The Abdus Salam
International Centre for Theoretical Physics

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2168-20

Joint ICTP-IAEA Workshop on Dense Magnetized Plasma and Plasma Diagnostics

15 - 26 November 2010

Similarities and differences in plasma focus devices from 1MJ to less than 1J

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Similarities and differences in plasma focus devices from 1MJ to less than 1J

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Population: 17.000.000

Physicists:

~ 250

Researchers in physics:

~ 170

Plasma Physicits:

~ 25

ICPP INTERNATIONAL CONGRESS
LAWPP LATIN AMERICAN WORKSHOP

PLASMA PHYSICS

8-13 AUGUST 2010 SANTIAGO CHILE

August 2010

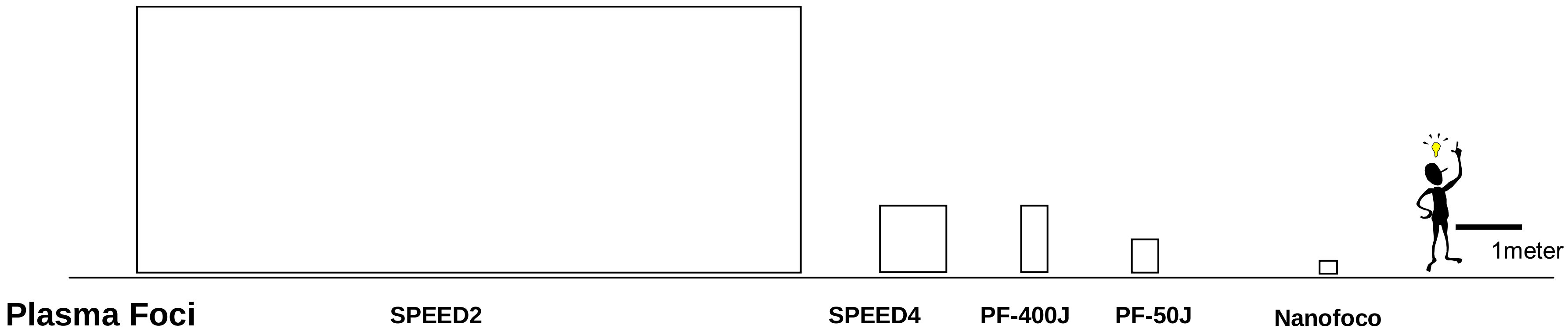
1st – 7th Plasma Physics School

8th – 13th ICPP-LAWPP conference

Research at CCHEN

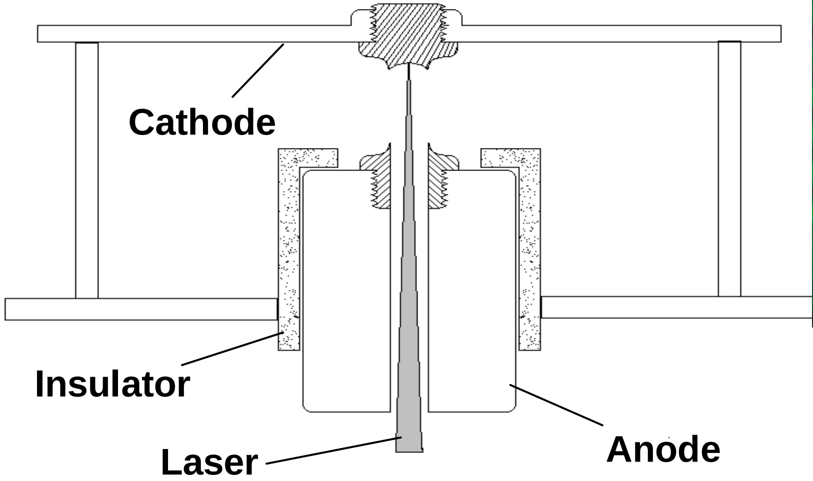
Our research program includes:

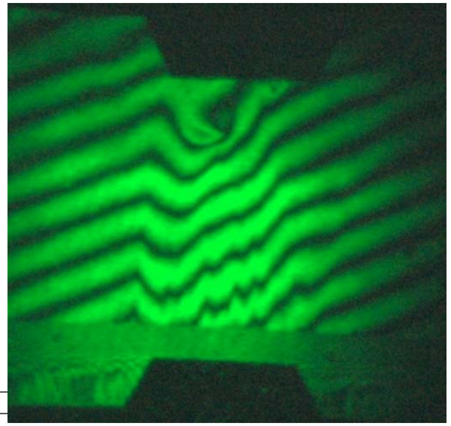
- **Plasma physics related with thermonuclear fusion in Z-pinches:**
  - Stability in gas embedded Z-pinch at MA currents
  - Plasma foci: increasing the plasma energy density in order to increase the thermonuclear neutron yield.
- **Miniaturization of PF devices:**
  - Nanoflashes of radiation from miniaturized devices.
  - Scaling studies

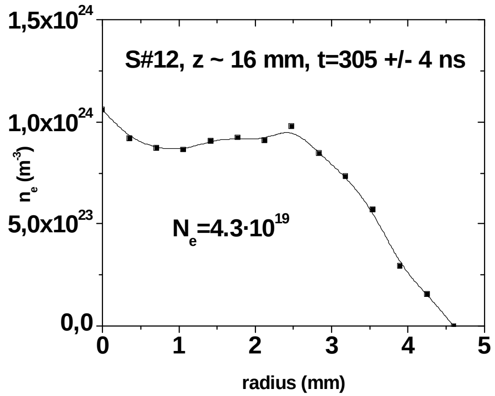


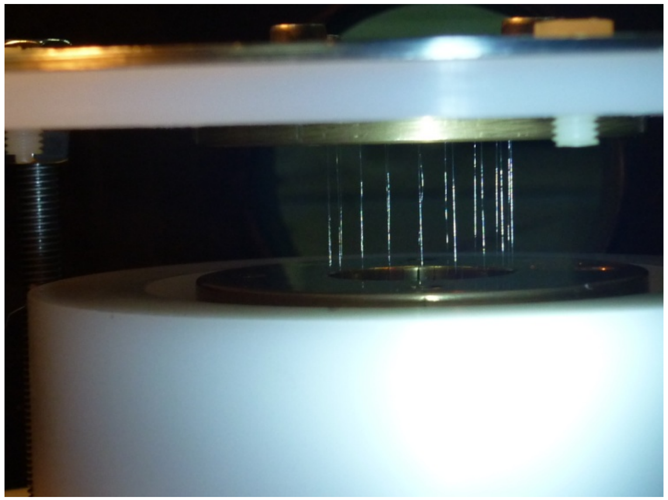
- **Main diagostics:**
  - Nd-YAG laser, 8ns, 1J
  - Neutrons and X-rays detection
  - ICCD, 4ns to 100ns gated frame
  - Electrical signals

Z-pinches driven by SPEED2 at CCHEN-Chile







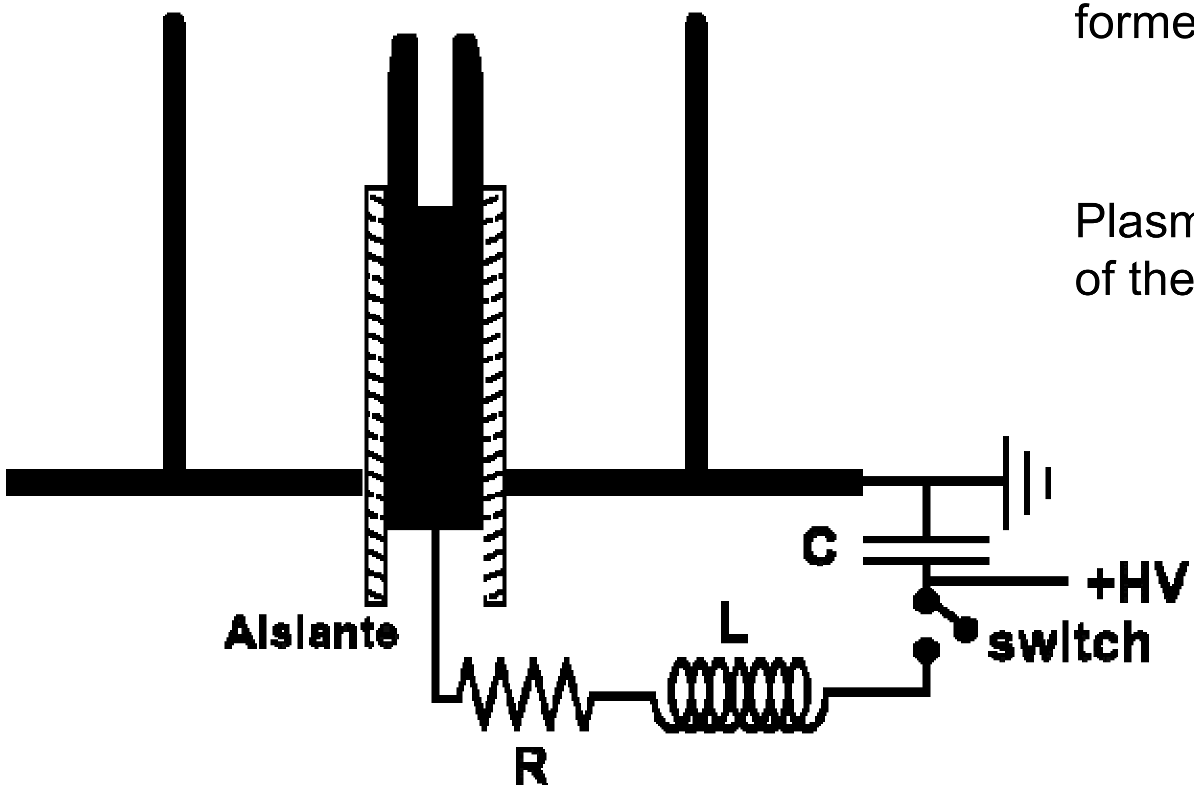


L. Soto, C. Pavez, J. Moreno et al, Physica Scripta T131, 014031 (2008)

Overview talk

- Brief introduction and motivation
- Experiments at CCHEN – Chile: Scaling begins
- Remarks on scaling laws in PF devices
- A portable PF for field applications.

Plasma Focus Devices

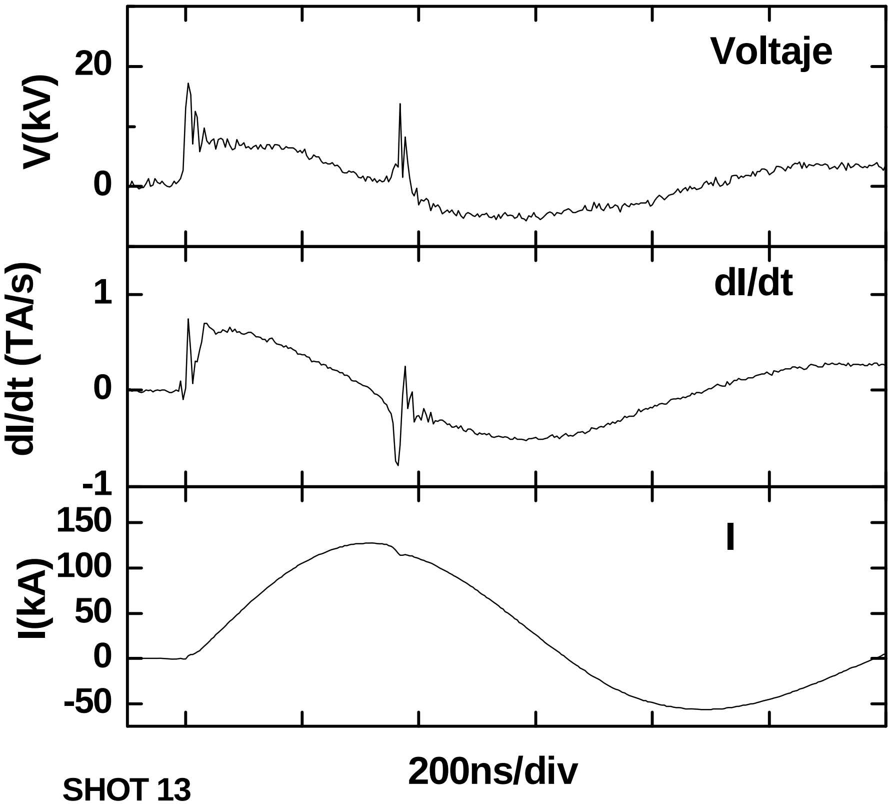


A hot-dense plasma column is formed in the top of the anode

Plasma focus is an old member of the z-pinch family

Non-radiactive source of radiation
(on-off emission of x-rays and neutrons)

Electrical signals



SHOT 13
J290802

- Neutrons are produced from fusion D-D reactions.

- 2 main mechanism are involved:

  - thermonuclear

  - beam target (deuterons on the background plasma and on the background gas)

From the point of view of applications PF´s are interesting beacuse produce nanosecond pulses of X-rays ($\lambda \sim$nm) and neutrons.

- Non radioactive sources of X-rays and Neutrons
    - Nanoflashes of X-rays and neutrons

Fields applications requiere portable devices.

- Portable non-radioactive sources based on accelerators need power supply of ~100kV.

- Plasma Foci can work with power suply of 10kV or less.

Specific objective:

To develop a portable plasma focus for field applications

P^4 project

CRP-IAEA Neutron techniques for detection of illicit substances and materials

OUR APPROACH

PLASMA ENERGY DENSITY

~10^{12} J/m^3

1J in a sub millimeter volume

0.1J in a sphere of 60μm of diameter

PLASMA PHYSICS IN SMALL DEVICES

Device [reference]	Energy (kJ)	Anode diameter (cm)	Operation mode
PF-1000 [6]	1000	23	Single shot
SPEED 2 [3]	100	11.7	Single shot
GN1 [17]	4.7	3.8	Single shot
AAAPT [7]	3	1.9	Single shot
Fraunhofer Insitute ILT-Aachen RWTH LLT [11]	2-5	______	Repetitive, 2Hz
Research Lab., Alameda [12]	2	______	Repetitive, 2Hz
NX1 [13]	3	3	Repetitive, 3Hz
NX2 [13]	1.9	4	Repetitive, 16Hz
PF-400J (CCHEN)	0.4	1.2	Single shot
PF-50J (CCHEN)	0.05	0.6	Single shot

Some plasma focus devices with their characteristic energy, size anode electrode and operation mode. PF-1000: at the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland; SPEED 2: at Heinrich-Heine-Universität, Düsseldorf, Germany (1986-2000), at present in operation at the Comisión Chilena de Energía Nuclear, Chile; GN1: at the Universidad de Buenos Aires, Argentina; AAAPT: Asian-African Association for Plasma Training Network, ILT-LLT: Fraunhofer Insititut für Lasertechnik and Lehrstuhl für Lasertechnik, Aachen, Germany; SRL: Science Research Laboratory, Alameda, USA; NX1 and NX2: at Nanyang Technological University, Singapore. It can be seen that the energy of the device described in the present article is relatively very low.

