A self scale Z-pinch
Scalability, Similarities and Differences in Plasma Focus Devices:
Basic Research and Applications

Part 3
How to build a small Plasma Focus?
Recipes and tricks

Leopoldo Soto

Comisión Chilena de Energía Nuclear (CCHEN)
Center for Research and Aplications in Plasma Physics and Pulsed Power, P4
Santiago, Chile

LEOPOLDO.SOTO@CCHEN.CL

Topics

Part 1. Basic concepts. Z-pinch, pulsed power, plasma focus.

Part 2. How to obtain information from a dense transient plasma? Plasma diagnostics

Basic Research and Applications

Part 3. How to design and to build a small plasma focus? Tricks and Recipes

L. Soto
Plasma Physics and Nuclear Fusion Laboratory
Chilean Nuclear Energy Commission

Designing a PF

Energy density parameter

$$28E/a^3 \sim 5\times10^{10} J/m^{-3}$$

Drive parameter

$$I_0 /ap^{1/2} \sim 77 kA/cm\ mbar^{1/2}$$

- S. Lee and A. Serban, IEEE Trans. Plasma Science **24**, 1101 (1996).
- L. Soto, Plasma Phys. Control. Fusion **47**, A361 (2005)
- T. Zhang, R. S. Rawat, S. M. Hassan, J. J. Lin, S. Mahmood, T. L. Tan, S. V. Springham, V. A. Gribkov, P. Lee, and S. Lee, IEEE, Trans. Plasma Sci. **34**, 2356 (2006)
- L. Soto, C. Pavez, J. Moreno, A. Tarifeño and F. Veloso, Plasma Sources Sci. Technol. **19** ,055017 (2010)

Design

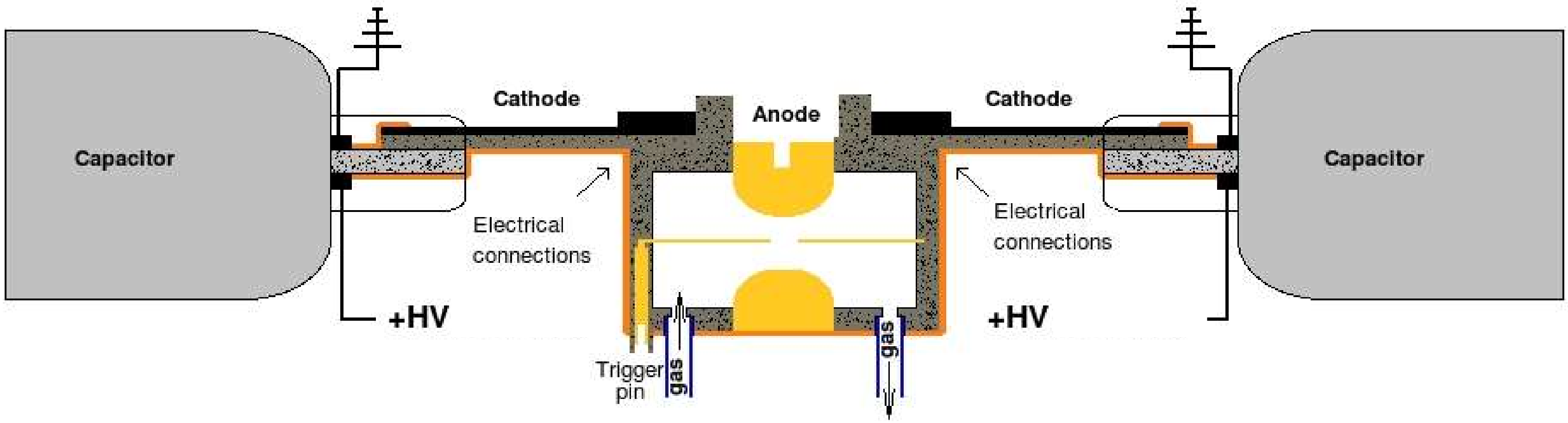
How to start the design? Example

Assume that we have a 2 capacitors of 120nF each



C=120nF
L= 20nH
Vmax= 50kV

Anode radius, a?



C=2x120nF=240nF

L_T= 50nH (expected)

Vo=25kV

E=1/2 C V^2 = 75J

$28E/a^3 = 5\times10^{10} J/m^{-3} \rightarrow$ **a=3.5 mm**

Note: When your capacitor bank (included the spark gap) was already constructed, to measure L_T in short circuit and use that data.

Anode radius, a?

