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Potential medical applications of the plasma focus in the radioisotope production for PET imaging

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ABSTRACT

Devices other than the accelerators are desired to be investigated for generating high energy particles to induce nuclear reaction and positron emission tomography (PET) producing radioisotopes. The experimental data of plasma focus devices (PF) are studied and the activity scaling law for External Solid Target (EST) activation is established. Based on the scaling law and the techniques to enhance the radioisotopes production, the feasibility of generating the required activity for PET imaging is studied.

1. Introduction

Positron Emission Tomography (PET) has become a major diagnostic imaging modality used predominantly in determining the presence and severity of cancers, neurological conditions, and cardiovascular disease. A radiopharmaceutical (containing a radioactive nucleus such as ^{13}N) is injected into the patient and its emissions are measured by a PET scanner [1].

In PET facilities, the short-lived radioisotopes may be derived from suitable targets by bombarding the targets with high-energy particles; usually proton beams in current facilities obtained from a particle accelerator – in most cases a cyclotron. But the cyclotrons suitable for use in medical environment are large and expensive and require heavy shielding. A brief comparison between Siemens cyclotron and NX2 PF has been made in Table 1. Production of low quantities of Short-Lived Radioisotopes (SLR) has also been demonstrated using femto-second lasers, but such systems are still very expensive and the yield of isotopes is very low [2]. It is desirable to investigate other methods for generating high energy particles to induce nuclear reaction, and PET producing radioisotopes.

If expensive cyclotron isotope production facilities for PET can be replaced with simpler, cheaper and more easily maintainable repetitive plasma focus devices (PF), this would help to make PET an affordable procedure for many countries. Consequently, this would bring considerable benefits to the medical services in particular for the early diagnosis and treatment of cancer. Pulsed plasma systems, wherein self-generated $J \times B$ Lorentz forces act on ionized gas through the interaction of a large current discharge with the induced magnetic fields, have been extensively studied. Although several geometries have been employed, e.g. parallel plate and coaxial accelerators, inverse and linear pinches, and plasma focus, the sequence of electromagnetic interactions is much the same for each [3]. Namely, capacitively stored energy is abruptly switched across a pair of electrodes separated by ambient gas in the pressure range of 0.01–14 mbar [4,5]. The gas breaks down, the current rises rapidly in the circuit, and the discharge forms as a thin sheet of current which presents a minimum inductance configuration to the external circuit. The magnetic field enclosed by the circuit then interacts with the discharge current to accelerate the sheath through the ambient gas, ionizing it, and under proper circumstances, accelerating it to a high velocity.

Table 1
Comparison between cyclotron and PF.

Device	Cyclotron	NX2
Energy efficiency	~1%	~0.01%
Received dose through shielding	20 μSv h^{-1}	1.2 μSv shot^{-1}
Weight	50 ton (10 ton for device itself and 40 ton for shielding)	0.5 ton device lonely

The capacitor bank voltage for a plasma focus device is typically 10 to 30 kV. But, results from many experiments [6] have shown that deuteron beams emitted from the plasma pinch column have a wide range of energies: up to a few MeV. The acceleration of ions to such high energies (many times the charging voltage) is one of the most unexpected aspects of plasma focus devices. A number of models for the acceleration mechanism have been proposed [6].

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Table 2
SLR activity results of NX3.

Pressure (mbar)	Activity (kBq)
2	1.45 ± %0.2
3	23.26 ± %0.8
4	1.57 ± %0.2
5	1.07 ± %0.17

However the ion acceleration mechanism within the plasma focus pinch column is still far from being well understood. Many previous plasma focus experiments have concentrated on the characteristics of the neutron yield (e.g. emission time and anisotropy), but since the bulk of fusion neutrons are produced by relatively low energy deuterons (≤100 keV [7]), the neutron characteristics are not very informative with regard to the high energy tail of the deuteron spectrum.

