DENSE PLASMA FOCUS BASED NEUTRON SOURCE FOR DETECTION OF ILLICIT MATERIALS AND EXPLOSIVES BY A SINGLE-SHOT NANOSECOND NEUTRON PULSE TECHNIQUE

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INTRODUCTION

The **terrorists’ attacks** on civil objects throughout the world are well known. **Mining** of buildings, roads, trains, railway stations, airplanes and public places in various cities is a permanent danger of present days in Russia. Thus mining in the ground and water, **illegal traffic** of explosives in vehicles by sea, water and air inside the country, as well as to and from abroad is of a great concern. All of these facts demand elaboration of **fast** and **efficient** methods of screening of suspicious objects.
Between promising approaches to the problem methods of the use of penetrating radiation mainly *neutrons* are of a permanent interest at present time. They use *low-power sources* of penetrating radiations like isotopes, classical neutron generators (direct-type accelerators - \(~10^8\) n/pulse of 10-µs pulse’s duration or \(~10^3\) n/pulse during a 2-ns flash) and X-Ray tubes. These methods may give the necessary solution for interrogation of all the above-mentioned materials by non-intrusive inspection technique; yet the task meets some important problems. Between them the most important one is rather *low* *signal-to-noise ratio* at the detection part of a system.
The problem results in a necessity to produce many shots with the above neutron sources (for generators – $\gg 10^6$ pulses) or in a long operation time (for isotope sources – $>\frac{1}{2}$ an hour) and consequently in high doses and in a long period of an interrogation.

*Dense Plasma Foci devices of small sizes* might occupy a niche within the contemporary neutron-based methods of the interrogation of hidden objects; they can produce very short ($\sim 10$ ns) and bright flashes of neutrons (up to $10^{20}$ n/s·steradian) and X-Rays (a few J)

It would be interesting to verify whether with these pulses they may be used in an express check of any objects (including those of a large size) for a possible presence of illicit materials inside them?
Dense Plasma Focus (DPF) device is a type of plasma accelerator that produces:

- **directed** powerful hot \((T \sim 1 \text{ keV})\) fast \((v > 10^7 \text{ cm/s})\) dense \((n_{pl} \approx 10^{16} \ldots 10^{19} \text{ cm}^{-3})\) plasma streams,

- high energy ion \((E_i \approx 0.01 \ldots 100 \text{ MeV})\) and

- electron \((E_e \approx 0.01 \ldots 1.0 \text{ MeV})\) beams

- **soft** \((E_{hv} \sim 0.1 \ldots 10 \text{ keV})\) and

- **hard** \((E_{hv} \sim 10 \ldots 1000 \text{ keV})\) **X-Rays** and

- **fusion neutrons** \((E_n \sim 2.45, 14, 2 - 11.4 \text{ MeV})\)

due to a number of collective effects taking place inside the plasma because of its turbulence
Compared with classical accelerators, fission reactors and isotopes DPF is an ecologically more friendly radiation-producing device because:

- it uses low charging voltage (~10 kV), which can exploit usual mains (230 V, 6 A) for charging its capacitor bank

- it becomes a radiation source just for a few nanoseconds and only on demands (a push-button source)

- it is a radiation-safe device, i.e. it has no fission materials and doesn’t need any special containers for its preservation
We intend to take advantage of the unique features of Dense Plasma Focus device, namely, *nanosecond* time duration of neutron and hard X-ray radiation pulses and their *very high brightness*, to test and develop different detection methods based on Pulsed Fast Neutron Analysis (PFNA) concept where *elastically and inelastically scattered pulses of neutrons* are used simultaneously with *X-Ray transmission inspection technique*

The ultimate aim is the elaboration of a *single-shot Nanosecond Impulse Neutron Inspection System (NINIS)*
We believe that this method will ensure a decrease of signal/noise ratio and a minimization of the irradiation dose together with the interrogation time by 1-2 orders of magnitude compared with existing techniques.

It will result also in a lower activation of items under inspection and in a decrease of a false alarm rate.

