2370-12

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

8 - 12 October 2012

How to build a small Plasma Focus - Recipes and tricks

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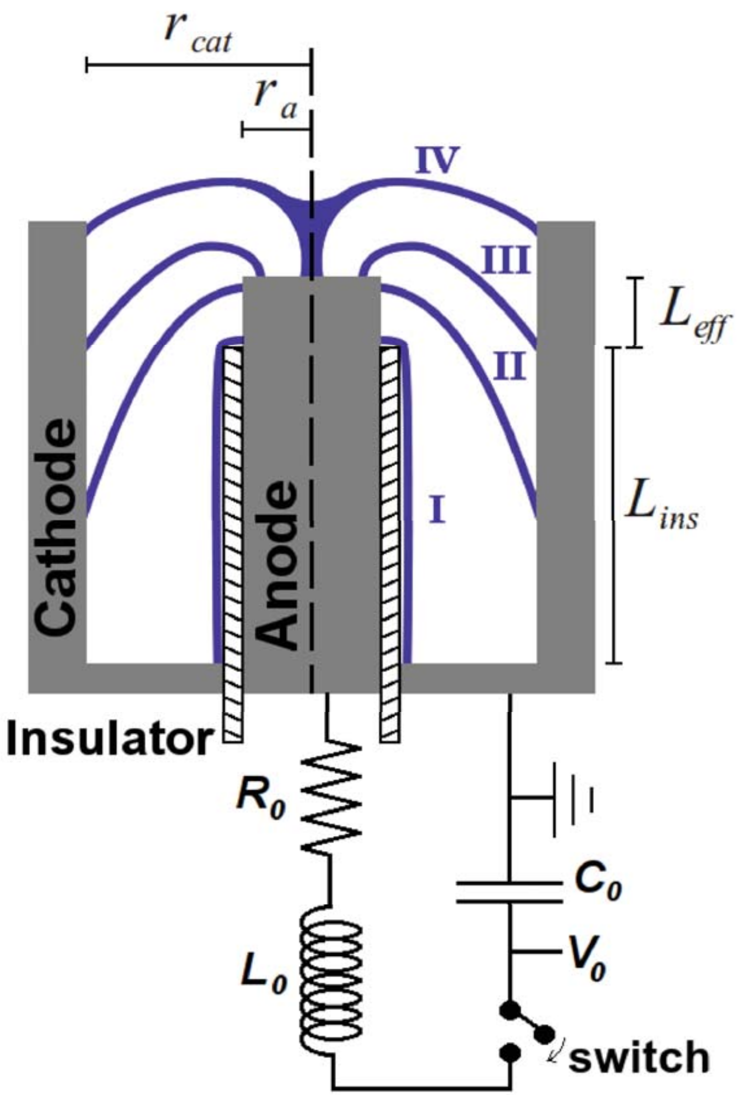
To build a plasma focus it is necessary to defin the followings parameters:

- Energy ?
- Capacitor, C?
- Voltage operation, V_0?
- Inductance, L?
- Current peak, I_0 ?
- Anode radius, a?
- Effective anode length (over the insulator), z?
- Operational pressure, p?
- Insulator length, l_{ins} ?
- Cathode radius, b?



Why and for what a small PF?

To do plasma research

- To study plasma dynamics and intabilities
- To study the X-ray emmited
- To study the neutrons emmited
- To study plasma jets
- …

Why and for what a small PF?

To develop a non radioactive source

- To do flash radiography and non destructive testing
- To do litography
- To develop a portable non-radiactive source of neutrons for field applications
- …

To teach experimental plasma physics and nuclear techniques, to train students

You must make a decision about that PF you want

- Free decision about energy and voltage operation
- A motived decision, because you have a suitable set of capacitors (somebody gift to you or you found its in a old storeroom or laboratory). Some kV and tens of nF - few μF

A plasma focus is a self-scale plasma device

Devices operated in a wide range of bank energy (0.1 J – 1 MJ) have the same phenomenology

L. Soto, C. Pavez, J. Moreno, A. Tarifeño and F. Veloso, Plasma Sources Sci. Technol. 19 ,055017 (2010)

Motivation, Scaling rules

Scaling parameters allow to reproduce similar phenomenology in devices operated in a wide range of bank energy (0.1 J – 1 MJ)

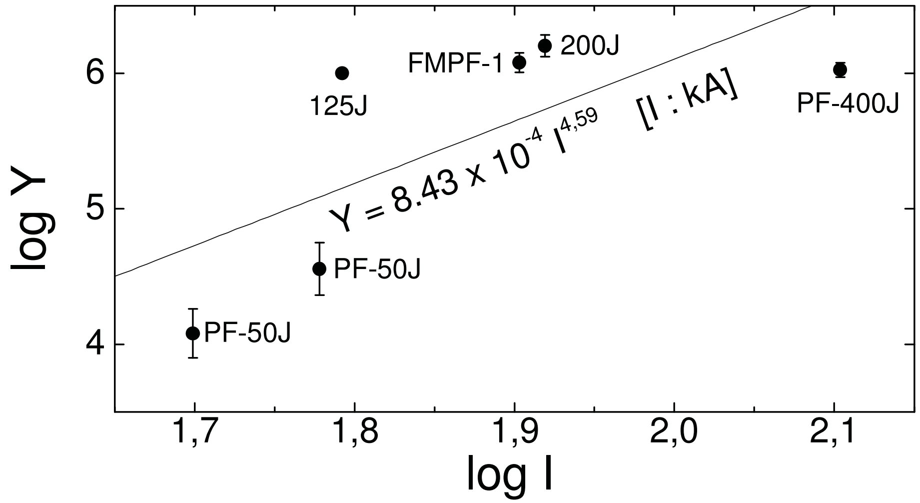
Device-location	Energy E (kJ)	Anode radius a (cm)	Peak current (kA)	Pressure (mbar)	Energy density parameter $28\ E/a^3$ (J m^{-3})	Drive parameter $I/p^{1/2}a$ (kA mbar$^{-1/2}$ cm^{-1})	Energy per mass parameter E/a^3p ($\times 10^7$ J m^{-3} mbar^{-1})
PF-1000-Poland	1064	12.2	2300	6.6	1.6×10^{10}	73.4	8.5
PF-360 -Poland	130	6	1200	1.6	1.7×10^{10}	61.4	38
SPEED2-Chile	70	5.4	2400	2.7	1.2×10^{10}	—	15.9
7 kJ PF-Japan	7	1.75	390	6	3.7×10^{10}	91	22
GN1-Argentina	4.7	1.9	—	—	1.9×10^{10}	—	—
Fuego Nuevo II -Mexico	4.6	2.5	350	3.7	0.8×10^{10}	73	7.7
UNU/ICTP-PF - Asia and Africa	2.9	0.95	172	8.5	9.5×10^{10}	81	4.1
PACO[a]-Argentina	2	2.5	250	1.5	3.6×10^{9}	95	8.5
PF-400J -Chile	0.4	0.6	127	9	5.2×10^{10}	70	2
FMPF-1 Singapore	0.23	0.35	80	5.5	1.5×10^{11}	97	5.35
200J[a] Batt-PF India	0.2	0.5	83	10	4.5×10^{10}	52[a]	1.6[a]
125J PF Argentina	0.125	0.75	62	2	0.83×10^{10}	58[a]	1.5[a]
PF-50J -Chile	0.07	0.3	60	9	7.3×10^{10}	66.7	2.9
	0.05	0.3	50	6	5.2×10^{10}	68	
NF[a]-Chile	0.00025	0.021	6	16	7.6×10^{11}	70	16.9
	0.0001	0.08	4.5	3	5.5×10^{9}	32[a]	0.65[a]

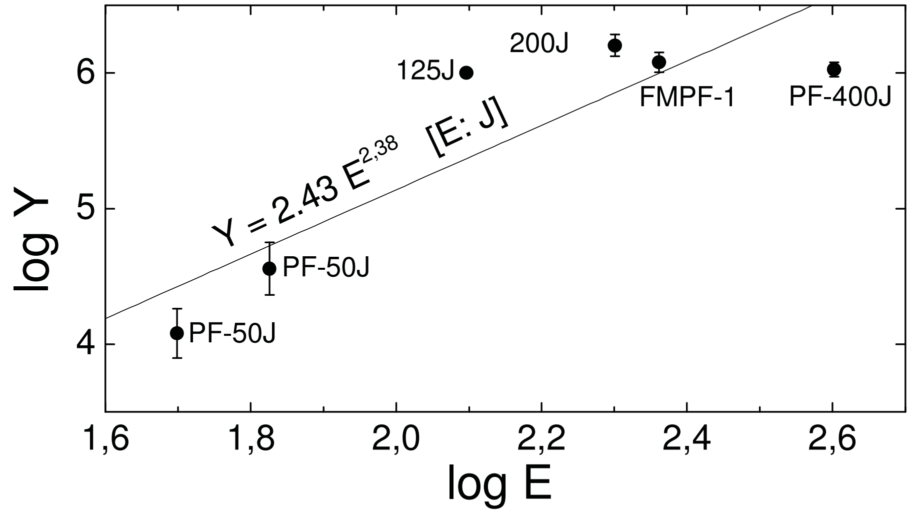
[a] Some very small devices, recently developed, are probably not optimized yet. The energy density parameter has a value of the order of (1–10) $\times 10^{10}$ J m^{-3} for all the experimentally optimized machines listed. The drive parameter has practically the same value for all the experimentally optimized machines listed (68–95 kA cm^{-1} mbar$^{-1/2}$). A new parameter related to the energy per mass was introduced now, 'energy per mass parameter' E/a^3p. Note that the three parameters listed in the right-hand side columns are practically constant in comparison throughout the eight orders of magnitude in stored energy range.