Different aspects of producing short-lived radioisotopes (SLRs), with significant activity required for PET imaging, using pulsed plasma facilities are investigated in this work. The main approach is the foundation of experimental activity scaling law for ^{13}N from external solid targets. Comparison with neutron scaling law, reaction cross section, deuteron spectra, and repetition mode is made.

2. SLR production in NX3

The NX3 (20 kJ at 20 kV) plasma focus device is driven by eight 2.5 kJ (12.5 μF, 20 kV) low inductance (<40 nH) capacitors connected in parallel. Simultaneous discharge from eight modules, cumulatively delivers peak current in the range of 200 kA to 600 kA depending upon the charging voltage. The quarter time period of the discharge current is about 3 μs. For rapidly transferring the energy stored in capacitors to the PF load, a 150 kA/20 kV pseudospark switch has been installed on each of the eight capacitors. The specified inductance of each switch is less than 20 nH.

The bombardment of a graphite target by accelerated deuterons produces radioactive ^{13}N through the reaction ^{12}C(d,n)^{13}N. The threshold energy for the reaction is 328 keV [8]. The interaction of high energy deuterons with the graphite target results in the production of ^{13}N, which is a short-lived radioisotope, and decays with the half-life of 9.96 min, producing a positron. The positrons slow-down in the graphite and annihilate with electrons. Two oppositely directed 511 keV gamma-rays are produced by each positron annihilation event. BGO scintillation detector along with Multi-Channel Analyzer (MCA) system are used for gamma-ray measurements.

After each series of shots (30 shots at 0.5 Hz), the graphite target is removed from the chamber and placed in contact with BGO. The BGO crystal is 7.62 cm in diameter and 2.54 cm thick. The graphite target ($15 \times 15 \times 0.7$ cm^3) was placed normal to the deuteron beam with 0.5 sr solid angle covered by the target. Output pulses from the scintillation detector are measured by a Multi-Channel Analyzer (MCA) system. Following graphite target activation, gamma-ray energy spectra are collected over eight consecutive 10 minute intervals. The photo-peak of the spectrum represents 511 keV gamma-rays which undergo photoelectric absorption in the scintillator crystal. The detection efficiency for $\beta+$ decay was found to be 52%, for an energy window from 400 to 600 keV in the BGO spectrum. The procedure described in Ref. [8] was used to measure the activity induced in the NX3 at four different pressures.

As shown in Table 2, the maximum activity of 23 kBq is obtained at 3 mbar. The optimum pressure for neutrons produced in NX3, however, is about 6 mbar.

Table 3
SLR activity of some PF devices.

Type	PF/Year	SLR	PF energy (kJ)	Activity (kBq)
EST	NX2/2010 [8]	^{13}N	1.7	5.2
EST	SBU [private communication]	^{13}N	5	13
EST	2011 [15]	^{13}N	6.3	18.5
EST	NX3/2012 [current]	^{13}N	10	23
EST	1996 [9]	^{13}N	20	28
EST	1978 [7]	^{13}N	76	160
IGT	2001 [10]	^{18}F	7	5.5
IGT	2005 [11]	^{13}N, ^{15}O, ^{17}F	7	37

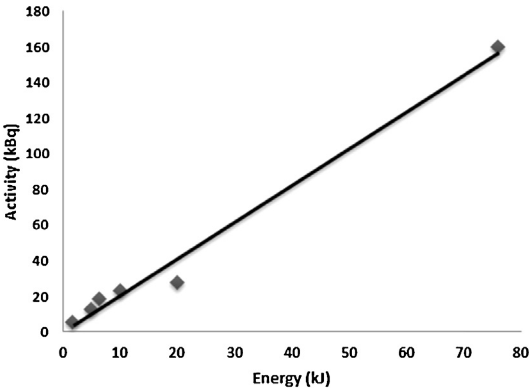

Fig. 1. Activity vs. PF capacitor bank energy.

