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

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Topics

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

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

Basic Research and Applications

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

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Part 1: outline

- What is a pinch plasma: Z-pinch, θ-pinch, Screw pinch
- Why Z-pinches are interesting?
- Z-pinch in equilibrium
- Stability
- Pulsed power
- Plasma focus

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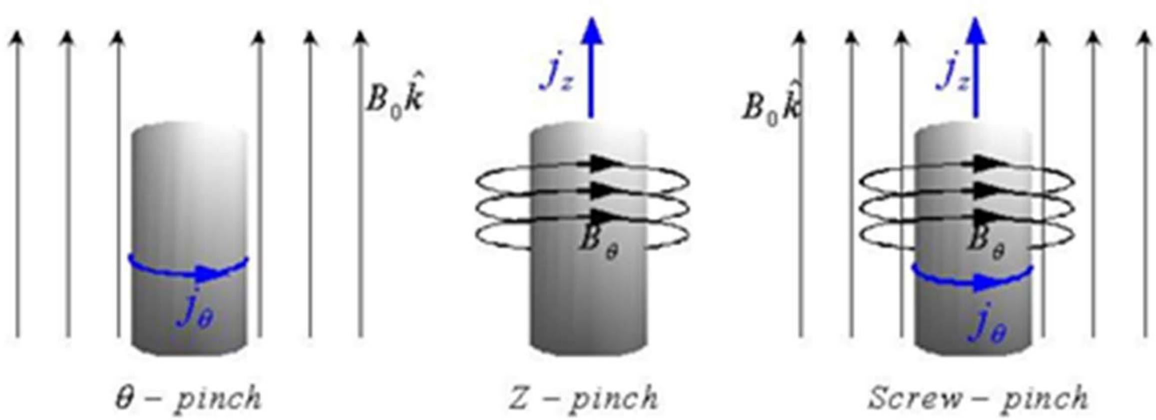
Pinch plasmas



Thermal pressure vs Magnetic pressure

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

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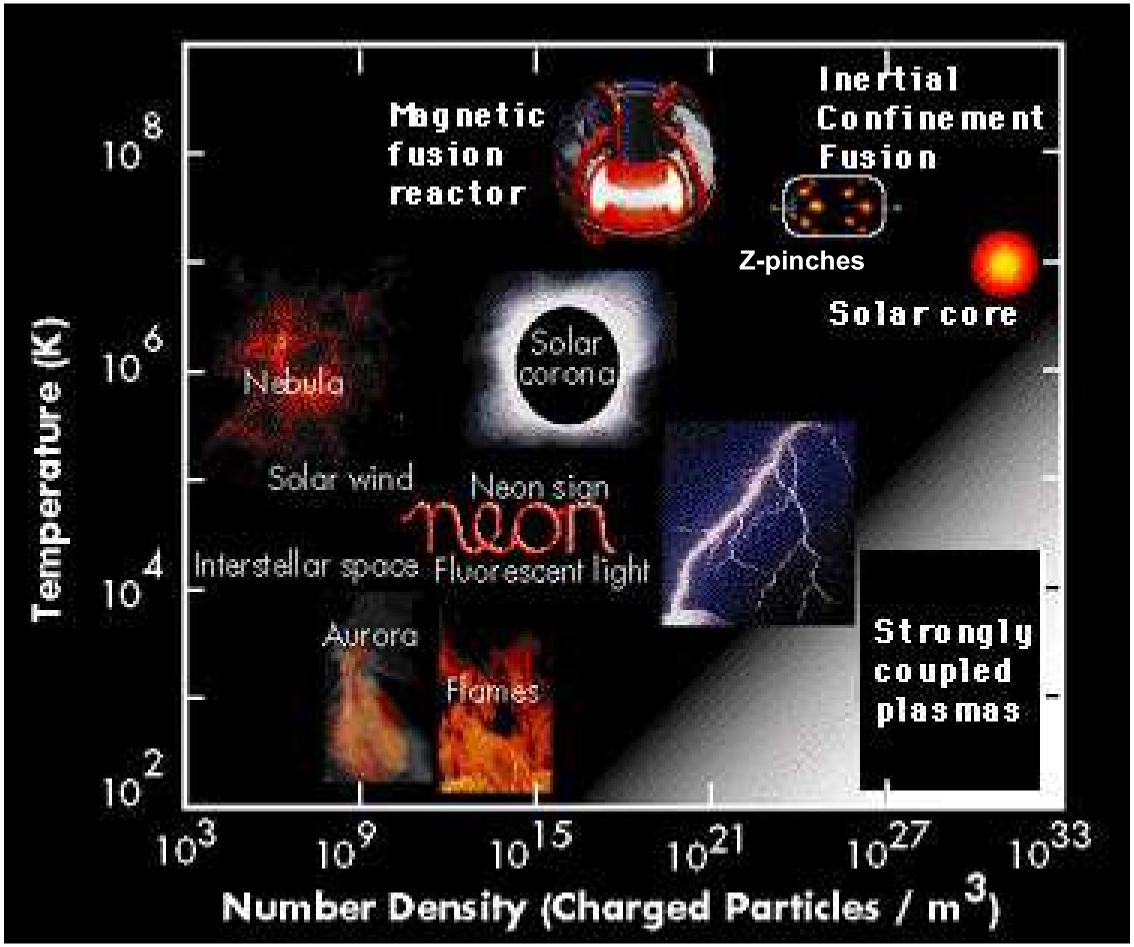
Magnetic fusion reactor
Inertial Confinement Fusion
Z-pinches
Solar core
Solar corona
Nebula
Solar wind
Neon sign
neon
Interstellar space
Fluorescent light
Aurora
Flames
Strongly coupled plasmas
Temperature (K)
10^2
10^4
10^6
10^8
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)

Why Z-pinches are interesting?

Physics- Possibility to study:

- Dense-hot plasmas
- High energy density and high mass density state of matter
- Fast plasma dynamics (instabilities, turbulence, magnetic field reconnection, filaments, anomalous transport phenomena)

Fusion:

- Basic studies
- The pinch is used as a very intense soft X-ray source which irradiates a D-T target.

Applications. Pinches produce:

- Ion and electron beams
- X-ray
- Neutrons (from fusion reactions in D_2)
- Plasma jets

X-ray and neutron nanoflashes (high resolution X-ray tomography, substance detection, non-destructive testing)

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Z-pinch: a hot-dense plasma

Momentum equation

$$\vec{\nabla} p = \vec{J} \times \vec{B} \Rightarrow -\frac{dp}{dr} = J_z B_\theta \qquad (1)$$

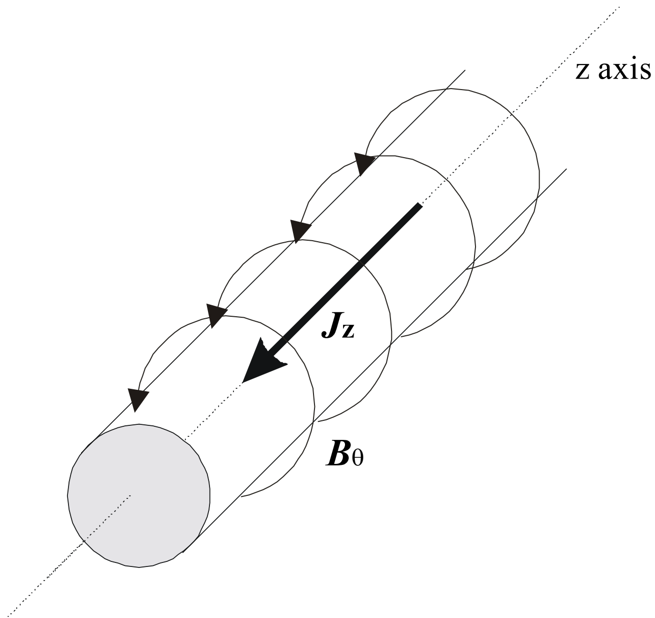
Ampère law

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} \Rightarrow J_z = \frac{1}{\mu_0 r} \frac{d(rB_\theta)}{dr} \qquad (2)$$

