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Introduction to Plasma Focus Device and Applications
Dense Pulsed Plasmas Using Small Experimental Devices

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CHILE

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Population:
18.000.000

Physicists:

~ 400

Researchers in physics:

~ 300

Plasma Physicits:

~ 25

(7 at CCHEN)

A few words about myself

A few words about myself

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Public secondary School 1978-1981

Undergraduate in Physics, PUC, Chile, 1982-1988

PhD in Physics, PUC, Chile, 1988-1993

Chilean Nuclear Energy Commission 1993 - present

At present:

- Researcher at P^2mc, Chilean Nuclear Energy Commission.
- President of the Chilean Physical Society.
- Representative of Chile at the Latin American Center for Physics, CLAF, Chairman of the Board of Directors.
- Founder and coordinator of the Latin American Network of Nuclear Fusion of the Latin American Center for Physics, CLAF, May 2024 – present.
- Scientific Advisory of the Commission of Challenges of the Future in Science, Technology and Innovation of the Senate of the Republic of Chile.
- Weekly TV column in a broadcast television news, T13 Noche, Canal 13.

Plasma Physics and Nuclear Fusion at the Chilean Nuclear Energy Commission

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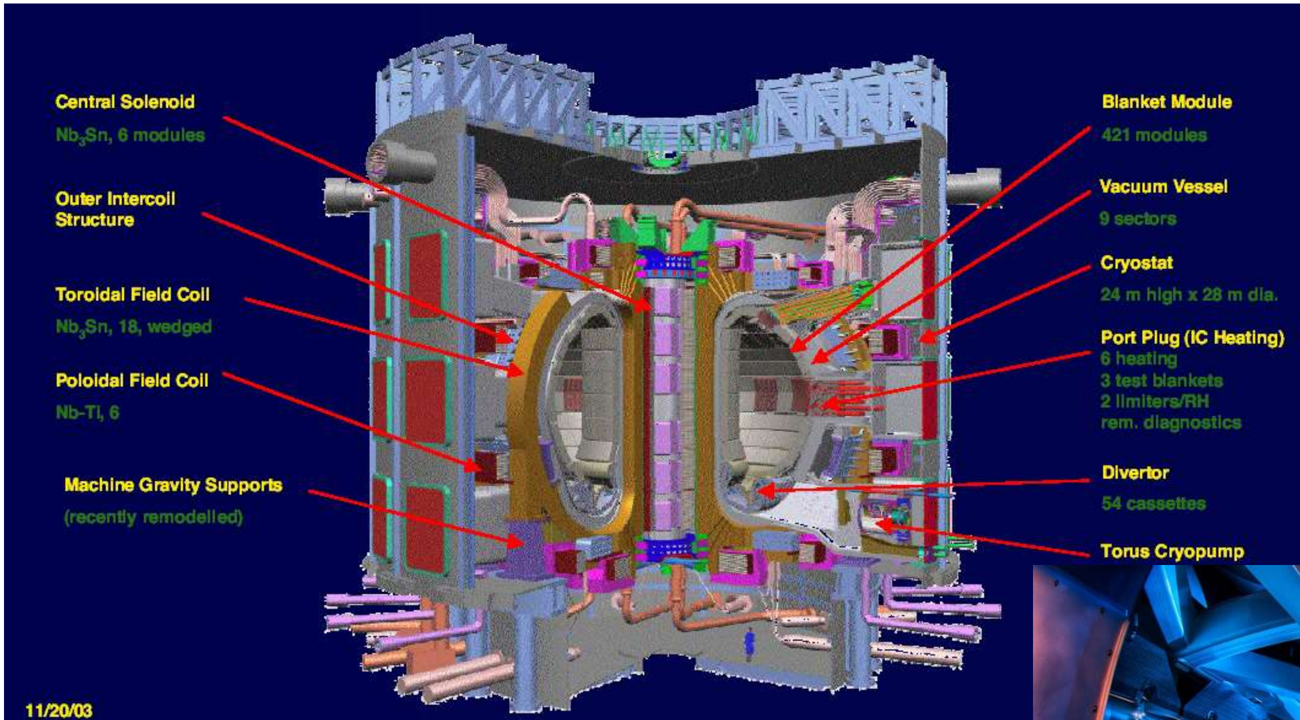
Our research program includes:

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

Team

Researchers:
Biswajit Bora
Sergio Davis
Jalaj Jain
Rodrigo López
José Moreno
Cristian Pavez
Leopoldo Soto
Technicians:
Marcelo Vásquez

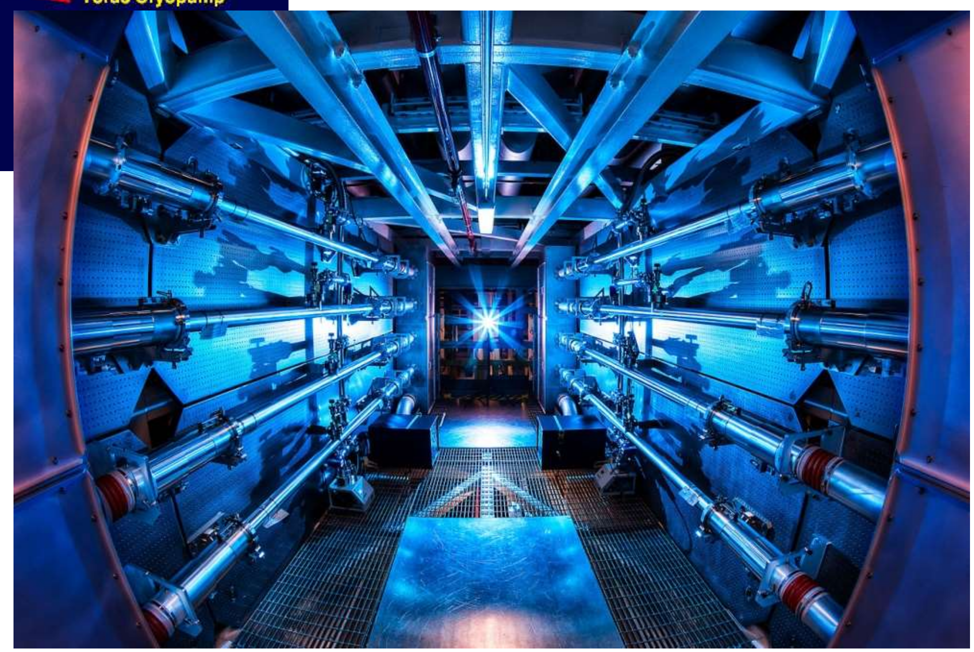


Magnetic Fusion Experiment ITER

More than 30,000 M€

Inertial Fusion Experiment NIF

More than 4,000 M USD



Motivation

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

Pinch plasmas

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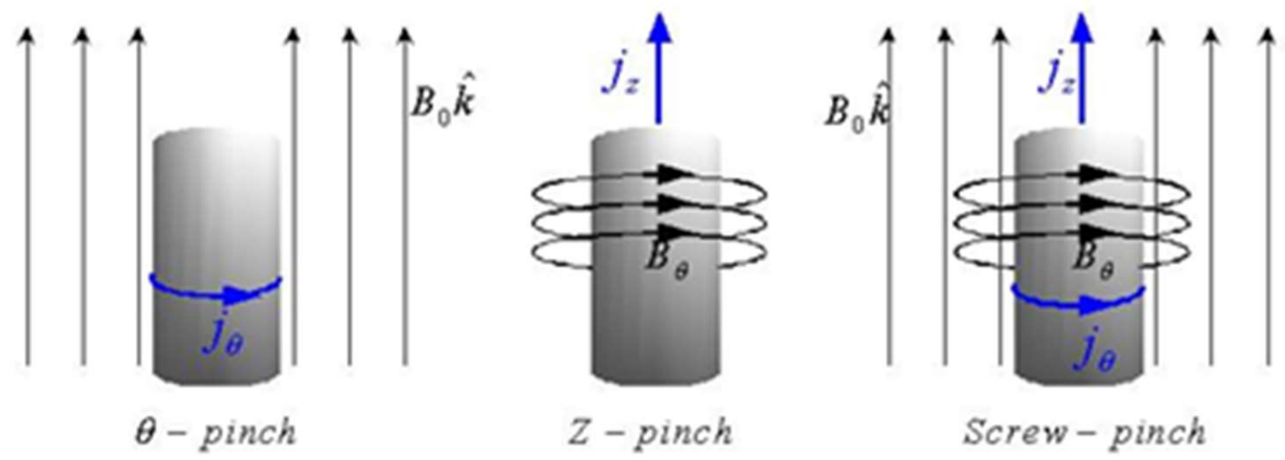


Thermal pressure vs Magnetic pressure

In quilibrium $\Longrightarrow$ $\nabla p = J \times \vec{B}$

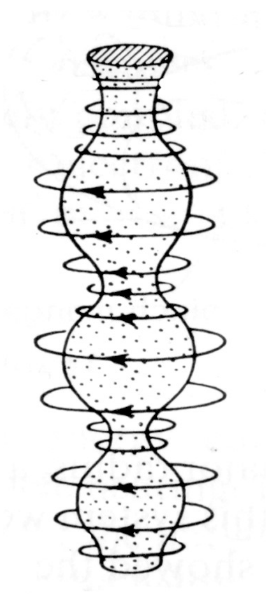
Z-pinch

$$\nabla p = J \times \vec{B} \Longrightarrow \mu_0 I^2 = 8\pi(1+Z)N_i k_B T$$

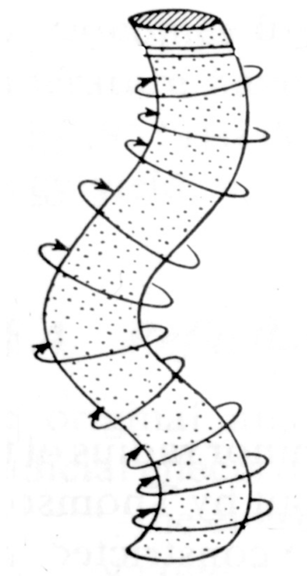
D_2 $\quad T = 1.56 \times 10^{11}\, I^2/N \quad (eV, A, m^{-1})$

Stability

MHD instabilities appears in nanoseconds



m = 0
Sausage instability
(a)



m = 1
Kink instability
(b)

How to obtain a dense-hot Z-pinch?

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$$\nabla p = J \times \vec{B} \quad \Longrightarrow \quad \mu_0 I^2 = 8\pi(1+Z)N_i k_B T$$

For D_2 $\quad T = 1.56 \times 10^{11}\, I^2/N \quad (eV,\, A,\, m^{-1})$

T=10keV and $N = 1 \times 10^{19}\ m^{-1}$

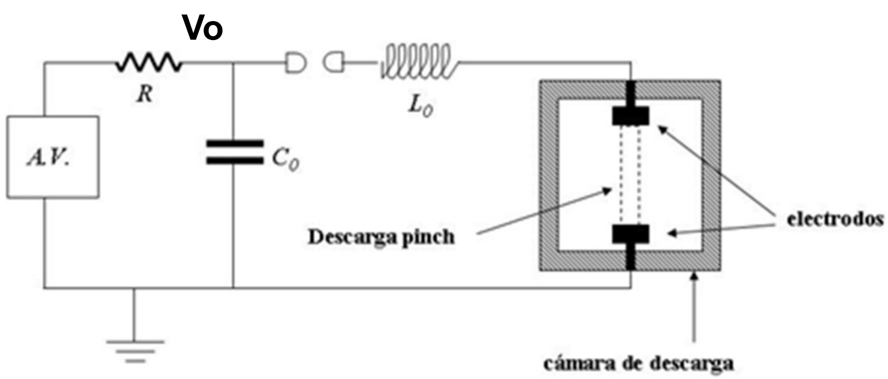
$\Longrightarrow$ I = 800kA

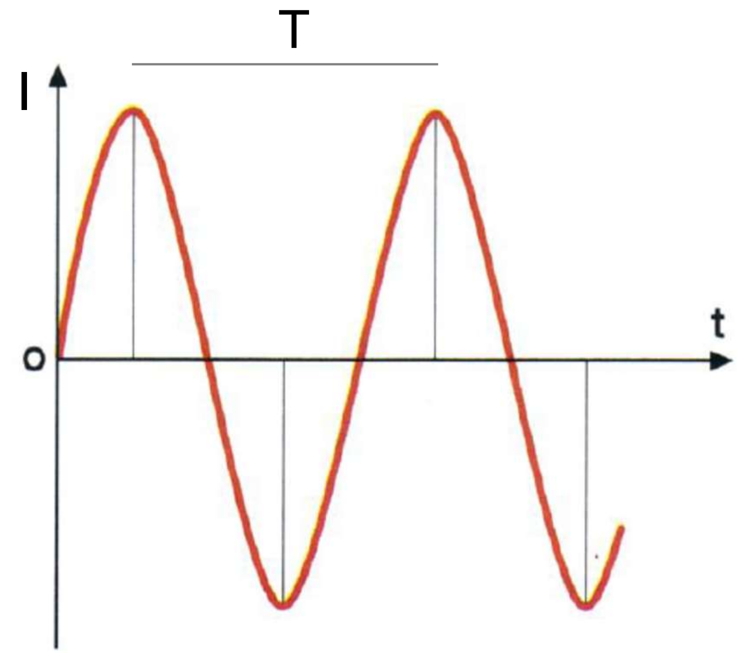
Currents of the order of ~ 1MA are required and must achieved in a short time < 100ns

Pulsed Power

Basic circuits for pulsed discharges

The simplest generator, a LC circuit





I_{max}=Vo/Zo dI/dt~Vo/L

Zo=$(L/C)^{1/2}$

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

dI/dt~ $I_{max}/(T/4)$

Is it posible obtain MA in 100ns using this kind of generator?

I_{max} ~ 1MA requires Vo ~ 300kV

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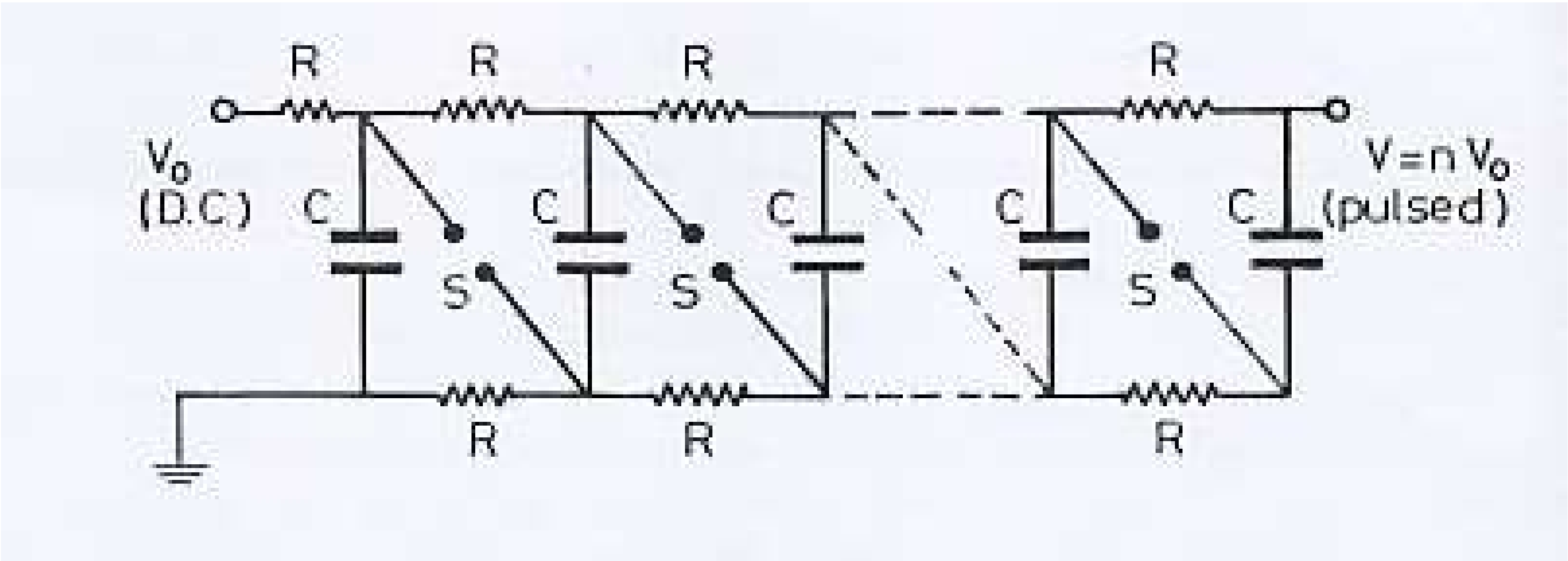
Marx generator

Capacitor bank charged in parallel and discharges in series

$V_{out}=nV_o$, n=number of capacitors



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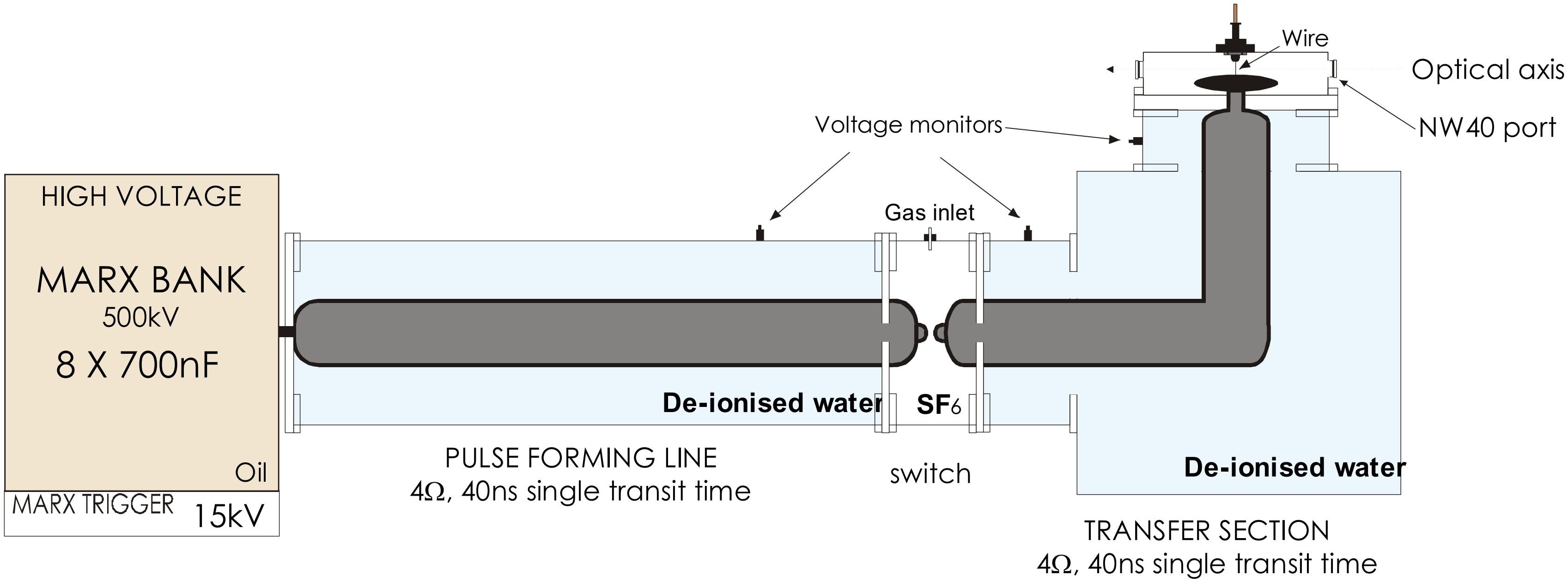
Pulse power generator



. Schematic of IMP generator

Marx generator

Capacitor bank charged in parallel and discharges in series

$V_{out}=nV_o$, n=number of capacitors

Pulse forming line, PFL

Pulse duration is 2 transist time

Examples of Electrical Pulsed Power

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E-M pulsed gun

Examples of Electrical Pulsed Power

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E-M pulsed compresor

Z-pinch experiments in Sandia National Laboratories, USA

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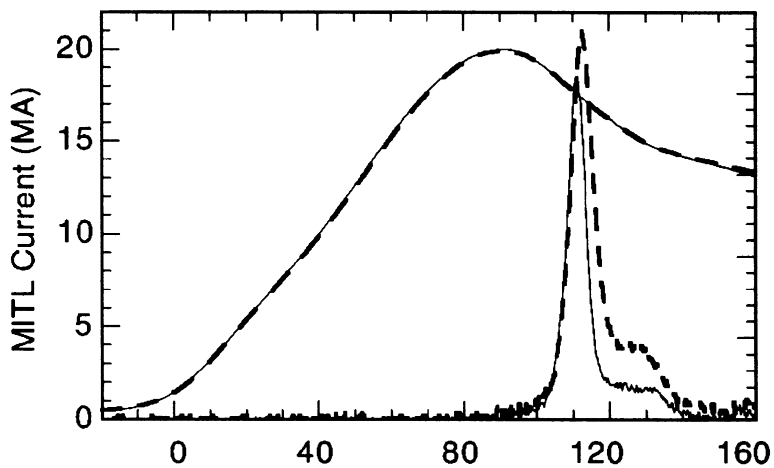
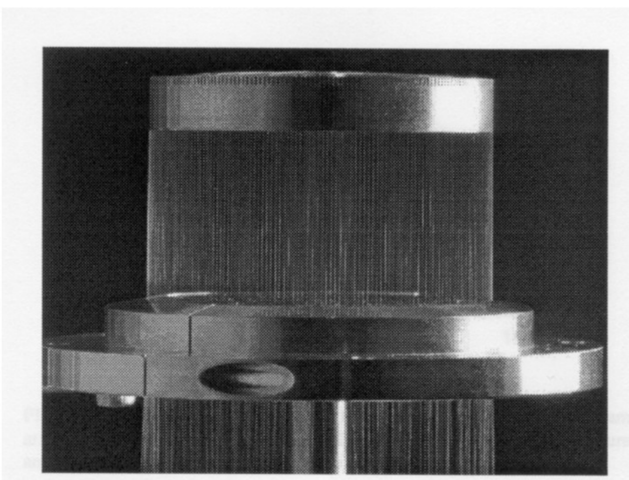
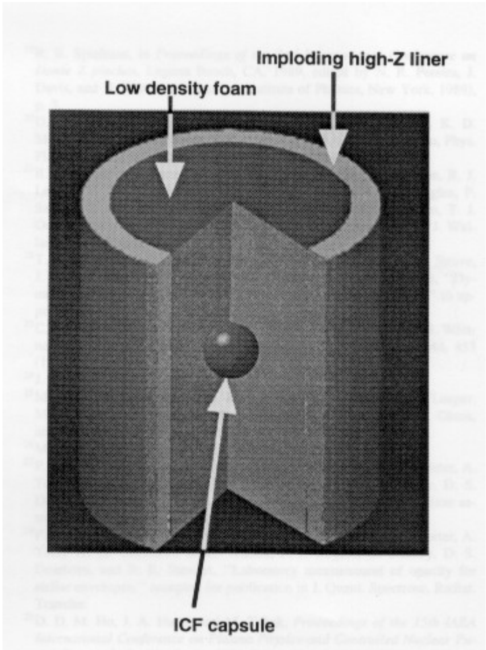


(10-20 MJ)





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

OUR APPROACH

PLASMA ENERGY DENSITY

$\sim 10^{12}$ J/m^3

1J in a sub millimeter volume

0.1J in a sphere of 60μm of diameter

PLASMA PHYSICS IN SMALL DEVICES

The plasma focus discharge: a kind of Z-pinch

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

(I) The discharge starts over the insulator.

