# Applications of the Dense Plasma Focus to Nuclear Fusion and Plasma Astrophysics

Jorge Osvaldo Pouzo, *Member, IEEE*, and Maria Magdalena Milanese

***Abstract*—This paper investigates the dense plasma focus (DPF) for applications to nuclear fusion processes in reactors and in astrophysical plasmas. The scaling derived from experiments suggests a DPF of 100 MJ could reach break-even in a reactor and provides parameter space information for astrophysical problems. The cost and technological problems associated with this achievement are analyzed and environmental concerns discussed. The results, as applied to several fields of science and technology and space plasma physics, are presented.**

***Index Terms*—Astrophysics studies, corpuscular and electromagnetic radiation, plasma focus.**

*Jorge Osvaldo Pouzo passed away November 28, 2003, one month before the publication of this Special Issue. He was recognized as one of the leading, most meticulous, and strongest advocates of the dense plasma focus, from laboratory to cosmos. This paper is an indication of the legacy he forged. However, the international plasma and fusion communities will remember him not only as a gifted researcher, but as a man who enjoyed life and gave strength and enthusiasm to seminal ideas and his activities in general. It was contagious and we shall sorely miss him (A. Peratt, Guest Editor).*

## I. INTRODUCTION

THE PROBLEM of contamination associated with carbon dioxide releases to the atmosphere is well known in relation to energy from fossil fuels. This paper suggests a solution to this problem, namely the use of the dense plasma focus (DPF) as a source for fusion energy.

The plasma focus device is characterized by plasma with a short lifetime but very high density and temperature. The phenomena that occur in the DPF include intense soft and hard X-ray pulses, electron and ion beams, and fusion neutron pulses. Each of these may have a variety of applications. The neutron yield of DPF has, by far, the highest fusion energy per invested energy unit, as compared with other fusion machines. Notwithstanding, the physical processes involved with the DPF are not simple and they are not even entirely understood. However, preliminary results are promising for use of the DPF as a fusion reactor and helping to understand fusion processes in astrophysical objects.

This paper is a review of the theoretical and experimental results obtained by the authors and their DPF research team during the past 20 years. An optimized design of DPF as a reactor and its possibilities as a first generation generator is presented. The paper also covers advances in the application of the DPF as both a neutron and X-ray pulse generator.

The data as derived from DPF machines are also applied to outstanding problems in space plasmas. These include such fundamental problems as plasma instability problems such as vorticity and fundamental problems in ionization processes.

## II. CRITERIA FOR THE USE OF A DPF AS A FUSION REACTOR

In the past 20 years, the authors and colleagues have developed a set of design criteria. These may be divided into two parts. The first criteria deal with the mechanism responsible for fusion neutrons D-D in the focus [1]–[3]. The second criteria deals with the upper and lower $D_2$ pressure limits for D-D neutron production [4]–[8].

With respect to the mechanisms that produce the nuclear fusion reactions in the focus, it is found experimentally that both thermal and nonthermal mechanisms are present [1], [2], [9].

The limits for DPF neutron production can be summarized as follows.

1) The upper pressure limit [4], [5] is due to the fact that the radial compression of the plasma sheath of the focus column must have enough energy to ionize the neutral gas to be swept in by electromagnetic forces to be part of the fusion source. If the gas is deuterium, the specific energy of the plasma sheath must be at least 1 MJ per gram of swept mass. During the compression, this is simply the critical ionization velocity (CIV) of Alfvén for a magnetized plasma shock wave in the space [10]. If the plasma sheath velocity is slower than the CIV, it takes a filamentary shape and the compression (or radial) stage is less effective [11]. This filamentary shape could be associated with a minimum energy configuration.
2) The lower pressure limit for DPF neutron production can result in a plasma sheath velocity that is higher than the CIV [8]. In this situation, a heat wave that preheats the focus zone is produced. This effect reduces the compression in the focus with a concomitant drop in the neutron production.

