Journal of Modern Physics, 2014, 5, 82-88
Published Online January 2014 (http://www.scirp.org/journal/jmp)
http://dx.doi.org/10.4236/jmp.2014.52013

Plasma Focus Studies in Serbia

Vladimir Udovičić[1], Nikola Veselinović[1], Dušan Joksimović[2], Radomir Banjanac[1], Dimitrije Maletić[1], Dejan Joković[1], Dragan Lukić[1]
[1]Institute of Physics, University of Belgrade, Belgrade, Serbia
[2]Faculty of Business Studies, Megatrend University, Belgrade, Serbia
Email: udovicic@ipb.ac.rs

Received October 18, 2013; revised November 16, 2013; accepted December 15, 2013

ABSTRACT

The plasma focus experiment in Belgrade, Serbia started in the late eighties of the last century. The historical overview of the research activity on the Belgrade plasma focus device (BPFD) will be presented in this work. The special attention has been made to the present status and the future plans for the fundamental and applied research as a part of the project of the studies of rare nuclear and particle processes in nature. BPFD is intended to operate as optimized neutron source or hard X-ray source. Using Lee model code as a reference, several upgrades of BPFD must be made: better shielding against EMI pulse, rearrangement of capacitors bank so that higher repetition rate can be achieved and also faster digital acquisition system. BPFD can be used for neutron activation or production of short-living radioisotopes. These radioisotopes will have very low activity which can be analyzed in the underground Low-Background Laboratory for Nuclear Physics, Zemun. Also, we compared the obtained experimental data (neutron yield, total current waveform, working gas pressure) with the numerical simulation code (The Lee model code) to test our plasma focus machine. Comparison between neutron yield from our experimental data and neutron scaling laws and neutron yields derived from computation using the Lee Model code shows good matching, but for better verification of the code, more experimental data are needed.

KEYWORDS

Plasma Focus; The Lee Model Code

1. Introduction

Controlled thermonuclear fusion is in the last sixty years, a major challenge for researchers. The main goal, also the main problem, is how to achieve conditions for plasma ignition and the related construction of economical and environmentally friendly reactor. Parameter which characterizes the ignition condition is the product $R = n\tau_E T_i$ (plasma reactivity), where n is the plasma ion concentrations, confinement time τ_E and T_i ions in the plasma temperature, and the value must be greater than 3×10^{21} $m^{-3}\cdot s$ keV. Over time they have developed various devices for magnetic plasma confinement based on two different approaches [1]. The first group devices are pulse-current electrical discharge accompanied by pinch-effects in different geometries (linear z-pinch, toroidal pinch, theta-pinch, plasma focus). The second group of devices is based on the use of a variety of magnetic traps, where the magnetic fields needed to achieve plasma confinement with the external currents (device with a minimum-B, stelarator, tokamak). The topic of this paper is the devices that generate fusion plasma in a pulsed electric discharge, a dense plasma focus device.

Plasma focus device was invented in the early 1960s by J.W. Mather [2], and independently, by N.V. Filippov [3]. It should be noted that the Filippov's type plasma focus device differs from Mather's type in absence of axial phase, so the plasma column is already formed immediately after the discharge. An important characteristic of the dense plasma focus is energy density of the focused plasma which is practically a constant over the whole range of machines, from sub-kilojoule machines to megajoule machines.

Currently, perhaps the best guide to the future of plasma focus is given in [4]. In this paper, the open questions are still waiting for adequate responses in future studies. The first issue is the possibility of obtaining high energy ions, greater than 100 keV, in so-called hot spots, so that plasma focus can stand as a candidate for a future fusion energy machine with advanced hydrogen fuel-type boron-11. Next trend refers to the construction of miniature plasma focus with capacitor bank energy of 1 J and less. The group of researchers from Italy, the collaboration of the University of Ferrara and Bologna, has been active in neutron activation analysis on the reaction of ^{197}Au (n, n′γ) ^{197}Au^{m} induced by neutrons from 6.9 kJ deuterium plasma focus [5]. In addition, on the same device, preliminary results were obtained of the short-living radioisotopes' production. The obtained radioisotopes in the plasma focus are ^{15}O, ^{17}F and ^{13}N, and the corresponding reactions are ^{14}N (d, n) ^{15}O, ^{16}O (d, n) ^{17}F and ^{12}C (d, n) ^{13}N, respectively. Activity of the short-living radioisotope was to 1 µCi per discharge [6]. Importance of the short-living radioisotopes' production is pointed out because of the possible use of the plasma focus device as an alternative to cyclotrons in positron emission tomography (PET) [7,8].