L. Soto, C. Pavez, J. Moreno, A. Tarifeño and F. Veloso, Plasma Sources Sci. Technol. 19 ,055017 (2010)

Motivation

Scaling law for neutron yield, Y, to E<1kJ





L. Soto et al. Plasma Sources Sci. Technol. 19 ,055017 (2010)

Motivation

Scaling parameters allow to reproduce similar phenomenology in devices operated in a wide range of bank energy (0.1 J – 1 MJ)

Similarities and differences in devices from 1MJ to 0.1J

Similarities

The **pinch radius and pinch length scale with the anode radius**, and $r_p \sim (0.1\text{-}0.2)\ a$, $z_p \sim (0.8\text{-}1)\ a$

The mean value of the **pinch ion density scale with the filling gas density**, and **$\langle n \rangle \sim 18n_0 \sim 5 \times 10^{24}\ m^{-3}$**.

The **drive parameter**, the **energy density parameter** and the **energy per mass parameter have practically the same value for any plasma focus experimentally optimized for neutron emission**. This implies that:

The **magnetic field** at the pinch radius has a value of the order of **30 to 40 T** for any PF experimentally optimized for neutron emission.

The **Alfvén speed** in the pinch has practically the same value in any PF experimentally optimized for neutron emission.

Any PF device with a similar drive parameter, energy density parameter and ion density, has a **temperature** of the same order. Thus, an experimental measure of temperature in a particular PF could be used to estimate the temperature of any PF experimentally optimized for neutron emission. **The temperature was measured by other authors in a plasma focus of some kJ by means of spectroscopy techniques in ~ 0.6 - 1 keV. Then, it is possible to assume that the temperature in any plasma focus operating properly, included the smallest ones like the PF-50J and the Nanofocus, has a temperature of that order.**

L. Soto, C. Pavez, J. Moreno, A. Tarifeño and F. Veloso, Plasma Sources Sci. Technol. 19 ,055017 (2010)

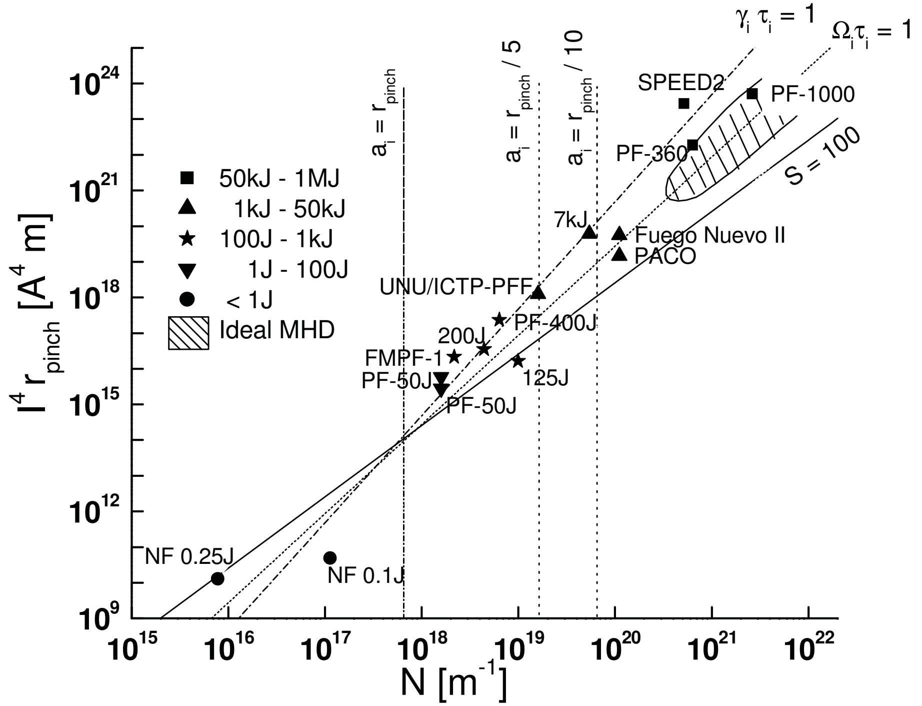
"Drive parameter of neutron-optimized dense plasma foci", D. Klir and L. Soto, accepted in in IEEE TPS to e published in December 2012)

Motivation

Similarities and differences in devices from 1MJ to 0.1J

Differences

The plasma focus is a self scale device. However, 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. Large PF devices (hundred of kJ and MJ) are in the ideal MHD region, and are unstable. On the contrary, the smallest device with stored energy less than 1J, Nanofocus, could be presents enhanced stability by means of resistive effects. PF devices in the range of hundred and tens of joules could be present enhanced stability by means of LLR effects.



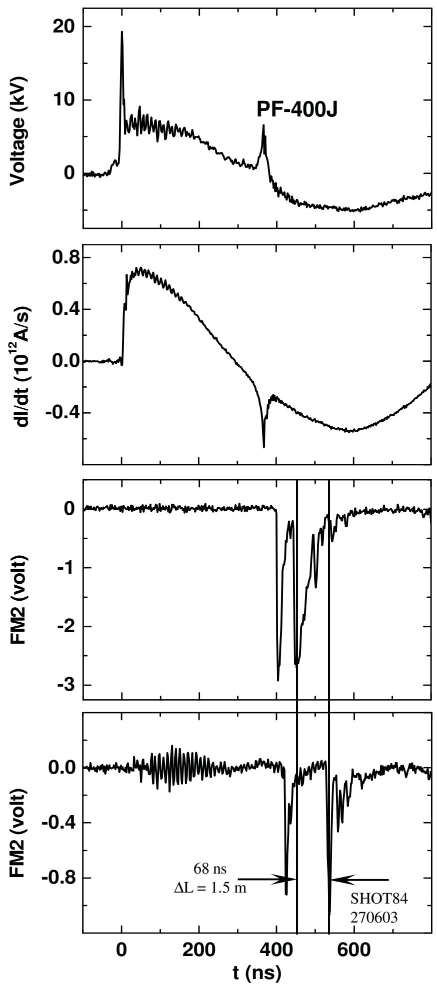
$N \;\; \alpha \;\; E/a$

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

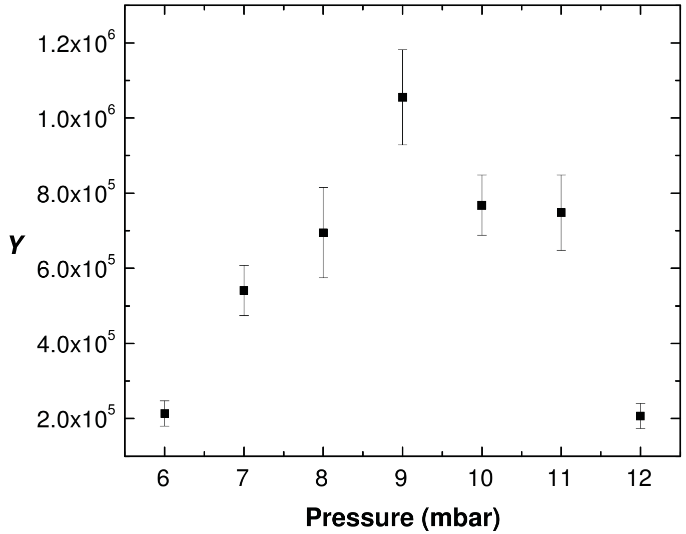
L. Soto, C. Pavez, J. Moreno, A. Tarifeño and F. Veloso, Plasma Sources Sci. Technol. 19 ,055017 (2010)

