CONFERENCE PRE-PRINT

FUSION STUDIES WITH SMALL AND TABLETOP PLASMA FOCUS DEVICES: *Investigations on New Operational Regimes, Non-Equilibrium Thermodynamics, Extreme Material Conditions, and Biological Effects*

LEOPOLDO SOTO[1,2,*], JOSÉ MORENO[1,2], JALAJ JAIN[1,2], OCTAVIO ORELLANA-SERRADELL[1], BISWAJIT BORA[1,2], SERGIO DAVIS[1,2], RODRIGO A. LÓPEZ[1,2], GONZALO AVARIA[3], VALENTINA VERDEJO-PARADA[4], ANALÍA RADL[4]

*Email: LEOPOLDO.SOTO@CCHEN.CL

[1] Research Center on the Intersection of Plasma Physics, Matter and Complexity, Chilean Nuclear Energy Commission, Santiago, Chile
[2] Department de Ciencias Físicas, Universidad Andres Bello, Santiago, Chile
[3] Departamento de Física, Universidad Técnica Federico Santa María, Santiago, Chile
[4] Cytogenetic Dosimetry Laboratory, Chilean Nuclear Energy Commission, Santiago, Chile

Abstract

Plasma Focus (PF) devices are pulsed electrical discharges belonging to the Z-pinch family, providing compact and versatile laboratories for the study of plasma physics and nuclear fusion. Their intrinsic self-scaling allows construction at energy ranges from a few joules to several kilojoules, enabling both fundamental and applied research. When operated in deuterium, PF devices produce a dense plasma column where nuclear fusion reactions occur, exhibiting phenomena such as ion pulses, X-ray bursts, UHF radiation, neutron pulses, plasma filaments, shocks, and plasma jets. Recent studies at the Chilean Nuclear Energy Commission (CCHEN) have advanced the understanding of these discharges and their applications. New operational regimes have been identified, together with refined diagnostics such as Zeeman spectroscopy, Thomson-scattering modeling, and artificial intelligence applied to signal analysis. Experiments on materials under extreme pulsed conditions have revealed melting, cracking, and crater formation relevant to plasma-facing components in fusion reactors. Radiobiological studies have shown distinctive responses of living matter to pulsed radiation, including hyper-radiosensitivity and high relative biological effectiveness at low doses, opening perspectives for dosimetry and flash radiotherapy research. These developments have motivated the design and construction of the Plasma Focus for Fundamental and Applied Research (PFFAR-5 kJ), currently under characterization at the P^2mc-CCHEN. Theoretical advances in statistical physics of non-equilibrium plasmas have provided a framework for understanding non-Maxwellian distributions and the connection between microscopic correlations and macroscopic thermodynamic quantities. The work presented here is also aligned with the vision of the Nuclear Fusion Unit of the Latin American Center of Physics (CLAF–UNESCO), which aims to articulate and complement the different research efforts on fusion in the region, including tokamaks, stellarators, plasma focus devices, other plasma configurations, computational modelling, and theoretical developments, promoting scientific cooperation, technological progress, and the equitable participation of Latin American countries in the global advance toward fusion energy.

1. INTRODUCTION

Plasma Focus (PF) devices, as compact members of the Z-pinch family, provide unique laboratory platforms for studying high-energy-density plasmas, fusion reactions, and radiation sources. Their intrinsic self-scaling allows the design of systems from tabletop energies of a few kilojoules to less than one joule [1-3], enabling both fundamental studies and applications. Beyond their role as pulsed sources of neutrons, X-rays, ions, and plasma jets, PF discharges offer valuable opportunities to investigate material response under extreme conditions, radiobiological effects relevant to flash radiotherapy, and statistical physics of non-equilibrium systems. This paper reviews recent advances obtained at the Chilean Nuclear Energy Commission (CCHEN) with small and tabletop PF devices, highlighting new operational regimes, diagnostic methodologies, material and biological studies, and the emerging connection between plasma physics, artificial intelligence, and societal challenges such as energy justice and equity.

2. NEUTRONS, X-RAYS, CHARGED PARTICLES, UHF RADIATION, MAGNETIC FIELD, TEMPERATURE, AND NEW OPERATIONAL REGIMES OF PLASMA FOCUS

Comprehensive studies on plasma focus discharges in deuterium have provided new insights into neutron emission, X-ray production, charged particles, and plasma parameters. High-energy neutrons (>5 MeV) have been detected in a kilojoule plasma focus (PF-2kJ), with Geant4 simulations suggesting contributions from D-D and D-T fusion mechanisms, the latter likely resulting from residual tritium produced in D-D reactions [4]. Zeeman splitting spectroscopy estimated a ~4T magnetic field at the pinch volume (~100 kA) [5]. A deep learning method enabled indirect hard X-ray detection via UHF radiation [6]. New operational regimes have been studied obtained neutron yield one order of magnitude than previous works in PF devices of hundred joules [7]. A Thomson scattering model was developed, identifying a characteristic spectral temperature and demonstrating the necessity of dual observation directions to fully determine velocity distributions [8] and collaborative experiments with the plasma physics group of the Pontifical Catholic University of Chile are being conducted to determine plasma temperatures in a hundred-joule plasma focus.