<1kJ

PF´s operating at hundred joules

- A. Shyam and M. Srinivasan, Applied Physics A: Material Science and Proccessing **17**, 425, (1978)
- P. Silva, J. Moreno, L. Soto, L. Birstein, R. Mayer, and W. Kies, App. Phys. Lett. **83**, 3269 (2003).
- M. Milanese, R. Moroso, J. Pouzo, Eur. Phys. J. D **27**, 77 (2003)
- R. K. Rout, P. Mishra, A. M. Rawool, L. V. Kulkarani and S. C. Gupta, J. Phys. D: Appl. Phys. **41**, 205211 (2008)
- R. Verma, R. S. Rawat, P. Lee, M. Krishnan, S. V. Sprinham and T. L. Tan, Plasma Phys. Control. Fusion **51**, 075008 (2009)

- Russian Federation: ViNIIA, 200J

< 100 J

PF´s operating at tens of joules

- P. Silva, L. Soto, J. Moreno, G. Sylvester, M. Zambra, L. Altamirano, H. Bruzzone, A. Clausse, and C. Moreno, Rev. Sci. Instrum. **73**, 2583 (2002)
- P.Silva, L. Soto, W. Kies and J. Moreno, Plasma Sources: Sci. and Technol. **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)
- R. Shukla, S. K. Sharma, P. Banerjee, R. Das, P. Deb, T. Prabahar, B. K. Das, B. Adhikary, and A. Shyam, Rev. Sci. Instrum. 81, 083501 (2010)
- A. Tarifeño, C. Pavez, J. Moreno and L. Soto, IEEE Trans. Plasma Science, accepted for publication, to be published in January 2011.

< 1 J

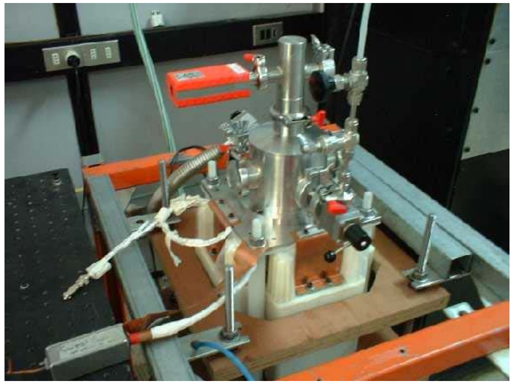
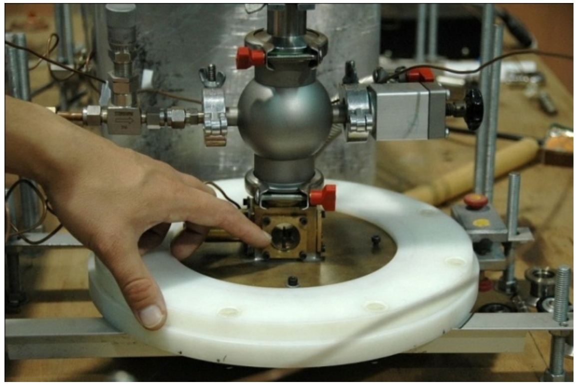
PF´s operating at less than 1 joule

- L. Soto, C. Pavez and J. Moreno, M. Barbaglia and A. Clausse , Plasma Sources Sci. and Technol. **18**, 015007 (2009)
- C. Pavez and L. Soto, IEEE trans. Plasma Science, **38**, 1132 (2010)

Research at CCHEN
Research at CCHEN

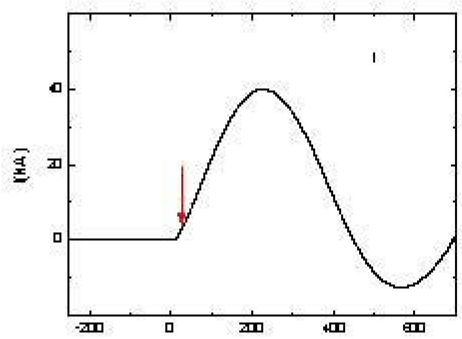
Our devices

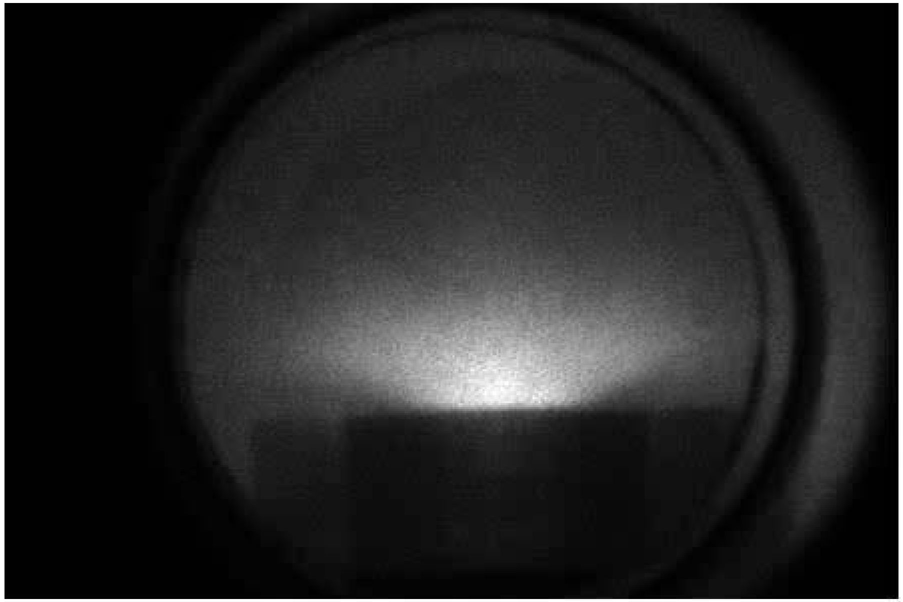
•SPEED2:	70kJ, 2.4MA, 400ns
• PF-400J:	400J, 130kA, 300ns
• PF-50J:	50J, 50kA, 150ns
• Multipurpose generator:	520J, 170kA, 350ns
• PF-2J:	2J, 15kA, 80ns
• Nanofocus, NF:	0.1J, 5kA, 10ns

PF-50J

Visible plasma images obtained with a ICCD, 5ns exposure time

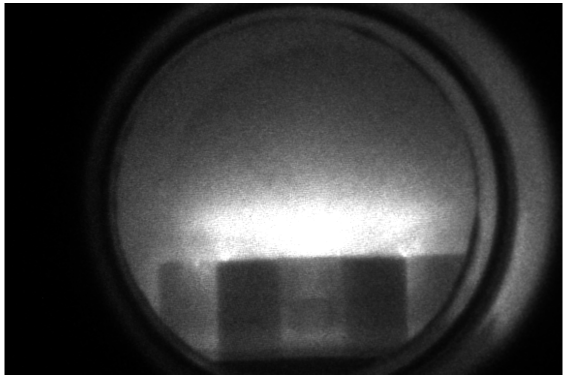




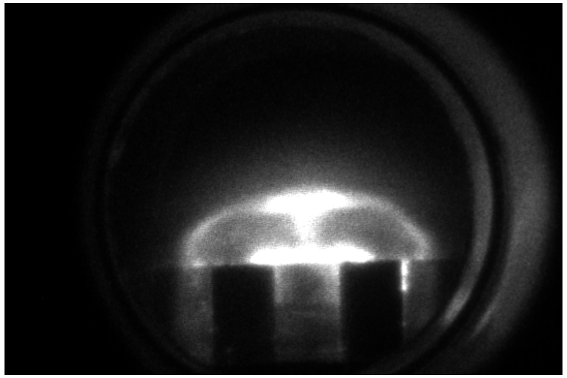
J. Moreno, P. Silva and L. Soto, Plasma Sources Sci. and Technol. 12, 39 (2003)

PF-50J

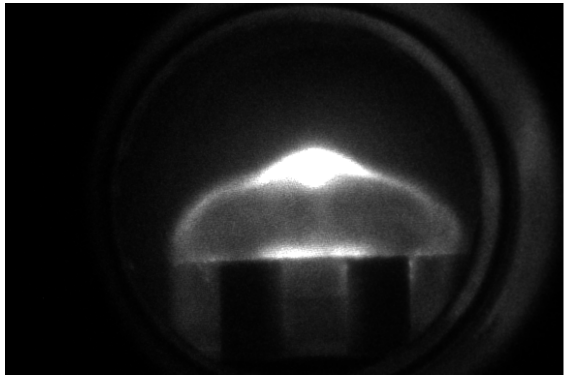
Visible plasma images obtained with a ICCD, 5ns exposure time



37 ns



222 ns



309 ns

J. Moreno, P. Silva and L. Soto, Plasma Sources Sci. and Technol. 12, 39 (2003)

PF-50J

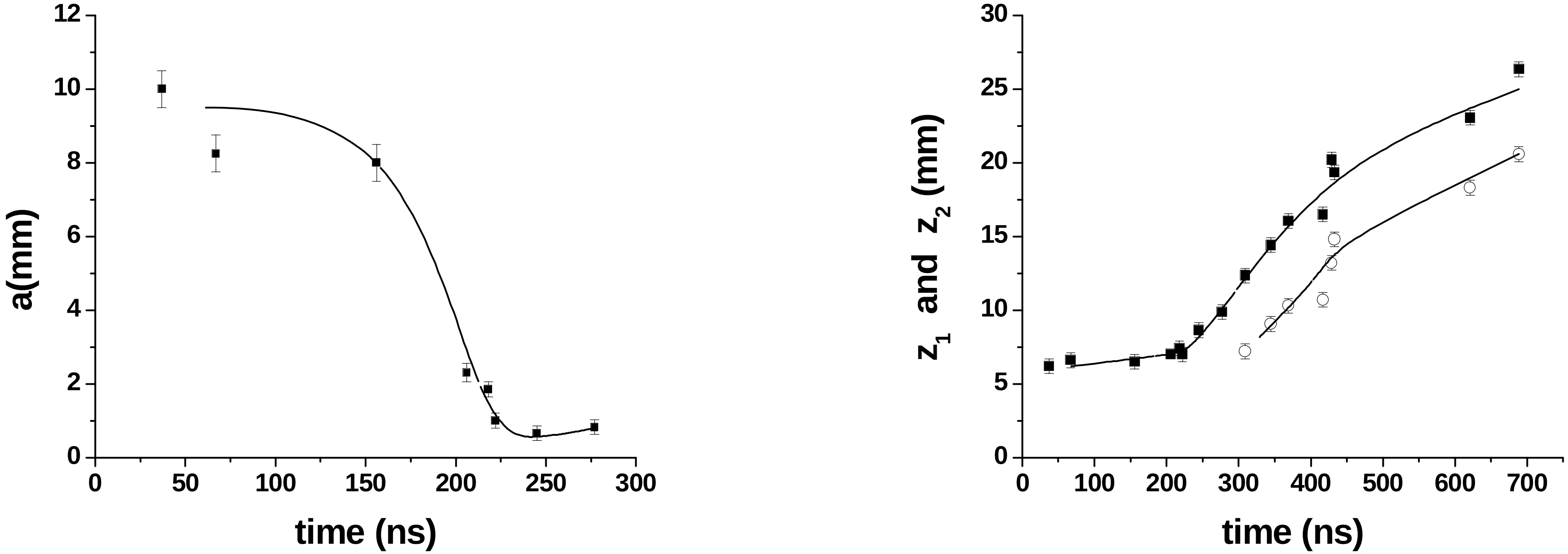
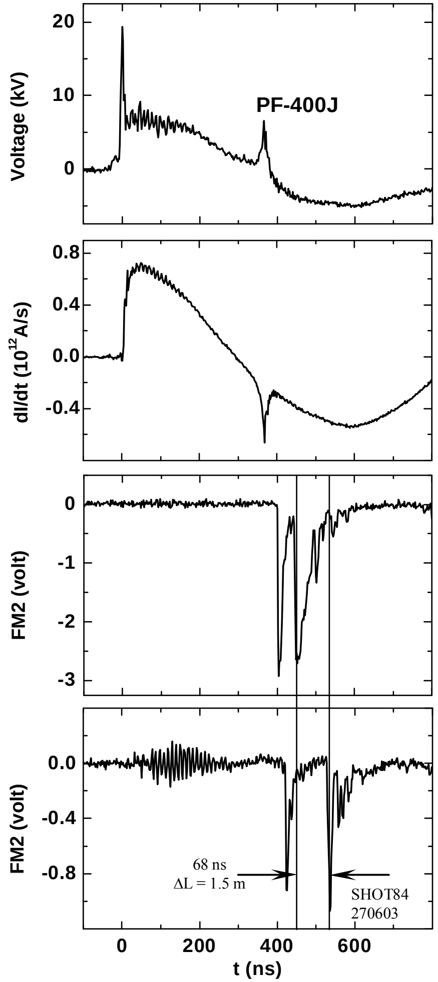


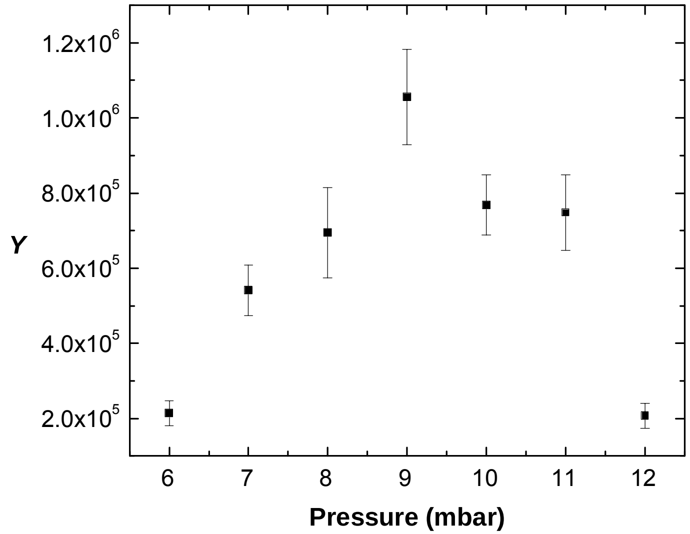
Fig. 5. Radial plasma motion a(t) and motion of the frontal and rear axial plasma edge, $z_1(t)$ and $z_2(t)$

