إمكانية استخدام أجهزة البلازما المحرقية الكثيفة لإنتاج نظائر مشعة قصيرة العمر المستخدمة في PET – دراسة عددية

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الملخص:

تم في هذا البحث إجراء دراسة عددية لإمكانية استخدام أجهزة البلازما المحرقية الكثيفة في إنتاج النظائر المشعة قصيرة العمر (SLRs) من خلال الاستفادة من حزم أيونات الديوتيريوم الناتجة عن انهيار قبضة البلازما. أجريت الدراسة على النظيرين C^11 وO^15، حيث تم إيجاد عدد الأيونات المتفاعلة مع الهدف ومن ثم حساب النشاط الإشعاعي، ومن خلال مقارنة القيم الناتجة مع قيم النشاط الإشعاعي التي ينتجها السيكلوترون، كانت القيم منخفضة جداً، تم الاستفادة من إمكانية تغيير ضغط غاز الديوتيريوم وحساب النشاط الإشعاعي عند تغير الضغط حيث ارتفعت قيمة النشاط إلى 0.002 GBq للكربون و0.013 GBq للأكسجين مع زيادة الضغط ولكن لم نتمكن من الوصول إلى القيمة المطلوبة. تم حساب النشاط الإشعاعي عند ترددات وأوقات تشغيل مختلفة. حصلنا على القيمة المطلوبة للكربون عند 275 هرتز، 1000 ثانية، وللأكسجين عند 75 هرتز، 1000 ثانية.

الكلمات المفتاحية: البلازما المحرقية الكثيفة، قبضة البلازما، PET، النظائر المشعة قصيرة العمر، النشاط الإشعاعي.

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Possibility of Using Dense Plasma Focus Devices to Produce Short-Lived Radioisotopes Used in PET – Numerical Study

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ABSTRACT:

In this paper, a numerical study was conducted of the possibility of using dense plasma focus devices in the production of short-lived radioisotopes (SLRs) by taking advantage of the deuterium ion beams resulting from the collapse of the plasma pinch. The study was done on the two isotopes C^11 and O^15, where the number of ions interacting with the target was found and then the radioactivity was calculated. Comparing the resulting values with the values of the radioactivity when produced by the cyclotron, the values were very low, and by taking advantage of the possibility of changing the pressure of deuterium gas. The radioactivity was calculated when changing the pressure, as the activity value increased to 0.002 GBq for carbon and 0.013 GBq for oxygen with increasing pressure, but we could not reach the required value. The radioactivity was calculated at different frequencies and operating times. We obtained the required value for carbon at 275 Hz, 1000 s, and for oxygen at 75 Hz, 1000 s.

KEYWORDS: Dense Plasma Focus, Plasma Pinch, PET, short-lived radioisotopes, radioactivity.

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1. Introduction

Positron emission tomography (PET) is a functional molecular imaging technique using probes called radiotracers that consist of biologically active molecules (glucose or oxygen). Labeled with positron-emitting radioactive nuclei (eg carbon 11, nitrogen 13, oxygen 15, fluoride 18); Where the positron travels for a short distance in the tissues until it collides with an electron and produces a pair of gamma rays that emit in opposite directions with an energy of 511 KeV each. By directly measuring the radioactivity of the member to be studied at large angles and distances. This method of radiography is one of the fastest growing areas of radiology [1,2].

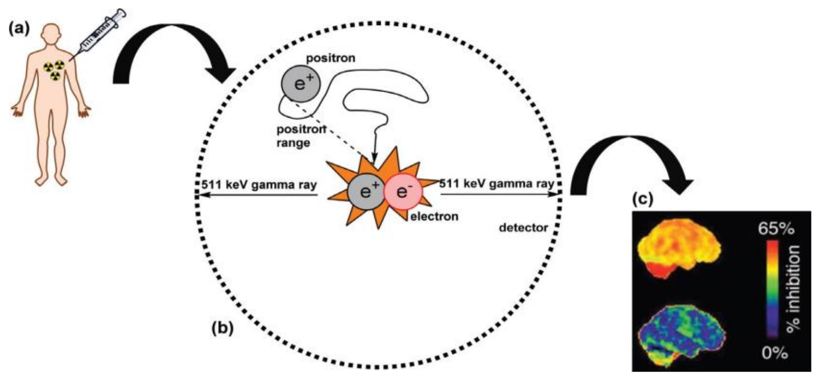

Figure (1): Principle of PET scan: (a) injection of the radioactive isotope, (b) the positron travels a short distance and hits the electron and then a pair of gamma rays with an energy of 511 KeV simultaneously at 180^0 each (c) Detecting gamma rays and converting them into three-dimensional images [1]

