 10^{8}$  neutrons per 15-ns pulse



R = 1.0 m



R = 18.5 m

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 <u>neutron pulse</u> (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 Comparative analysis of about 100 oscilloscope traces demonstrates us that the *time interval between HXRP and NP* <u>varies</u> from shot to shot (jitter) within the limits of less than 4%

#### **NINIS schemes and tests**

The described PF-6 device may be effectively used 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 circa 20 cm long whereas the same length for 14-MeV neutron pulse is about 50 cm)

This is important because it means that *in a* distance of the order of several 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  $\gamma$ -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

This <u>single</u> nanosecond pulse of the DPF increases <u>signal-to-noise</u> 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 method 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 very powerful nanosecond pulse of hard X-rays (of ~100-keV photon energy) almost 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 fullscale 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<sup>11</sup> neutrons of 14-MeV energy per a single shot), are such as:

- <u>Fast Neutron Scattering Analysis (FNSA)</u> as in the case of FNSA with Van de Graaff accelerator (in fact it is a complex of methods including elastic and inelastic scattering)

- Pulsed *n-gamma* method based on registration of gamma-photons irradiated 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); in our case these ns gamma-ray pulses will be detected by *an array* of PM and may give information on localization of suspicious objects by time delay of the pulses - Neutron Activation Analysis (NAA) based on detection of hidden materials by a reaction *n*, 2*n* with a registration of 2 gamma-photons of 0.511-MeV energy (positron annihilation)









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In our present *initial* tests we used mainly the above-mentioned *small* DPF chamber, charging voltage not higher than 16 kV, *deuterium* as a working gas, a glass bottle with methanol ( $\approx 1$ 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 Ll = 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 is not an artefact



#### Layout chart of equipment during the NINIS tests

#### **NINIS tests with ethanol**



1 m





18.5 m

Traces here are taken for almost the same conditions of the DPF operation (shot No. 164, 15 kV, 4.48 Torr) as the previous one (taken for the shot No. 153 - 14 kV, 4 Torr of deuterium pressure - with removed the shadow shielding (SS) and without a sample) but in this very case with the sample installed in a close vicinity (approximately 30 cm) to the chamber (SP1) at a certain angle to the directions NBD1 and NBD2

One may see a *clear additional peak* at the trace of S+PM-2

This peak *delays* to the main neutron pulse by <u>415 ns</u> whereas the main (direct) pulse of neutrons arrives to the S+PM-2 with the *same delay as without* the sample of course

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 because of strong *overlapping* of both direct and scattered pulses

We have checked this supposition by *changing* (*decreasing*) *the distance* from the source to the S+PM2 by *two times* (*L*2=9.25 m) preserving the geometry (angles) the same as in the previous case and changing the distance from the bottle to the S+PM2 by about *five times* (*increasing it* to approximately 1.5 m) Time delay for the *direct* neutron beam became shorter by two times as it was expected whereas the *second peak* of scattered from the bottle neutrons demonstrated features of elastic scattering – lower energy neutrons *came later* 

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 a *small angle* to the NBD2 (thus organizing a low-angle scattering geometry) and install the screen SS We saw a *multi-peak structure* in the scattered neutron pulse For one example of the results of the experiments we made *correlative calculations* of neutron energies corresponding to each peak of the trace



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	

In these computations we supposed the *mean neutron energy to be 2.5 MeV* (previously checked) and at the same time we took into consideration HXRP TOF (our shield 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

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

# We have made also several shots with our large chamber:



#### Main results look as follows:

- Total neutron yield with operation of the chamber with pure deuterium appeared to be on the level of 10<sup>9</sup> neutrons/pulse, what means that with DT mixture (14-MeV neutrons) it will be on the order of 10<sup>11</sup> n/p
- Jitter between the fronts of the X-Rays and neutron pulses is again within the limits of 4%
- Changing initial pressure we can change resulting neutron spectra making it extremely narrow for the lower pressure values



## 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 on the ways of *apparatus improvements* and *NINIS technique calibration* 

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