Finally, we should mention the multiple use of radiation emitted from the plasma focus in the industry. A technique is developed based on X-ray radiographs of moving and soft metal objects using plasma focus machine as a pulse source of X-rays. Using commercial radiographic film, and specially written computer codes tomographic reconstruction of metallic objects is possible in great detail. The application of soft X-rays in medicine is reflected in the application of radiation, transmission and detection of microradiography microscopy [4].

Emitted neutrons from deuterium plasma focus are used in neutron radiography and analysis of the constituent elements of a small unknown material sequence number Z. The latter is particularly important and relevant in recent years as a technique that allows the detection of explosives and various narcotics-containing exactly the elements of a small Z (hydrogen, carbon, nitrogen and oxygen). The methods are also developed based on the detection of neutrons elastically scattered on the tested substances and to compare the neutron detector with a response when questioned substance is not present. With this procedure, it is possible to determine the presence and quantity of water in the vicinity of the complete detector system, with an accuracy of a few percents. This technique, among other things, is particularly suited for the determination of soil moisture [4].

The plasma focus experiments in the Belgrade are dedicated to the nuclear aspects of the processes occurring in the plasma focus device. The first preliminary results obtained from BPFD were published in [9]. The experiments described in this work are divided into groups according to the type of gas. In the case of deuterium as the working gas, experiments included measurements of fluxes and energy of accelerated deuterons, discrimination of the positive particles, measurements of their angular distribution, and analysis of the hot spots, and finally measuring the angular distribution of neutrons emitted from the BPFD.

With the hydrogen as a working gas, the experiments are measurements of the angular distribution and the energies of the high-energy protons, especially axial protons. The results are important in terms of testing the possibility of using hydrogen plasma focus as a source of proton energies up to 500 keV, the yield for significant (p, α) nuclear reaction. First of all, some of these nuclear reactions (^{7}Li (p, α) ^{4}He, ^{11}B (p, α) 2 ^{4}He) have a good energy balance and is even mentioned as an alternative to D-T fusion fuel.

2. Belgrade Plasma Focus Device

The plasma focus experiment in the Belgrade, Serbia was performed on small plasma focus machine (**Figure 1**).

The basic characteristics of BPFD used in the experiments are summarized in the **Table 1**.

The main part of the data acquisition system was a digital oscilloscope Tektronix TDS 540A (1 Samples/s). The voltage measurements are taken with high voltage probe (Tektronix P 6015A) with uncertainty of 1%. A Rogowski coil, placed between the power transmission plates, monitors the derivative of the current signal dI/dt. The good focusing can be obtained if the time of current peak is in coincidence with the current sheath coming on the top of the central electrode. In this case, the oscillogram shows the dI/dt signal with the strong electromagnetic interferences (EMI) pulse added near the maximum

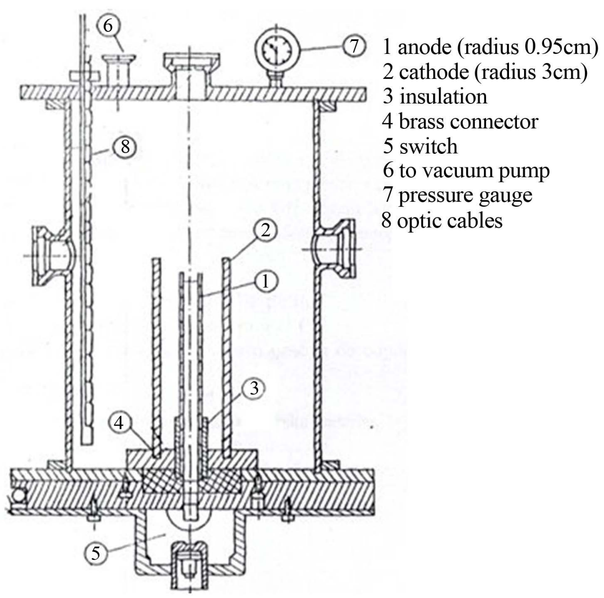

Figure 1. The Belgrade plasma focus device structure.