It's known that these radioactive isotopes are obtained by bombarding suitable targets with ion beams produced in accelerators. Table (1) shows a number of radioactive isotopes that are obtained through accelerators and the radioactivity of each of them [3]:

Table (1): Some of the isotopes that are produced by the cyclotron, nuclear reactions and radioactivity [3]

Medical Isotope	Life-time $T_{1/2}$	Use	Nuclear Reaction	Target Abun-dance (%)	Energy Range (MeV)	Production Yield (mCi @ sat)	Typical Dose (mCi)
^{11}C	20.4m	PET	^{11}B(p,n)	80.3	8 - 20	40/µA	
^{11}C	20.4m	PET	^{14}N(p,α)	99.6	12	100/µA	
^{11}C	20.4m	PET	^{10}B(d,n)	19.7	7	10/µA	
^{13}N	9.96m	PET	^{13}C(p,n)	1.1	5 - 10	115/µA	
^{13}N	9.96m	PET	^{12}C(d,n)	98.9	2 - 6	50/µA	
^{13}N	9.96m	PET	^{16}O(p,α)	99.8	8 - 18	65/µA	
^{15}O	2m	PET	^{15}N(p,n)	0.36	10 - 15	47/µA	
^{15}O	2m	PET	^{16}O(p,pn)	99.8	>26	25/µA	
^{15}O	2m	PET	^{14}N(d,n)	99.6	8 - 6	27/µA	
^{18}F	109.8m	PET	^{18}O(p,n)	0.20	8 - 17	180/µA	5 - 20
^{18}F	109.8m	PET	^{20}Ne(d,α)	90.5		82/µA	
^{64}Cu	12.7h	SPECT	^{64}Ni(p,n)	0.93	5 - 20	5/µA	
^{67}Cu	61.9h	SPECT	^{68}Zn(p,2p)	19.0	>40	0.02/µA	
^{67}Ga	78.3h	SPECT	^{68}Zn(p,2n)	19.0	20 – 40	4.5/µA	10
^{82}Sr/^{82m}Rb	25d/5m	PET	^{85}Rb(p,4n)^{82}Sr Produces Rb	72.2	50 -70	0.18 /µAh	
^{99m}Tc	6h	SPECT	^{100}Mo(p,2n)	9.7	19	14/µAh	20
^{103}Pd	17.5d	Therapy	^{103}Rh(p,n)	100	10 -15	0.52/µAh	
^{111}In	67.2h	SPECT	^{112}Cd(p,2n)	24.1	18 - 30	6/µAh	3
^{123}I	13.2h	SPECT	^{124}Xe(p,2n)^{123}Cs $\rightarrow{}^{123}$Xe$\rightarrow{}^{123}$I	0.10	25 - 35	27/µAh	
^{123}I	13.2h	SPECT	^{123}Te(d,2n) ^{123}I	0.89	10 - 15	20/µAh	
^{124}I	4.1d	PET	^{124}Te(p,n)	4.7	10 - 18	0.1/µAh	
^{124}I	4.1d	PET	^{124}Te(d,2n)	4.7	>20	0.15/µAh	
^{186}Re	90.6h	Therapy /SPECT	^{186}W(p,n)	28.4	18		
^{201}Tl	73.5h	SPECT	^{203}Tl(p,3n)^{201}Pb $\rightarrow{}^{201}$Tl	29.5	27 - 35	0.7/µAh	4
^{211}At	7.2h	Therapy	^{209}Bi(α,n)	100	28	1/µAh	0.05-.01

Due to the short half–life of these radioisotopes, they must be produced where they are expected to be used, and therefore accelerators must be used in hospitals. But the production of PET radioisotopes via accelerators is an expensive method, so plasma focus devices are offered as an alternative in the production of short–lived radioisotopes because they are low–cost and easy to use and maintain [4].