- Current of operation

$I_o = (C/L_T)^{1/2} V_o$

240nF, 50nH, 25kV $\rightarrow$ I_o=55kA

- Working pressure

Deuterium PF works at 1 mbar < p < 10 mbar

To continuous with the stimations we chose p=5mbar

Using I_0= 55kA y p=5mbar in $I/ap^{1/2} \sim 77 kA/cm\ mbar^{1/2}$

we obtain a better value for the anode radius

a= 3.2mm

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Plasma Physics and Nuclear Fusion Laboratory
Chilean Nuclear Energy Commission

Effective anode length, z?

- The pinch must be close to the maximum current. Thus, we impose the condition that the plasma reaches the end of the electrodes coincident with maximum current, i.e. at a time of quarter of period of the discharge t = T/4.

$T=2\pi\,(L_T\,C)^{1/2}$

$C=240nF$, $L_T=50nH \rightarrow T = 688ns \rightarrow T/4=172ns$

$T/4 = t_z + t_r$

It is known $\langle v_z \rangle \sim 0.5x10^5$ m/s (0 - 1x 10^5 m/s)

$\langle v_r \rangle \sim 1.75x10^5$ m/s (1x 10^5 m/s – 2.5x 10^5 m/s)

a=3.2mm $\rightarrow$ $t_r = a/\langle v_r \rangle = 18ns$

- Thus for t_z we have $t_z = T/4 - t_r = 154ns$

And t_z = time of breakdown and time before to start the axial motion + time of axial motion

$$t_z = t_d + z/\langle v_z \rangle$$

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Plasma Physics and Nuclear Fusion Laboratory
Chilean Nuclear Energy Commission

Effective anode length, z?

t_d ?

In Mather PF t_d can be neglected in comparison with T/4

However, according to our observations in small fast hybrid PF ($a/z \sim 1$, $z/l_{ins} \leq 1$), t_d is an important fraction of T/4

In PF-400J and in PF-50J it is of the order of

$$t_d \sim (1/3)T/4$$

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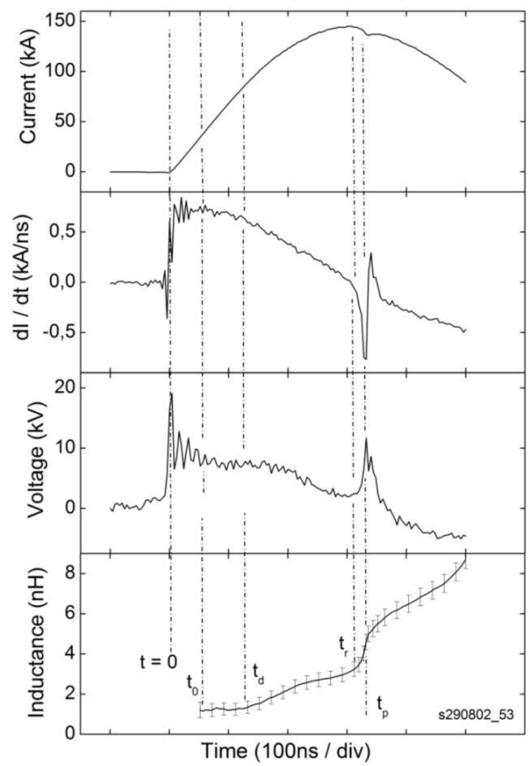
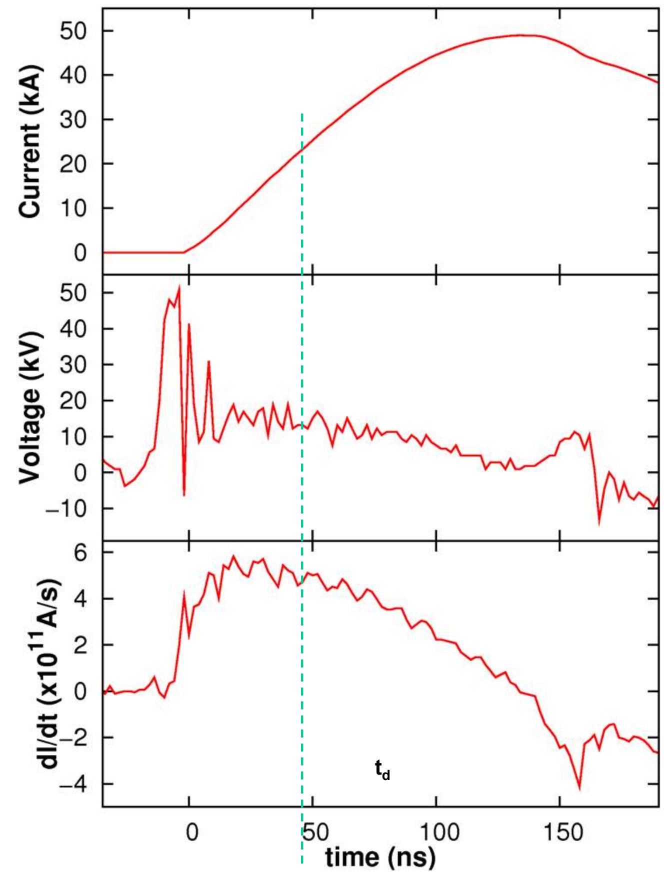
Chilean Nuclear Energy Commission

