Fusion studies using plasma focus devices from hundred of kilojoules to less than one joule. Scaling, Stability and Fusion Mechanisms

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Abstract. Fusion studies using plasma focus devices from hundred of kilojoules to less than one joule performed at the Chilean Nuclear Energy Commission are presented. The similarity of the physical behaviour and the scaling observed in these machines are emphasized. Experiments on actual devices show that scaling holds at least through six order of magnitude. In particular all of these devices, from the largest to the smallest, keep the same quantity of energy per particle. Therefore, fusion reactions are possible to be obtained in ultraminiature devices (driven by generators of 0.1J), as they are in the bigger devices (driven by generators of 1MJ). However, the stability of the plasma depends on the size and energy of the device.

1. Introduction

A Plasma Focus (PF) is a kind of pinch discharge in which a high-pulsed voltage is applied to a low-pressure gas between coaxial cylindrical electrodes, generating a short-duration high-density plasma region in the axis on the anode. In the majority of the devices the discharge last a few microseconds, and less than 500 ns in a new generation of fast plasma foci [1]. The maximum pinch compression should be close with the peak current in order to achieve the best efficiency. Depending on the energy of the pulse power generator, the current in the pinch varies from tens of kA to some MA. The pinch generates beams of ions and electrons, and ultra-short X-ray pulses. The duration of these pulses is of the order of tens to hundreds of nanoseconds. Using deuterium gas, plasma focus devices produce fusion D-D reactions, generating fast-neutron pulses (~ 2.5 MeV) and protons (leaving behind ^{3}He and ^{3}H).

A feature of the PF devices is that there are plasma parameters that remain relatively constant for facilities in a wide range of energy, from 50J to 1MJ, electron density ~10^{25} m^{-3}, temperature in the range 300eV - 1keV. Other interesting feature is that the velocity of the current sheath is practically the same in every optimized plasma foci (for discharges in deuterium is the order of 1x10^5 m/s in the axial phase and of the order of 2.5x10^5 m/s in the pinch compression in every optimized plasma foci). Those features are related with two parameters that remain practically constant in a wide range of plasma focus devices and these are the "drive parameter" $I_O/ap^{1/2}$ [8] and "energy density" $28E/a^3$ [1, 5], where E is the energy stored in the capacitor bank, I_O is the peak current, a the anode radius, and p the gas filling pressure for the maximum neutron yield. For Mather-type and hybrid-type plasma focus devices operated in the neutron emission optimized regime, the driver parameter has the value of 77 ±7 kA/cm•mbar$^{1/2}$ [1].

The Thermonuclear Plasma Department of the Chilean Nuclear Energy Commission (CCHEN) has, from around ten years ago, managed plasma production devices to study dense hot plasmas [1-7]. The aim of the current research work has been to characterize the physics of these plasmas and also to carry out the design and construction of smaller plasma focus devices –in terms of both input energy and size– capable of providing dense hot plasmas. Fusion reactions are obtained in these devices when deuterium is used as working gas. The saga to push ahead the current status of the field has had several achievements. For instance, it was made and put into work a device of very low energy (less than 1J, i.e., three or four orders of magnitude lower than the smallest device previously developed) that still produces radiating dense hot plasmas. In fact, recent experimental evidence shows that even the ultraminiature device is capable to produce neutrons from fusion reactions [7].

The research work and the expertise developed in the group include transient electrical discharges going from 100kJ to 0.1J, plasma diagnosis and pulsed power technology. Experimental results about the plasma dynamics, electron density, neutron yield, neutron energy and x-rays have been obtained. In this work, results obtained from experiments in plasma focus devices, of which stored energies are 0.1J , 50J, 400J, and 70kJ are presented. In addition, theoretical simulations in order to evaluate the energy transfer from the electrical generator to the plasma are being developed. The similarity of the physical behavior and the scaling observed in these machines is emphasized. Experiments on actual devices show that scaling holds at least through six order of magnitude. In particular all of these devices, from the largest to the smallest, keep the same quantity of energy per particle. Therefore, fusion reactions are possible to be obtained in the ultraminiature device, as they are in the bigger devices. However, the stability regimes for the plasma depends on the size and energy of the device.