Besides we intend to test NINIS for disclosure of hidden fission materials by means of measurements of an increase of the number of neutrons scattered by an object and by the characteristic change of spectrum in these scattered neutron pulses for our cases of practically monochromatic fusion neutrons.
Transportable device PF-10: 5 кДж, 350 кА, $3 \times 10^8 D_2$ n/pulse, weight - 150 кг (ITEP + MPS)
Transportable device PF-6: 7 кДж, 750 кА, $10^9$
$D_2$ n/pulse, weight - 400 кг (IPPLM + MPS)
Neutron-producing camera at its operation with circa 1 cps
Transportable device at ICTP: 5 кДж, assembling stages
Portable device ING-102: 100 Дж, 150 кА, $10^8 D-T$

n/pulse, weight - 15 кг (MPS + ITEP + VNIIA, RF)
DPF chambers of transportable devices
(VNIIA + MPS, IPPLM, ICDMP, ICTP)
Being invented in the 50’s DPF is one of the most well-diagnosed plasma devices at present time exploiting methods with a very good temporal, spatial, spectral and angular resolution of the device’s radiations.

E.g. to have data on parameters of the hard X-Ray radiation and neutrons (spectrum, angular distribution, absolute yields, fluence, power flux density, etc.) we use a number of diagnostics, having about 1-ns temporal, few micrometers spatial, high spectral and angular resolution.
Between them:
- Multi-frame X-Ray pin-hole cameras (1-ns resolution time) for investigation of X-Ray dynamics and parameters
- Spectroscopy, calorimetry, dosimetry and metrology, temporal and spatial monitoring of X-Ray radiation in a broad wavelength range: hard and soft X-Ray
- Activation counters, bubble detectors, multi-channel PMT-based spectrometer for neutron emission parameters measurements, etc.
A side-view of the PMT+S detector having 3-ns resolution time (ITEP)
Oscilloscope trace, which demonstrate pulses of hard X-Rays and neutrons taken at a close vicinity to the DPF chamber (PF-10)
Parameters of radiations

DPF usually operates with deuterium/deuterium-tritium mixture as working media in its chamber; it is possible also to use a pure tritium filling.

Measurements have shown that in any well-working DPF we have about the same parameters for all radiation types except of their pulse duration and volume, occupied by sources of them. These two latter parameters are increased with the energy stored in the capacitor bank.

Thus we may have in a DPF the parameters of the penetrating radiations with their upper limits for the transportable-size devices as follows:
- hard X-rays (0.02...1.0 MeV): $P = 10^{10} \text{ W/m}^2$

$\tau = 10 \text{ ns}$

spectrum – 10 keV...1 MeV (with a maximum at about 100 keV)

-neutrons (2.5 MeV – D-D, 14.0 MeV D-T fusion reactions respectively, in $4\pi$): $10^{10}, 10^{12} \text{ n/pulse}$

$\tau = 10-30 \text{ ns}$

spectrum: $\Delta E/E$ about 0.02-0.03

-neutrons (T-T reaction, 11.4-peak MeV, in $4\pi$): $10^{10} \text{ neutrons/pulse}$

$\tau = 10-30 \text{ ns};$ spectrum 2...11.4 MeV
New experiments on the Nanosecond Impulse Neutron Investigation System (NINIS)

In the trials currently presented we have experienced an opportunity to use much lower bank energy (~2-3 kJ instead of previous 7 kJ), smaller DPF chamber, decreased neutron yield (1-3⋅10^8 n/shot versus 10^9), and TOF base as well (2.2 and 7 meters instead of 18.5 m).

Such a facility (a modification of the PF-6 device in this case) would be more convenient, energy-saving and ecologically friendly compared with the previous one.

We use also much lower voltage at PMT (1.1 kV as a replacement for the previous 2.4 kV).
Target – a 1-litre bottle with $\text{H}_3\text{PO}_4$

$\beta' \approx 35^\circ$, $\beta'' \approx \beta''' \approx 27^\circ$, $L' = 2.2 \text{ m}$, $L'' = 8 \text{ cm}$, $\theta \approx 10^\circ$, $L''' = 7 \text{ m}$
NINIS tests with phosphoric acid

Neutrons with a screen (a) and without it (b)
TOF of X-Ray and neutron pulses at 2.2 and 7 meters giving a possibility to calculate a time-delay between the X-Ray front and neutron pulse maximum given for the above two experiments.
DISCUSSION

For calculations of the expected points on the oscilloscope traces where we have to find peaks of direct neutrons as well as neutrons scattered by our target (peaks 1, 2 and 3) we used the procedure described previously.