Dense Plasma Focus Device:

The Dense Plasma Focus DPF device is a bidirectional ion accelerator. The device takes advantage of the Lorenz force $F=J\times B$, where J is the current density and B is the magnetic field to accelerate the gas molecules, which are axially swept by the plasma envelope at a high speed to a specific position (the end of the electrodes), the flow is then converted into a radial flow with a higher velocity and the formation of high-density filaments of plasma called the plasma focus [5]. The device is originally a coaxial accelerator [6] consisting of a chamber inside which a central electrode forms an anode surrounded by a group of electrodes that form a cathode isolated from each other by an insulator connected with a capacitor bank (The charge potential of a capacitor bank is several tens of kV), a chamber containing a gas or group of gases under a certain pressure. The principle of operation of the device is based on transferring the energy stored in the capacitor bank to the electrodes through a discharge current (up to several hundred kA in medium-power devices and up to MA in high-power devices) which generates a magnetic field. The induced magnetic field is stored behind an ionized layer of gas. A plasma sheath moving under the influence of a magnetic field is referred to as a magnetic piston [7]; this ionizing layer extends between the internal and external electrodes (the anode and the cathode) and is responsible for transmitting electric current between them. The ionized layer that carries the current is called the current sheet (Current Sheet CS). It represents the J component of the Lorenz force. The electric current passes through the cathode from its base to the position of the current sheet causing an angular magnetic field to be excited around the cathode in the angular direction (B_θ)as shown in Figure (2). The magnetic field is behind the current sheet, J_r and B_θ push the current sheet with a Lorenz force (F_z) to reach a high axial velocity of 10^7 cm/s which doubles in diagonal direction, and the density increases to reach $10^{19}/\mathrm{cm}^3$ to produce very plasma filaments with several energy. A small column of very hot and very dense plasma that collapses after a very short period (tens of ns) due to the instability of the plasma and the presence of a high voltage, which leads to the emission of beams of ions and electrons in opposite directions [5].

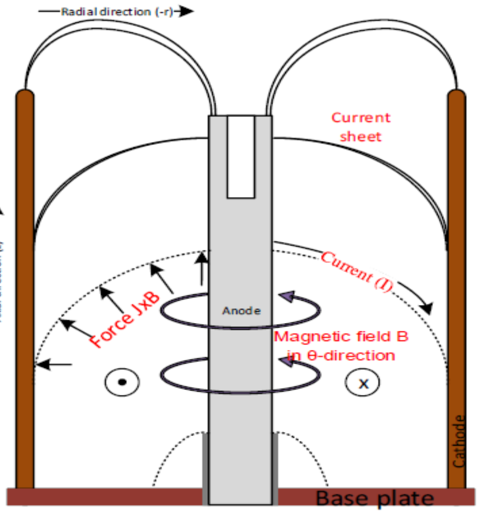

Figure (2): Axial and radial motion of the current sheet in a dense plasma focus [5]

In the case that deuterium gas is used in the dense plasma device, it is possible to take advantage of the energy ion beams produced after the collapse of the plasma pinch and its collision with a suitable target in order to cause the desired reaction. To this aim, many researche and experimental and numerical studies have been conducted to investigate the possibility of benefiting from the ion beams emitted by the collapse of a column of plasma formed in the dense plasma focus device, especially when using deuterium gas as a working gas in order to bring about the nuclear reaction required for the production of radioactive isotopes short-live. Sumini [8] designed a 150 kJ dense plasma focus device operating in a 1 Hz frequency mode to produce the 18F radioactive isotope 1 Curi in a time of 2 hours and put the engineering designs of the electrodes and the parameters of the electrical circuit, and 128 shots were carried out.