(1) in (2)

$$\frac{dp}{dr} + \frac{B_\theta}{\mu_0 r} \frac{d(rB_\theta)}{dr} = 0 \qquad (3)$$

$$\frac{d}{dr}\left(p + \frac{B_\theta^2}{2\mu_0} \right) + \frac{B_\theta^2}{\mu_0 r} = 0 \qquad (4)$$



Z-pinch geometry

Considering a pinch of radius a, multiplying (4) by r^2 and integrating over the pinch cross section,

$$\int_0^a r^2 \frac{dp}{dr} dr = -\frac{1}{\mu_0} \int_0^a (rB) d(rB) \qquad (5)$$

Integrating by parts the left hand side

$$\left[r^2 p \right]_0^a - 2\int_0^a prdr = -\frac{1}{2\mu_0} \left[(rB)^2 \right]_a \qquad (6)$$

$p = 0$ at $r = a$ *and* $T(r) = T_i = T_e = T$, and for a cuasi neutral fully ionized gas, $n_i = n_e = n$, can be considered as an ideal gas,

$$p = (1+Z) n_i k_B T \qquad (7)$$

$$(n_e = Z n_i; T_e = T_i = T) \qquad (8)$$

n_i, n_e number of ions or electrons per unit volumen
Ti , Te ions or electrons temperature

Obtaing the number of ions per unit lenght of the pinch

$$N_i = \int_0^a 2\pi r n_i(r) dr \qquad (9)$$

Integrating the Ampere law over the pinch

$$\left[(rB)^2\right]_a = \frac{(\mu_0 I)^2}{4\pi^2} \qquad (10)$$

Finally, (10), (9), (8) and (7) in (6)

$$\mu_0 I^2 = 8\pi(1+Z)N_i k_B T \qquad (10)$$

Bennett relation

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Bennett relation

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

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

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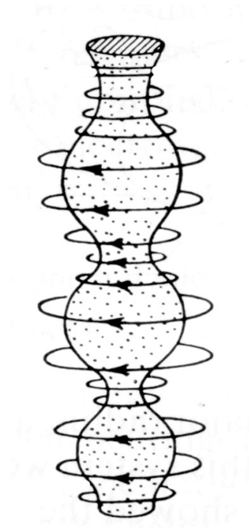
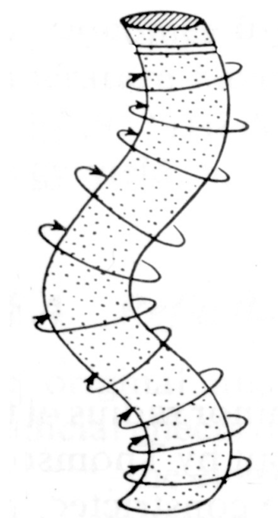
Stability

MHD instabilities appears in nanoseconds



m = 0
Sausage instability
(a)



m = 1
Kink instability
(b)

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Stability

Stability parameters it is depends on I, a, N

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

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

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

Lundsquisdt number, $S \;\alpha\; I^4aN^{-2}$

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

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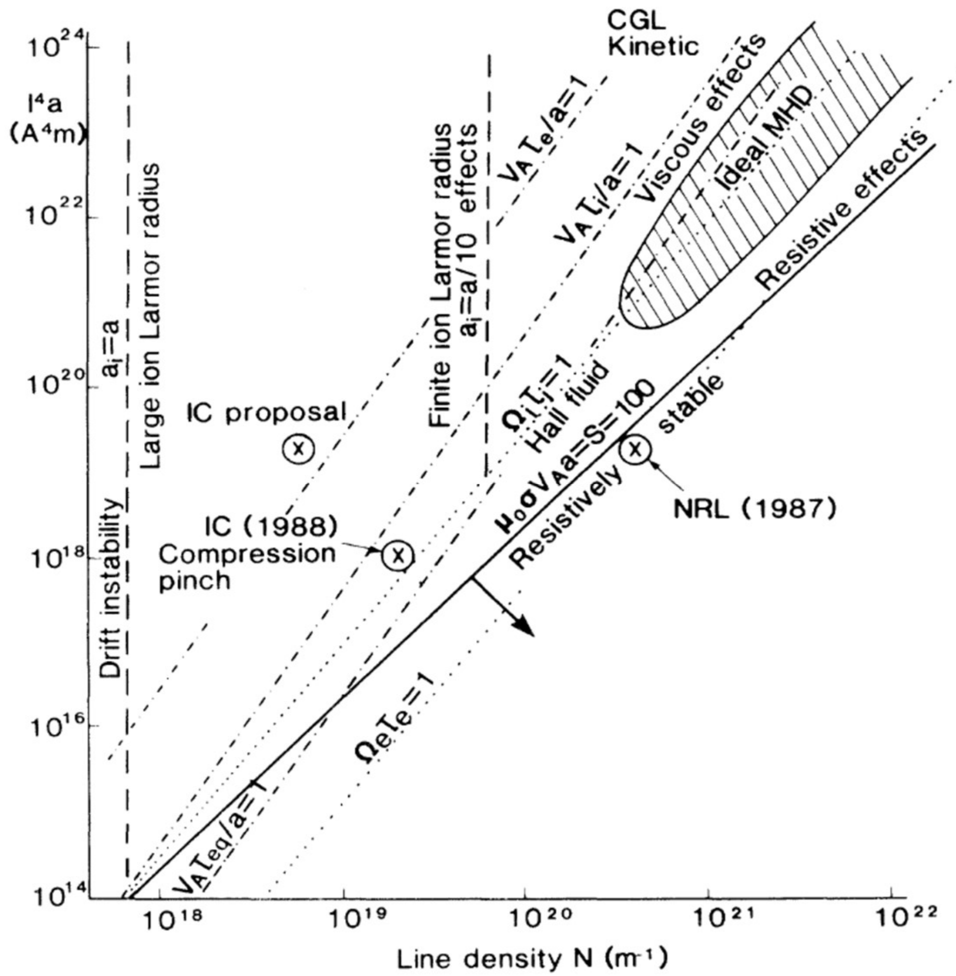
Universal Diagram for Z-pinch Stability



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

Various Z-pinch Configurations

IOP Publishing — Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion 53 (2011) 093001 (168pp) — doi:10.1088/0741-3335/53/9/093001

TOPICAL REVIEW

A review of the dense Z-pinch

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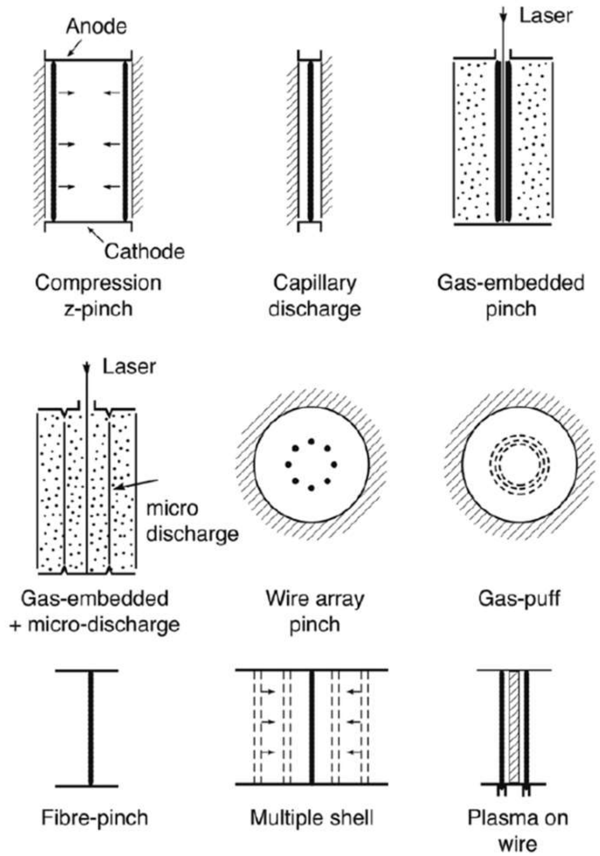


Figure 3. Various Z-pinch configurations. Reprinted from [52], copyright 1948, with kind permission from Springer Science + Business Media B.V..

will flow at first along the axis of the vessel. This is the gas-embedded Z-pinch [53]. This type of Z-pinch is the only one to be dominated by the $m = 1$ or kink instability, which we will discuss in section 3. A variant of this employing an additional hollow micro-discharge has been studied by Soto *et al* [54], figure 3.