2.1. High-energy neutrons

The neutron emission from plasma focus devices is reported around 2.45 MeV in the radial direction and around ~3 MeV in the axial direction [18]. In recent work, the presence of high-energy neutrons in neutron pulses emitted from a kilojoule plasma focus device is reported while working with deuterium as a working gas [4]. A kilo-joule plasma focus device, PF-2kJ, is used as a pulsed neutron generator. Time of flight and neutron spectroscopic measurements suggest neutron energies larger than 5 MeV in the radial and axial directions. The anisotropy in neutron emission suggested a beam-target nuclear fusion mechanism. A simulation tool kit Geant4 is used to interpret and verify the experimentally observed spectroscopic results of neutrons' energies. Based on the findings, it was hypothesized that the pinch and pre-pinch phases invoke suitable conditions for the D–D reaction that produces proton and tritium. The produced tritium nuclei further collide with deuterons in the pinch and post-pinch phases and produce high-energy neutrons. However, the observed high-energy neutrons could be of mixed origin, including beam-target nuclear fusion mechanism and D–T fusion reactions. Further diagnostics, such as measuring the alpha particle, which is a product of the D–T fusion reaction, and detecting the proton that originates via a D–D fusion reaction branch that produces tritium, were proposed to test the hypothesis. In Figure 1 (A) and 2 (B), neutron signals captured using a combination of a scintillator (Bicron BC-408) and a photomultiplier tube (FM1: Axial, FM2: radial) are shown [4]. Fig. 2(A) is obtained without neutron spectroscopy experimental conditions, which constitutes X-ray shielding by a 5 cm lead block, and Fig. 2(B) was obtained with neutron spectroscopy experimental conditions, which constitutes shielding of X-rays (by a 5 cm lead block) and neutrons (using a 48 cm high-density polyethylene block). The details can be found in reference [4].

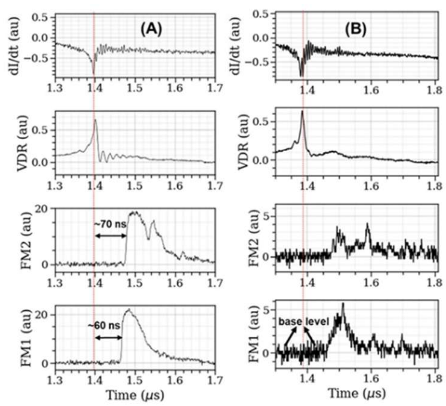

FIG 1. Neutron signals (A) without a neutron spectroscopy experimental setup, (B) with a neutron spectroscopy experimental setup. The figure is taken from reference [4].

2.2. High-energy Magnetic field distribution

Magnetic field distribution estimations with Zeeman splitting spectroscopy at the radial phase of the PF-400J device were obtained [5]. Discharge current measurements in Plasma Focus discharges are usually made with inductive probes such as Rogowskii coils, which present the disadvantage that it cannot determine the current circulating through the plasma column. This indeterminacy makes it more difficult to estimate plasma characteristics such as the temperature inside the column through the Bennett relation. Zeeman splitting, based on the spectral separation of optical emission lines, enables the estimation of the magnetic field in the plasma column when a high current is present. The emitted photons have a distinct polarization identified as σ+ and σ-, possible to be separated by a λ/4 polarizing plate. Preliminary measurements of the magnetic field at the plasma column of the PF-400J discharge in a high current density configuration (Φanode = 4.5 - 6.0 mm and Zeff = 10 - 20 mm) are presented, by using the Zeeman splitting spectroscopic technique of the Ar III emission at 330.18 nm. The measurements are spatially resolved in the radial direction, with the use of the combination of a polarizing crystal and λ/4 polarizing plate, and a bifurcated fiber optic bundle focused on the entrance of a 0.5m spectrometer with a 2400 l/mm grating. With this experimental configuration a magnetic field of around 2T is estimated at the pinch volume, when the maximum current (~100kA) is achieved.

2.3. Hard X-ray emission detection using deep learning analysis of the radiated UHF electromagnetic signal.

A method to determine the presence of hard X-ray emission processes from a dense plasma focus (205 J, 22 kV, 6.5 mbar H_2) using Ultra High Frequency (UHF) measurements and deep learning techniques were performed. Simultaneously, the electromagnetic UHF radiation emitted from the plasma focus was measured with a Vivaldi

UHF antenna, while the hard X-ray emission was measured with a scintillator-photomultiplier system [6]. A classification algorithm based on deep learning methods, using two-dimensional convolutional layers, was implemented to predict the hard X-ray signal standard deviation value using only the antenna signal measurement. Two independent datasets, consisting of 999 and 1761 data pairs each, were used in the analysis. Different realizations of the training/validation process using a deep learning model, obtained overall better results in comparison to other machine learning methods like k-neighbors, decision trees, gradient boost, and random forest. The results of the deep learning algorithm, and even its comparison with other machine learning methods, indicate that a relationship between the electromagnetic UHF radiation and hard X-ray emission can be established, enabling the indirect detection of hard X-ray pulses only using the UHF antenna signal. This indirect detection presents the opportunity to have a simple and low-cost diagnostic, compared to the methods currently used to characterize the pulses of X-rays emitted from plasma focus discharges.

