Breeding 10^{10}/s Radioactive Nuclei in a Compact Plasma Focus Device [1]

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Abstract. In the early 90's, it was discovered that a Plasma Focus (PF) system self-creates a plasma-target in which high energy-threshold nuclear-reactions occur at high reaction rates. Short life radioisotopes (SLR)s such as ^{18}F, ^{17}F, ^{15}O, ^{14}O, ^{13}N have been generated (10^6 - 10^8 per pulse) with a PF-machine using 7 kJ energy storage to produce the plasmas. β^- radioactivity from the SLRs is measured with rugged, Geiger counters inserted into the PF-chamber, and a specific SLR is identified by its half-life. The PF chamber (before discharge) is filled with a mixture of gases that constitutes the latter plasma-target – beam system, *e.g.*, the elements required to produce specific SLRs through nuclear reactions. In this paper, arguments are presented showing that a modest sized PF-machine, using a 50 -75 kJ fast capacitor-bank, when operated at pulse frequencies of 1-10 Hz can produce ≥ 10^9 SLRs/pulse. This paper reports the results of testing a PF as a breeder of SLRs with dual applications for: (*i*) Secondary Radioactive Nuclear Beams ion-sources ($Z < 35$), and (*ii*) as a breeder of radioisotopes for biomedicine ($Z \leq 10$) and/or PET imaging.

1. INTRODUCTION

The Plasma Focus (PF) was independently discovered by J. Mather [1] and N.V.Filippov [2] in the late 50's. Since then, many laboratories have studied the plasma-focus phenomenon and its remarkable capabilities for producing short pulses (1 ns – 300 ns) of X-rays, neutrons and fast ions depending on PF mode of operation. PF operation can be briefly described as a five stage process (see Fig. 1) with the appearance of high-energy ions and nuclear reactions in occurring in the last stage.

Measurements of fast ion spectra have been carried out elsewhere and with the use of various methods ranging from time-of-flight, filters, faraday cups, Thomson spectrometers to track detectors and blisters method.

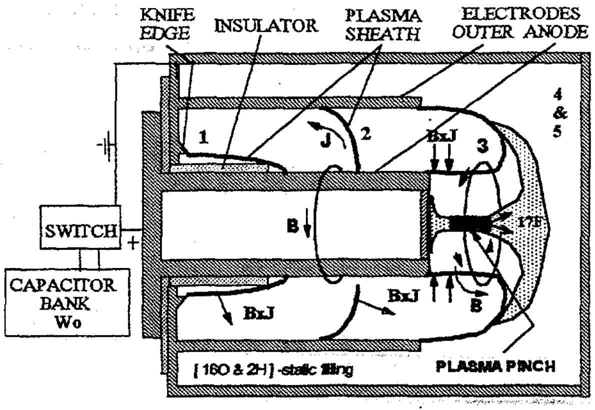

FIGURE 1. Conceptual drawing of the plasma focus header indicating the sequence of plasma sheath positions. The central electrode diameter is $\phi \approx 50$ mm, the chamber is filled with gas mixture at p = 0.1 – 7 Torr. Numbers refer to plasma development stages: 1 – the plasma sheath is formed, 2 - the plasma sheath moves toward the anode nozzle ($v \approx 10^5$ /s), 3 - the sheath arrives at the end of anode and rearranges itself into a cylinder with a conical opening, 4 - the plasma is compressed at the axis (10^{25} ions/m^3), 5 - the plasma column quickly develops instabilities associated with high-energy acceleration, high nuclear reactivity and X-ray emission.

Small (ϕ: 20 - ϕ: 300 μm) plasma domains are created. The domains have above solid state densities, kT ≥ 3 keV and magnetic fields sufficient to trap ions of 5 MeV/nucleon.

