

An ultra miniature pinch-focus discharge

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Abstract

As a way to investigate the minimum energy to produce a pinch plasma focus discharge, an ultra miniature device has been designed and constructed (nanofocus NF: 5nF, 5-10kV, 5-10kA, 60-250 mJ, 16 ns ns time to peak current). Sub-millimetric anode radius covered by a coaxial insulator were used for experiments in hydrogen. Evidence of pinch was observed in electrical signals in discharges operating at 60 mJ. A single-frame image converter camera (4ns exposure) was used to obtain plasma images in the visible range. The dynamics observed from the photographs is consistent with: a) formation of a plasma sheath close to the insulator surface, b) fast axial motion of the plasma sheath, c) radial compression over the anode, and d) finally the plasma is detached from the anode in the axial direction. The total time since stage a) to d) was observed in ~30 ns. X ray and neutron emission is being studied. Neutron yield of the order of 10^3 neutron per shot is expected for discharges operating in deuterium at 10kA.

Introduction

In the past, there has been some scepticism among the researchers toward the possibility to construct and operate PF devices below 1 kJ. In particular, the main objection is there would not be sufficient energy available to generate, accelerate and compress the plasma. Recently, it has been experimentally demonstrated that neutrons can be produced in very small PF devices down to energies of 50 J and peak currents of 40 kA [1-3, 5, 6]. Contrary to the popular believe that devices powered by such low energies would not function properly, X rays and neutrons produced in pinch plasma foci were measured in 400 J and 50 J PF devices. The average neutron yields were 10^6 for 400 J and 10^4 for 50 J [4, 6].

The main motivation for the low energy limit accounts for the possibility to design pulsed radiation sources operating with discharge trains at high frequency. In addition, these small devices are very useful to study the physics of high energy plasma densities.

A characteristic feature of the PF devices is that the plasma parameters remain relatively constant for facilities in a wide range of energy, from 1kJ to 1MJ, electron density in the range $5 \times 10^{24} - 10^{26} \text{ m}^{-3}$, electron temperature in the range 200eV - 2keV, ion temperature in the range 300eV - 1.5 keV. Other interesting feature is that the velocity of the current sheath is of the order of $1 \times 10^5 \text{ m/s}$ in the axial phase and of the order of $2.5 \times 10^5 \text{ m/s}$ in the pinch compression in every optimized plasma foci. It is interesting note that plasma parameters practically constant in plasma focus devices are correlated with the value of electrical and geometrical parameter of the devices, this is useful for design considerations.

A comparison between plasma foci of different energies is interesting. Although only fraction of the initial energy stored E in the capacitor bank is transferred to the plasma, the

parameter E/V_p (with V_p the plasma volume) is usually used to characterize the plasma energy density in order to compare different devices. According with scaling laws [7] and optical diagnostics [3] the final pinch radius (previous to appearance of instabilities with the subsequent appearance of smaller inhomogeneities in the plasma column) is of the order of $0.12a$ and the maximum pinch length is of the order $0.8a$. Thus the final plasma volume V_p (previous to appearance of probable instabilities) is of the order of $\pi(0.12a^2) \times (0.8a) = 0.036a^3$, and the plasma energy density at the pinch moment is proportional to $E/V_p \sim 28E/a^3$. In references [5, 8] the parameter $28E/a^3$ is listed for various PF devices and his value is of the order of $(1-10) \times 10^{10} \text{ J/m}^3$.

Other relevant parameter in plasma foci is the called drive parameter $(I_o/ap^{1/2})$ [7], where I_o is the peak current, a the anode radius, and p the gas filling pressure for the maximum neutron yield. This drive parameter $(I_o/ap^{1/2})$ is related with the velocity of the axial and radial phase of the plasma motion (of the order of $(0.8-1) \times 10^5$ and $(2-2.5) \times 10^5$ m/s respectively for a wide range of plasma focus sizes). In fact the axial and radial velocity are proportional to $(I_o/ap^{1/2})$ [7]. For devices over the range 50J-1MJ operating in deuterium the drive parameter $I_o/ap^{1/2} = 77 \pm 7 \text{ kA/cm} \cdot \text{mbar}^{1/2}$ [7, 8].

Design

Considering that the plasma energy density parameter $E/V_p = 28E/a^3$ and the drive parameter $(I_o/ap^{1/2})$ are practically constant in all of plasma focus devices that operate in the range from 50J to 1MJ we can question, how low can we go in loading energy and still obtaining the plasma and neutron emission?

