Research on the Enhancement of the Thermonuclear Component of the Neutron Yield in Pinch Plasma Focus Devices

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Abstract. The possibility to enhance the thermonuclear component against the beam target component of the neutron yield in plasma focus devices is being studied. At present, the Chilean Nuclear Energy Commission (CCHEN) has the experimental facilities and diagnostics in order to study plasma focus discharges in a wide range of energies (50J to 100kJ) and currents (40kA to MA). The devices at CCHEN are PF-50J, PF-400J, SPEED4 and SPEED2. As a part of our research program the possibility to study how to enhance the drive parameter (related with the plasma sheath velocity) and the plasma energy density and their role in the thermonuclear component of the neutron yield has been recently included. There are theoretical conjectures suggesting that increasing the drive parameter, it could be possible to increase the thermonuclear component of the neutron yield and to decrease the beam target component. Preliminary results of this research program are presented.

1. Introduction

The plasma focus is a kind of pinch discharge, it reproduces the scenario of high energy density, intense beams of charged and neutral particles, and radiation emission. Thus it becomes a laboratory for fundamental and applied research related to fusion, neutron production, hard X ray and high brightness soft X-ray production. A plasma focus is a particular pinch discharge in which a high pulsed voltage is applied to a low pressure gas between coaxial cylindrical electrodes. The central electrode is the anode partially covered with a coaxial insulator. The discharge starts over the insulator surface, and afterwards the current sheath is magnetically accelerated along the coaxial electrodes. After the current sheath runs over the ends of the electrodes the plasma is compressed in a small cylindrical column (focus or pinch). In most of the devices these three stages last a few microseconds. The maximum pinch compression should be coincident with peak current in order to achieve the best efficiency. The pinch generates beams of ions and electrons, and ultra-short X-ray pulses. In the pinch the temperature is ~1keV and the density is $\sim 10^{25}\mathrm{m}^{-3}$. Using deuterium gas, plasma focus devices produce fusion D-D reactions, generating fast-neutrons pulses (~ 2.5 MeV) and protons (leaving behind ^{3}He and ^{3}H).

At present the Plasma Physics and Plasma Technology Group of the Comisión Chilena de Energía Nuclear (CCHEN) has the experimental facilities in order to study dense transient discharges, particularly plasma focus, in a wide range of energy and current keeping the same time scale. The program research includes: a) mechanism of X-ray emission (thermal vs. beam bremsstrahlung), mechanism of neutron emission (thermonuclear vs. beam-target), charged particles beams emission; b) development of diagnostics; and c) development of optimized apparatus for flash sources of neutrons and x-rays (nanoflashes) and possible applications and d) studies about of how to enhance the drive parameter (related with the plasma sheath velocity) and its role in the thermonuclear component of the neutron yield. This last topic has been recently included.

Several diagnostics have been implemented: voltage, total current and current derivative monitors; plasma images with an intensified CCD camera gated at 5 ns exposure time; silver activation counter and ^{3}He detectors for neutron yield measurements; plastic scintillator with photomultiplier for X-ray and neutron detection with temporal resolution; VUV and soft X-ray spectroscopy; and pulsed optical refractive diagnostics using a pulsed Nd-YAG laser.

In this article we present and discuss results related to the neutron emission and discuss the mechanisms of the emission in our plasma focus devices.

2. The Devices

An area of research that is not well explored is that of the very-small low-energy plasma foci. Feasibility objections have been made to devices with lower energies (less than 1kJ), for not having enough energy and time to create, move and compress the plasma. We have shown that those objections are not applicable [1- 3].

As first stage of a program to design a repetitive pulsed radiation generator for industrial applications we constructed two very small plasma focus operating at an energy level of the order of a) tens of joules (PF-50J, 160 nF capacitor bank, 20-35 kV, 32-100 J, ~150 ns time to peak current) [8-10] and b) hundred of joules (PF-400J, 880 nF, 20-35 kV, 176-539 J, ~300 ns time to peak current) [1].