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

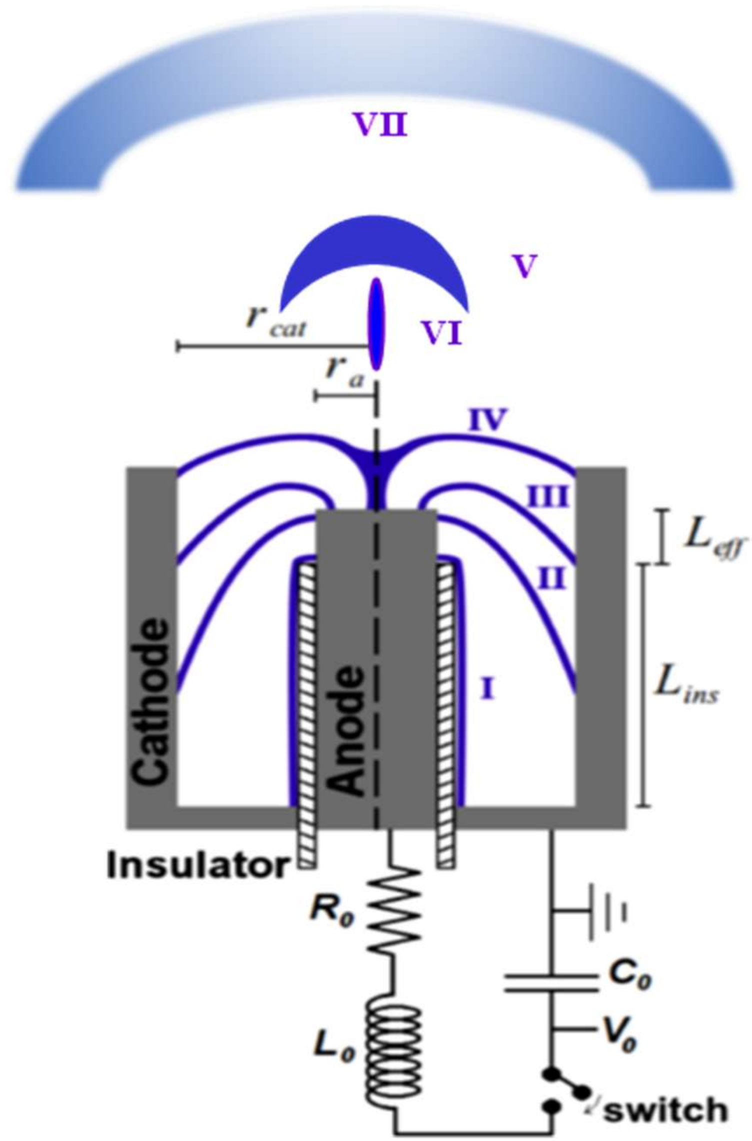
(III) and then to move radially (sometimes plasma filaments appears).

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

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

(VI) plasma jets are ejected

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



The plasma focus discharge

E ~ kJ - MJ

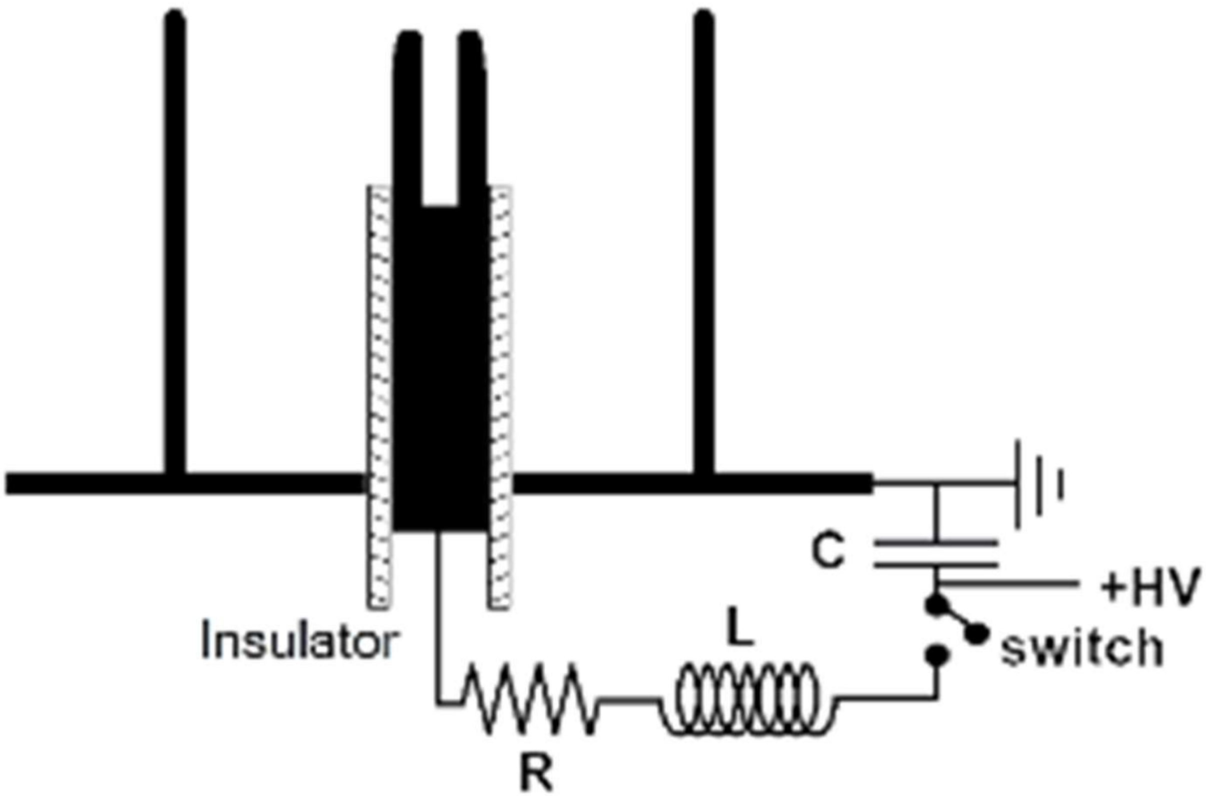
I ~ 100kA - 1MA

t_p ~ 10ns - 100ns

$Y_n \alpha E^2$

$Y_n \alpha I^{3.3-4.7}$

n ~ 10^{25} m^{-3}



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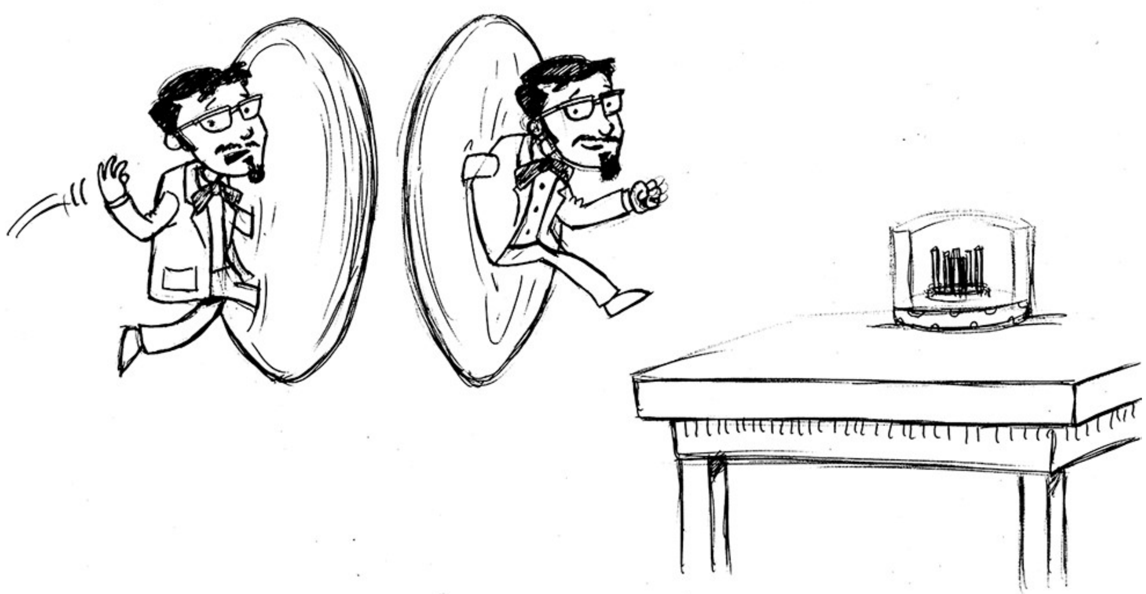
Our goal:

Miniature Plasma Focus Devices
< 1kJ
To find scaling laws



How to obtain information from a dense transient plasma

Diagnostics

- **Electrical signals**
- **Visible plasma images**
- **X-ray detections (temporal and spatial resolution)**
- **Neutron detection (in particular low yield pulses)**
- **Charged particles**
- **Optical refractive diagnostics**
- **Spectroscopy (visible, X-rays, UHF)**

Electrical signals

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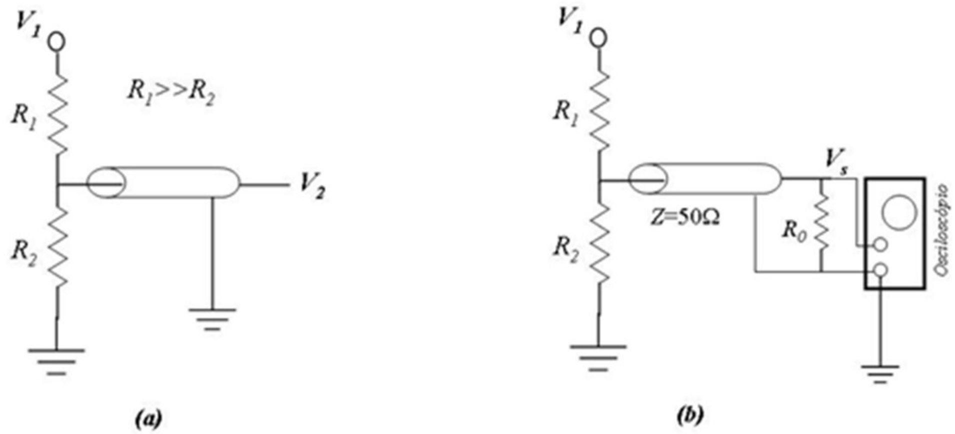
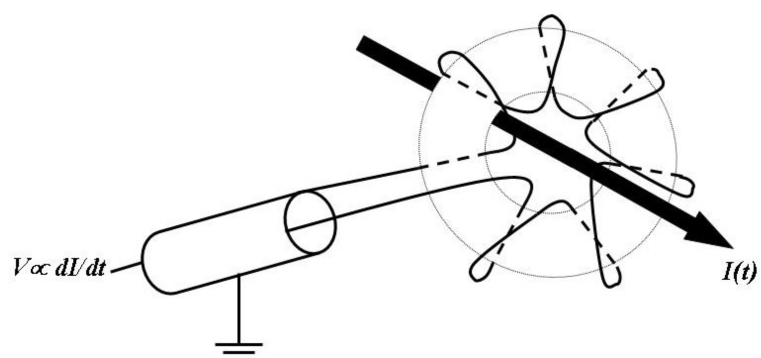
$$V_2 = \frac{R_2}{R_1 + R_2} V_1$$



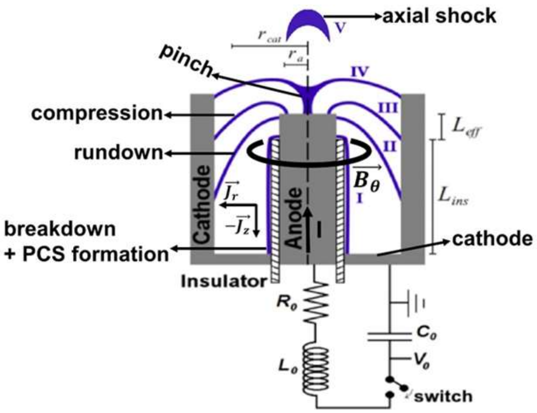
Voltage monitor: resistive divider

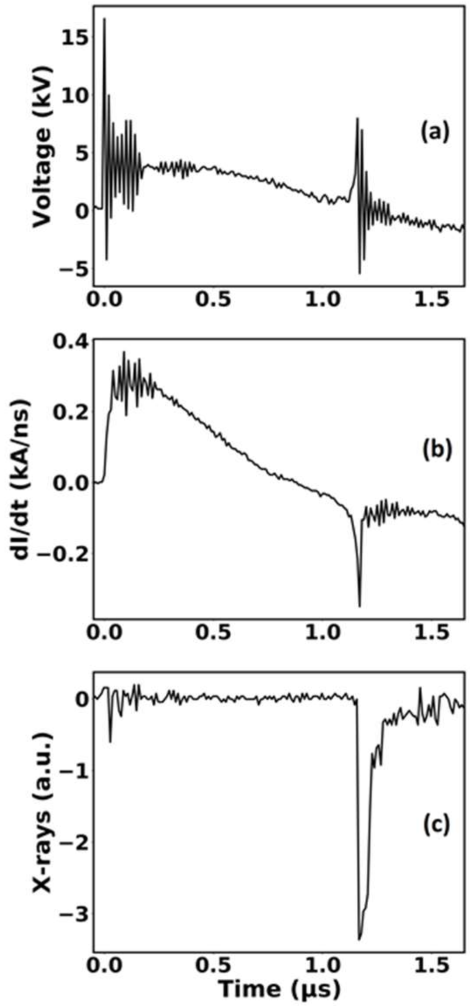
$$V \alpha \ dI/dt$$



Current monitor: Rogowski coil

Electrical signals





$$V(t) = \frac{d}{dt}[(L_p(t) + L_0)I(t)] \tag{1}$$

That gives

$$L_p(t) = \frac{\int_{to}^{t} V(t)dt + (L_0 + L_p(t_0))I(t_0)}{I(t)} - L_0$$

or

$$L_p(t) + L_0 = \frac{\int_{to}^{t} V(t)dt+(L_0+L_p(t_0))I(t_0)}{I(t)} \tag{2}$$

$$L_P(t) = L_P(t_c) + L'_P(t) \tag{4}$$

for $t > t_c$:

$$V(t) = [L_0 + L_P(t_c)]\frac{dI}{dt} + \frac{d}{dt}(IL'_P) \tag{5}$$

$$V_P = V(t) - \left(L_0 + L_P(t_c)\right)\frac{dI}{dt} \tag{6}$$

with

$$V_P = \frac{d(IL'_P)}{dt} \tag{7}$$

Electrical signals

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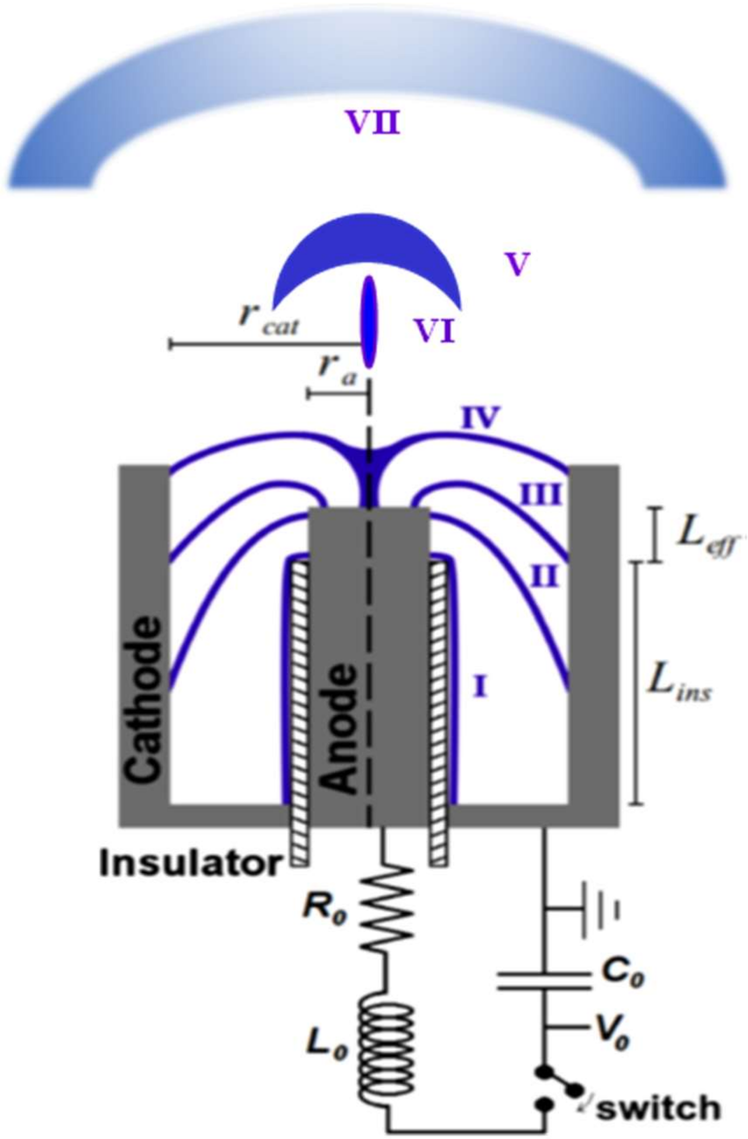
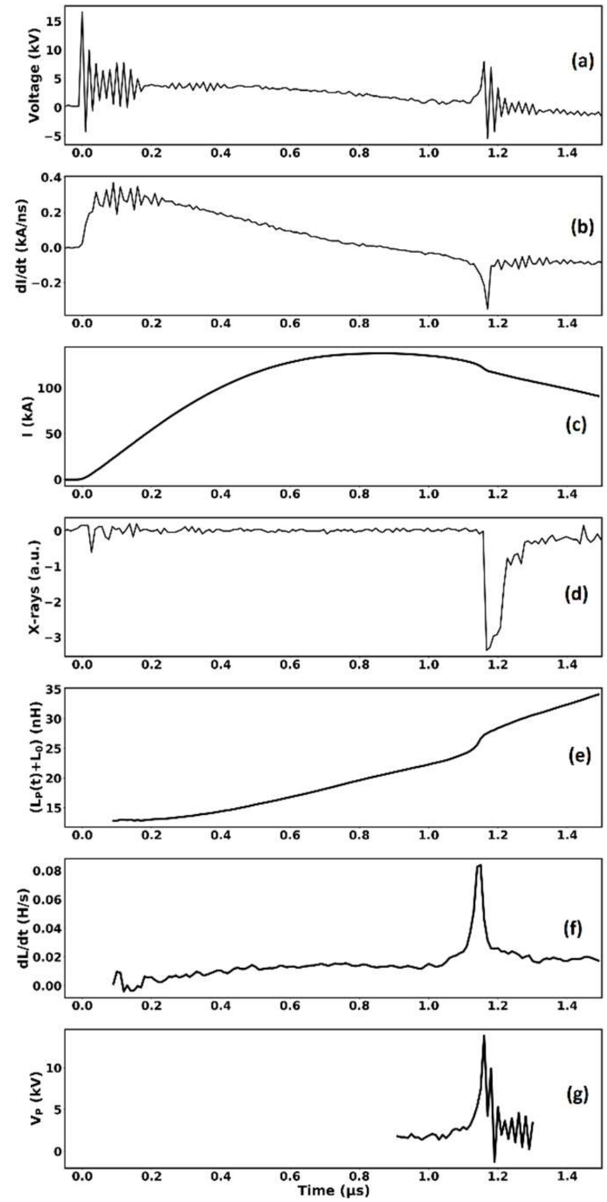


$$L_p(t) = (\mu_0 / 2\pi)\, z(t)\, \ln(\, b/r(t)\,)$$



Visible plasma images

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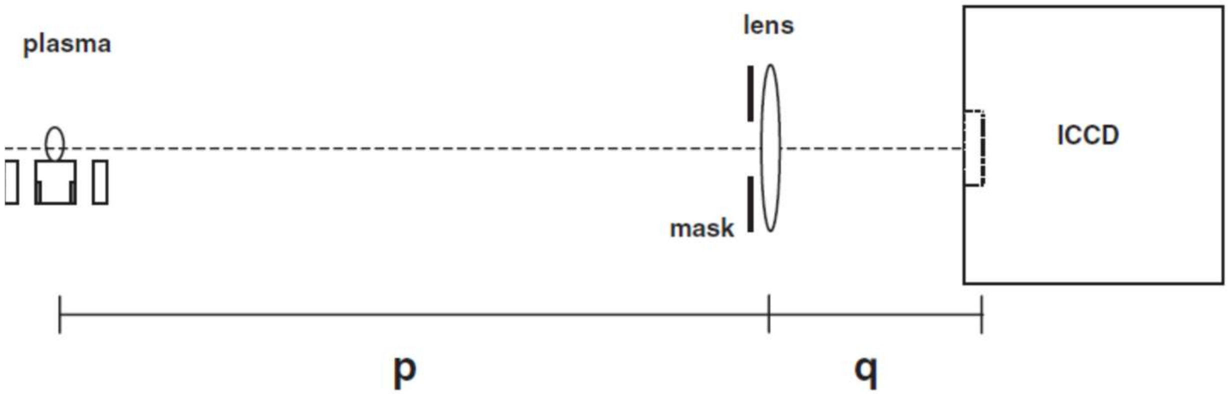
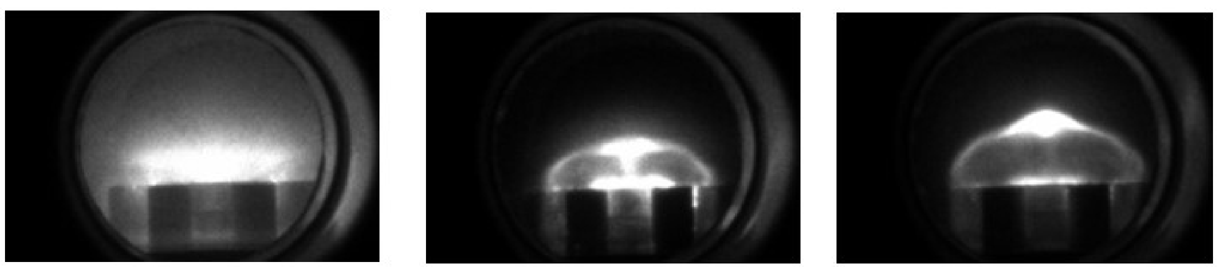
Images from plasma light are captured with a ICCD camera, 4ns exposure time



- Plasma Dynamics



before the pinch | pinch | after the pinch

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

PF dynamics

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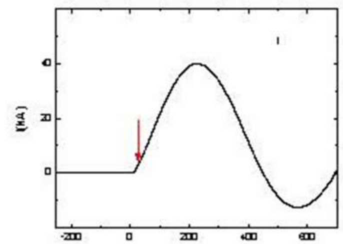

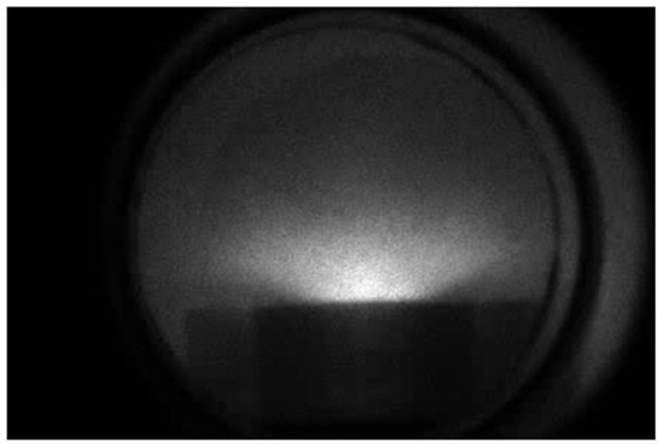

J. Moreno, P. Silva, and L. Soto, Plasma Sources Science and Technology 12, 39 (2003).

Under kJ PF devices at CCHEN

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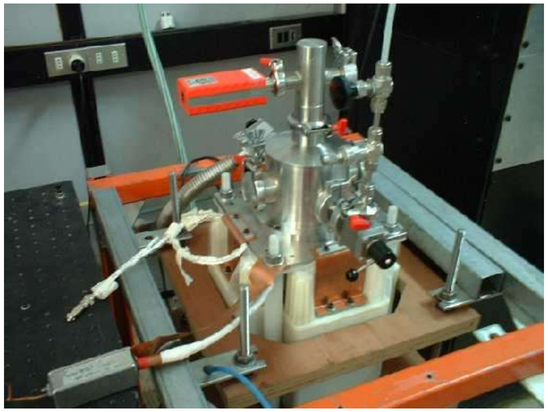