2.4. Model of Thomson scattering and temperature

A model of Thomson scattering (TS) for z-pinch plasmas was developed [8]. Sustained on the phenomenology observed in dynamical-pinch discharges of interest in fusion studies, the plasma dynamics is modelled by axisymmetric bi-Maxwellian velocity distribution with axial and radial drift velocities. Expressions for TS form factor and screening integrals are deduced, and TS spectra are reconstructed. A characteristic temperature of the spectrum is identified, which is determined by a weighted-sum of the axial and radial temperatures, whose coefficients are given by the square of the respective axial and radial components of the wave vector $\vec{k}$ over the square of the magnitude of $\vec{k}$. It is shown that it is not possible to determine the velocity distribution function of the plasma from just one direction of measurement. Additionally, an experimental setup, which requires two complementary observation directions for a complete determination of the proposed distribution function, is analysed and its capacity to measure thermal anisotropy and drift velocities is studied for plasma conditions expected in the pinch phase of a plasma focus discharge. Collaborative experiments with the plasma physics group of the Pontifical Catholic University of Chile are being conducted to determine plasma temperatures in a hundred-joule plasma focus.

2.5. New Operational regimes

One of our current research interests in low-energy, low-current Plasma focus devices focuses on studying high-efficiency operational regimes for neutron and X-ray production, reproducing many of the dynamic scenarios observed in higher-energy and higher-current devices (E >1 kJ; I >250 kA). Additionally, this behaviour leads to two main objectives: i) to obtain an efficient source for field research and applications, and ii) to enable a more comprehensive (spatial-temporal) study of plasma dynamics and properties. The latter aims to validate computational models, which are of interest in studies of fusion via high-current pulsed power discharges [27]. Our approach to improving neutron and X-ray generation efficiency is primarily based on increasing the ratio I/a for a given device (where I is the current in the pinch and a is the anode radius). This criterion allows achieving high current densities and, consequently, greater compression forces. Moreover, the temperature at the pinch stagnation depends on the I/a ratio. For a given current, reducing the anode size enables operation in high-pressure regimes (deuterium pressure $p_{D2} > 10$ $mbar$), resulting in higher plasma densities ($\geq 1\times10^{25}$ m^{-3}). It also allows operation in long axial phase regimes ($z_{eff} >> a$, where z_{eff} and a are the effective length and radius of the anode, respectively), which favours the elimination of dense structures generated during plasma breakdown, such as filaments observed in Reference [7]. In the case where filaments are observed the average and maximum neutron yields are 5×10^5 and $(1\text{-}2)\times10^6$ respectively, while in the case where filaments are not observed the average and maximum neutron yields are one order of magnitude greater, i. e., 5×10^6 and $(1\text{-}2)\times10^7$ respectively [7].

3. TESTING OF MATERIALS UNDER EXTREME CONDITIONS TO STUDY THE DAMAGES ON NUCLEAR FUSION REACTOR RELATED MATERIALS

One of the pressing problems in the design and construction of nuclear fusion reactors is the selection of candidate materials for its plasma facing components. The essential constraint is that such a material must be able to withstand extreme heat fluxes, together with high fluxes of neutrons, ions beams, and He and H isotopes such as deuterium.

The time of interaction, peak power and deposited energy on materials in inertial and magnetic confinement differ. However, it has been observed that radiation sources producing high power flux Q with a short time interaction τ on a specific material, have similar thermomechanical effects if the material is irradiated with a source with less Q and longer τ, if in both situation the damage factor F has the same value. The damage factor, F, is an empirical parameter that has been recognized as a good measure of the damage in an irradiated sample. F is defined as $Q\sqrt{\tau}$ (with Q the power flux and τ the time of interaction with the material). The damage factor F reach values as high as ≥ 70 (MWm^{-2} $s^{1/2}$) for both, magnetic confinement experiments (like ITER), and inertial confinement experiments (like NIF). It is noticed that the damage factor does not depend of the kind of the irradiation, and a theoretical explanation of the damage factor was proposed for our group [19]. Experimental studies have evaluated the resistance of materials under extreme conditions relevant to nuclear fusion reactors. The PF-2J was upgraded as a tabletop pulsed plasma shock irradiator, enabling controlled application of the damage factor (FFF) from 10 to 1000 ($MWm^{-2}\ s^{1/2}$) [9].

3.1. Miniaturized 2-Joule pulsed plasma source based on plasma focus technology for applications in extreme condition materials

It has been shown that the axial plasma shock after the pinch observed in tabletop plasma foci operating at hundred joules can produce damage on materials equivalent to the expected in the first wall of Inertial Fusion Energy (IFE) devices and in Magnetic Fusion Energy devices. PF devices can produce F in the order of ~ 10^4 (W/cm^2)$s^{1/2}$ and greater.

Using the scaling rules for the damage factor, F, with plasma foci energy, E, a tunable damage factor pulsed plasma shock irradiator device based on the PF-2J was designed and constructed (F scale as $E^{1/6}$). This device produces a damage factor, F, ranging from 10^2 to 10^4 (W/cm^2) $s^{1/2}$, the F value can be adjusted varying the distance of the sample from the anode top [9]. The damage factor F has a strong dependence on the distance to the target, thus a micrometric positioner for the material samples was designed and included.