Using the relation $28E/a^3 = 5 \times 10^{10} \text{ J/m}^3$, and if we are thinking in design a PF of 0.25J for example, immediately it is obtained that the anode radius must have a sub millimeter size, $a \sim 0.5 \text{ mm}$. A device with a capacity of 5nF and an inductance of 5nH, charged at 10kV (0.25J) produces in short circuit a current peak $I_o = 10 \text{ kA}$. To produce a good ionization over the insulator a pressure of $p = 3 \text{ mbar}$ can be used. Thus using the relation for deuterium $(I_o/ap^{1/2}) = 77 \text{ kA cm mbar}^{1/2}$ an anode radius is $a = 0.8 \text{ mm}$. To determine the effective anode length, z_a , is necessary consider that the peak current must be coincident with the moment of the pinch, so the relation $z_a = 0.8 (v_a) (T/4)$ is used ($v_a = 1 \times 10^5 \text{ m/s}$ is the axial velocity of the current sheath and T is the period of the discharge) and the anode length is $z_a \sim 0.6 \text{ mm}$. A device with such characteristics have been constructed at CCHEN. The capacitor was constructed with two parallel plates. A 1.6 mm Cu tube covered with Alumina is attached to the center of the anode plate, and pass through a small hole in the cathode center. PVDF film was placed as dielectric between both plates. The total dimensions of the device are 20cm x 20cm x 5cm. Details of the design and of the experimental observations are currently in publication process [9].

Results and conclusions

The current temporal derivative was measured using a Rogowski coil, the charging voltage was controlled using a resistive divider. Discharges in hydrogen at high pressure (20 mbar), were performed in order to measure the electrical parameters of the device. Simultaneously images from the plasma were obtained with a visible ICCD camera gated at 4ns exposure time. Figure 1 shows the electrical signals during a discharge in Hydrogen at 20 mbar, with

an initial charge of 5 kV. A current peak of 5.07 kA was obtained. Fig. 1 also shows a photograph of the plasma at later time of the discharge. It can be seen that the plasma remains attached to the insulator, which is consistent with the behaviour of plasma-focus discharges at high pressure. Essentially this discharge is a short-circuit, and therefore it can be used to calculate the electrical characteristics of the effective LC system, which resulted: $C=4.9$ nF, $T=30$ ns, $L=4.8$ nH. The first quarter of period was 16 ns, this suggest that the time to create the current sheath is of the order of 8 ns.

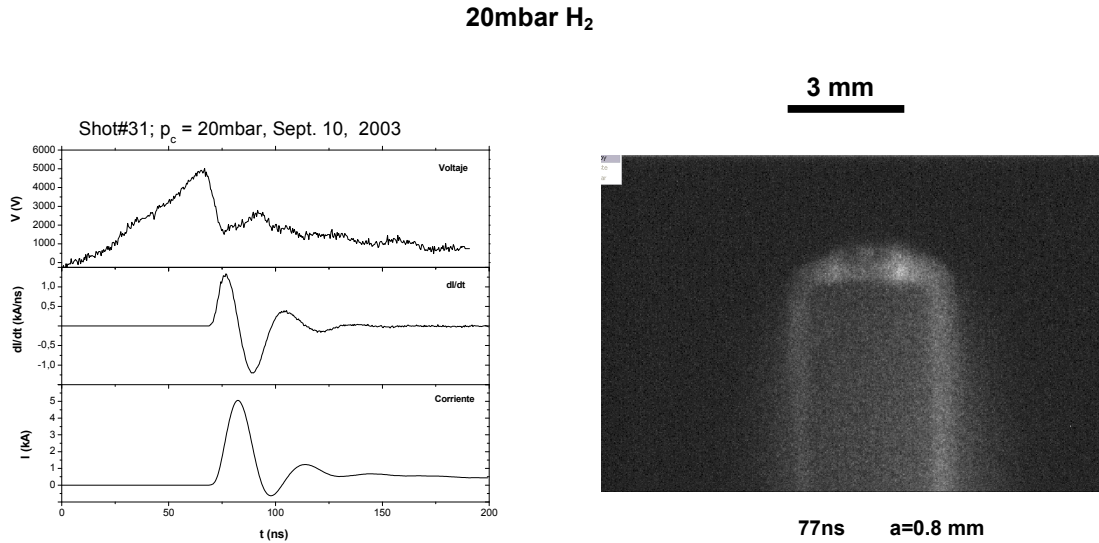


Figure 1. Electrical signals during a discharge in Hydrogen at 20 mbar, with an initial charge of 5 kV. Also a photograph of the plasma at later time of the discharge is shown.

Figure 2 shows the electrical signals during a discharge in Hydrogen at 3 mbar, with an initial charge of 6.5 kV (*i.e.*, 0.1 J). A current peak of 4.5 kA was obtained. Fig. 5 also shows the sequence of photographs of the evolving plasma. The following phenomena can be extracted from the pictures observation: a) the plasma is initiated over the insulator, b) the plasma covers the anode, c) there is a radial compression of the plasma over the anode, d) finally the plasma separates from the anode in the axial direction. The time from stages (a) to (d) is about 30 ns.