Fig. 1 shows a sequence of pictures of the plasma sheath radial compression and focus phenomena as taken through an image converter camera photographs with a 5-ns exposure time. These photographs were taken on the PACO device of the Tandil Laboratory [3]. It is clear from this photographic data of the plasma sheath, or "penumbra," that the focus phenomenon is quite complex. We conclude, as the same results are found over

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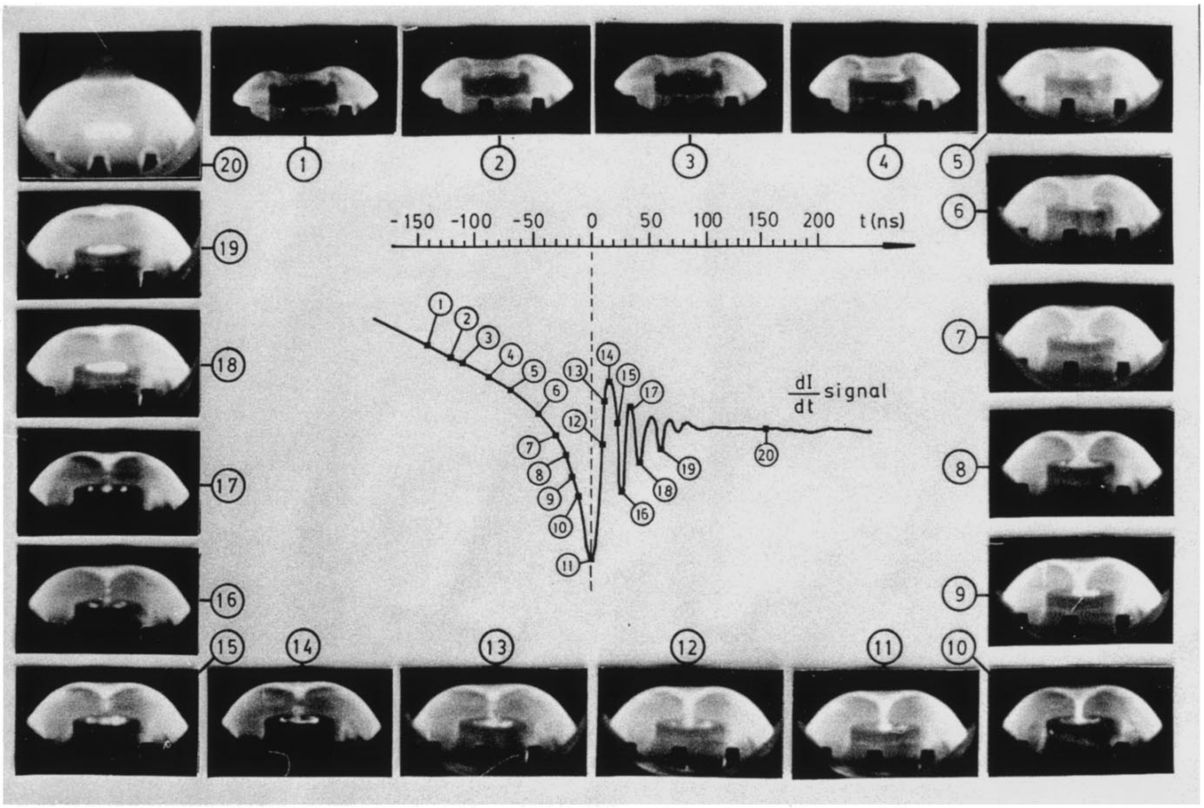

Fig. 1. Plasma sheath evolution from roll-off to plasma bubble stages, time-referred to the total current derivative.

a number of DPF machines with a variety of operational parameters, that the thermonuclear effect is dominant in high-energy devices and the fusion scaling law predictable [7]–[10].

Based on the above, criteria of optimization of the DPF for fusion reaction can be obtained with a theoretical model based on the assumption that the main reactor mechanism is due to the thermal collisions [12].