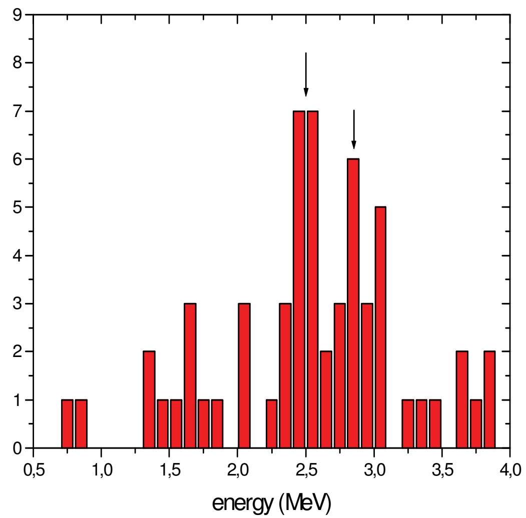
Motivation

A hundred joules PF as a neutron source, PF-400J



PF-400J

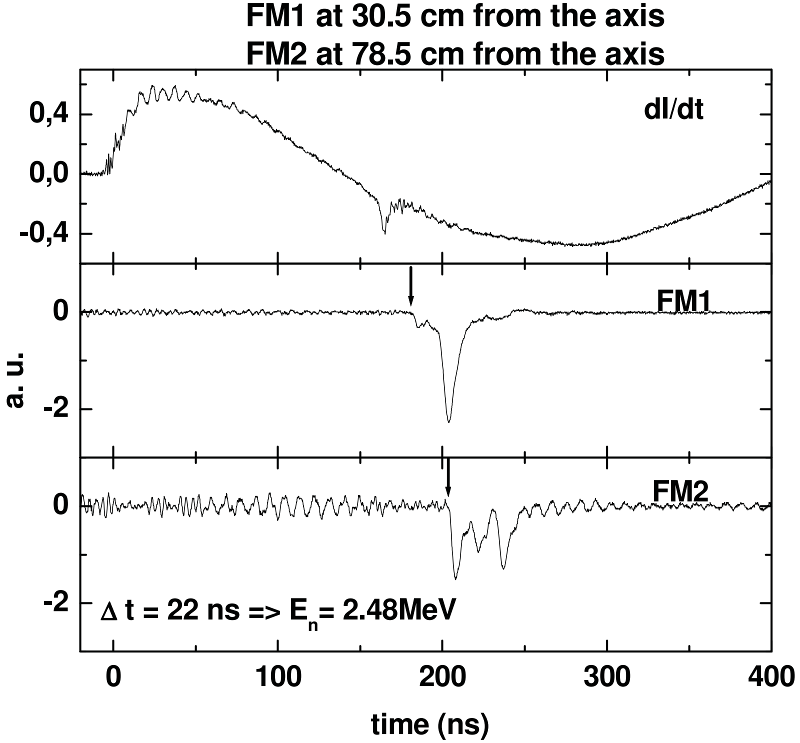


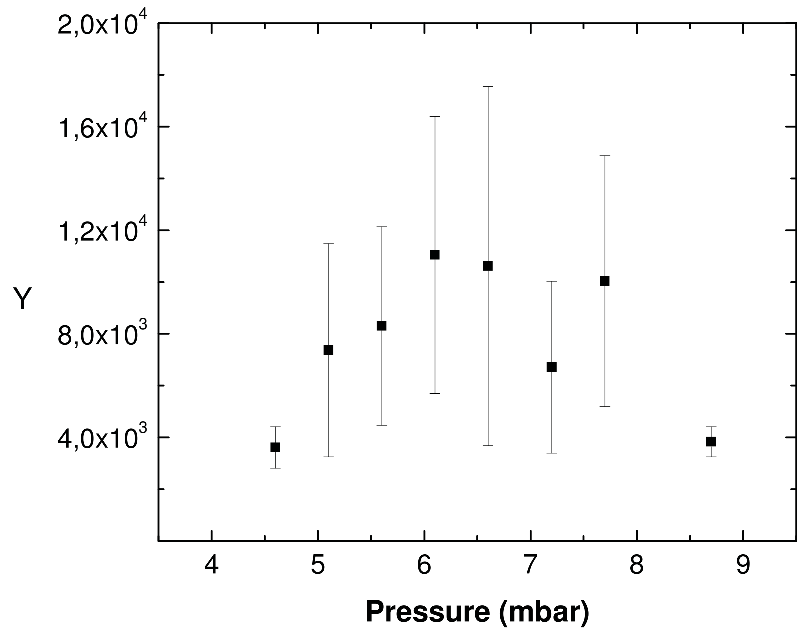


P. Silva, J. Moreno, L. Soto, L. Birstein, R. Mayer, and W. Kies, App. Phys. Lett. 83, 3269 (2003)

Motivation

A tens joules PF as a neutron source, PF-50J





Average over 20 shots

Neutrons maximum mean energy of 2.7 MeV, dispersion of 1.8 MeV

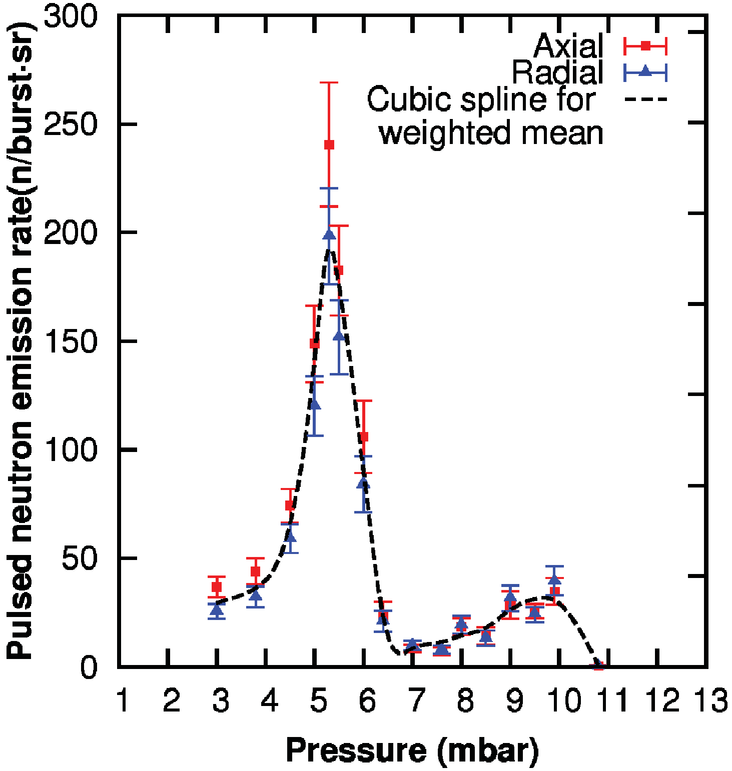
L. Soto, P. Silva, J. Moreno, M. Zambra, W. Kies, R. E. Mayer, A. Clausse, L. Altamirano, C. Pavez, and L. Huerta "Demonstration of neutron production in a table top pinch plasma focus device operated at only tens of joules". J. Phys. D: App. Phys. 41, 205215 (2008)

