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APPLICATION OF THE ION BEAM EMITTED FROM PLASMA FOCUS DEVICE FOR TARGET ACTIVATION

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The paper reports on experimental results and numerical studies of a possibility of the application of ion beams emitted from plasma focus discharges for target activation. The complete data obtained from the activation of a carbon target and also numerical prognoses for the ^{13}N isotope production are presented. Deuterons emitted from a plasma focus facility bombarded a carbon target and they produced positron-emitting isotopes. Gamma quanta with energy 511 keV were obtained from annihilation of positron-electron pairs. Gamma spectrometry has been used to measure the induced activity. The activity of isotopes was determined using a multichannel analyzer and a high purity germanium detector. The activity of the ^{13}N isotope was of the order of tens of thousands Bq and was compared with that obtained by numerical estimation.

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1 Introduction

The Dense Plasma Focus (DPF) facility belongs to a class of pinch formation discharges [1] (Fig. 1). An intense electric current ($0.1 \div 4$ MA) produces plasma inside a metallic chamber (between the anode and the cathode) filled with a gas (usually hydrogen or deuterium) under initial pressure of hundreds Pa during a fast electrical discharge of a capacitor battery. The magnetic field generated by the high intensity current compresses the plasma towards the electrode axis. At this moment, the energy released from the bank is converted to the magnetic field energy and is concentrated mainly near the compressed plasma column (so-called "pinch"). After that, due to plasma instabilities the pinch current is broken and the high voltage (about few hundreds kV) is induced. The voltage is much higher than the initial bank charging voltage ($\sim 20 \div 40$ kV). This field accelerates electrons to the anode side, whereas ions are accelerated in the opposite direction (Fig. 1).

The Dense Plasma Focus (DPF) generates not only fast electrons and ions, but also soft and hard X-rays, which result from high temperature plasma formation and the interaction of fast

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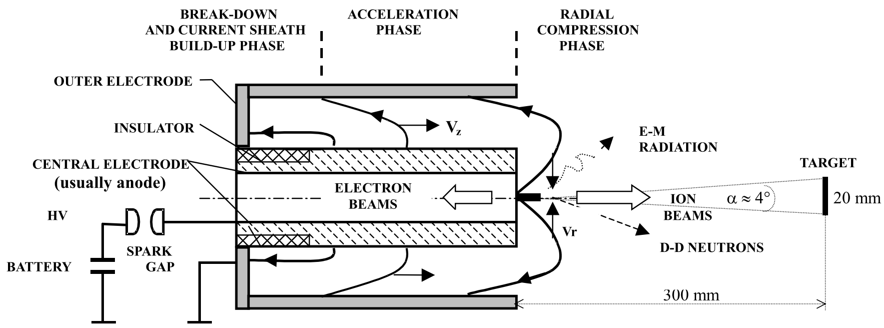

Fig. 1. Scheme of dense plasma-focus processes and target location

electrons with the anode surface respectively. The neutron emission is considered to be the effect of the interaction of medium energy ions with the pinch plasma.

In view of these facts it is of interest to examine whether ion beams ejected from a DPF facility with certain energy spectral distribution are good enough to produce positron emitting isotopes in solid targets. The main objective of this work is to show the possibility of solid target activation by deuteron beams ejected from the DPF pinch.

2 Activation method

Time-averaged energy spectral distribution of ions emitted from the DPF can be evaluated as [2]

$$f(E) = CE^{-m}, \tag{1}$$

where $2 < m < 3.5$ fits the experimental D^+ spectral amplitude and C is connected to the total number of deuterons N_{od} emitted from the DPF,

$$C = N_{od}\frac{1-m}{E_{\max}^{1-m} - E_{\min}^{1-m}}, \tag{2}$$

$E_{\min}$, $E_{\max}$ are the minimum and the maximum energy of ions registered in the experiment. Therefore, the energy spectral distribution of ions is