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All these studies [3] suggest the following empirical formula ($E_i \geq 0.1$ MeV):

$$d\Phi_i/dE_i \propto E_i^{-m} \quad (2 \leq m \leq 3) \qquad (1)$$

Similar (as in Eq.1) spectral dependence for the trapped and reacting in plasma ions was drawn by unfolding of the D(d,n) neutron spectra. The data provide evidence that the fast beam yields (Φ_i) as well as reaction yields in plasma (Y_p) and/or on external targets (Y_t) scale with the square of the energy (W) stored in the capacitor bank [4], *i.e.*

$$\Phi_i \propto W^2; \qquad Y_p \propto W^2; \qquad Y_t \propto W^2 \qquad (2)$$

In addition to direct ion-beam observation, the activation methods have also been broadly used. In such approaches energy threshold reactions leading to formation of radioactive species in externally positioned solid targets (exposed to D^+ irradiation) have been used as PF-diagnostics. Under these conditions, radioisotopes such as ^{11}C, ^{11}N, ^{15}O, ^{17}F, ^{28}Al, ^{66}Cu have been observed and are reported elsewhere.

The scope of this paper is to evaluate/demonstrate of potential of the PF device as a breeder of radioactive isotopes that can be utilized for the production of exotic and/or radioactive ion beams for radioactive ion beam applications and/or for medical imaging (PET) and biomedicine applications.

2. NUCLEAR REACTIONS INDUCED IN THE MAGNETIZED PLASMA-TARGET BY FAST IONS TRAPPED IN THE TARGET

In this section, the experimental evidence and discussion is oriented to the situation where fast ions are trapped in domains of magnetized plasma. Such fast ions can induce nuclear reactions by collisions with nuclei in the background plasma. To produce a selected nuclear reaction and as a result, produce a specific radioisotope, one has to create a dense, magnetized plasma composed of two isotopes with different atomic numbers and an appreciable population of high-energy (fast) ions. The cross-section for the production of the radioisotope of interest (reaction product) has to be sufficiently large ($\sigma \geq 100$ mb) at the ion-projectile energy of 0.5 MeV/nucleon.

Only one experimental group has achieved high efficiency (yield per kJ of stored energy) for the production of short-lived radioisotopes in a plasma environment [5]. The experiments reported here were carried out with a Mather-type PF device with a capacitor bank energy of W= 7 kJ (V = 18 kV) and at a total gas mixture pressure of $p \approx 5$ Torr. Gas mixtures were composed of low-Z (LZ) isotopes (H, D, ^{3}He) mixed with high-Z (HZ) isotopes.

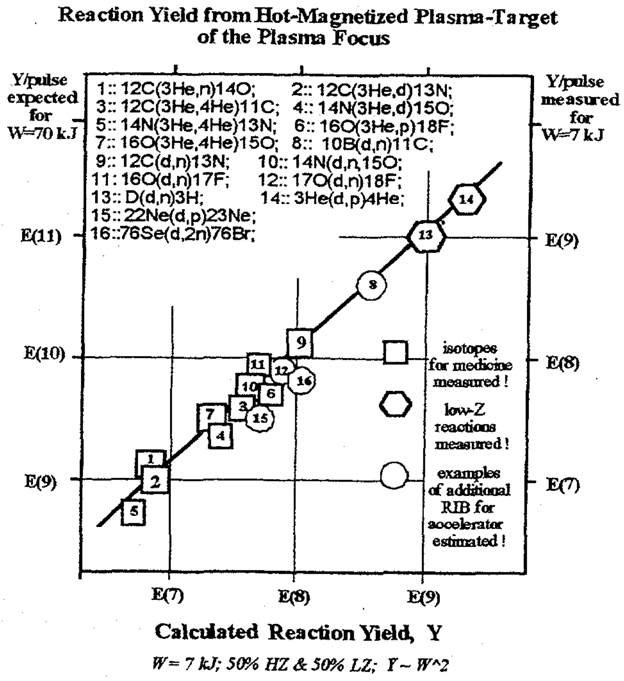

FIGURE 2. Compilation of experimental data measured with a PF (W= 7 kJ) filled with a mixture of HZ and LZ gases. The box sizes are representative of standard deviations (vertically) obtained by averaging many experimental points (discharges) and model uncertainties (horizontal). For convenience experimental data are adjusted (see Eq. 3 and 4) to $n_{HZ}/n_{LZ} \approx \rho_{HZ}/\rho_{LZ} \approx 1$.