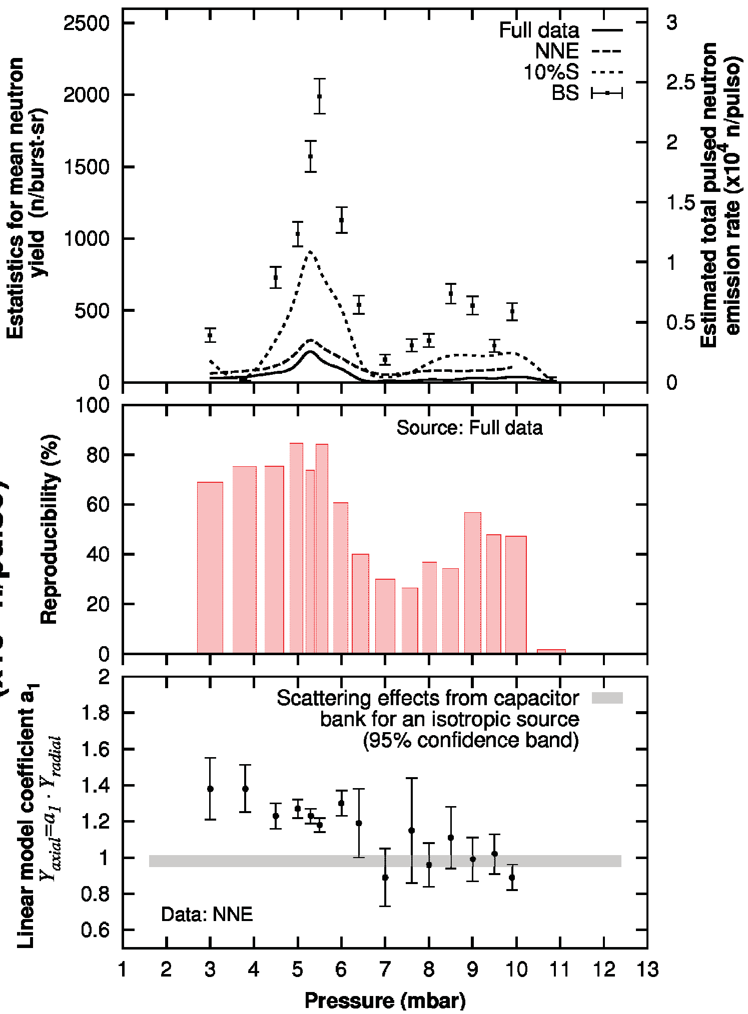
Motivation

A tens joules PF as a neutron source, PF-50J

L_{ef}=6.3mm, r_a=3mm, r_{cat}=6.5mm,

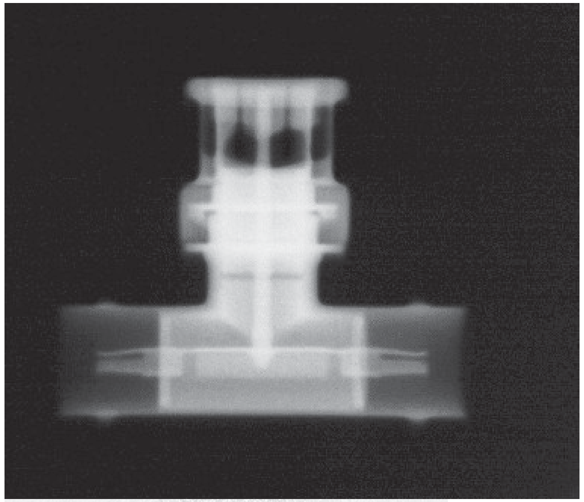
r_{cat}/r_a=2.17, V_c=28.7(8) kV,

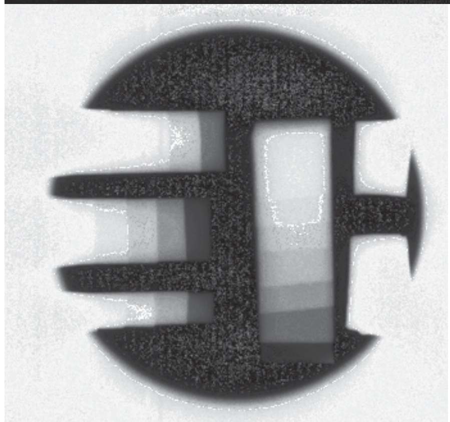


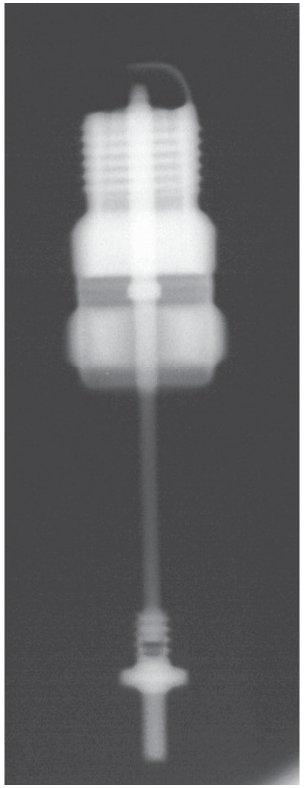


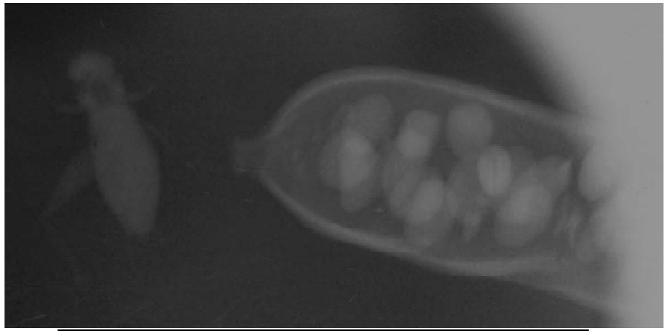
"Statistical characterization of the reproducibility of neutron emission of small plasma focus devices"
A. Tarifeño-Saldivia and L. Soto, Physics of Plasmas 19, 092512 (2012)

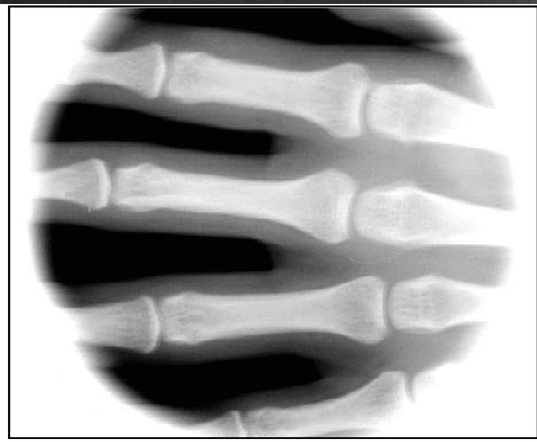
Motivation
A hundred joules PF as a flash X-ray source, PF-400J









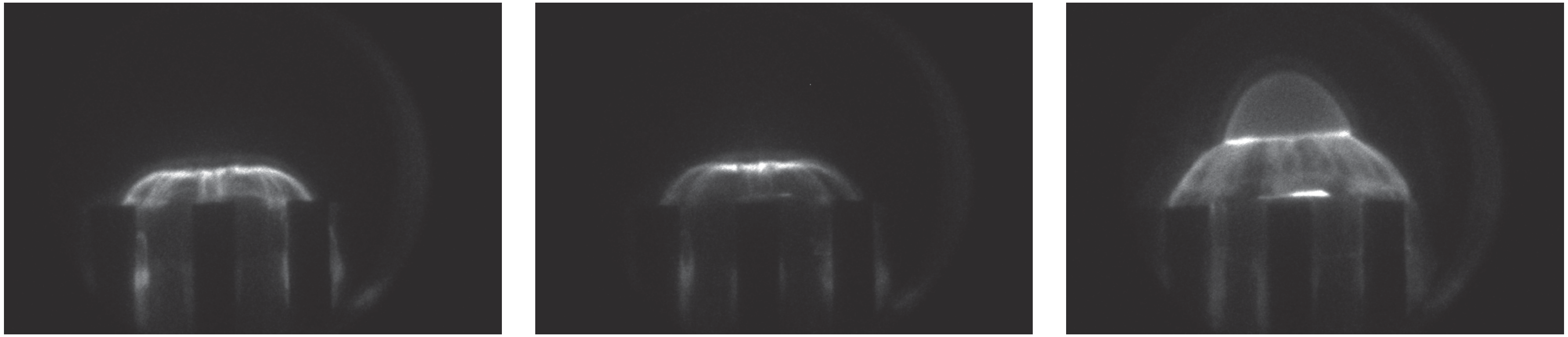


X-ray from PF-400J

~ 90±5 keV energy

C Pavez, J Pedreros, M Zambra, F Veloso, J Moreno, A Tarifeño-Saldivia and L. Soto, PPCF, 54, 105018 (2012)

Filaments



-16ns -6ns 49ns

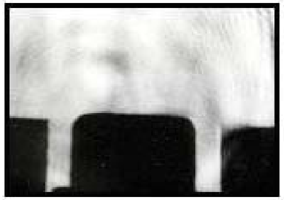
Visible ICCD camera

L. Soto, S. K. H. Auluck et al in preparation

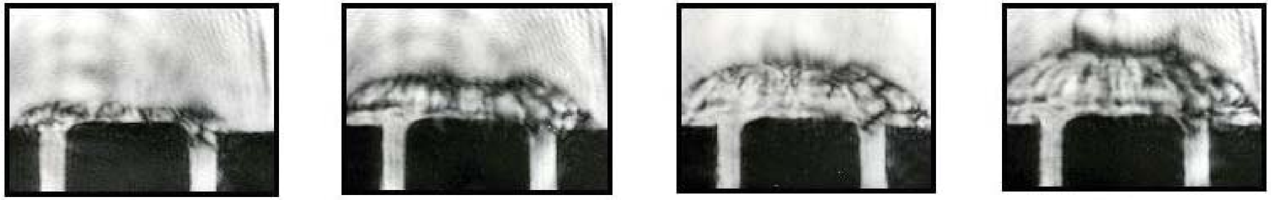
Motivation
A hundred joules PF to study basic physics, PF-400J

Filaments

Schlieren



fondo



- 40 *ns*   - 8 *ns*   11 *ns*   26 *ns*

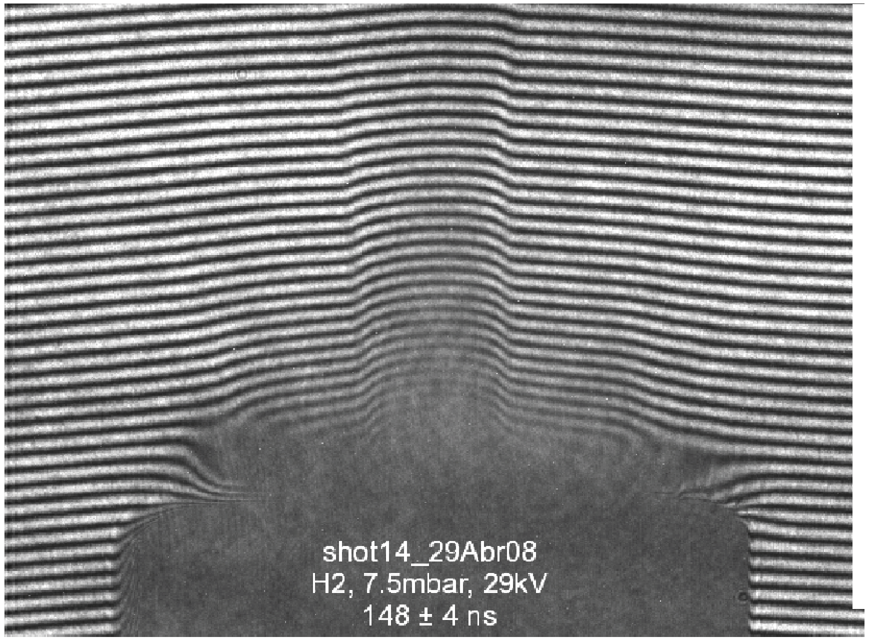
Interferogram

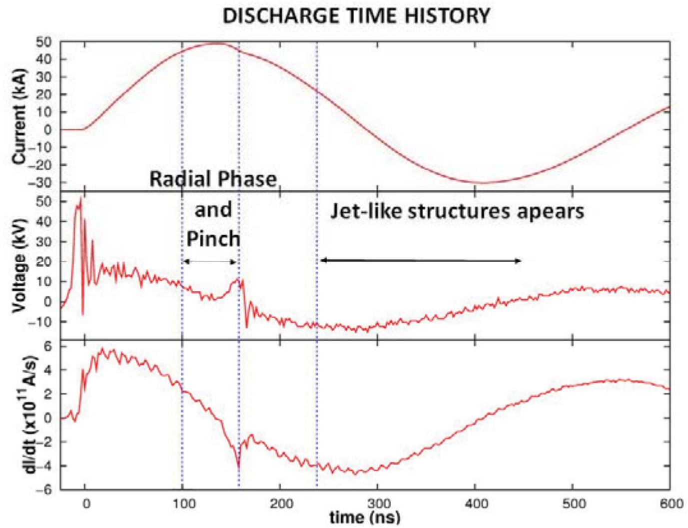
Filaments diameter ~ 300µm, $n_e \sim 10^{25}$ m^{-3}