$$f(E) = N_{od}\frac{1-m}{E_{\max}^{1-m} - E_{\min}^{1-m}}E^{-m}. \tag{3}$$

So far, the yield from an external solid target can be written as

$$N_a = N_{od}\frac{\alpha}{\Omega}\frac{1-m}{E_{\max}^{1-m} - E_{\min}^{1-m}}\int_{E_{\min}}^{E_{\max}} E^{-m}Y(E)dE, \tag{4}$$

where N_{od} is the number of deuterons ejected from the pinch into solid angle Ω, α is the solid angle subtended by the target (α is defined in Fig. 1), $N_{od}(\alpha/\Omega)$ the part of the number of deuterons impinging on the external solid target, and $Y(E)$ the yield from the nuclear reaction of one deuteron in the solid target. Further, $E_{\max}$ is the energy limit of ions, above which the ion spectral amplitude and corresponding integral contribution are negligible, and $E_{\min}$ is the lower limit of the energy of ions; deuterons of the energy less than $E_{\min}$ do not contribute essentially to the reaction yield.

The radioactivity induced by fast ions in the external solid target is

$$A = N_a \frac{\ln 2}{T_{1/2}}, \tag{5}$$

where $T_{1/2}$ is the halftime of the decay of particular radionuclide. Substituting N_a from (4) to (5), we determine the relation between the radioactivity and the number of deuterons ejected from the DPF pinch. It holds that

$$A = N_{od} \langle Y \rangle \frac{\ln 2}{T_{1/2}}, \tag{6}$$

where

$$\langle Y \rangle = \frac{\alpha}{\Omega} \frac{1-m}{E_{\max}^{1-m} - E_{\min}^{1-m}} \int_{E_{\min}}^{E_{\max}} E^{-m} Y(E) dE. \tag{7}$$

Here, the angular distribution of the fast primary deuterons is the one which was obtained from a series of ten successive discharges performed with the D_2 filling [3]. This angular distribution has shown that almost all ions were emitted within a cone of an apex angle $\sim 40^{\circ}$.

3 Solid targets for activation method

In order to prove that fast ions emitted from PF discharges can induce radioactivity in a target we have selected a suitable nuclear reaction and thereby the target material. Some reactions useful for deuteron beam diagnostic as well as for nuclear medicine which are good candidates for target activation purposes are listed in Table 1.

Only a few of the listed reactions could be used for the production of the positron emitters in respect of the DPF ability. Some of the reactions are marked with the superscripts 1 and 2 — the usefulness of a particular reaction has been already checked [4] in these cases.

The nuclear reaction ^{12}C(d,n)^{13}N seems to be very attractive for the target activation. The target is manufactured from soot melted in polyurethane. Such material is flexible and durable enough as well as it withstands the shock wave, which proceeds from the plasma focus and plasma streams generated simultaneously.

The yield from the nuclear reaction ^{12}C(d,n)^{13}N is shown in Fig. 2 and it is fitted by:

$$Y(E) = a + b_1 E + b_2 E^2 + b_3 E^3 + b_4 E^4, \tag{8}$$

where the coefficients a and b's are: $a = 2.46 \times 10^{-6}$, $b_1 = -7.97 \times 10^{-6}$ MeV^{-1}, $b_2 = 4.13 \times 10^{-6}$ MeV^{-2}, $b_3 = 4.51 \times 10^{-6}$ MeV^{-3} and $b_4 = -9.20 \times 10^{-7}$ MeV^{-4}. The integral

Tab. 1. Table 1. Nuclear reactions useful for deuteron beams diagnostic and PET radiotracer production.

	Product	Nuclear reaction	Remarks
1.	^{18}F	^{18}O(p,n)^{18}F	1)
2.		^{16}O(^{3}He,n)^{18}F	
3.		^{16}O(^{4}He,2n)^{18}Ne $\rightarrow$ ^{18}F	
4.		^{20}Ne(d,α)^{18}F	
5.	^{11}C	^{14}N(p,α)^{11}C	1)
6.		^{11}B(p,n)^{11}C	1),2)
7.		^{10}B(d,n)^{11}C	2)
8.		^{14}N(d,n)^{15}O	1)
9.	^{15}O	^{14}N(d,n)^{15}O	1)
10.		^{15}N(p,n)^{15}O	1)
11.		^{16}O(^{3}He,α)^{15}O	
12.	^{13}N	^{12}C(d,n)^{13}N	1),2)
13.		^{13}C(p,n)^{13}N	1)
14.		^{16}O(p,α)^{13}N	1)