$$L_p(t) = \frac{\int_{t0}^{t} V(t)dt + \left(L_0^{'} + L_p(t_0)\right) I(t_0)}{I(t)} - L_0^{'}$$





$L_p(t) = (\mu_0 / 2\pi)\, z(t) \ln(b/r(t))$

PF-400J
T/4=300ns, t_d = 130ns

$t_d \sim$ (1/3) T/4

PF-50J
T/4=150ns, t_d = 50ns

F. Veloso, C. Pavez, J. Moreno, V. Galaz, M. Zambra and L. Soto, Journal of Fusion Energy 31, 30-37 (2012)

Effective anode length, z?

Therefore

$t_z = t_d + z/\langle v_z \rangle$

$t_z = T/12 + z/\langle v_z \rangle$

As t_z= 154ns, T/12= 57ns, $\langle v_z \rangle \sim 0.5 \times 10^5$ m/s

$z = (97 \times 10^{-9}\text{s})\ (0.5 \times 10^5)\text{m/s} = 4.85\text{mm}$

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Summary of parameters

- C= 240 nF
- Voltage operation ~25kV
- Total inductance, L_T ~ 50nH
- Energy ~ 75J
- I peak ~55kA
- Anode radius, a= 3.2mm (copper)
- Effective anode length, z=4.85mm
- Operational pressure: 1mbar < p < 10mbar (D_2 , H_2)
- Insulator length, l_{ins} ,according to our experience ~0.9mm/kV,
  l_{ins} = 22mm (alumina, quartz)
- Cathode radius, : 2.5 a

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Practical considerations

When your capacitor bank (included the spark gap) was already constructed, to obtain a measure of L_T in short circuit and use that data.

Some modifications could be necessary (anode length).

You will must optimize your device experimentally.

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Homework

- To design a PF from this capacitor

  C=2.6μF

  L=20nH

  Vmax=50kV

Homework

- To design a PF to operate a 500J, 15kV and T/4 of the order of 0.5 to 1μs

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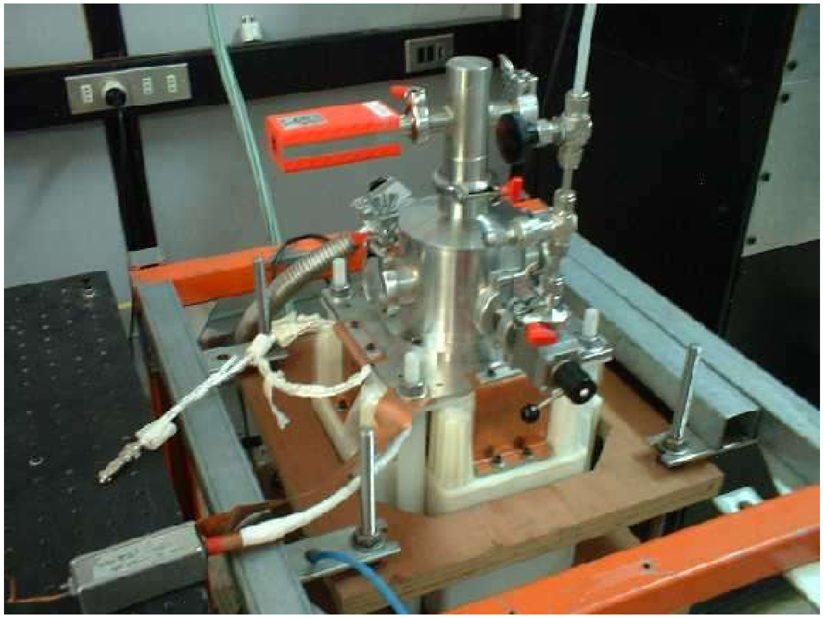
Examples of devices designed and constructed in Chile