The compact and fast plasma foci devices constructed by CCHEN, PF-400J and PF-50J, consists of capacitors banks that discharge over coaxial electrodes through spark-gaps. The capacitor bank consists in four capacitors connected in parallel. Four capacitors of 220 nF-20 nH in PF-400J case and 40 nF-20 nH in PF-50J case. The devices operate with charging voltages of 20 to 35 kV. In order to obtain low inductance the capacitors were connected in a compact layout. Short and coaxial spark-gaps were designed for the same purpose. The measured total external inductance is 38 nH. The total impedance of the generator is of the order of 0.2 Ω for the PF-400J and 0.5 Ω for the PF-50J. To determine the size of the electrodes the design relations suggested by S. Lee [4] and a theoretical model of plasma focus for neutron production [5] were applied. It is known that the pinch phase in a plasma focus is highly dependent of the current sheath formation over the insulator. Unfortunately, there are still not validated theoretical models to determine the dimensions of the insulator. Therefore, several tests with different insulator length and diameter, scanning pressure range from 1 to 12 mbar, were necessary to determine the size of the insulator in order to obtain a homogeneous initial sheath. The current sheath was studied with an image converter camera with 5ns exposure time. The final electrodes for the PF-400J consist of a 28 mm long, 12 mm diameter cooper tube anode, and an outer cathode of eight 5mm diameter copper rods uniformly spaced on a 31mm diameter circumference. The anode and cathode were separated by an alumina tube of 21 mm length. In the case of the PF-50J after some improvements from the original design [6, 7, 2], the electrodes configuration consists of a 29 mm long, 6 mm diameter copper tube anode, and an outer cathode of eight, 5 mm diameter cooper rods uniformly spaced on a circumference with diameter of 27 mm. Anode and cathode were separated by an alumina tube of 24 mm length. Such configurations resulted from the short first quarter period of the discharge current (200-300 ns, due to the small bank capacity), which require a short effective anode (6-7 mm). The size of these devices is of the order of 25 cm x 25 cm x 50 cm. The design calculations indicate that neutrons yields of 10^4 – 10^5 neutrons per shot are expected with discharges in deuterium in the PF-50J and $5x10^5$ – $5x10^6$ neutrons per shot in the PF-400J.

On the other hand, SPEED2 and SPEED4 are generators based on Marx technology and were designed in the University of Düsseldorf. SPEED2 consists on 40 +/- Marx modules connected in parallel. Each module has 6 capacitors (50kV, 0.625 μF, 20nH) and 3 sparkgaps, so the pulse power generator SPEED2 is a medium energy and large current device (4.1 μF equivalent Marx generator capacity, 300 kV, 4 MA in short circuit, 187 kJ, 400 ns rise time, dI/dt~10^{13} A/s) [8].The SPEED2 arrived at the CCHEN in May 2001 from Düsseldorf University, Germany, and it is in operation since January 2002, being the most powerful and energetic device for dense transient plasma in the Southern Hemisphere. Moreover, SPEED2 is the unique dense plasma transient experiment operating at currents of Mega-amperes in Chile. Simultaneously an intermediate device, SPEED4, has been constructed. It consists of 4 +/- Marx modules connected in parallel, each module has 2 capacitors and 1 sparkgap (50kV, 0.625 μF, 20nH), and currently is being set up in operation (SPEED4: 1.25 μF equivalent Marx generator capacity, 100 kV, 550 kA, 350 ns rise time, dI/ dt~10^{12} A/s).

Experiments in different Z-pinch configurations, at current of hundred of kiloamperes to mega-amperes, using the SPEED 2 generator will be carried out. A device designed 15 years ago will be used for the research of scientific topics relevant today and for the research and development of new ideas.