A clear evidence that a radial compression (pinch) actually occurred is the dip observed in the current-derivative signal (it is the frequency change of the dI/dt oscillation and it has used as time 0 in the graph), concurring with a drop in the electrical current and a small peak in the voltage signal. In turn, the mentioned features were not observed in the electrical signals of the discharge at 20 mbar. Unfortunately the temporal response of the voltage monitor is slow as to follow properly the fast changes in discharge voltage, however the frequency change of the dI/dt signal and the drop in the current is the evidence of the pinch.

The characteristic parameters of the miniaturized plasma focus operating with hydrogen at 3 mbar were $E/Vp=5.6 \times 10^9$ J/m³ and $I_0 / (p^{1/2}a) = 33$ kA/mbar^{1/2} cm. To increase this

parameters the current must be increased or the anode radius must be decreased. Both possibilities are currently in develop. Also measurements of neutron and x-ray is being implemented. In spite of considerations of optimization it has been demonstrated that is possible scaling a plasma focus to operate with energies lower than 1 joule [9].

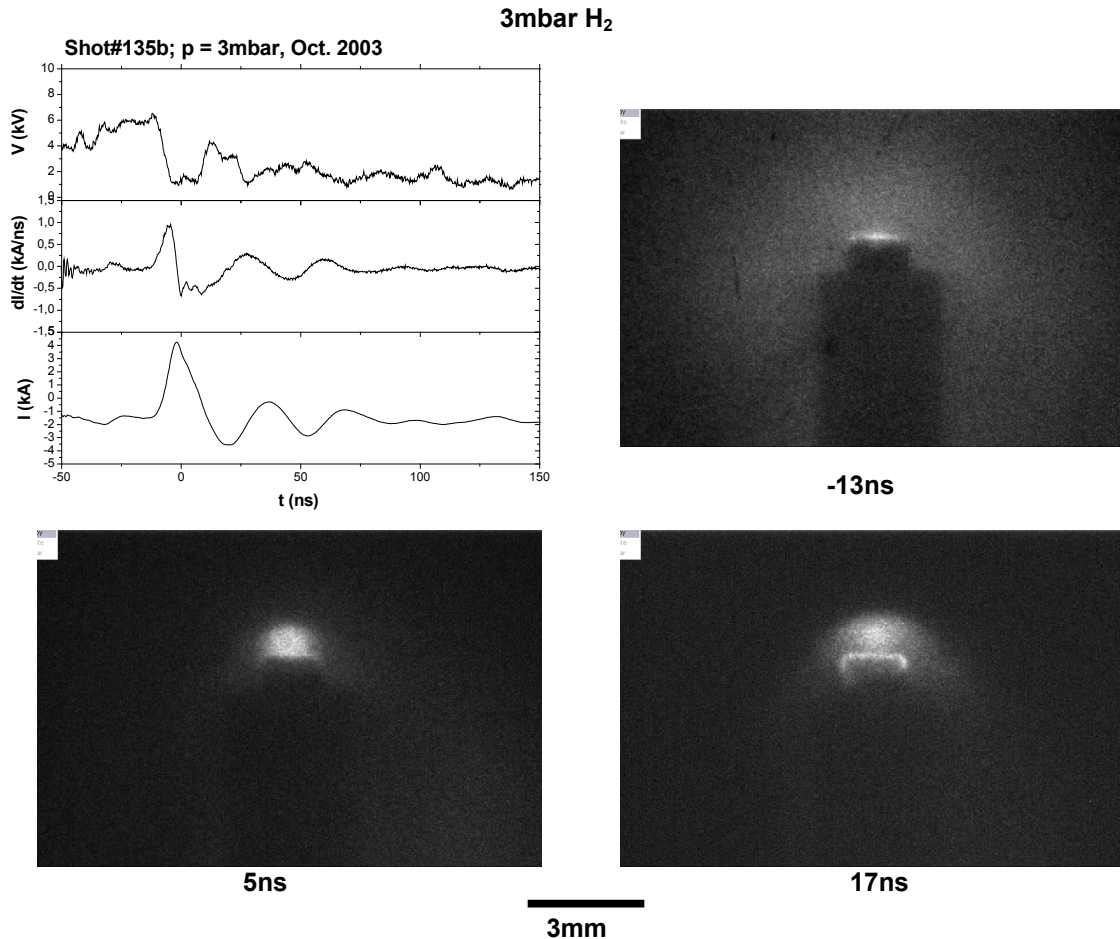


Figure 2. Electrical signals during a discharge in Hydrogen at 3 mbar, with an initial charge of 6.5 kV (*i.e.*, 0.1 J). A current peak of 4.5 kA was obtained. Also the sequence of photographs of the evolving plasma is shown. The following phenomena can be extracted from the pictures observation: a) the plasma is initiated over the insulator, b) the plasma covers the anode, c) there is a radial compression of the plasma over the anode, d) finally the plasma separates from the anode in the axial direction. The time from stages (a) to (d) is about 30 ns.

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