L. Soto, S. K. H: Auluck et al in preparation

Motivation
A tens joules PF to study basic physics, PF-50J

Plasma jets





A. Tarifeño-Saldivia, C. Pavez and L. Soto, ICPP-LAWPP 2010, Santiago, August 2010

Motivation
A portable PF to field applications

HYDAD-D
HYdrogen Densisty Anomaly Detection
F. D. Brooks and M. Drosg, Applied Radiation Physics 63, 565 (2005)

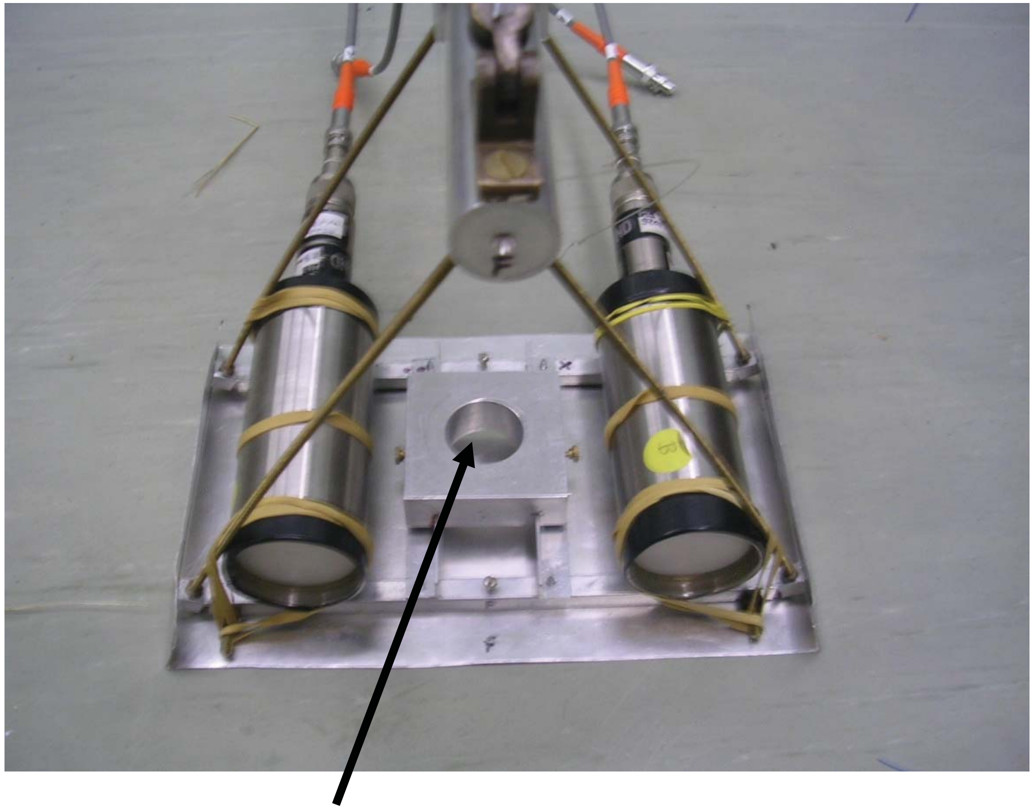
HYDAD-D at a simulated field with hydrogenated objects under controlled conditions

Arica, Atacama desert, North of Chile, September 11, 2009

C. Pavez, F. D. Brooks, F. D Smit, J. Moreno, L. Altamirano, L. Soto "Tests of the HYDAD Landmine Detector on Dry Soil in Northen Chile, VII Latin American Symposium on Nuclear Physics and Applications, Santiago, Chile, Dec. 2009.

Motivation
A portable PF to field applications

HYDAD-D in Chile



HYDAD-D use a conventional radiactive neutron source, Am-Be
Our challenge: To change the radioactive source by a portable PF

Testing materials for fusion systems

An important issue still to be resolved in the research for fusion energy production is the characterization, testing and development of advanced plasma facing materials capable of resisting the extreme radiation and heat loads expected in fusion reactors. Fundamental understanding of plasma-wall interaction processes in mainstream fusion devices, such as tokamaks and inertial confinement, requires dedicated R&D activities in plasma simulators used in close connection with material characterization facilities, as well as, with theory and modelling activities.

R. Kamendje et al. , "Summary of the 1st Research Coordination Meeting of the IAEA-CRP F1.30.13, Investigations of Materials under high repetition and intense fusion-relevant pulses". 6-9 December 2011, Vienna Austria.

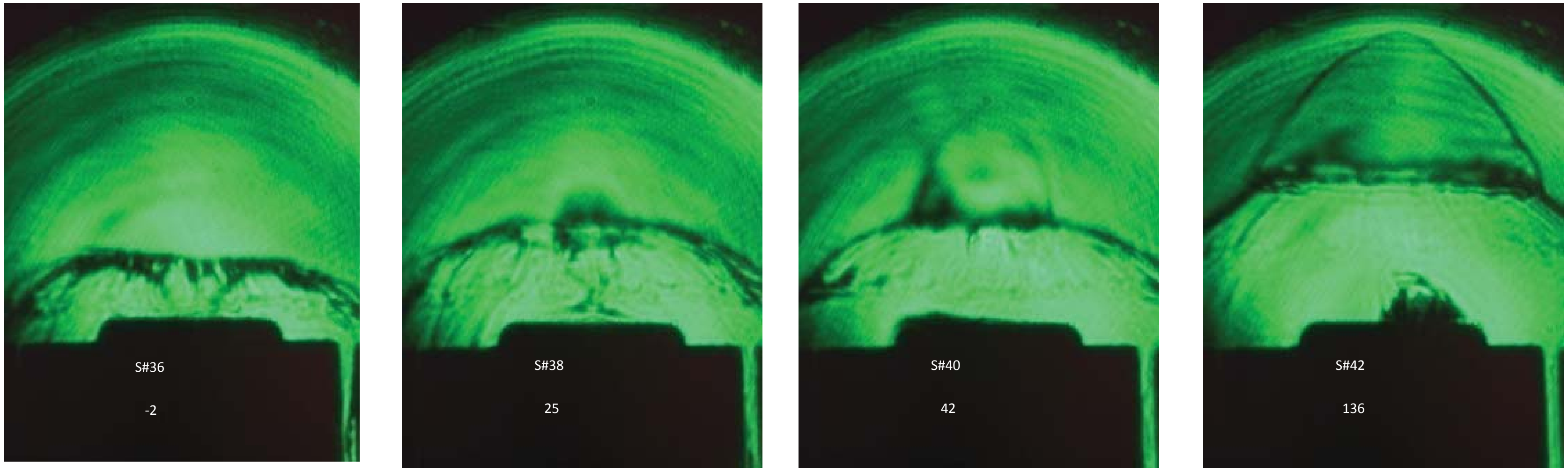
Motivation
A PF to test or to modify materials, PF-400J

After the pinch, the plasma column is disrupted. No special attention have been devoted, by the plasma focus community, to the plasma dynamic after the pinch. However is during this stage when an axial plasma burst is produced.

1.- To study the plasma dynamics including the phase after the pinch.
2.- To characterize the velocity and energy of the plasma axially ejected.
3.- To use this plasma gun to study the accumulative effect of several plasma bursts on targets using materials relevant to the first wall of a fusion reactor.

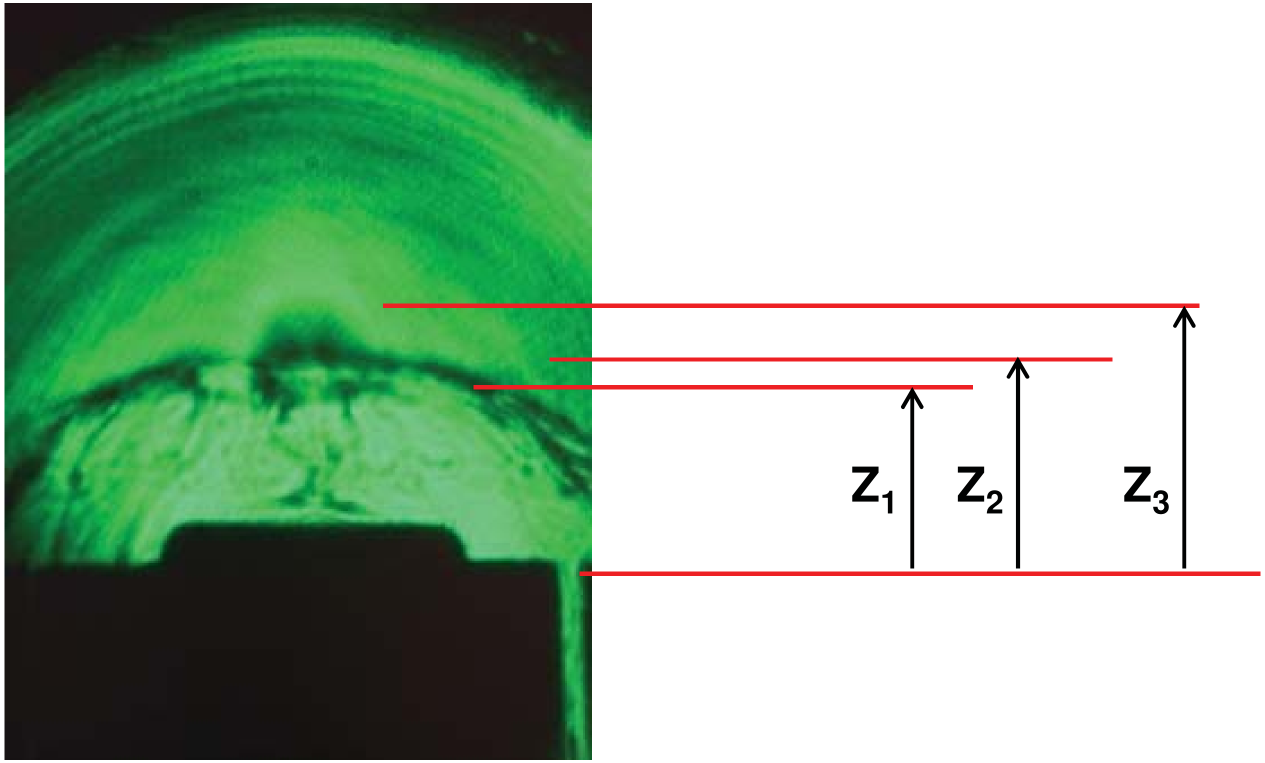
Motivation
A PF to test or to modify materials, PF-400J