Shirani [9] also studied the possibility of obtaining the radioactive isotope 13N from a low-energy dense plasma focus device, and the value of the radioactivity was obtained 10 kBq for one shot, and the value of the radioactivity increased to several tens of MBq from an operating rate of f=1Hz for an operating time of 600s, while the medically required radioactivity is about 4 GBq, the idea of changing the design of the electrodes or the pressure of deuterium gas was proposed to increase The energy of the outgoing detrons spectrum .Akel [10] conducted numerical experiments using the Lee code to calculate the characteristics of the ion beams emitted by a number of dense plasma devices with different operating energies and to calculate the radioactivity of the 12C(d,n)13N reaction, and that they concluded the device must operate in a repetitive mode (f=25Hz repetition rate for a period of 600s of operation) to reach the value of the medically required radioactivity and that this possibility of operation is not available in the current devices in addition to the emergence of the problem of endurance of targets for thermal loads resulting. In 2019, Sadeghi and others [11] proposed the idea of adding magnetic lenses in order to focus and direct the outgoing ion beams and reduce the scattering ratio, Simulations were carried out on 16 different plasma incinerators with different energies 400 J to 500 kJ and a radioactivity value of 0.016−7.71 GBq was reached, and that 9 of the studied devices had the ability to reach the medically required value of the isotope 13N by using this technique.

2. Research Method

The most important factor in the production of short-lived radioisotopes using dense plasma focus devices is the number of deuterium ions from the pinch, which can be estimated by the potential generated in the pinch due to a sharp increase in plasma induction during the radial phase. The

Lee code was used to find the pinch parameters, and then the method followed by Razazi and Gharehbagh [12] was used to calculate the radioactivity as follows:

The number of deuterium ions resulting from the collapse of pinch is calculated using the relation:

$$N_{out} = \pi \frac{r_p^2}{e} J_i \tau_p \qquad (1)$$

where: τ_p duration of pinch stays above the top of the anode, r_p the pinch radius

J_i is the density of ions, which is calculated by:

$$J_i = \frac{\frac{4}{9}\varepsilon_0 \left(\frac{2e}{2m_e}\right)^{1/2} \left(\frac{\phi^2}{z_{max}^2}\right)}{1 + \left(\frac{m_i}{m_e}\right)^{1/2}} \qquad (2)$$

where: ε_0 the electrical permittivity, e the charge of the electronm_e the mass of the electron, m_i the mass of the deuterium ion, z_{max} the length pinch, ϕ the voltage generated within the pinch which is calculated by:

$$\phi = I_{max}\left(\frac{dL}{dt}\right) \qquad (3)$$

I_{max} is the current formed within the pinch, $\frac{dL}{dt}$ the induction within the pinch, and is calculated by:

$$\frac{dL}{dt} = \frac{\mu_0}{2\pi}\left[ln\left(\frac{b}{r_p}\right)V_a + \frac{z}{r_p}V_r\right] \qquad (4)$$

where: b is the radius of the cathode, V_a is the axial velocity of the plasma sheet, V_r is the radial velocity of the plasma sheet.

Calculate the number of radionuclides produced at each shot using the relation:

$$N_p = N_{out} n_t \tau_p \frac{1}{3.5-2}\sqrt{\frac{2}{M_d}\int_{m=2}^{m=3.5} \cdot \int_{E_{min}}^{E_{max}} \frac{1-m}{E_{max}^{1-m} - E_{min}^{1-m}} \sigma(E) E^{-m+1/2} dm dE} \qquad (5)$$

where: n_t the target density, M_d the mass of the deuterium ion, E_{min} and E_{max}, the minimum and maximum energy of the ions produced by the collapse of the deuterium plasma pinch, m is a constant having the value $2 < m < 3.5$, $\sigma(E)$ is the cross-section of the studied reaction.