2. Results

Results obtained in the PF research program at CCHEN can be summarized in the following list:

2.1 Installation, design and construction of PF devices.

Installation and operation of the SPEED2 device. SPEED2 was transferred from University of Düsseldorf to CCHEN and it is in operation since 2001. It is based in Marx technology (SPEED2: 4.1 μF equivalent Marx generator capacity, 300 kV, 187kJ, 4 MA in short circuit, 400 ns time to peak current).

Construction of the SPEED4 device. SPEED4 has been assembled, however evidence of pinch in the electrical signals it has not been observed yet. Also SPEED4 is based in Marx technology (SPEED4: 1.25 μF equivalent Marx generator capacity, 70 kV, 3kJ, 350 ns time to peak current)

Design and construction of compact and fast devices with energy lower than 1kJ. An area of research that is not well explored corresponds to very-small low-energy plasma foci. Feasibility objections have been made to devices with lower energies (less than 1kJ), for not having energy and time enough to create, move and compress the plasma. We have shown that those objections are not applicable [2-4]. PF devices of 400J, 50J and 0.1J have been designed and constructed in our laboratory (PF-400J: 880 nF, 20-35 kV, 176-539 J, ~300 ns time to peak current; PF-50J, 160 nF, 20-35 kV, 32-100 J, ~150 ns time to peak current; Nanofocus, (NF: 5nF, 5nH, 5-10kV, 60-250mJ, 16ns time to peak current) [5, 7]. Evidence of pinch have been obtained in these three devices. After our works in PF devices operating under 1kJ, an increased interest in the research and development of this kind plasma focus devices operating with hundred of joules or less has started in other laboratories.

Design considerations of plasma focus devices. After our experience in the design and construction of the PF-400J and PF-50J devices we have observed that the plasma parameters, which are practically constant in plasma focus devices, are correlated with the value of electrical and geometrical parameters of the devices. This is useful for considerations of design. The first criterion applied to design miniaturized plasma focus devices is to keep in the plasma pinch the same energy density of the larger devices. The "energy density parameter" and the drive parameter are used for us to design PF devices. To design PF devices we start by defining the features of the capacitor bank (capacity, voltage operation and inductance of the whole generator), then we calculate the dimensions of the anode electrode using the following relations: a) $28E/a^3 = 5\text{x}10^{10}$ J/m^3 , b) $I_o/ap^{1/2} = 77$ kA/cm·mbar$^{1/2}$, and c) the time used in the axial phase plus the time for the radial phase must be equal to the quarter of period of the discharge. Using this procedure, the Nanofocus was designed [5].

Design and construction of a repetitive PF device. A repetitive Plasma focus was designed and built (PFR: 1. 2μF, 30 kV, 160kA, 400ns rise time, dI/ dt~ 4x10^{11} A/s, 3 to 6Hz). In addition, the Nanofocus (5nF, 5nH, 5-10kV, 60-250mJ, 16ns time to peak current) is operating at 20Hz [7].

2.2 Diagnostics.

Several diagnostics have been implemented: voltage and current derivative signals; total neutron yield measurements using silver activation counters and ^{3}He tubes; plastic scintillator with photomultiplier for detection of X-rays and neutron pulses with temporal resolution; plasma images with temporal resolution from visible light; time integrated and temporal resolution X-ray plasma images with filters; pulsed optical refractive diagnostics, interferometry and Schlieren.

