Small Dense Pulsed Plasma Discharges Program at the Chilean Nuclear Energy Commission Basic Research and Applications to Fusion, Materials and Biology

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Motivation

Is it possible to do relevant experimental plasma physics and fusion research in a small country?
Z-pincho experiments in Sandia

Z MACHINE
Pulsed Power Facility
Visitor’s Guide

(10-20 MJ)
OUR APPROACH

PLASMA ENERGY DENSITY

\[ \sim 10^{12} \text{ J/m}^3 \]

1J in a sub millimeter volume

0.1J in a sphere of 60\( \mu \text{m} \) of diameter

PLASMA PHYSICS IN SMALL DEVICES
The plasma focus discharge

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.

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

\( E \sim kJ - MJ \)
\( I \sim 100kA - 1MA \)
\( t_p \sim 10ns - 100ns \)
\( Y_n \propto E^2 \)
\( Y_n \propto I^{3.3-4.7} \)
\( n \sim 10^{25} \text{ m}^{-3} \)
### Some PF devices in operation in the world during the period 1990-2000

<table>
<thead>
<tr>
<th>Device, location</th>
<th>Energy E (kJ)</th>
<th>Anode radius a (cm)</th>
<th>Peak current (kA)</th>
<th>Operation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF-1000, Poland</td>
<td>1064</td>
<td>12.2</td>
<td>2300</td>
<td>Single shot</td>
</tr>
<tr>
<td>PF-360, Poland</td>
<td>130</td>
<td>6</td>
<td>1200</td>
<td>Single shot</td>
</tr>
<tr>
<td>SPEED2, Germany</td>
<td>70</td>
<td>5.4</td>
<td>2400</td>
<td>Single shot</td>
</tr>
<tr>
<td>7kJ PF, Japan</td>
<td>7</td>
<td>1.75</td>
<td>390</td>
<td>Single shot</td>
</tr>
<tr>
<td>GN1, Argentina</td>
<td>4.7</td>
<td>1.9</td>
<td>-</td>
<td>Single shot</td>
</tr>
<tr>
<td>Fuego Nuevo, Mexico</td>
<td>4.6</td>
<td>2.5</td>
<td>350</td>
<td>Single shot</td>
</tr>
<tr>
<td>UNU/ICTP-PF, AAAPT-Asia and Africa</td>
<td>2.9</td>
<td>0.95</td>
<td>172</td>
<td>Single shot</td>
</tr>
<tr>
<td>Fraunhofer Insitute ILT-Aachen, Germany</td>
<td>2-5</td>
<td></td>
<td></td>
<td>Repetitive, 2Hz</td>
</tr>
<tr>
<td>Research Lab. Alameda, USA</td>
<td>2</td>
<td></td>
<td></td>
<td>Repetitive, 2Hz</td>
</tr>
<tr>
<td>NX1, Singapore</td>
<td>3</td>
<td>3</td>
<td>250</td>
<td>Repetitive, 3Hz</td>
</tr>
<tr>
<td>NX2, Singapore</td>
<td>1.9</td>
<td>4</td>
<td>170</td>
<td>Repetitive, 16Hz</td>
</tr>
</tbody>
</table>
Energy density parameter
28E/a³ ~ 5x10¹⁰ J/m⁻³

Drive parameter
l/ap¹/² ~ 77kA/cm mbar¹/²

\[ v_a \propto l/ap^{1/2} \quad v_r \propto l/ap^{1/2} \]

\[ r_p \sim (0.1-0.2) \, a, \quad z_p \sim (0.8-1) \, a \]

\[ a: \text{anode radius} \]

Our goal:
Miniature Plasma Focus Devices < 1kJ
To find scaling laws
Under kJ PF devices at CCHEN

PF-400J | PF-50J | PF-2J | NF
Demonstration of neutron production in a table-top pinch plasma focus device operating at only tens of joules