Table 1. **The basic characteristics of the BPFD used in this experiment.**

Capacity (µF)	45
Charging voltage (kV)	15
Inductance (nH)	62
Peak current (kA)	300
Stored energy (kJ)	5
Anode radius a (cm)	0.95
Distance between outer and inner electrode b (cm)	3
Length of the inner electrode z_0 (cm)	19
Working pressure (mbar)	3.5
Drive parameter (kA·cm^{-1}·mbar$^{-1/2}$)	90
Average neutron yield (neutron/pulse)	2×10^7

current value. Current signals oscillogram showed in Figure 2 where R3 represent the good shot with plasma focus while the R2 current signal is the bad one. Good signals were analyzed with OriginPro 7.5 software from which is obtained data for the peak discharge current.

The existence of the EMI pulse that followed every good shot strongly affects use of the electronic diagnostic instruments. Because of the sensitivity of our nuclear electronic components to EMI, signals from the photomultiplier tubes are mixed and recorded on the oscilloscope, which is excellently protected against EMI. Measurements of the total neutron yield were carried out using large volume (600 l.) liquid scintillation detector loaded with a gadolinium Gd-155 and Gd-157 (NE343). The detection system is able to detect D-D fusion neutrons emitted simultaneously in a broad time interval (about 40 µs) with an efficiency of about 80%. The calibration of the detector to impulsive neutron sources, such as plasma focus device, is completely described in [10].

3. Theory

The plasma focus device operating with deuterium gas (DPF) is intensive source of 2.45 MeV neutrons, produced in D-D fusion reaction. Mechanisms of producing neutron yields Yn depend of energy of DPF but two main processes are dominant: termonuclear fusion and ion beam-target fusion. These two components have different contribution to the total neutron yield. If the fusion mechanism is thermonuclear, an isotropic emission of the neutrons is expected. On the other side, experimentally observed anisotropic component in the neutron emission [11] is related to ion beam-target fusion. The second component usually contributes less and ranges from 4% to 38% of the total neutron yield. The main dynamical properties of plasma focus discharge evolution is computed reasonable well with Lee model. The Lee model couples the electric circuit with plasma dynamics, thermodynamics and radiation, enabling realistic simulation of all gross focus properies. This model code, equipped with a beam-target mechanism can compute the Yn for a wide range of plasma focus machines from a sub-kilojoule to the megajoule. Basic Lee model, described in 1984, with two phase (axial and radial) was used to assist several experiments. D. Joksimovic using this model has developed the computer code for the numerical integration of the differential equations systems which describe axial and radial phase of the plasma evolution in the plasma focus device [12].

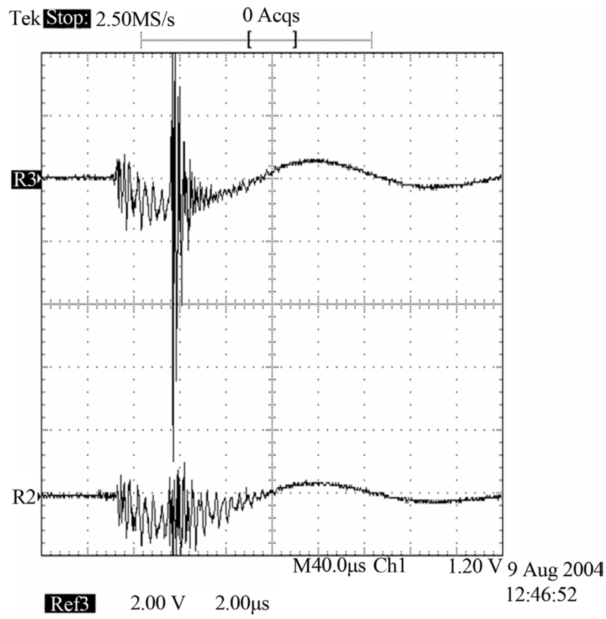

Figure 2. **Plasma focus current signals oscillogram: R3 indicates a typical example of the good shot (successful focusing) and R2 represents the bad shot (no focusing) [17].**