It allows for a repetition rate of ~0.1 Hz, enabling material irradiation with 10, 100, and 1000 shots in 100 seconds, 20 minutes, and 3.2 hours, respectively.

A methodology to calibrate the value of the damage factor produced by the tunable pulsed plasma shock irradiator was implemented using a pulsed laser (Nd-YAG: 0.5 J, 8 ns FWMH) to irradiate materials. Different materials were irradiated using the pulsed plasma shock irradiator at different positions from the anode top, z, and also with the pulsed laser, to determinate the threshold to produce melting. The damage factor was calculated from the experiments with laser where Q and the time interaction τ is known. Thus, the distance z in which the threshold melting was observed using the pulsed plasma shock irradiator (based in the PF-2J) was associated to the respective value of the damage factor obtained with laser irradiation and with values obtained from literature. It is noted that the PF-2J technology allows the development of a miniaturized pulsed plasma thruster for CubeSat-standard nanosatellites [9].

3.2. Plasma-induced damage on the tungsten surface using a kilojoule plasma focus device

Damages induced on the tungsten surface at two different operating conditions of a kilojoule plasma focus device are studied. In one condition, the tungsten samples were exposed to axial plasma shocks that are formed after pinch disruption, and in the other condition, the pinch phenomenon was absent or weak. Melting, craters, and cracking on the surfaces were observed in both cases. In the former case, the charged particle beams and post-pinch material ejection will play a role in impacting the surface; however, in the latter case, those phenomena will have small contributions because of the absence or weak formation of the pinch. A damage factor of $\sim 10^9\ W\ m^{-2}\ s^{0.5}$ was estimated at a distance of 3 cm from the pinch exit using the method given in Akel *et al.* [20] and Klimov *et al.* [21] for the former case. It is revealed in this work that at pressures lower than the pinch-occurring pressure, only axial plasma shock effects on the targeted surface can be studied, and that they can be separated from the effects produced by the charged particle beams mixed with axial plasma shocks in the case of pinch occurrence. Fig. 2 shows the estimated damage factors in the case of (A) pinch occurrence, (B) in the absence of the pinch, and AFM images that show melting on the tungsten surface (Fig. 2(D): 5 shots at pinch occurring pressure) and crater formation with melting (Fig. 3(E): 5 shots without pinch). Fig. 3(C) shows an AFM image of an untreated sample. Details of the experimental setup can be found in [10].

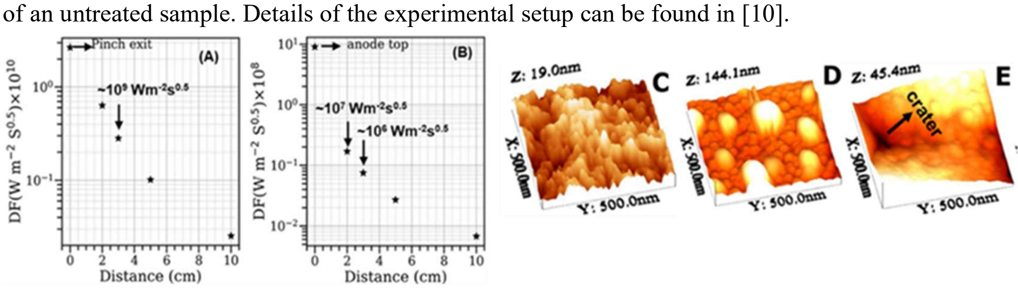

FIG. 2. Estimated damage factor, DF, for hydrogen gas (A) in the presence of the pinching phenomenon (B) in the absence of the pinching phenomenon. The AFM images show melting and crater formation on the tungsten surface in the case of (D) pinch occurrence and (E) in the absence of pinch. (C) is an untreated sample. The figure is taken from reference [10].

3.3. Studies on the effects of intense radiation on biological systems, pulsed radiation dosimetry and cancer ultra flash radiotherapy

Several fusion experiments work in the pulsed regime of nanosecond to hundreds of nanoseconds. Thus, studying the effects of pulsed radiation in biological systems is an inevitable step toward developing ad-hoc radiation protection systems and protocols for operators in pulsed radiation enviroments. On the other hand, it opens the opportunity to use this same type of pulsed experiments to study, for example, innovative therapies for cancer treatment, such as ultra flash radiation therapy.

CONFERENCE PRE-PRINT

3.3.1. Dosimetry for pulsed radiation environments

It has been reported that there is a positive correlation between the number of shots with pulsed X-ray emission from a PF device, with DNA damage (Fig. 3), this damage has been evidenced by the conventional biodosimetric marker (unstable chromosomal aberrations, UCA) [12]. Currently, there is interest in the study of the mechanisms by which DNA is damaged in scenarios of exposure to pulsed ionizing radiation, since it has been shown that the biological effects are far from those expected with respect to exposure to conventional sources of ionizing radiation (continuous sources).