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Nanofocus: an ultra-miniature dense pinch plasma focus device with submillimetric anode operating at 0.1 J

Leopoldo Soto,2,3, Cristian Pavez2,3, José Moreno1,3, Mario Barbaglia1 and Alejandro Chausse5

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Diagnostics

- Electrical signals
- Visible plasma images
- X-ray detections (temporal and spatial resolution)
- Neutron detection (in particular low yield pulsed)
- Charged particles
- Optical refractive diagnostics
- Spectroscopy
Basic Physics

- Plasma Focus characterization
- Before the pinch
- During the pinch
- After pinch

PF-400J
Schlieren images

S#10
-40
S#21
-32
S#08
-18
S#35
-7
S#19
-4
S#36
-2
S#20
12

Radial Dynamic in D$_2$

$\nu_m = -8 \times 10^4 \pm 0.8 \times 10^4$ m/s

$r_p \sim 0.1 \ r_a$

$z_p \sim 0.8 \ r_a$
PF-2J
Schlieren images

a) the plasma sheath is moving axially
b) the pinch moment
c) after the pinch disruptions.

This is the first time in which optical refractive diagnostics from a PF of only 2 joules is reported.

\[ r_p \sim 0.1 \, r_a \]
\[ z_p \sim 0.8 \, r_a \]

L. Soto, C. Pavez, F. Castillo, J. Jain, J. Pedreros  in preparation
PF-400J Interferograms

\[ t = 4 \pm 4 \text{ ns} \]

\[ p = 5 \text{ mbar} (\text{H}_2); t = 4 \text{ ns}; z_p = 4 \text{ mm} \]

\[ r_p \sim 0.1 r_a \]

\[ z_p \sim 0.8 r_a \]
A hundred joules PF as a neutron source, PF-400J

Toroidal High-Density Singularity in a Small Plasma Focus

Federico Casanova · Ariel Tarifeño-Saldívia · Felipe Veloso · Cristian Pavez · Alejandro Clausse · Leopoldo Soto
Toroidal High-Density Singularity in a Small Plasma Focus

Federico Casanova · Ariel Tarifeño-Saldivia · Felipe Veloso · Cristian Pavez · Alejandro Clausse · Leopoldo Soto

Fig. 5 Shape of the current sheet at different times. Numerical (black), experimental (solid grey). The numbers at the right indicate the corresponding time relative to dip.
Filamentary structures in dense plasma focus: Current filaments or vortex filaments?

Leopoldo Soto,\textsuperscript{1,2,3,a)} Cristian Pavez,\textsuperscript{1,2,3} Fermin Castillo,\textsuperscript{4} Felipe Veloso,\textsuperscript{5} José Moreno,\textsuperscript{1,2,3} and S. K. H. Auluck\textsuperscript{6}

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\textsuperscript{6}Bhabha Atomic Research Center, Mumbai 400 085, India
Filaments

PF-400J

Visible images

Schlieren

-16ns
-6ns
49ns

Filaments diameter \(\sim 300\mu m\), \(n_e \sim 10^{25} \text{ m}^{-3}\)
Characterization of the axial plasma shock in a table top plasma focus after the pinch and its possible application to testing materials for fusion reactors

Leopoldo Soto, Cristian Pavez, José Moreno, María José Inestrosa-Izurieta, Felipe Veloso, Gonzalo Gutiérrez, Julio Vergara, Alejandro Clausse, Horacio Bruzzone, Fermín Castillo, and Luis F. Delgado-Aparicio

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10 Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA

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Plasma bursts after the pinch

Previous studies did not pay attention after the pinch disruptions

PF- 400J

D₂  9mbar

-7ns  -4ns  25ns  43ns

68ns  102ns  145ns  172ns

10mm

Plasma bursts after the pinch

Plasma bursts after the pinch

\[ Z_3(t) - Z_3(t_0) = \left[ \frac{75}{16\pi} \frac{(\gamma - 1)(1 + \gamma)^2}{(3\gamma - 1)} \frac{E}{\rho_0} \right]^{1/5} (t - t_0)^{2/5} \]