## III. EMPIRICAL FUSION SCALING LAW; ORIGIN OF THE REACTIONS

The DPF column (Fig. 1) is uniform at the maximum compression time. However, there also exist a number of stages in the instability of the sheath shape entailing successive disruptions and restorations of the column. This behavior of the plasma column leads to the possibility of two mechanisms for fusion reaction. The first is thermal and the second is nonthermal [11], [12]. These mechanisms are addressed in the time-of flight neutron spectra measurements at the Frascati 1-MJ DPF [1]. As shown in Fig. 2, the neutrons $(Y)$ produced by $D\ (d,n)$ He$^3$ nuclear fusion reaction have an empirical relation with the current at the focus time $(I)$ $Y = k \cdot I^n$, where $k$ is a constant and $n$ is a factor between 4 and 5.

## IV. DPF THERMONUCLEAR MODEL

The scaling law $Y = k\_I^n$ is predicted by a thermonuclear model [13]. In this model, the following are assumed.

1) The bulk of plasma is a pinch in which the Bennett equation $I^2 = NT$ ($N$ is the linear density) is fulfilled in average.
2) The length of the focus is determined considering those deuterons that can participate in the focus (this is calculated from the relation between axial and radial plasma velocities).
3) The lifetime of fusion plasma in the focus is determined by the escape velocity (sound speed) of deuterons along the axis (assuming complete radial confinement).

Thus, in this way, both the factor $k$ and exponent $n$ give results coincident with those observed in the empirical scaling law $Y$ versus $I$ (see Fig. 2). Through a beam-target model, it is shown that the index $n$ could be larger in smaller machines. In other words, the extrapolation of the nuclear fusion scaling laws for the DPF would be estimated with a minimum index $n = 4$. Hence, the possibility of the DPF as a fusion reactor is based on the $Y \sim I^4$ law. It is also deduced though beam-target effects that a law of the type of $Y \sim I$ exists. This adds a factor of approximately two to the neutron production. As noted, the thermonuclear effect is primary in the DPF [13].

## V. DPF AS FUSION REACTOR

The need for a contaminant-free fusion reactor is omnipresent [14].

To achieve this end, experiments are continuing to be carried out on a 3-MJ DPF. The experiments provide an investigation

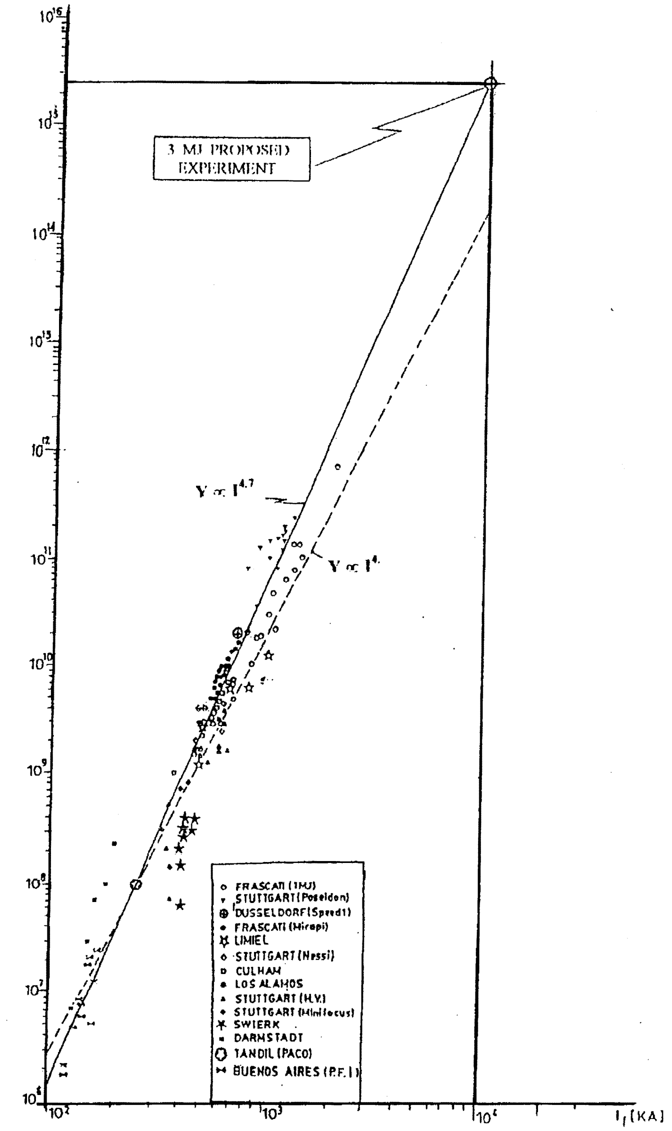

Fig. 2. Neutron yield $Y$ versus pinch current $I$ of 117 experiments performed in 14 PF devices.