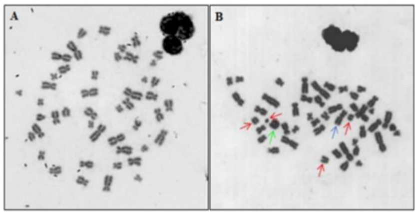

FIG. 3. Metaphase observed after 0 pulses (A), and after exposure to 10 x-ray pulses (B). In (B), the metaphase has one dicentric chromosome (blue arrow), one centric ring (green arrow), and four acentric fragments (red arrows). The figure is taken from reference [12].

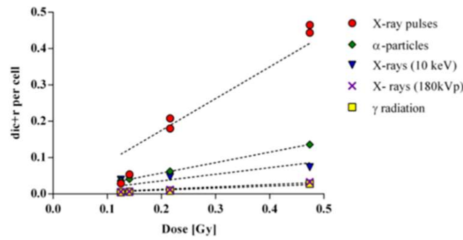

FIG. 4. Comparison of dicentric plus ring (dic + r) frequency observed in the present study (red circles), and frequencies calculated using previously published curves for α-particles (green diamonds [22] x rays (blue invert triangles for 10 keV [23]; and purple crosses for 180 kVp [24]), and γ radiation (yellow squares) [25].Broken lines represent the linear fit. The figure is taken from reference [12].

An analysis of (UCA) produced by X-ray pulses (full width at half-maximum ~ 90 ns, dose rate ~ 10^7 Gy min^{-1}) on irradiated monolayer of peripheral blood mononucleated cells, using the PF-2kJ kilojoule plasma focus device were made [12]. Four different exposure conditions were evaluated using 5, 10, 20, and 40 pulses, with the mean dose measured by TLD-100 (Term Luminescent Dosimeter, 100) being 0.12 ± 0.02 mGy, 0.14 ± 0.03 mGy, 0.22 ± 0.06 mGy, and 0.47 ± 0.09 mGy, respectively. Cytogenetic analysis showed an increase in all types of chromosomal aberrations following exposure to x-ray pulses. The distribution of dicentrics and centric rings was overdispersed after 5, 10, 20, and 40 pulses. Additionally, after 20 and 40 pulses, the presence of tricentric chromosomes is detected. Chromosome aberration frequencies found in this study were always higher than the estimated frequencies of chromosome aberrations using published dose–effect curves for conventional radiation sources. The overdispersion observed, the elevated maximum relative biological effectiveness (RBE_M) and the presence of tricentric chromosomes at the relatively low doses of exposure (<0.5 Gy) seem to indicate that low doses of pulsed x-rays of low energy show similar biological effects as those observed for high-LET (high Lineal Energy Transfer) radiation. X-ray pulses emitted by PF-2kJ were found to be more efficient in inducing chromosome aberrations, even more than α particles (Fig. 4).

3.3.2. Effects of pulsed radiation on cancer cells. Ultra flash radiotherapy.

A kilojoule plasma focus device, PF-2 kJ, is adopted as a pulsed x-ray source to study the effects of pulsed X-ray on cancer cells and the obtained results were compared with the conventional X-ray irradiation results. Cell death was evaluated in human colorectal (DLD-1 and HCT-116) and breast (MCF-7) cancer cell lines (monolayer cell cultures) irradiated with 10 (~0.24 Gy), 20 (0.61 Gy), and 40 (~1.1 Gy) pulses (FWHM ~ 90 ns, dose rate ~10^7 Gy/min with a dose of 0.025 Gy per pulse). The effects of 10 (~0.24 Gy), 20 (0.6 Gy), and 40 (~1 Gy) X-ray pulses, and their comparison with conventional X-ray irradiation on the same cell line DLD-1 are shown in Figure 4. It can be seen that at two orders of magnitude lower doses (10 pulses ~0.24 Gy, Fig. 4(C)), more cell death than conventional X-ray irradiation for 12 Gy could be obtained (Fig. 4(D) [26]. Besides, a normal colorectal cell line, CCD-841-CoN, does not show a significant cell death for 10 X-ray pulses. These preliminary results suggest a selective effect of high-dose rate and a total low-dose pulsed x-rays on cancer cells. This work demonstrates the applicability of plasma focus devices for cancer research. Details can be found in [11].

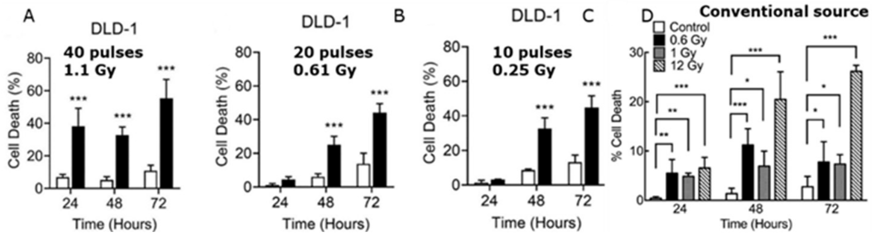

FIG. 4. Cancer cell line DLD-1 shows larger cell death at two orders of magnitude lower doses in comparison to conventional x-ray irradiation. The details can be found in [11]. Conventional x-ray irradiation results can be found in [28].