Radiation coupled dynamics was introduced in now five-phase Lee's code leading to numerical experiments on various plasma focus machines. These five phases are axial phase, described by a snowplough model with an equation of motion of plasma coupled to a circuit equation, radial inward shock phase, described by 4 coupled equations using elongating slug model. Other three phases are: Radial reflected shock (RS) phase, when the reflected shock front from the axis moves radially outwards, whilst radial current sheath piston continues to move inwards, Pinch phase, when the out-going reflected shock hits the ingoing piston and compression enters a radiative phase and expanded column phase where snowplough is again used. This phase is not considered important as it occurs after the focus pinch axial and radial phase. Model code is configured to work as any plasma focus by inputting the bank parameters, inductance L_0, capacity C_0, and stray circuit resistance r_0, the tube parameters such are anode and cathode radii b, a and hight of anode z_0 and operational parameters as charching voltage V_0, pressure P_0 of the fill gass. The standard practice is to fit the computed total current waveform to an experimentally measured total current waveform using four model parameters representing the mass swept up factor, the plasma current factor for the axial phase and two more for radial phases of plasma focus. The exact time profile of the total current trace is governed by the bank parameters, focus tube geometry and operational parameters. These parameters, along with numerical model parameters determine the axial and radial dynamics.

4. Experiment

The experiments described in this work are divided into two groups according to the type of gas D_2 and H_2.

The first experiments on BPFD moved towards the detection and measurement of the fluxes and energy of accelerated deuterons. Particularly, to pointed out two direction of movement for accelerated deuterons, along the central axis of the electrode and 90˚ relative to that direction. Along with measuring the flux and energy of deuterons, measurements were performed for neutron yield, energy capacitor bank and the strength and shape of the discharge current.

Working discharge conditions were optimized for the BPFD machine. Positive particles were detected using solid-type trace detectors CR-39 and LR-115 type I (Kodak). Detectors with or without Al absorber (5 microns thick) were located at a distance of 15 cm from the tip center electrode glued to a pin-hole camera in position 90˚. All detector probes were exposed to successive discharges without re-vacuuming chamber plasma focus.

Special experimental setting was implemented to measure the angular distribution of positive particles, products of primary and secondary D-D fusion reactions, as well as soft X-rays (about 5 keV energy, [12]) that accompany the process of intense, pulsed electrical discharge. For this purpose, a special bracket was made for positive particle detector type LR-115 Type I, and film for the detection of X-radiation commercial type Kodak Company. The detectors holder was a semi spherical shape (diameter 250 mm) and was located inside the plasma focus chamber.

Detector LR-115 type I were covered with macrofol (manufacturer "Bayer") thickness of 10 μm. Movies for measuring X-rays were covered with aluminum foil thickness of 60 μm. After exposure (by successive discharges without re-vacuuming chamber plasma focus), the detectors were subjected to the standard procedure. The optical density of the developed X-films was measured with microfotometer manufacturer "C. Zeiss".

The existence of hot spots in the plasma focus BPFD was analyzed using solid track detectors LR-115 type I. The detectors were covered with Al absorber thickness of 7 mm and were located at the ends of the pin-hole camera. Pin-hole cameras were placed in the holes on the side of the diagnostic chamber of the plasma focus device. We were used the both types of pin-hole cameras, diaphragm and integrated collimators (**Figure 3**).

Measurement of the angular distribution of neutrons from a plasma focus was done by the special method: we used a combination of uranium thin targets (89% 238U, 235U 2%) and muscovite mica as a fission solid track detectors. Fission of uranium was induced by neutrons from a plasma focus. Obtained fission track density is in directly proportional to the neutron flux.