Special mention deserves the detection of neutron pulses of low total yield. Miniaturized plasma foci require neutron detection technique capable to detect pulses with less than 10^5 neutrons per pulse. For neutron yields less than 10^6 neutron/pulse, the well known techniques (activation counter, bubble counter system, etc.) are not effective. A conventional neutron detection technique was adapted to measure low neutron yields from D-D fusion pulses. This method uses a ^{3}He proportional counter surrounded by a paraffin moderator. Electric signals generated in the ^{3}He tube are fed into a preamplifier. The output of the preamplifier was directly connected to a digital oscilloscope. The time-integrated signals represent the charge generated in the ^{3}He tube which is proportional to the total neutron yield. Integration time is determined by the preamplifier and moderator characteristics within some hundreds of microseconds. No meaningful neutron background was detected during this time window. The system, previously calibrated, was used to measure the neutron yield (< 10^6 neutron/pulse) generated in a fast and very small plasma focus device designed to operate with energies of tens of joules. Neutron yields as low as 10^3 neutrons per pulse were measured. Details of the system and calibration were published in reference [6].

2.3 Results in plasma focus research.

Neutron yield. Neutron yield vs. deuterium filled pressure have been obtained for PF-400J operating at ~400J and for PF-50J operating at 50 and 70J. The maximum measured neutron yield was $(1.06\pm0.13)\text{x}10^6$ neutrons per shot at 9 mbar in the PF-400J [2] and $(3.6\pm1.5)\text{x}10^4$ neutrons per shot at 9 mbar in the PF-50J operating at 70 J and $(1.3\pm0.5)\text{x}10^4$ neutrons per shot at 6 mbar in the PF-50J operating at 50 J [4]. From these results the following scale rules for PF devices operating under 1kJ have been obtained: $Y \sim 7.73\text{x}10^{-5} I_o^{\ 4.82}$ (with I_o the pinch current in kA), $Y \sim 3.15\ E^{\ 2.13}$ (with E the energy in the capacitor bank in J).

In the SPEED2 the neutron yield vs. deuterium filled pressure is being characterized yet. SPEED2 uses an especial insulator, quartz covered with alumina, and it requires several shots of preparation in order to obtain a neutron yield with 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 at 2-3mbar, 70kJ, 2.4MA. In Düsseldorf a neutron yield of the order of 10^{11}-10^{12} neutrons per shot was obtained [14].

The PF repetitive, PFR, working at 30kV with deuterium at a pressure of 9.2 mbar with a repetition rate from 3 to 6Hz produces 2.1 ± 0.34 $x10^7$, for each burst of 5 seconds of duration, i.e. 15 to 30 shots per burst.

In addition, evidence of neutron emission has been observed in the ultra miniature device Nanofocus operating at 0.1J of stored energy and 20Hz of repetition rate. However, the reproducibility of this miniature device is low and several technological subjects have to be previously solved in order to produce neutrons for periods greater than minutes.

Angular distribution of neutron emission. Angular distribution of the neutron emission was obtained in the PF-400J device using CR-39 nuclear track detectors covered with polyethylene located at several positions (between -90º to 90º). The angular measurements were compared with the total neutron yield (integral of the angular measurements). The results are consistent with an angular uniform plateau (isotropic emission) plus a shape peaked in the direction of the axis of the discharge (anisotropic emission). Isotropic components accounts for 57.5% of the accumulative emission, while the anisotropy component accounts for the remaining 42.5%. Anisotropic component appears between +50º and –50º approximately.

Energy distribution of the neutrons. Five scintillation detectors (scintillator + photomultiplier) were located at different distance in radial orientation with the discharge in the PF-400J, the energy spectrum was obtained, with an average energy and dispersion of (2,5 ± 1) MeV. In the case of the PF-50J only two scintillation detectors were used and the energy of the neutrons was estimated 2.7 ± 1.8 MeV.

X-ray emission. Hard X-ray emission has been studied in the PF-400J using Commercial radiographic film (13x18 cm^2), Curix ST-G2 from AGFA was used together with AGFA suggested developer and fixer for this film. The film is placed inside a plastic light tight cassette, Curix from AGFA, containing intensifying plastic screen sensitive to X radiation. The cassette with film was placed as close to the object to be imaged as possible to favor the image quality. The object is placed between the plasma focus device and the cassette. A photomultiplier tube with plastic scintillator is used to monitor the x-ray emission in each shot. This diagnostic is placed perpendicularly to the symmetry axis at anode top level. Radiographs of an array of filters of different materials of mm thickness were obtained with the PF-400J.