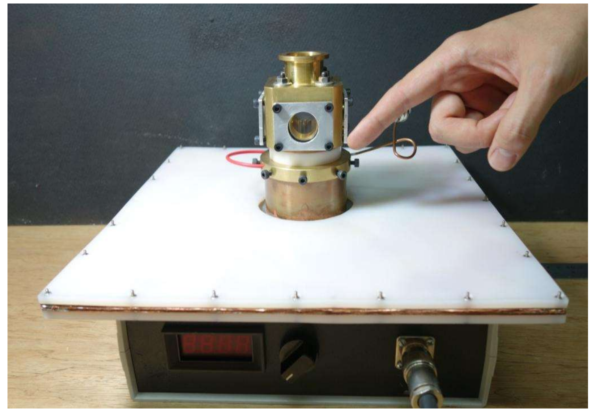

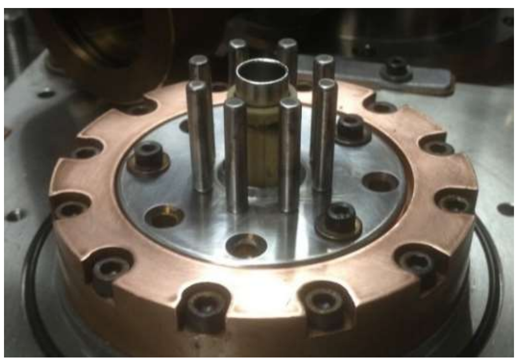

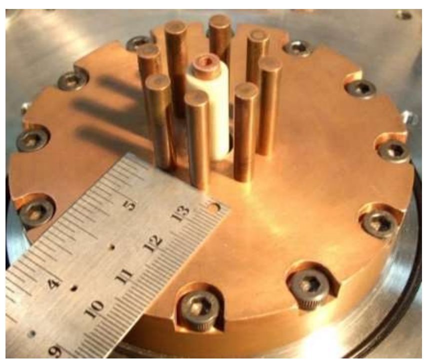

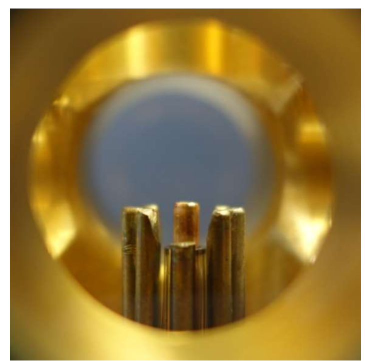

PF-400J **PF-50J** **PF-2J** **NF**

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APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 16 20 OCTOBER 2003

Neutron emission from a fast plasma focus of 400 Joules

Patricio Silva, José Moreno, Leopoldo Soto,[a] Lipo Birstein, Roberto E. Mayer,[b] and Walter Kies[c]
Comisión Chilena de Energía Nuclear, Casilla 188 D, Santiago, Chile

(Received 29 April 2003; accepted 2 September 2003)

IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. 41 (2008) 205215 (7pp) doi:10.1088/0022-3727/41/20/205215

Demonstration of neutron production in a table-top pinch plasma focus device operating at only tens of joules

Leopoldo Soto[1,2,7] Patricio Silva[1], José Moreno[1,2], Marcelo Zambra[1], Walter Kies[2], Roberto E Mayer[3], Alejandro Clausse[4], Luis Altamirano[2,5], Cristian Pavez[1,2] and Luis Huerta[2,6]

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[2] Center for Research and Applications in Plasma Physics and Pulsed Power, P[4], Chile
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[4] CNEA-CONICET and Universidad Nacional del Centro, 7000 Tandil, Argentina
[5] Dicontek, Pasaje Galicia 1365, La Florida, Santiago, Chile
[6] Universidad de Talca, Facultad de Ingeniería, Campus Curicó, Kilómetro 1 Camino a Los Niches, Curicó, Chile

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PHYSICS OF PLASMAS **24**, 082703 (2017)

Evidence of nuclear fusion neutrons in an extremely small plasma focus device operating at 0.1 Joules

Leopoldo Soto,[1,2,3,a)] Cristián Pavéz,[1,2,3] José Moreno,[1,2,3] Luis Altamirano,[2,4] Luis Huerta,[2,5] Mario Barbaglia,[6] Alejandro Clausse,[6] and Roberto E. Mayer[7]
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Plasma Focus of 0.1 joule Nanofocus

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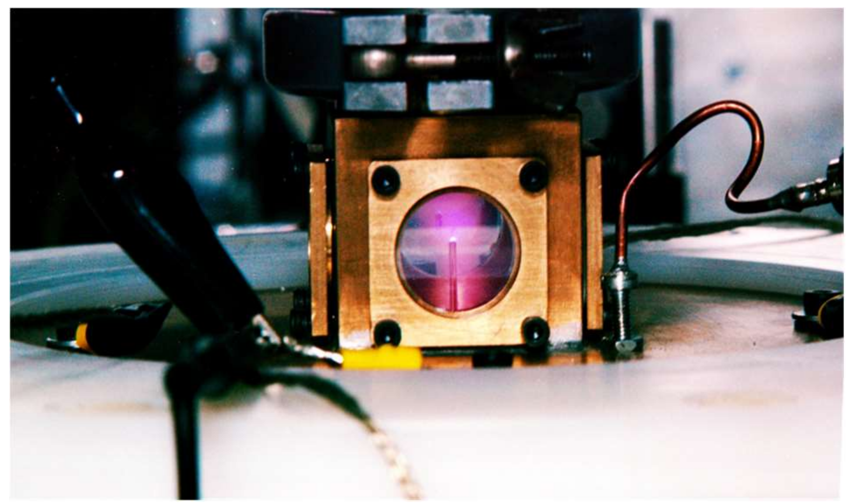
Conceptual design and electrical parameters expected:
C=5-10nF
L=5-10nH
Vo=5-15kV (E~ 0.06 - 1 J)
Ipeak= 3kA-15kA, T/4=8ns-16ns

Expected neutron yield at 10kA
Y ~ 10^3 neutron/shot



- L. Soto, C. Pavez, 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).
- M. Barbaglia, H. Bruzzone, H. Acuña, L. Soto and A. Clausse, IEEE TPS 42, 138 (2014)

Plasma Focus of 0.1 joule Nanofocus

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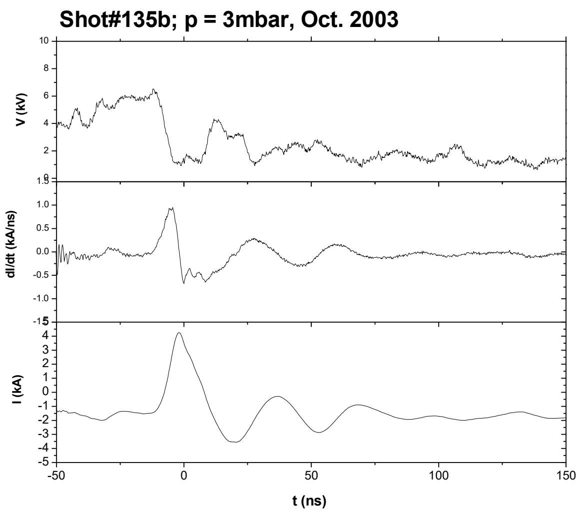
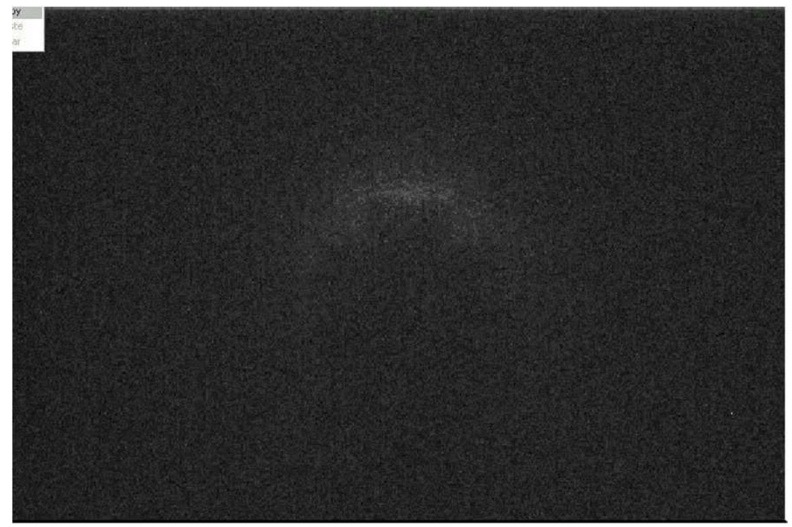


$E=1/2\ CV^2$

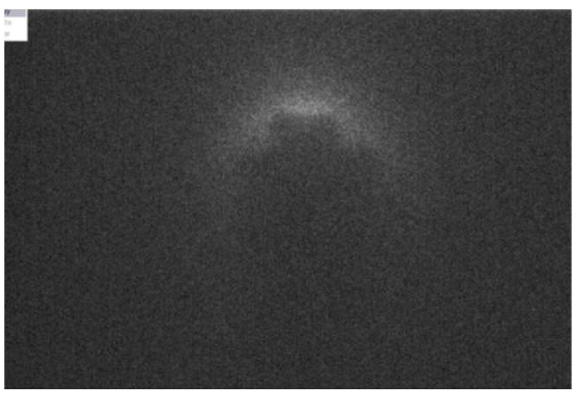
$C \sim 5 \pm 1nF$

$V=6.5 \pm 0.3kV$

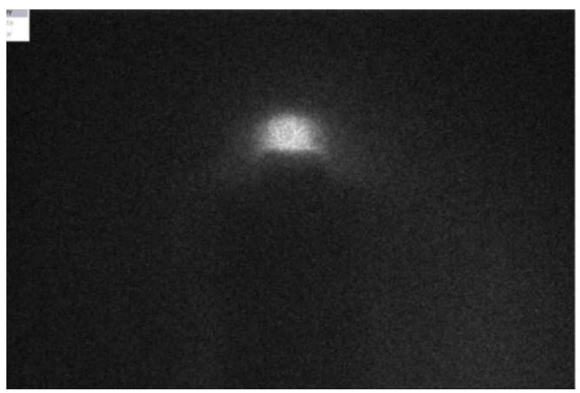
E ~ 100mJ!



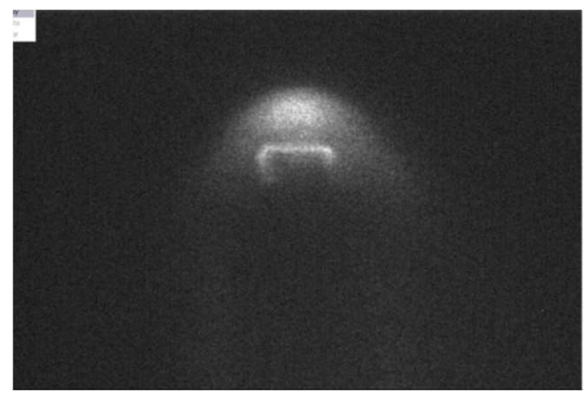
-26ns



5ns



30ns

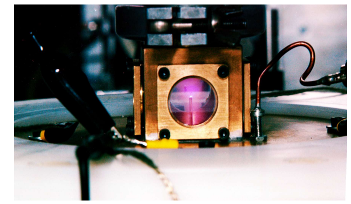


3mm

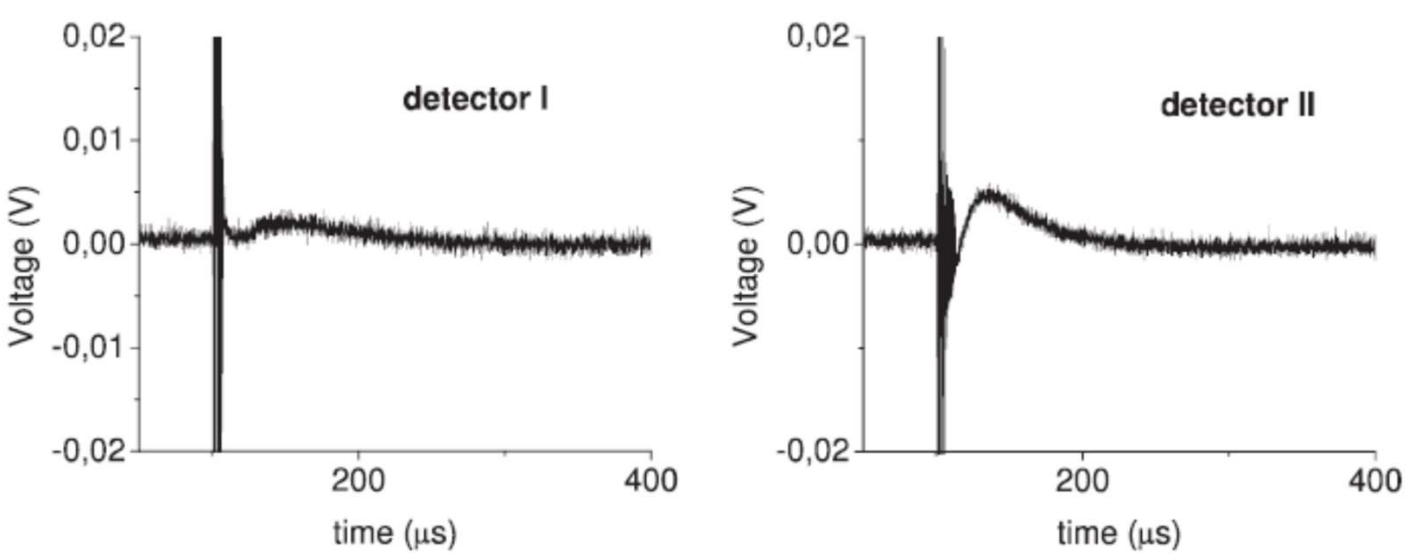
L. Soto, C. Pavez, J. Moreno, M. Barbaglia, and A. Clausse, Plasma Sources Sci. and Technol. 18, 015007 (2009)

Neutrons were detected from Nanofocus

Fusion in a flashbulb



~ 500 n /shot **~ 1000 n / shot**



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

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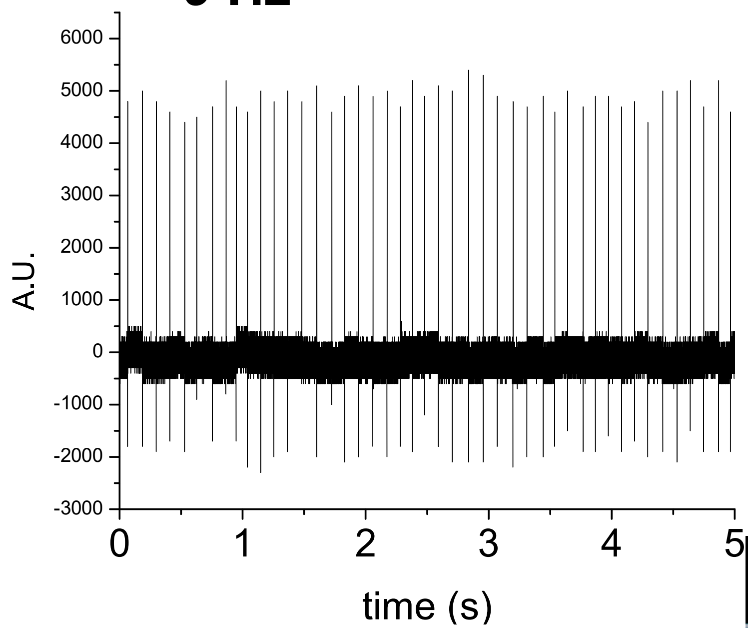
Repetition rate

a = 210μm **p = 16mbar**

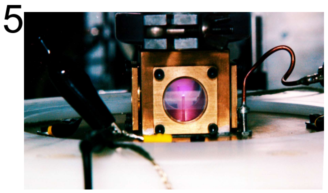
V= 6.5kV **E=0.1J**

P_{peak} ~ 10MW

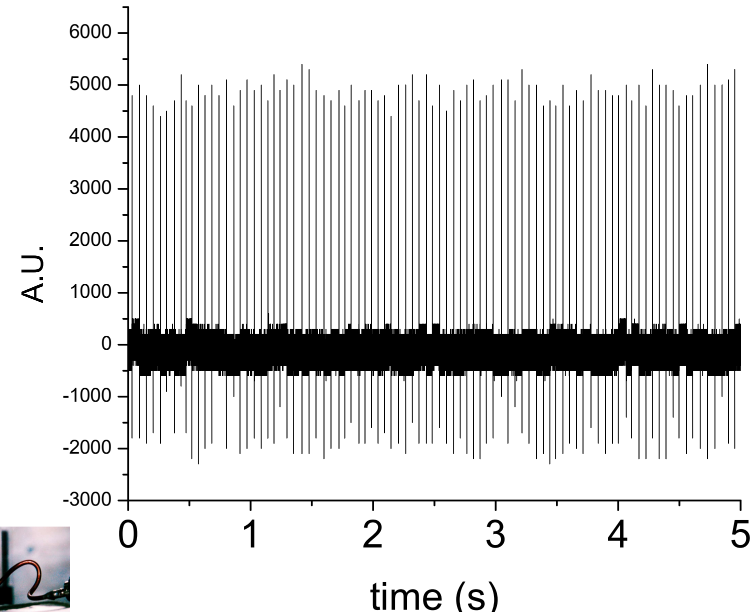
9 Hz



<P> ~ 1W



18 Hz



<P> ~ 2W

Lantern of neutrons

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

Leopoldo Soto

Santiago-Bariloche-Santiago

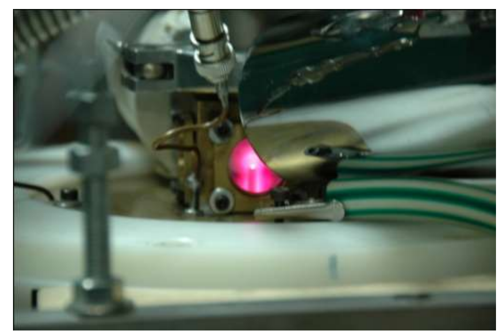
P²mc

Centro Atómico Bariloche
Argentina

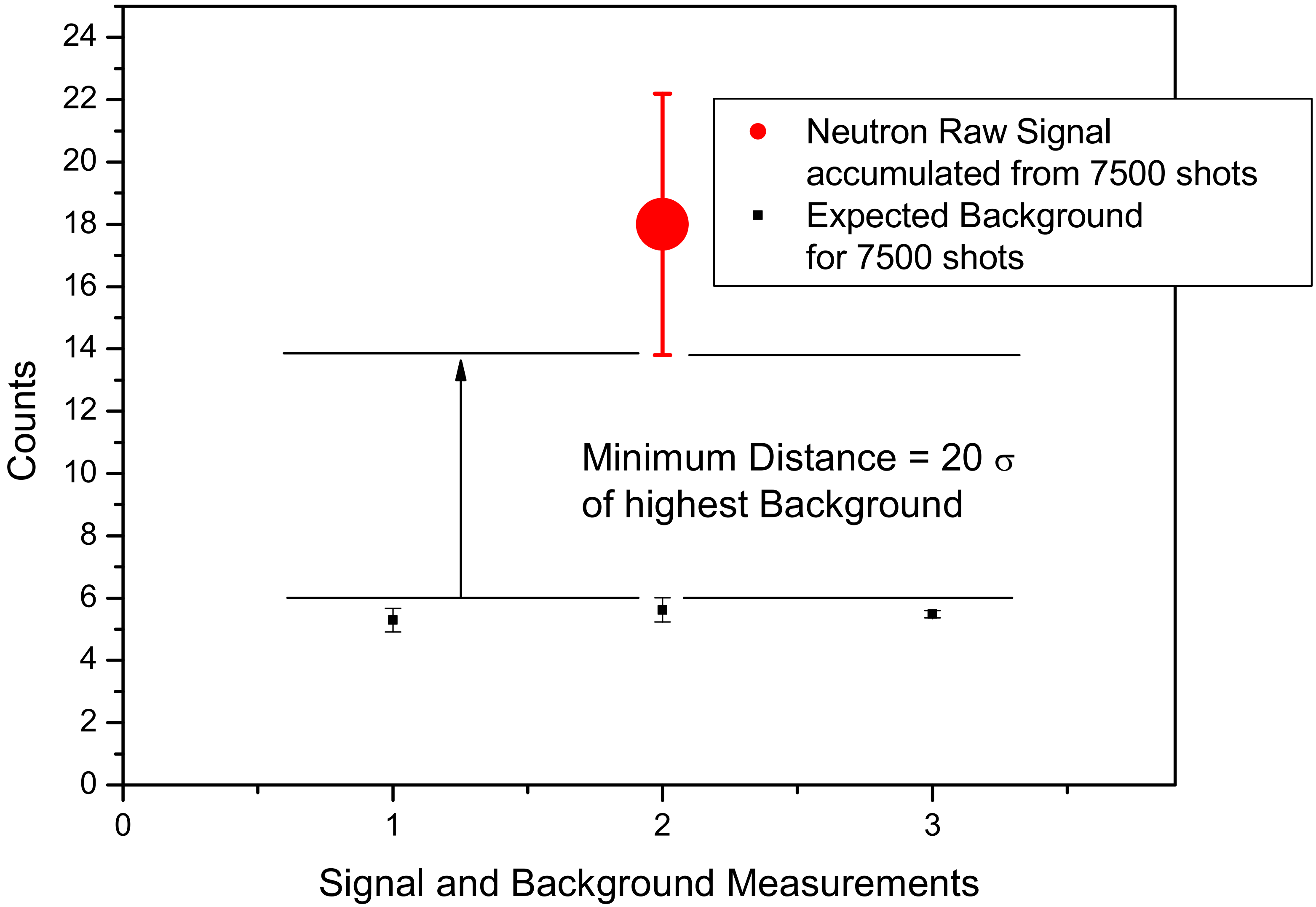
P²mc







P²mc



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

Neutron detection was confirmed with enough sigma over background.

"Veni, Vidi, Vinci", Julio César

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	0.000 25	0.021	6	16	7.6×10^{11}	70	16.9
	0.000 1	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)

Energy density parameter

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

Drive parameter

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

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

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

a: anode radius

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

Similarities in PF devices operated in a wide range of bank energy (0.1 J – 1 MJ)

P²mc

- $r_p \sim (0.1\text{-}0.2)\ a$, $z_p \sim (0.8\text{-}1)\ a$
- $\langle v_a \rangle \sim 5 \times 10^4$ m/s, $v_{af} \sim 1 \times 10^5$ m/s
- $\langle v_r \rangle \sim 1 \times 10^5$ m/s, $v_{rf} \sim 2 \times 10^5$ m/s
- $\langle n \rangle \sim 18 n_0 \sim 5 \times 10^{24}\ m^{-3}$ $n \sim 1 \times 10^{25}\ m^{-3}$
- Energy density parameter $28E/a^3 \sim 5 \times 10^{10} J/m^{-3}$
- Drive parameter $I/ap^{1/2} \sim 77 kA/cm\ mbar^{1/2}$
- The magnetic field at the pinch radius ~30 to 40 T
- Similar Alfvén speed in the pinch
- Similar drive parameter, energy density parameter and ion density → similar temperature

  - L. Soto, C. Pavez, A. Tarifeño, J. Moreno and F. Veloso, Plasma Sources Sci. and Technol. **19**, 055017 (2010).
  - D. Klir and L. Soto, IEEE Trans. Plasma Science **40**, 3273 (2012)

Temperature does not depend on the energy of the device P^2mc

E/a^3

On the one hand,

$E/V_p \sim \boldsymbol{E/a^3} \sim$ const

and $n \sim$ const

$E\,/\,ions \;\sim E\,/\,nV_p$ const

Therefore, temperature is constant.

$I/a\ p^{1/2}$

On the other hand, the contribution to heating by the current can be estimated by the Bennett relation:

$$kT_B = (\mu_0/16\pi)I^2/N,$$

with N the number of ions per unit length (ion line density),

$$N = 2\pi \int nr\,\mathrm{d}r,$$

$$\langle n \rangle = N/\pi r_p^2,$$

$$N = \langle n \rangle \pi r_p^2 \propto n_0 a^2,$$

$$kT_B \propto I^2/n_0 a^2 \propto I^2/a^2 p.$$

Therefore, the Bennett temperature is proportional to the square value of the drive parameter.