of the parameter space of interest to fusion reactors and fusion relation in plasma astrophysics [15].

Fig. 3 shows the different options for a reactor: in D-T or D-D fusion-fission hybrid schemes (HDD and HDT), D-T and D-D pure fusion schemes (PDD and PDT) for an extrapolation $n = 4$. If thermonuclear and beam-target fusion produce a similar contribution to $Y(k = 2)$, a break-even machine could only be obtained in the energy range of 0.48–3 MJ for HDT, and a range 1–6 MJ for HDT with only thermonuclear reactions $(k = 1)$.

The break-even machine in PDT for $k = 2$ could be obtained for an energy of approximately 16 MJ, and for $k = 1$ for an energy of approximately 30 MJ. For the HDD break-even machine $(k = 2)$, the energy must reach the level of 100 MJ. But it must be taken into account that at a level of 100 MJ a D-T pure reactor with a total gain $E_f/E$ of about 3 could be also obtained if only the neutron energy were considered. Considering secondary reactions as D-D or T-T, recoveries of plasma heat would increase the efficiency. An accurate calculation of energy efficiency is obtainable from the methods proposed by Panarella [16].

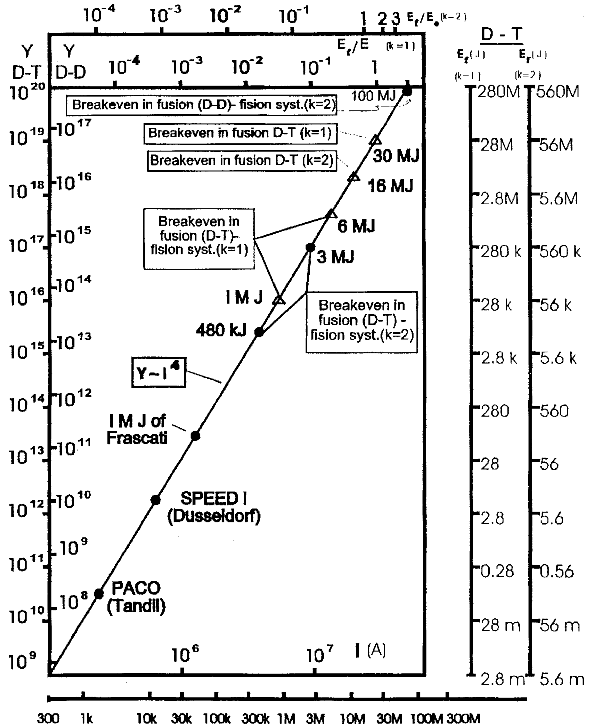

Fig. 3. Graph of the neutron yield $Y$ in D-D and D-T reaction versus the focus current $I$, under the supposition that the scaling law $Y \sim I^4$ can be extrapolated. It is graphed also the ratio $E_r/E$ between the neutron energy and the device energy as a function of $I$, assuming an optimized design. The factor $k = 1$ or 2 indicates thermonuclear neutrons (only) and with nonthermal contributions, respectively.