How to obtain a dense-hot Z-pinch?

$$\mu_0 I^2 = 8\pi(1+Z)N_i k_B T$$

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}

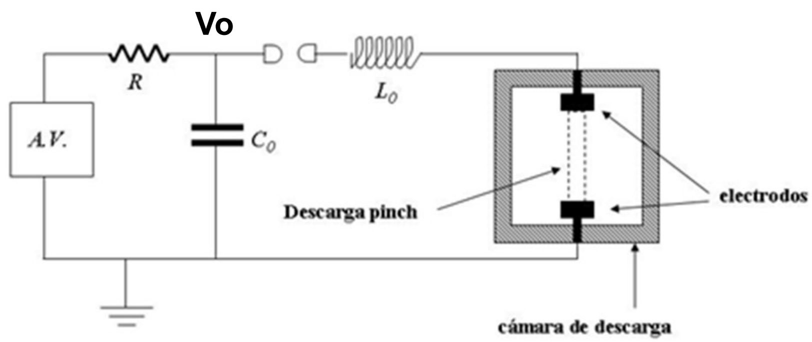
⟹ I = 800kA

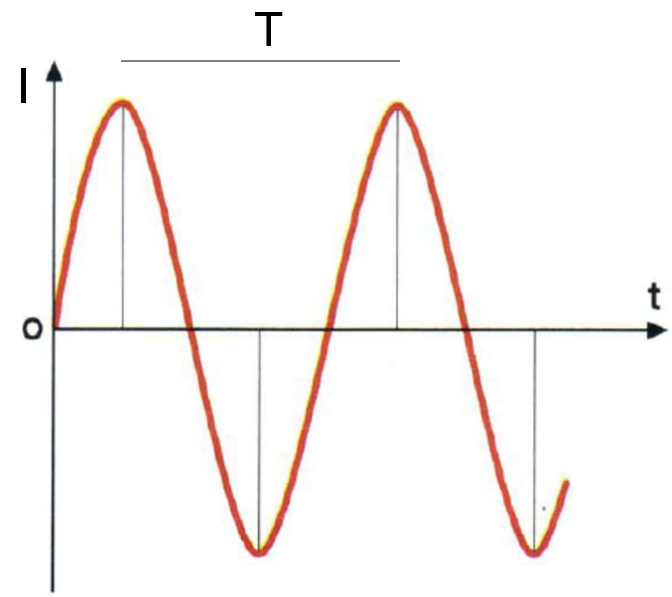
Currents of the order of ~ 1MA are required and must achieved in a short time < 100ns

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?

Is it posible obtain MA in 100ns using a LC circuit as generator?

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)

Low inductance is required. 20nH is a real value but is not easy to obtain

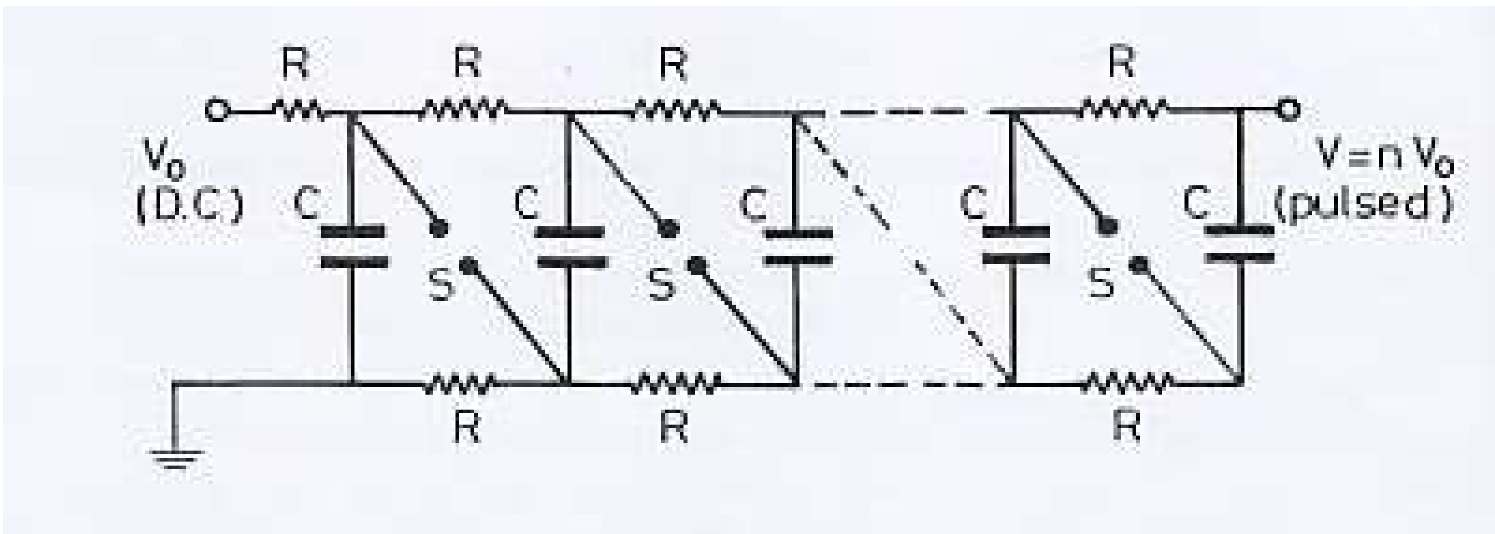
L ~ 20nH and T/4~100ns $\rightarrow$ C~200nF

Thus, Zo ~ 0.3Ω, I_{max} ~ 1MA requires Vo ~ 300kV

Marx generator

Capacitor bank charged in parallel and discharges in series

Vout=nVo, n=number of capacitors



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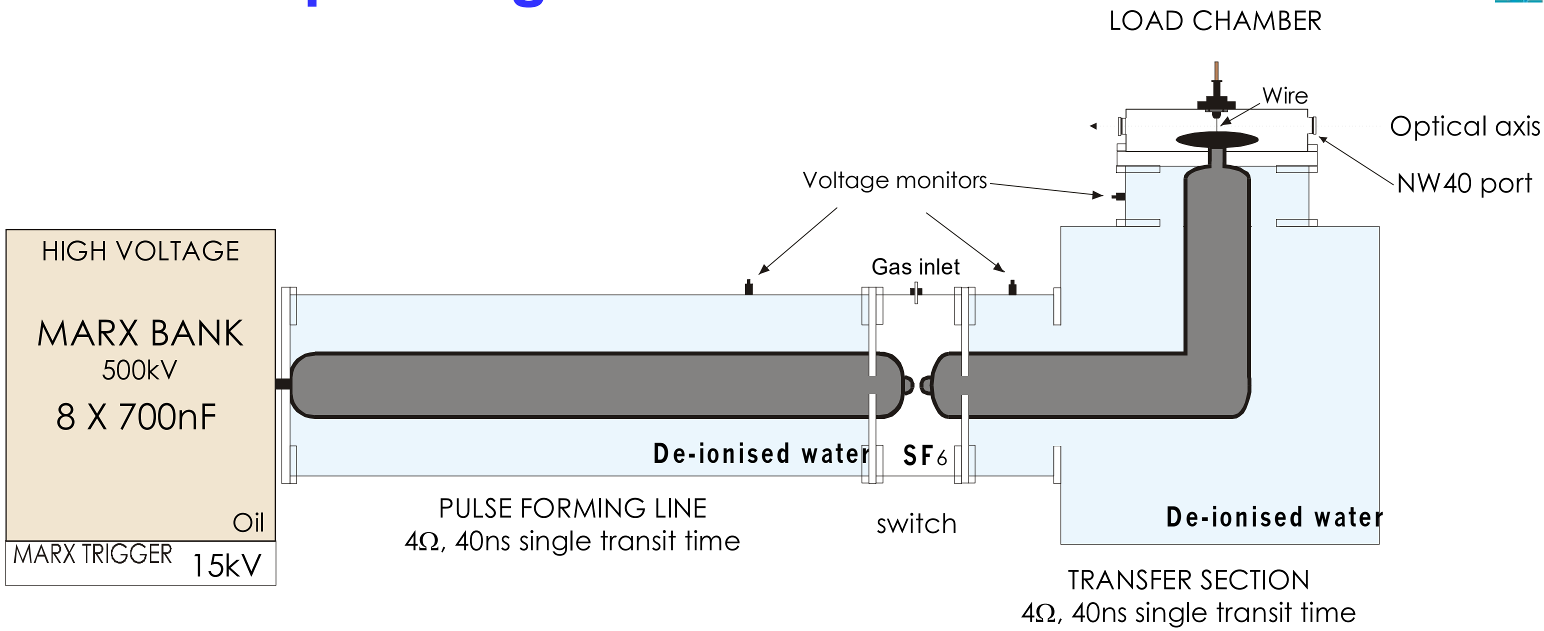
Pulse power generator