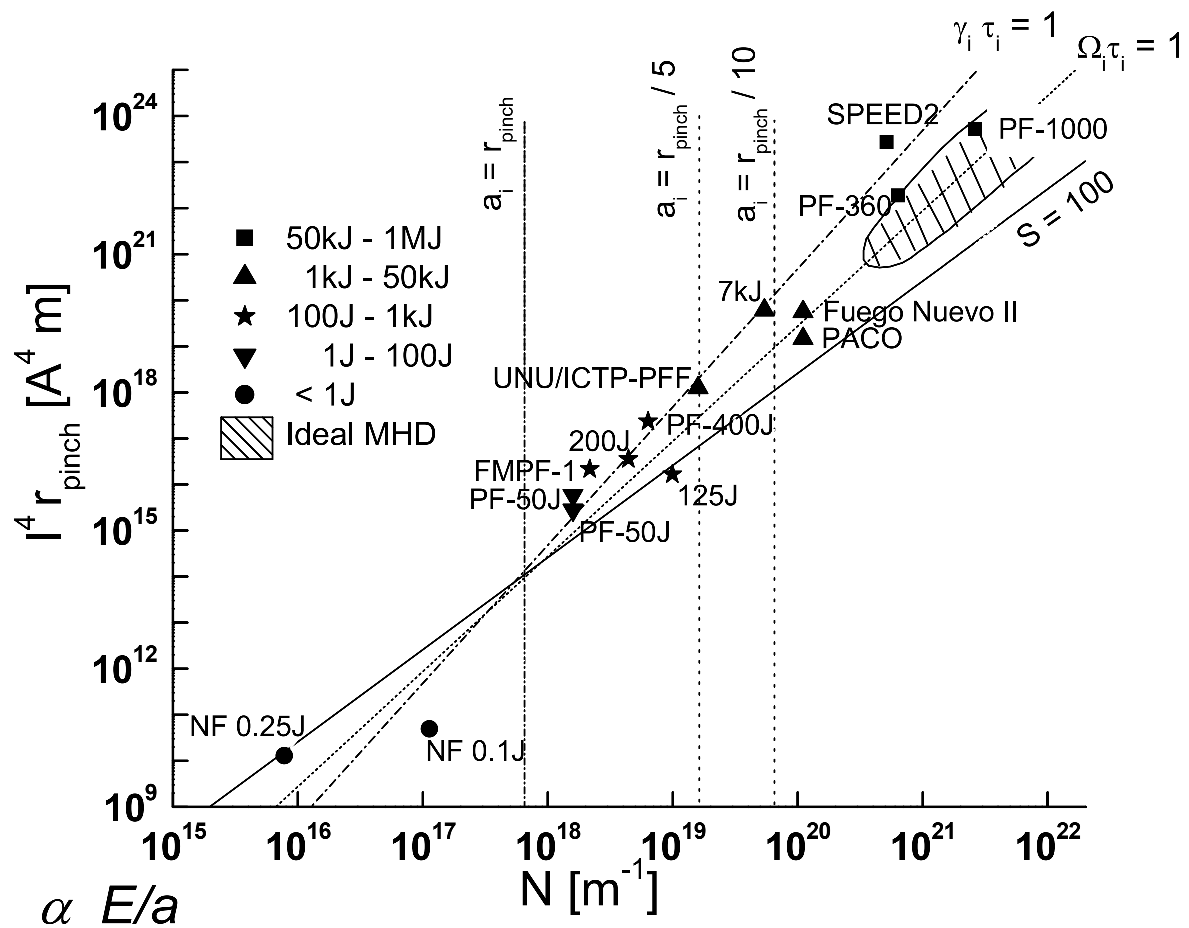
Therefore, most nuclear and atomic reactions occurring in large plasma foci should also be expected in a miniaturized pinch, given the proper scaled design.

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

Differences in PF devices operated in a wide range of bank energy (0.1 J – 1 MJ)

P²mc

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



$N \ \alpha \ E/a$

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

S / V effects α 1/a

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

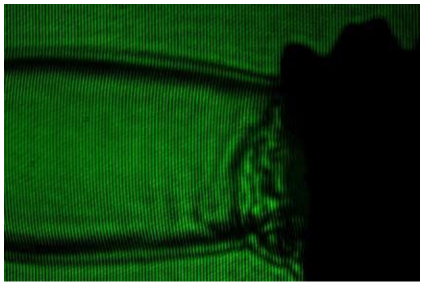
Fundamental research

Optical refractive diagnostics

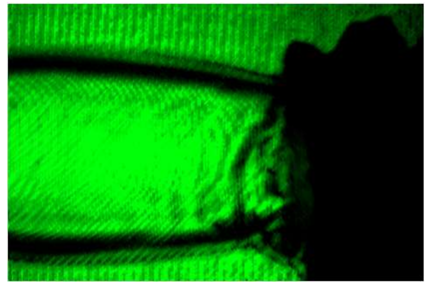
P²mc

$$\mu_e = 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}$$

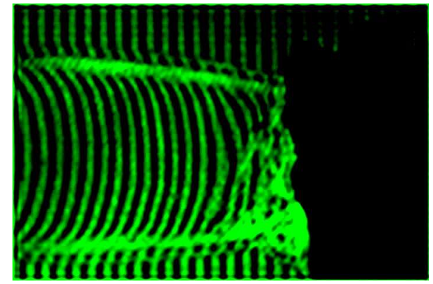
$$\mu_e - 1 = -4{,}49 \cdot 10^{-16}\,\lambda^2 n_e$$



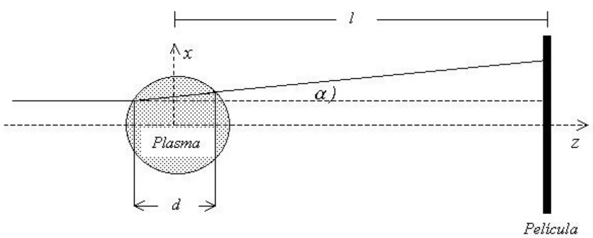
Shadowgraph

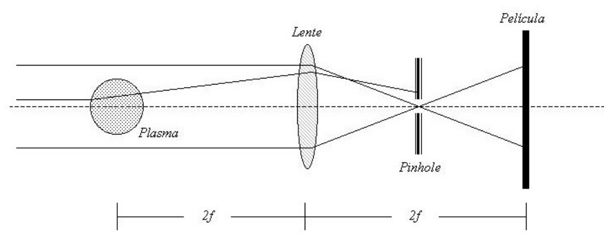


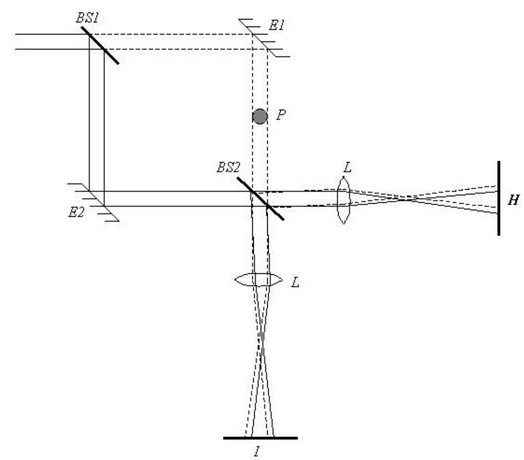
Schlieren



Interferometry







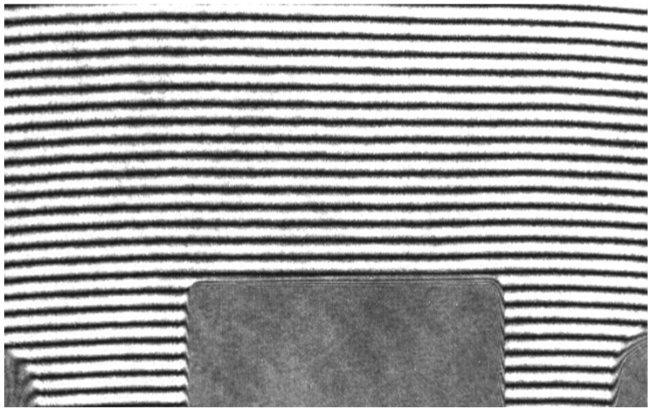
$$\frac{\Delta I}{I} \approx l \int_{z_1}^{z_2} \nabla_\perp^2 \mu(x,y,z)\,dy$$

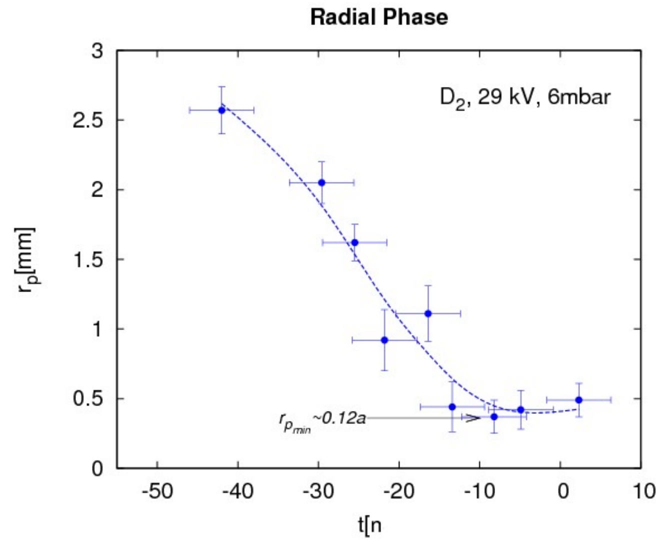
$$\alpha_x = \int_0^d \frac{1}{\mu}(\partial\mu / \partial x)\,dz$$

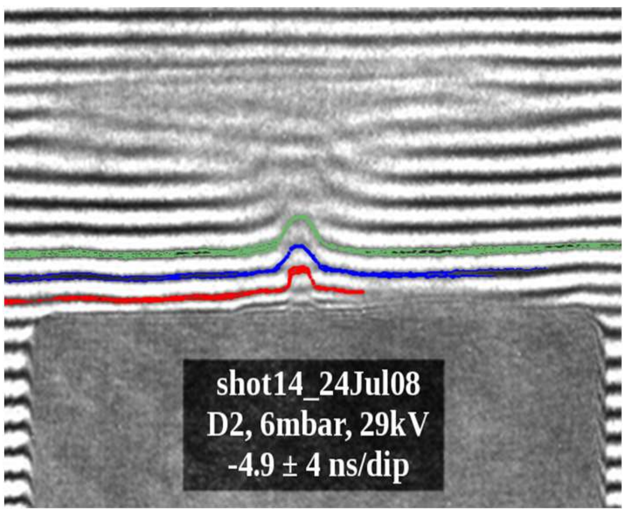
$$\Delta\varphi = \frac{2\pi}{\lambda}\int_{x_1}^{x_2} (\mu(x,y,z) - \mu_0)\,dx$$

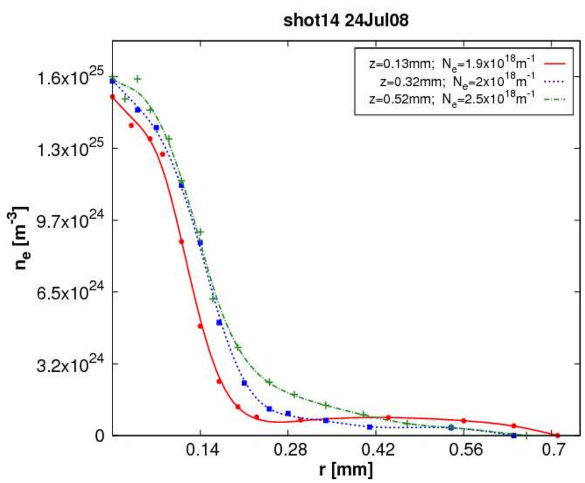
PF-50J

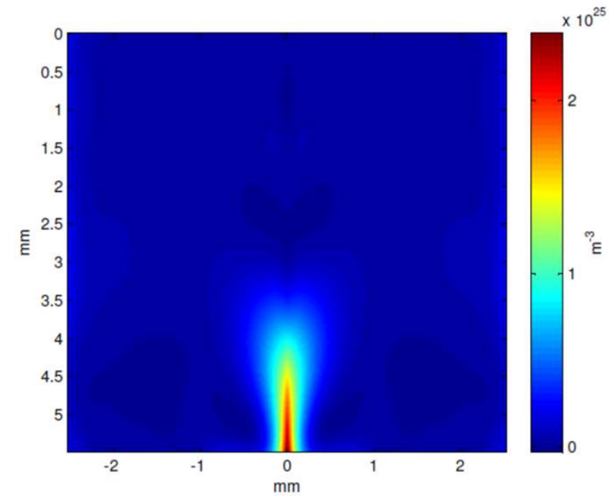
P^{2}mc











A. Tarifeño, C. Pavez, J. Moreno and L. Soto, IEEE Trans. Plasma Science, **39**, 756 (2011)

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Gobierno de Chile

Neutrons, particles and X-ray emission

P²mc

IOP Publishing — Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **57** (2015) 035008 (6pp) — doi:10.1088/0741-3335/57/3/035008

Neutron energy distribution and temporal correlations with hard x-ray emission from a hundreds of joules plasma focus device

José Moreno[1,2,3], Felipe Veloso[4], Cristian Pavez[1,2,3], Ariel Tarifeño-Saldivia[1,2,6], Daniel Klir[5] and Leopoldo Soto[1,2,3]

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Experimental evidence of more than one ions acceleration mechanisms in plasma focus device: Observations and interpretations

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Jalaj Jain,[1,2,a)] José Moreno,[1,2,3] Sergio Davis,[1,2,3] Biswajit Bora,[1,2,3] Cristian Pavez,[1,2,3] Gonzalo Avaria,[1,2,3] and Leopoldo Soto[1,2,3]

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Experimental measurements of high-energy photons in X-rays pulses emitted from a hundred joules plasma focus device and its interpretations

Jalaj Jain[a,b,*], Jose Moreno[a,b,c], Sergio Davis[a,b,c], Biswajit Bora[a,b,c], Cristian Pavez[a,b,c], Gonzalo Avaria[a,b,c], Leopoldo Soto[a,b,c]

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Results in Physics 23 (2021) 104016
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Influence of electrode geometry on X-ray emission, plasma inductance, voltage, and current derivative signals obtained from a plasma focus device

Jalaj Jain[a,b,*], Jose Moreno[a,b,c], Biswajit Bora[a,b,c], Leopoldo Soto[a,b,c]

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Hard X-Ray Emission Detection Using Deep Learning Analysis of the Radiated UHF Electromagnetic Signal From a Plasma Focus Discharge

GONZALO AVARIA[1,3], JORGE ARDILA-REY[2], SERGIO DAVIS[1,3], LUIS ORELLANA[2], BENJAMÍN CEVALLOS[2], CRISTIAN PAVEZ[1,3], AND LEOPOLDO SOTO[1,3]
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Temperature

P²mc

Results in Physics 40 (2022) 105831

Contents lists available at ScienceDirect

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Model of Thomson scattering from z-pinch plasma: Application in experimental design for Plasma Focus

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A R T I C L E   I N F O

Keywords:
Non-Maxwellian
Bi-Maxwellian
Anisotropy
Drift velocity
Velocity distribution
Optical diagnostic

A B S T R A C T

The present work develops a model of Thomson scattering (TS) for z-pinch plasmas. Sustained on the phenomenology observed in dynamical-pinch discharges of interest in fusion studies, the plasma dynamics is modeled by axisymmetric bi-Maxwellian velocity distribution with axial and radial drift velocities. Expressions for TS form factor and screening integrals are deduced, and TS spectra are reconstructed. A characteristic temperature of the spectrum is identified, which is determined by a weighted-sum of the axial and radial temperatures, whose coefficients are given by the square of the respective axial and radial components of $\vec{k}$ over the square of the magnitude of $\vec{k}$. It is shown that it is not possible to determine the velocity distribution function of the plasma from just one direction of measurement. Additionally, an experimental setup, which requires two complementary observation directions for a complete determination of the proposed distribution function, is analyzed and its capacity to measure thermal anisotropy and drift velocities is studied for plasma conditions expected in the pinch phase of a plasma focus discharge.

Toroidal singularities, filamentary structures, plasma shocks and plasma jets generations

P^{2}mc

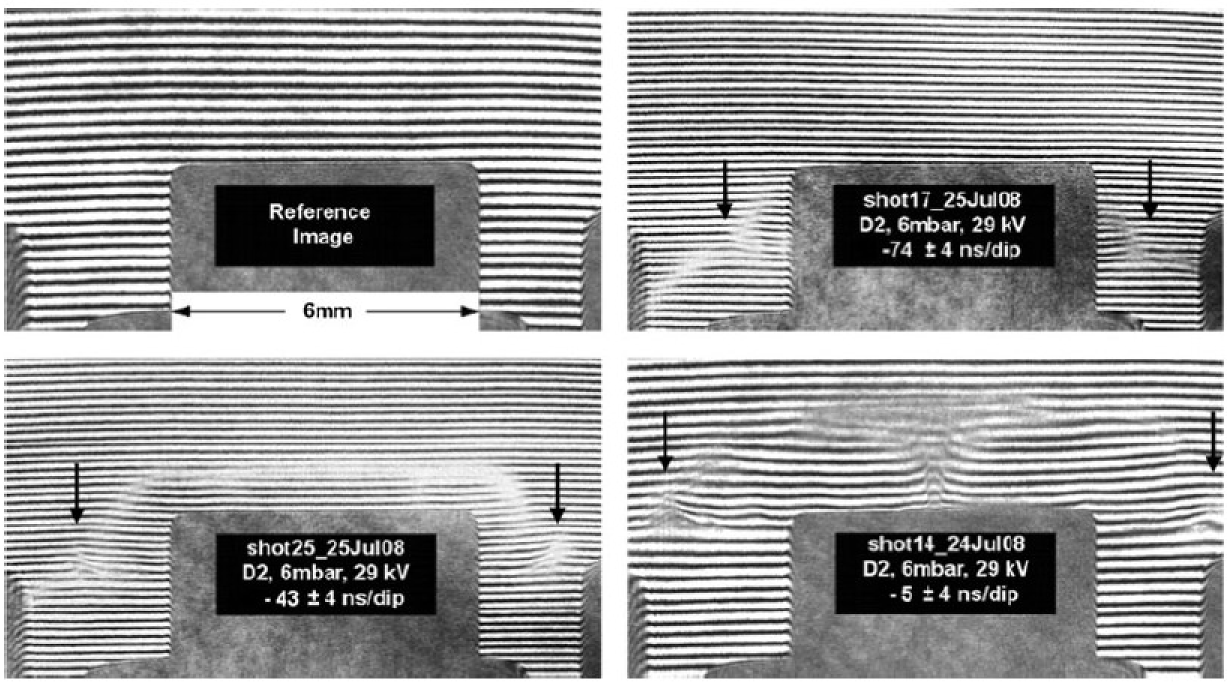
PF-50J

J Fusion Energ (2012) 31:279–283
DOI 10.1007/s10894-011-9469-1

ORIGINAL RESEARCH

Toroidal High-Density Singularity in a Small Plasma Focus

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



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J Fusion Energ (2012) 31:279–283
DOI 10.1007/s10894-011-9469-1

ORIGINAL RESEARCH

PF-50J

Toroidal High-Density Singularity in a Small Plasma Focus

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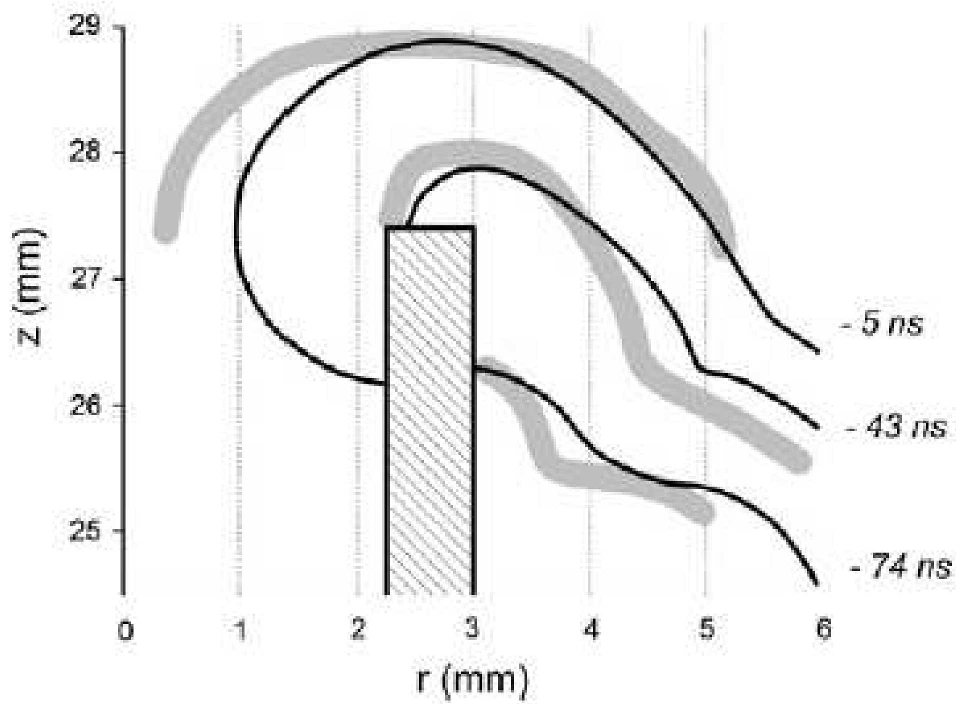

Fig. 5 Shape of the current sheet at different times. Numerical (*black*), experimental (*solid grey*). The *numbers* at the right indicate the corresponding time relative to dip

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Bayesian inference of spectrometric data and validation with numerical simulations of plasma sheath diagnostics of a plasma focus discharge

Gonzalo Avaria[1,2,6], Alejandro Clausse[3,6], Sergio Davis[1,2,6], Cristian Pavez[1,2,6], Nelson Villalba[4], Osvaldo Cuadrado[1], Jose Moreno[1,2], H. Marcelo Ruiz[5] & Leopoldo Soto[1,2]

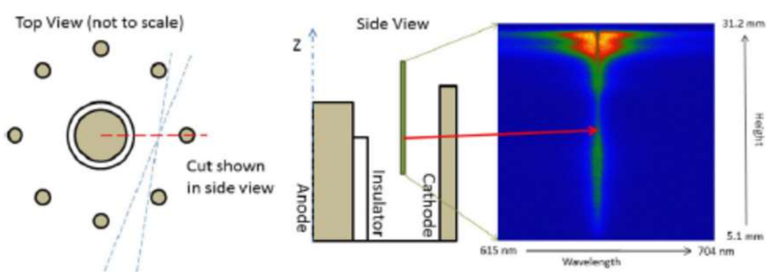

Figure 11. Scheme of the focus plane inside the inter-electrode volume and the representation of the strip that is imaged at the spectrometer slit, which produces a spectral image of the plasma sheath during an instant of the discharge. The spatial resolution is given by the magnification of the system.

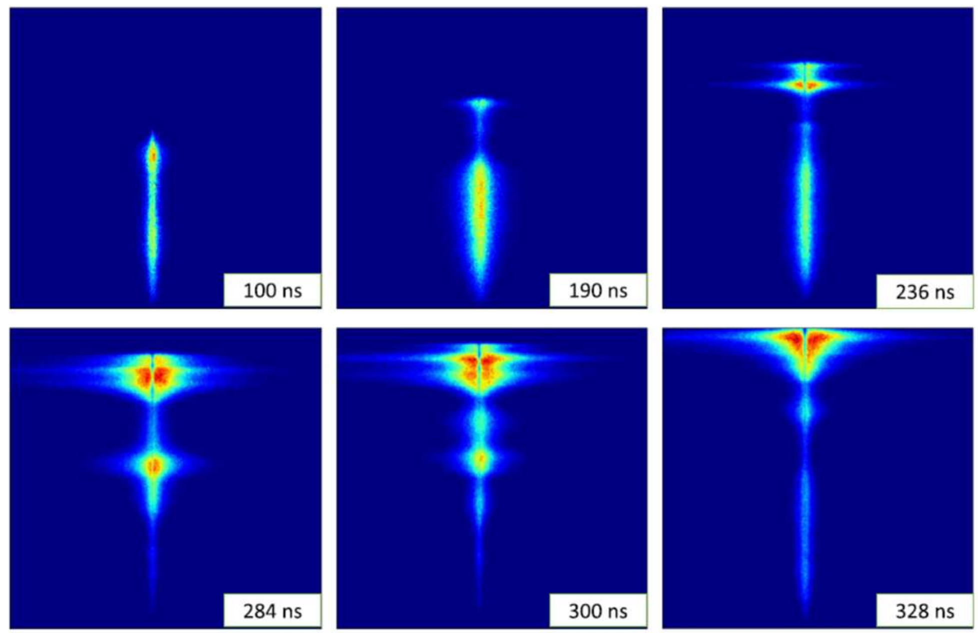

Figure 2. Time sequence of the spectral images for the discharge. At earlier times it can be seen that a plasma is formed at the inter-electrode volume, which later starts to move towards the top of the electrodes.