Observation of plasma jets in a table top plasma focus discharge

Cristian Pavez, José Pedreros, Ariel Tarifeño-Saldívia, and Leopoldo Soto

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After plasma jets are observed

PF-50J

DISCHARGE TIME HISTORY

- Radial Phase
- Jet-like structures appear
- Plasma bursts
After plasma jets are observed

Hollow anode

\( n_e \sim 10^{24} - 10^{25} \text{ m}^{-3} \) \( v \sim 4 \times 10^4 \text{ m/s} \)

Plasma jets

Solid anode

\( n_e \sim 10^{24} - 10^{25} \text{ m}^{-3} \quad v \sim 4 \times 10^4 \text{ m/s} \)

PF dynamics including times after the pinch disruption
C. Pavez et al, RUSFD 2017

Vo = 22-23 kV, p = 12 mbar

Vo = 22-23 kV, p = 12 mbar

75.40 mm

35.15 mm

φ 6.10 mm
C. Pavez et al, RUSFD 2017
**Spectroscopy**
G. Avaria et al, RUSFD 2017

**Discharge:**
- Charging voltage ~27kV (~310 J)
- Frequency 0.06Hz (~ 16 s)

**Diagnostics**
- 0.5 m Cerny-Turner *Imaging* Spectrometer
  - 300 l/mm
  - Optical resolution (FWHM): 0.4 nm
- ICCD
  - FWHM: 3 ns
Results: Use of impurities

- To observe the ionization degree evolution of the plasma sheath, we added small impurities.

- Hydrogen at 98%, Nitrogen at 2%. Pressure was calculated to be equivalent to 9 mbar of pure hydrogen, by maintaining the mass of the mixture.
Applications
Feasibility study of a hybrid subcritical fission system driven by Plasma-Focus fusion neutrons

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Pulsed reactor

\textbf{ABSTRACT}

A feasibility analysis of a hybrid fusion–fission system consisting of a two-stage spherical subcritical cascade driven by a Plasma Focus device is presented. The analysis is based on the one-group neutron diffusion equation, which was appropriately cast to assess the neutronic amplification of a spherical configuration. A design chart was produced to estimate the optimum dimensions of the fissile shells required to achieve different levels of neutron amplification. It is found that cascades driven by Plasma Focus of tens of kJ are feasible. The results were corroborated by means of Monte Carlo calculations.

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Materials for fusion reactors
Damage factor

\[ F \sim q \cdot \tau^{1/2} = \frac{E}{S \tau^{1/2}} \]

q: power flux, \( \tau \): interaction time, S: interaction area
Expected Damage in Fusion Reactor

ITER:

\[ F \sim q \cdot \tau^{1/2} \sim 10^8 (W/m^2) \cdot s^{1/2} = 10^4 (W/cm^2) \cdot s^{1/2} \]

at 0.5 – 1 Hz, 10³ pulses

IFE:

\[ F \sim q \cdot \tau^{1/2} \sim 10^4 (W/cm^2) \cdot s^{1/2} \]

at 10 Hz

PF-400J:

\[ F \sim q \cdot \tau^{1/2} \sim 10^3 - 10^5 (W/cm^2) \cdot s^{1/2} \]

at 0.05 Hz
1 ELMs would be “equivalent” to a wagon of train of 100 tons at 220 km/h shocking on a wall.
Damage factor

\[ F \sim q \cdot \tau^{1/2} = \frac{E}{S} \tau^{1/2} \]

\( q \): power flux density, \( \tau \): interaction time, \( S \): interaction area
Total mass inside the bubble, \( m \): \( \sim \) total pinch mass

(the pinch is ejected through Z2, creating so the bubble)