A summary of these experiments is shown in Fig.2. From Fig.2 it is clear that a broad range of radioisotopes, with large yield, can be produced in a PF device. A relatively small PF-machine, operated at a discharge power of W= 7 kJ, can produce $\times 10^6$ to 5×10^8 radio-nuclei per pulse, while with a medium size machine, operated at discharge power of, W = 70 kJ, one can expect a hundred times higher yields.

The semi-empirical model assumes: *(i)* the instantaneous creation of a magnetized plasma domain, containing fast trapped-ions, *(ii)* a domain stability period, $\tau \approx 0.5$-5 ns, and *(iii)* an instantaneous domain destabilization, causing fast ions to be ejected out of the pinch zone. For briefness, and demonstration of trends, a simplified formula (instead of full theory [5]) for (HZ-LZ) radioisotope production is used here:

$$Y_p = n_{HZ} \times \tau \times \Phi_p^{\circ} \times \int_0^{E_m} (d\Phi_p/dE) \times \sigma(E) \times (2E/M)^{1/2} \times dE \qquad (3)$$

In the Eq.3, $d\Phi_p/dE$, (see Eq.1) is normalized to unity in the range, $E_0 \leq E \leq E_m$; Φ_p° is the total number of the projectile ions that are accelerated and trapped in the plasma; n_{HZ} is the numeric density of plasma nuclei that serve as target during radioisotope production; $\sigma(E)$ is the reaction cross section and M is the mass of the LZ ion. Eq.3 neglects stopping powers of fast ions in the plasma domain and considers only LZ as projectiles inducing nuclear reactions. Eq.3 simplifies further if one assumes that: (*i*) the density of HZ particles in the plasma target, n_{HZ}, is proportional to the atomic density, ρ_{HZ}, of the HZ in the filling gas (constant plasma compression), *i.e.*, $n_{HZ} \propto \rho_{HZ}$; (*ii*) the number of accelerated LZ ions is proportional to the abundance of such ions in the plasma target, *i.e.*, $\Phi_p \propto n_{LZ} \propto \rho_{LZ}$. As a result, Eq.3 converts to the following form:

$$Y_p \propto \tau\times\rho_{HZ}\times\rho_{LZ}\times\int_0^{E_m}\sigma(E)\times E^{-m+1/2}\times dE \qquad (4)$$

The theoretical values (in Fig.2) are calculated by use of Eq. 3. The beam yield in the plasma was assumed to be the same as those activating the external targets. The $n\times\tau$ product was taken from Ref. 13. Eq. 4 agrees well with experimental results (see Fig.2).

3. EXPERIMENTAL TESTS OF RADIOISOTOPES PRODUCTION IN THE PF-PLASMA

Radioactivity (decay curve) is measured by use of a thin-wall, cylindrical Geiger-Muller counters (GM) having walls (cathode) made of high resistivity metal alloy (no Al or Cu). GM counters were used because they can survive an electromagnetic shock and jets of plasma emitted during PF operation. In the course of experiments, various geometrical set-ups were used [5], one of which is shown in Fig.3.