. Schematic of IMP generator

Marx generator
Capacitor bank charged in parallel and discharges in series

Vout=nVo, n=number of capacitors

Pulse forming line, PFL

Pulse duration is 2 transist time

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	GEPOPU (PUC, Chile)	Llampüdkeñ (PUC, Chile)	SPEED 2 (CCHEN, Chile)	MAGPIE (Imperial College, UK)	Z Acelerator (Sandia NL, USA)
Stored Energy	2kJ	28kJ	187kJ	86kJ	11.4MJ
Power	0.02 TW		0.5 TW	1 TW	50 TW
Max. load voltaje	300kV	450kV	300kV	2MV	2.5MV
Max. current	200kA	400kA	4MA	1.5MA	20MA
Rise time	100ns	260ns	400ns	150ns	100ns
dI/dt	1×10^{12} A/s	2×10^{12} A/s	1×10^{13} A/s	1×10^{13} A/s	2×10^{14} A/s
Impedance	1.5Ω	variable	0.070Ω	1.24Ω (5/4 Ω)	0.120Ω (4.32/36 Ω)
PFL´s	Yes (1)	Yes(2)	No	Yes (4)	Yes (36)

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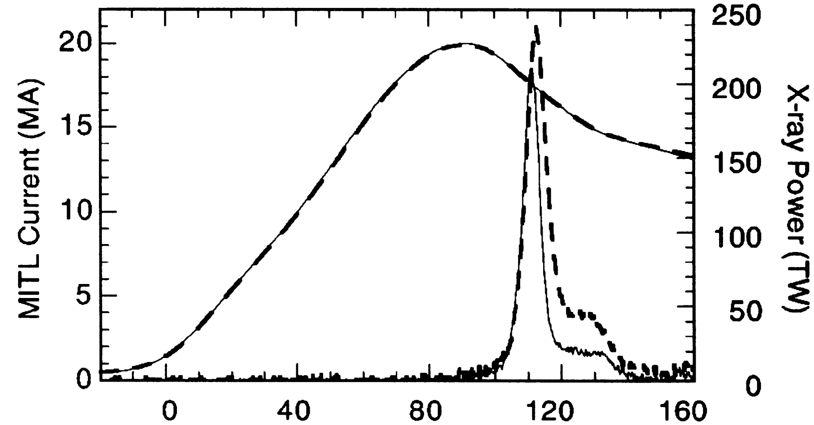
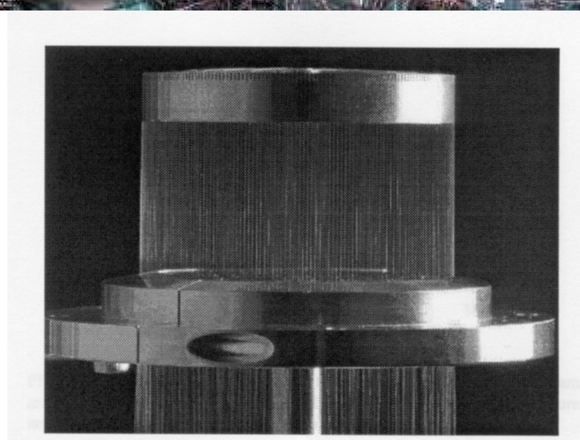
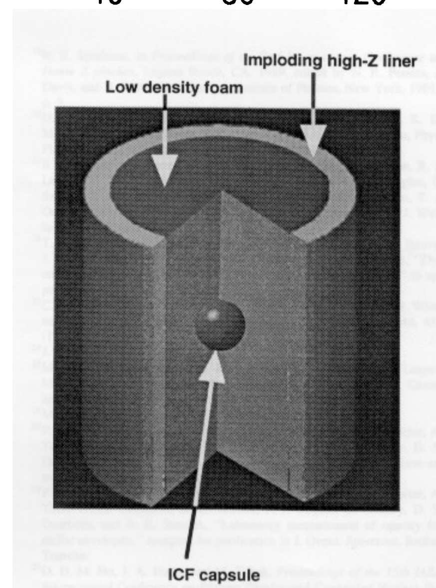
Z-pinch experiments in Sandia

(10-20 MJ)







Motivation

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

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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

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The plasma focus discharge

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

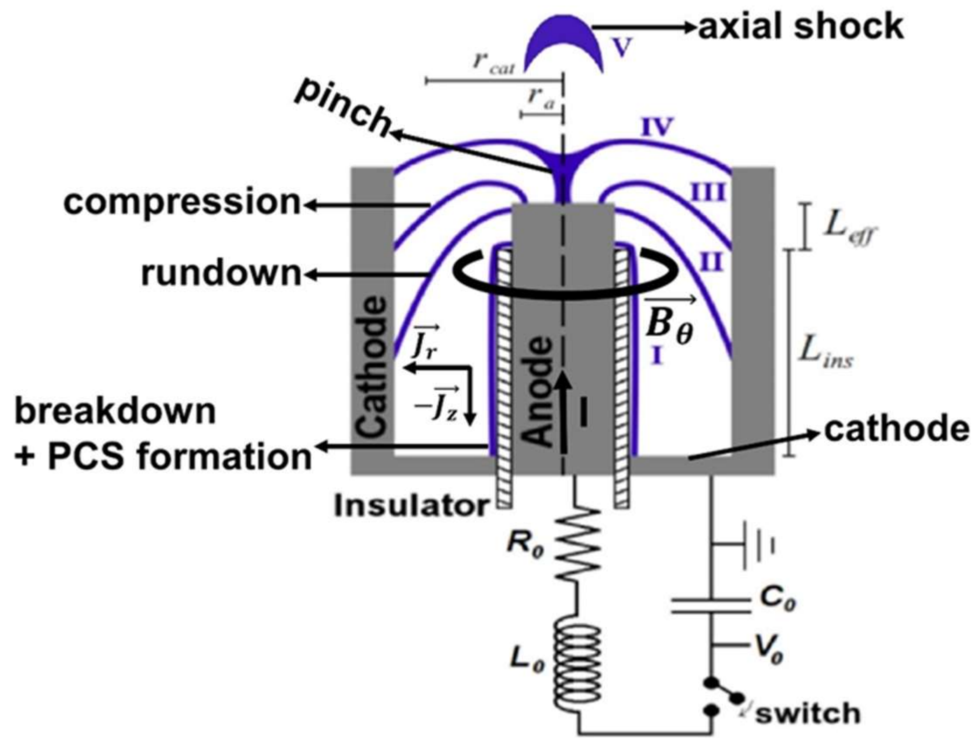
(I) The discharge starts over the insulator.

