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

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Our research program includes:

- **Plasma physics related with thermonuclear fusion in Z-pinches:**
  - Stability in gas embedded Z-pinch at MA currents
  - Plasma foci: increasing the plasma energy density in order to increase the thermonuclear neutron yield.
- **Miniaturization of Plasma Focus devices:**
  - Nanoflashes of radiation from miniaturized devices.
  - Scaling studies
- **Other pinch configuration:**
  - Wires arrays, X-pinches, capillary discharges
- **Effects of pulsed radiation on materials**
  - First wall materials for fusion reactors
- **Effects of pulsed radiation on biological systems**
  - Cancer treatment
  - Pulsed dosimetry
- **Pulsed plasma thruster for nanosatellites**
- **Low temperature plasmas (RF and continuous discharges)**
  - Plasma Torch for materials environment applications
  - Plasma needles for biomedicine applications
  - **Theoretical studies**
  - Statistical mechanics in non canonical systems
  - Non equilibrium plasmas, temperature definition
  - Bayesian statistics
- **Main diagnostics and tools:**
  - Electrical signals
  - Visible plasma images, ICCD, 4ns to 100ns gated frame
  - Optical Refractive diagnostics, Nd-YAG laser: 8ns, 1J; 170ps, 100mJ
  - Neutrons detecton (in particular low yield pulses)
  - X-rays detection (with spatial en temporal resolution
  - Ions detection
  - Espectroscopy (visible, VUV and soft X- rays)
  - UHV radiation detection and analysis
  - Thomson scattering
  - Material characterization
  - Bayesian analysis
  - AI, Machine learning

THE PLASMA FOCUS DISCHARGE: A KIND OF Z-PINCH

The Mather Plasma Focus (PF) is a transient electrical discharge produced in arranged coaxial electrodes, separated by an insulator, and driven typically by a capacitive pulsed power generator, which is controlled by a spark-gap switch.

(I) The discharge starts over the insulator.

(II) The Lorentz force pushes the plasma sheet to move axially.

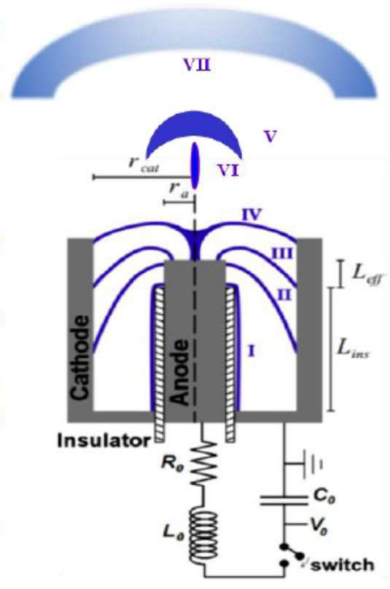
(III) and then to move radially (sometimes plasma filaments appears).

(IV) The sheet collapses to form a dense column of plasma (pinch). During these stage, X-rays and neutron pulses (when operating with deuterium), are generated.

(V) after the pinch is disrupted an axial shock is produced.

(VI) plasma jets are ejected

(VII) a cooler and less dense plasma reaches farther from the anode.

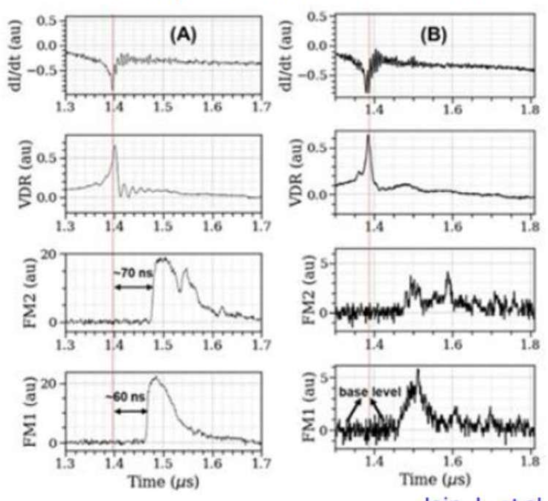


Plasma focus devices at P²mc-CCHEN

Device	PF-2kJ	PF-400J	MPG	PF-2J
Energy stored	867-2500	275-396	240-735	1.3-5.5
Capacity (nF)	6000- 8000	880	1200	110
Inductance (nH)	64	38	43	40
Charging voltage (kV)	17-25	25-30	20-35	5-10
Maximum current (kA)	160-280	90-140	100-180	8-16
Time to maximum current (ns)	1125	320	400	105
Anode radius (mm)	12.5-6	6-3	6-3	1.1
Effective anode length (mm)	20-30	6-30	6-30	1-2

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. **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.**



In Fig. (A) and (B), neutron signals captured using a combination of a scintillator (Bicron BC-408) and a photomultiplier tube (FM1: Axial, FM2: radial) are shown. Fig. (A) is obtained without neutron spectroscopy experimental conditions, which constitutes X-ray shielding by a 5 cm lead block, and Fig. (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).