In order to estimate an average energy of the X-ray emitted by the PF devices a monoenergetic radiation was assumed. When a monoenergetic radiation interacts with an element, the classical exponential radiation decay relation through the matter is, $I(x)/I_0 = exp(-K\cdot x)$, where $I(x)/I_0$ is the normalized radiation intensity after travelling a distance x inside the material characterized by a linear attenuation coefficient K. From this relation it is possible to obtain an effective linear attenuation coefficient K when different grey shades of the digitalised images are linked to the $I(x)/I_0$ ratio This method allows to obtain a correlation between K and the X-ray energy. Thus, an effective mean energy of 90±5 keV was obtained for the PF-400J using the Curix ST-G2 AGFA system as recording media.

The same method was used to characterize the X-ray emission from the Nanofocus device operating at 0.1J. Radiographs of an array of aluminum filters of 30, 45 and 60 μm on HP5 Ilford film were obtained integrating 1200 shots on the film. An effective mean energy of 4.3±0.3 keV was obtained.

Plasma dynamics and electron density. An intensified CCD camera (ICCD) gated at 5 ns exposure time, and synchronized with the discharge has been used in order to obtain side view images of the visible light emitted from the plasma. A sequence of the plasma dynamics was obtained for the PF-50J [9]. From the observations, a radial velocity of the order of 10^5m/s was obtained (near the axis was measured $\sim 2\times10^5$ m/s). The pinch radius observed was of the order of 0.12*a*, with *a* the anode radius. This diagnostics also was used to characterize the plasma motion in the Nanofocus device. The dynamics observed from the photographs in this ultraminiaturized device operating at only 0.1J is consistent with the dynamics observed in devices operating at energies several orders of magnitude higher [5].

In addition, an optical refractive system was implemented in order to measure the electron density and the dimensions of pinch column. A Mach-Zender interferometer using a pulsed Nd-YAG laser was implemented (600mJ, 532nm, 8ns). The diagnostics was applied to the PF-400J, a maximum electron density of $(8.4 \pm 1.3) \times 10^{24}$ m^{-3} was measured on the axis. The pinch radius observed with this method in the PF-400J was also of the order of 0.12*a*.

Table 1 summarized the main characteristics of the plasma focus devices at the Chilean Nuclear Energy Commission.

3 Discussions and conclusions.

Several physical magnitudes are practically invariable in plasma focus devices operating with energies from 1kJ to 1MJ. From our researches, we have observed that several of these magnitudes are kept in the devices operating at hundred of joules and tens of joule. One of them is the ion density (of the order of 10^{25} m^{-3} for devices from 1MJ to 1kJ), in the PF-400J device of hundred of joules was measured in 8.4×10^{24} m^{-3} on the axis, same order of magnitude. It is reasonable to expect a similar value of ion density in the PF-50J. In fact, to estimate the maximum ion density in the pinch, $n_{e\,max}$, in PF devices, we consider the sweep gas onto the anode from the filling gas density, n_0, compressed to the pinch radius, r_p , thus $n_{e\,max}=n_0(r_p/a)^2$. Considering that $r_p=0.12a$, and total ionization in the radial phase, a maximum pinch ion density of the order of $n_{e\,max}= 70n_0$ could be obtained. From calculations based in the model developed by S. Lee, a factor of ionization in the radial phase with a value of ~0.3 fits with experimental results of several devices of different energies. Thus, it is reasonable to expect an average pinch ion density of the order of n_e~$21n_0$ in any plasma focus device. Thus in the PF-50J operating at 6 to 9mbar the ion density would be of the order of 6.8×10^{24} m^{-3} to 1×10^{25} m^{-3} .