PF-400J D_2 9mbar



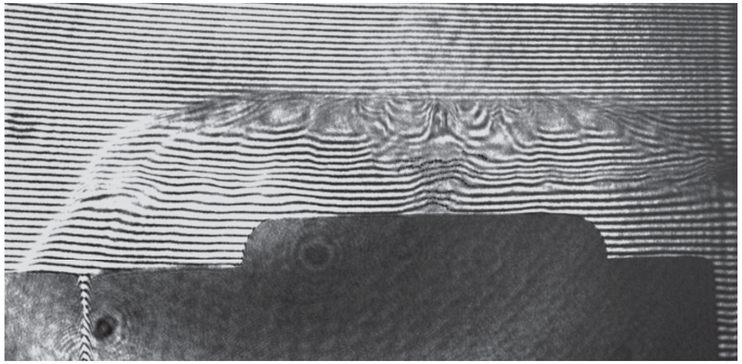
PF Plasma dynamics after the pinch, to be published, L. Soto et al.

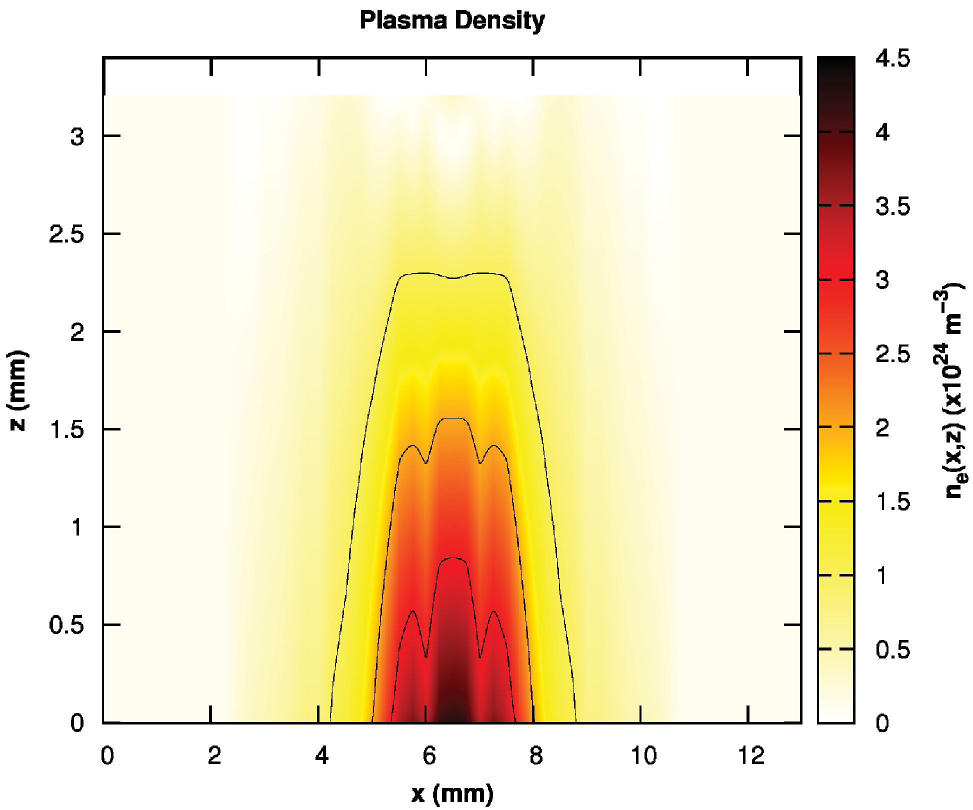
Motivation
A PF to test or to modify materials, PF-400J



"Characterization of plasma and radiation bursts from plasma focus devices for investigations of materials under intense fusion-relevant pulses" L. Soto, A Tarifeño-Saldivia, C. Pavez, J. Moreno, G. Avaria, M Zambra, E. Ramos, Symposium on Fusion Technology, SOFT 2012.

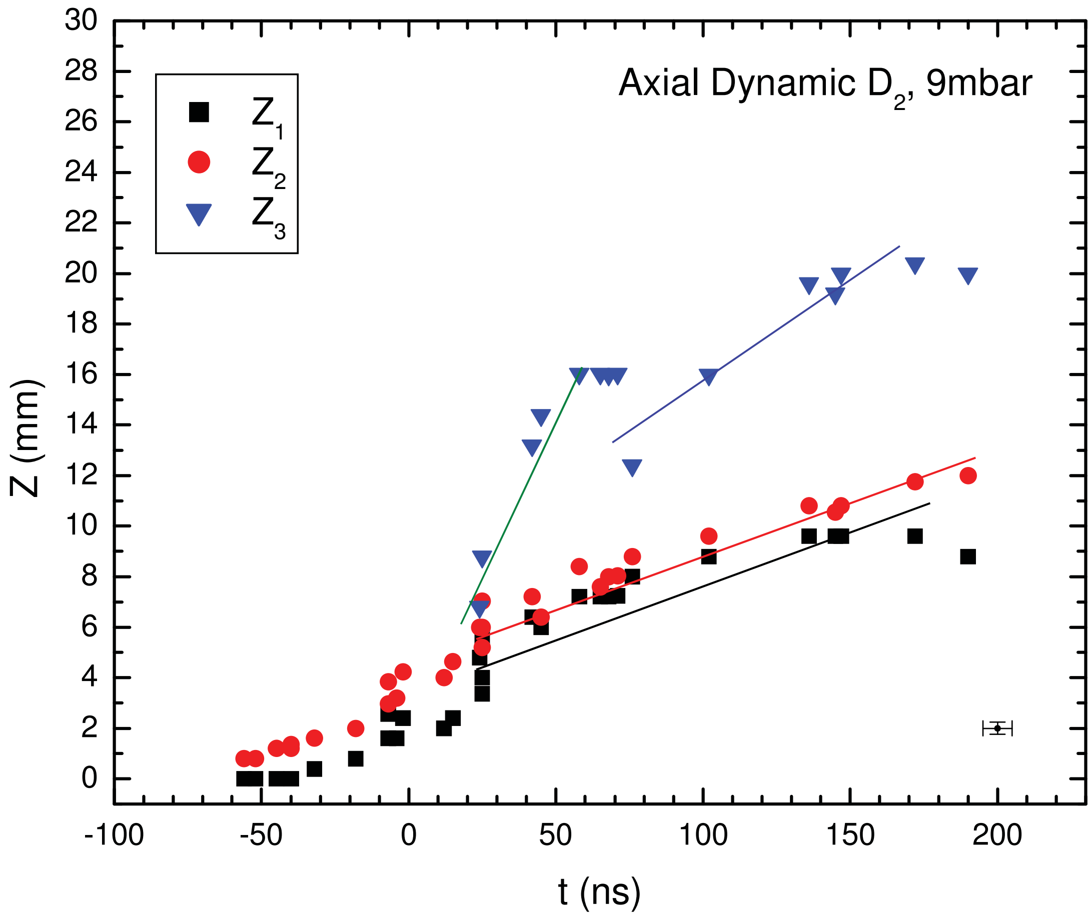
Pinch density





"Characterization of the Compression Phase of a Plasma Focus Discharge in Low-Energy Regime by Means of Refractive Optical Diagnostics: Radial Dynamic in PF-400J" C. Pavez et al, *Dense Z-pinches Conference Biarritz, France, 5-9 June 2011, Submitted to AIP Conf. Proc.*

Motivation
A PF to test or to modify materials, PF-400J



V_{Z1} ~ 2.5×10^5 m/s

V_{Z1} ~ 6×10^4 m/s

V_{Z2} ~ 6×10^4 m/s

V_{Z3} ~ 8×10^4 m/s

"Characterization of plasma and radiation bursts from plasma focus devices for investigations of materials under intense fusion-relevant pulses" L. Soto, A Tarifeño-Saldivia, C. Pavez, J. Moreno, G. Avaria, M Zambra, E. Ramos, Symposium on Fusion Technology, SOFT 2012.