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

(III) and then to move radially (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 and an axial shock and plasma jets are produced



The plasma focus discharge

$E \sim$ kJ - MJ

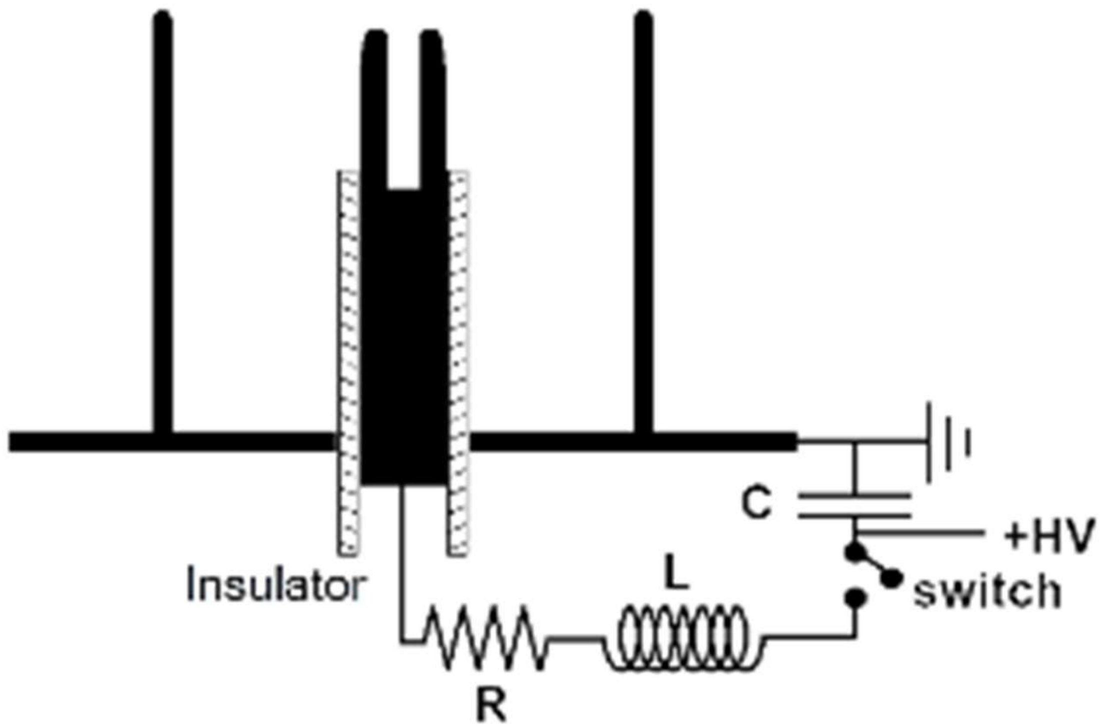
$I \sim$ 100kA - 1MA

$t_p \sim$ 10ns - 100ns

$Y_n \propto E^2$

$Y_n \propto I^{3.3\text{-}4.7}$

$n \sim 10^{25}$ m^{-3}



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Some PF devices in operation in the world during the period 1990-2000

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

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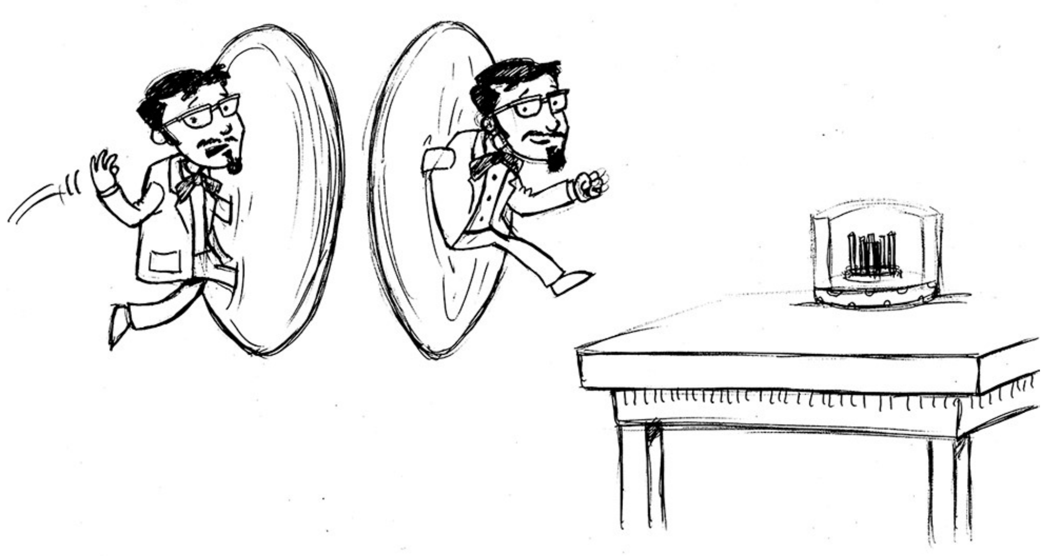
Our goal:

Miniature Plasma Focus Devices
< 1kJ
To find scaling laws



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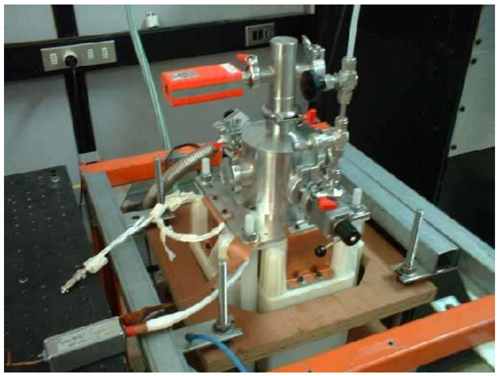
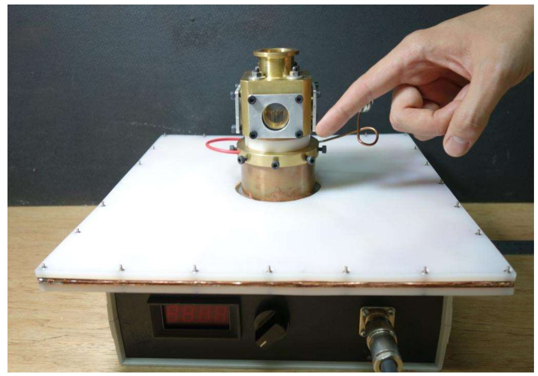
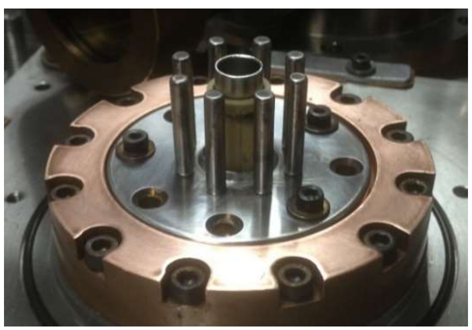
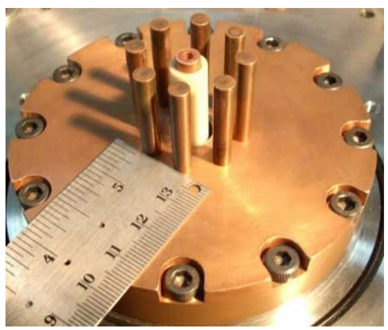
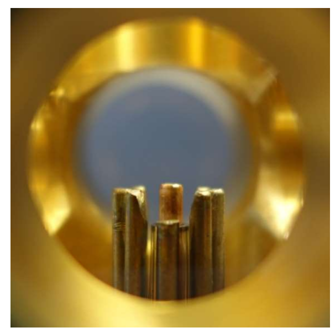
Under kJ PF devices at CCHEN