PF-400J

Designed to operate at hundred joules

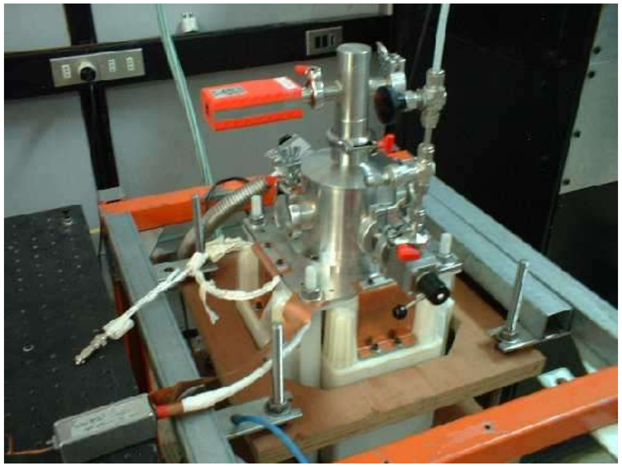


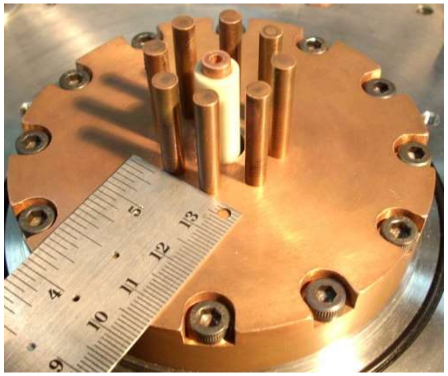
P. Silva, J. Moreno, L. Soto, L. Birstein, R. Mayer, and W. Kies, App. Phys. Lett. 83, 3269 (2003)

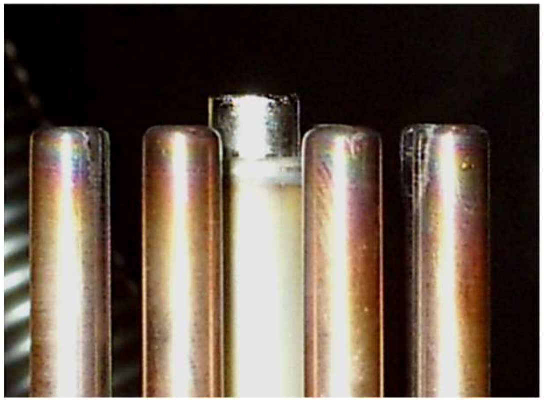
Examples of devices designed and constructed in Chile

PF-50J

Designed to operate at tens joules



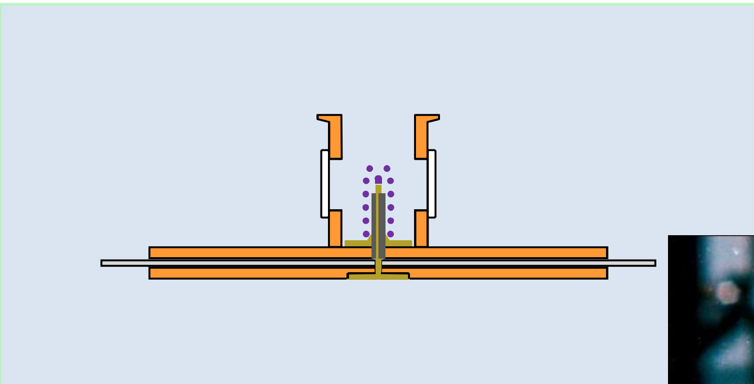


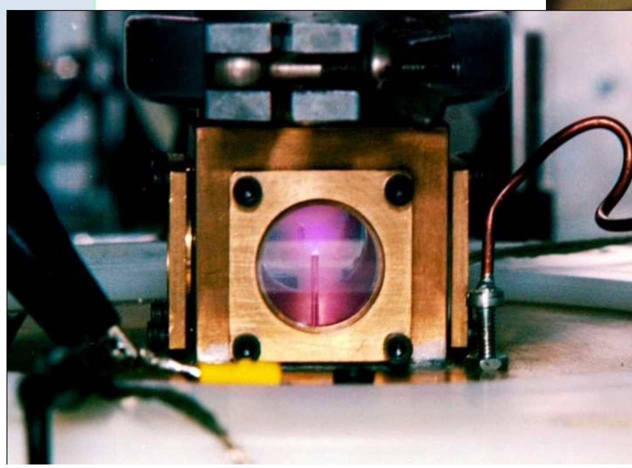


P. Silva, L. Soto, W. Kies and J. Moreno, Plasma Sources Science and Technology 13, 329 (2004).
L. Soto, P. Silva, J. Moreno, M. Zambra, W. Kies, R. E. Mayer, A. Clausse, L. Altamirano, C. Pavez, and L. Huerta J. Phys. D: App. Phys. 41, 205215 (2008)