1) useful for DPF diagnostic methods
2) already used with the DPF method

(7) is calculated for the energy region from $E_{\min} = 0.5$ MeV to $E_{\max} = 4$ MeV. The yield (8) becomes

$$\langle Y \rangle = 1.2 \cdot 10^{-5} \frac{\alpha}{\Omega}. \tag{9}$$

The angle α is about 4° for the carbon target of the radius 10 mm, placed 300 mm from the DPF pinch. The activity of the nuclide ^{13}N ($T_{1/2} = 600$ s) can be transcribed from (6) as

$$A = 1.39 \cdot 10^{-9} N_{od} \;\; [\mathrm{Bq}]. \tag{10}$$

The number of ions ejected from the DPF is evaluated as

$$N_{od} = \frac{\tau_p}{e} I_i, \tag{11}$$

where τ_p is the time of the ion emission from the pinch and I_i is the ion current.

It was shown [5] that in a certain moment a plasma diode is formed within the plasma column of the DPF. It consists of a high-conductivity plasma, a low-conductivity layer (an acceleration gap) and again plasma with a high conductivity. An ion current is ruled by a space charge and the density of the ion current and it is given by

$$j_i = 1.86 \left(\frac{m_e}{m_i} \right)^{1/2} j_0, \tag{12}$$

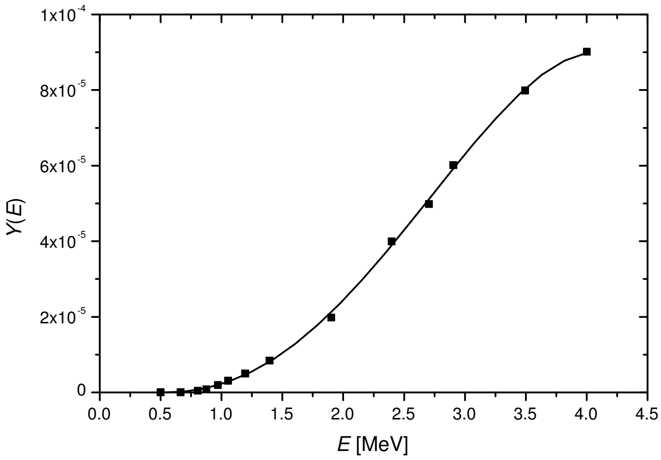

Fig. 2. Nuclear reaction yield for the ^{12}C(d,n)^{13}N reaction [2].

where m_e and m_i are the electron and the ion masses, respectively. The current density j_0 can be expressed from the Langmuir-Child formula as

$$j_0 = \frac{\sqrt{2}}{9\pi}\left(\frac{e}{m_e}\right)^{1/2}\frac{\Phi^{3/2}}{d^2}, \tag{13}$$

where e is the elementary charge, d the width of the low conductivity layer and Φ the potential between the plasma anode and cathode. The ion beam current emitted from the pinch plasma is calculated from (12) and (13)

$$I_i = j_i \pi r_p^2 = 1.86\frac{\sqrt{2}}{9}\left(\frac{e}{m_i}\right)^{1/2}\Phi^{3/2}\left(\frac{r_p}{d}\right)^2, \tag{14}$$

where r_p is the pinch radius. The number of ions ejected from the DPF pinch can be estimated from (11) and (14) as

$$N_{od} = 1.4 \cdot 10^{12}\Phi^{3/2}\left(\frac{r_p}{d}\right)\tau_p, \tag{15}$$

where are Φ [V], r_p [cm] and d [cm]. For Φ about 150 kV, $(r_p/d) = 1$ and $\tau_p = 100$ ns for used PF device, we get $N_{od} = 8.13 \times 10^{12}$ and $A = 1.13 \times 10^4$ Bq.