The pinch density was previously measured using pulsed interferometry, thus the total pinch mass is \( m \sim 1.5 \times 10^{-10} \) kg


Length of the ejected mass: \( \sim \) pinch length, \( L = 5.6 \) mm

Time of interaction, \( \tau \sim L / v \)
Plasma bursts after the pinch

\[ Z_3(t) - Z_3(t_0) = \left[ \frac{75}{16\pi} \frac{(\gamma - 1)(1 + \gamma)^2}{(3\gamma - 1)} \frac{E}{\rho_0} \right]^{1/5} (t - t_0)^{2/5} \]

Tunable Damage Factor
damage factor, $F \sim q \cdot \tau^{1/2} \alpha \tau^{1/2} a^{1/2} \alpha (E^{1/3})^{1/2}$

$$F \propto E^{1/6}$$

<table>
<thead>
<tr>
<th>Energy</th>
<th>Damage Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF, 1MJ</td>
<td>$F$</td>
</tr>
<tr>
<td>PF, 1kJ</td>
<td>$\sim 1/3 F$</td>
</tr>
<tr>
<td>PF, 100J</td>
<td>$\sim 1/5 F$</td>
</tr>
<tr>
<td>PF, 10J</td>
<td>$\sim 1/7 F$</td>
</tr>
<tr>
<td>PF, 1J</td>
<td>$\sim 1/10 F$</td>
</tr>
</tbody>
</table>

Roughly speaking

The damage factor for the PF-1000 (1MJ) at Poland is only 3.65 times greater than the damage factor for the PF- 400J (400J) at Chile.

L. Soto et al, in preparation
Morphological and structural effects on tungsten targets produced by fusion plasma pulses from a table top plasma focus

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$^3$ Instituto de Física, Pontificia Universidad Católica de Chile, Santiago 7820436, Chile

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PF400J: Fusion Plasma Pulses Source

Implementation of:

- Sample holder → avoiding ablation
- Shutter → control exposure
- Hollow anode → avoid anode material deposition
PF400J: Fusion Plasma Pulses Source
Tungsten target

\[ m \sim 1.5 \times 10^{-10} \text{ kg} \]
\[ L = 5.6 \text{ mm} \]
\[ \tau \sim \frac{L}{v} \]

<table>
<thead>
<tr>
<th>Z (mm)</th>
<th>V (m/s)</th>
<th>S (cm²)</th>
<th>E/S (J/cm²)</th>
<th>( \tau ) (ns)</th>
<th>q (W/cm²)</th>
<th>( F = q \tau^{1/2} ) (W/cm²)s^{1/2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>7.5×10^4</td>
<td>0.6</td>
<td>0.69</td>
<td>75</td>
<td>9.2×10^6</td>
<td>2.5×10^3</td>
</tr>
<tr>
<td>25</td>
<td>2.08×10^4</td>
<td>2.54</td>
<td>1.3×10^{-2}</td>
<td>270</td>
<td>4.7×10^4</td>
<td>24</td>
</tr>
<tr>
<td>35</td>
<td>1.05×10^4</td>
<td>5.87</td>
<td>1.4×10^{-3}</td>
<td>533</td>
<td>2.6×10^3</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Morphological Effects on W SEM

15 mm

Reference

15 mm

Scanning Electron Microscope images to comparison the extreme irradiation targets

25 mm

35 mm

Deposition of DLC
M. J. Inestrosa-Izurieta, RUSFD 2017

SEM images of: 10 mm - 8 pulses and 10 mm - 42 pulses

8 pulses → rough surface (big grains or agglomeration)
42 pulses → smooth surface filled with microcracks and holes

⇒ cumulative melting effect
Effects of pulsed radiation in cell
J. Jain et al, RUSFD 2017

Hundreds of joule plasma focus device as a potential source of pulsed x-rays and neutrons for in vitro cancer cell irradiation, J. Jain et al, RUSFD 2017
Hundreds of joule plasma focus device as a potential source of pulsed x-rays and neutrons for in vitro cancer cell irradiation, J. Jain et al, RUSFD 2017

Mock control

Irradiated (pulsed x-rays)

DNA damage DSB
J. Jain et al, RUSFD 2017

• DSB induction was found at low doses (0.12 Gy) in case of pulsed x-rays.