Examples of devices designed and constructed in Chile

Nanofocus
Designed to operate at less than 1 joule (0.1J – 0.25J)





L. Soto, C. Pavez, J. Moreno, A. Clausse and M. Barbaglia PSST 18, 015007 (2009)
L. Soto, C. Pavez, J. Moreno, L. Altamirano, L. Huerta, M. Barbaglia, A. Clausse, and R. E. Mayer, Physics of Plasmas 24, 082703 (2017)

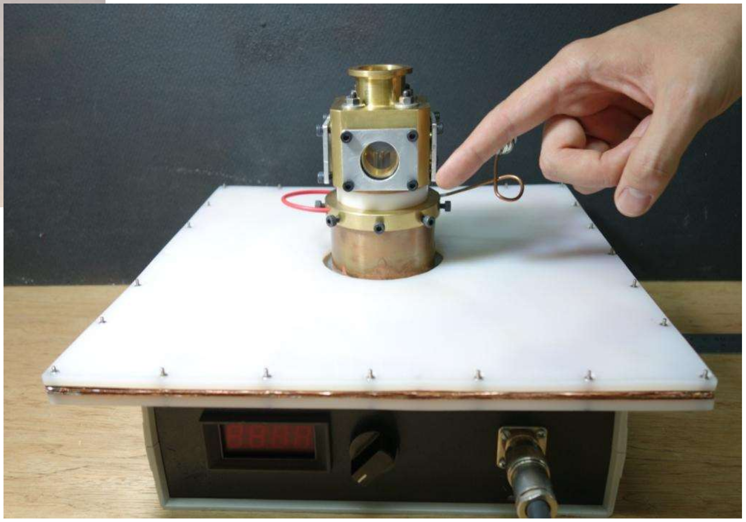
Examples of devices designed and constructed in Chile

PF-2J

Designed to operate at 2J- 3J

A portable device For field applications

2012



2015

L. Soto
Plasma Physics and Nuclear Fusion Laboratory
Chilean Nuclear Energy Commission

Some words about nuclear fusion

S. Lee and Serban, IEEE Trans. Plasma Science 24, 1101 (1996), suggested

$Y_{th} \alpha I^{4} v^{4}$ and $Y_{bt} \alpha I^{4.5} v^{-1.5}$

Increasing v (or *I/a*), $Y_{th} \alpha I^{8}$ and $Y_{bt} \alpha I^{3}$

With this improved or enhanced yield dependence, the thermonuclear component of neutron yield will rapidly outstrip the beam target component.

Some references related to PF and diagnostics in PF < 1kJ

"Optical Observations of the Plasma Motion in a Fast Plasma Focus Operating at 50 Joules". José Moreno, Patricio Silva, and Leopoldo Soto, Plasma Sources Science and Technology 12, 39 (2003).

"Neutron Emission from a Fast Plasma Focus of 400 Joules", P. Silva, J. Moreno, L. Soto, L. Birstein, R. Mayer, W. Kies, Applied Physics Letters 83, 3269 (2003)

"Pinch evidence in a fast and small plasma focus of only tens of joules", P. Silva, L. Soto, W. Kies and J. Moreno, Plasma Sources Science and Technology 13, 329 (2004).

"New Trends and Future Perspectives on Plasma Focus Research", (**Invited paper** in ICPP2004), Leopoldo Soto, Plasma Physics and Controlled Fusion **47**, A361 (2005).

"Dense transient pinches and pulsed power technology. Research and applications using medium and small devices" Leopoldo Soto, Cristian Pavez, Jose Moreno, Miguel Cárdenas, Ariel Tarifeño, Patricio Silva, Marcelo Zambra, Luis Huerta, Jorge Ramos, Rodrigo Escobar, Claudio Tenreiro, Miguel Lagos, Cesar Retamal, and J. Luis Giordano, Physica Scripta T131, 014031 (2008)

"System for measurements of low yield neutron pulses from D-D fusion reactions based upon a ^{3}He proportional counter", J. Moreno, L. Birstein, R. Mayer, P. Silva, L. Soto, Meas. Sci. and Technol. 19, 087002 (2008)

"Demonstration of neutron production in a table top pinch plasma focus device operated at only tens of joules". Leopoldo Soto, Patricio Silva, José Moreno Moreno, Marcelo Zambra, Walter Kies, Roberto E. Mayer, Alejandro Clausse, Luis Altamirano, Cristian Pavez, and Luis Huerta J. Phys. D: App. Phys. 41, 205215 (2008).