4. DEVELOPMENT OF THE PFFAR-5KJ PLASMA FOCUS DEVICE

Considering the versatile nature of plasma focus devices, a 5 kJ plasma focus system, named *Plasma Focus for Fundamental and Applied Research – PFFAR-5kJ*, has been developed and is currently under characterization at the P^{2}mc, Chilean Nuclear Energy Commission, Santiago de Chile. The device is designed to study the fundamentals of plasma and nuclear fusion physics, as well as applications related to materials under extreme conditions, and the effects of intense pulsed radiation on biological systems and dosimetry in pulsed radiation environments. In Fig. 5, a three-dimensional design (A) and a photograph (B) of the installed PFFAR-5kJ are shown.

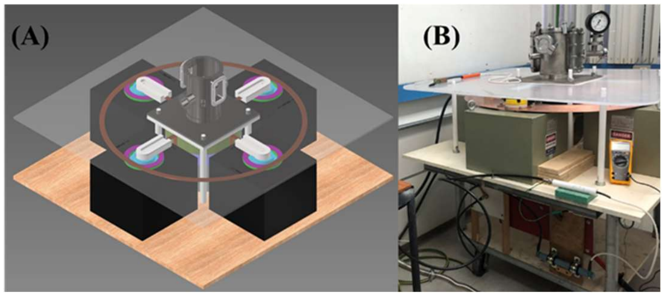

FIG. 5. (A) 3-D design and (B) photograph of the installed plasma focus device (PFFAR-5kJ) to operate in the energy range 5 -6 kJ at P^{2}mc, Chilean Nuclear Energy Commission.

5. APPLICATION OF ARTIFICIAL INTELLIGENCE IN DATA ANALYSIS, PREDICTIVE MODELING, AND OPTIMIZATION OF FUSION SYSTEMS

Artificial intelligence and Bayesian statistical methods have been applied to improve plasma focus discharge diagnostics [6, 13]. These results highlight the effectiveness of Bayesian methods in refining plasma diagnostics, reducing uncertainties, and enhancing predictive modelling in fusion plasma research. Hard X-ray emission detection using deep learning analysis of the radiated UHF electromagnetic signal from a plasma focus discharge was described in section 2.3.

Bayesian inference of spectrometric data and validation with numerical simulations of plasma sheath diagnostics of a plasma focus discharge were implemented [13]. Although the physics answered much of the processes involved in these discharges, many related fundamental questions still remains doggedly unresolved. One of the obstacles to deeper knowledge is the scarcity of reliable experimental data. An elaborate experimental assessment of the electron density in the rundown phase of a 400 J Plasma Focus operating with hydrogen was performed. The rundown of the plasma sheath is basically a hypersonic shock wave between two coaxial electrodes accelerated by the Lorentz force, and it is important to control the pinch formation. The electron density of the passing sheath is measured by means of the Stark broadened hydrogen alpha emission with spatial and temporal resolution. The experimental data is post-processed using Bayesian posterior probability assessment. The results are conflated with the numerical model CShock to construe an educated explanation of the sheath behavior during the rundown. In particular, it is possible to reckon the formation of a toroidal instability reported in previous experiments, and to estimate the plasma sheath temperature (4–20 eV) and velocity (62.5 km/s) at this stage [13].

6. PLASMA PHYSICS AND STATISTICAL PHYSICS OF NON-EQUILIBRIUM SYSTEMS

The presence of non-Maxwellian velocity distributions in non-equilibrium plasmas, both in space and laboratory settings, has been known for decades. In particular, the so-called kappa distribution of velocities [34, 35] commonly replaces the Maxwellian distribution especially in space plasmas found in the magnetosphere and the solar wind, and it has also been considered as a candidate model for the description of empirical velocity distributions in laboratory plasmas [30, 33]. However, the explanation of its origin based on solid theoretical foundations still remains a challenge. Although Tsallis' non-extensive statistical mechanics [29], based on generalization of the Boltzmann-Gibbs entropy, is often invoked as the standard explanation for the existence of q-canonical distributions (including the kappa distribution) the use of generalized entropy functionals has been shown to be in contradiction with fundamental principles of statistical inference [31, 32] and convex optimization [39].

The more recent theory of superstatistics [28] provides an internally consistent, alternative explanation for kappa distributions, in which these generalized ensembles arise as statistical mixtures of Maxwellian distributions having a probability distribution of inverse temperatures, without the need for postulating a different entropy functional. Following this line of research, we have provided a rigorous framework [14] that shows superstatistics arises naturally in the context of velocity distributions for individual particles in collisionless plasmas. In fact, a superstatistical description is always possible in such systems, with different inverse temperature distributions giving rise to a wide family of non-equilibrium steady state ensembles. On the other hand, we have also provided an interpretation of kappa distributions as models encapsulating correlations between kinetic energies of individual particles [37]. The framework that makes both results possible is based on the novel concept of *fundamental inverse temperature* β_F [15], a function of energy that uniquely determines many of the properties of the non-equilibrium ensemble. This inverse temperature has a natural interpretation in superstatistics but is valid far beyond [36]; in fact, we have recently proposed a classification of non-equilibrium steady states, including but not limited to superstatistical states, based on two invariant measures of temperature and its uncertainty: namely β_S, the mean value of the inverse temperature and U, the covariance between the values of inverse temperature of two connected subsystems [37].