Likely, plasma compression with an average radial velocity of about 10^5 m/s (near the axis $\sim 2 \times 10^5$ m/s) was measured in the PF-50J [9]. This value is similar to the compression velocity in higher energy devices.

Another relevant invariant parameter in plasma foci, related to neutron production, is the so-called drive parameter ($I_o/ap^{1/2}$) [8], where I_o is the peak current, *a* is the anode radius, and *p* is the gas filling pressure for the maximum neutron yield. For neutron-producing devices ranging 3kJ-1MJ, the drive parameter is practically the same, $I_o/ap^{1/2} = 77 \pm 7$ kA/cm·mbar$^{1/2}$ [1]. The drive parameter for the PF-400J and PF-50J were calculated as 70 kA/cm·mbar$^{1/2}$ and 68kA/cm·mbar$^{1/2}$, respectively.

A theoretical explanation of the observed constant parameters in PF devices based on a similarity approach is being explored at CCHEN.

As was mentioned in the introduction of section 2, it is customary to use the parameter E/V_p (being *E* the initial energy stored in the capacitor bank) to compare the plasma energy density between devices. Of course, this number should only be used for comparison, since only a fraction of the initial energy is transferred to the plasma. For devices from 1kJ to 1MJ, the value is between $(1 - 10) \times 10^{10}$ J/m^3. For the PF-400J and PF-50J, this value is 5×10^{10} J/m^3. Furthermore, it is worth noting that the energy density parameter E/V_p, the ion density *n,* and consequently the energy per ion, is proportional to $E/(V_p\, n)$, in the devices operating at hundred and tens of joules, are similar to the corresponding numbers in devices operating between kJ and MJ.

Device	SPEED2	SPEED4	PF-400J	PF-50J	NF
Capacity (nF)	4.16*	1.25*	880	160	5
Charging voltage (kV) Maximum Typical operation	 300 150	 100 60	 35 30	 35 25-30	 15 5-10
Inductance (nH)	20	40	38	38	5
Time to peak current (ns)	400	350	300	150	16
Stored energy (J) Maximum Typical operation	 187 67	 6.25 2.25	 540 400	 100 50-70	 0.56 0.1
Peak current (kA) Maximum Typical operation	 4000 2400	 550 330	 168 127	 70 50-60	 15 5-10
Anode radius (cm)	5.4	1.6	0.6	0.3	0.08-0.022
Cathode radius (cm)	11	4.5	1.3	1.1	-
Effective anode lenght (cm)	1.5-2.5	1-2	0.7	0.48	0.04
Insulator lenght (cm)	6.5	2.7-3.9	2.1	2.4	1
Maximum repetition rate (Hz) Typical operation	single shot	single shot	1 single shot	1 single shot	50 1-20
Neutron yield per shot	~ 10^{11}-10^{12} (Düsseldorf) [14] ~2×10^{10} (CCHEN)	_	1.2×10^{6} at 400J and 9mbar in D_2 [2]	3.6×10^{4} at 70J and 9mbar in D_2 1.3×10^{4} at 50J and 6mbar in D_2 [4]	10^{3} with low reproducibility **
Size (capacitor bank and discharge chamber)	8mx8mx2m	1mx1mx0.5m	50cmx30cmx30cm	50cmx30cmx20cm	25cmx25cmx5cm
Weight (capacitor bank and discharge chamber) (kg)	10000	200	50	50	5
Energy of the neutrons ± dispersion (MeV)	-	-	2.5±1	2.7±1.8	-
Maximum neutron flux In repetitive operation	-	-	10^{6} n/s	3.6×10^{4} n/s	~10^{4} n/s expected for short periods (less than 1 min.)

Table 1. Main characteristics of the plasma focus devices at CCHEN.
(*) Equivalent capacity of the SPEED generators
(**)An independent measure it being developed in the Centro Atómico Bariloche, Argentina to corroborate the results obtained at CCHEN, Chile.