Protons were detected by obtained tracks in solid detectors LR-115 type I (6 μm thick). The energy detection threshold for protons, for a given type of detector is a 100 keV. Upper discrimination is determined by placing a polycarbonate absorber (5 microns thick) on the front side of the detector. Protons have been emitted at detectors using a pin-hole camera with 32 integrated collimators, each has a diameter of 600 μm. One camera was located in the axial direction away from the center electrode tip 14 cm. Another camera is located in one of the side openings diagnostic (**Figure 3**).

Similar measurements of the angular distribution of positive particles emitted from deuterium plasma focus was performed with protons from the hydrogen plasma focus. In order to thoroughly investigate the axial proton beam, proton energy and flux emitted in the axial direction, the measurement was done using a CR-39 detector. Unlike the LR-115, CR-39 detectors have a lower detection threshold for protons (80 keV-a). Unfortunately, in the case of CR-39 detectors there is a track's saturation in the axial direction. To overcome this problem, we performed two types of experiments. CR-39 detectors were placed on top of the plasma focus chamber, just above

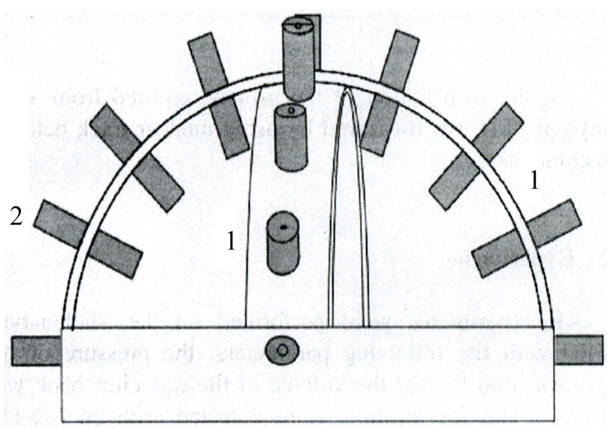

Figure 3. The semi spherical detectors holder (1) with pin-hole cameras (2) used in the all spatial distribution measurements [16].

the center electrode at a distance of 15 cm, pasted on the pin-hole camera. On the detector side of the CR-39 we placed the absorbers (makrofol) of different thicknesses (2, 5, and 10 μm). In addition, the known information about the proton flux for a given thickness of the absorber, it was possible to get the information about energy of the protons on the basis of well-known range-energy relation for protons in Makrofol. Operating conditions were: gas pressure of 400 Pa and the voltage of 16 kV, which corresponds to 5.76 kJ of stored energy. Another way to avoid saturation in the density of proton tracks in CR-39 detector is the discharge at low working gas pressure. A working pressure of hydrogen in the plasma focus chamber was 200 Pa. Working gas pressure for good focusing, corresponding operating voltage of 8 kV-a (capacitor bank energy of 1.44 kJ). The detectors were exposed to only one complete discharge.

On the basis of the experimental data, we have performed experiment with the lithium target, which was thick wire (thicknesses of about 100 μm) placed on the CR-39 plate (2 cm × 2 cm). CR-39 nuclear track detectors manufactured by the Intercast were used for the detection of the α particles produced in the ^{7}Li(p, α)α fusion reaction. Both the lithium target and CR-39 plate were placed in one of the diagnostical windows positioned at the top of the plasma focus chamber along the central electrode axis. The fast protons were collimated with integrated collimators, so that the protons bombarded target at right angles. The phases of the discharges in the experiment with Li target are shown in the **Figure 4**.

5. Results and Discussion

D. Joksimovic used computer code for the numerical integration of the differential equations systems which describe axial and radial phase of the plasma evolution in the plasma focus device [12] with BPFD characteristics (**Table 1**) as an input parameters. The following results were obtained: the radius of the plasma column r_m = 1.38 mm, duration of radial phase t = 46.69 ns, duration of compression phase t_k = 45.1 ns and duration of pinch phase t_p = 19.5 ns.