7. CONNECTING RESEARCH WITH SOCIETY AND INDUSTRY, PROMOTION OF ENERGY JUSTICE AND EQUITY

Recently, this topic has been added to the program and is being developed as part of the Nuclear Fusion Unit (NFU) of the Latin American Center of Physics (CLAF). The NFU-CLAF was established in October 2024 and has laid the groundwork for coordinated efforts among laboratories and research groups in Argentina, Bolivia, Brazil, Chile, Costa Rica, Honduras, Mexico and Uruguay [16]. In addition, in August 2025, the first "Interamerican Conference on the Science and Technology of Nuclear Fusion and its Applications: Science, Government and Industry", was organized in the Chilean Energy Commission resulting in a rich meeting between scientists, governments authorities and represents from the industry sectors [17].

8. CONCUSIONS

The studies summarized in this work confirm that small and tabletop Plasma Focus (PF) devices are powerful and versatile platforms for investigating the physics of high-energy-density plasmas and for developing applications that bridge fusion research with materials science and biology. New operational regimes have been identified, improving the efficiency of neutron and X-ray generation, while advanced diagnostics, including Zeeman spectroscopy, Thomson scattering modeling, and artificial intelligence applied to plasma signal analysis, have contributed to a deeper understanding of plasma dynamics and emission processes.

Material studies under extreme pulsed conditions, conducted with kilojoule and joule-class PF systems, have provided insight into the mechanisms of damage, melting, and cracking relevant to plasma-facing components in fusion reactors, and at the same time, have enabled the design of compact plasma shock irradiators and miniaturized thrusters for nanosatellites. In parallel, radiobiological studies have shown distinctive responses of living matter to pulsed radiation, including hyper-radiosensitivity and high relative biological effectiveness at low doses, which are also relevant for the development of accurate dosimetry systems in pulsed radiation environments typical of fusion experiments. These advances motivated the design and construction of a new 5 kJ plasma focus device, the Plasma Focus for Fundamental and Applied Research (PFFAR-5 kJ), currently under characterization at the P^2mc-CCHEN. The PFFAR-5 kJ extends the experimental capabilities for studying plasma and nuclear fusion fundamentals, material response under extreme conditions, and the biological and dosimetric effects of pulsed radiation.

At the theoretical level, advances in the statistical physics of non-equilibrium systems have provided a rigorous framework linking microscopic correlations with macroscopic thermodynamic quantities such as temperature and its fluctuations, contributing to the understanding of non-Maxwellian plasma behavior.

Finally, the establishment of the Nuclear Fusion Unit at the Latin American Center of Physics (CLAF) has enabled coordinated regional collaboration, connecting scientific research with social and technological development. Together, these achievements illustrate that compact plasma focus devices can serve not only as key instruments for fusion studies but also as bridges between fundamental science, technological innovation, and the equitable development of knowledge and energy.

ACKNOWLEDGEMENTS

Supported by ANID-Chile under the following grants: ANID/FONDECYT Regular 1211695, ANID FONDECYT Regular 1240370, FONDECYT Regular 1220651, FONDECYT Regular 1211131, ANID FONDECYT Iniciación 11230595 and IAEA Research Contract 24222.

REFERENCES

[1] Soto, L. (2005). New trends and future perspectives on plasma focus research. *Plasma Physics and Controlled Fusion*, *47*(5A), A361.
[2] Auluck, S., et al. (2021). Update on the scientific status of the plasma focus. *Plasma*, *4*(3), 450-669.
[3] Soto, L., et al. (2010). Studies on scalability and scaling laws for the plasma focus: Similarities and differences in devices from 1 MJ to 0.1 J. *Plasma Sources Science and Technology*, *19*(5), 055017.
[4] Jain, J., et al. (2023). The presence of high-energy neutrons in neutron pulses emitted from a kilojoule plasma focus device: Deuterium as a working gas. *Physics of Plasmas*, *30*(10), 102706.
[5] Avaria, G., et al. (2023). Magnetic field distribution estimations with Zeeman splitting spectroscopy at the radial phase of the PF-400J device. In APS DPP Meeting Abstracts (Vol. 2023, pp. PP11-080).

[6] Avaria, G., et al. (2019). Hard X-ray emission detection using deep learning analysis of the radiated UHF electromagnetic signal from a plasma focus discharge. *IEEE Access*, *7*, 74899-74908.

[7] Pavez, C., et al. (2022). New evidence about the nature of plasma filaments in plasma accelerators of type plasma-focus. *Plasma Physics and Controlled Fusion*, *65*(1), 015003.

[8] Zorondo, M., et al. (2022). Model of Thomson scattering from z-pinch plasma: Application in experimental design for Plasma Focus. *Results in Physics*, *40*, 105831.

[9] Soto, L., et al. (2024). Development of a Miniaturized 2-Joule Pulsed Plasma Source Based on Plasma Focus Technology: Applications in Extreme Condition Materials and Nanosatellite Orientation. *Micromachines*, *15*(9), 1123.