• Cell death was absent in case pulsed x-rays irradiation.

• Neutron irradiation provides cell death at ultralow doses but DNA damage with higher statistical insignificance.

Hundreds of joule plasma focus device as a potential source of pulsed x-rays and neutrons for in vitro cancer cell irradiation, J. Jain et al, RUSFD 2017
Recently

- Continuos plasmas, Plasma torch. Biswajit Bora

- Theory and simulations. Sergio Davis, Karla Kauffmann
Current research focuses on the development of plasma devices for various applications such as plasma cutting, surface hardening, and medical treatments. A pulse voltage multiplier is developed for improving the efficiency of plasma devices. The potentiality of a tabletop plasma focus as an X-ray source for radiographic applications is investigated.

Some studies include:

Collaborators

- R. Gonzalez, A. Rivera, M. Perlado, M. Panizo, Universidad Politécnica de Madrid, Spain
- K. Marcelain, R. Andaur, D. Diez, Institute of Biomedical Sciences Universidad de Chile
- G. Gutierrez, GNM Universidad de Chile
- F. Veloso, P. Universidad Católica de Chile
- A. Clausse, Comisión Nacional de Energía Atómica, Argentina and Universidad del Centro, Tandil, Argentina
- M. Barbaglia, Universidad del Centro, Tandil, Argentina
- H. Bruzzone, Universidad de Mar del Plata, Argentina
- F. Castillo, México
- D. Klir, Czech Technical University in Prague, Czech Republic
- Luis F. Delagado-Aparicio, PPPL, USA
- S. K. H. Auluck, BARC, India
- F. Gonzalez Cataldo, University of California, Berkeley, USA.
Future work

To keep on playing
Thank you!

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The stability regime in which a particular PF device lives, depends on the energy of the device and of the size of the anode radius.

Different plasma foci that work with stored energy ranging from 0.1 J to 1MJ are plotted in the diagram for Z-pinch stability given by Haines and Coppins.

\[ S / V \text{ effects } \alpha 1/a \]

Power flux density does not depend on PF energy

For PF devices:

\[ \frac{E}{a^3} \sim \text{const} \]
\[ n \sim \text{const} \]
\[ v \sim \text{const} \]
\[ T \sim \text{const} \]
\[ r_p \sim 0.1a \]
\[ z_p \sim 0.8a \]

Plasma ejected from the pinch (burst) on a target at \( Z \), \( 1.5a < Z < 2.7a \)

\[ m \sim m_p \alpha V_p \alpha a^3 \]

Thickness \( \sim \) pinch length \( L_p \alpha a \)

Time of interaction \( \tau = \frac{L}{v} \alpha a \)

Cross section \( S: a^2 \)

\[ q \sim \frac{KE}{\tau S} \alpha \frac{m}{\tau S} \alpha \frac{a^3}{a a^2} \sim \text{const} \]

L. Soto et al, in preparation
6 order of magnitud in energy translates in only 1 order of magnitude in damage factor

damage factor, $F \sim q \cdot \tau^{1/2} \alpha \tau^{1/2} \alpha a^{1/2} \alpha (E^{1/3})^{1/2}$

$$F \propto E^{1/6}$$

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Roughly speaking

The damage factor for the PF-1000 (1MJ) at Poland is only 3.65 times greater than the damage factor for the PF-400J (400J) at Chile.

