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Development of portable neutron generators based on pinch and plasma focus discharges[1]

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Introduction.

The Thermonuclear Plasma Department of the Chilean Nuclear Energy Commission (DPTN-CCHEN) has in the last years worked in the miniaturization of neutron generators based on plasma focus (PF) physics as non radioactive sources of neutrons [1, 2]. Devices to produce pinch PF discharges from deuterium, driven by generators with stored energies lower than one kilojoule have been designed and constructed a) at hundreds of joules (PF-400J, 880 nF, 20-35 kV, 176-539 J, ~300 ns time to peak current) [3] and b) at tens of joules (PF-50J, 160 nF capacitor bank, 20-35 kV, 32-100 J, ~150 ns time to peak current) [4-7]. These very small devices produce pinch plasmas, neutrons and X-rays pulses. Recently, a device named Nanofocus (NF) that works with only 0.1 joules was designed and built [8]. Evidence of X-rays and neutrons emission in this ultraminiaturized device has been obtained. The last improvement in this ultraminiature device was to set it into repetitive operation. In fact, the NF is currently working at a repetition rate of 20 Hz.

The PF-400J produces $\sim 10^6$ neutrons per shot, the PF-50J produces $\sim 10^4$ neutrons per shot and evidence of a production of $\sim 10^3$ neutrons per shot has been obtained in the Nanofocus,

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however several technological subjects must be solved in order to produce neutrons for periods greater than some minutes in this ultraminiature device.

To achieve the results mentioned above a systematic work on the scaling of plasma focus devices in a wide range of size and energies has been developed. In addition, several diagnostics has been carried out and applied.

Design criteria for PF devices.

A characteristic feature of the PF devices is that the plasma parameters remain relatively constant for facilities in a wide range of energy, from tens of joules to 1MJ: electron density is of the order of 10^{25} m^{-3}, the velocity of the current sheath is of the order of $1x10^5$ m/s in the final stage of the axial phase and of the order of $2.5x10^5$ m/s in the pinch compression in every optimized plasma foci for neutron production, and in the optimized devices the plasma temperature is of the order of 1 keV. It is worth to mention that 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 criterium applied to design miniaturized plasma focus devices is to keep in the plasma pinch the same energy density of the larger devices. An "energy density parameter" has been defined [6] as $E/V_p \sim 28E/a^3$ (*E* is the energy stored in the capacitor bank, V_p the pinch volume, and *a* the anode radius) . The "energy density parameter" $28E/a^3$ has a value of the order of $(1\text{-}10)x10^{10}$ J/m^3 [2] for devices operating from 1MJ to tens of joules [2].

Another relevant parameter in plasma foci is the drive parameter ($I_o/ap^{1/2}$) [10], 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 to the velocity of the axial and radial phase of the plasma motion. In fact, the axial and radial velocities are proportional to ($I_o/ap^{1/2}$) [10]. For devices in the range of 1MJ to tens of joules operating in deuterium, the drive parameter is $I_o/ap^{1/2} = 77\pm7$ kA/cm·mbar$^{1/2}$ [2].

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

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) $28E/a^3 = 5x10^{10}$ 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 [2].

Diagnostics.

The set of diagnostics developed and applied includes: electrical signals; fast visible photography; pulsed interferometry; neutron detection using silver activation counters, ^{3}He proportional counters, CR39 plastics; radiography with different filters for X-rays detection and characterization; and plastic scitillators coupled to photomultipliers for X-ray and neutron detection.

Special mention deserves the detection of neutron pulses of low total yield. Miniaturized plasma foci require neutron detection techniques capables 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. In particular the most common technique to measure the total neutron yield in deuterium z-pinches is the activation counter. The limitation to measure low neutron yields using activation counters is the level of the background radiation. As a reference, in a typical silver activation counter it is necessary to integrate the counts by a period of time no less than ~30s (the mean time life of the activated silver, ^{109}Ag, is 24.6s). In a typical silver activation counter the background radiation contributes with 100 to 150 counts in 30s. Those figures would correspond to $5x10^5$ to 10^6 neutrons, thus the lower limit of detection of a typical silver activation counter is of the order of that number of neutrons. A conventional neutron detection technique was adapted to measure low neutron yields from D-D fusion pulses [9]. This method uses a ^{3}He proportional counter "in current mode". The ^{3}He tube is polarized with high voltage and surrounded by a paraffin moderator. An analogue 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 represents the charge generated in the ^{3}He tube and it is proportional to the neutron yield. Integration time is determined by the preamplifier and moderator characteristics and it is about some hundred of microseconds. No neutron background is detected during this temporal window. To calibrate the ^{3}He based detection system (with the 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 a small plasma focus of 400J (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. The system was used to measure the neutron yield (< 10^6 neutron/pulse) in the device designed to operate with energies of tens of joules, PF-50J. Neutron yields as low as 10^3 neutrons per pulse were measured in this devices. Also with this technique evidence of neutrons emission from the Nanofocus operating with only 0.1 joule was obtained.

Main results on neutrons emission in compact and miniaturized devices.

Table 1 is a summary of the main characteristics of the devices designed and constructed at the Chilean Nuclear Energy Commission, CCHEN.