"Nanofocus: ultra-miniature dense pinch plasma focus device with submillimetric anode operating at 0.1J", Leopoldo Soto, Cristian Pavez, José Moreno, Mario Barbaglia, and Alejandro Clausse, Plasma Sources Sci. and Technol. 18, 015007 (2009)

"Experimental results on hard x-ray energy emitted by a low energy plasma focus device: a radiographic image analysis", M. Zambra, P. Silva, M. Moreno, C. Pavez and L. Soto, Plasma Physics Controlled Fusion 51, 125003 (2009)

"Numerical experiments on plasma focus neutron yield versus pressure compared with laboratory experiments", S. Lee, S. H. Saw, **L. Soto**, S. V. Springham, S. P. Moo, Plasma Physics and Controlled Fusion **51**, 075006 (2009).

"Experimental results on hard x-ray energy emitted by a low energy plasma focus device: a radiographic image analysis", M. Zambra, P. Silva, M. Moreno, C. Pavez and L. Soto, Plasma Physics Controlled Fusion 51, 125003 (2009)

"Demonstration of x-ray Emission from an ultraminiature pinch plasma focus discharge operating at 0.1 J. Nanofocus", Cristian pavez and Leopoldo Soto, IEEE Trans. Plasma Science, 38, 1132 (2010).

"Studies on scalability and scaling laws for the plasma focus: similarities and differences in devices from 1MJ to 0.1J", Leopoldo Soto, Cristian Pavez, Ariel Tarifeño, José Moreno and Felipe Veloso, Plasma Sources Sci. and Technol. 19, 055017 (2010).

"Dynamics and Density Measurements in a Small Plasma Focus of Tens of Joules Emitting Neutrons", Ariel Tarifeño, Cristian Pavez, José Moreno and Leopoldo Soto, IEEE Trans. Plasma Science, **39**, 756 (2011)

Some references related to PF and diagnostics in PF < 1kJ

"Potentiality of a small and fast dense plasma focus as hard x-ray source for radiographic applications", C Pavez, J. Pedreros, M Zambra, F Veloso, J Moreno, A Tarifeño-Saldivia and L. Soto, Plasma Phys. and Control. Fusion. 54 105018 (2012).

"Correlations among neutron yield and dynamical discharge characteristics obtained from electrical signals in a 400 joules plasma focus", Felipe Veloso, Cristian Pavez, Jose Moreno, Victor Galaz, Marcelo Zambra and Leopoldo Soto, Journal of Fusion Energy 31, 30-37 (2012).

"Dependence of hard x-ray emissions with the charging pressure in a small Plasma Focus" M. Barbaglia, **L. Soto** and A. Clausse, Journal of Fusion Energy **31**, 105 (2012).

"Toroidal high-density singularities in a small Plasma Focus", Federico Casanova, Ariel Tarifeño-Saldivia, Felipe Veloso, Cristian Pavez, Leopoldo Soto and Alejandro Clausse, Journal of Fusion Energy 31, 279 (2012)

"Modelling of the internal dynamics and density in a tens of joules plasma focus device", Ariel Marquez, José Gonzalez, Ariel Tarifeño-Saldivia, Cristian Pavez, Leopoldo Soto y Alejandro Clausse, Physics of Plasmas 19, 012703 (2012)

"Non-intrusive plasma diagnostics for mesuring sheath kinematics in plasma focus discharges", Felipe Veloso, José Moreno, Ariel Tarifeño-Saldivia, Cristian Pavez, Marcelo Zambra and Leopoldo Soto, Meas. Sci. And Technol. 23, 087002 (2012)

"Plasma sheath kinematics and some implications on the modeling of very low energy plasma focus", Felipe Veloso, José Moreno, Ariel Tarifeño-Saldivia, Cristian Pavez, Marcelo Zambra and Leopoldo Soto, Plasma Phys. and Control. Fusion. 54, 095007 (2012)

"Statistical characterization of the reproducibility of neutron emission of small plasma focus devices" A. Tarifeño-Saldivia and L. Soto, Physics of Plasmas 19, 092512 (2012)

"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". L. Soto, C. Pavez, J. Moreno, M. J. Inestrosa-Izurieta, F. Veloso, G. Gutiérrez, J. Vergara, A. Clausse, H. Bruzzone, F. Castillo, and L. F. Delgado-Aparicio, Physics of Plasma 21, 122703 (2014)

"Observations of plasma jets in a table top plasma focus discharge" C. Pavez, J. Pedreros, A. Tarifeño Saldivia and L. Soto, Physics of Plasmas 22, 040705 (2015)

"Morphological and structural effects on tungsten targets produced by fusion plasma pulses from a table top plasma focus" M.J. Inestrosa-Izurieta, E. Ramos-Moore and L. Soto, Nuclear Fusion 55, 093011 (2015)