L. Soto et al, in preparation
Plasma ejected after the pinch

Plasma shock from the bubble:

(the pinch is ejected creating so the bubble)

**Total mass inside the bubble, m: ~ total pinch mass**

The pinch density was previously measured using pulsed interferometry, thus the total pinch mass is $m \sim 1.5 \times 10^{-10} \text{ kg}$


- Length of the ejected mass: ~ pinch length, $L = 5.6 \text{ mm}$
- $V_{Z3} = V(z)$
- Kinetic energy = $E(z)$
- Time of interaction $\tau = L / <V_{Z3}> = \tau(z)$
- Cross $S = S(z)$
Plasma ejected after the pinch

Plasma from the gun

Total mass swept from the gun:

Is the gas mass between the coaxial electrodes multiplied by the axial mass factor, $f_m$. For the PF-400J experimental conditions, $f_m = 0.08$ and $m_{\text{gun}} \sim 2 \times 10^{-9} \text{ kg}$


- Thickness $(Z_2 - Z_1) \sim 2 \text{ mm}$
- Mean velocity $<V> \sim 3.2 \times 10^4 \text{ m/s}$
- Mass, $m_{12} \sim 2 \times 10^{-9} \text{ kg}$
- Kinetic energy $\sim 1 \text{ J}$
- Time of interaction $\tau = (Z_2 - Z_1) \times V_{Z1} \sim 60 \text{ ns}$
Tunable Damage Factor

\begin{align*}
& \text{z (mm)} \\
& \text{t (ns)} \\
& \text{v (m/s)} \\
& \tau (\text{ns})
\end{align*}
Tunable Damage Factor

Graphs showing the relationship between E (J), S (cm²), F (Ws²/cm²), and z (mm).
Tunable Damage Factor
Differences in damage factor at different position of the target

a) Close to the top of the pinch, between ~9 mm to ~16 mm from the anode top, ~1.5a < Z < 2.7a

Burst: \( q \sim 125\text{MW/cm}^2, \tau \sim 20\text{ns} \), \( F \sim q \cdot \tau^{1/2} \sim 1.8 \times 10^4 \text{(W/cm}^2\text{)} \text{s}^{1/2} \)

Plasma swept by the gun: \( q \sim 2.4 \text{ MW/cm}^2, \tau \sim 30\text{ns}, F \sim q \cdot \tau^{1/2} \sim 5.9 \times 10^2 \text{(W/cm}^2\text{)} \text{s}^{1/2} \)

The effects from the plasma bubble shock is 36 times greater than the effects from the plasma swept in the coaxial gun.

b) between ~16 to ~20 mm from the anode top, ~2.7a < Z < 3.5a

Burst: \( q \sim 0.4 \text{ MW/cm}^2, \tau \sim 120\text{ns}, F \sim q \cdot \tau^{1/2} \sim 1.4 \times 10^2 \text{(W/cm}^2\text{)} \text{s}^{1/2} \)

Plasma swept by the gun: \( q \sim 2.4 \text{ MW/cm}^2, \tau \sim 60\text{ns}; F \sim q \cdot \tau^{1/2} \sim 5.9 \times 10^2 \text{(W/cm}^2\text{)} \text{s}^{1/2} \).

The effects from the plasma burst is less than the effects from the plasma swept in the coaxial gun (1 ÷ 4)
Expected Damage in Fusion Reactor

**ITER:**

\[ F \sim q \cdot \tau^{\frac{1}{2}} \sim 10^8 (W/m^2) \cdot s^{1/2} = 10^4 (W/cm^2) \cdot s^{1/2} \]

at 0.5 – 1 Hz , 10^3 pulses

**IFE:**

\[ F \sim q \cdot \tau^{\frac{1}{2}} \sim 10^4 (W/cm^2) \cdot s^{1/2} \]

at 10 Hz

**PF-400J:**

\[ F \sim q \cdot \tau^{\frac{1}{2}} \sim 10^3 - 10^5 (W/cm^2) \cdot s^{1/2} \]

at 0.05 Hz