Jain, J., et al. (2023). Physics of Plasmas, 30(10), 102706

MAGNETIC FIELD, X-RAYS, UHF RADIATION

- **High-energy Magnetic field distribution**

Magnetic field distribution estimations with Zeeman splitting spectroscopy at the radial phase of the PF-400J device were obtained. Zeeman splitting spectroscopic technique of the Ar III emission at 330.18 nm was using. A **magnetic field of around 2T is estimated at the pinch volume**, when the **maximum current (~100kA)** is achieved.

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

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. 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.** 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.**

Avaria, G., et al. (2019). IEEE Access, 7, 74899-74908

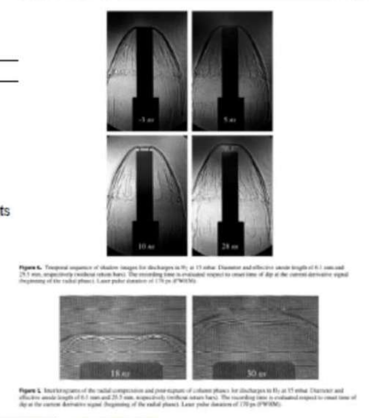
THOMSON SCATTERING

A model of Thomson scattering (TS) for z-pinch plasmas was developed. 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. 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.

Zorondo, M., et al. (2022). Results in Physics, 40, 105831

NEW OPERATIONAL REGIMES

	PF-400J	MPG
Peak current (kA)	120-140	90-100
Stored energy (J)	320-370	290-345
Average neutron yield	5×10^5	5×10^6
Maximum neutron yield	$(1\text{-}2)\times10^6$	$(1\text{-}2)\times10^7$
Efficiency (neutrons /J)	3×10^3	5.3×10^4
Efficiency (neutrons /A)	7.1	175-240
Filaments in the radial phase	with filaments	without filaments
Compression mean velocity (m/s) (From the dip of current-derivative signal)	$(6\text{-}8)\times10^4$	$(1\text{-}2)\times10^5$
Compression mean velocity (m/s) (From the shadowgrams sequence)		$(2\text{-}4)\times10^5$
Ratio $\frac{I}{a}$ $\left(\frac{kA}{cm}\right)$	200-233	300-333
Drive parameters $S=\frac{I}{a\sqrt{p}}(kA\cdot mbar^{-\frac{1}{2}}\cdot cm^{-1})$	67-78	84-93

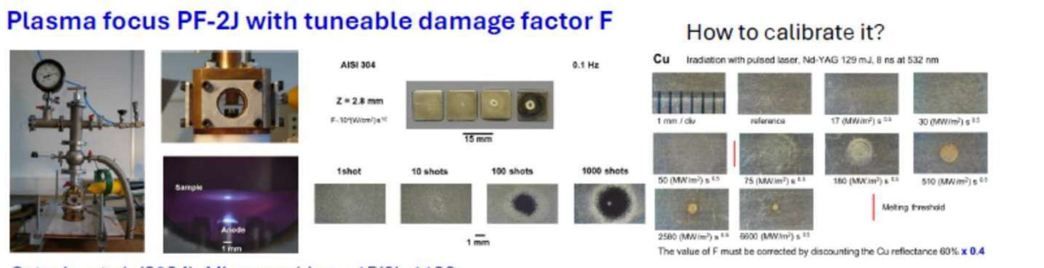


Pavez, C., et al. (2022). Plasma Physics and Controlled Fusion, 65(1), 015003

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

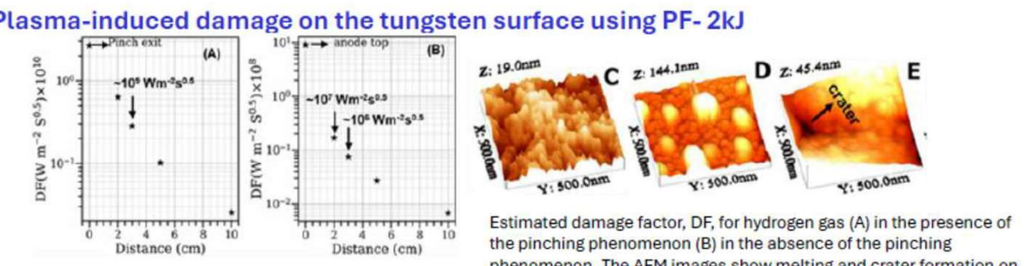
Plasma focus PF-2J with tuneable damage factor F

How to calibrate it?