4 Results

The target was activated by the ion beams emitted from PF-150 plasma-focus facility operated at energy level of 20 kJ. The discharge chamber was usually filled with deuterium gas under the initial pressure of 0.665 kPa. The initial charging voltage was 28 kV.

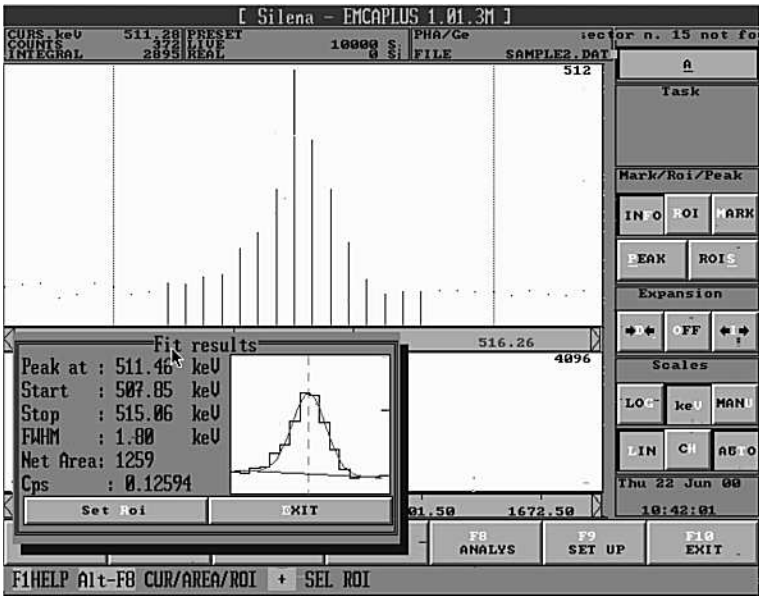

Fig. 3. The spectrum of gamma quanta emitted from activated carbon target. Photo peak with energy 511 keV has been expanded and analyzed in the left down corner.

The carbon targets were placed 300 mm from the face of the inner electrode. The activation of the targets was measured with a high purity germanium detector with the detection efficiency 18%. The quantitative and qualitative analyses of the induced radiation were done using the 16 k multichannel analyzer (MCA) with 2.04 keV resolution measured at 1332 keV. The calibrations of the energy and of the efficiency of the detection of the gamma rays were done. They were based on the calibration source containing 12 energetic lines with the different efficiencies. The source was obtained from the Amersham standard solution QCY-48 and then attested in ORIPI-Świerk. The natural radiation background has been subtracted from each spectrum after its collection.

The evaluation of the target radioactivity was based on the spectrum analysis using the criteria of the peak area. Fig. 3 shows a typical spectrum obtained from the MCA. The peak with the energy 511 keV is exposed for better expression of the mentioned phenomenon. The following equation was used for the radioactivity evaluation:

$$A = \frac{N}{t \cdot \epsilon \cdot \gamma \cdot f \cdot f'} \pm \frac{\sigma}{t \cdot \epsilon \cdot \gamma \cdot f \cdot f'}, \tag{16}$$

where A is the radioactivity, N the number of registration under the peak, t the measurement time, ϵ the efficiency of the registration, γ the effect of the delay, f the correction factor representing difference between the sample activation and its measurement, f' the correction factors representing disintegration of the sample during measurement and σ the counting error.

The case results of the measurements were obtained for the nuclear reaction ^{12}C(d,n)^{13}N, for shots with high neutron yield. The radioactivity induced in the carbon target by ion beams obtained from the plasma focus PF-150 was $A = 2.8 \times 10^4$ Bq $\pm 3\%$.

5 Conclusions

The results of our measurements can be summarized as follows:

- The carbon target installed at the distance of 300 mm from the end of the electrode was activated by deuterons emitted from pinch plasma.
- The measured radioactivity has been compared with the calculated radioactivity; their values are comparable: $A_{\mathrm{cal}} = 1.13 \times 10^4$ Bq, $A_{\mathrm{exp}} = 2.8 \times 10^4$ Bq.
- This activation method seems to be attractive for the production of the short-lived isotopes.

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