We took into consideration average energy of neutrons $E_0'$ irradiating the target (2.55 MeV), energy of neutrons directly arrived to the scintillator from the DPF chamber $E_0''$ (2.70 MeV), angles of irradiation of the target ($\beta'$), of direct beams propagation to the S+PMT ($\beta''$ and $\beta'''$) and of scattering beams ($\alpha$), distances from the source to the axis of the bottle (target) (0.08 m) and from the target centre to the scintillator of PMT (2.2 m), effective irradiation angle of the target for our geometry ($\theta$), and time delay of neutron maximum in relation to the front of hard X-Rays inside the DPF chamber (6 and 13.5 ns respectively for both shots).
The neutron detector signals contain in this our case of low dose of neutrons an essential noise component.

Fragment of the oscilloscope trace of the above figure with signals under discussion.
Trying to de-noise this signal, we used wavelet method suggested by MATLAB Wavelet Toolbox.

We used De-noising 1-D; we considered the noise to be un-scaled white.

The signal was presented by 2048 numerical points.

We used soft fixed form of the threshold method.

After a number of calculations in de-noising we prefer level 2, because the peaks 1 through 3 are well seen here with their amplitudes close to those at the initial oscilloscope trace.
De-noising of the above oscilloscope traces obtained with different wavelet types, level 2 (a) and two variants of de-noising where the “dmey” wavelet was used (b)
The same good de-noising result we have received for the case when we haven’t use a screen for direct neutron beam:

We compared also *amplitudes* of the two peaks at these oscilloscope traces taking into consideration *kinematics* of the reaction, *chemical composition* of the two nuclei within the phosphoric acid molecule and *cross-sections* of elastic neutron scattering on these nuclei.
Cross-section of elastic neutron scattering by $O^{16}$ nuclei in the range 2.45-2.70 MeV (a) and by the $P^{31}$ nuclei (b).

Respective calculations demonstrated a very good agreement with experimental measurements.

In this geometry we received for the number of neutrons forming all our pulses the figure circa $10^5$ neutrons; this is a reasonable body for several pulses of acceptable quality.
Another issue of the NINIS technology is whether it is possible to use this method for interrogation of lengthy objects (e.g. sea containers).

In this case the most remote point to be irradiated could be at a distance of about 10 meters apart from the DPF chamber.

To have good statistics in this geometry we must increase neutron yield of the DPF device by 3 orders of magnitude ($\sim 1-3 \times 10^{11} \text{ n/shot}$).

It can be done either by an increase of the energy of the DPF battery by $(10^3)^{1/2}$ times for deuterium as a working gas (2.5-MeV neutrons), i.e. up to the energy of approximately 100 kJ, or by use lower energy ($\sim 7-10$ kJ) of the bank but with DPF chamber operating with \textbf{D-T mixture as a working gas}.
The simplest way to fulfill the task is to use one DPF and a number of PMTs with collimators; PMTs will be placed along the object as it is shown at the right-hand side (we can use two sets of collimated PMTs in two perpendicular directions). Distances between these PMTs have to be about the space occupied by the neutron pulse (20-30 cm in the case of 2.5-MeV neutrons and 50 cm for 14-MeV neutrons).
However side by side with the above-mentioned configuration of the interrogation procedure there are two another opportunities.

First is rather trivial – use of two DPF chambers with collimation of neutron beams from them and movement of these chambers in two mutually perpendicular directions; the procedure here will be the same as above.

Another opportunity will exploit also two DPF irradiating the object from two orthogonal directions but without collimation and movement.

In both these options two sets of PMTs without collimators may be used.
CONCLUSION

Our present experiments has shown that DPF can be used in simple cases of relatively small objects for chemical characterization of an object and consequently for detection of illicit materials just in a single ns shot of the device.

This technique that shorten the whole procedure, in particular in a case of hidden fission materials, may occupy a specific niche in the interrogation procedure: namely it can be used for a preliminary express check of illicit materials inside any object for a possible presence of illicit materials, especially when it will be used together with X-Rays.

More experiments should be done to verify this method for items of a complicated staff having an intricate chemical composition but in particular for lengthy objects.
Thank you!