## VI. APPLICATIONS OF THE DPF AS AN X-RAY SOURCE

A small DPF machine (using a kilojoule-capacity capacitor bank) can lead to maximum compression of the plasma and produce a short, intense hard X-ray pulse $(X_h)$. This pulse is produced by the collision of a tightly collimated fast electron beam with an anode surface [17], [18]. In a recent work [19], the authors measured characteristics of $X_h$ in the small machine PACO ($E = 2$ kJ, $I = 250$ kA, $Y = 4 \times 10^8$ neutrons in D-D). In this case, the duration of $X_h$ was 10–20 ns. Using deuterium as filling gas, the $X_h$ dose was approximately 1 m rad. This dose was measured with TLD detectors, and shows a uniform intensity in a surface of 20 cm diameter. This data showed that the $X_h$ dose results are linear with the signal amplitude obtained with a plastic scintillator-photomultiplier, time-resolved detector. From this, it is possible to estimate the dose emitted in a single shot at real time.

The energy of $X_h$ is some hundred kiloelectronvolts [18], [19]. Fig. 4 shows the radiograph obtained of a live mouse in a single shot from the PACO device. As shown, the quality of the radiograph is high. The high quality is due to two factors: the very short duration of the emission, and the small (less than 1 mm) size of the source. Using different fill gases and anode

Fig. 4. Radiograph of a live mouse, taken with an X-ray flash 10-ns exposure time. It is obtained in a single shot of PACO device. White circle corresponds to an iron bar of 1 cm diameter and 1 cm length.

materials, the field of DPF $X_h$ emitter could be appreciably higher, especially for radiographs of very dynamic biological systems and microradiographs.

## VII. DPF AS A NEUTRON SOURCE

A very small and portable DPF device (142 J, 16 kV) was developed with the purpose to be used as neutron probe in soil humidity measurements [20]. The neutron yield produced in this "nanofocus" results, on average, the order of $10^6$ D-D neutrons per pulse ($10^7$ as maximum). Such a value exceeds by two orders of magnitude the $Y = 10^4$ that should correspond to the empirical scaling law (see Fig. 5). The nanofocus DPF could see many applications, one of which is soil humidity detection.

## VIII. DPF APPLICATIONS IN TECHNOLOGY AND PLASMA ASTROPHYSICS

As mentioned, ecological problems connected with current fusion schemes present an environmental problem. These problems are exacerbated with the probability that strong climatic and geophysical changes could take place. For example, it is projected that ocean levels can increase 10 cm or more in the next ten years. This is mainly due to increased $CO_2$ generation from the burn of organic matter (especially petroleum) with increased energy needs in the industrial and transportation sectors, i.e., the so-called greenhouse effect.

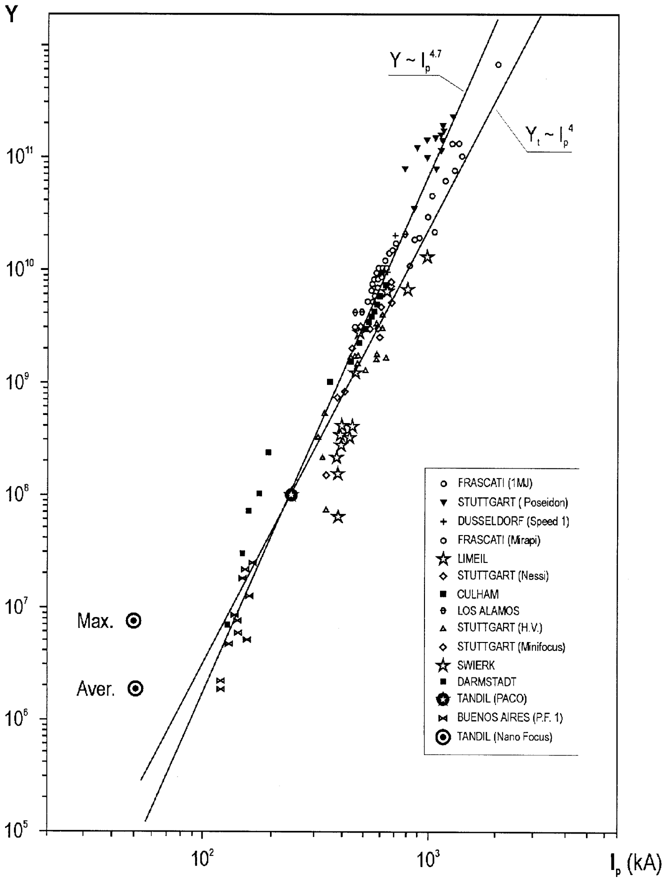

Fig. 5. Position of nDPF in the general scaling law $Y$ versus $I_p$.