Motivation
A PF to test or to modify materials, PF-400J

Total mass between Z1 and Z2 (m_{12}) :

Is the gas mass between the coaxial electrodes multiplied by the axial mass factor, f_m [4]:

For the PF-400J experimental conditions , f_m = 0.08 [5] and $\mathbf{m_{12} \sim 10x10^{-10}}$ **Kg**

Total mass inside the bubble (between Z2 and Z3, m_{12}) :

Is the total pinch mass (the pinch is ejected trough Z2, creating so the bubble)

The pinch density was previously measured using pulsed interferometry [6, 7], thus the total pinch mass is $\mathbf{m_{23} \sim 1.3x10^{-10}}$ **Kg**

4.- S. Lee 2000/2007 http://ckplee.myplace.nie.edu.sg/plasmaphysics/
5.- S. Lee, S. H. Saw, L. Soto, S. V. Springham, S. P. Moo, Plasma Physics and Controlled Fusion **51**, 075006 (2009)
6.- C. Pavez and L. Soto, Physica Scripta **T131**, 014030 (2008)
7.- "Characterization of the Compression Phase of a Plasma Focus Discharge in Low-Energy Regime by Means of Refractive Optical Diagnostics: Radial Dynamic in PF-400J" C. Pavez et al, *Dense Z-pinches Conference Biarritz, France, 5-9 June 2011, Submitted to AIP Conf. Proc.*

Motivation
A PF to test or to modify materials, PF-400J

If a target is placed at 20 mm from the anode top a shock of plasma with the following characteristics arrives to the target:

A first shock of plasma (Z3):
- Cross section ~ 3 cm^2
- velocity ~ 8×10^4 m/s
- mass ~ 1.3×10^{-10} Kg
- Kinetic energy ~ 0.42 J

A second shock of plasma (Z2) arrived to the target (Z3) ~ 130 ns after:
- Cross section ~ 7 cm^2
- velocity ~ 6×10^4 m/s
- mass ~ 10×10^{-10} Kg
- Kinetic energy ~ 1.8 J
- time of interaction ~ 5ns
- power density ~ 50 MW/cm^2

Designing a PF

Energy density parameter

$$28E/a^3 \sim 5x10^{10} J/m^{-3}$$

Drive parameter

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

- 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

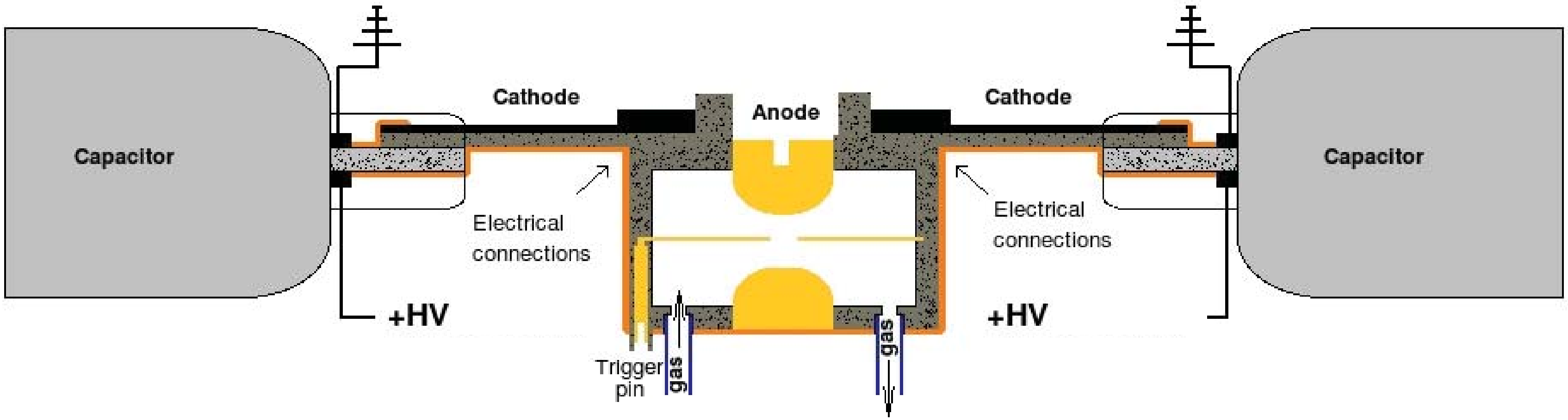
How to start the design? Example

Assume that we have a 2 capacitors of 120nF each

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

L. Soto, Thermonuclear Plasma Department
Chilean Nuclear Energy Commission

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 obtain a measure of 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 $I/ap^{1/2}$ ~ 77kA/cm $mbar^{1/2}$

  we obtain a better value for the anode radius

  a= 3.2mm

Effective anode length, z?

- The pinch must be close to the maximum current, i. e. close to $t = T/4 = (\pi/2)(L_T\ C)^{1/2}$

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

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

$T/4 = t_z + t_r$

It is known $\langle v_z \rangle \sim 0.5\times10^5$ m/s ($0 - 1\times 10^5$ m/s)

$\langle v_r \rangle \sim 1.75\times10^5$ m/s (1×10^5 m/s – 2.5×10^5 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

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

Effective anode length, z?

t_d ?

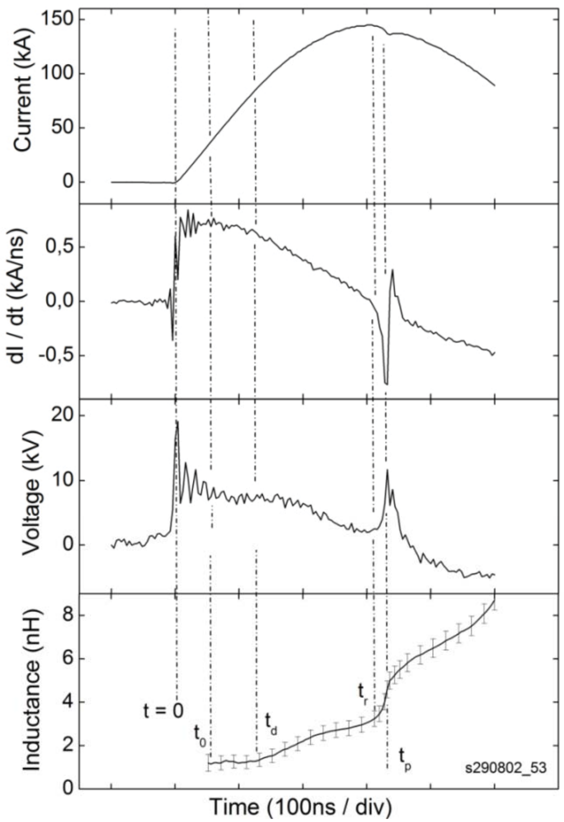
In Mather PF t_d can be neglected in comparison with T/4

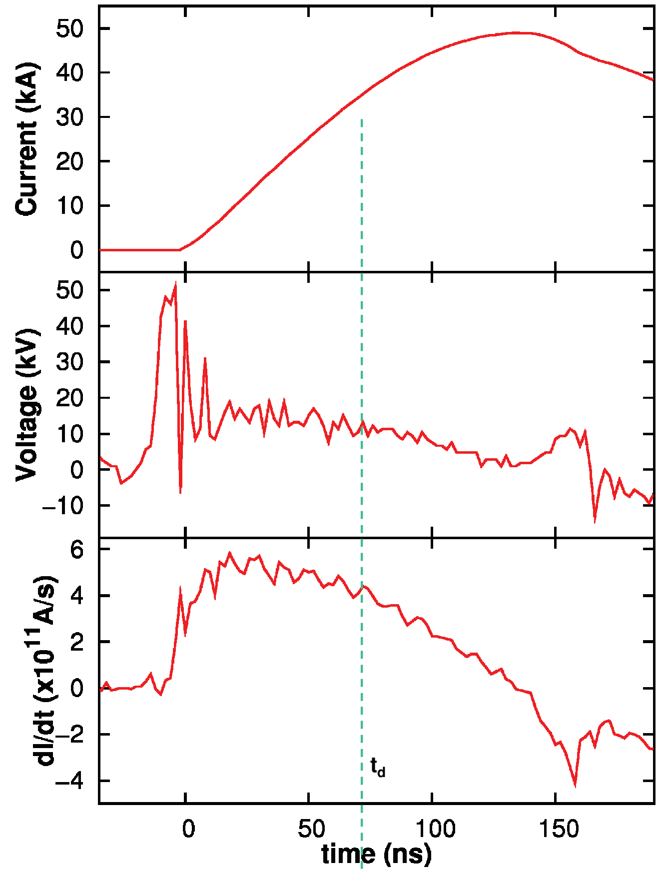
However, according to our observations in small fast hybrid PF ($a/z \sim 1$, $z/l_{ins} \leq 1$), t_d is an important fraction of T/4

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

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

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





PF-400J

T/4=300ns, t_d = 130ns

t_d ~ (1/3) T/4

PF-50J

T/4=150ns, t_d = 50ns

“Correlations among neutron yield and dynamical discharge characteristics obtained from electrical signals in a 400 joules plasma focus” F. Veloso, C. Pavez, J. Moreno, V. Galaz, M. Zambra and L. Soto, subbmitted to PPCF, 2010

Effective anode length, z?

Therefore

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

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

As $t_z = 154$ns, $T/12 = 57$ns, $\langle v_z \rangle \sim 0.5\times10^5$ m/s

$z = (97\times10^{-9}s)\ (0.5\times10^5)m/s = 4.85mm$

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

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.