Most of the previous works developed in SPEED2 at Düsseldorf were done in a plasma focus configuration for X-ray emission and the neutron emission from SPEED2 was not completely studied. The Chilean operation has begun implementing and developing diagnostics in a conventional plasma focus configuration in order to characterized the neutron emission. Then, after getting the experimental expertise with SPEED2, new experiments in a quasi-static Z-pinch [9-12], gas puffed plasma focus, and wires array will be developed to extend the device capabilities. Also SPEED2 and SPEED4 will be used in the development of applications of radiation pulses from hot, dense plasmas, including X-ray and neutron radiography, detection of substances, micro-radiography for applications to microelectronic lithography and diagnostics of nanostructures. Plasma focus on SPEED 2 is an intense pulsed source of neutrons (10^{11}-10^{12} neutrons per pulse) and X-rays. Plasma focus in SPEED 4 with heavy gases will be used as an intense source of soft X-rays. The applications will be developed using the above generators in order to determine the radiation threshold for the various types of applications (radiography, neutrography, substances detection). This information will be used to design smaller devices suited for applications.

In the table I the principal parameters of the plasma focus devices at the CCHEN are listed.

3. Neutrons detection

A silver activation counter, calibrated with an Am-Be source, placed at 30 cm in the side-on direction was used to record the integrated neutron signal for total yield over $5x10^5$ neutrons per shot (PF-400J, SPEED4 and SPEED2). For total neutron yield lower than $5x10^5$ neutrons per shot (PF-50J) a system based on ^{3}He detector was developed [13]. A conventional neutron detection technique was adapted to measure low neutron yields from D-D fusion pulses. ^{3}He proportional counters are well known neutron detectors whose detection principle is based on the nuclear reaction, n(He^3,H^3)p. An analogic signal corresponding to the current generated in the ^{3}He tube is registered through a preamplifier whose output is directly connected to a digital oscilloscope. The time-integrated signal is the charge generated in the ^{3}He tube and it is proportional to the neutron yield. Time of integration is determined by the characteristics of the preamplifier and is about some hundred of microseconds. No neutron background is detected during this temporal window. To calibrate the ^{3}He detection system (with moderator included) a silver activation counter (previously calibrated with an Am-Be source) was used as a neutron calibration reference. Both detectors, the adapted ^{3}He and the silver activation counter were used simultaneously in the PF-400J detecting neutron yields from 5x10^5 to 2x10^6 neutrons per shot. A linear proportional relation was obtained between the ^{3}He time integrated signal and the neutron yield measured by the silver activation counter. Neutron yields lower than 10^3 neutrons per pulse were possible to be measured with this detector [13]. Also detectors based on plastic scintillator connected to photomultiplier for X-ray and neutron detection with temporal resolution have been implemented.technique.

TABLE I: PRINCIPAL PARAMETERS OF THE PLASMA FOCUS DEVICES AT CCHEN

Device	**PF-50J**	**PF-400J**	**SPEED 4**	**SPEED 2**
Capacity (μF)	0.160	0.880	1.25 *	4.16*
Charging voltage (kV) Maximum Typical operation	 35 25-30	 35 30	 100 60	 300 180
Inductance (nH)	38	38	40	20
Time to peak current (ns)	150	300	350	400
Stored energy (kJ) Maximum Typical operation	 0.1 0.05-0.07	 0.54 0.4	 6.25 2.25	 187 67
Peak current (kA) Maximum Typical operation	 70 50-60	 168 127	 550 330	 4000 2400
Anode radius (cm)	0.3	0.6	1.6	5.4
Cathode radius (cm)	1.1	1.3	4.5	11
Effective anode length (cm)	0.48	0.7	1-2	1.5-2.5
Insulator length (cm)	2.4	2.1	2.7-3.9	6.5