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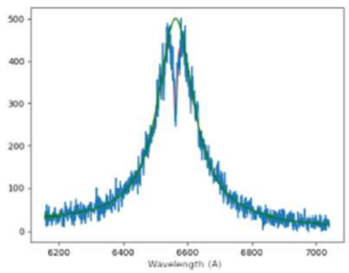


Figure 3. Intensity profile for the H-alpha emission, showing the fitted curve following the model proposed by Kielkopf[58] (red) and the opacity corrected profile (green) which is used for the electron density calculations.

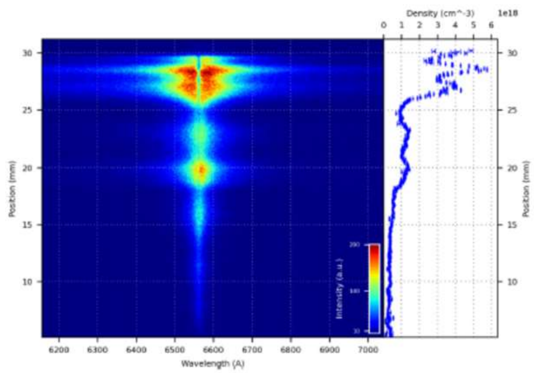
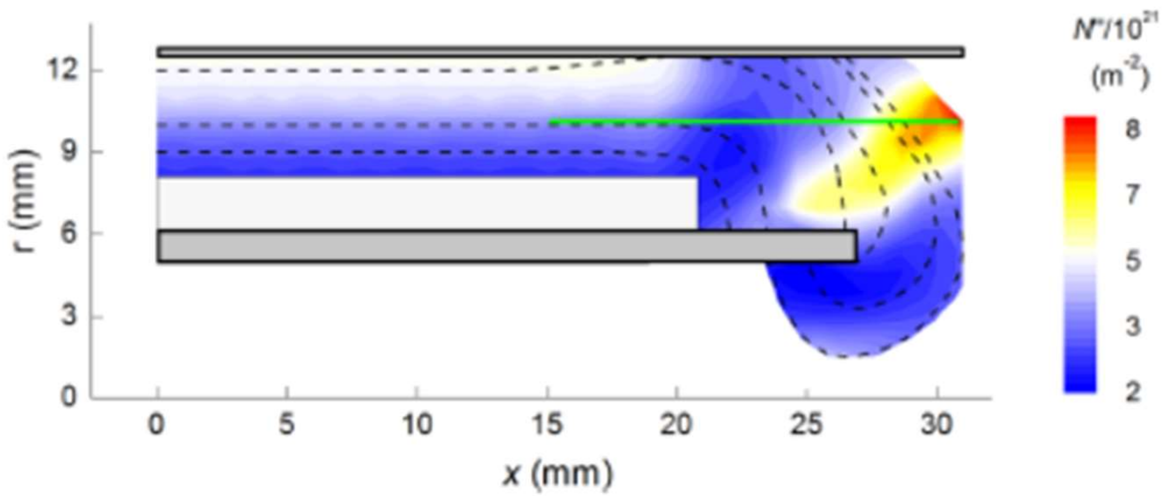


Figure 4. Spectral image of the inter-electrode space, 300 ns after the onset of the current. As seen from the density profile, the electron density is around 6×10^{18} cm^{-3} at approximately 28 mm from the bottom of the electrodes.



P²mc

PHYSICS OF PLASMAS **21**, 072702 (2014)

Filamentary structures in dense plasma focus: Current filaments or vortex filaments?

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

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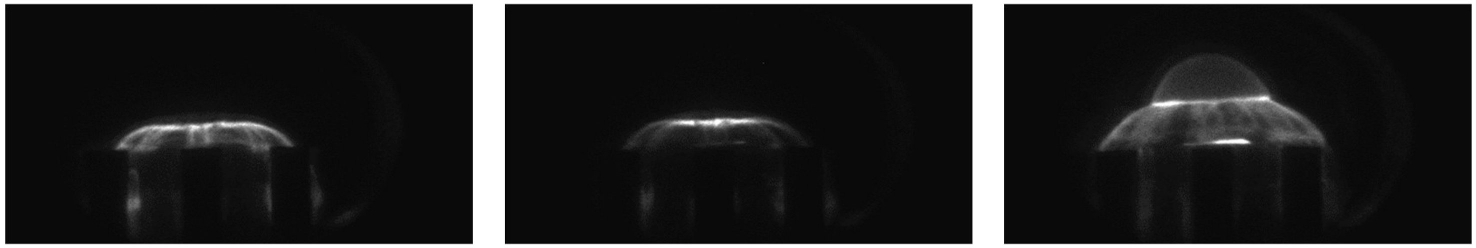
[6]*Bhabha Atomic Research Center, Mumbai 400 085, India*

Filaments

P^{2}mc

PF-400J

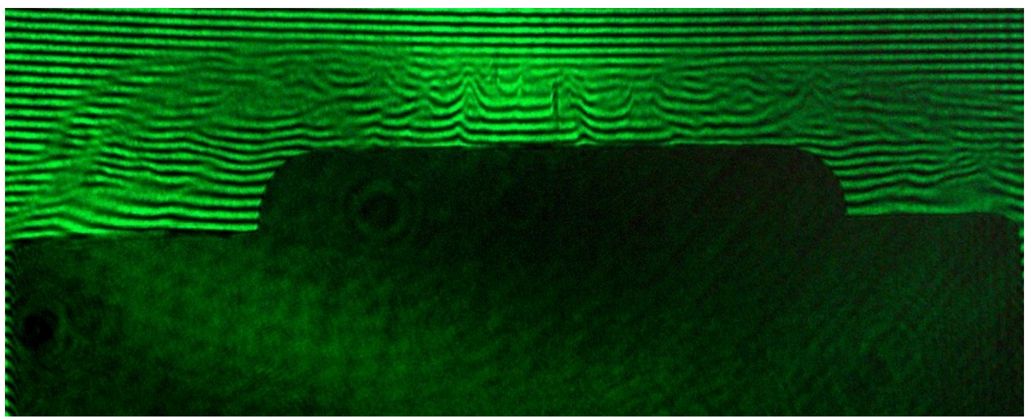
Visible images



-16ns   - 6ns   49ns

Schlieren

Interferogram



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

IOP Publishing   Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion 65 (2023) 015003 (13pp)   https://doi.org/10.1088/1361-6587/aca358

New evidence about the nature of plasma filaments in plasma accelerators of type plasma-focus

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Abstract
In this work, new evidence and information about both the origin and evolution of filamentary structures observed in the current sheath of a small plasma focus (PF) discharge are reported. The experiments were carried out in a small generator of low energy (multipurpose generator) at the PF configuration, under different operating conditions. These include different anode and insulator geometries, without return bars and in a high-performance regime of the generator at high pressures (>10 mbar). The evolution of the plasma structures is characterized by means of refractive optical techniques. The electrical behavior of the discharge, as well as its performance, are monitored with conventional electrical diagnostics and neutron and x-ray detectors, respectively. Plasma filaments of the same species are present in all tested configurations, however, in experiments with larger effective anode length (and smaller anode radii), the plasma region containing the filaments moves away from the anode surface and remains confined in a region of the plasma sheath, such as a toroidal plasma belt, without reaching the top of the anode nor participating in the radial compression phase. According to images of the plasma sheath in its early phase, the filaments originate and evolve from a precursor annular plasma formed in the lower part of the anode next to the insulator, during the process of electrical breakdown. The local character that these dense-filamentary structures acquire in the evolution of the plasma sheath would discard the current-filament hypothesis. On the other hand, experiments performed in deuterium gas with anodes of larger effective lengths and without filaments in the radial compression phase allowed the production of neutrons and x-rays at a high performance.

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Plasma Phys. Control. Fusion **65** (2023) 015003 C Pavez *et al*

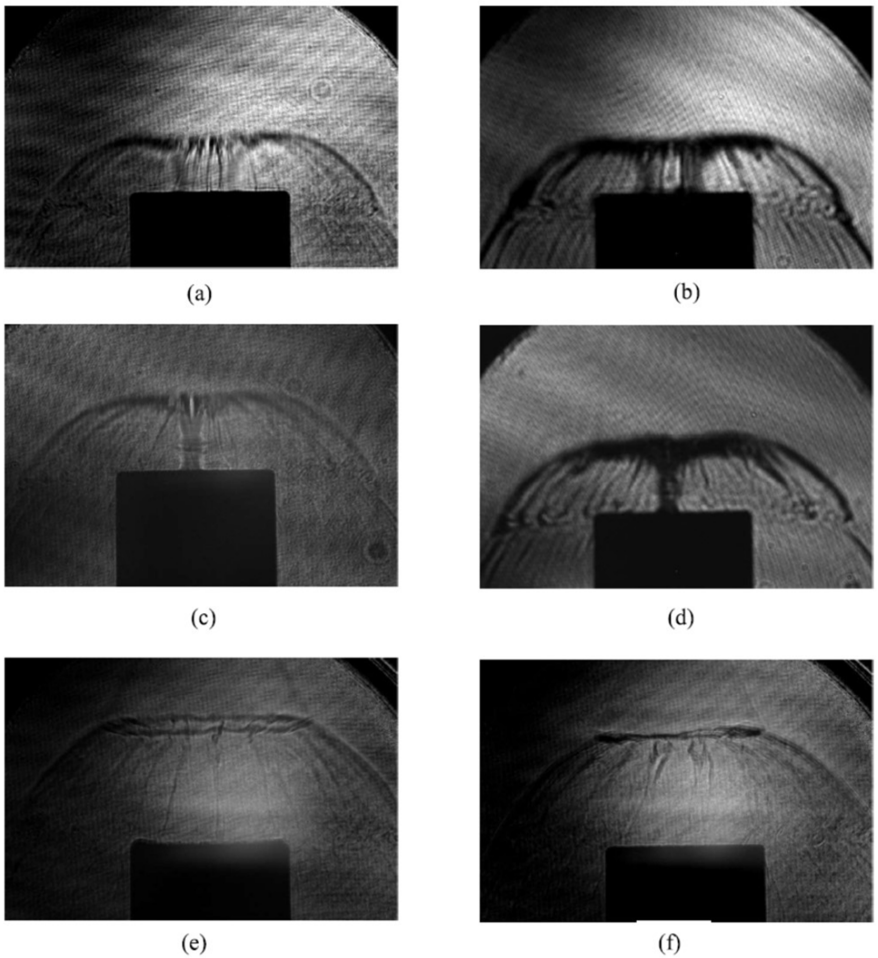

Figure 3. Simultaneous shadowgrams (left column) and schlieren (right column) images for discharges in H_2 at 13 mbar. Diameter and effective anode length are 12 mm and 10.5 mm, respectively (without return bars). (a) and (b) correspond to radial compression phase images. (c) and (d) correspond to phase after maximum compression. (e) and (f) late phase, post column-disruption. Laser pulse duration of 10 ns (FWHM).

Plasma Phys. Control. Fusion **65** (2023) 015003 C Pavez *et al*

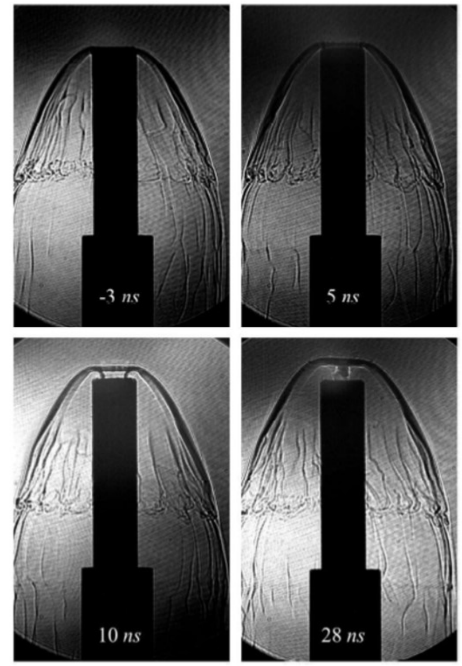

Figure 6. Temporal sequence of shadow images for discharges in H_2 at 15 mbar. Diameter and effective anode length of 6.1 mm and 25.5 mm, respectively (without return bars). The recording time is evaluated respect to onset time of dip at the current derivative signal (beginning of the radial phase). Laser pulse duration of 170 ps (FWHM).

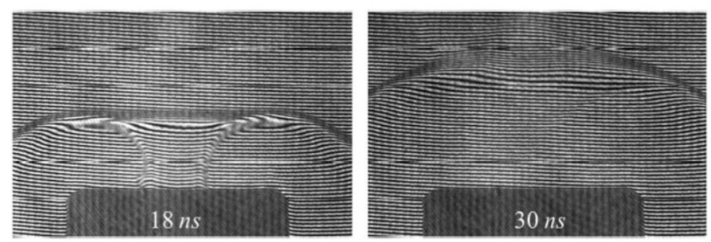

Figure 7. Interferograms of the radial compression and post-rupture of column phases for discharges in H_2 at 15 mbar. Diameter and effective anode length of 6.1 mm and 25.5 mm, respectively (without return bars). The recording time is evaluated respect to onset time of dip at the current derivative signal (beginning of the radial phase). Laser pulse duration of 170 ps (FWHM).

PHYSICS OF PLASMAS **21**, 122703 (2014)

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,[1,2,3,a)] Cristian Pavez,[1,2,3] José Moreno,[1,2,3] María José Inestrosa-Izurieta,[1,2] Felipe Veloso,[4] Gonzalo Gutiérrez,[5] Julio Vergara,[6] Alejandro Clausse,[7] Horacio Bruzzone,[8] Fermín Castillo,[9] and Luis F. Delgado-Aparicio[10]

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Plasma bursts after the pinch

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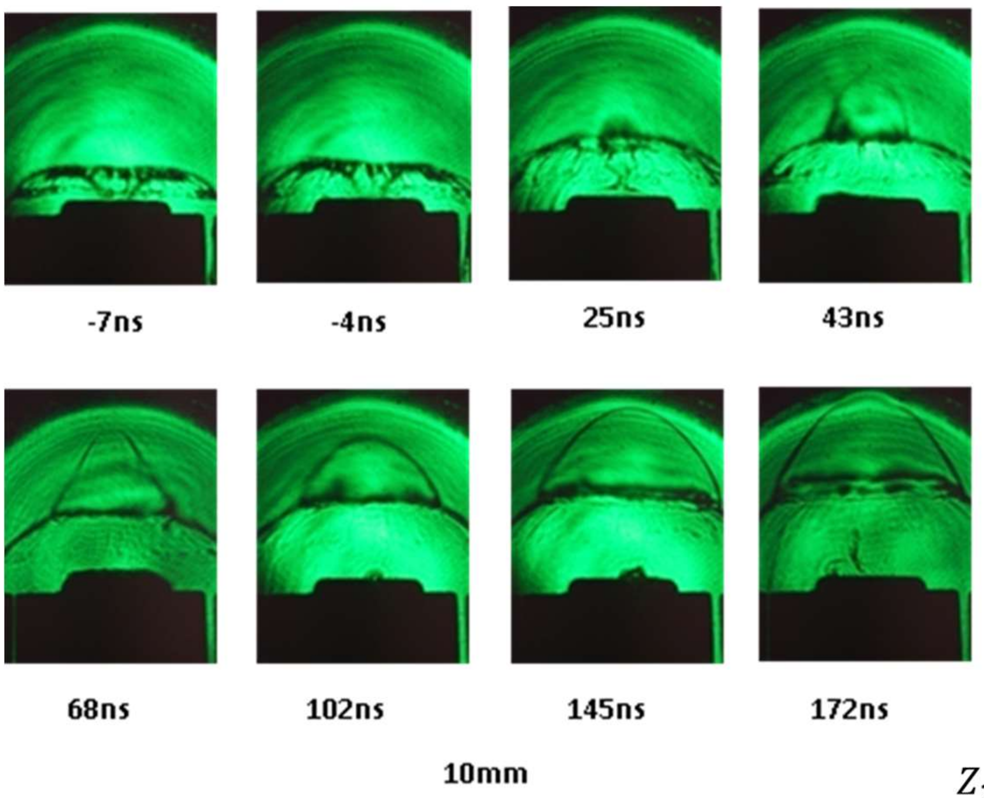
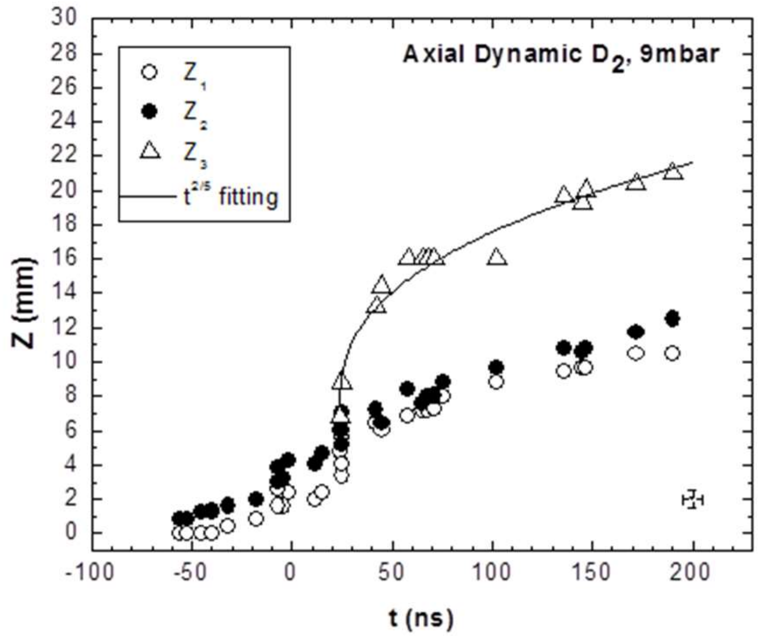
Previus studies did not pay atention after the pinch disruptions

PF- 400J D_2 **9mbar**





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

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

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PHYSICS OF PLASMAS **22**, 040705 (2015)

Observation of plasma jets in a table top plasma focus discharge

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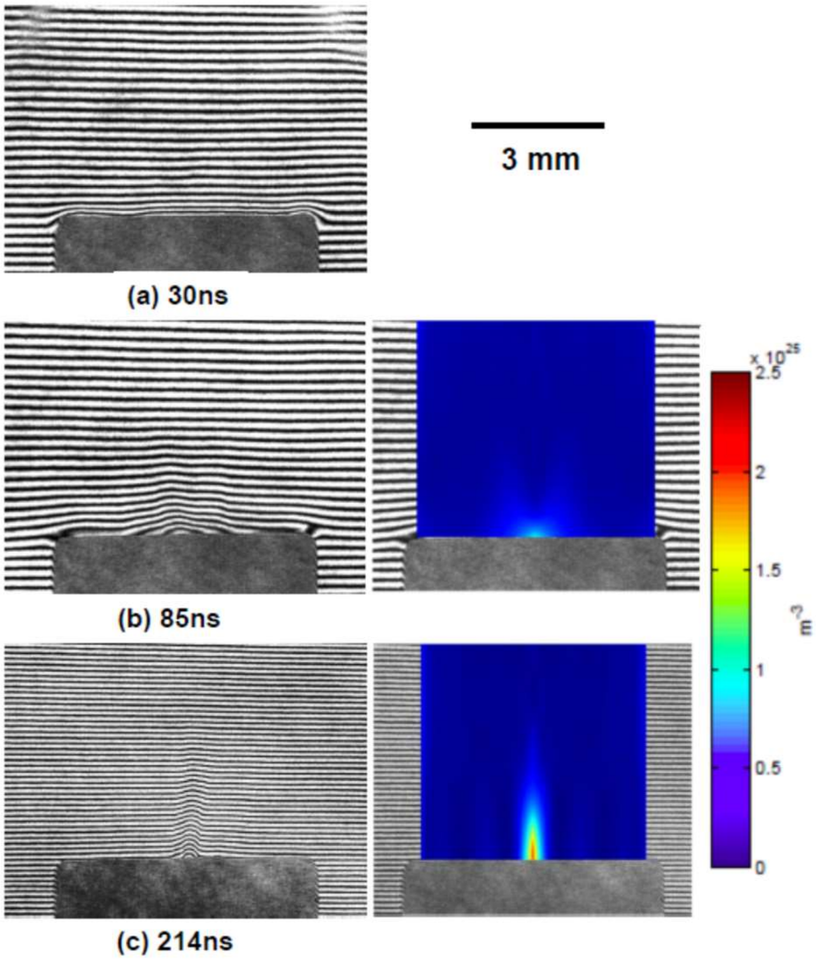
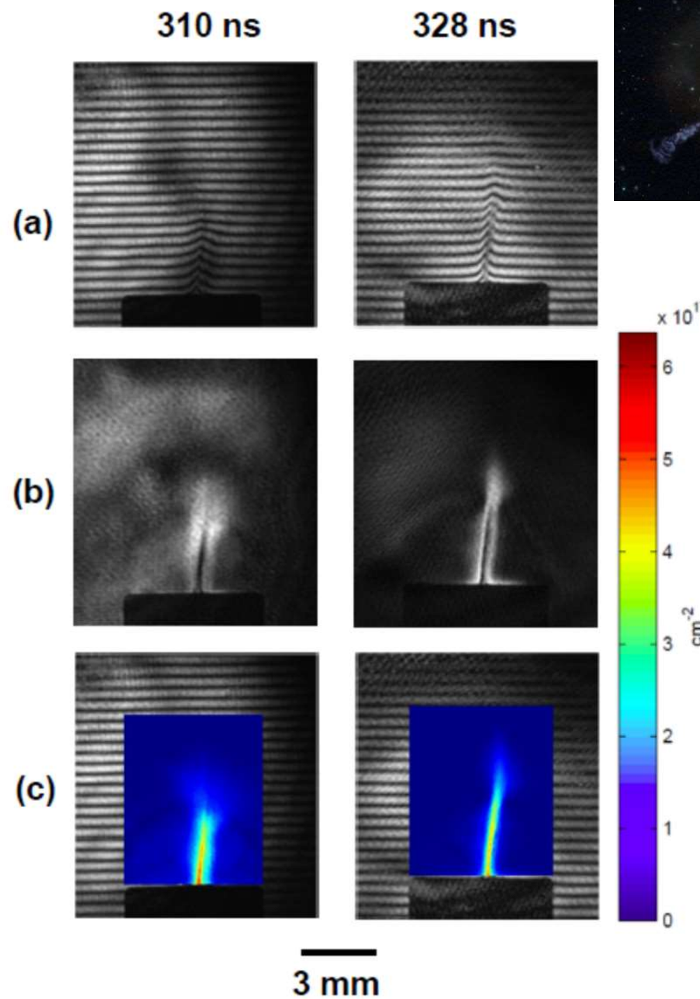
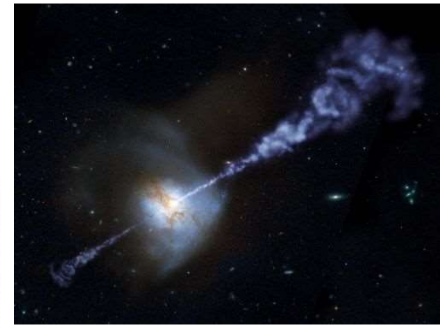
(Received 2 October 2014; accepted 15 April 2015; published online 24 April 2015)