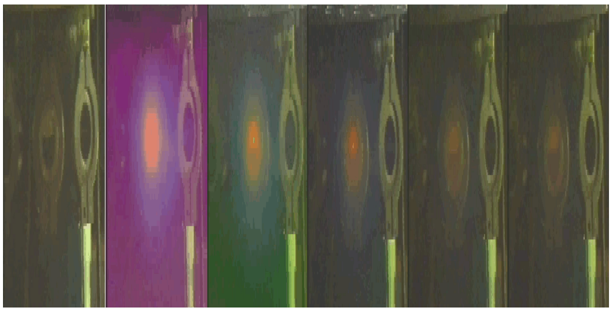

Figure 4. The phases of the discharge in the experiment with Li target.

On the basis of the performed experiments with the deuterium as working gas, we obtained results: angular distributions of the ^{4}He and soft X-ray (~5 keV) emitted in described experimental conditions are nearly isotropic. Distribution of emitted deuterons has the maximum in the direction of central electrode [13]. In the deuterium plasma focus ^{4}He are produced in the several points above central electrode (hot spots). Emission of the deuterons has not nuclear origin. Dimension of emission space show that deuterons was emitted before plasma collapse, similaraly to the soft X-ray [14]. The obtained neutron spatial distribution show anisotropy in the axial direction and can be explained on the basis of the existence of "hot spots" above the central electrode [15].

On the other side, the experiments with the hydrogen as a working gas show that the accelerated protons can achieve energy up to 500 keV with the total proton yield of (1.1 ± 0.2) × 10^9 per shot [16]. The spatial distribution of the accelerated protons shows anisotropy similar to that of deuterium ions [17]. The overall intensity and angular distribution of high-energy protons give the chance to study nuclear reactions (^{7}Li (p, α) ^{4}He, ^{11}B (p, α) 2 ^{4}He). The special attention was made to the profile of the axial protons emitted from the hydrogen plasma focus [18]. Unfortunately, the obtained experimental results show that it is not possible to realized ^{7}Li(p, α)α fusion reaction in a small plasma focus device (stored energy of 5.76 kJ) [19].

For BPFD with deuterium as working gas we investigate correlation on neutron yield with peak discharged current. In [20,21] proposed scaling law is Y_n - $I_{peak}^{3.9}$ and we performed a series of experiments to test this scaling law. For numerical simulation of BPFD we used numerical simulation code developed by Lee *et al*. (The Lee model code version File7RADPF05.15b). The Lee model code couples the electrical circuit with plasma focus dynamics, thermodynamics and radiation, enabling realistic simulation of all gross focus properties. For comparison of experimental and simulated neutron yields we used, in Lee's code, the same inputting machine parameters: inductance, capacitance, electrode radii and length and operating parameters: charging voltage and fill gas pressure as in experiments and default numerical model parameters.

In the **Figure 5**, we represented our results within our range of operations. The obtained plot of the total neutron yield as a function of the peak discharge current is similar to the published plot with proposed scaling law.

Comparison between neutron yield from our experimental data and neutron scaling laws and neutron yields derived from computation using the Lee Model code shows good matching but for better verification of the code more experimental data is needed (**Table 2**).

Measurements of X-radiation from a BPFD, are de-

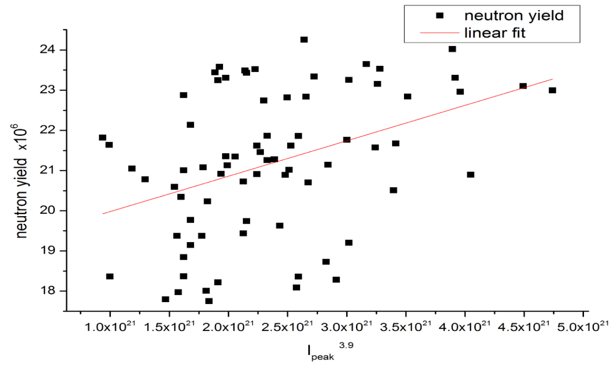

Figure 5. Total neutron yield as a function of peak discharges current. Discharges at 15 kV and 3.5 mbar D_2.