[10] Jain, J., et al. (2024). Plasma-induced damage on the tungsten surface using a kilojoule plasma focus device: Applicable to study the damages on nuclear fusion reactor related materials. *Physics of Plasmas*, *31*(8).

[11] Jain, J., et al. (2021). Hyper-radiosensitivity in tumor cells following exposure to low dose pulsed x-rays emitted from a kilojoule plasma focus device. *Journal of Applied Physics*, *130*(16).

[12] Verdejo, V., et al. (2023). Use of a plasma focus device to study pulsed X-ray effects on peripheral blood lymphocytes: Analysis of chromosome aberrations. *Journal of applied physics*, *133*(16).

[13] Avaria, G., et al. (2022). Bayesian inference of spectrometric data and validation with numerical simulations of plasma sheath diagnostics of a plasma focus discharge. *Scientific Reports*, *12*(1), 15601.

[14] Davis, S., et al. (2019). Single-particle velocity distributions of collisionless, steady-state plasmas must follow superstatistics. *Physical Review E*, *100*(2), 023205.

[15] Davis, S., et al. (2023). Kappa distribution from particle correlations in nonequilibrium, steady-state plasmas. *Physical Review E*, *108*(6), 065207.

[16] Nuclear Fusion Unit (NFU) of the Latin American Center of Physics (CLAF) https://claffisica.org.br/module/unidad-de-fusin-nuclear

[17] Interamerican Conference on the Science and Technology of Nuclear Fusion and Its Applications: Science, Government and Industry. https://www.fusionlatam.cl/english.html

[18] Moreno, J., et al. (2015). Neutron energy distribution and temporal correlations with hard x-ray emission from a hundreds of joules plasma focus device. *Plasma Physics and Controlled Fusion*, *57*(3), 035008.

[19] Davis, S., et al. (2021). A model for defect formation in materials exposed to radiation. *Matter and Radiation at Extremes*, *6*(1).

[20] Akel, M., et al. (2016). Deuterium plasma focus as a tool for testing materials of plasma facing walls in thermonuclear fusion reactors. *Journal of fusion Energy*, *35*(4), 694-701.

[21] Klimov, N., et al. (2009). Experimental study of PFCs erosion under ITER-like transient loads at plasma gun facility QSPA. *Journal of Nuclear Materials*, *390*, 721-726.

[22] Schmid, E., et al. (1996). Analysis of chromosome aberrations in human peripheral lymphocytes induced by in vitro α-particle irradiation. *Radiation and environmental biophysics*, *35*(3), 179-184.

[23] Krumrey, M., et al. (2004). Dicentric chromosomes in monolayers of human lymphocytes produced by monochromatized synchrotron radiation with photon energies from 1.83 keV to 17.4 keV. *Radiation and environmental biophysics*, *43*(1), 1-6.

[24] Barquinero, F., et al. (1997). Biological dosimetry in simulated in vitro partial irradiations. *International journal of radiation biology*, *71*(4), 435-440.

[25] Barquinero, F., et al. (1995). Establishment and validation of a dose-effect curve for γ-rays by cytogenetic analysis. *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis*, *326*(1), 65-69.

[26] Andaur, R., et al. (2018). Differential miRNA expression profiling reveals miR-205-3p to be a potential radiosensitizer for low-dose ionizing radiation in DLD-1 cells. *Oncotarget*, *9*(41), 26387.

[27] Schmidt, A., et al. (2014). Comparisons of dense-plasma-focus kinetic simulations with experimental measurements. *Physical Review E*, *89*(6), 061101.

[28] Beck, C. and Cohen, E. (2003) *Superstatistics*. Physica A 322, 267-275.

[29] Tsallis, C. *Introduction to Nonextensive Statistical Mechanics: Approaching a Complex World.* Springer (2009).

[30] Knapp, P. F. et al. (2013) *Diagnosing suprathermal ion populations in Z-pinch plasmas using fusion neutron spectra*. Physics of Plasmas 20, 062701.

[31] Pressé, S. et al. (2013) *Nonadditive Entropies Yield Probability Distributions with Biases not Warranted by the Data*. Physical Review Letters 111, 180604.

[32] Pressé, S. (2014) *Nonadditive entropy maximization is inconsistent with Bayesian updating*. Physical Review E 90, 052149

[33] Klir, D., et al. (2015). *Efficient generation of fast neutrons by magnetized deuterons in an optimized deuterium gas-puff Z-pinch*. Plasma Physics and Controlled Fusion 57, 044005.

[34] Livadiotis, G. (2017) *Kappa distributions: Theory and Applications in Plasmas*. Elsevier.

[35] Lazar, M., Fichtner, H. Kappa distributions. Springer.

[36] Davis, S. (2022) *Fluctuating temperature outside superstatistics: Thermodynamics of small systems*. Physica A 589, 126665.

[37] Davis, S. (2022) *A classification of nonequilibrium steady states based on temperature correlations*. Physica A 608, 128249.

[38] Davis, S. (2023) *Superstatistics and the fundamental temperature of steady states*. AIP Conference Proceedings 2731, 030006.

[39] Maréchal, P. et al. (2024) *On the foundations of the maximum entropy principle using Fenchel duality for Shannon and Tsallis entropies*. Physica Scripta **99**, 075265 (2024).