3. SLR activity scaling law

Several attempts have been made to measure SLR activity at different PF capacitor bank energies. Table 3 shows the activities of some PF devices with two methods namely External Solid Target (EST) and Internal Gas Target (IGT).

Literature survey for IGT results, unlike EST, does not provide enough data for specific radioisotope to establish the scaling law. Therefore, the EST SLR production mechanism is addressed. However, in the EST mode, the activity results are all for a single radioisotope (^{13}N) and more importantly, the activity varies with PF bank energy. This enables foundation of the scaling law for SLR production as a function of capacitor bank energy, shown in Fig. 1, as:

$$A \approx kE \tag{1}$$

where A is the activity in kBq, E is the PF capacitor bank energy in kJ, respectively, and $k \sim 2$.

At 1 MJ, the SLR activity, produced by EST mechanism, is about 2 MBq, and by further increasing capacitor bank energy up to 10 MJ, the activity will be about 20 MBq, which is much less than the activity required for PET imaging (about 1 GBq [8]).

The scaling law for EST SLR production mechanism shows that considering larger PF devices does not make any sense and a small device at high repetition mode produces higher activities. However, the activity saturation and technical obstacles are further discussed in the next section.

4. Discussion

Deuterons energy spectra well fitted with a power function of the form $\frac{dN}{dE} \propto E^{-n}$, where E is the deuteron energy and n is a number between 4–6 [13]. In a PF device, fusion neutrons (beam-target mechanism) and SLRs (induced activity in the external solid target) are produced by this deuteron spectrum. Neutrons are produced by low energy part of the spectrum (≤100 keV) [7], while graphite activation occurs by deuteron energies exceeding

328 keV [8]. Therefore, low energy part of the spectrum containing greater number of deuterons is responsible for fusion neutron production. In contrary, high energy tail of the spectrum, which has less number of deuterons, activates the target. For specific capacitor bank energy, the total number of neutrons is always more than that of SLRs. The number of deuterons in the pinch increases with the PF energy. Consequently, neutron yield increases, whereas SLRs does not. Therefore, neutron yield changes faster ($\boldsymbol{E}^2$) with PF energy, compared to the activity ($\boldsymbol{E}$).

Based on the Lee Model, neutron scaling law for capacitor bank energies of the order of kilo joules is $Y_n \approx E^2$ and for higher energy values is $Y_n \approx E^{0.8}$. By increasing the PF energy, Y_n saturates and reaches a constant value and further energy increment does not cause dramatic change in Y_n [12]. If neutron generation is limited at higher PF energies, clearly the activity saturates with energy as well.

5. Repetition mode

A small PF is capable of producing ^{13}N nuclides in the order of a few kBq in one shot. This can be increased to 10 MBq in a repetition mode operation of 16 Hz, which is far less than the required amount of activity for PET imaging. So even if a small plasma focus device works at a high frequency cannot produce adequate activity for PET imaging [8].

Technically, increasing repetition rate in order to increase system efficiency is not always possible and has some limitations. Since the time required for capacitor discharge is several microseconds, so discharge circuit must be equipped with special switches which are capable of maintaining such frequencies in current range in the order of several tens of kA. By increasing number of shots, time becomes more important since the PET radioisotopes are short-lived.

Selection of switching frequency is a trade-off between size and efficiency, therefore at high energies, increasing repetition rate is not possible. Transformer, inductor and capacitor filter dimensions at high frequencies decrease significantly. Moreover, not only switching and transformer core loss increases with frequency but also system's total efficiency decreases [14]. This fact imposes third limitation on operating the PF at high repetition rate in order to increase the activity.

6. Conclusion

The experimental results of newly designed NX3 and other PF devices with a range of energies were used to establish the scaling law for activity with the PF energy in EST mode. The experimental results show that the activity changes linearly with the PF energy. Therefore, with the largest PF available, the required activity for PET imaging is still far from being achieved.