Device	**PF-400J**	**PF-50J**	**NF**
Capacity (nF)	880	160	5
Charging voltage (kV) Maximum Typical operation	 35 30	 35 25-30	 15 5-10
Inductance (nH)	38	38	5
Time to peak current (ns)	300	150	16
Stored energy (J) Maximum Typical operation	 540 400	 100 50-70	 0.56 0.1
Peak current (kA) Maximum Typical operation	 168 127	 70 50-60	 15 5-10
Anode radius (cm)	0.6	0.3	0.08-0.022
Cathode radius (cm)	1.3	1.1	-
Effective anode lenght (cm)	0.7	0.48	0.04
Insulator lenght (cm)	2.1	2.4	1
Maximum repetition rate (Hz) Typical operation	1 single shot	1 single shot	50 1-20
Neutron yield per shot	$1.1x10^6$ at 400J and 9mbar in D_2	$3.3x10^4$ at 70J and 9mbar in D_2 $1.1x10^4$ at 50J and 6mbar in D_2	10^3 with low reproducibility
Size (capacitor bank and discharge chamber)	50cmx30cmx30cm	50cmx30cmx20cm	25cmx25cmx5cm
Weight (capacitor bank and discharge chamber) (kg)	50	50	5
Energy of the neutrons ± dispersion (MeV)	2.5±1	2.7±1.8	-
Maximum neutron flux	10^6 n/s	$3.3x10^4$ n/s	10^4 n/s for short periods (less than 1 min.)

Table 1. Main characteristics of the devices designed and constructed at CCHEN

The neutron yield as a function of the filling gas pressure was obtained for PF-400J and PF-50J. The maximum measured neutron yield was $(1.06\pm0.13)x10^6$ neutrons per shot at 9 mbar in the PF-400J [3] and $(3.3\pm1)x10^4$ neutrons per shot at 9 mbar in the PF-50J operating at 67 J and $(1.1\pm0.5)x10^4$ neutrons per shot at 6 mbar in the PF-50J operating at 50

J [7]. The mean energy of the neutrons was measured by means of time of flight techniques, as 2.5 MeV with a dispersion of 1 MeV for the PF-400J, and as 2.7 MeV, with a dispersion of 1.8 MeV for the PF-50J. On the oher hand, an emission of the order of 10^3 neutrons per shot has been observed in the Nanofocus. The ultimate improvement in this ultraminiature device was put it in repetitive operation, NF is working at a repetition rate of 20 Hz., and produces under laboratory conditions of the order of 10^4 n/s however, several technological subjects must be solved in order to produce neutrons for periods greater than minutes.

Discussions and future works.

Neutron pulses resulting from D-D in miniaturized plasma focus devices has been shown. In particular, a wide characterization of the emitted neutrons was obtained in devices working at hundred and tens of joules. In addition, evidence of neutron emission has been observed in a very small device operating at 0.1J of stored energy and 20Hz of repetition rate. However, the reproducibility of this very small device is low and several technological subjects have to be previously solved in order to produce neutrons for periods greater than minutes. Further studies in the Nanofocus will be carried out. In addition, a device with a stored energy between the boundaries of 50J and 0.1J will be explored. A compact, low weight, portable PF device for field applications is being designed in detail. A device to be operated with few kilovolts (10kV or less) with a stored energy of 2J and a repetition rate of 10Hz without cooling is being projected. The main parameters of the projected device are listed in table 2.

Projected Device	**PF-2J**
Capacity (nF) Inductance (nH) Time to peak current (ns)	200 20 100
Charging voltage (kV) Maximum Typical operation	 15 5
Stored energy (J) Maximum Typical operation	 22.5 2.5
Peak current (kA) Maximum Typical operation	 47 15
Anode radius (cm)	0.1
Typical repetition rate (Hz)	10
Neutron yield per shot	10^3 to 10^4
Size (capacitor bank and discharge chamber)	25cmx5cmx5cm
Weight (kg)	3
Neutron flux	10^4 - 10^5 n/s

Table 2. Main characteristics of the projected portable PF device for field applications.

The work plan for the next 18 months, divided in period of 3 months (Q) is the following:

- Q1: Study of the performance of the Nanofocus device operating at 10 and 20 Hz. To determine the reproducibility of neutrons emission per shot using ^{3}He proportional counters in current mode.
- Q1: Neutron yield characterization of the Nanofocus device operating at 10 and 20 Hz. To determine the neutron flux operating in repetitive regime, 10 and 20Hz, using activation counters and CR39 plastics, and bubble detectors.
- Q1: Design of a portable device that operate at 2 joules (200nF, 20nH, 5kV, 16kA), with a repetition rate of 10Hz.
- Q2 - Q3: Construction of a portable device that operate at 2 joules (200nF, 20nH, 5kV, 16kA), with a repetition rate of 10Hz.
- Q4 - Q6 : Characterization of the portable device that operate at 1 to 5 of joules (200nF, 20nH, 5kV, 16kA), with a repetition rate of 10Hz. To determine the reproducibility of neutrons emission per shot using ^{3}He proportional counters in current mode. To determine the neutron flux operating in repetitive regime, 10 and 20Hz, using activation counters and CR39 plastics, and bubble detectors.

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