"Filamentary structures in dense plasma focus: current filaments or vortex filaments", Leopoldo Soto, Cristian Pavez, Fermin Castillo, Felipe Veloso, José Moreno, and S. K. H. Auluck, Physics of Plasmas 21, 072702 (2014)

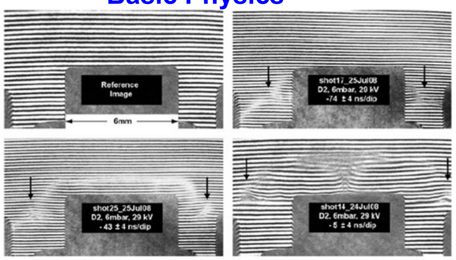
"Observation and interpretation of neutron origin prior to hard x-rays and pinch in a hundred joules plasma focus device", J. Jain, J Moreno, D Morales, S Davis, B Bora, G Avaria, M J Inestrosa-Izurieta and L Soto, Laser and Particle Beams 35, 656 (2017) doi:10.1017/S0263034617000672

"Hundred joules plasma focus device as a potential pulsed source for in vitro cancer cell irradiation", J. Jain, J. Moreno, R. Andaur, R. Armisen, D. Morales, K. Marcelain, G. Avaria, B. Bora, S. Davis, C. Pavez, and L. Soto, AIP Advances 7, 085121 (2017)

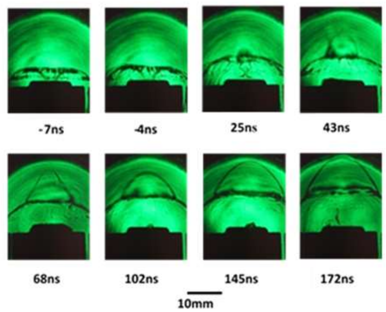
"Evidence of nuclear fusion neutrons in an extremely small plasma focus device", Leopoldo Soto, Cristian Pavéz, José Moreno, Luis Altamirano, Luis Huerta, Mario Barbaglia, Alejandro Clausse, and Roberto E. Mayer, Physics of Plasmas 24, 082703 (2017)