References

[1] J.M. Ollinger, J.A. Fessler, Positron emission tomography, IEEE Signal Process. Mag. 14 (1997) 43.

[2] S. Fritzler, V. Malka, G. Grillon, J.P. Rousseau, F. Burgy, E. Lefebvre, E. d'Humieres, P. McKenna, K.W.D. Ledingham, Proton beams generated with high-intensity lasers: applications to medical isotope production, Appl. Phys. Lett. 83 (2003) 3039.

[3] J.W. Mather, Formation of a high-density deuterium plasma focus, Phys. Fluids 8 (1965) 366.

[4] R.L. Burton, R.G. Jahn, Acceleration of plasma by a propagating current sheet, Phys. Fluids 11 (1968) 1231.

[5] R.S. Rawat, High energy density pulsed plasmas in plasma focus: novel plasma processing tool for nanophase hard magnetic material synthesis, Nanosci. Nanotechnol. Lett. 4 (3) (March 2012) 251–274, 24 pp.

[6] M.J. Bernstein, G.G. Comisar, Neutron energy and flux distributions from a crossed field acceleration model of plasma focus and Z-pinch discharges, Phys. Fluids 15 (1972) 700.

[7] R.L. Gullickson, H.L. Sahlin, Measurements of high energy deuterons in the plasma focus device, J. Appl. Phys. 49 (1978) 1099.

[8] M.V. Roshan, S.V. Springham, R.S. Rawat, P. Lee, Short-lived PET radioisotope production in a small plasma focus device, IEEE Trans. Plasma Sci. 38 (12, Suppl. 2) (Dec. 2010) 3393–3397.

[9] B. Bienkowska, S. Jednorog, I.M. Ivanova-Stanik, M. Scholz, A. Szydlowski, Application of ion beam emitted from plasma focus device for target activation, Acta Phys. Slovaca 54 (4) (August 2004) 401–407.

[10] J.S. Brzosko, K. Melzacki, C. Powell, M. Gai, Breeding 1010/s radioactive nuclei in a compact plasma focus device, in: Application of Accelerators in Research and Industry – Sixteenth Int'l Conf., in: AIP Conf. Proc., vol. 576, 2001.

[11] E. Angeli, A. Tartari, M. Frignani, D. Mostacci, F. Rocchi, M. Sumini, Preliminary results on the production of short-lived radioisotopes with a plasma focus device, Appl. Radiat. Isot. 63 (2005) 545–551.

[12] S.H. Saw, S. Lee, Scaling laws for plasma focus machines from numerical experiments, Energy Power Eng. (2010) 65–72.

[13] S.V. Springham, S. Lee, M.S. Rafique, Correlated deuteron energy spectra and neutron yield for a 3 kJ plasma focus, Plasma Phys. Control. Fusion 42 (10) (2000) 1023.

[14] H.R. Ali, Design and construction of the charging and controlling system with repetitive performance for pulsed plasma pinch generator systems, MSc Thesis, Amirkabir University of Technology, 2012.

[15] S.M. Sadat Kiai, M. Elahi, S. Adlparvar, E. Shahhoseini, S. Sheibani, H. Ranjberakivaj, S. Alhooie, A. Safarien, S. Farhangi, N. Aghaei, S. Amini, M.M. Khalaj, A.R. Zirak, A.A. Dabirzadeh, J. Soleimani, F. Torkzadeh, M.M. Mousazadeh, K. Moradi, M. Abdollahzadeh, A. Talaei, A.A. Zaeem, A. Moslehi, A. Kashani, A.R. Babazadeh, F. Bagiyan, M. Ardestani, A. Roozbahani, H. Pourbeigi, H. Tajik Ahmadi, M.A. Ahmadifaghih, M.S. Mahlooji, B.N. Mortazavi, F. Zahedi, Preliminary results of IS plasma focus as a breeder of short-lived radioisotopes ^{12}C(d,n)^{13}N, J. Fusion Energy 30 (2) (2011) 111–115.