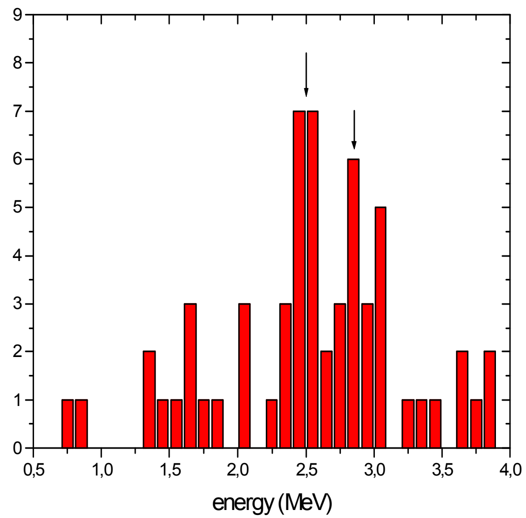
J. Moreno, P. Silva and L. Soto, Plasma Sources Sci. and Technol. 12, 39 (2003)

PF-400J



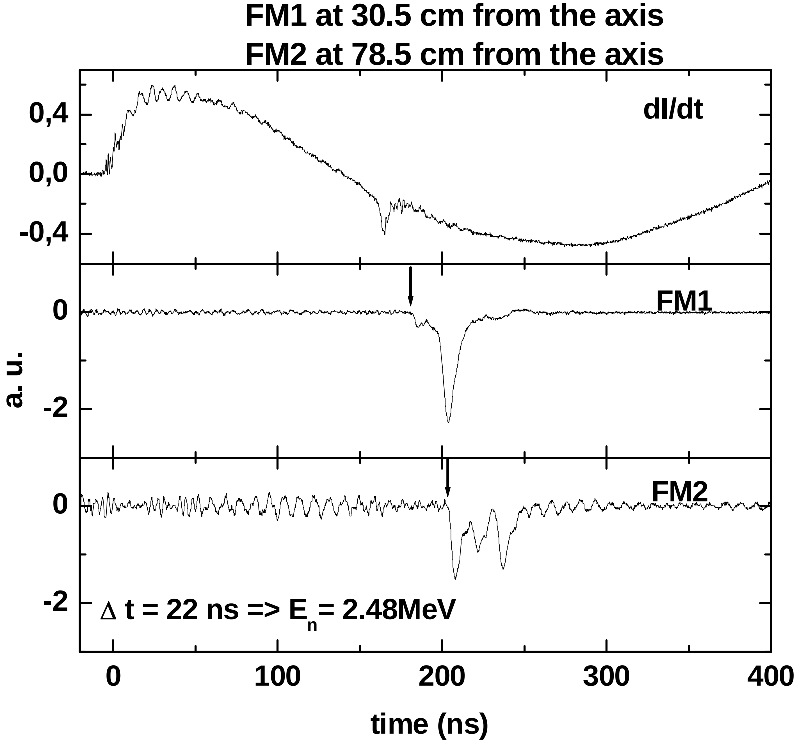
PF-400J

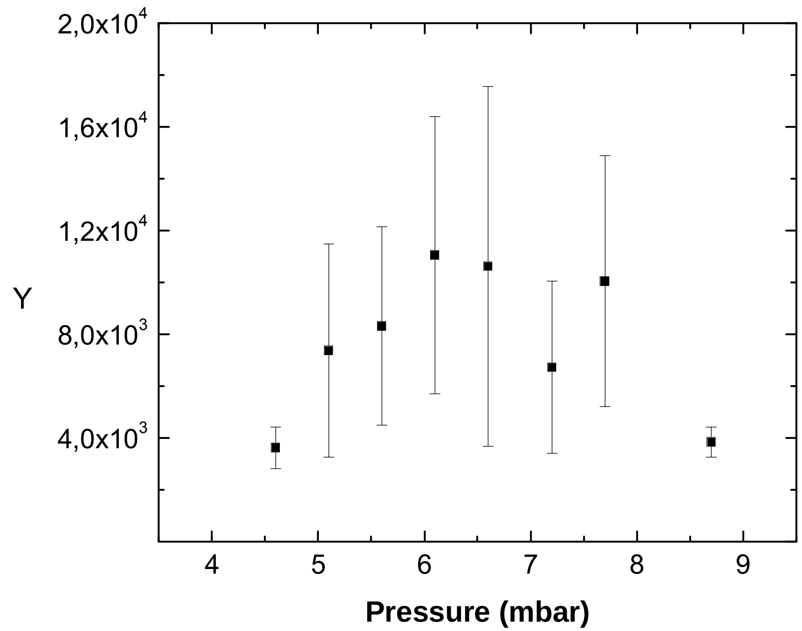




P. Silva, J. Moreno, L. Soto, L. Birstein, R. Mayer, and W. Kies, App. Phys. Lett. 83, 3269 (2003)

PF-50J





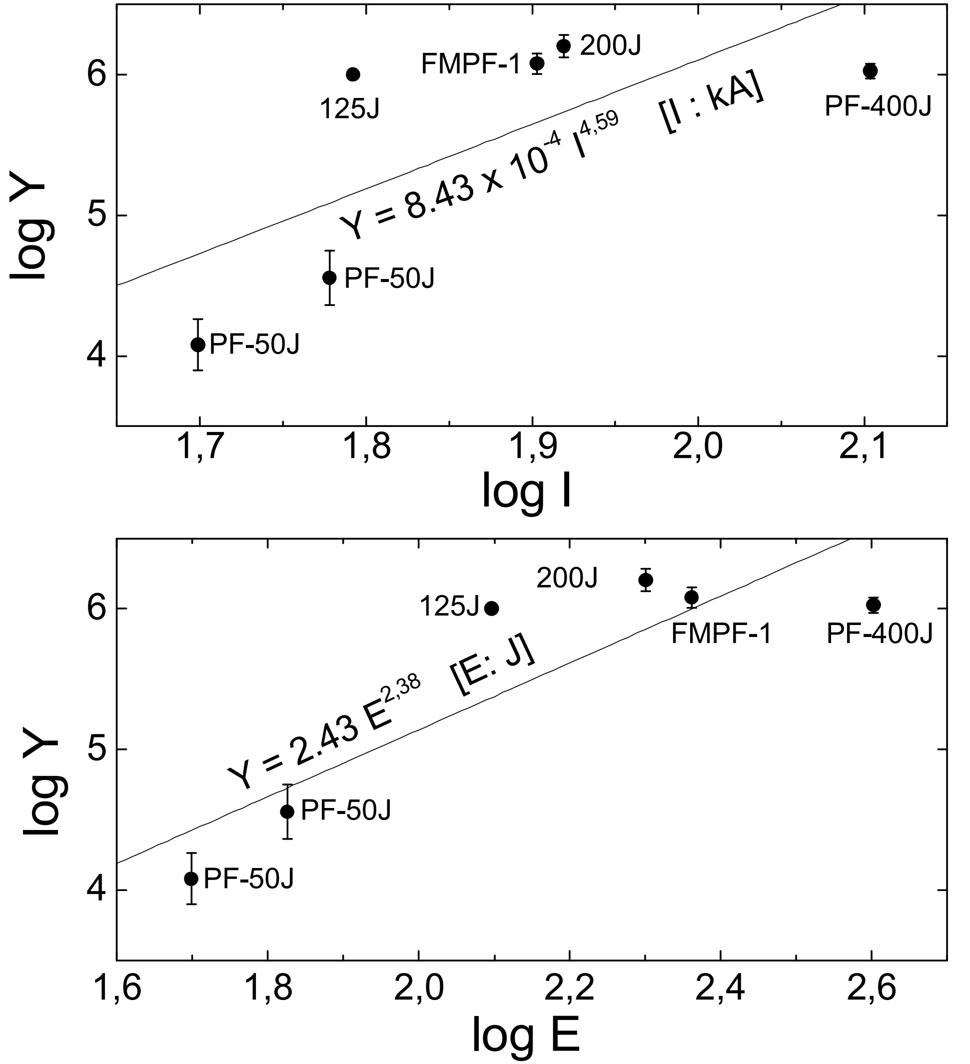
Average over 20 shots

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)

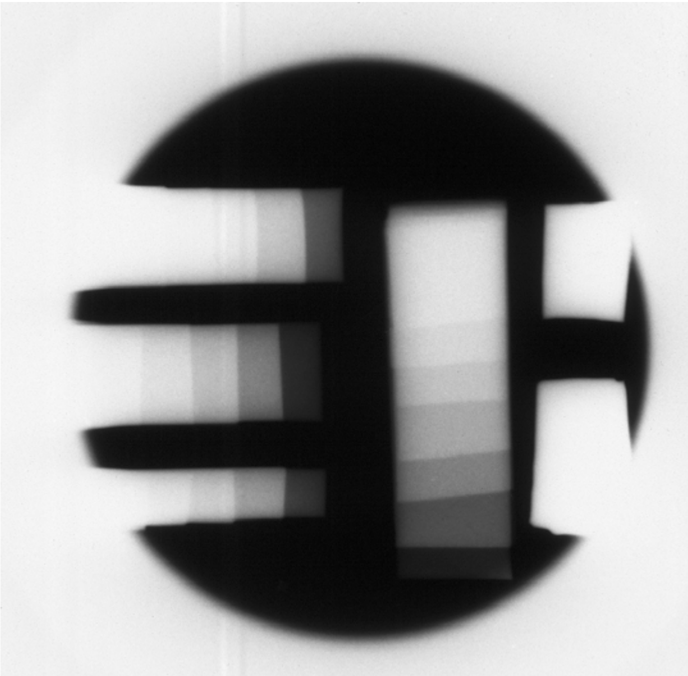
Scaling law for Y
E<1kJ

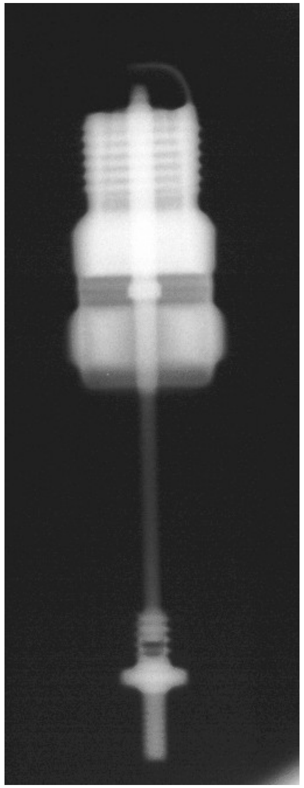
L. Soto (2010)