The pinch temperature in plasma foci is a controversial subject. However, it is possible to assume that every plasma focus that works properly has practically the same temperature. In fact, one of the heating mechanisms is by means of the radial shock wave compression, and the plasma temperature is proportional to the square value of the compression velocity. The axial and radial velocity of the plasma in devices operating from kJ to MJ has a value of the order of 1 and 2×10^{5}m/s respectively, the same values for the PF-50J. In addition, the axial and radial velocities of the plasma sheath in a plasma focus are proportional to the drive parameter, and the plasma temperature is proportional to the square value of the drive parameter [10, 11]. Thus, as the drive parameter is practically the same for devices from kJ to MJ, and the same for the PF-400J and PF-50J, it is possible to assume that the temperature has a value of the same order in every plasma focus that works properly. Moreover the plasma energy density parameter E/V_p and the ion density n are of the same order in every devices operating from kJ to MJ, the same for the PF-400J and PF-50J [2, 4]. This energy per ion, $E/(V_p\ n)$, is also of the same order for devices operating from tens of joules to MJ. Therefore, as the energy per ion is practically the same, the temperature should be practically the same for devices operating from tens of joules to MJ. In the reference [10] the temperature was measured in a plasma focus of some kJ by means of spectroscopy techniques in ~ 0.6 - 1 keV. Then, it is possible to assume that the temperature in any plasma focus operating properly, PF400J and PF-50J included, has a value of that order.

In is interesting note that even several plasma parameters in PF devices remain practically constant, the number of ions per unit length, N, in the pinch is varies with the size of the device. In fact, N is proportional to a^2. Thus, the stability regime in which a plasma focus operates will depend on the size of the device. Empirical and theoretical relationships based on the model developed by S. Lee and the scaling laws observed in plasma focus devices were considered to determine regime of operation, where the large Larmor radius (LLR) effects [12] would play a significant role in the reduction of the growth rate of the m=0 mode in the pinch column. This regime results in a range of values for the current of the pinch, the energy of the generator, the anode radius and an average filling pressure. It is found that the plasma foci in which enhanced stability could be observed, owing to LLR effects, are restricted to devices operating in a range of storage energy that goes from few hundreds of joules to few kilojoules [13].

The drive parameter and plasma density parameter were used as design tools to extend the studies in PF devices up to four orders of magnitude under the conventional small devices that operate with few kilojoules. A plasma focus operating with energy of the order of ~ 0.1-0.2 J was designed and constructed , Nanofocus [9]. Results using an anode radius of 0.8mm showed pinch evidence, however the values of the plasma energy density parameter and drive parameter turned out to be lower in comparison with the values observed in devices operating over the range 50J-1MJ. To increase the plasma energy density parameter and drive parameter experiments with an anode with a radius of only a=0.21mm were performed. Pinch evidence has been also observed under these conditions in discharges in hydrogen and in preliminary discharges in deuterium. The energy density parameter has a value of the order of $E/V_p \sim 3\times10^{11}$ J/m^3 , i.e. one order of magnitude greater than the value observed in devices operating over the range 50J-1MJ. The value of the drive parameter is $I_0 / (p^{1/2}a) \sim 126$ kA/mbar$^{1/2}$ cm, which is greater than the value observed in devices operating over the range 50J-1MJ. There are theoretical conjectures that suggest that the thermonuclear component of the neutron emission can be increased drastically when the drive parameter is increased [8, 1]. Future works in the Nanofocus include studying the X-ray emission using mixtures of gases. Currently, the neutron emission from de Nanofocus is being studied in discharges in Deuterium using a system for measurement of low yield neutron pulses from D-D fusion reactions based upon ^{3}He proportional counter in current mode [6]. Neutron yield of the order of 10^3 neutrons per shot is expected in 10 kA discharges. Improvements in the device are being developed in order to operate it at a repetitive rate of ~100 Hz.

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