After plasma shock, plasma jets are observed

P²mc







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

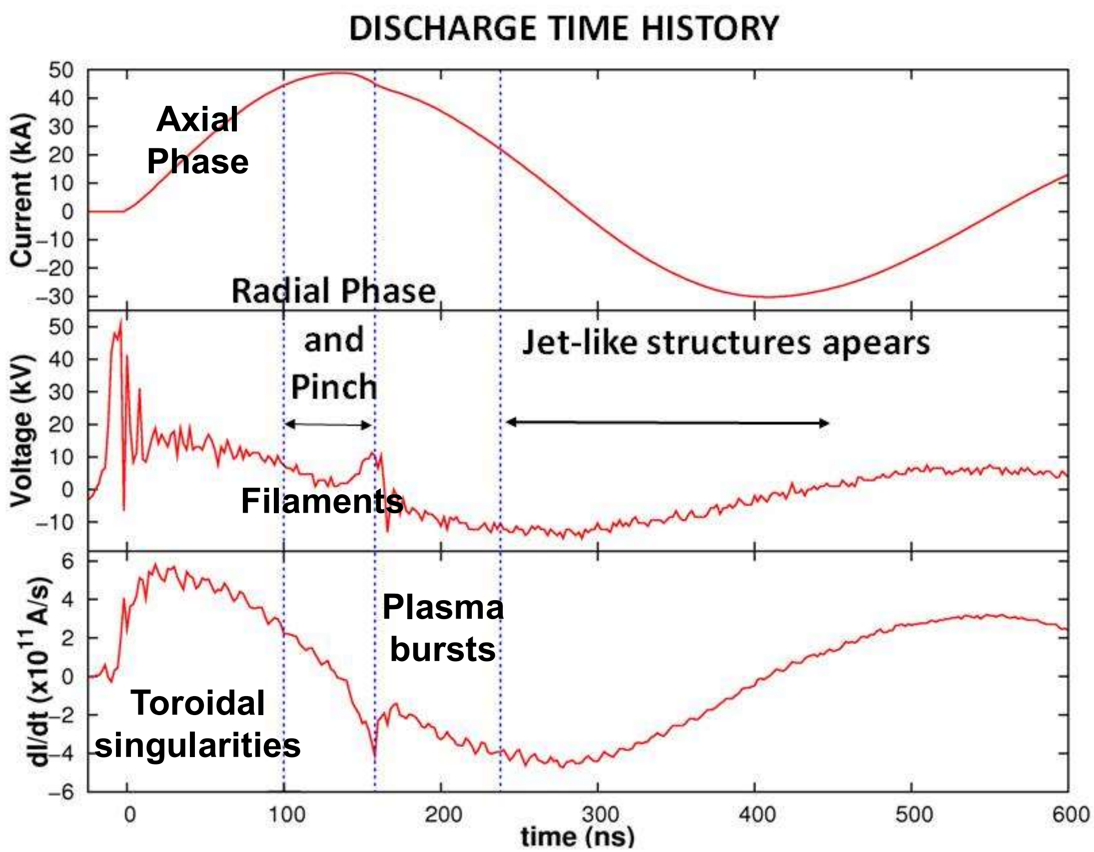
C. Pavez, J. Pedreros, A Tarifeño-Saldivia and L. Soto, Physics of Plasmas 22, 040705 (2015)

Comisión Chilena de Energía Nuclear
Ministerio de Energía
Gobierno de Chile

After plasma jets are observed

P²mc

PF-50J



PF dynamics including times after the pinch disruption

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Plasma Focus Aplications

A field application

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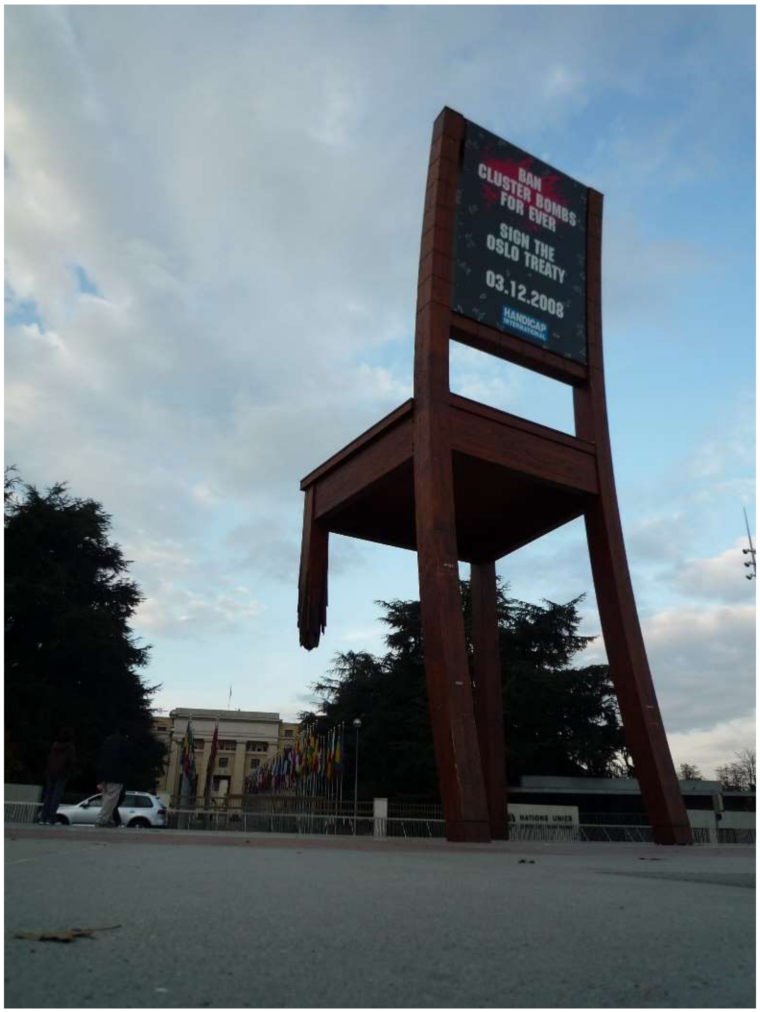

Landmines detection by means of back scattering neutrons .

IAEA TC Project

Comisión Chilena de Energía Nuclear
Ministerio de Energía
Gobierno de Chile

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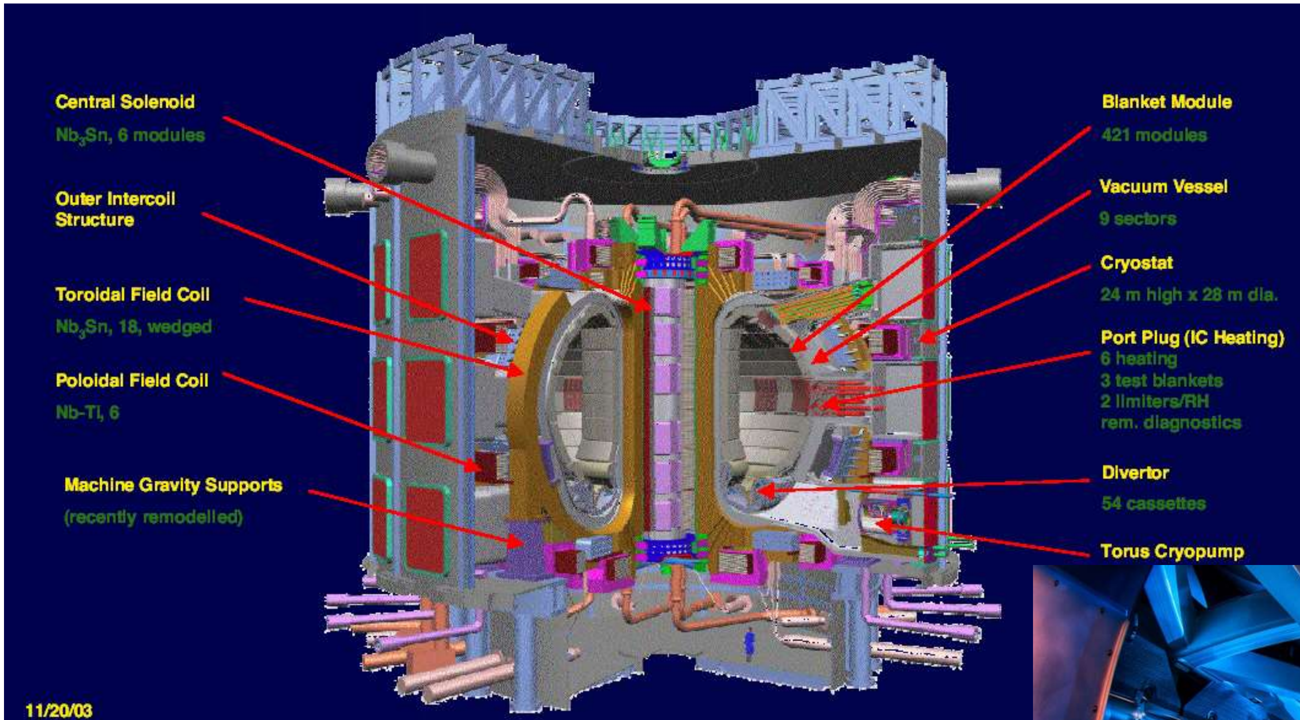
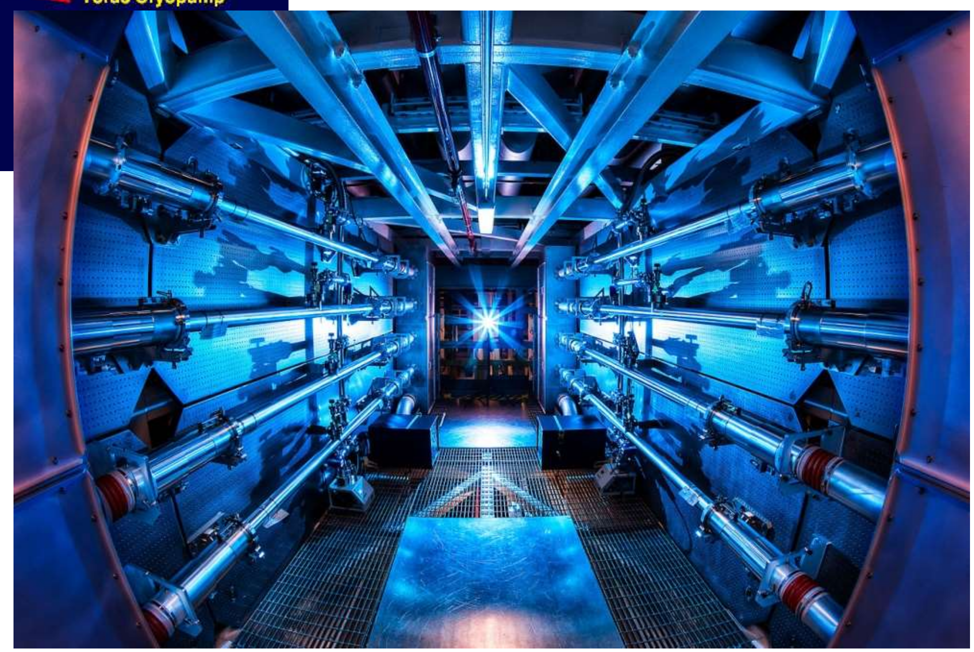
Outdoor laboratory under controlled conditions
HYDAD-D in a simulated field with hydrogenated objects

Arica, Atacama Desert, Northern Chile, September 11, 2009

Leopoldo Soto
Research Center on the Intersection of
Plasma Physics, Matter and Complexity, P²mc

Materials for fusion reactors





P^{2}mc

Damage factor

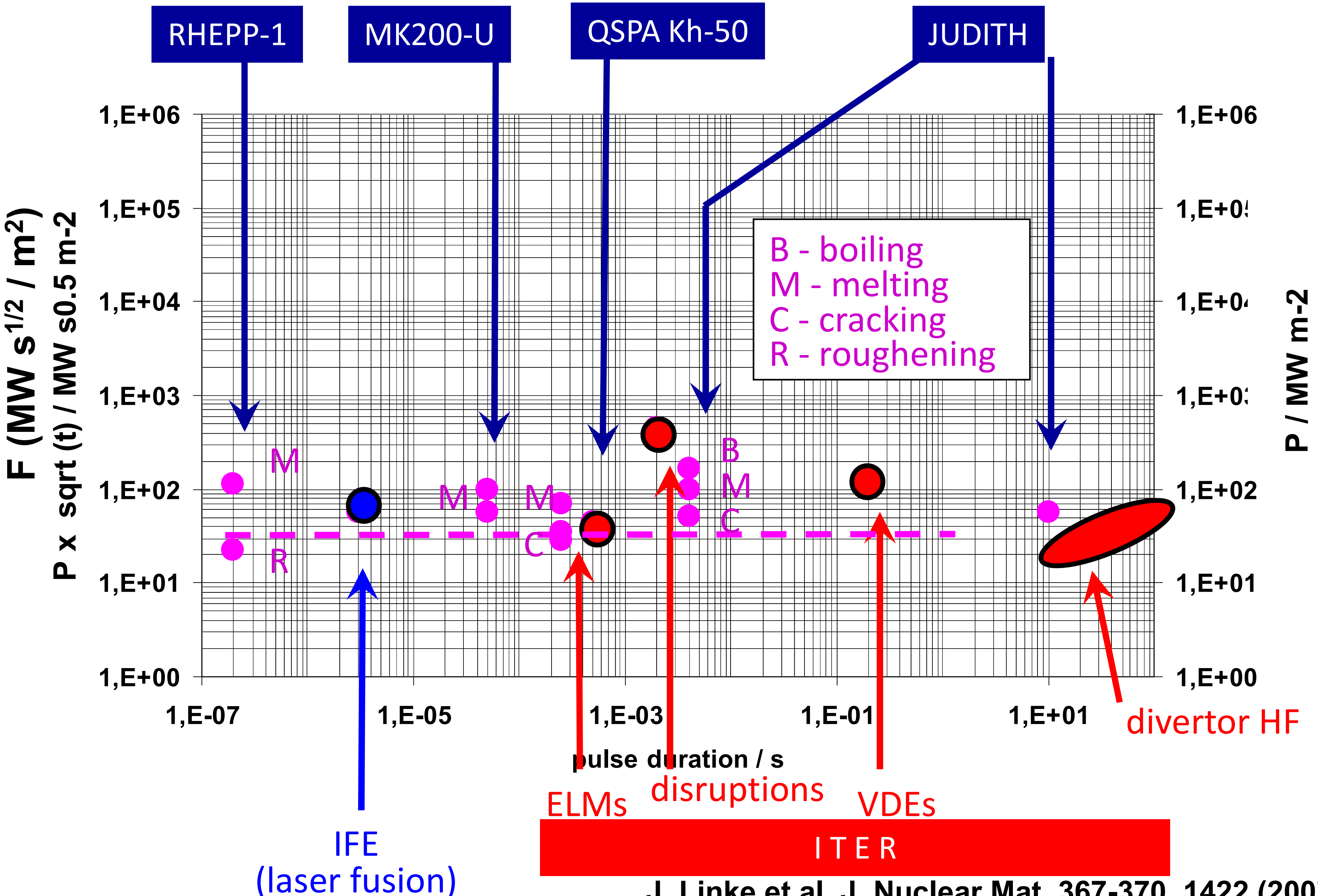
$$F \sim q \cdot \tau^{1/2} = E/S\tau^{1/2}$$

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

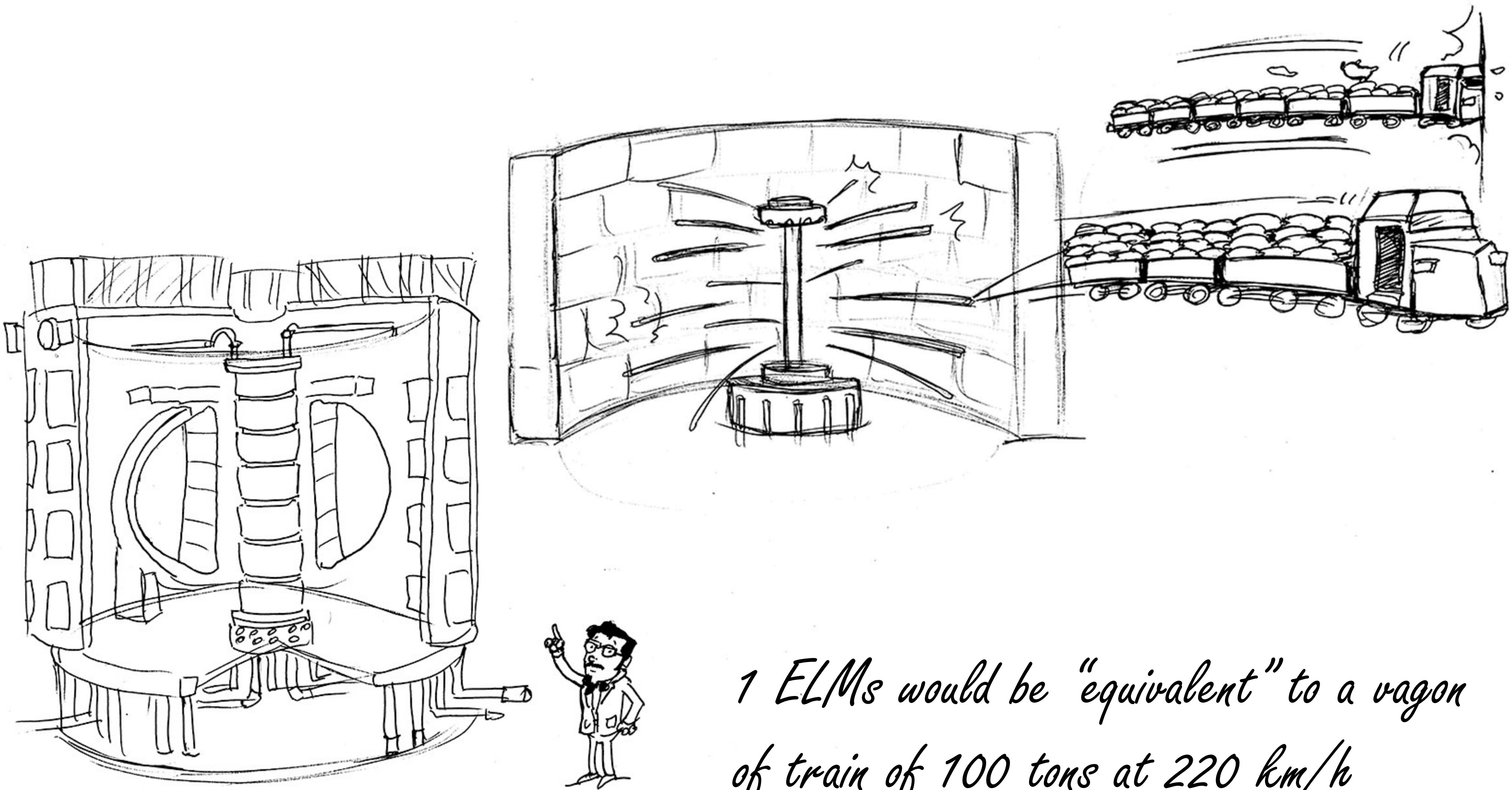
The damage factor F, is an empirical parameter that has been recognized that a good measure of the damage in an irradiated sample. In fact, it has observed that radiation sources producing high power flux q with a short time interaction τ on a specific material, have the similar thermomechanical effects if the material is irradiated with a source with less q and longer τ, if in both situation the damage factor F has the same value.

For a theoretical explanation of the damage factor, see:

“A model for defect formation in materials exposed to radiation”, S. Davis, F. González-Cataldo, G. Gutiérrez, G. Avaria, B. Bora, J. Jain, J. Moreno, C. Pavez, and L. Soto, Matter and Radiation at Extremes **6**, 015902 (2021); https://doi.org/10.1063/5.0030158



J. Linke et al, J. Nuclear Mat. 367-370, 1422 (2007)



1 ELMs would be "equivalent" to a vagon of train of 100 tons at 220 km/h shocking on a wall

Motivation

P²mc

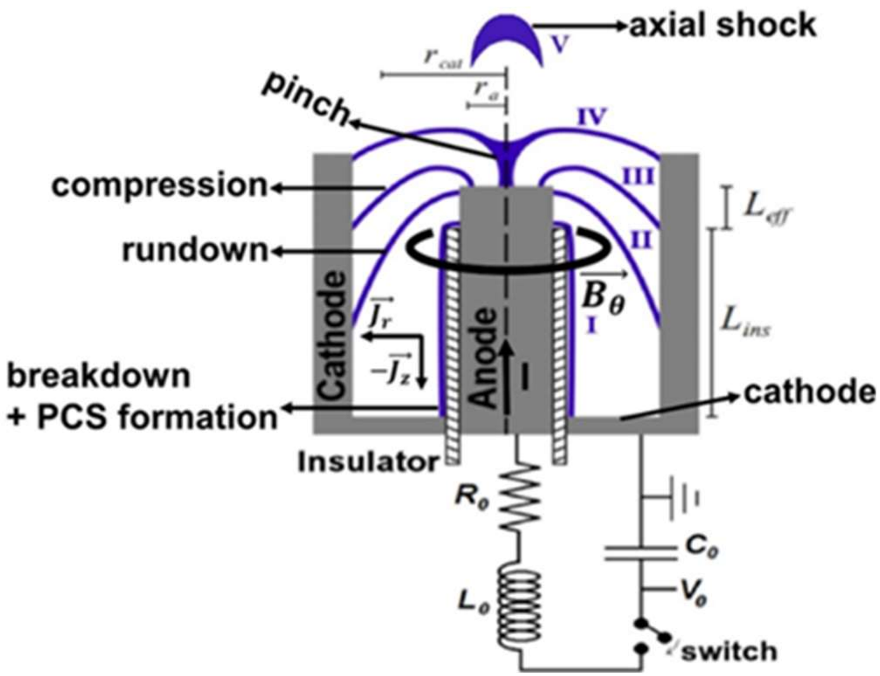
Plasma guns, accelerators and others large facilities are currently used to mimic the irradiation conditions that PFM have to withstand in a nuclear fusion reactor . These devices produce a few shots per day with low repetition rate.

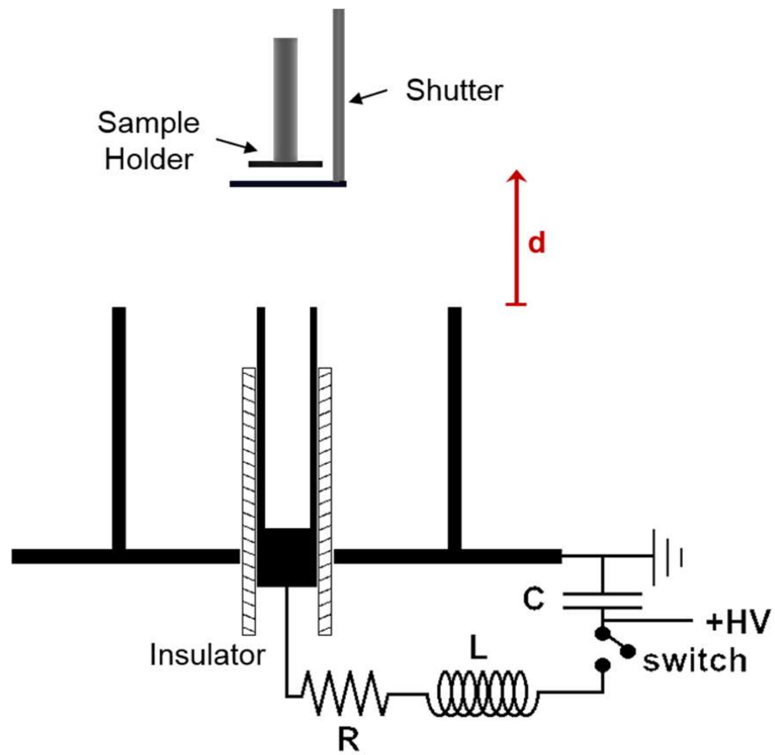
On this frame, a table top plasma source is highly desirable to reproduce the equivalent irradiation conditions to test PFM for fusion reactors.

Effects of pulsed radiation
on materials of interest for nuclear fusion reactors

P²mc

3 plasma focus devices (2kJ, 400J, 2J) were used to irradiate materials under equivalent condition than the expected in ITER and IFE.