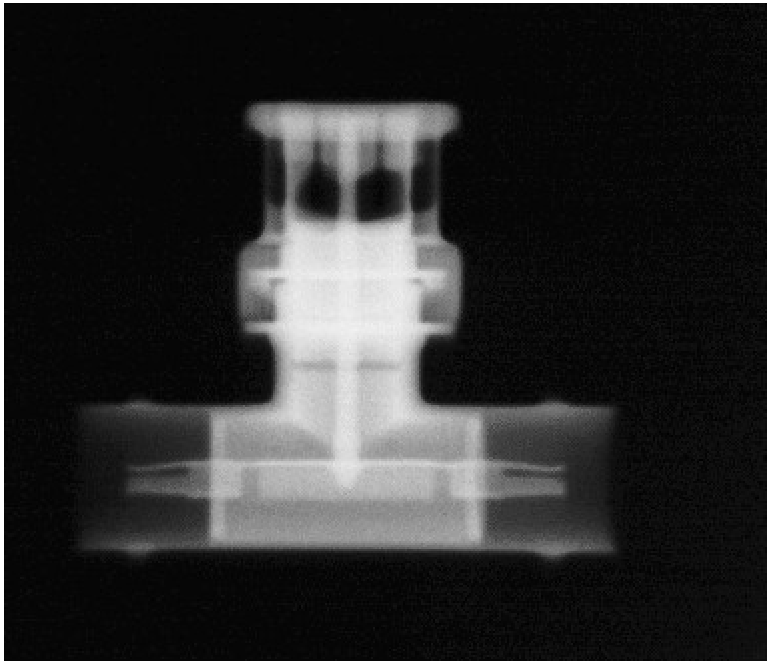


L. Soto et al. Plasma Sources Sci. Technol. 19 ,055017 (2010)

Hard X-ray nanoflash



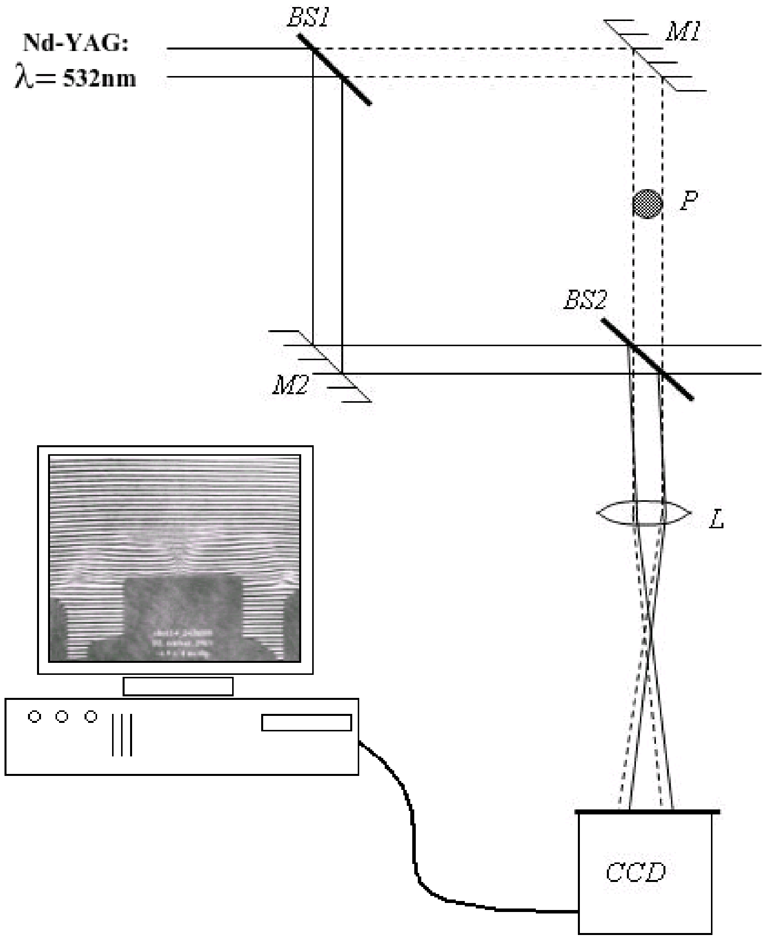


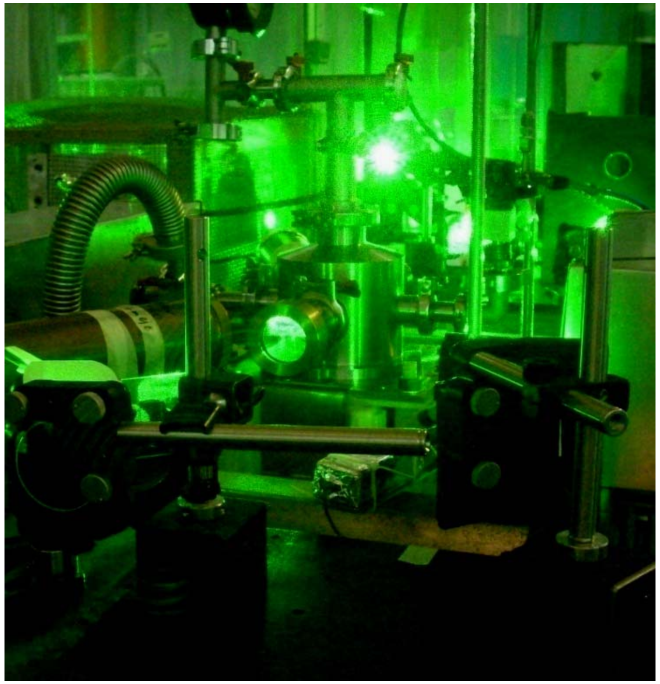


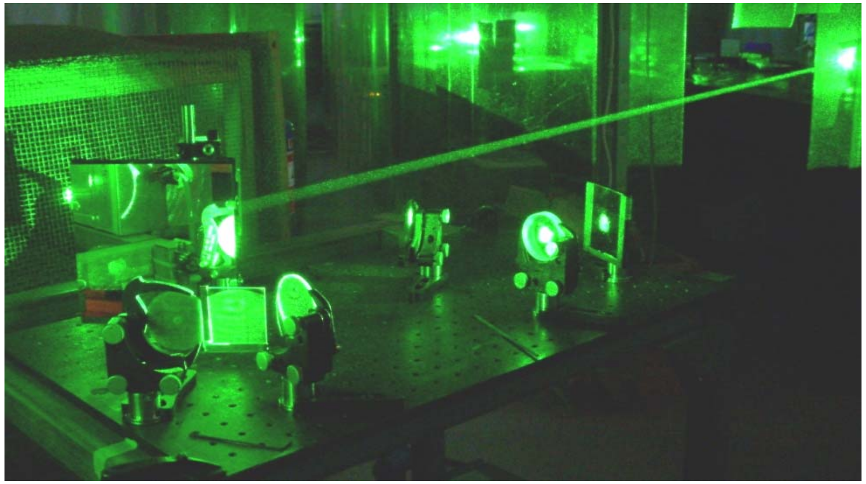
X-ray from PF-400J

~ 90±5 keV energy

Optical setup: Mach-Zender Interferometer

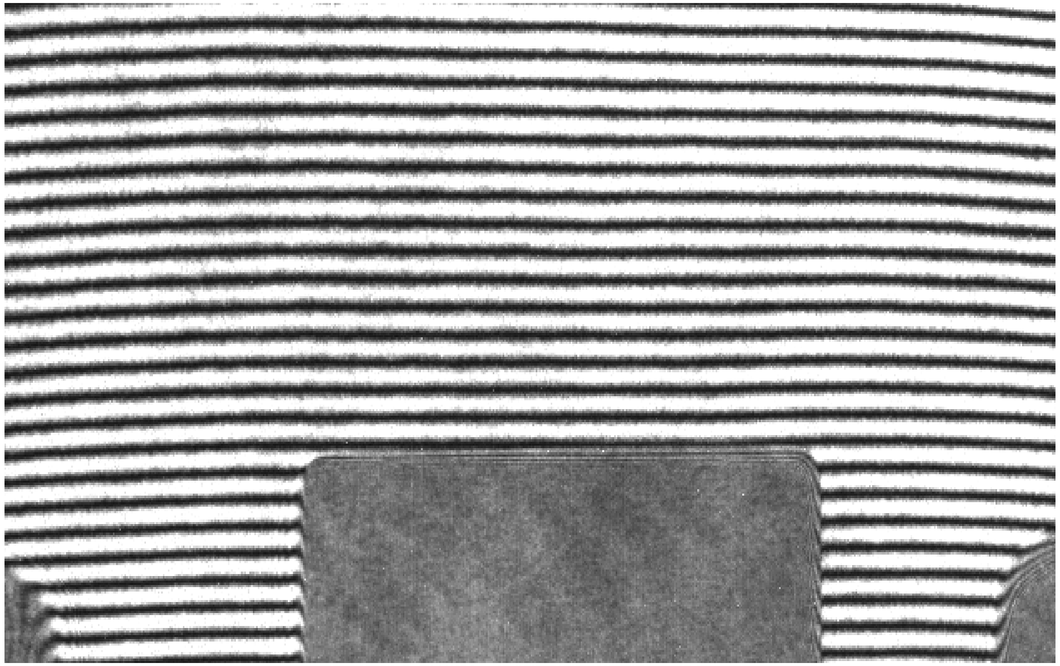




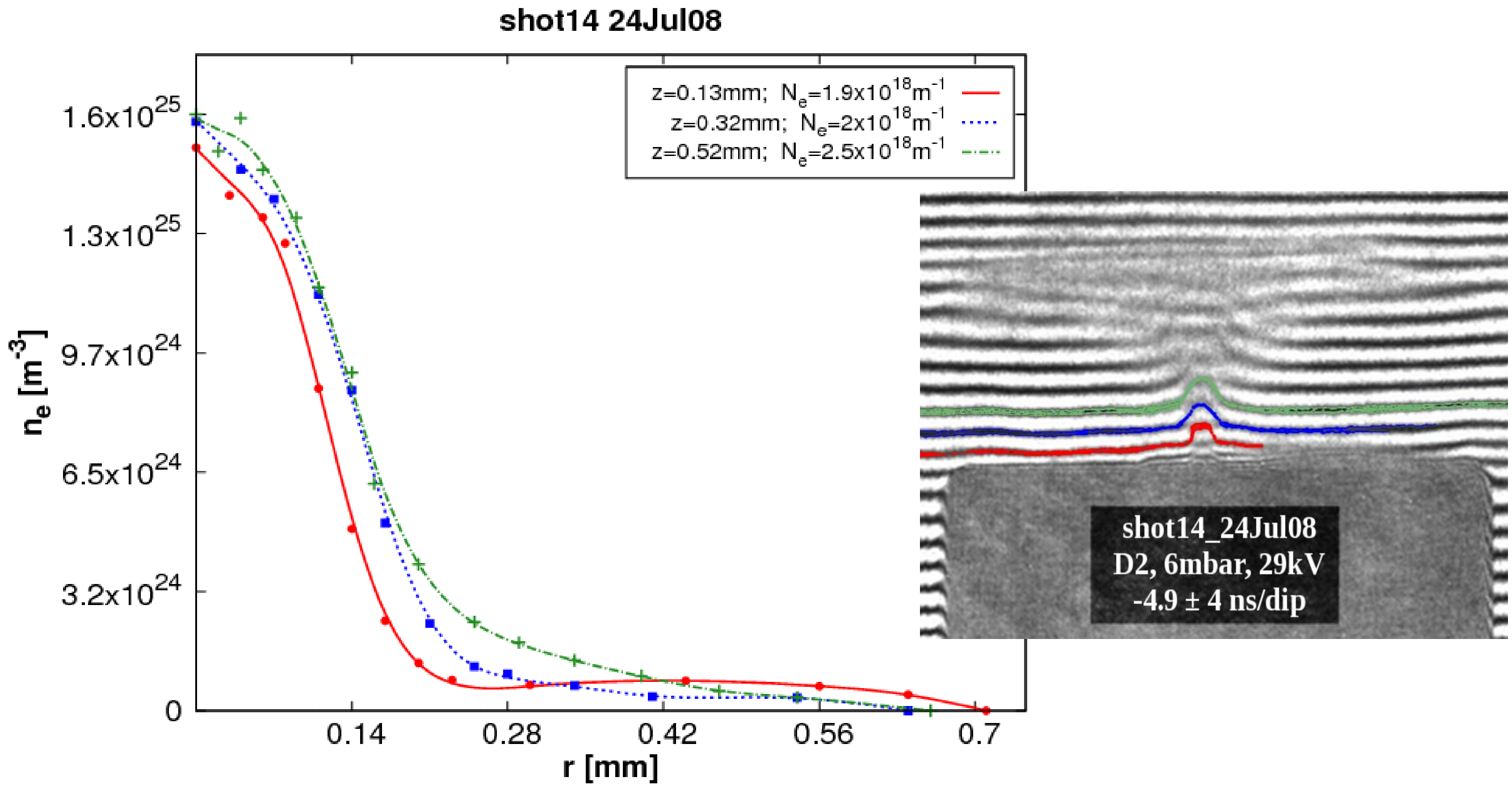


PF-50J

Plasma Density



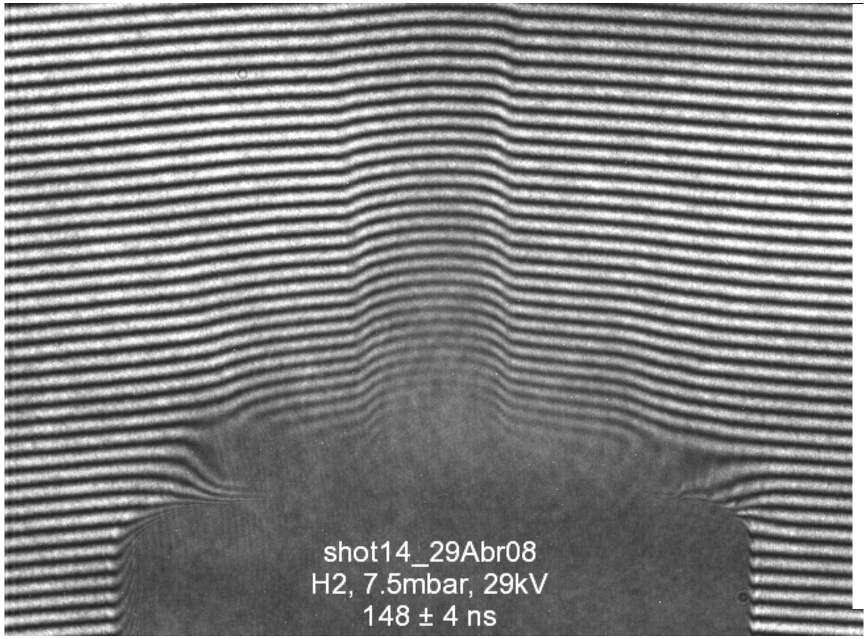
A. Tarifeño, C. Pavez, J. Moreno and L. Soto "Dynamics and Density Measurements in a Small Plasma Focus of Tens of Joules Emitting Neutrons", to be published by IEEE TPS

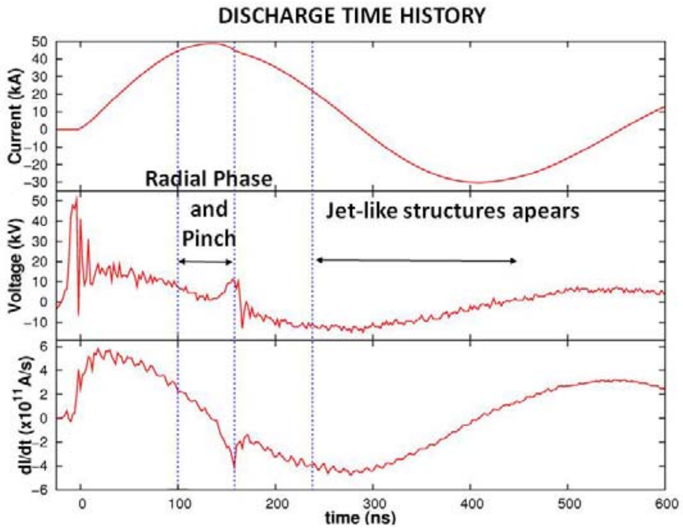


For Deuterium, it has been found that densities as high as 10^{25} m^{-3} are reached in the axis, while the line density is of the order of 10^{18} m^{-1}.

A. Tarifeño, C. Pavez, J. Moreno and L. Soto "Dynamics and Density Measurements in a Small Plasma Focus of Tens of Joules Emitting Neutrons", to be published by IEEE TPS

Plasma jets observations in a table top plasma focus, PF-50J



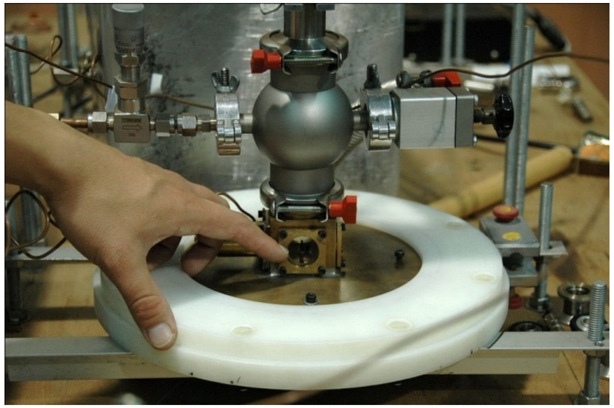


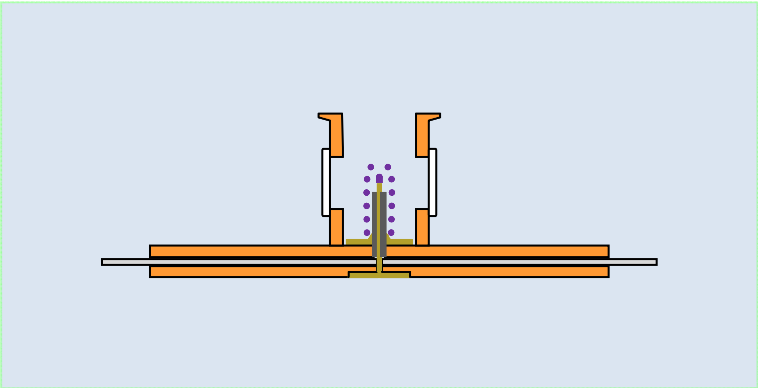
A. Tarifeño-Saldivia, C. Pavez and L. Soto, ICPP-LAWPP 2010

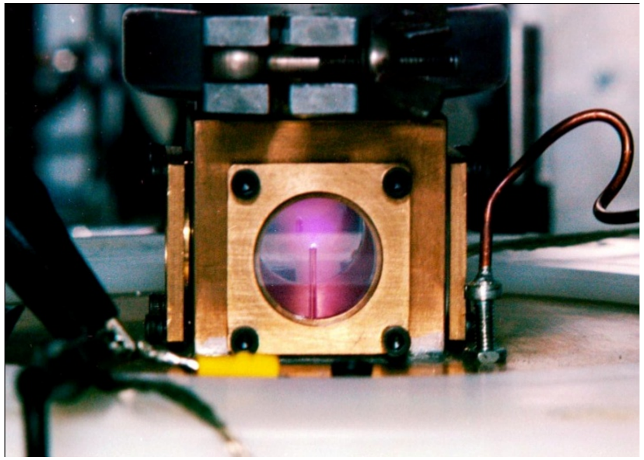
MINIATURIZATION: NANOFOCUS, E < 1J

Conceptual design and electrical parameters expected:
C=5-10nF, L=5-10nH, Vo=5-15kV (E~ 0.06 - 1 J)
Ipeak= 3kA-15kA, T/4=8ns-16ns