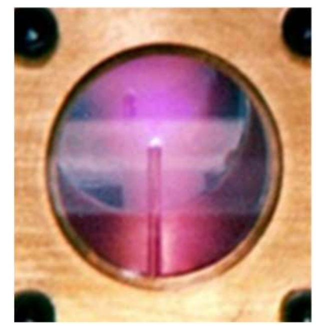






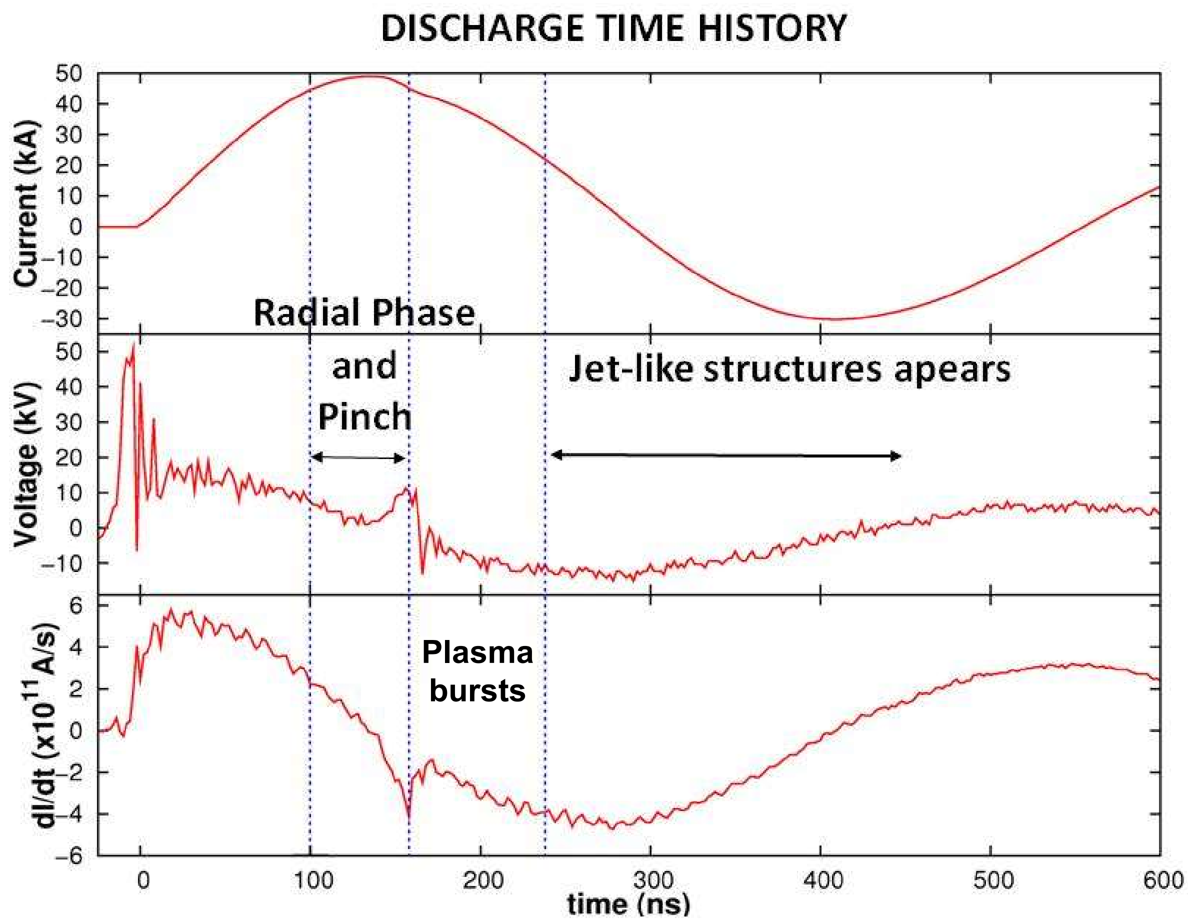






PF-400J **PF-50J** **PF-2J** **NF**

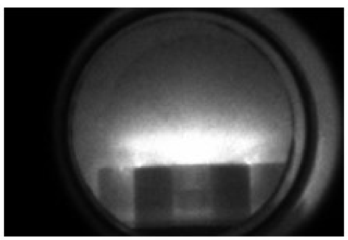
PF-50J


DISCHARGE TIME HISTORY
Current (kA)
Voltage (kV)
dI/dt (x10^11 A/s)
time (ns)
Radial Phase
and
Pinch
Jet-like structures apears
Plasma
bursts

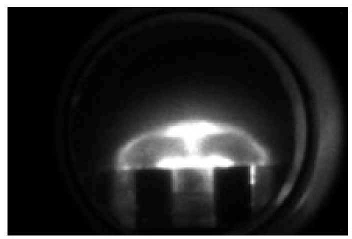
PF dynamics

- **Plasma Focus characterization**

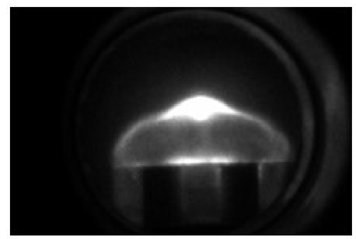
- **Before the pinch**
- **During the pinch**
- **After pinch**