Summary

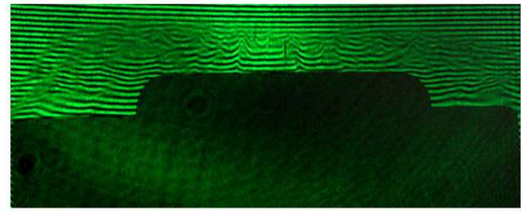
Basic Physics



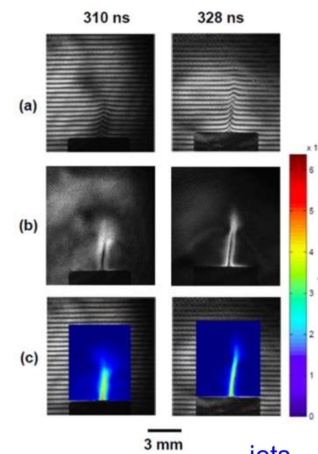
Toroidal singularity



shocks

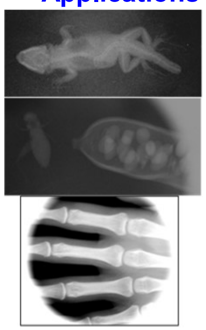


fillaments

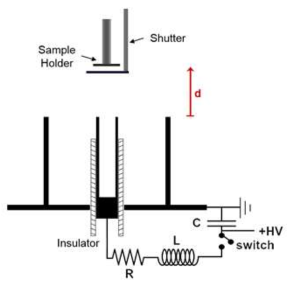


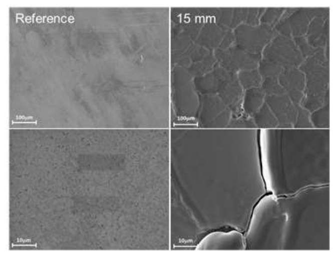
jets

Applications

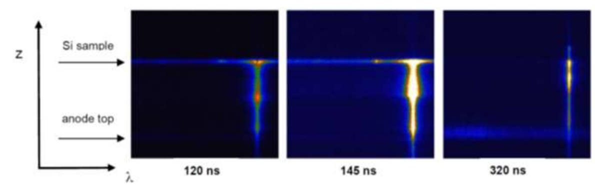


Pulsed x-ray and neuron sources

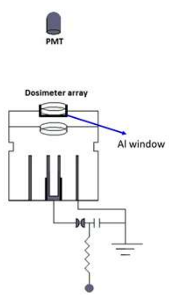


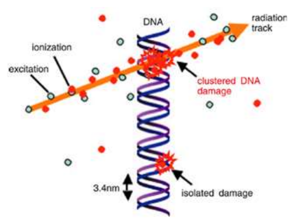


Effects on materials for 1st wall of nuclear fusion reactors

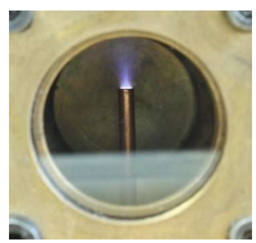


Plasmas interacting with materials, plasma facing components

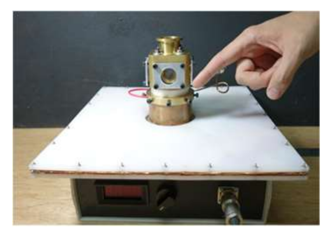




Effects of pulsed radiation in life matter



Pulsed plasma thruster for nanosatelites



How to design and build a small plasma focus
Tricks and recipes

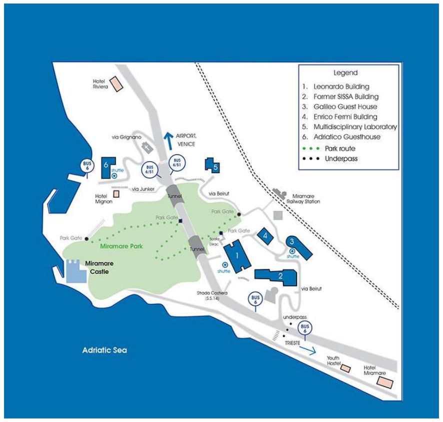
Our previous question

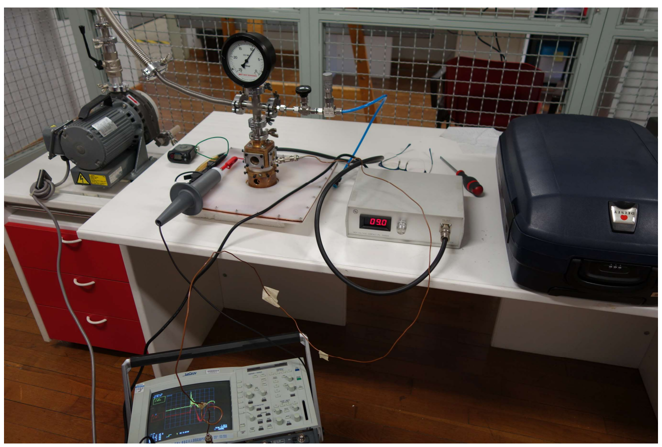
Is it posible to do relevant experimental plasma physics and fusion research in a small country?

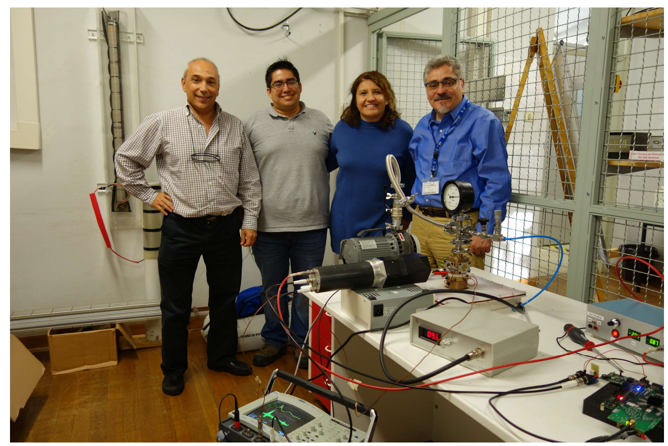
YES!

L. Soto
Plasma Physics and Nuclear Fusion Laboratory
Chilean Nuclear Energy Commission

Next week
Visit to Multidisciplinary Laboratory, ICTP







For this school the portable PF-2J was brought into a suitcase from Chile to Italy and it is operative at the Multidisciplinary Laboratory, ICTP

Outreach for general public

Canal Ciencia Entretenida en YouTube

https://www.youtube.com/user/cienciaentretenida

Entertaining Science YouTube Channel

5 chapters:

Capítulo 1. ¿Qué es el plasma?
Capítulo 2. ¿Qué es la potencia pulsada?
Capítulo 3. ¿Qué es la fusión nuclear?
Capítulo 4. Radiaciones pulsadas para la vida y la salud
Capítulo 5. Plasmas y potencia pulsada para materiales avanzados y fusión nuclear