The radiative yield of the reaction is calculated by:

$$A = N_p \frac{ln2}{T_{1/2}} \qquad (6)$$

The isotope C^{11} : This isotope is obtained by the reaction $B^{10}(d,n)C^{11}$ where this reaction has a cross section given by [12]:

$$\sigma_{10B(d,n)} = \frac{2.797}{E} \exp\left(\frac{-236}{\sqrt{E}}\right); 0 < E < 500 \text{ keV} \qquad (7)$$

3. Results and Discussion

The study was conducted on a number of dense plasma focus devices of different operating energy and geometric dimensions [13] as shown in the following table (2):

Table (2): Parameters of the studied plasma focus devices [13,14,15,16,17,18,19,7]

	FMPF3	PF400	PF12	INTI	BORA	PF6
E_0 (kJ)	0.2	0.4	2.6	3.4	3.5	6.2
C_0 (μF)	2.4	1	20	30	24.4	28
L_0 (nH)	34	40	80	110	54	21
r_0 (cm)	11	10	6.0	12	6	2.9
Cathode radius (cm)	1.5	1.6	2.7	3.2	2.5	5.1
Anode radius (cm)	0.6	0.6	0.9	1	1.5	3
z_0 (cm)	1.7	1.7	7.2	16	6	4
Voltage (kV)	6.6	28	16	15	17	21

A series of numerical experiments were carried out using Lee code [20] version (RADPFV5.15de.c1) in order to find the characteristics of the plasma pinch (ion source) at the pressure value of deuterium gas 1 Torr. These features include: pinch dimensions (length and radius), plasma sheet velocity (axial and radial), pinch duration time, pinch current, and induced voltage within the plasma pinch. We obtained the results shown in Table (3) as follows:

Table (3): Characteristics of the plasma pinch (ion source) at the pressure value of deuterium 1 Torr

	FMPF3	PF400	PF12	INTI	BORA	PF6
Pinch radius (cm)	0.09	0.08	0.12	0.14	0.3	0.51
Pinch Length (cm)	1	0.8	1.3	1.5	2.8	5.2
Axial velocity (cm/μs)	6.6	17	13.6	14.5	17.6	12.4
Radial velocity (cm/μs)	15.4	75.6	59.5	56.9	45.7	29.4
Pinch duration (ns)	11.8	2.3	4.4	5.1	13.5	34.8
Pinch current (kA)	32	72	102	109	154	268
Induced Voltage within the pinch (kV)	3	34	37	35	25	38

Then using relations (1), (5) and (6) and after making the required integrations, the number of ions emitted from the source, the number of ions interacting with the target, and the radioactivity of the radioactive isotope 11C of the studied devices were found as in Table (4):

Table (4): The number of ions released from the source, the number of ions interacting with the target, and the radioactivity of the radioactive isotope 11C

	FMPF3	PF400	PF12	INTI	BORA	PF6
number of ions emitted from the pinch N_{out} ($\sim\times10^7$ Ions)	9.2	66.5	148	177	640	1850
number of ions reacted with target N_p ($\sim\times10^7$ Ions)	0.2	0.26	1.1	1.5	15	109

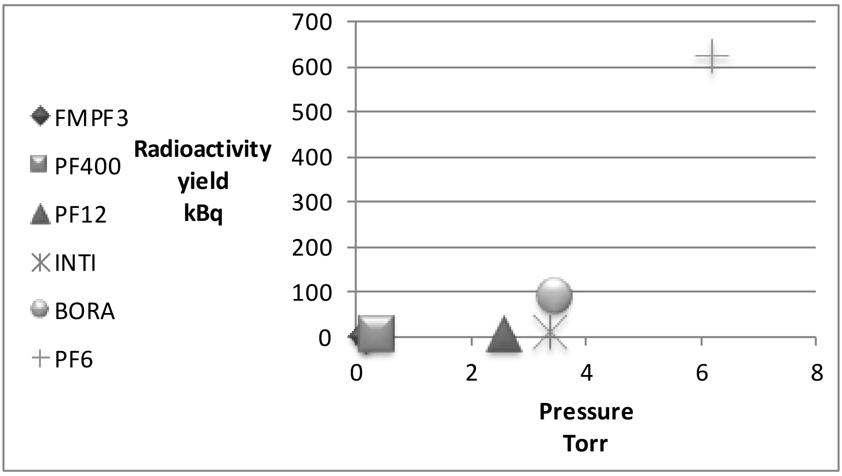

Figure (3): Radiative yield values according to the operating power of the studied devices at 1 Torr