***** equivalent Marx generator capacity

4. Results

4.1 PF-50J and PF-400J

Neutron emission studies were performed in discharges in deuterium at different pressures, 5 to 12 mbar, with a charging voltage of 30±2 kV in the PF-400J and 29±2 kV - 25±2kV in the PF-50J (~400 J and ~70-50 J stored in the capacitor bank respectively). The typical dip in the signals of the current derivative associated with the formation of a pinched plasma column on the axis was observed in both devices [1, 2]. From the current derivative signals the implosion time (pinch time, measured at the moment for the minimum in dI/dt) versus filling pressure was obtained. The maximum compression of the plasma occurs close to the peak current for a pressure close to 7mbar in the PF-400J and close to 6mbar in the PF-50J.). Also signals from two detectors based on plastic scintillator connected to photomultiplier were obtained. An energy of the order of (2.42 ±

0.39) MeV and (2.29 ± 1.28) MeV has been estimated for the PF-400J and PF-50J from time of flight measurements.

The neutron yield as a function of the filling gas pressure was obtained. The maximum measured neutron yield was $(1.06\pm0.13)x10^6$ neutrons per shot at 9 mbar in the PF-400J [1] and $(3\pm1.5)x10^4$ neutrons per shot at 9 mbar in the PF-50J operating at 70 J and $(1.1\pm0.5)x10^4$ neutrons per shot at 6 mbar in the PF-50J operating at 50 J [3].

4.2 SPEED2 and SPEED4

The Chilean operation of the SPEED2 device has begun implementing and developing diagnostics in a conventional plasma focus configuration. Discharges in plasma focus mode have been performed at +/-30 kV charging voltage in a (i.e. 180 kV, 67 kJ). A peak current greater than 2 MA was achieved.

SPEED2 uses a especial insulator, quartz covered with alumina, and it requires several shots of preparation in order to obtain a neutron yield with a dispersion lower than 30% between shots. We have not had enough shots with the same insulator in order to achieve the proper conditions of operation. Preliminary results obtained at CCHEN show a neutron yield of the order of 10^{10} neutrons per shot, the maximum value obtained up to now at CCHEN is $2x10^{10}$ neutrons per shot. In Düsseldorf a neutron yield of the order of 10^{11}-10^{12} neutrons per shot was obtained [14]. Time resolution neutron detection are now being implemented.

SPEED4 has been assembling, however evidence of pinch in the electrical signals it has not been observed yet.

5. Discussion

As part of our research program two very small plasma foci have been designed, constructed and set up in operation. One in the rage of hundred of joules (PF-400J) and other in the range of tens of joules (PF-50J). The region of tens joules was unexplored up to now. Neutron emission versus filling pressure have been obtained in both devices [1, 3]. An especial technique was necessary to develop to detect neutron pulsed of the order of 10^4 neutrons per shot. The maximum measured neutron yield was of the order of 10^6 and 10^4 neutrons per shot in the PF-400J and PF-50J respectively. On the other hand preliminary results on neutron emission from SPEED2 has been obtained. In table II the results related to the neutron yield obtained in the experiments at CCHEN are shown.

A comparison between plasma foci of different energies is necessary. Although only fraction of the initial energy stored E in the capacitor bank is transferred to the plasma, the parameter E/V_p (with V_p the plasma volume) is usually used to characterize the plasma energy density in order to compare different devices. According with scaling laws [15] and optical diagnostics [7] the final pinch radius (previous to appearance of instabilities with the subsequent appearance of smaller inhomogeneities in the plasma column) is of the order of $0.12a$ and the maximum pinch length is of the order $0.8a$. Thus the final plasma volume V_p (previous to appearance of probable instabilities) is of the order of $\pi(0.12a)^2x(0.8a)=0.036a^3$, and the plasma energy density at the pinch moment is proportional to $E/V_p \sim 28E/a^3$. In table 3 the parameter $28E/a^3$ is listed for various PF devices and his value is of the order of (1-10)x10^{10} J/m^3 [2]. The value of this energy density parameter in the case of the very small devices PF-400J and PF-50J is (5-7)x10^{10} J/m^3.