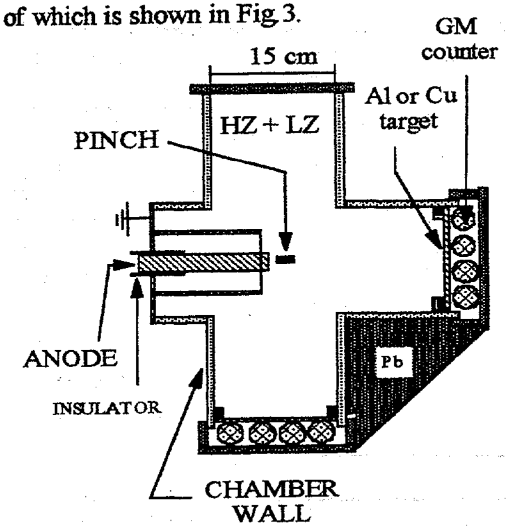

FIGURE 3. An experimental set-up used for simultaneous measurement of radioactivity induced in the plasma and on the target foils (Al or Cu). Each set of the four GMs is connected in parallel to a multi-scaler counter and counting begins 10 s after the PF-discharge is completed. The chamber walls are clad with Ta.

The identification of isomers is based on their lifetimes ($T_{½}$) and reaction yields are estimated from initial radioactivity of the component (associated with the identified radioisotope) and the efficiency (solid angle included) of the detection system.

Plasma origin of the radioisotopes breeding is supported by three observations: *(A)* For PF discharges with a chamber Ta-clad and filled with a mixture of deuterium and one HZ component (^{12}C, or ^{14}N and/or ^{16}O) only one $T_{½}$, as expected from (d,n) reaction product, is observed; no radioactivity occurs for pure D_2 fillings. *(B)* Whenever the PF-chamber is filled with different relative compositions of HZ and LZ gases while keeping the total atomic density constant – the resulting radioactivity changes proportionally to the product of $\rho_{HZ}\times\rho_{LZ}$ as expected from Eq.4. *(C)* In experiments with Al or Cu external targets and the chamber filled with HZ and LZ gases, two radioisotopes are produced: one in the plasma and one on the target. Fig.4 demonstrates complete disappearance of the plasma radioactivity when the chamber is instantly evacuated during measurements of the decay curve.

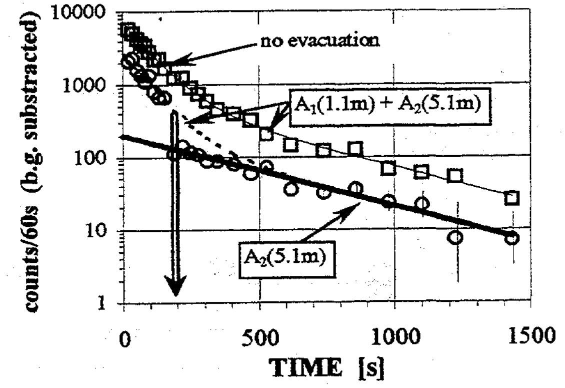

FIGURE 4. An example of the decay curves each composed of two half-lives: $T_{½}$ = 1.1 min (^{17}F) and 5.1 min (^{66}Cu). Three min after the discharge ($\rho_{HZ}/\rho_{LZ} \approx 0.1$), the chamber was pumped-out (radioactive gas evacuation) after which the plasma-induced radioactivity ($T_{½}$ = 1.1 min) disappeared. A decay curve, measured after another discharge and without gas evacuation, is shown for comparison.

4. PLASMA FOCUS AS AN EFFICIENT BREEDER OF SHORT LIFE RADIOISOTOPES FOR ACCELERATORS AND BIOMEDICINE

PF devices have the capability of producing radionuclei on external targets and in the plasma. This second application is addressed here. Data, such as shown in Fig.4, replicate results where the external target is assumed to be solid ^{16}O, accounting for differences in the ion stopping power, cross-sections, efficiency and considering a $\rho_O/\rho_D \approx 1$ plasma. In such cases, the production of ^{17}F radionuclei in the plasma system would be 45 times larger than production of ^{17}F in a solid oxygen target. This example demonstrates the superiority of a plasma breeder over a solid-target.