before the pinch



pinch

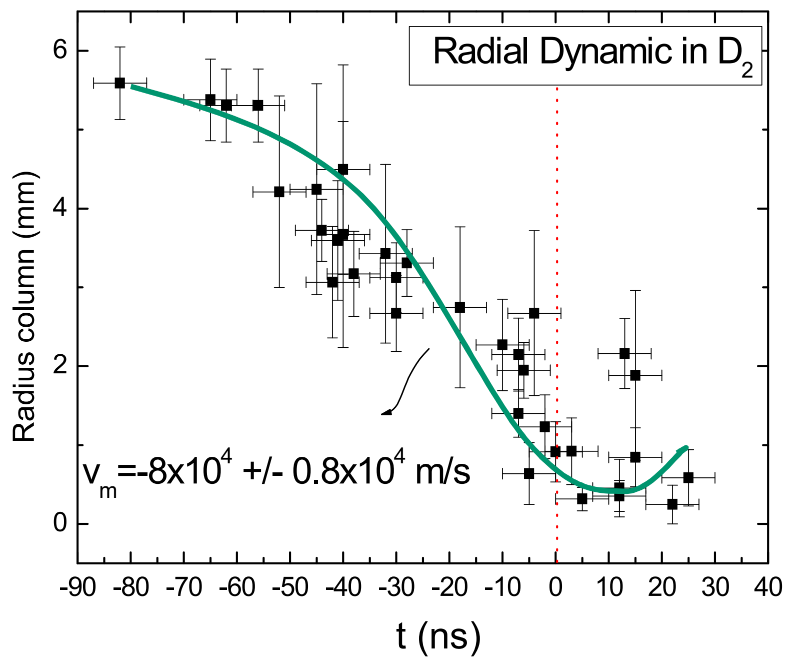


after the pinch

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

PF-400J

Schlieren images

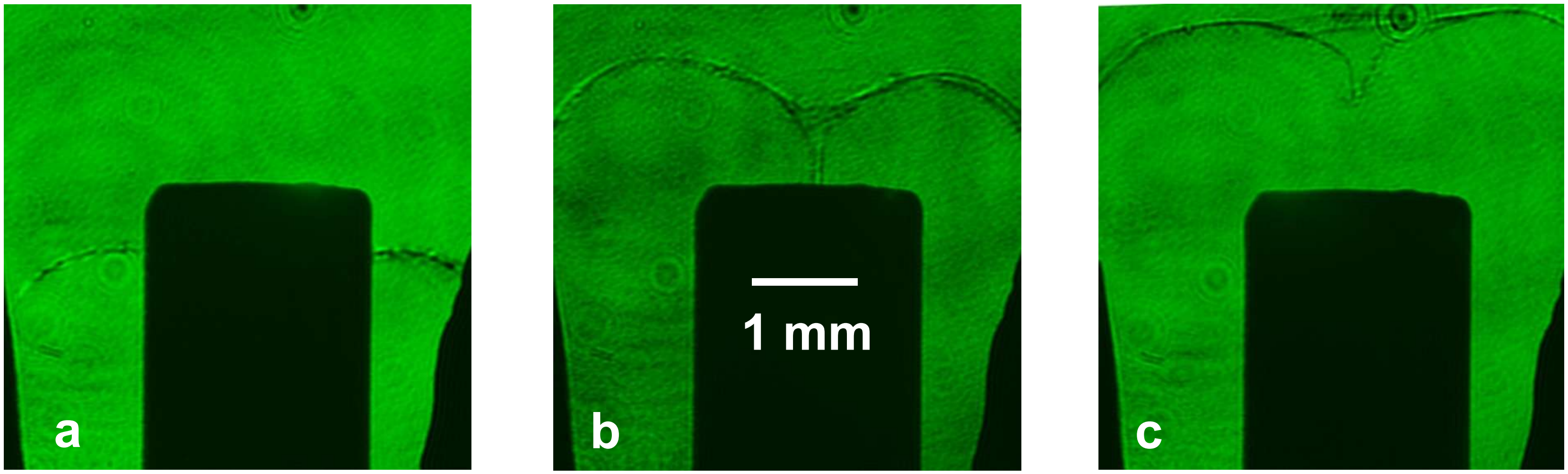


$r_p \sim 0.1\ r_a$

$z_p \sim 0.8\ r_a$

PF-2J

Schlieren images



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

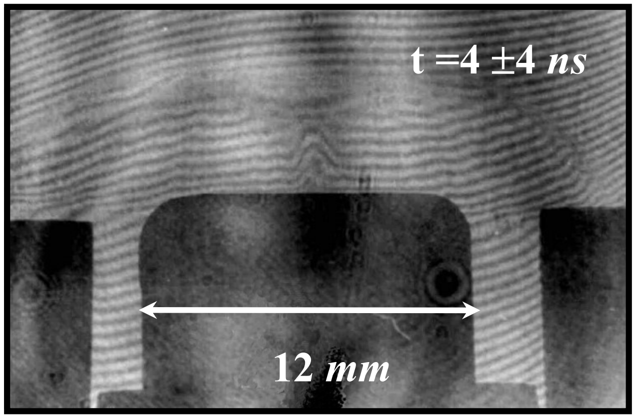
$r_p \sim 0.1\ r_a$

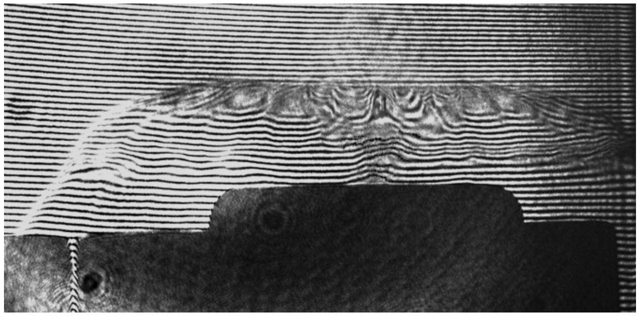
$z_p \sim 0.8\ r_a$

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

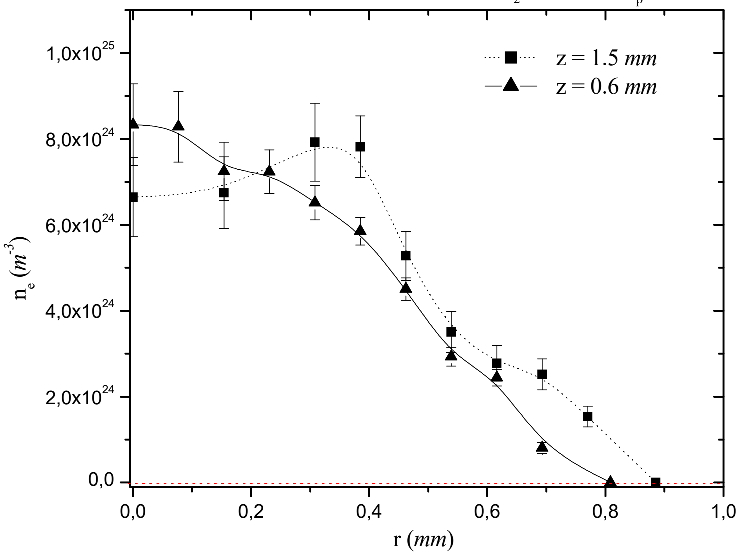
PF-400J

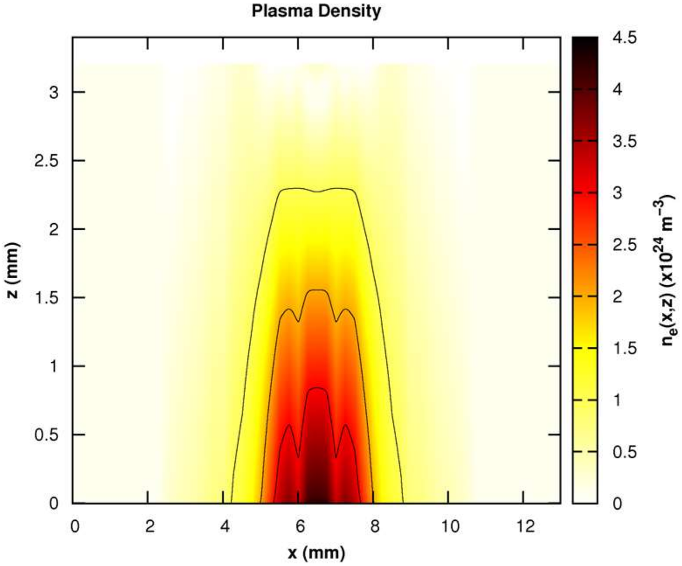
Interferograms





p = 5 mbar (H_2); t= 4 ns ; z_p = 4 mm





$r_p \sim 0.1\ r_a$

$z_p \sim 0.8\ r_a$

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

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 16 20 OCTOBER 2003

Neutron emission from a fast plasma focus of 400 Joules

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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

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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

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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)

- $r_p \sim (0.1\text{-}0.2)\ a$, $z_p \sim (0.8\text{-}1)\ a$
- $\langle v_a \rangle \sim 5 \times 10^4$ 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).
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Temperature does not depend on the energy of the device

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),

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

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

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

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

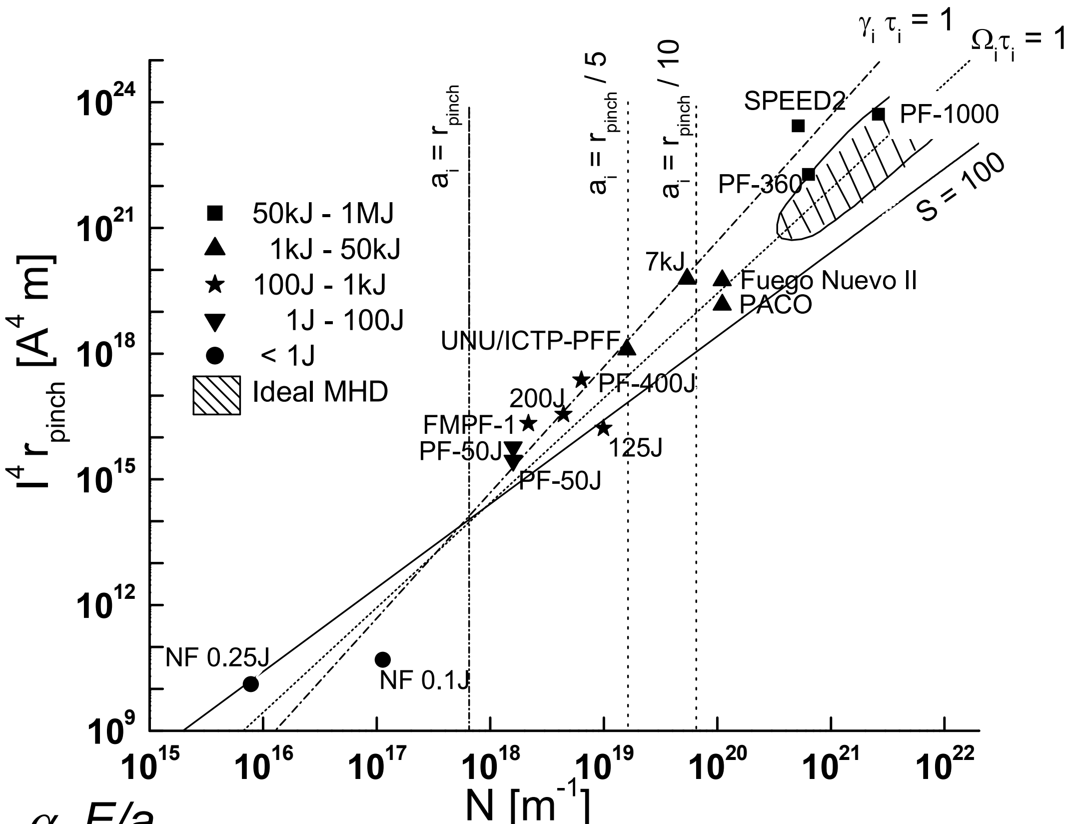
Therefore, the Bennett temperature is proportional to the square value of the drive parameter.