Soto, L., et al. (2024). Micromachines, 15(9), 1123.

Plasma-induced damage on the tungsten surface using PF- 2kJ



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.

Damage factor $F \sim q\cdot\tau^{1/2} = E/S\tau^{1/2}$

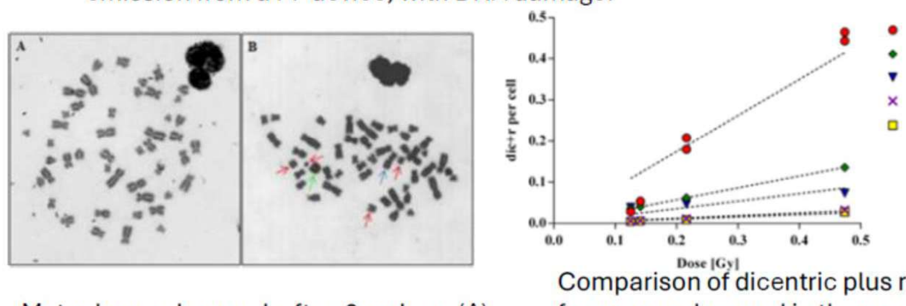
q: power flux, τ: interaction time, S: interaction area

Jain, J., et al. (2024). Physics of Plasmas, 31(8)

EFFECTS OF INTENSE RADIATION ON BIOLOGICAL SYSTEMS, PULSED RADIATION DOSIMETRY AND CANCER ULTRA FLASH RADIOTHERAPY

Dosimetry for pulsed radiation environments

There is a positive correlation between the number of shots with pulsed X-ray emission from a PF device, with DNA damage.



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).

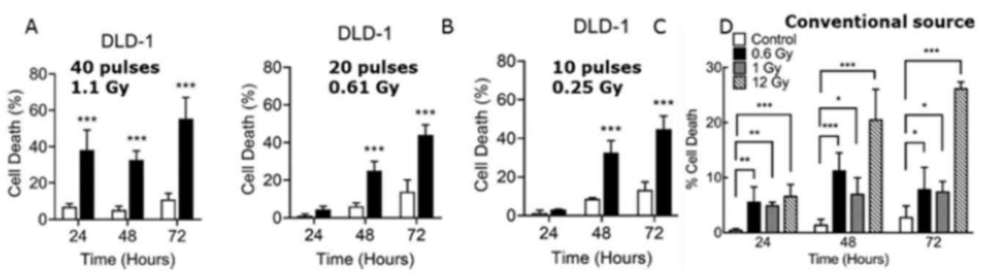
Comparison of dicentric plus ring (dic + r) frequency observed in the present study (red circles), and frequencies calculated using previously published curves for α-particles (green diamonds x rays (blue invert triangles for 10 keV; and purple crosses for 180 kVp), and γ radiation (yellow squares).

Verdejo, V., et al. (2023). Journal of applied physics, 133(16)

EFFECTS OF INTENSE RADIATION ON BIOLOGICAL SYSTEMS, PULSED RADIATION DOSIMETRY AND CANCER ULTRA FLASH RADIOTHERAPY

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.



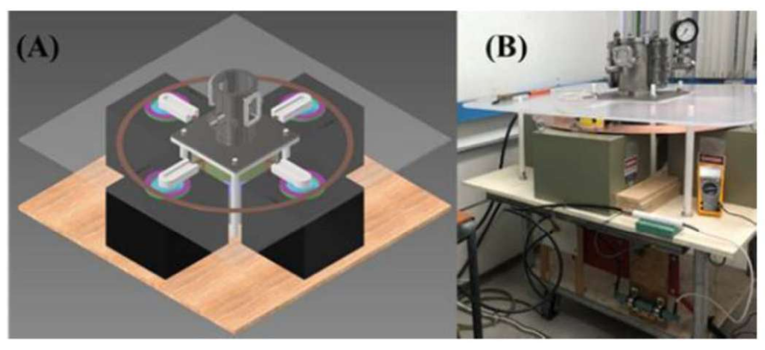
Cancer cell line DLD-1 shows larger cell death at two orders of magnitude lower doses in comparison to conventional x-ray irradiation.