Other relevant parameter in plasma foci is the called drive parameter ($I_o/ap^{1/2}$) [15], where I_o is the peak current, a the anode radius, and p the gas filling pressure for the maximum neutron yield. This drive parameter ($I_o/ap^{1/2}$) is related with the velocity of the axial and radial phase of the plasma motion (of the order of (0.8-1)x10^5 and (2-2.5)x10^5 m/s respectively for a wide range of plasma focus sizes). In fact the axial and radial velocity are proportional to ($I_o/ap^{1/2}$) [4, 15]. For devices over the range 3kJ-1MJ the drive parameter $I_o/ap^{1/2}$ = 77±7 kA/cm·mbar$^{1/2}$ [15]. In Table III the drive parameter ($I_o/ap^{1/2}$) is listed for various PF devices. The drive parameter for the very small devices PF-400J and PF-50J is evaluated in ~70 kA/cm·mbar$^{1/2}$.

TABLE II: MAXIMUM NEUTRON YIELD FOR PLASMA FOCI AT CCHEN

Device	**Operation energy (kJ)**	**Operation pressure (mbar)**	**Peak Current (kA)**	**Neutron Yield (neutrons)**
SPEED 2	67	2-3	2400	~ 10^{11}-10^{12} (Düsseldorf) [14] ~2x10^{10} (CCHEN)
SPEED 4	1.56	2-9	280	-
PF-400J	0.4	9	127	(1.06±0.13)x10^6
PF-50J	0.07 0.05	9 6	60 50	(3.3±1.6)x10^4 (1.1±0.5)x10^4

TABLE III: ENERGY DENSITY PARAMETER AND DRIVEN FACTOR FOR SEVERAL PLASMA FOCUS DEVICES

Device [reference]	**Energy E (kJ)**	**Anode radius *a* (cm)**	**Peak current (kA)**	**Pressure (mbar)**	**Energy density parameter $28\ E/a^3$ (J/m^3)**	**Driven factor $I/p^{1/2}a$ (kA/mbar$^{1/2}$cm)**
PF-1000 [21]	1000	11.5	2	6	1.8x10^{10}	72
PF-360 [22]	60	5	750	4	1.3x10^{10}	75
SPEED2 [8]	70	5.4	2400	2.7	1.2x10^{10}	270
GN1 [5]	4.7	1.9	-	-	1.9x10^{10}	-
UNU/ICTP-PFF [4]	2.9	0.95	172	8.5	9.5x10^{10}	81
Fuego Nuevo II [24, 25]	4.6	2.5	350	3.7	0.8x10^{10}	73
PF-400J [1]	0.4	0.6	127	9	5.2x10^{10}	70
PF-50J [3]	0.07 0.05	0.3 0.3	60 50	9 6	7.3x10^{10} 5.2x10^{10}	66.7 68

It is important to note that the parameters used in the design, construction and operation of the plasma focus at SPEED2 give a drive parameter very high in comparison with the other devices listed in the table III. It is remarkable that if this parameter is experimentally increased over 90kA/cm mbar$^{1/2}$ (modifying I_o, a, or p) the plasma focus does not work, this is the experience in the most of plasma focus [16]. However, in SPEED2 evidence of pinch has been observed and neutron yield has been measured with a high value of ($I_o/ap^{1/2}$). An exhaustive characterization of the neutron emission from the plasma focus at SPEED2 is required to clarify this point.

It is usually accepted for plasma focus devices operating in deuterium, that the total neutron yield Y, is $Y=Y_{th} + Y_{b-t}$, where Y_{th} is the thermonuclear component and Y_{b-t} is the beam target component.

Moo et al [17] have shown that Y_{th} : $Y_{b\text{-}t}$ is of the order of 15 : 85 in conventional plasma focus machines.