An example was the loosening of an ice block with the size of the Formosa province of Argentina (36 000 km$^2$) from Antarctica in the year 2000. More recently, a new block of 3200 km$^2$ is floating in the vicinity of the Malvinas (Falkland) Islands. These ice blocks, some 100 m thick, are one source of sea level increase.

A major concern is the effect of a rising ocean on cities such as Buenos Aires and New York (including Manhattan Island). The alternatives to petroleum sources of energy are nuclear fission and nuclear fusion; but each has well-known environmental problems.

At present, fission energy reactors may be the only solution. Technologies used in fission reactor, such as heavy water production, neutron-electricity conversion system, etc., are necessary. The remaining problem to eliminate or store the radioactive residues is a major scientific challenge.

It is useful to consider some of the quantitative attributes of nuclear fusion reactors. In a D-D fusion reactor, the burn of 1 g of $D_2$ is equivalent, in energy, to 400 tons of carbon. This gram of $D_2$ can be obtained from 1 m$^3$ of sea water, at the price of $10 U.S. Residue of D burn is He$^3$, a nonradioactive noble gas. In such reactors, temperatures over 900 °C are obtainable in the last wall. It is possible to crack water molecules on this wall and produce $H_2$ with a relative low cost (valuated in energy). The $H_2$ gas produced in such a way could be used for the exothermic reaction $H_2 + O = H_2O$. Through this reaction, $H_2$ can be the combustible for transport machines (cars, trains, buses, airplanes, etc.). The residue of this transport energy consume would be pure water vapor, an ecological acceptable residue.

Because of this, the authors recognize the urgency associated with a nuclear fusion reactor. In this sense, the DPF is the most economical and technologically feasible and quick scheme to obtain a first generation fusion reactor. If the D-T break-even experiment in DPF (100 MJ) is reached, an industrial reactor of 300 MJ/s (300 MW) could be projected. This type of DPF reactor could be economical (about $300 million per reactor plant) and could provide the energy for cities with a population among 100 000 or 200 000 habitants. Long transmission lines could also be alleviated in the energy distribution system.

## IX. CONCLUSION

The DPF reactor has a high probability of finding use in nuclear fusion and in studies involved with understanding fusion from astrophysical sources. The industrial applications include neutron probes to agriculture, soil humidity measurements, and the detection of water underground. Other applications include the DPF as an intense source of neutrons, an application for which it has been long recognized.

As a nanosecond or subnanosecond flash X-ray source [20], and because of its relative small size as compared to linear accelerators and inductive voltage adder X-ray facilities, its use in producing radiographs of materials undergoing high velocities of movement such as implosions are attractive in high-energy-density physics. It might also see use in measurements of biological fluids such as in cardiovascular measurements.

The DPF also has applications to space plasma physics and plasma astrophysics [21]. The understanding of the sheath, or "penumbra" or "chalice" is integral to problems in planetary physics where electric effects have played or are playing a major role not previously recognized in shaping the surfaces of planets. For example, the planet Venus shows the telltale signs on its surface that only the DPF, not geophysical forces, can imprint. The Jovian satellite Io, with a 400 kV potential across the satellite and a multimegaampere current as observed by the Voyager satellites to connect the two bodies, have resulted in "wandering" DPF sheaths identical to Fig. 1. These sheaths or penumbra are filamentary and converge onto a circular ring far from the penumbra's center as photographed by the planetary explorers [22]. The temperatures measured are four times that of the surface temperature of the Sun. As such, unlike volcanoes on Earth, emit radiation in the ultraviolet.

In conclusion, the study of the DPF is an area rich to plasma physics and planetary physics (plasma cosmogony) [23]. Its contribution as a fusion source is a problem that demands further investigation. Its application to planetary and space plasma physics is obvious.

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