Jain, J., et al. (2021Journal of Applied Physics, 130(16)

Andaur, R., et al. (2018). Oncotarget, 9(41), 26387

DEVELOPMENT OF THE PFFAR-5KJ PLASMA FOCUS DEVICE

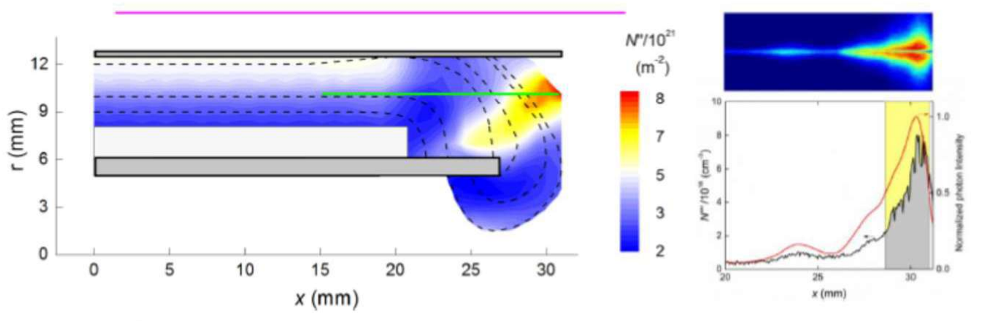
Considering the versatile nature of plasma focus devices, a 5 kJ plasma focus system, named Plasma Focus for Fundamental and Applied Research – PFFAR-5kJ, has been developed and is currently under characterization at the P²mc. The device is designed to study the fundamentals of plasma and nuclear fusion 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.



(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 P²mc.

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

Bayesian inference of spectrometric data and validation with numerical simulations of plasma sheath diagnostics of a plasma focus discharge were implemented. An experimental assessment of the electron density in the rundown phase of a 400 J Plasma Focus in hydrogen was performed. 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. It was 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.



Avaria, G., et al. (2022. Scientific Reports, 12(1), 15601

PLASMA PHYSICS AND STATISTICAL PHYSICS OF NON-EQUILIBRIUM SYSTEMS

Non-equilibrium plasmas, both in space and laboratory environments, often exhibit velocity distributions that deviate from the classical Maxwellian form. Among them, the kappa distribution has been widely used to describe empirical data in magnetospheric, solar, and laboratory plasmas. Traditional explanations based on generalized entropy formalisms, such as Tsallis' non-extensive statistical mechanics, lack consistency with fundamental statistical principles. Our recent work provides a rigorous alternative based on the theory of superstatistics, showing that non-Maxwellian distributions naturally emerge from statistical mixtures of Maxwellian ensembles with fluctuating inverse temperatures. This framework introduces the concept of fundamental inverse temperature (β_F), linking microscopic energy correlations with macroscopic thermodynamic quantities. It allows the classification of steady non-equilibrium plasma states through two invariant measures —the mean inverse temperature (β_0) and its covariance (U)— offering a unified description of complex plasma systems beyond equilibrium.

Davis, S., et al. (2019). Physical Review E, 100(2), 023205.
Davis, S., et al. (2023). Physical Review E, 108(6), 065207.
Davis, S. (2022). Physica A 589, 126665
Davis, S. (2022). Physica A 608, 128249

CONNECTING RESEARCH WITH SOCIETY AND INDUSTRY: ENERGY JUSTICE AND EQUITY

Nuclear Fusion Unit (CLAF–UNESCO): created in 2024 under the leadership of the Chilean Nuclear Energy Commission (CCHEN) to connect Latin American fusion research using small devices —tokamaks, stellarators, plasma focus — and theory fostering cooperation and equity. **In 2025, the First Interamerican Conference on Nuclear Fusion: Science, Government and Industry**, organized in Chile by the CCHEN, strengthened the link between research, policy, and society in the region.

https://claffisica.org.br/module/unidad-de-fusin-nuclear
https://www.fusionlatam.cl/english.html

FINAL REMARKS

- Small and tabletop Plasma Focus (PF) devices are powerful and versatile tools for fusion and high-energy-density plasma research.
- New operational regimes and advanced diagnostics —including Zeeman spectroscopy, Thomson scattering modeling, and AI analysis— have improved understanding of plasma dynamics and emission processes.
- Experiments on materials under extreme pulsed conditions revealed melting, cracking, and damage mechanisms relevant to plasma-facing components in fusion reactors.
- The same PF technology enabled the development of compact plasma shock irradiators and miniaturized thrusters for nanosatellites.
- Radiobiological studies with pulsed X-rays showed hyper-radiosensitivity and high biological effectiveness at low doses, supporting new approaches for dosimetry in pulsed radiation environments.
- These advances led to the construction of the PFFAR-5 kJ device at P2mc-CCHEN, expanding capabilities in plasma physics, material studies, and radiobiological applications.

FINAL REMARKS

- Theoretical progress in non-equilibrium statistical physics provided a consistent framework for understanding non-Maxwellian plasmas and temperature fluctuations.
- The Nuclear Fusion Unit (CLAF–UNESCO), led by CCHEN, promotes regional collaboration among Latin American fusion programs, connecting science, technology, and society.
- Together, these results show that compact PF devices act as bridges between fundamental research, technological innovation, and equitable scientific development.

ACKNOWLEDGEMENTS

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