Homework

- To design a PF from this capacitor

  C=2.6μF

  L=20nH

  Vmax=50kV

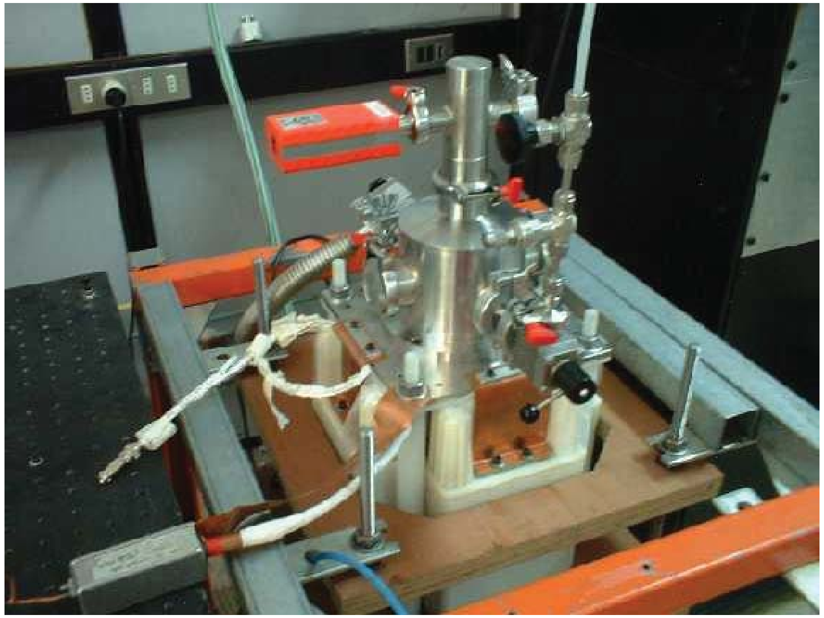
Homework

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

Examples of devices designed and constructed in Chile

PF-400J

Designed to operate at hundred joules



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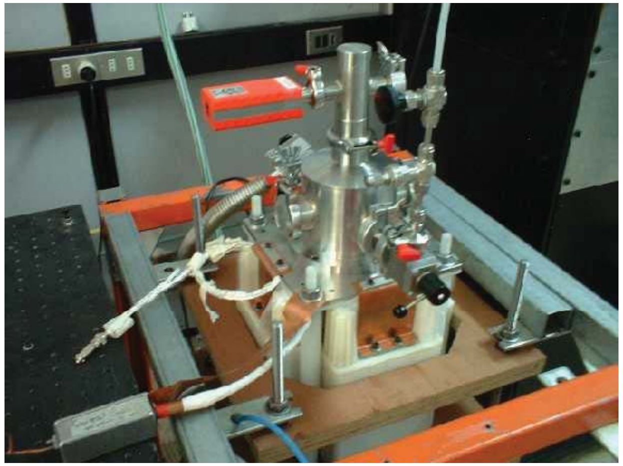
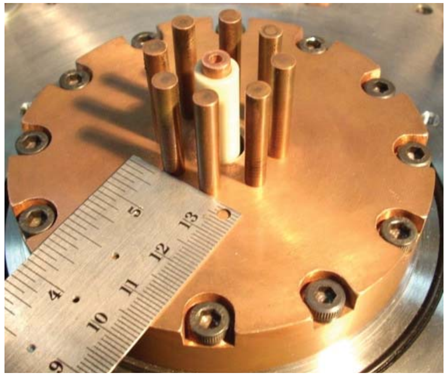
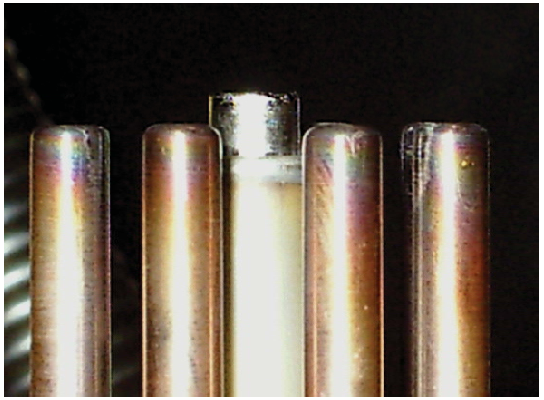
Examples of devices designed and constructed in Chile

PF-50J

Designed to operate at tens joules



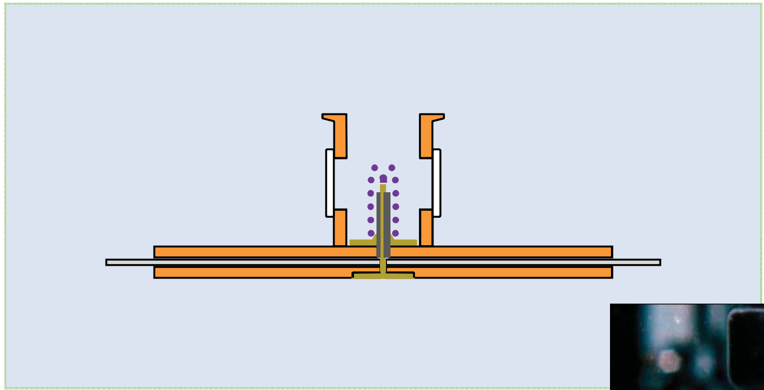


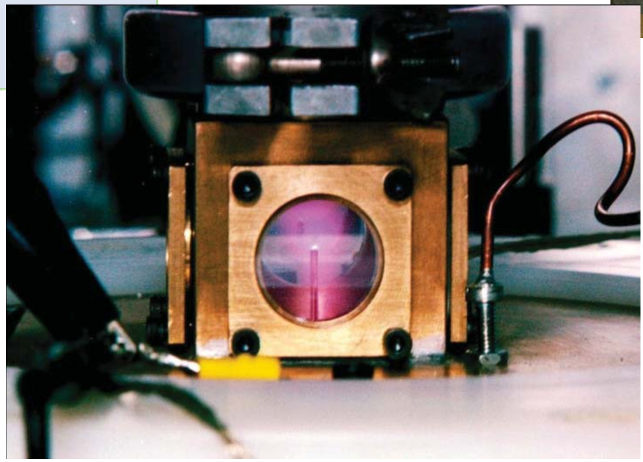


P. Silva, L. Soto, W. Kies and J. Moreno, Plasma Sources Science and Technology 13, 329 (2004).
L. Soto, P. Silva, J. Moreno, M. Zambra, W. Kies, R. E. Mayer, A. Clausse, L. Altamirano, C. Pavez, and L. Huerta J. Phys. D: App. Phys. 41, 205215 (2008)

Examples of devices designed and constructed in Chile

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





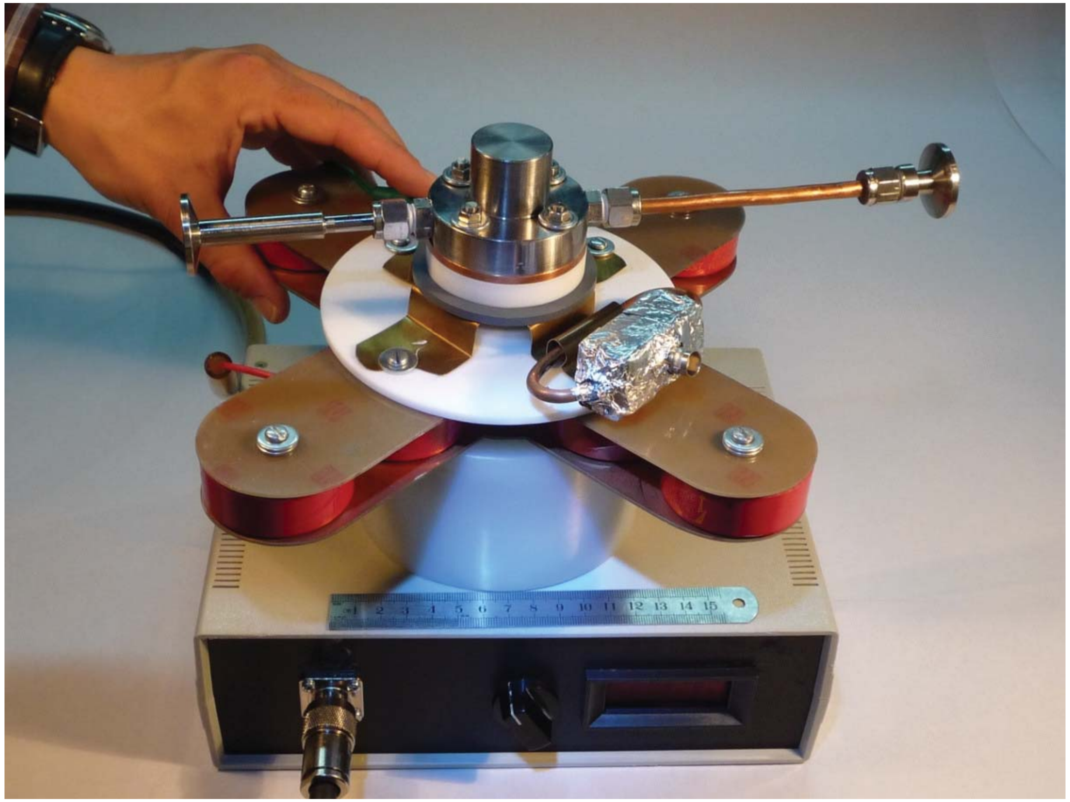
L. Soto, C. Pavez, J. Moreno, A. Clausse and M. Barbaglia PSST 18, 015007 (2009)

Examples of devices designed and constructed in Chile

PF-2J

Designed to operate at 2J- 3J

A portable device For field applications



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Outreach for general public

In the following links, you will find three videos where you can enjoy in an entertaining way:

Chapter 1, What is plasma?
http://www.youtube.com/user/EntertainingScience#p/a/u/2/cBy5mk_X3xo

Chapter 2, What is pulsed power?
http://www.youtube.com/user/EntertainingScience#p/a/u/1/0ndSt2bycR0

Chapter3, What is nuclear fusion?
http://www.youtube.com/watch?v=84XyLFn0JCY

Please share with children, school teachers and journalists in science.