Expected neutron yield at 10kA   Y ~ 10^2 neutron/shot

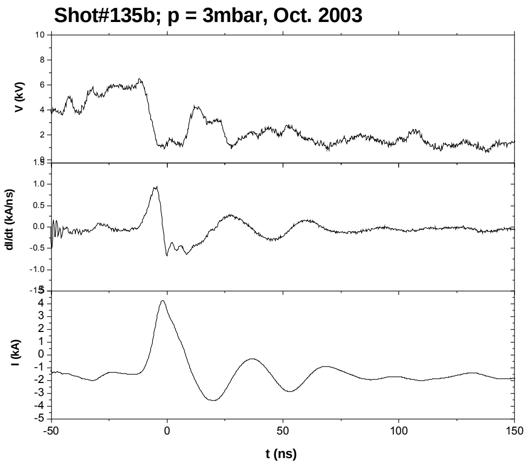






L. Soto, C. Pavez, J. Moreno, A. Clausse and M. Barbaglia PSST 18, 015007 (2009)

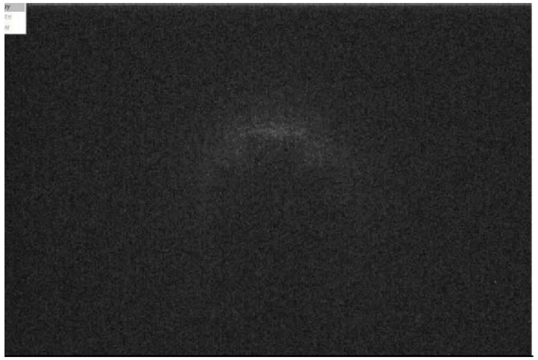
H_2 3 mbar



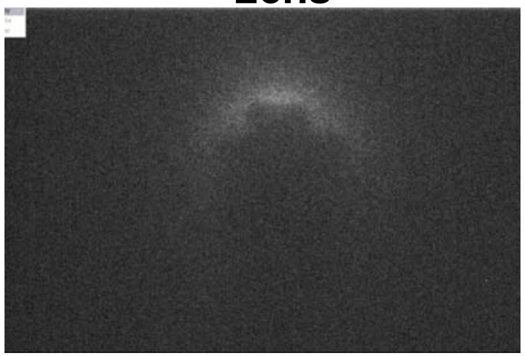
$E = 1/2\ CV^2$

C~ 5 ± 1nF
V=6.5±0.3kV

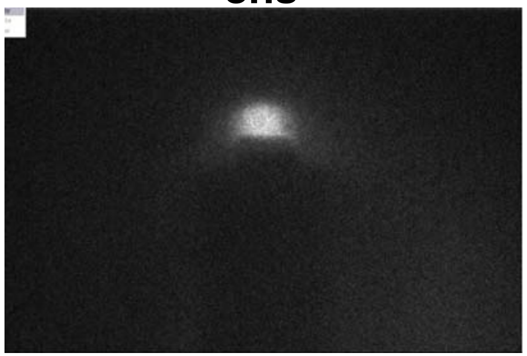
E ~ 100mJ!



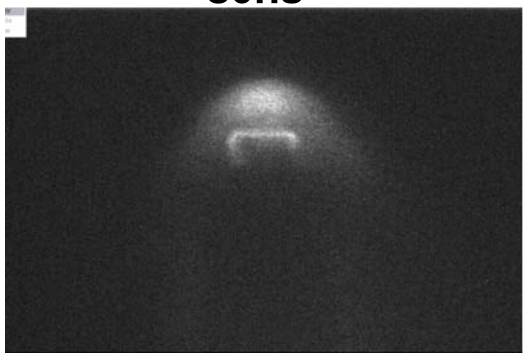
-26ns



5ns



30ns

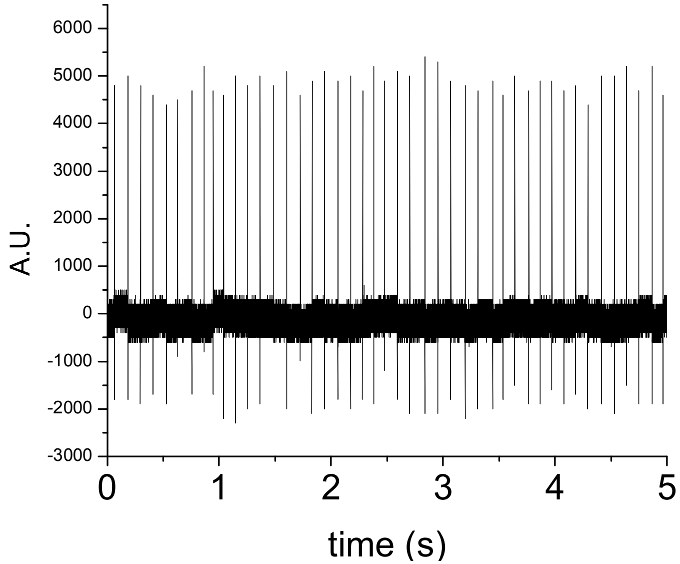


3mm

Repetetion rate

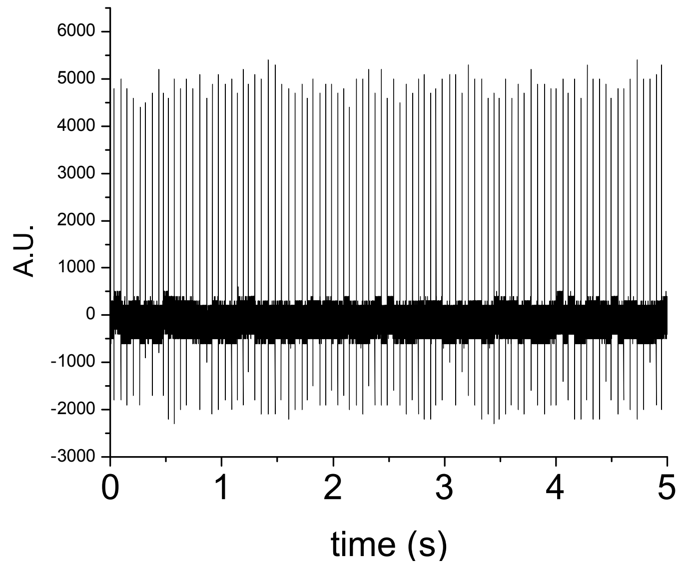
a = 210μm **p = 16mbar**
V= 6.5kV **E=0.1J** **P_{peak} ~ 10MW**

9 Hz



<P> ~ 1W

18 Hz

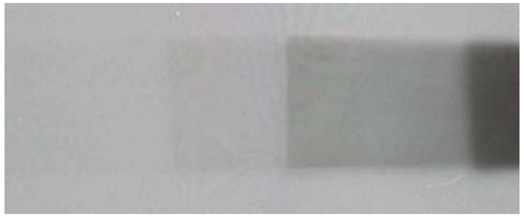


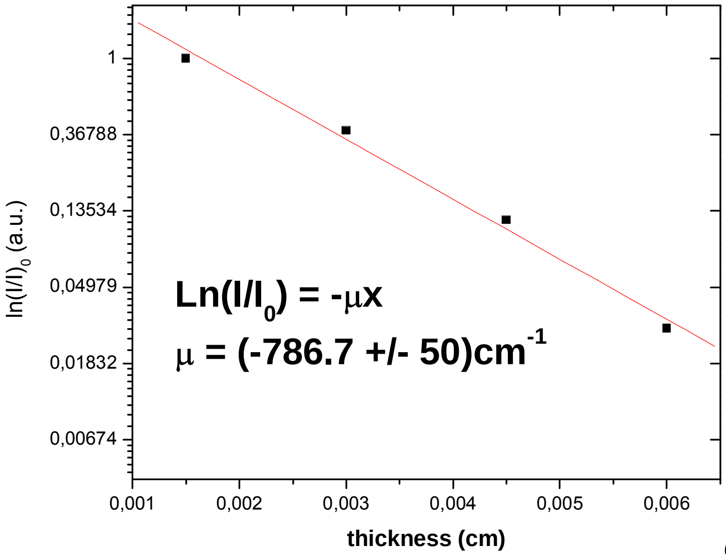
<P> ~ 2W

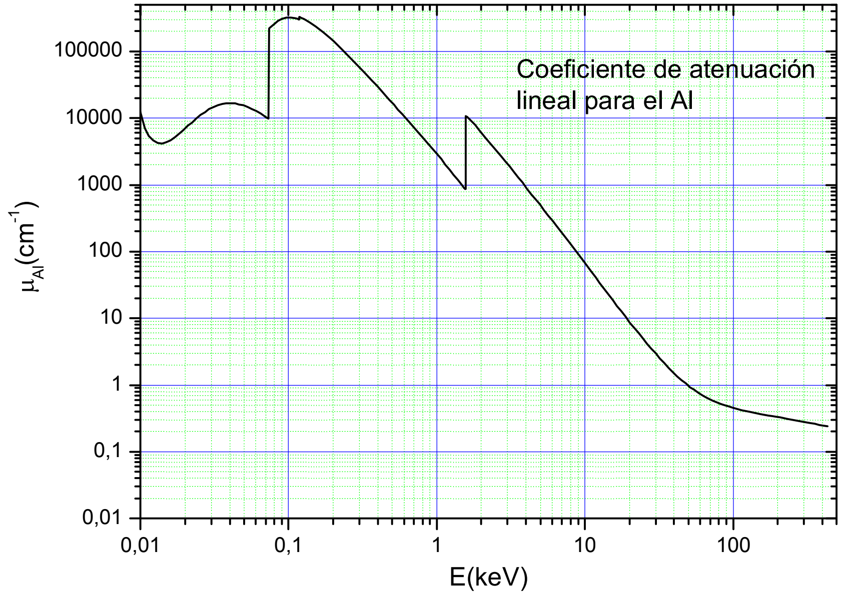
Estimation of X-ray energy

- Assuming a monoenergetic emission, $\mathbf{I = I_0\, e^{-\mu \Delta x}}$

Al



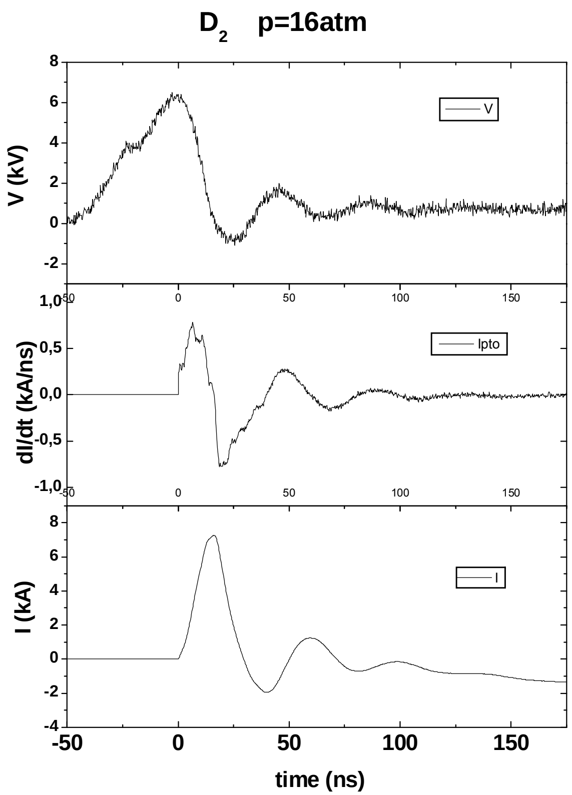




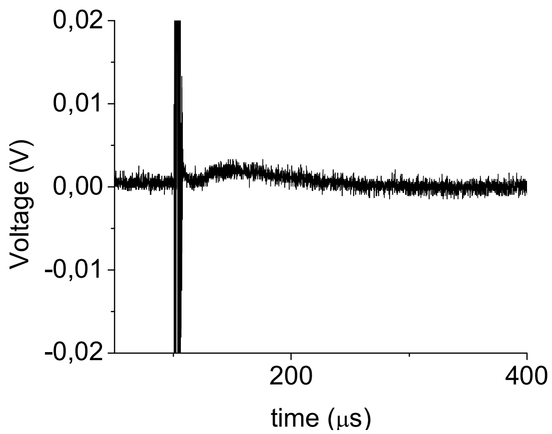
E~ 4 – 4.3 keV

C. Pavez and L.Soto, IEEE Trans. Plasma Sci. 38, 1132 (2010).

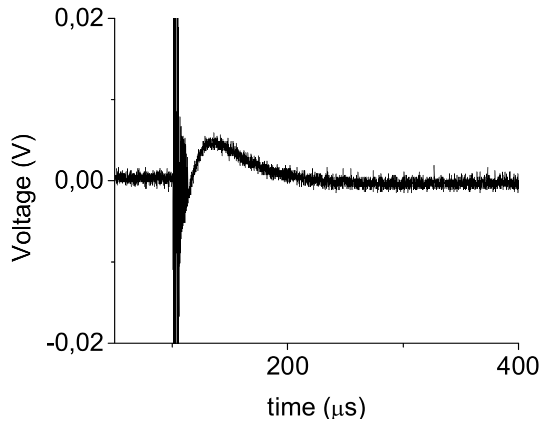
Neutrons have been detected from Nanofocus



a= 0.21 mm



~ 100±40 n / shot



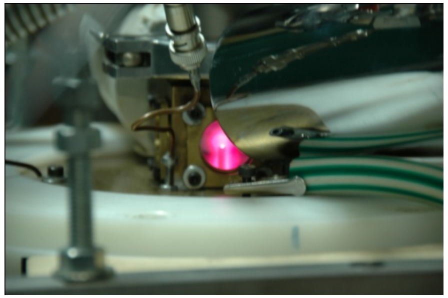
Santiago-Bariloche-Santiago

The neutrons detection was confirmed by an independent laboratory outside of Chile

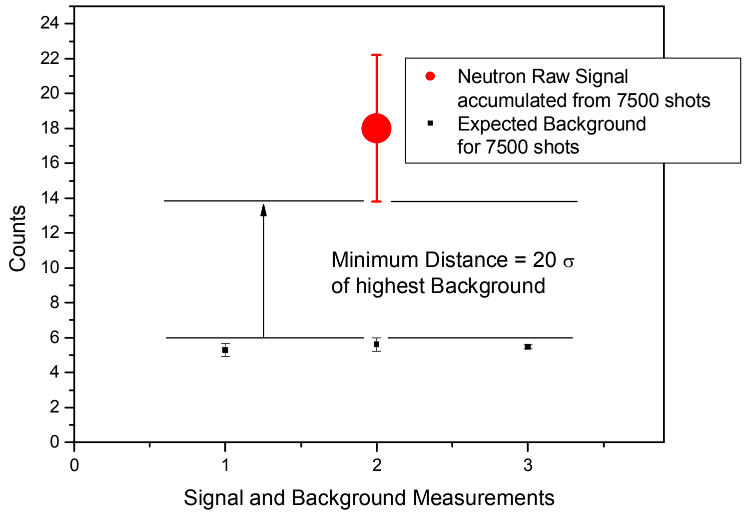
Centro Atómico Bariloche
Argentina







The neutron events observed are 20 standard deviations greater than the background.