We note from the previous results that the value of the radioactivity increased according to the increase in the operating energy of the device from 1.05 kBq in (FMPF3) to 621 kBq in (PF6) due to the increase in the volume of the pinch formed and thus the number of deuterium ions trapped within it, in addition to the value of the induced voltage in it, and thus the increase in the energy carried by the ions after the collapse of the pinch. The values of the radiation yield obtained for the studied devices were compared with the value of the radiation yield of the isotope 11C obtained when using the cyclotron (Table 1) (0.37 GBq). We note that all the studied plasma focus devices according to the basic parameters at a pressure 1 Torr deuterium gas cannot achieve the value of the radioactivity produced by the cyclotron.

In an attempt to increase the radioactivity of the isotope 11C, a series of numerical experiments were carried out when the pressure of deuterium gas changed from 1 Torr to the pressure value that does not occur focus after it according to the type of device studied and the radioactivity was calculated as shown in Table (5):

Table (5): The change in the radioactivity value of the radioactive isotope 11C when the pressure of deuterium gas changes

Pressure (Torr)	FMPF3	PF400	PF12	INTI	BORA	PF6
1	1.05	1.48	6.27	8.70	84	621
2	1.41	1.97	8.50	11.34	115	856
3		2.29	10.06	13.02	138	1023
4		2.54	11.28	14.19	157	1162
5		2.75	12.36	15.03	172	1287
6		2.93	13.28	15.64	186	1403
7		3.03	13.98	16.01	198	1513
8		3.15	14.69	16.26	210	1631
9		3.23	15.23	16.40	220	1739
10		3.33	15.76	16.47	228	1835
11		3.39	16.21	16.45	238	1952
12		3.45	16.64	16.35	247	2074
13		3.52	17.05	16.20	254	2226
14		3.56	17.37	16.08	262	2414
15		3.67	17.65	16.06	269	**2719**
16			17.98	15.93	275	
17			18.24		281	
18			18.42		287	
19			18.74		293	

We note that the value of the radioactivity increases with the increase in gas pressure, as shown in Figure (4). The highest value of radioactivity was 2719 kBq in (PF6), but the value is still very low than the value produced by the cyclotron.

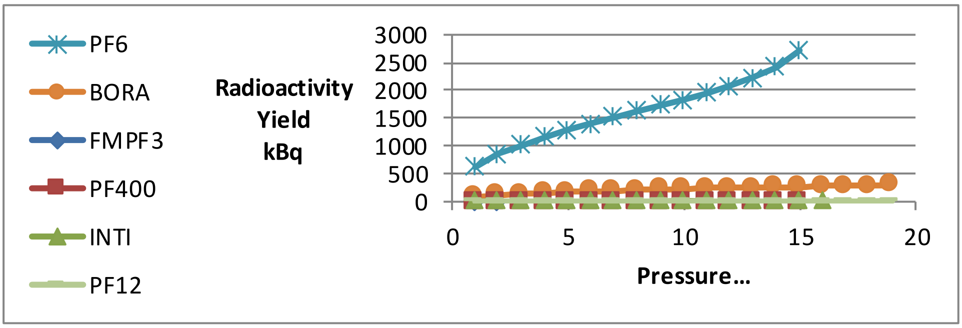

Figure (4): The values of the radiation yield of the studied devices at different values of deuterium gas pressure

We note from the results above that the value of the radioactivity obtained by the studied devices within the range $(1.4 \times 10^{-6} - 0.002\ GBq)$ and therefore we could not reach the value of the activity produced by the cyclotron at despite of increase in the number of ions interacting with the target. An attempt was made to increase the radioactivity by varying the time between shots and the number of shots based on the relation [21]:

$$A_\upsilon = A_0 . \upsilon . \left(1 - e^{-\lambda t}\right) \qquad (8)$$

where :$\lambda = \frac{ln2}{T_{1/2}}$: the radioisotope decay constant, υ : the operating frequency of the device and t : the time of the shots.