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)

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)

At present other groups are working in sub kJ PF devices

As example:

1kJ to Hundred joules

Japan:

S. R. Mohanty, T. Sakamoto, Y. Kobayashi, I. Song, M. Watanabe, T. Kawamura, A. Okino, K. Horioka and E. Hotta, Rev. Sci. Instrum. 77, 043506 (2006)

India:

R. K. Rout, P. Mishra, A. M. Rawool, L. V. Kulkarani and S. C. Gupta, J. Phys. D: Appl. Phys. **41**, 205211 (2008)

USA-Singapore:

R. Verma, R. S. Rawat, P. Lee, M. Krishnan, S. V. Sprinham and T. L. Tan, Plasma Phys. Control. Fusion **51**, 075008 (2009)

LLNL, USA:

Ellsworth, J. L.; Falabella, S.; Rusnak, B.; Schmidt, A.; Tang, V., 54th Annual Meeting of the APS, DPP Division (2012)

J. L. Ellsworth, S. Falabella, V. Tang, A. Schmidt, G. Guethlein, S. Hawkins and B. Rusnak, Rev. Sci. Instrum. **85**, 013504 (2014)

Tens of joules

India:

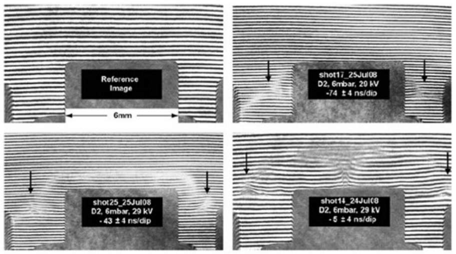
R. Shukla, S. K. Sharma, P. Banerjee, R. Das, P. Deb, T. Prabahar, B. K. Das, B. Adhikary, and A. Shyam, Rev. Sci. Instrum. 81, 083501 (2010)

Few Joules

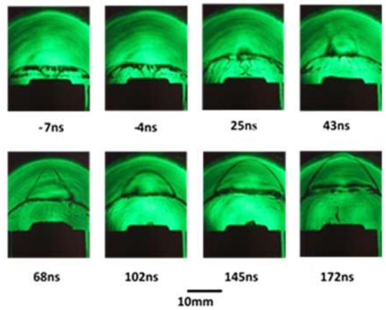
Iran:

Hossein Jafari, Morteza Habibi, Gholam Reza Eta'ati, Physics Letters A, 381, 2813 (2017)

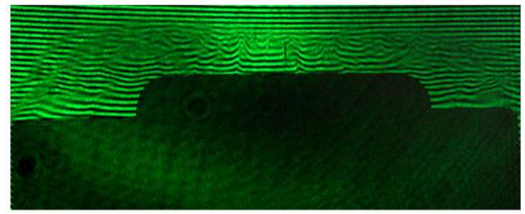
Next Lectures



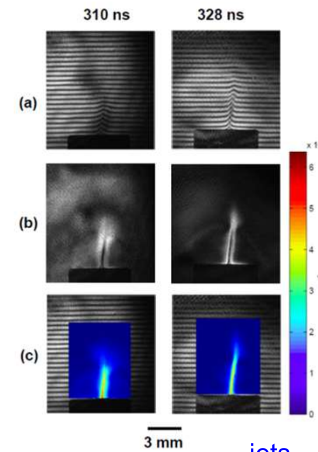
Toroidal singularity



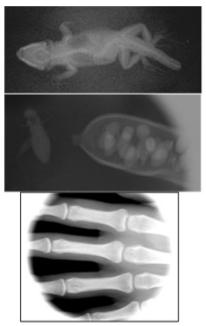
shocks



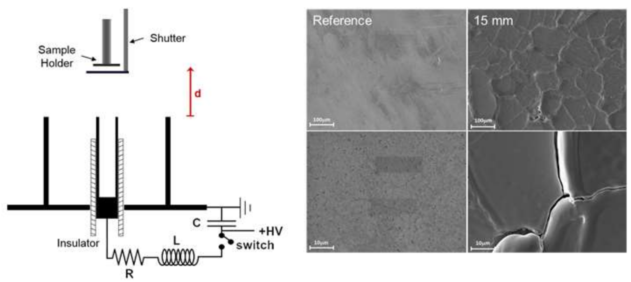
fillaments



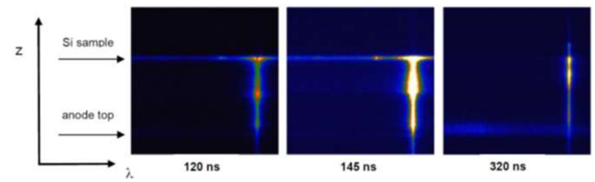
jets



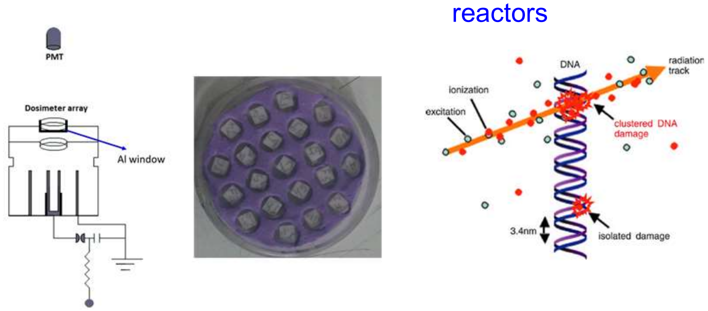
Pulsed x-ray and
neuron sources



Effects on materials for 1st wall of nuclear fusion reactors

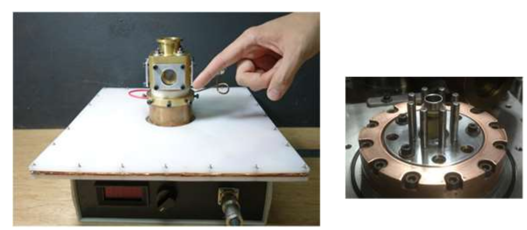


Plasmas interacting with materials, plasma facing components



Effects of pulsed radiation in life matter

Pulsed plasma thruster for nanosatelites



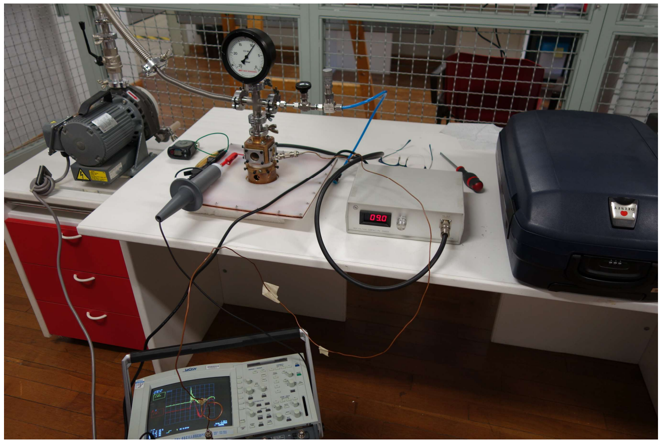
How to design and build a small plasma focus. Tricks and recipes

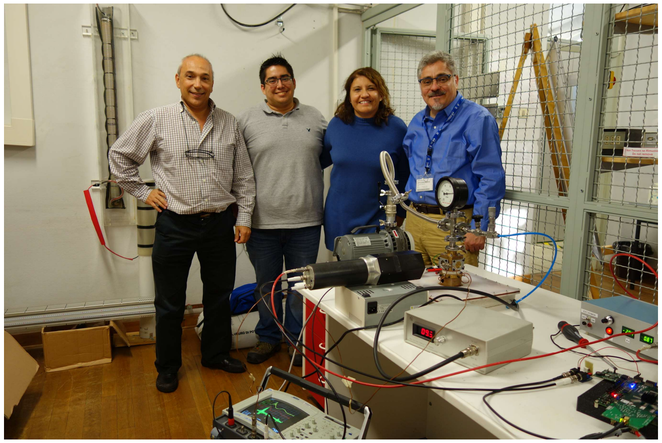
How to obtain information from a dense transient plasma

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**

Portable plasma focus





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

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