Energy density parameter

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

Drive parameter

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

$$v_a \ \alpha\ I/ap^{1/2} \qquad v_r \ \alpha\ I/ap^{1/2}$$

$$r_p \sim (0.1\text{-}0.2)\ a,\ z_p \sim (0.8\text{-}1)\ a$$

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Device	Energy E (kJ)	Anode radius *a* (cm)	Peak current I_0 (kA)	Pressure (mbar)	Energy density parameter $28\ E/a^3$ (J/m^3)	Driven factor $I_0/p^{1/2}a$ (kA/mbar$^{1/2}$cm)	Ratio Surface to Volume S/V (cm^{-1})
PF-1000	1000	11.5	2000	6	$1.8x10^{10}$	72	0.08
PF-360	60	5	750	4	$1.3x10^{10}$	75	0.17
7kJ PF-Japan	7	1.75	390	6	$3.7x10^{10}$	91	0.57
GN1	4.7	1.9	-	-	$1.9x10^{10}$	-	0.53
Fuego Nuevo II	4.6	2.5	350	3.7	$0.8x10^{10}$	73	0.4
UNU/ICTP-PFF]	2.9	0.95	172	8.5	$9.5x10^{10}$	81	1.05
PACO	2	2.5	250	1.5	$3.6x10^{9}$	95	0.4
PF-400J	0.4	0.6	127	9	$5.2x10^{10}$	70	1.67
PF-50J	0.07 0.05	0.3 0.3	60 50	9 6	$7.3x10^{10}$ $5.2x10^{10}$	66.7 68	3.3

Energy Density Parameter: $5\ 10^{10}$ J/m^3

Very few variation

Drive Parameter: 77 kA/cm mbar½

Device	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)	Energy per mass parameter E/a^3p (x10^7 J/m^{3}mbar)
PF-1000	1064	12.2	2300	6.6	1.6x10^{10}	73.4	8.5
PF-360	130	6	1200	1.6	1.7x10^{10}	61.4	38
SPEED2	70	5.4	2400	2.7	1.2x10^{10}	-	15.9
7kJ PF [27]-	7	1.75	390	6	3.7x10^{10}	91	22
GN1	4.7	1.9	-	-	1.9x10^{10}	-	-
Fuego Nuevo II	4.6	2.5	350	3.7	0.8x10^{10}	73	7.7
UNU/ICTP- AAAPT	2.9	0.95	172	8.5	9.5x10^{10}	81	4.1
PACO*	2	2.5	250	1.5	3.6x10^{9}	95	8.5
PF-400J	0.4	0.6	127	9	5.2x10^{10}	70	2
FMPF-1	0.23	0.35	80	5.5	1.5x10^{11}	97	5.35
200J* Batt-PF	0.2	0.5	83	10	4.5x10^{10}	52*	1.6*
125J PF	0.125	0.75	62	2	0.83x10^{10}	58*	1.5*
PF-50J	0.07 0.05	0.3 0.3	60 50	9 6	7.3x10^{10} 5.2x10^{10}	66.7 68	2.9
NF* [9]-Chile	0.00025 0.0001	0.021 0.08	6 4.5	16 3	7.6x10^{11} 5.5x10^{9}	70 32*	16.9 0.65*

What have we learned?

Studies on scaling laws for plasma focus
Similarities and differences in devices from 1MJ to 0.1J

It is possible to summarize the following conclusions for any plasma focus experimentally optimized for neutron emission, independent of the initial stored energy:

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 **$\langle n \rangle \sim 18n_0 \sim 5\times10^{24}$ 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 $\sim$ 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)

Stability parameters

It is depends on I, a, N

Haines and Coppins, Phys. Rev. Lett. 66, 1462 (1991)

Larmor radius over pinch radius, a_i/a α $N^{-1/2}$

Transient Alfvén time, $\iota_A = a/v_A$ α $aN^{1/2}I^{-1}$

Lundsquisdt number, S α $I^4 a N^{-2}$

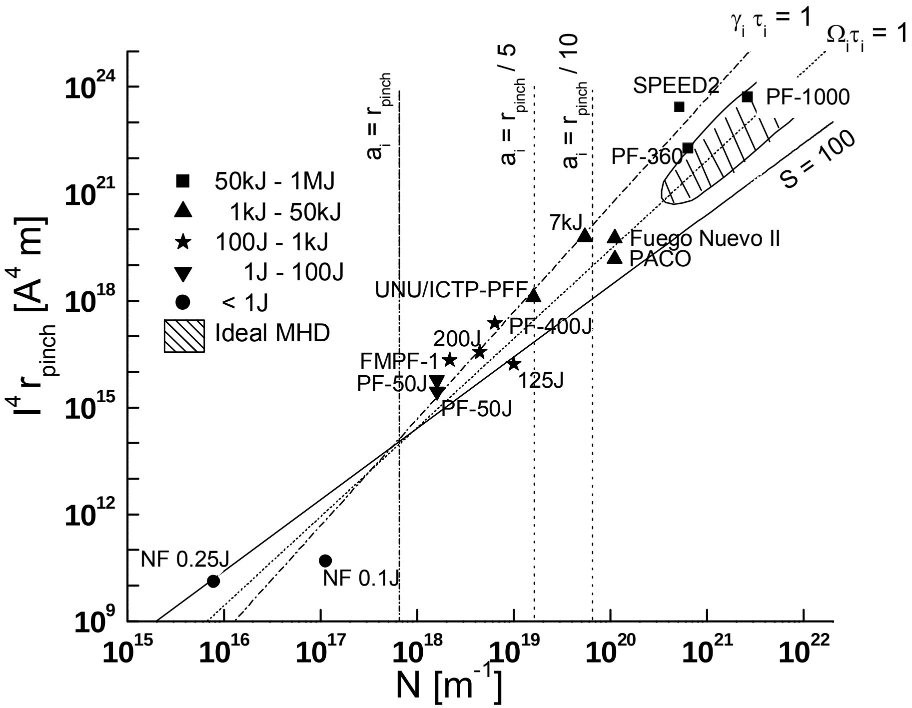
Ion cyclotron frecuency Ω_i by collision time for the ions ι_i . $\Omega_i \iota_i$ α I^4 a $N^{-5/2}$

What have we learned?

Studies on scaling laws for plasma focus
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.



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

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)

A PF for field applications

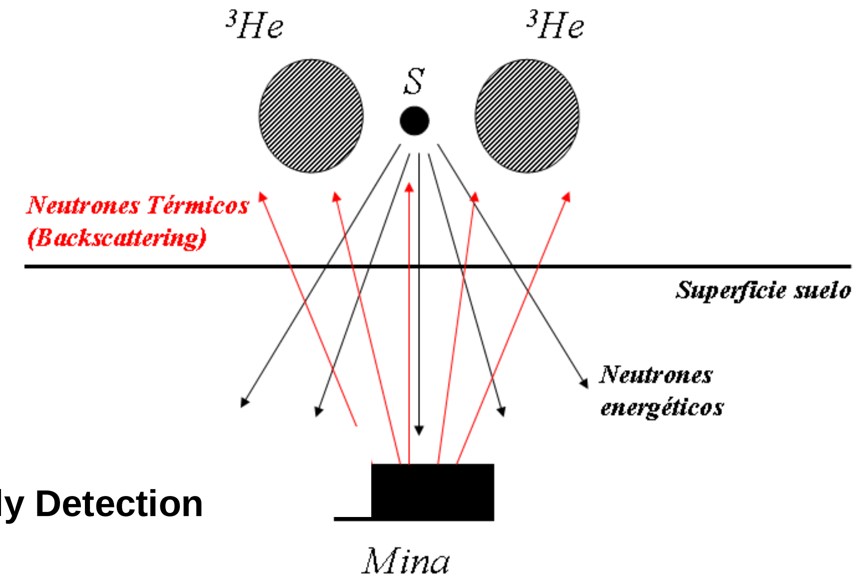
Motivation

Development of a confirmation method using the neutron backscattering technique for detection of landmines in arid soils

TC IAEA Project

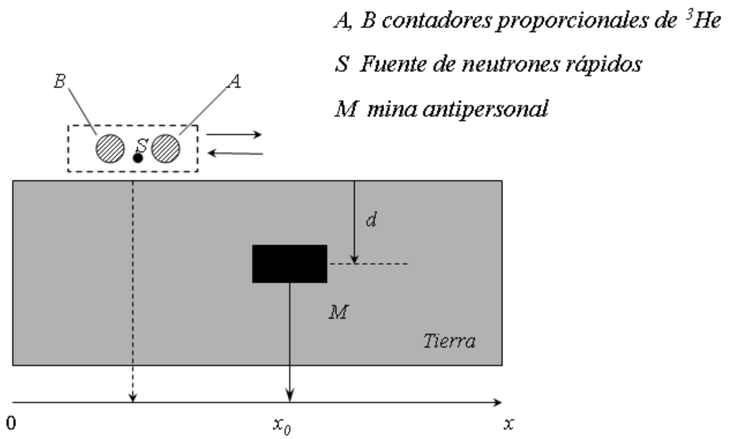
Motivation

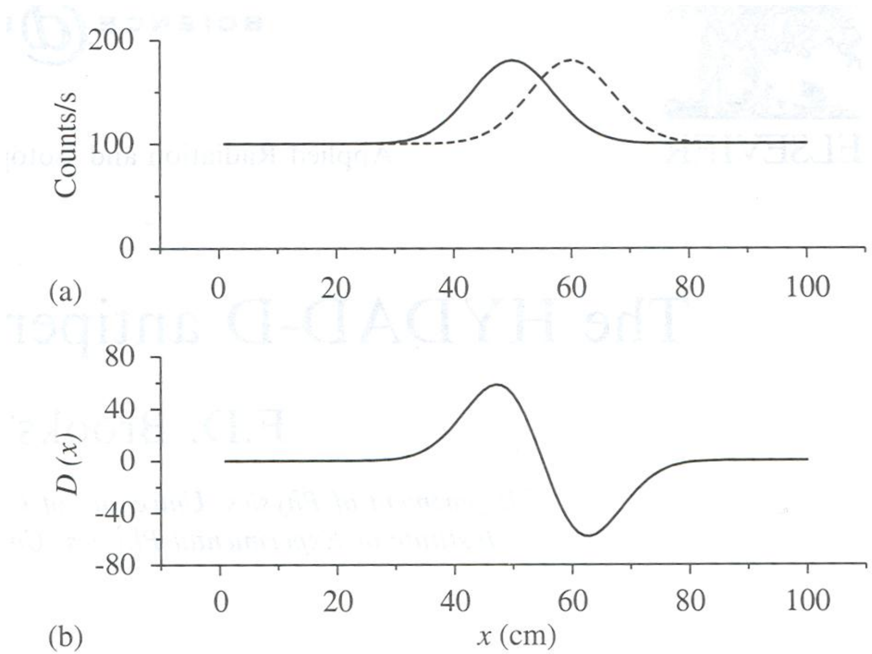
Development of a confirmation method using the neutron backscattering technique for detection of landmines in arid soils
TC IAEA Project



HYDAD-D
HYdrogen Densisty Anomaly Detection

F. D. Brooks and M. Drosg, Applied Radiation Physics 63, 565 (2005)





HYDAD-D
HYdrogen Densisty Anomaly Detection

F. D. Brooks and M. Drosg, Applied Radiation Physics 63, 565 (2005)

Sources of Am-Be, ^{252}Cf: 5x10^4 neutrons/s scan 0.5m in 5 min

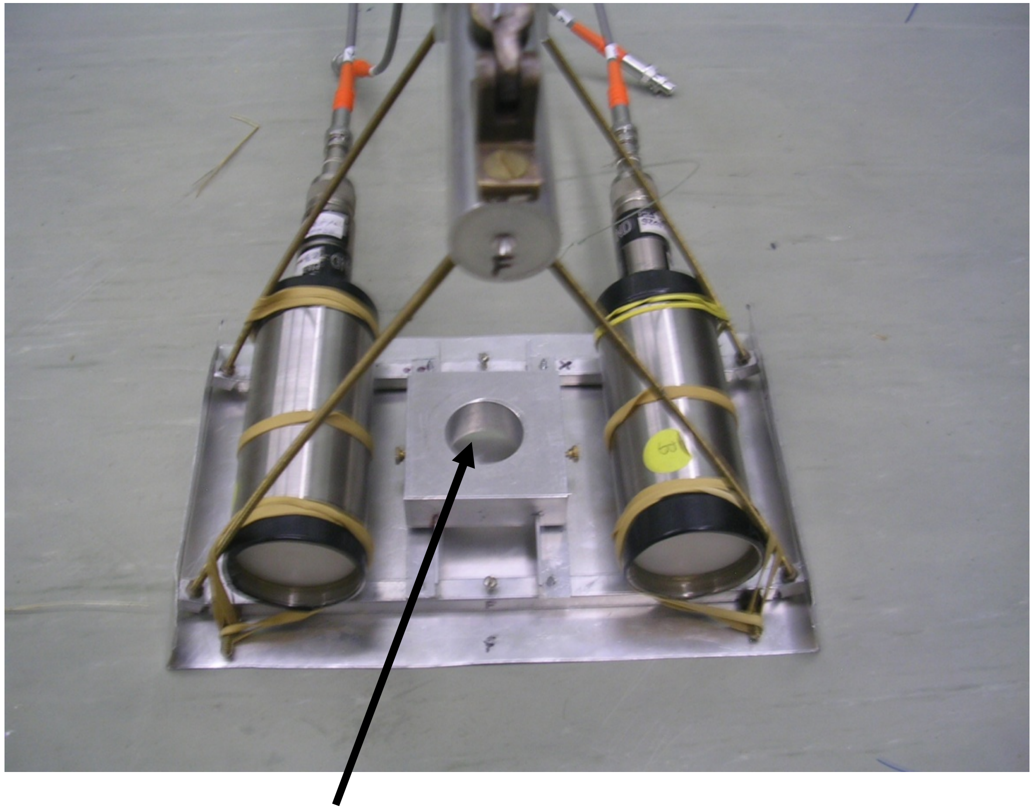
HYDAD-D at a simulated field with hydrogenated objects under controlled conditions [6]

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.