Table 2. Numerical experiments on plasma focus neutron yield versus pressure compared with laboratory experiments.

Working pressure (mbar)	Voltage (V)	Number of successful shot	Neutron yield Lee model ($\times 10^7$)	Neutron yield experiment ($\times 10^7$)
3	15	37	1.53	2.04
3.25	15	17	1.66	2.03
3.5	15	60	1.80	1.99
3.75	15	14	2.36	2.09
4	15	7	2.05	2.12

scribed in detail in reference [12]. When all that is taken into account, and considering Table 1, with high degree of confidence, the conclusion is that the BPFD dominant production mechanism of thermonuclear neutrons. This finding fits with general picture obtained by comparing the results of different devices with similar energy. It was noted that the contribution of neutrons generated beam-target mechanism increases with the power capacitor and the size of the device.

6. Conclusions

Numerical experiments carried out using the universal plasma focus laboratory facility based on the Lee model code give reliable scaling laws for neutrons production for BPFD comparable with experimental data from BPFD. This scaling law is also useful for design considerations of improving performances of our machine.

BPFD is intended to operate as optimized neutron source or hard X-ray source. Using Lee model code as a reference, several upgrades of BPFD must be made: better shielding against EMI pulse, rearrangement of capacitors bank so that higher repetition rate can be achieved and also faster digital acquisition system. BPFD can be used for neutron activation or production of short-living radioisotopes. These radioisotopes will have very low activity which can be analyzed in the underground Low-Background Laboratory for Nuclear Physics, Zemun [22]. BPFD can be also optimized as a hard X-ray source for industrial purpose, and several new plasma diagnostic windows are already added for better understanding of heavier gases' plasma, such as Ar, N_2, O_2, as a source of hard X-rays.

The results indicate that this code, now incorporated with a beam-target mechanism, gives realistic plasma dynamics and focus properties together with a realistic neutron yield, applicable to a wide range of plasma focus devices, without the need of any adjustable parameter, needing only to fit the computed current trace to a measured current trace. We may also remark that to do a better evaluation of any model for the mechanism of neutron production in plasma focus devices, it is necessary to use experimental diagnostics with high spatial and temporal resolution. Temporal and spatial resolution close to the pinch moment is crucial to describe properly the plasma heating.

Acknowledgements

This work is supported by the Ministry of Education, Science and Technological Development of Republic of Serbia under project OI171002.

REFERENCES

[1] J. Raeder, *et al.*, "Controlled Nuclear Fusion," John Wiley & Sons, Hoboken, 1986.

[2] J. W. Mather, "Dense Plasma Focus," In: R. H. Lovberg and H. R. Griem, Eds., Methods of Experimental Physics, Vol. 9B, Academic Press, New York, 1971, pp. 187-250.

[3] N. V. Filippov, T. I. Filippova and V. P. Vinogradov, *Nuclear Fusion*, Suppl. 2, 1962, pp. 577-587.

[4] L. Soto, *Plasma Physics and Controlled Fusion*, Vol. 47, 2005, pp. A361-A381. http://dx.doi.org/10.1088/0741-3335/47/5A/027

[5] A. Tartari, G. Verri, A. D. Re, F. Mezzeti, C. Bonifazzi and L. Rapezzi, *Measurement Science and Technology*, Vol. 13, 2002, pp. 939-945. http://dx.doi.org/10.1088/0957-0233/13/6/316

[6] E. Angeli, A. Tartari, M. Frignani, V. Molinari, D. Mostacci, F. Rocchi and M. Sumini, *Nuclear Technology & Radiation Protection*, Vol. XX, 2005, pp. 33-37. http://dx.doi.org/10.2298/NTRP0501033A

[7] B. Shirani, F. Abbasi and M. Nikbakht, *Applied Radiation and Isotopes*, Vol. 74, 2013, pp. 86-90. http://dx.doi.org/10.1016/j.apradiso.2013.01.011

[8] A. Talaei, S. M. Sadat Kiai and A. A. Zaeem, *Applied Radiation and Isotopes*, Vol. 68, 2010, pp. 2218-2222. http://dx.doi.org/10.1016/j.apradiso.2010.06.012

[9] R. Antanasijević, I. Lakićević, Z. Marić, D. Šević, A. Zarić and J. P. Vigier, *Physics Letters A*, Vol. 180, 1993, pp. 25-32.

http://dx.doi.org/10.1016/0375-9601(93)90489-M

[10] V. Udovičić, "Yields of Light Ion-Ion Nuclear Reactions in Plasma Induced by Pulse Electrical Discharges," Ph.D. Thesis, University of Belgrade, 2006.