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

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

Damage Factor produced by Plasma bursts after the pinch

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PF- 400J

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

(the pinch is ejected trough 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**

C. Pavez and L. Soto, Physica Scripta T131, 014030 (2008)

Energy of the axial ejected plasma: $\frac{1}{2} mv^2$

Length of the ejected mass: ~ pinch length, L = 5.6 mm

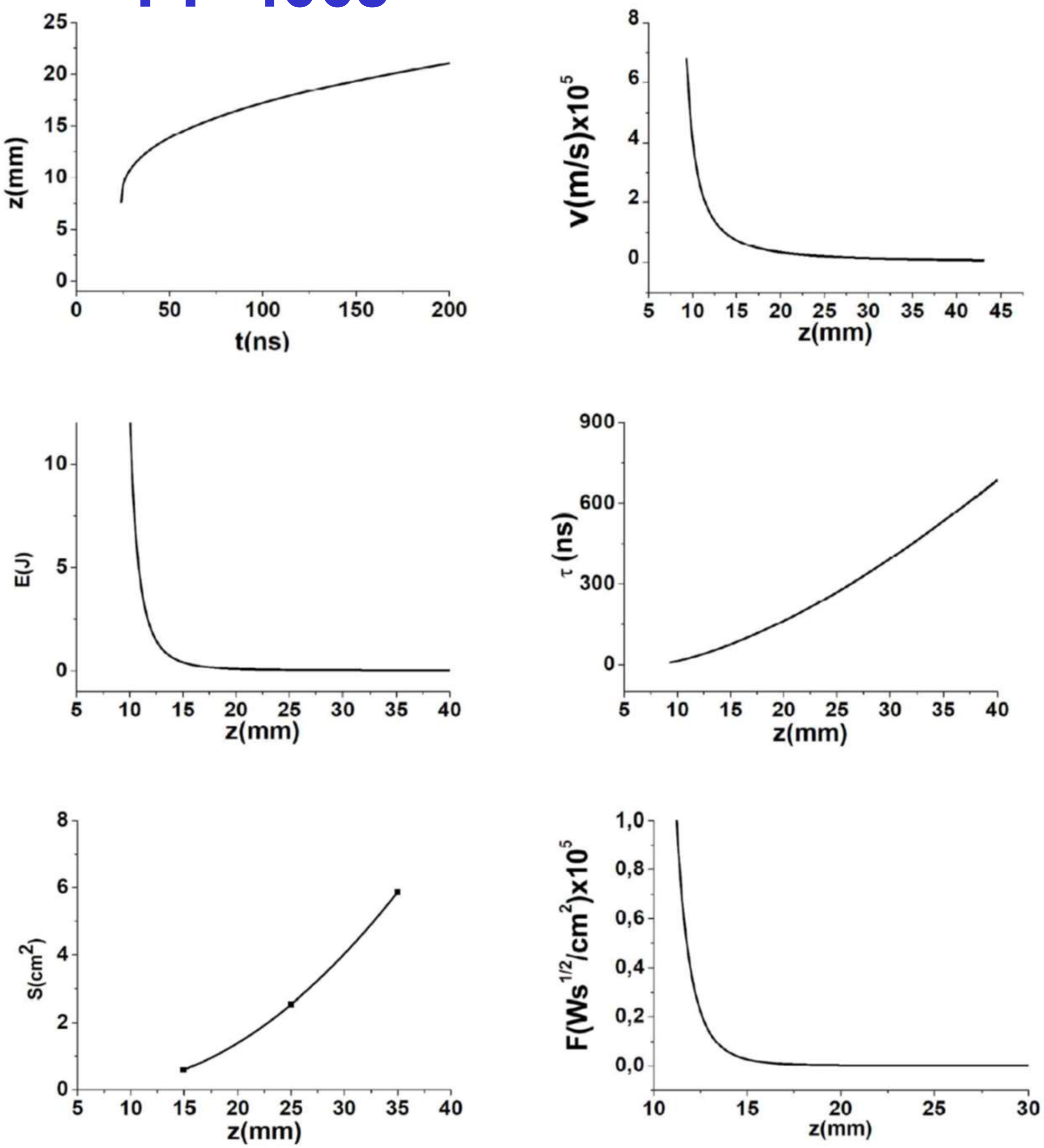
Time of interaction, $\tau \sim L / v$

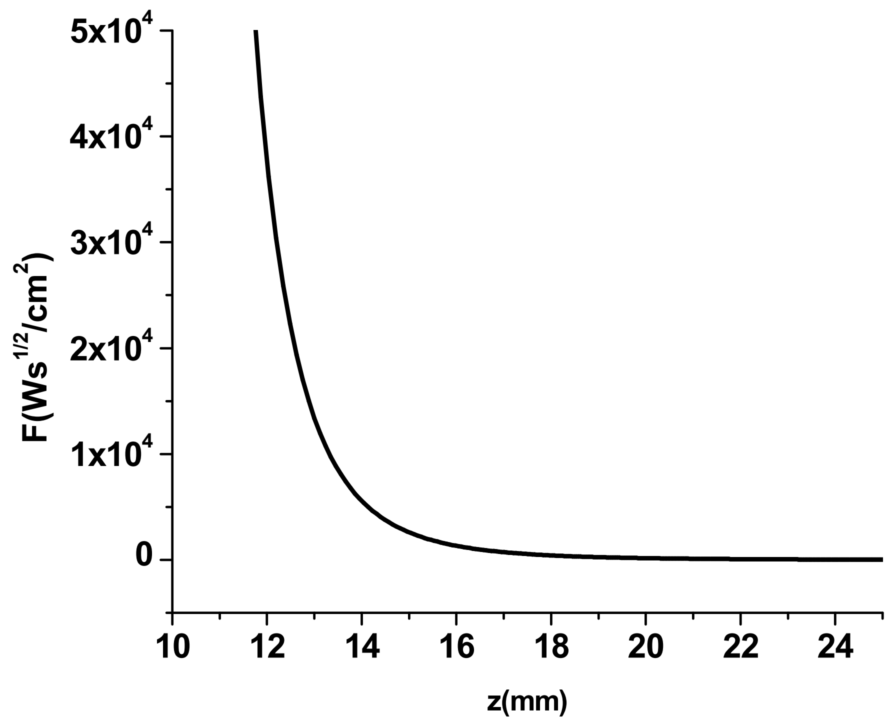
Interaction area, S, is measured from images of irradiated samples

Tunable Damage Factor

P²mc

PF-400J





Expected Damage in Fusion Reactor

ITER:

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

at 0.5 – 1 Hz , 10^3 pulses

IFE:

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

at 10 Hz

PF-400J:

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

at 0.05 Hz

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IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion 55 (2015) 093011 (8pp) doi:10.1088/0029-5515/55/9/093011

Morphological and structural effects on tungsten targets produced by fusion plasma pulses from a table top plasma focus

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Matter and Radiation at Extremes RESEARCH ARTICLE scitation.org/journal/mre

A model for defect formation in materials exposed to radiation

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Sergio Davis,[1,2,a)] Felipe González-Cataldo,[3,4,b)] Gonzalo Gutiérrez,[4,c)] Gonzalo Avaria,[1,2] Biswajit Bora,[1,2] Jalaj Jain,[1] José Moreno,[1,2] Cristian Pavez,[1,2] and Leopoldo Soto[1,2,d)]

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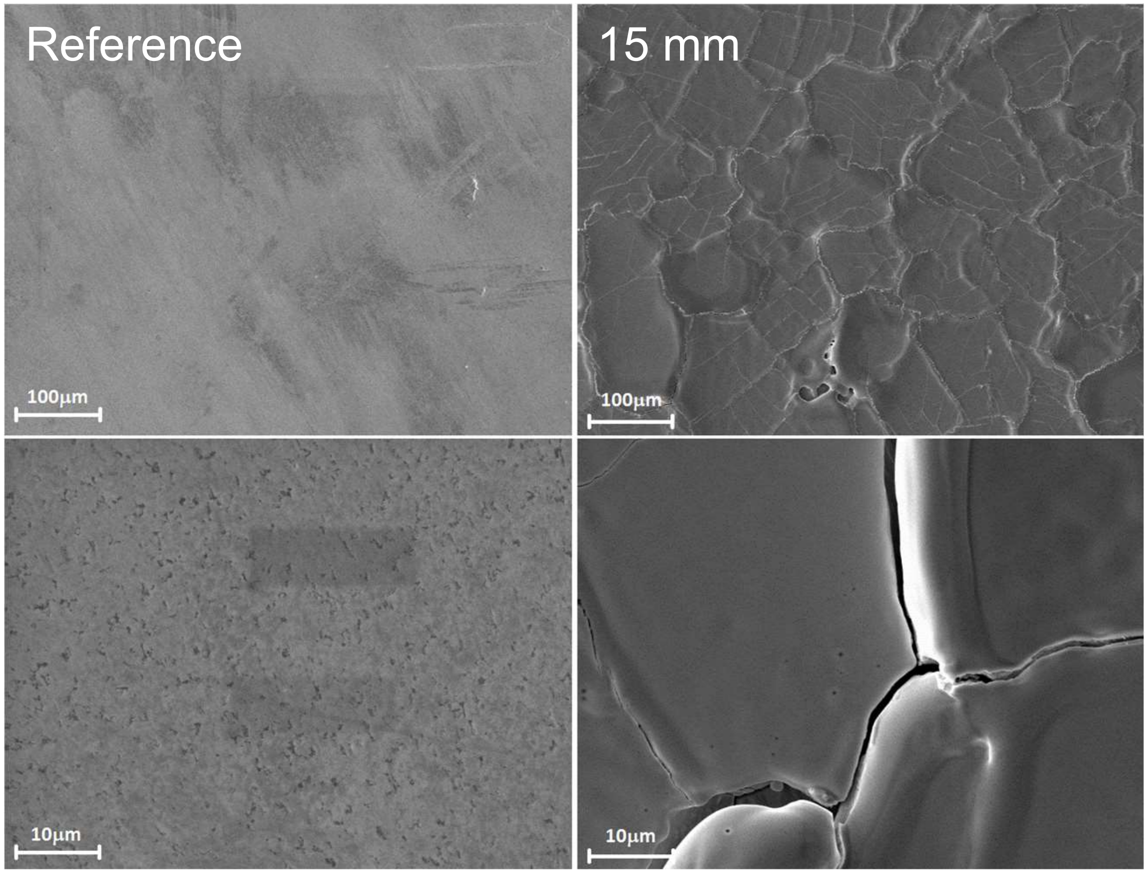
PF-400J

Morphological Effects on W SEM

P²mc

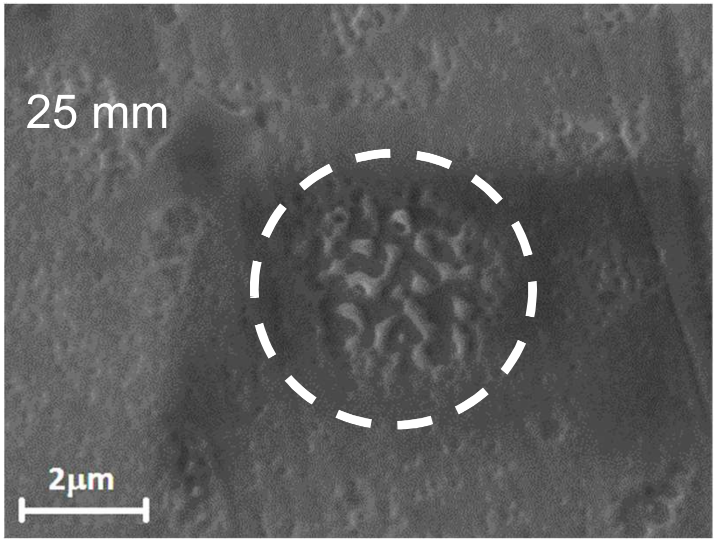
15 mm



Scanning Electron Microscope images to comparison the extreme irradiation targets

Scanning Electron Microscope image showing targets.

- ✓ Ref. ➡ smooth surface
- ✓ 15 mm ➡ microcracks and holes surface melting
- ✓ 25 mm ➡ some melting
- ✓ 35 mm ➡ no melting



M. J. Inestrosa Izurieta, E. Ramos-Moore and L. Soto, Nuclear Fusion 55, 093011 (2015)

6 order of magnitud in energy translates in only 1 order of magnitude in damage factor

damage factor, F ~ q·$\tau^{1/2}$ α $\tau^{1/2}$ α $a^{1/2}$ α $(E^{1/3})^{1/2}$

$a^3 \, \alpha \, E$

$$F \, \alpha \, E^{1/6}$$

PF, 1MJ	F
PF, 1kJ	~ 1/3 F
PF, 100J	~ 1/5 F
PF, 10J	~ 1/7 F
PF, 1J	~ 1/10 F

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

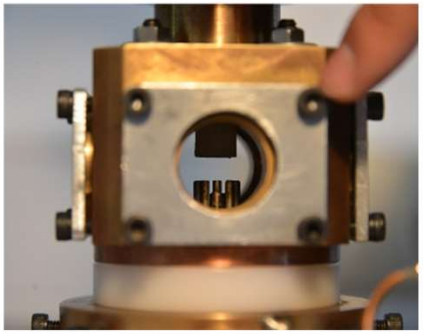
A repetitive table top pulsed plasma device to study materials under intense fusion relevant pulses

Plasma focus PF-2J with tuneable damage factor F

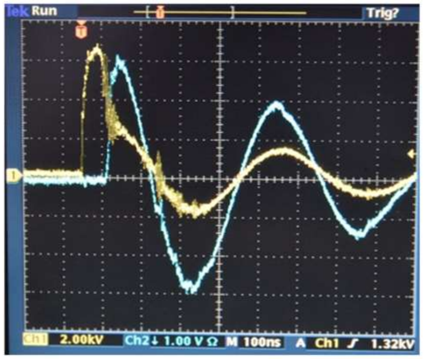
The damage factor F, is tune in, adjusting the distance of the sample from the anode top.

a)

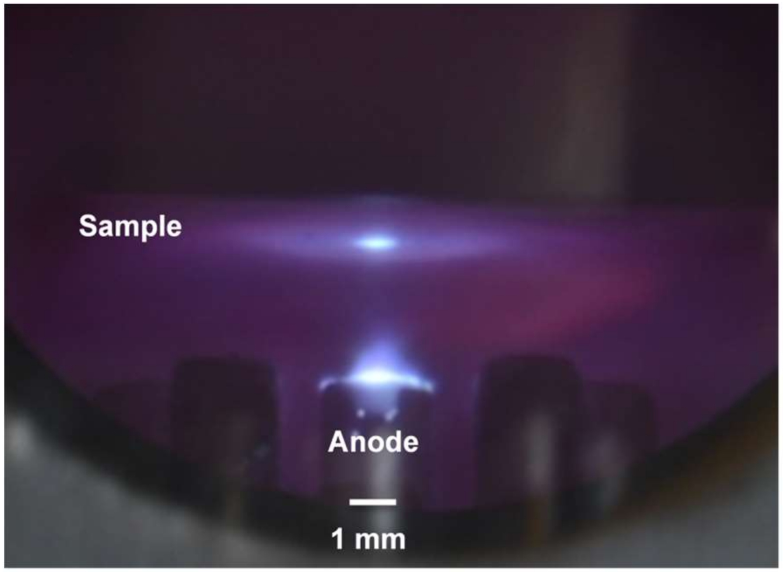
b)



c)



a) The whole device, including the X, Y, Z positions for materials samples. In the axis Z is a micro positioner. b) Discharge chamber details, cathode bars and anode at center. Over the anode is the sample holder that is axially adjusted. c) Electrical signals, voltage and current derivative for a discharge in hydrogen at 6 mbar.



Time integrated photograph of a single discharge in the PF-2J. It can see plasma on the top of the anode (anode diameter 2.2mm). Also a bright spot it can see in the sample located over de anode due to the axial plasma shock interacting with the sample.

L. Soto et al, in preparation

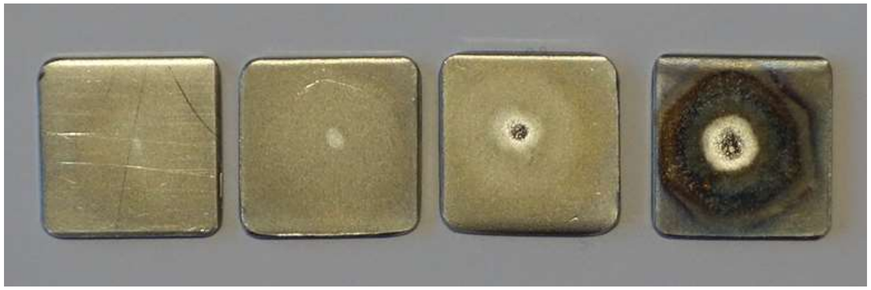
Plasma focus PF-2J with tuneable damage factor F

P²mc

AISI 304

Z = 2.8 mm

$F \sim 10^4 (W/cm^2)\ s^{1/2}$



15 mm

0.1 Hz

1shot **10 shots** **100 shots** **1000 shots**

1 mm

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Plasma focus PF-2J with tuneable damage factor F

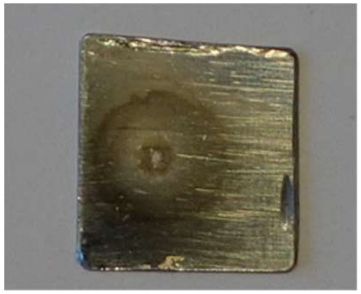
P^2mc

Mo

513 shots

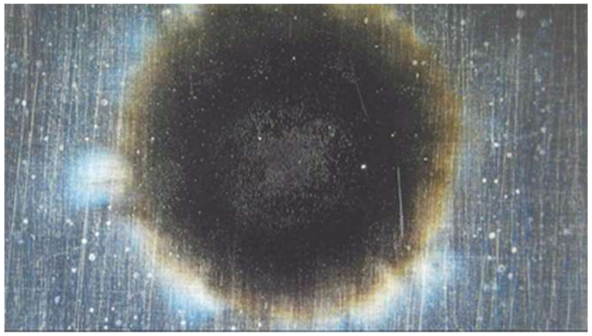
Z = 2.8 mm

$F \sim 10^4 (W/cm^2)\ s^{1/2}$



15 mm

0.1 Hz



1 mm

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Applications to biology and biomedicine

P²mc

Effects of pulsed radiation in cell

AIP ADVANCES 7, 085121 (2017)

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Hundred joules plasma focus device as a potential pulsed source for *in vitro* cancer cell irradiation

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Journal of Applied Physics | ARTICLE | scitation.org/journal/jap

Hyper-radiosensitivity in tumor cells following exposure to low dose pulsed x-rays emitted from a kilojoule plasma focus device

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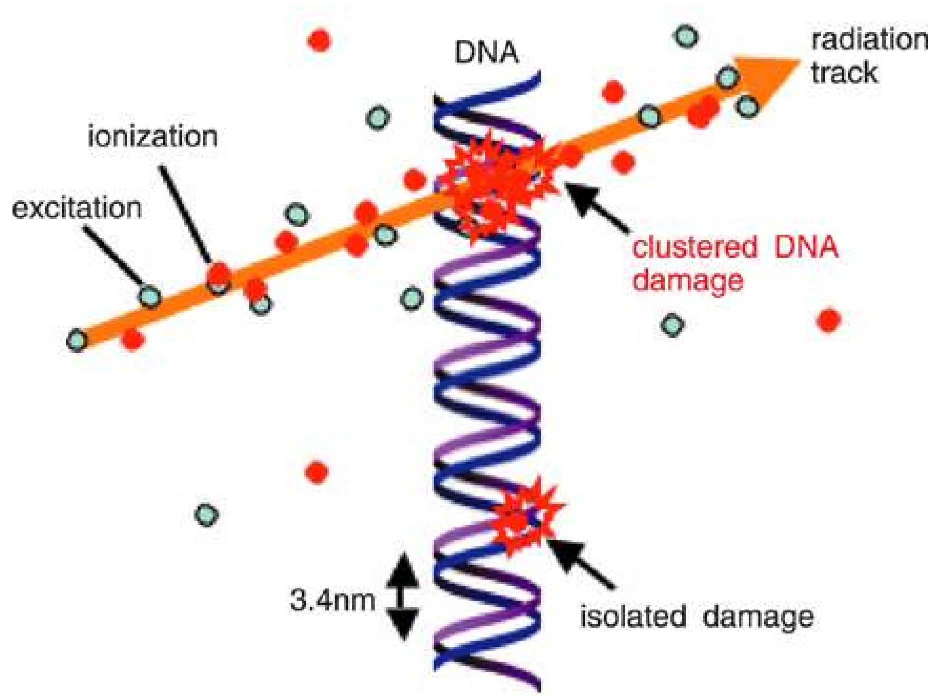
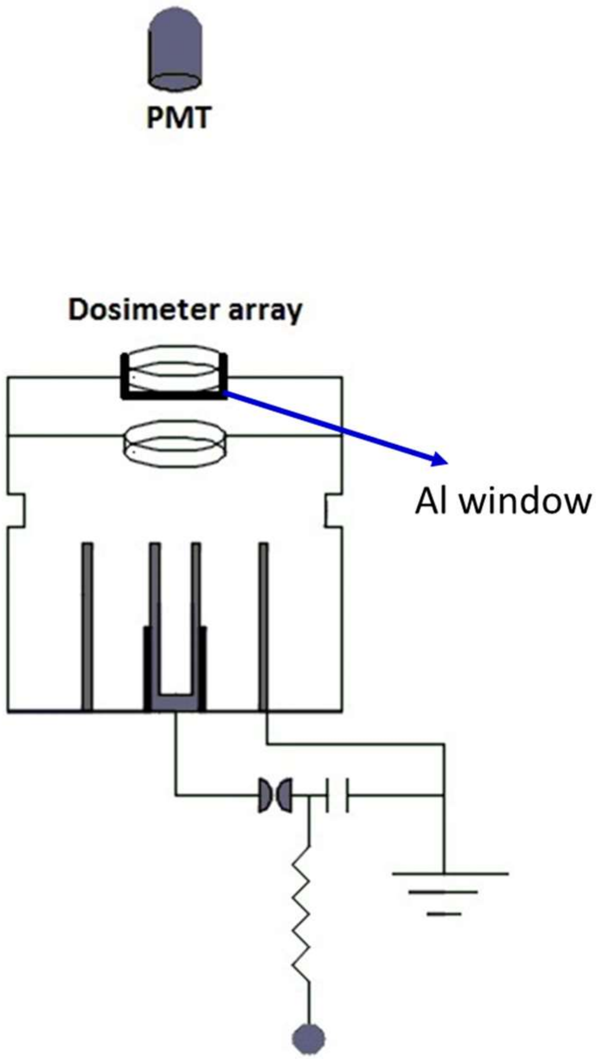
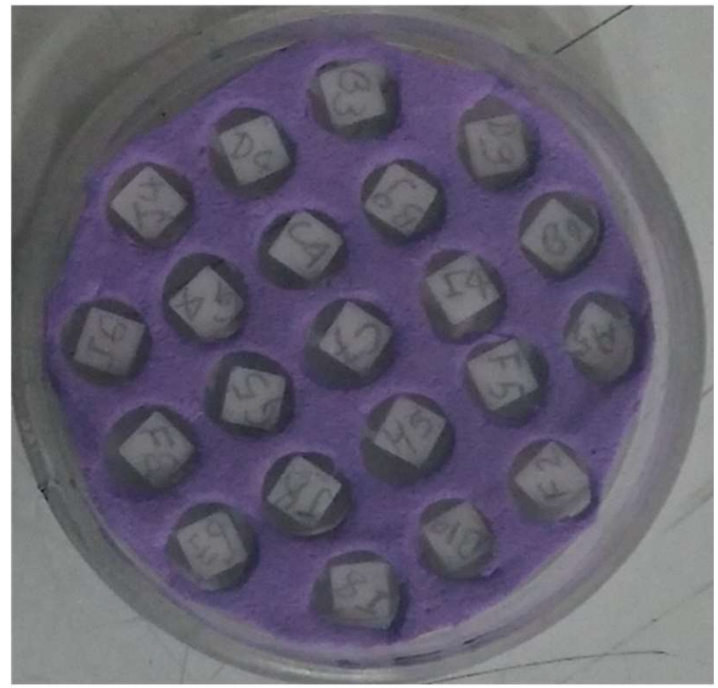