HYDAD-D at a simulated field with hydrogenated objects under controlled conditions [6]

HYDAD-D in Chile

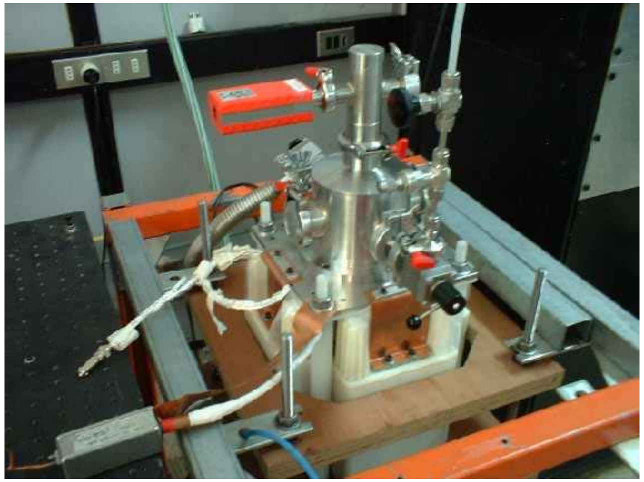


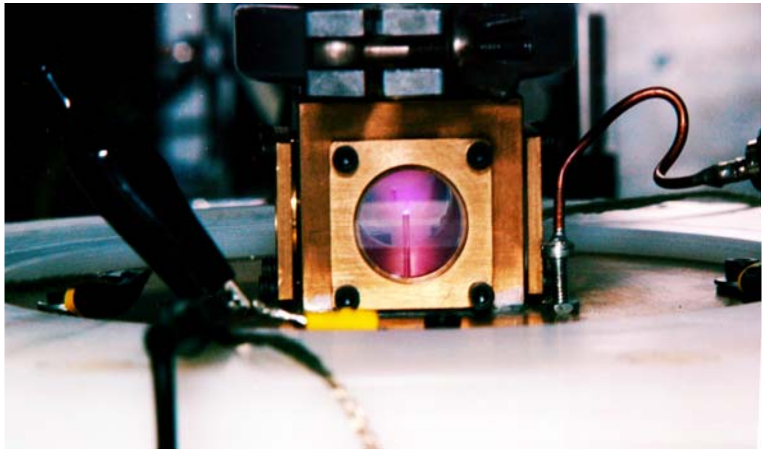
Challenge: To change the radioactive source by a portable PF

A PF for field applications
PF-2J

PF-50J

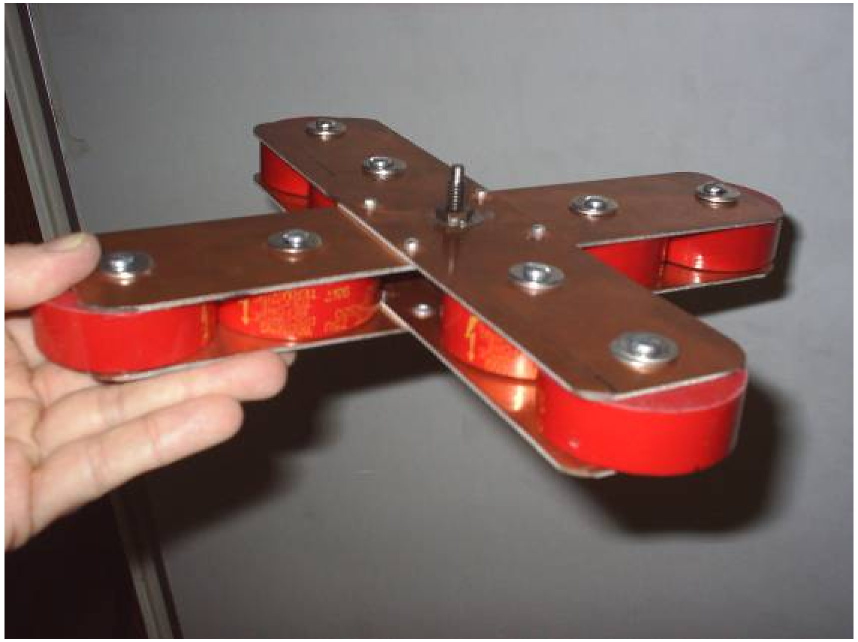
Nanofocus, 0.1J

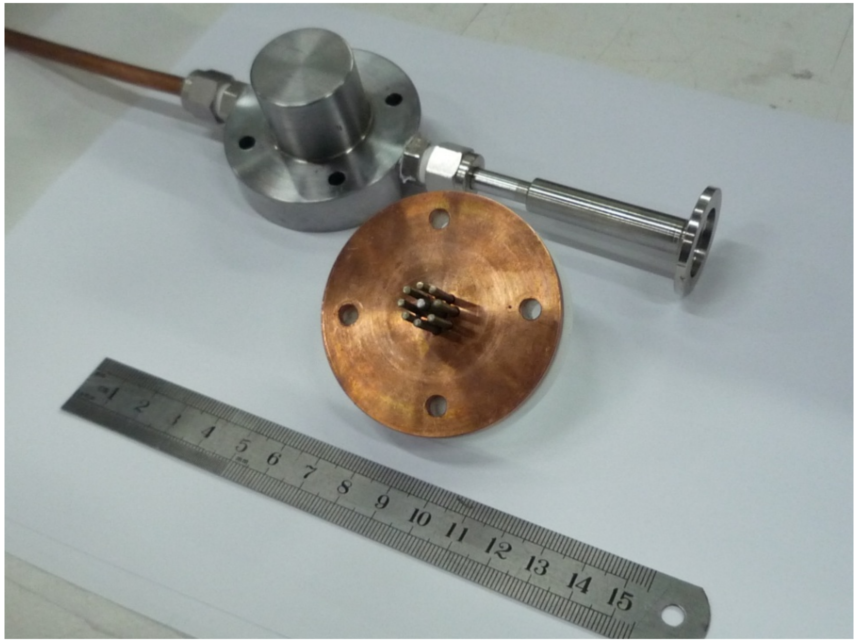




A PF for field applications
PF-2J

C = 180 nF, L = 40 nH, V_0 = 5-8 kV, E = 2 - 5 J, I_0 = 10 – 17 kA





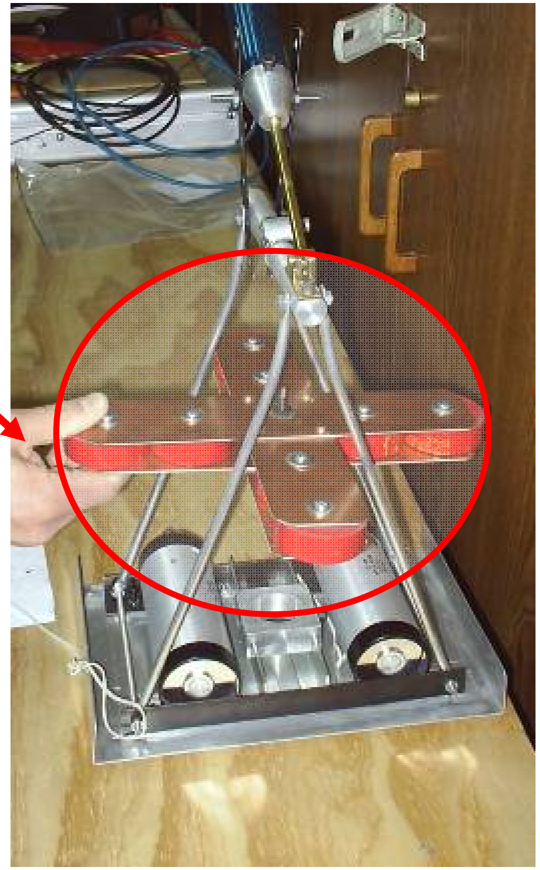
Expected neutron emission 10^3-10^4 n/shot

10^4-10^5 n/s at 10 Hz 10^5-10^6 n/s at 100 Hz

Non- radiactive source

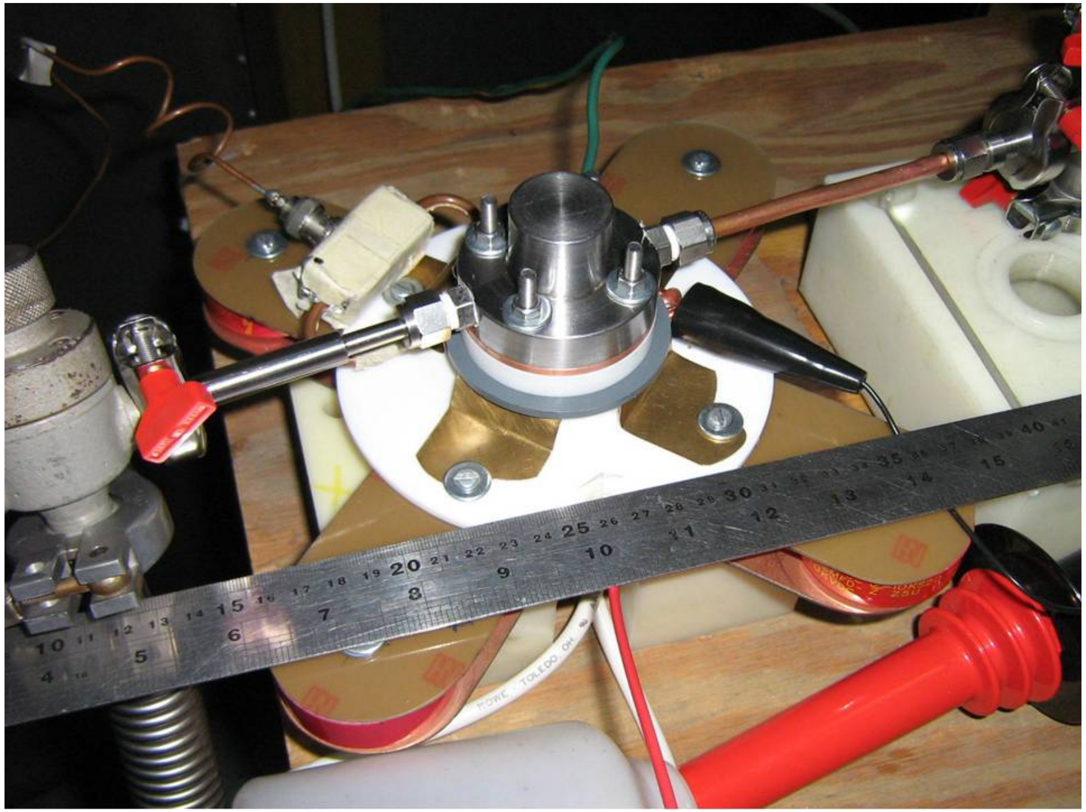
PF-2J

Radiactive source

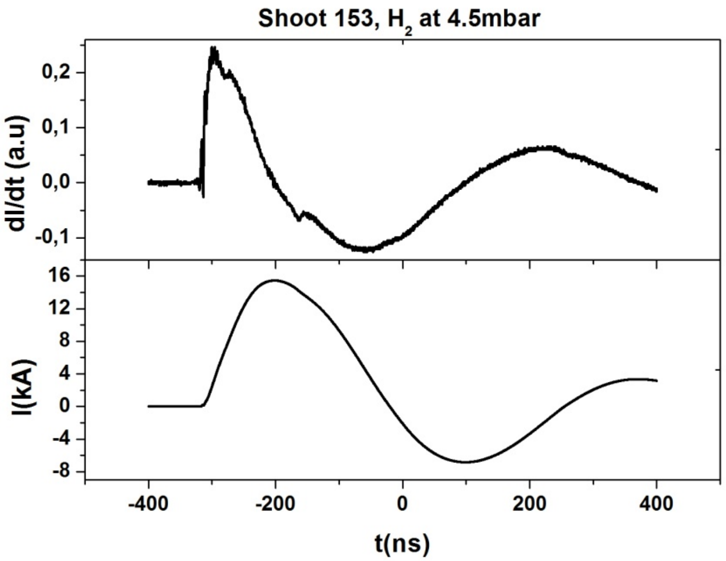


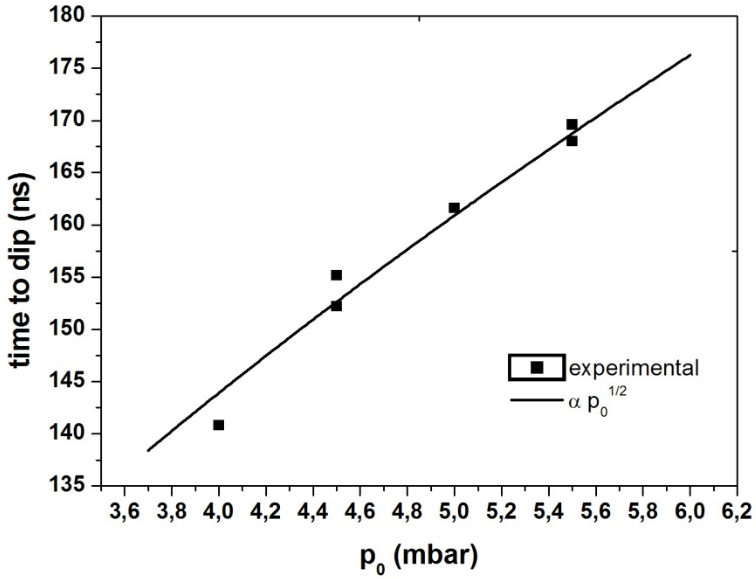
A PF for field applications
PF-2J

C = 180 nF, L = 40 nH, V_0 = 5-8 kV, E = 2 - 5 J, I_0 = 10 – 17 kA



Pinch Evidence
PF-2J





Electrical signals of the current derivative dI/dt and current I. The typical dip in the dI/dt and the drop in I, that correspond to the pinch effect is observed.

Time to dip vs filling pressure for discharges in hydrogen. The time to dip dependence on presuure, $\alpha\ \sqrt{p_0}$, shows that the device is working as plasma focus.

- A PF device for field applications was designed and constructed, PF-2J

  $C = 180$ nF, $L = 40$ nH, $V_0 = 5\text{-}8$ kV, $E = 2\text{-}5$J, $I_0 = 10 – 17$ kA
  Capacitor bank and discharge chamber: <2000cm^2 volume, 5 Kg weigth

- Evidence of pinch was obtained

- Next step: Discharges in D_2

Thank you

References

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[3] L. Soto, C. Pavez and J. Moreno, M. Barbaglia and A. Clausse , Plasma Sources Sci. and Technol. 18, 015007 (2009).

[4] C. Pavez and L.Soto, IEEE Trans. Plasma Sci. **38**, 1132 (2010).

[5] L. Soto, C. Pavez, A. Tarifeño, J. Moreno and F. Veloso "Studies on Scalability and Scaling Laws in Plasma Focus. Similarities and Differences in Devices from 1MJ to 0.1J", PSST, in press.