[11] R. Antanasijević, Z. Marić, R. Banjanac, A. Dragić, J. Stanojević, D. Đorđević, D. Joksimović, V. Udovičić and J. B. Vuković, *Radiation Measurements*, Vol. 31, 1999, pp. 443-446. http://dx.doi.org/10.1016/S1350-4487(99)00147-X

[12] D. Joksimović, "Analysis of the Characteristics of Soft X-Rays Emitted from the Plasma Focus," Ph.D. Thesis, University of Belgrade, 2001.

[13] R. Antanasijević, J. B. Vuković, D. Šević, D. Joksimović, A. Dragić, V. Udovičić, J. Purić and M. Ćuk, *Radiation Measurements*, Vol. 28, 1997, pp. 245-248. http://dx.doi.org/10.1016/S1350-4487(97)00076-0

[14] R. Antanasijević, A. Dragić, D. Joksimović, Z. Marić, D. Šević, Ž. Todorović and V. Udovičić, *Radiation Measurements*, Vol. 28, 1997, pp. 241-243. http://dx.doi.org/10.1016/S1350-4487(97)00075-9

[15] R. Antanasijević, Z. Marić, R. Banjanac, A. Dragić, J. Stanojević, D. Đorđević, D. Joksimović, V. Udovičić and J. B. Vuković, *Radiation Measurements*, Vol. 31, 1999, pp. 443-446. http://dx.doi.org/10.1016/S1350-4487(99)00147-X

[16] R. Antanasijević, R. Banjanac, A. Dragić, Z. Marić, J. Stanojević, V. Udovičić and J. Vuković, *Radiation Measurements*, Vol. 34, 2001, pp. 615-616. http://dx.doi.org/10.1016/S1350-4487(01)00240-2

[17] R. Antanasijević, R. Banjanac, A. Dragić, D. Joković, D. Joksimović, B. Grabež, V. Udovičić, D. Đorđević, J. Stanojević and J. Vuković, *Radiation Measurements*, Vol. 36, 2003, pp. 327-328. http://dx.doi.org/10.1016/S1350-4487(03)00145-8

[18] R. Banjanac, V. Udovičić, B. Grabež, B. Panić, Z. Marić, A. Dragić, D. Joković, D. Joksimović and I. Aničin, *Radiation Measurements*, Vol. 40, 2005, pp. 483-485. http://dx.doi.org/10.1016/j.radmeas.2005.06.012

[19] V. Udovičić, A. Dragić, R. Banjanac, D. Joković, N. Veselinović, I. Aničin, M. Savić and J. Puzović, *Journal of Fusion Energy*, Vol. 30, 2011, pp. 487-489. http://dx.doi.org/10.1007/s10894-011-9418-z

[20] S. Lee and S. H. Saw, *Journal of Fusion Energy*, Vol. 27, 2008, pp. 292-295. http://dx.doi.org/10.1007/s10894-008-9132-7

[21] S. Lee, S. H. Saw, L. Soto, S. V. Springham and S. P. Moo, *Plasma Physics and Controlled Fusion*, Vol. 51, 2009, Article ID: 075006. http://dx.doi.org/10.1088/0741-3335/51/7/075006

[22] A. Dragić, V. Udovičić, R. Banjanac, D. Joković, D. Maletić, N. Veselinović, M. Savić, J. Puzović and I. V. Aničin, *Nuclear Technology and Radiation Protection*, Vol. XXVI, 2011, pp. 181-192. http://dx.doi.org/10.2298/NTRP1103181D