This relation was applied to the highest value of the radioactivity in the (PF6) device (PF6) 2719 kBq and the radioactivity was calculated at different frequencies and different shots times as shown in Figure (5):

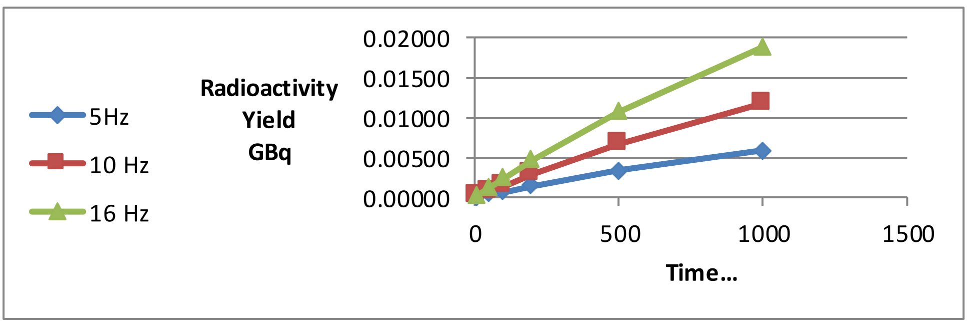

Figure (5): Radiative yield values at different frequencies and operating times

We note that the highest value of radioactivity obtained is 0.018 GBq at a frequency of 16 Hz and a shot time of 1000 s. We note that this value is about 3% of the value produced by the cyclotron.

The calculations were completed at higher repetition rates, as we reached the required value of radioactivity 0.3 GBq at a frequency of 275 Hz and a shot time of 1000 s. Of course, this value of operating frequency of the device is difficult to achieve in practice, so we must search in other methods such as increasing the operating energy of the dense plasma device focus or resorting to the geometrical change of the dimensions of the vacuum chamber.

Isotope O^{15} : This isotope is obtained through the reaction $N^{14}(d,n)O^{15}$ where this reaction has a cross section given by [12]:

$$\sigma_{14N\,(d,n)} = \frac{2.45}{E}\exp\left(\frac{-239.3}{\sqrt{E}}\right); 0 < E < 700\ keV \qquad (9)$$

The value of the radioactivity of the oxygen isotope O^15 produced by the cyclotron is (0.99 GBq) [3], a series of numerical experiments were carried out on the studied dense plasma focus devices in order to calculate the value of the radioactive yield when changing the pressure of a Deuterium and the results are as shown in Table (6):

Table (6): The change in the radioactivity value of the isotope O^{15} when the pressure of deuterium gas changes

	The radioactivity yield (kBq)					
Pressure (Torr)	**FMPF3**	**PF400**	**PF12**	**INTI**	**BORA**	**PF6**
1	5.15	7	31	43	219	3036
2	6.91	10	42	55	295	4189
3		11	49	64	352	5004
4		12	55	69	395	5685

5	13	60	74	431	6296
6	14	65	77	464	6862
7	15	68	78	492	7405
8	15	72	80	520	7978
9	16	75	80	542	8510
10	16	77	81	562	8976
11	17	79	80	584	9551
12	17	81	80	603	10148
13	17	83	79	626	10891
14	17	85	79	645	11812
15	18	86	79	660	**13301**
16		88	78	677	
17		89		691	
18		90		700	
19		92		710	

We note from the above results that the value of the radioactivity obtained by the studied devices within the range $(6.91\times10^{-6}-0.013$GBq) and therefore we could not reach the value produced by the cyclotron despite the increase in the number of ions interacting with target .

Using the relation (8) the value of the radioactivity value of the oxygen isotope O^{15} was calculated at different rates and operating times, we reached the required radioactivity value of 0.99 GBq at a frequency of 75 Hz and a launch time of 1000 s.

3. Conclusions

This study was conducted to show the possibility of using dense plasma focus devices with different operating energy and geometric dimensions to obtain the radioactive isotopes C^{11} and O^{15}. The results revealed that the highest value of radioactivity was obtained in a device (PF6) but a very low value even when the pressure of deuterium gas is increased. The results also showed that to obtain the two isotopes studied from the device (PF6), the rate and operating time of the device must be increased to be 275 Hz and operating time of 1000 s in the case of C^11 and 75 Hz and a operating time of 1000 s in the O^15 state.

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