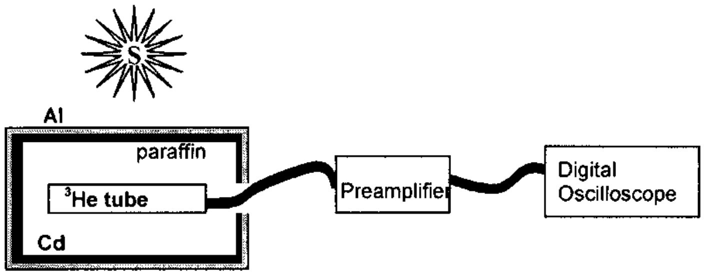
[6] C. Pavez, F. D. Brooks, F. D Smit, J. Moreno, L. Altamirano, L. Soto "Tests of the HYDAD Landmine Detector on Dry Soil in Northen Chile, VII Latin American Symposium on Nuclear Physics and Applications, Santiago, Chile, Dec. 2009.

APPENDIXES

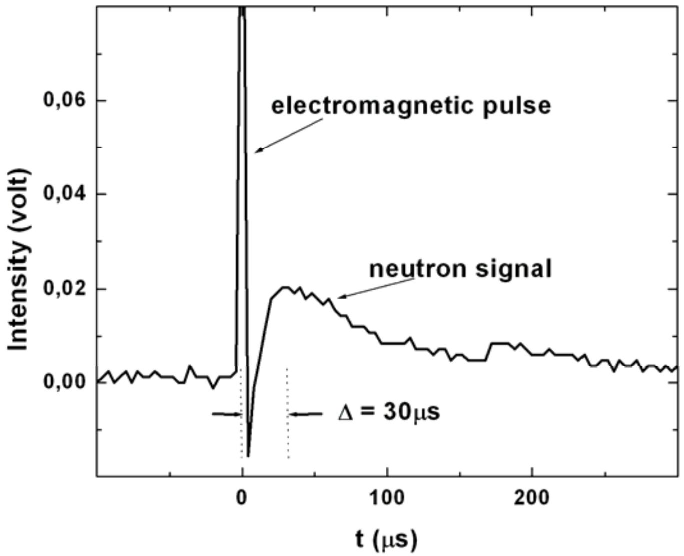
Neutrons detection in Nanofocus Method (a) Santiago-Chile

Neutron detection in Chile involved a detection technique to measure low neutron yields from D-D fusion pulses [2, 6] based on well-known ^{3}He proportional neutron detectors. The detection principle is based on the $^{3}He(n,p)^{3}H$ nuclear reaction [3]. The ^{3}He proportional tube is embedded in a hydrogenated material to moderate (or slow down) the neutrons and exploit the increased ^{3}He reaction cross-section at lower neutron energies. Meanwhile, a cadmium wrapping effectively provides shielding from environmental thermal neutrons. The analogue signal corresponding to the current generated in the ^{3}He tube is pre-amplified and received by a digital oscilloscope triggered by the plasma discharge electromagnetic pulse. This registers the integrated charge based on a burst of almost simultaneous neutrons interacting with the detectors, which is proportional to the neutron yield. This is called the charge-integration mode, as opposed to the usual “counter” or the “DC” modes of operation. As the electromagnetic pulse from the plasma discharge triggers the oscilloscope, the neutron detection is coincident with the discharge shot. The moderator provides an additional and useful characteristic insofar as neutrons that are generated in the PF pulse (~ 10-100 ns) are dispersed in a time window of some hundreds of μs, depending on moderator volume and geometry. Thus, neutron signals become separated from initial electromagnetic perturbations (~1 μs) and are also leaked into the ^{3}He tubes at a reduced rate. Essentially, no neutron background is detected during this observation time window.

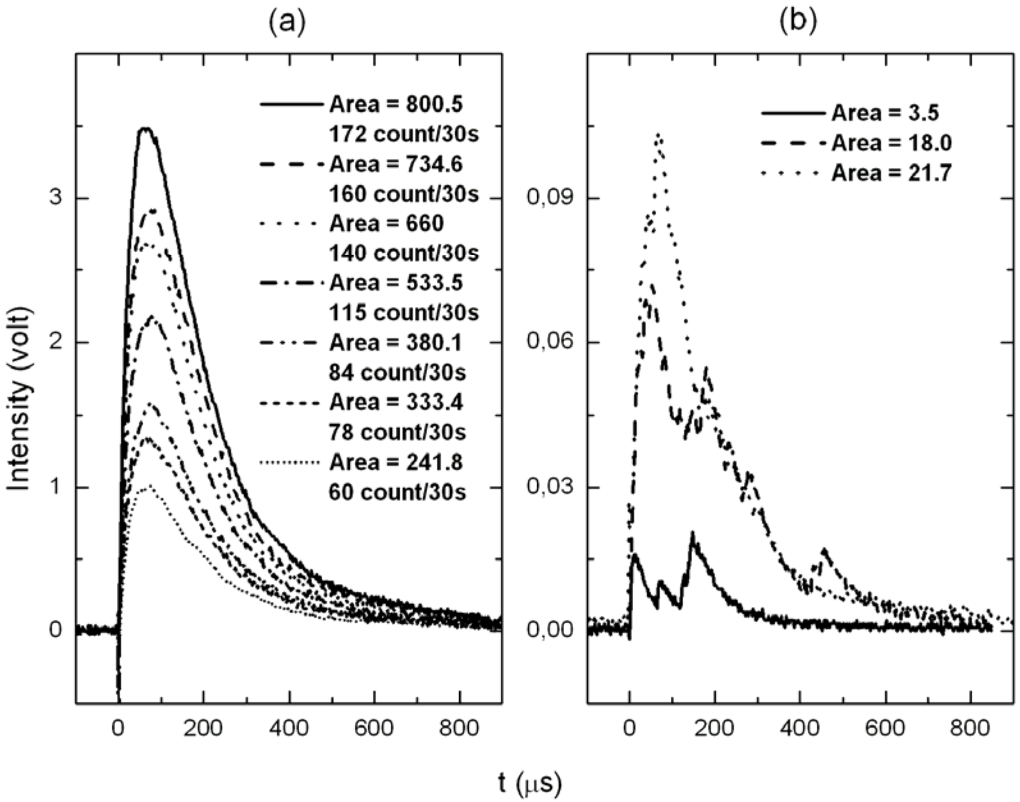
A reference silver activation counter was used to calibrate this neutron detection system (including the moderator). In this process, the adapted ^{3}He and silver activation counter were simultaneously placed in front of a higher-energy plasma focus device (PF-400J [6]) operating at hundreds of joules and producing 5×10^{5} to 2×10^{6} neutrons per shot, which resulted in a linearly proportional relationship. Note that this technique can detect neutron yields lower than 10^{3} neutrons per shot [2].
Discharges in deuterium at pressures of less than 1 to 20 mbar were performed. Two identical neutron detectors with a 45 cm $\times$ 15 cm sensitive area were located 23.5 and 14.5 cm from the plasma pinch for detectors I and II, respectively. Neutron signals were observed between 15 to 16 mbar. Figure 3a shows the electrical discharge signals for a shot at 16 mbar in Deuterium operating at 0.1 J (6.5 kV charging voltage). Evidence for a pinch is observed, as indicated by the dip in the derivative of the current. Figure 3b shows the signals simultaneously obtained in both detectors. The calibration scales were 780$\pm$270 neutrons/V μs and 300$\pm$120 neutrons/V μs for detectors I and II, respectively. This gives an estimated total neutron yield for the shot of 100$\pm$40 neutrons. No signals in the neutron detectors were observed for discharges in hydrogen.



The moderator (paraffin) offers three functions to the system detector: a) thermalize the fast neutrons of ~ 2.45 MeV, b) the neutrons generated in the plasma focus pulse (~ 10-100 ns) are dispersed in time (~ 300μs), reducing saturation effects in the detector, and c) as PF devices generate intense electromagnetic pulses associated with the main discharge (~1μs) that could contribute to a very significant distortion to the measurement signal, the moderator assures the separation (~30μs between the electromagnetic noise and the maximum of the neutron signal) of these two signals namely, the true neutron signal from the electromagnetic pulse.



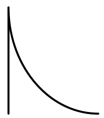
In addition as the neutron signal is preceded by the electromagnetic pulse of the plasma focus discharge, the neutron signal is coincident with the discharge and it is possible secure that the signal is from the plasma focus event. In discharges in hydrogen in which neutrons are not emitted only the electrical noise is register in the signal, background radiation is not detected in that small temporal windows of hundreds of microseconds.



Count rate vs. area under the curve of the signal and the count rate vs. the maximum intensity of the signal, show that a linear relation exists in both cases.

- We will use the linearity with the area under the curve because the objective is use the detector in the region of very low neutron emission, it becomes evident in that independent pulses may not contribute to the 'height' of the recorded signal, but contribute to the total area under the signal.

- In fact individual neutrons produce a voltage signal like



$V_i \exp(-t/RC)$, with RC the decay time of the preamplifier (50µs in this case)

- and its integrated area is $A_i = RC\, V_i$.

- From the nominal gain, α, of the preamplifier (Canberra model 2006),

  α = 47mV/Mpi, it is obtained that the charge per volt is $1/\alpha = 3.4\text{x}10^{-12}$ C/V.

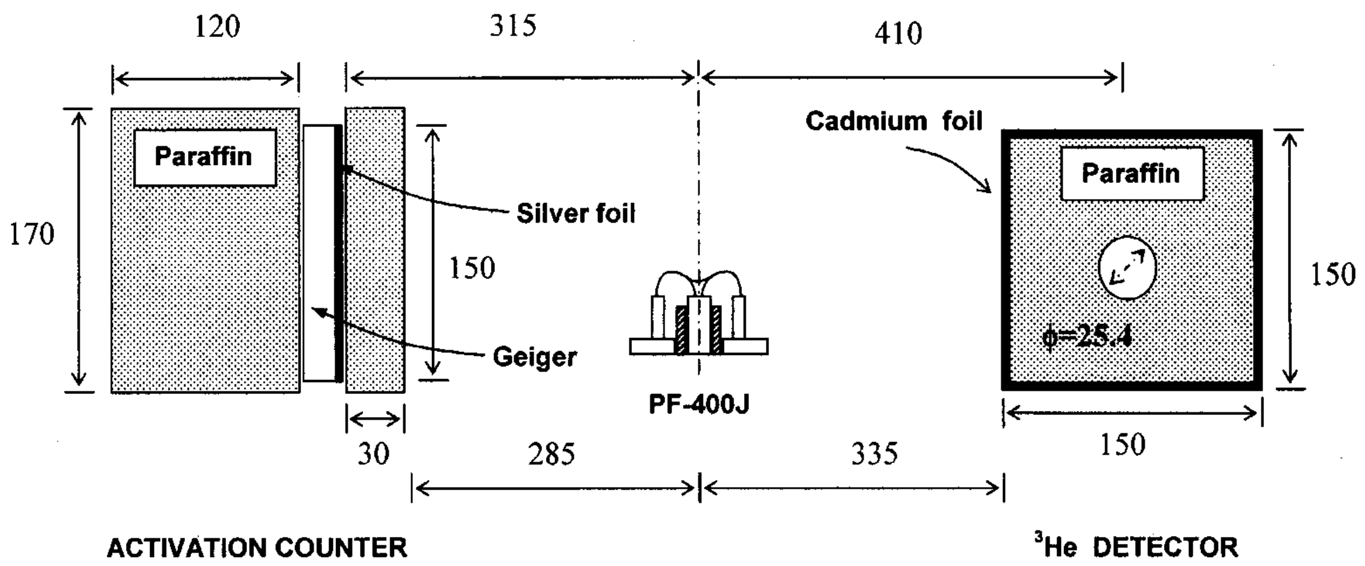
- Thus the charge produce for one neutron is $Q_i = V_i/\alpha = A_i/RC\alpha$.

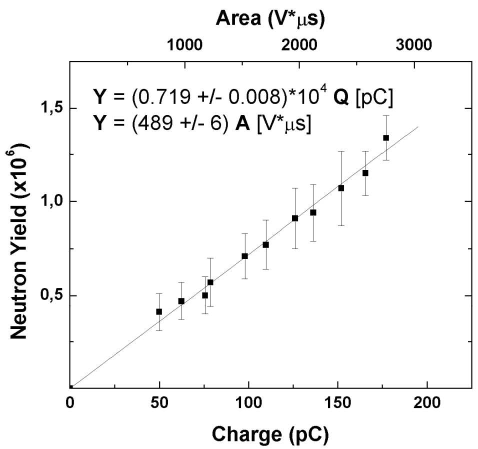
- The total charge produced, QT, is obtained summating all the individual events, and

  $Q_T = A_T/RC\alpha$, where A_T is the total area under the curve of the signal.

- Therefore the total number of neutrons is proportional to the total charge (or to the total area under the curve of the signal).

Calibration of the system





Neutrons detection in Nanofocus Method (b) Bariloche-Argentina

Neutron detection was confirmed in the experiment at Argentina. A neutron detector (A) composed of ten ^{3}He tubes connected in parallel with 4 atm filling gas pressure was embedded in a polythene moderator and wrapped in cadmium. This provided a 110 cm × 130 cm area sensitive to neutrons. In addition, another moderated detector (B) composed of six ^{3}He tubes with 10 atm filling gas pressure was also used. This detector had a 25 cm × 40 cm sensitive area. Wrapping both systems in cadmium provided background reduction due to slow ambient neutrons. Digitising oscilloscopes registered the detector signals corresponding to events with the correct pulse shape. In this case, the ^{3}He tubes are polarized in the proportional regime and employed in the “counter” mode of operation. The A and B detectors were located 22 cm and 16 cm from the plasma pinch, respectively. The oscilloscope triggered by the electromagnetic pulse discharged by the plasma registered data 360 μs after the trigger, which was considered an appropriate time window for the moderator with the largest dimensions due to its exponential decay time of 180 μs. An exponential moderator decay time refers to the time distribution according to which moderated neutrons leak out of a given system. In our case, the neutrons may reach the ^{3}He detectors and cause the ^{3}He(n,p)^{3}H reaction.

In order to determine the influence of the discharge on the detectors, 3000 discharges were performed using an electrode configuration in a gas atmosphere that cannot produce fusion reactions. The oscilloscope was triggered by the electromagnetic pulse of the discharges; it detected no signals related to neutron counts. Therefore, we conclude that both A and B ^{3}He detector arrays are adequately shielded and insensitive to induction of spurious counts due to the influence of NF operations. Thus, it was possible to measure the background using different methods over more extended periods in order to gather a useful amount of counts that lend themselves to numerical evaluation. In all cases, the corresponding Poisson uncertainty is the square root of those counts.

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