The possibility to enhance the thermonuclear component of the neutron yield increasing the drive parameter ($I_o/ap^{1/2}$) has been discussed by S. Lee and A. Serban [18, 19]. Lee and Serban have proposed, as the square root of the pressure, $p^{1/2}$, varies very little (less than 40%) relative to the variation of I (10 times or more), (I/a) may by considered to have the almost a fixed value for a wide range of devices. The pinch plasma in the range of 3kJ to MJ all having practically the same temperature, T~1keV, and density, n ~ 10^{25} m^{-3}, the thermonuclear component of the neutron yield will thus be proportional to a^4 (a^3 from the volume dependence and another factor a from the pinch lifetime dependence). This gives the well-known law Y_{th} α I^4 that is observed in plasma focus devices. The above argument also suggests that this observed law is due to the fixed speed (or fixed energy density) operation over the whole range of plasma focus machines. If the value of (I/a) is increased, speed will increase with (I/a), and T will increase with $(I/a)^2$. In the present range of operation of plasma focus (~1keV when is used D_2), increase in T will lead to increase in fusion cross section $\langle\sigma v\rangle$ proportional to T^{ν}, with ν ~ 4, thus $\langle\sigma v\rangle \sim (I/a)^8$. Thus $Y_{th} \sim \langle\sigma v\rangle$ (volume)(pinch lifetime) α $(I/a)^8$ $(a^3)(a) = (I/a)^4 I^4$. Thus, if (I/a) is a constant, this reduces to Y_{th} α I^4 as noted above. Otherwise $(I/a)^4 I^4$ (or $v^4 I^4$), if (a) is kept constant as I is increased then Y_{th} α I^8 . With this improved or enhanced yield dependence, the thermonuclear component of neutron yield will rapidly outstrip the beam target component. Assuming a simple model for the beam target component of the neutron yield, the relation $Y_{b\text{-}t}$ α $I^{9/2}/v^{3/2}$ α $I^{9/2}/(I/a)^{3/2}$ was obtained in the reference [16]. Thus in the limit, if a is keeping constant whilst increasing I, $Y_{b\text{-}t}$ α I^3 and Y_{th} α I^8. In reference [18] as way to obtain a plasma focus operating with a high value of the drive parameter a composite anode was used (a one piece anode with diameter reduced at the end was used), and a enhanced of the order of 12 to 16% in the neutron yield was reported.

In the above frame the evidence of pinch and measured neutron yield obtained in the SPEED2 with a high value of ($I_o/ap^{1/2}$) deserve an exhaustive study and characterization of the neutron emission. On the other hand from our experiments in plasma foci with hundred and tens of joules (PF-400J and PF-50J in table 2) it is observed that the total neutron yield scaling as $Y \sim 7.73\text{x}10^{-5} I^{4.82}$ (with I in kA). This last observation motives future experiments in order to determinate the contribution of Y_{th} and $Y_{b\text{-}t}$ to the total neutron yield and to corroborate this preliminary scaling law for the region of hundred and tens of joules. In addition experiments with composite anodes and different shape anodes will be developed in this very small devices.

In the idea to scale a plasma focus to very low energy our question is, how low can we go in loading energy and still obtaining the plasma pinch and neutron emission? When do the plasma surface effects start to be relevant? Could these effects be favorable in order to increase the plasma energy density for much smaller devices improving the generation of fusion reactions and radiation? An extremely small device has been recently designed and constructed by us, a "nanofocus" (5nF, 10kV, 10kA, 0.25J, 10 ns time to peak current, dI/dt~10^{12} A/s) and is currently being characterized [23].

The future diagnostics program in our devices considers time integrated and time resolution X-ray images, PIN diode and plastic scintillator with photomultiplier, X-ray spectroscopy and pulsed interferometry. Also a characterization of the isotropic and anisotropic components of the neutron yield is being performed using CR-39 nuclear track detectors distributed angularly [20].

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