DNA
radiation track
ionization
excitation
clustered DNA damage
3.4nm
isolated damage

Effects of pulsed radiation in cell

P²mc



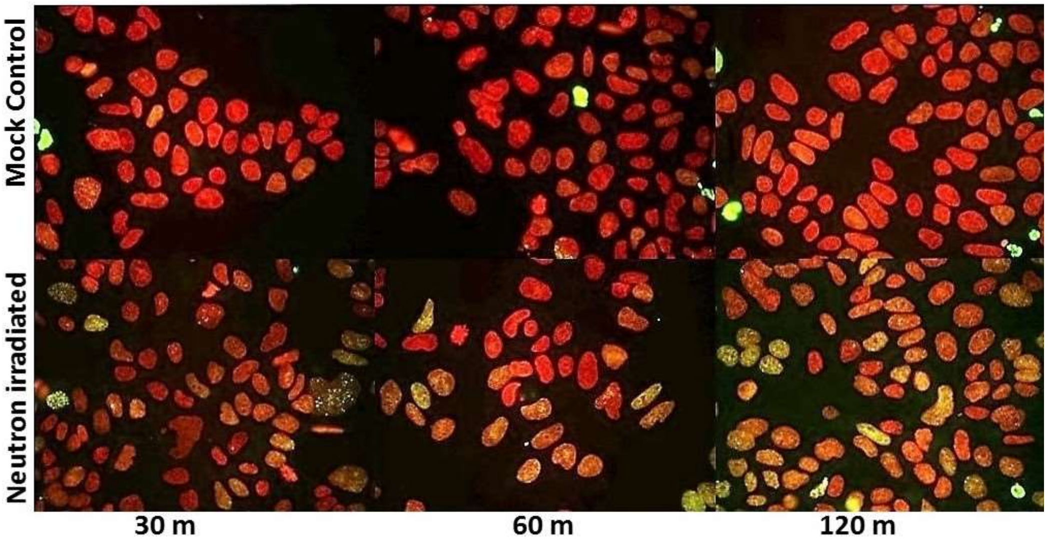


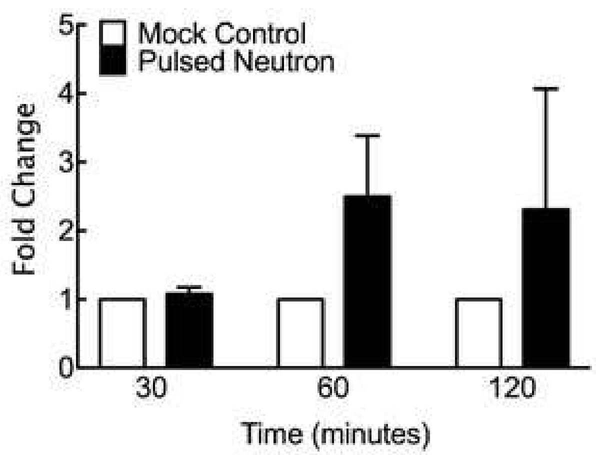
J. Jain, J. Moreno, R. Andaur, R. Armisen, D. Morales, K. Marcelain, G. Avaria, B. Bora, S. Davis, C. Pavez, and L. Soto, AIP Advances **7**, 085121 (2017)

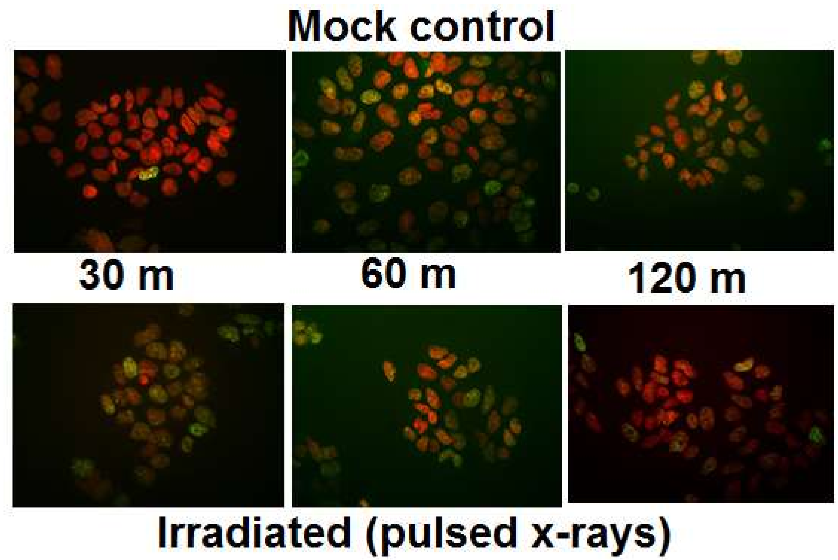
Effects of neutron and x-ray pulses on cancer cell

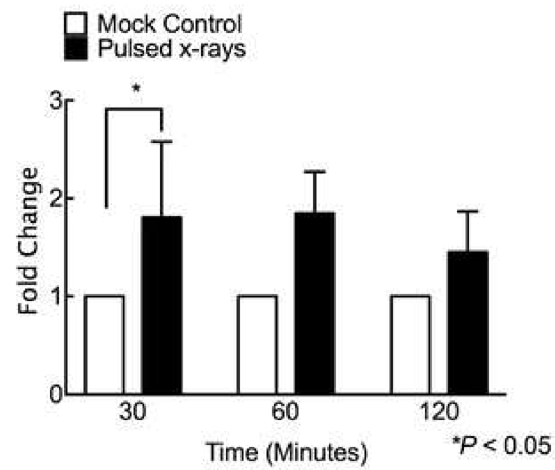
P²mc

DNA damage DSB









"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)

- **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.**
- **The effect depends on the repair time of the cells. Therefore, the time between pulses is a relevant parameter**

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)

J. Jain, H. Araya, J. Moreno, S. Davis, R. Andaur, B. Bora, C. Pavez, K. Marcelain, and L. Soto, J. App. Phys **130**, 164902 (2021)

Miniaturized plasma thruster for CubeSat nanosatellites

Leopoldo Soto
Research Center on the Intersection of
Plasma Physics, Matter and Complexity, P^2mc

MOTIVATION

P²mc

Nanosatellite SUCHAI, University of Chile

SUCHAI-1
10 cm x 10 cm x 10 cm
At present in orbit and in operation, but without orientation system

SUCHAI-2 and 3
Ready to be launched

M. Diaz *et al*., Advances in Space Research, 58, 2134-2147 (2016)

Pulsed Plasma Thrusters, PPT

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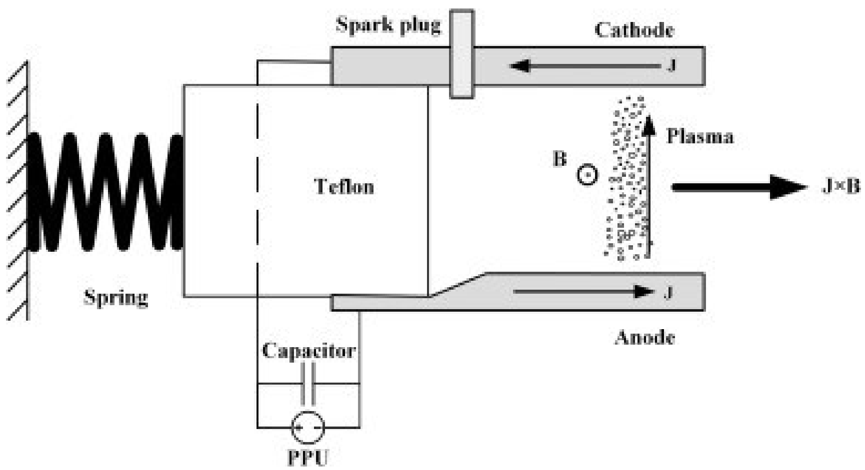
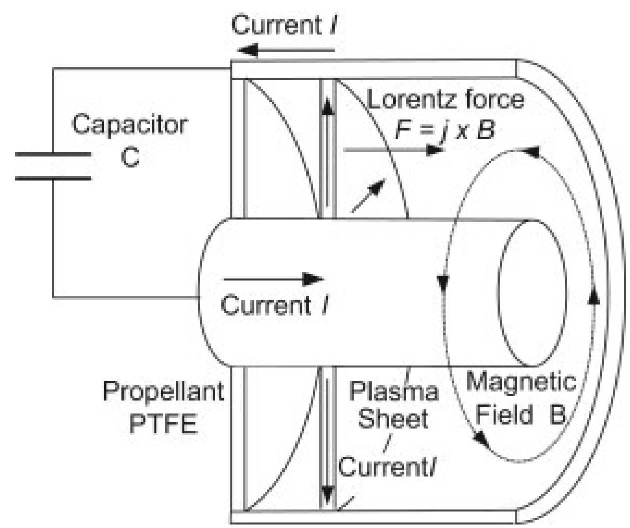
Typical PPT´s diagram



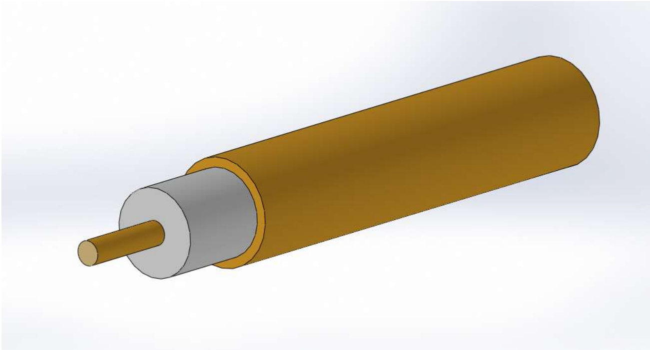
parallel plate electrodes



Coaxial electrodes

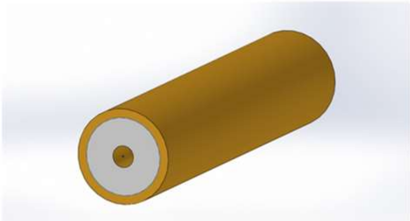
Electrode used to make the plasma guns

Exterior diameter: 2.2 mm
Interior electrode diameter: 0.5 mm
Insulator between electrodes Teflon

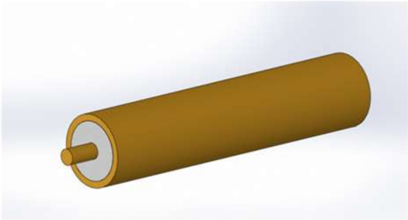


4 different geometry electrodes were tested at pressure < 10^{-4} mbar

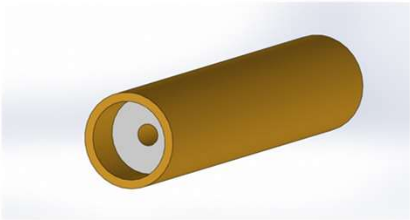
Flat



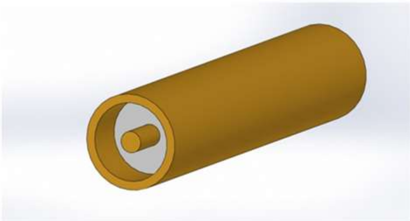
Anode extended



Cathode extended



Anode and cathode extended



Experiments on PPT in modified Nanofocus

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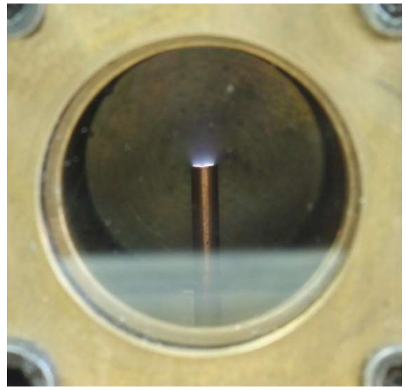
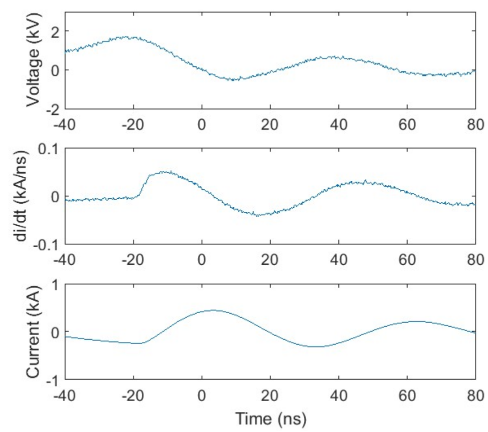
Coaxial plasma gun with cathode and anode e



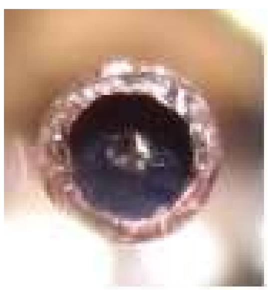



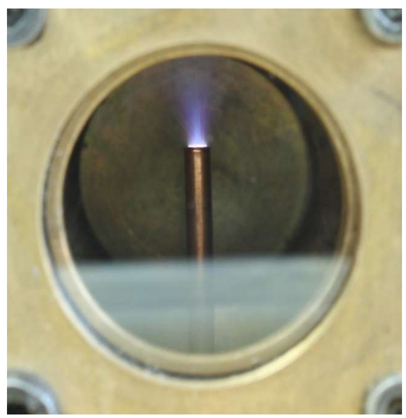
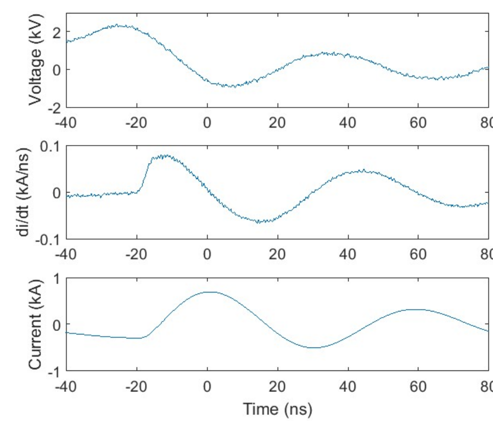
plasma gun

plasma discharge

V(t), dI/dt, I(t) signals
Vbreakdown = 1.7 kV ; Imax = 0.4 kA

Coaxial plasma gun with cathode extended



plasma gun

plasma discharge

V(t), dI/dt, I(t) signals
Vbreakdown = 2.3 kV ; Imax = 0.7 kA

"Pulsed Plasma Thruster Based On Ultra-miniaturized Plasma Focus" L. Soto, J. Pedreros, R. Silva, P. Maldonado, G. Avaria, C. Pavez, J. Moreno, and M. Diaz, 19th International Congress on Plasma Physics, ICPP 2018, Vancouver, Canada, June 2018.

Miniaturized Pulsed Plasma Thrusters, μPPT

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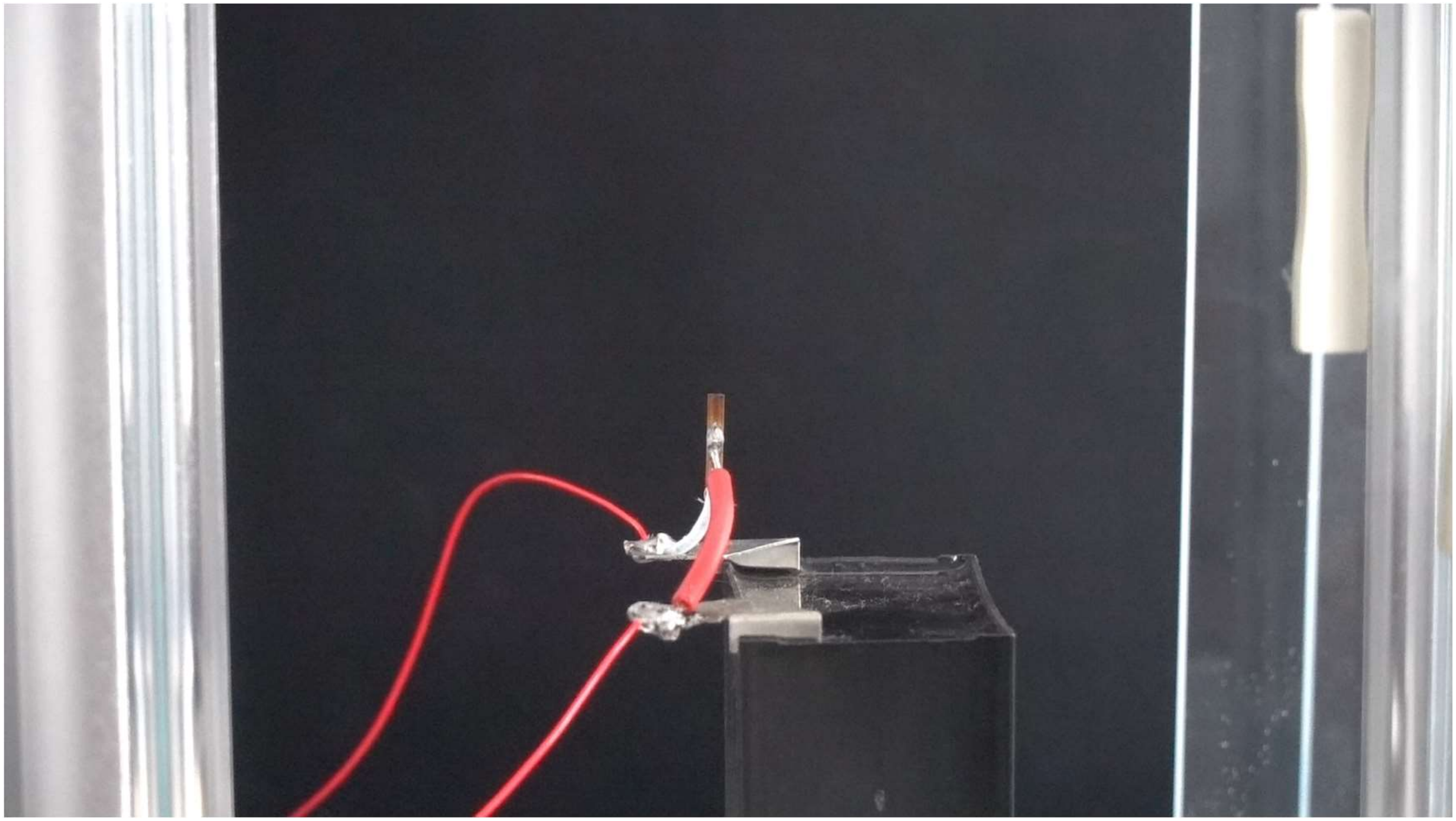

Plasma Physics and Nuclear Fusion at the Chilean Nuclear Energy Commission

Comisión Chilena de Energía Nuclear
Ministerio de Energía
Gobierno de Chile

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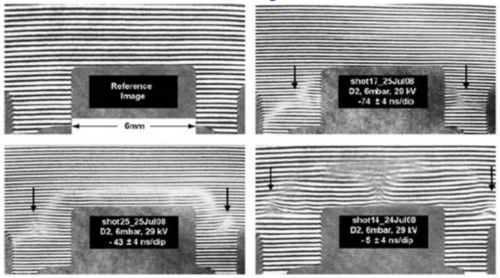
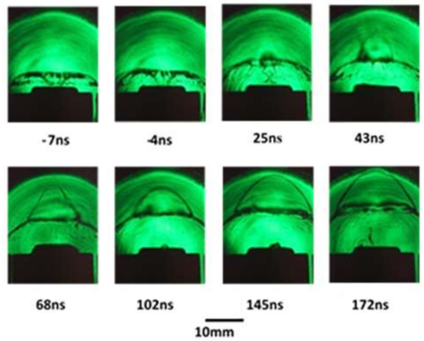
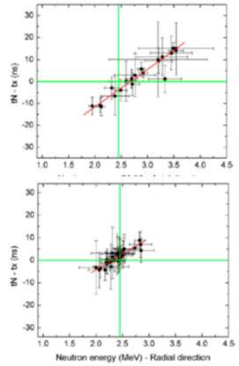
Basic Physics



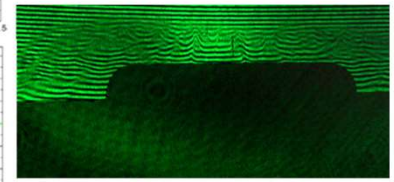
Toroidal singularity



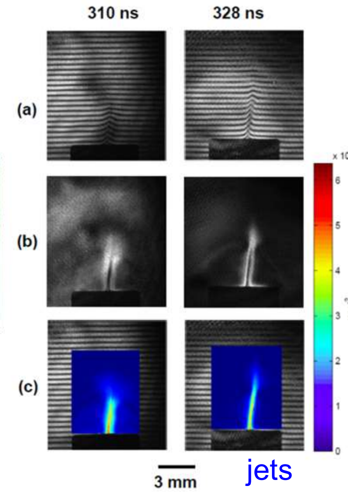
shocks



neutron energy distribution

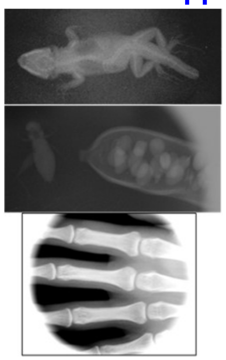


fillaments

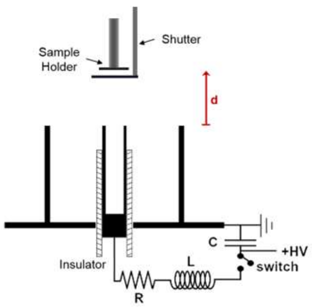


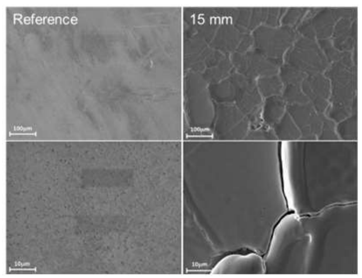
jets

Applications



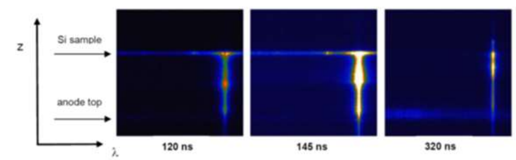
Pulsed x-ray and neuron sources



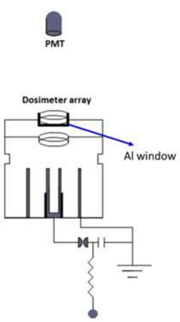


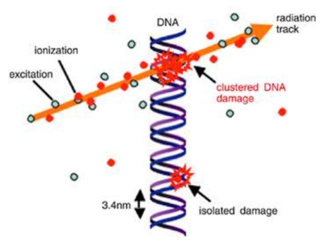
Effects on materials for 1st wall of nuclear fusion reactors

Plasma torch 20kW and microtorch 2 milliwats for materials and matter proccesing

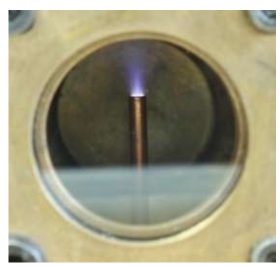


spectroscopy





Effects of pulsed radiation in life matter



Pulsed plasma thruster for nanosatelites

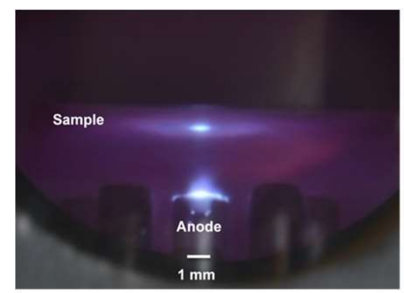


Table top plasma focus with tuneable damage factor F

Leopoldo Soto
Research Center on the Intersection of
Plasma Physics, Matter and Complexity, P²mc

Comisión Chilena de Energía Nuclear
Ministerio de Energía
Gobierno de Chile

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Conclusion

YES!
It is posible to do relevant experimental plasma physics, fusion research and to produce new relevant knowledge in a small country.

Our facilities are open to researchers from different countries.

Our small and portable devices are available to be reproduced in other countries.

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

THANK YOU
FOR YOUR ATENTION

LEOPOLDO.SOTO@CCHEN.CL