The number of radionuclei in the chamber, N, at the end of the breeding cycle (Δt) in various PF-operating conditions can be roughly estimated from the Y_p data shown in Fig.2 ($W_o = 7$ kJ) and Eqs. 2 ÷4.

$$N \equiv Y_p \times [\rho_{HZ} \times \rho_{LZ}/(\rho_{HZ}+\rho_{LZ})^2] \times (W/W_o)^2 \times f \times (1-e^{-\lambda \times \Delta t}) \quad (5)$$

where: W is the capacitor bank energy, f is the discharge repetition frequency, $\lambda \equiv \ln 2/T_{½}$.

Some examples of expected breeding capability are shown in Fig. 5. Chosen activities reflects typical biomedical and/or accelerator demands. Between biomedical urgent market demands one can refer to compounds labeled with ON, very recently recognized by the 1998 Noble prize committee for its importance. Other examples include the use of ^{18}F-radio tracers as Fluoro-Deoxy Glucose (FDG) in oncology, cardiology and neurology [6]. Applications for short-life radio-nuclei have been well documented in the literature but have been used sparingly because cyclotron breeders are costly and radiation must be handled with heavy shields.

Secondary Radioactive Nuclear Beams provide one of the most powerful tools for studying Nuclear Physics and Astrophysics phenomena [7, 8]. The Holifield Radioactive Ion Beam Facility (HRIBF) [9], Oak Ridge National Laboratory (ORNL) is the first US-Isotope Separator On-line (ISOL) facility. In addition to present capabilities, some experiments will require higher intensities, than ISOL can provide, specially for studies of nuclear structure of short-life radioisotopes with A ≥ 20. Their short life-times make it difficult to generate useful beam in of isotopes with lifetime less than several seconds at ISOL type facilities. For these isotopes, the recently proposed method of producing radioisotopes in a PF type ion source could overcome these handicaps and be substituted for the equivalent ISOL method.

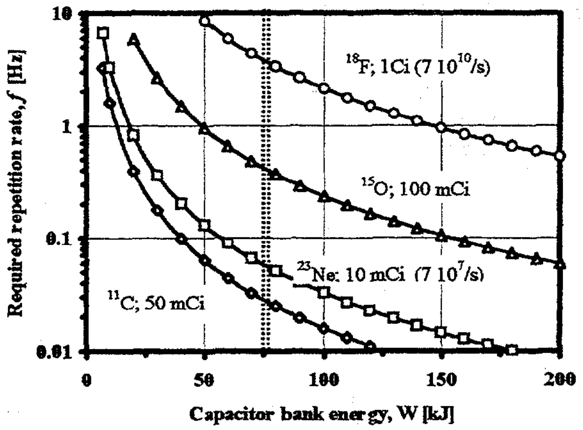

FIGURE 5. Expected relation between discharge repetition rate and capacitor bank energy for obtaining useful radioactivity of specific radioisotopes after evacuation from the discharge chamber. The time of PF operation is equal to the half-life of the particular radioisotope, *i.e.* the radioactivity is equal to $\frac{1}{2}$ of the radio-nucleus production rate (given in brackets). The assumed mixture of fill gas is $\rho_{HZ}/\rho_{LZ} = 1$.

5. SUMMARY

The data presented in this paper consistently show the remarkable ability to produce intense levels of radioisotopes (including those with short half-lives). The existing mathematical models constitute reliable tools for extrapolation of experimental data to other radioisotopes as well as for scaling plasma focus breeders.

Radioisotopes produced in a PF device are embedded in the low-pressure (up to 5 Torr) gas of reacting components and are ready to be transported as ions and/or as neutral atoms to an accelerator or to an ion source.

As already noted the proposed PF-breeding method could be utilized for the production of radioisotopes needed in nuclear as well as in biomedical applications. In fact, the needs in both fields overlap, as the same isotopes are used for different applications.

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