Plasma Sources Sci. Technol. **18** (2009) 015007 (5pp) doi:10.1088/0963-0252/18/1/015007

Nanofocus: an ultra-miniature dense pinch plasma focus device with submillimetric anode operating at 0.1 J

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Received 4 June 2008, in final form 2 September 2008
Published 26 November 2008
Online at stacks.iop.org/PSST/18/015007

Abstract
As a method for investigating the minimum energy to produce a pinch plasma focus (PF) discharge, an ultra-miniature device for pinch discharges has been designed, constructed and characterized (nanofocus (NF): 5 nF, 5–10 kV, 5–10 kA, 60–250 mJ, 16 ns time to peak current). Submillimetric anode radii (0.8 and 0.21 mm) covered by coaxial insulators were used for experiments in hydrogen. Evidence of pinch was observed in electrical signals in discharges operating at 3 mbar and ∼100 mJ. A single-frame image converter camera (4 ns exposure) was used to obtain plasma images in the visible range. The dynamics observed from the photographs is consistent with (a) the formation of a plasma sheath close to the insulator surface, (b) the plasma covering the anode, (c) radial compression over the anode; (d) finally the plasma is detached from the anode in the axial direction. The total time from stages (a) to (d) was observed in ∼30 ns. This ultra-miniature device has a value for the 'plasma energy density parameter' and for the 'drive parameter' of the same order or greater than PF devices operating at energies several orders of magnitude higher.

1. Introduction

In the past, there has been some skepticism among researchers towards the possibility of constructing and operating plasma focus (PF) devices below 1 kJ. The main objection is that there might not be sufficient energy available to generate, accelerate and compress the plasma. Another objection is related to the capability of measuring the emitted radiation if it were possible to build a PF device below 1 kJ. 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 50 kA [1–3, 5, 6]. Contrary to the popular belief that devices powered by such low energies would not function properly, x-rays and neutrons produced in pinch plasma foci were measured in 400 and 50 J PF devices. The average neutron yields were $\sim 10^6$ for 400 J and $\sim 10^4$ for 50 J [4, 6].

The main motivation to study the low energy limit is to explore the possibility of designing 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 all PF devices is that the plasma parameters remain relatively constant for facilities in a wide range of energy, from 50 J to 1 MJ, electron densities of the order of $10^{25}\,\mathrm{m^{-3}}$, electron temperatures in the range 200 eV–2 keV and ion temperatures in the range 300 eV–1.5 keV [8]. Other quantities remarkably similar on every optimized PF are the axial velocity of the current sheath ($\sim 1 \times 10^5\,\mathrm{m\,s^{-1}}$) and the pinch-compression velocity ($\sim 2.5 \times 10^5\,\mathrm{m\,s^{-1}}$) [10]. The fact that these plasma parameters are correlated with the electrical and geometrical

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characteristics of the devices can be used to derive important design criteria.

A comparison between plasma foci of different energies is interesting. Although only a fraction of the initial energy E stored in the capacitor bank is transferred to the plasma, the parameter E/V_p (V_p being the plasma volume) is usually used to characterize the plasma energy density in order to compare different devices. According to scaling laws [7] and optical diagnostics [3] the final pinch radius and the maximum pinch length (before the appearance of instabilities and subsequent inhomogeneities in the plasma column) are proportional to the anode radius a ($\sim 0.12a$ and $\sim 0.8a$, respectively). Thus the final plasma volume V_p (previous to the 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 [5, 8] the parameter $28E/a^3$ is listed for various PF devices and its value is of the order of (1–10) $\times 10^{10}$ J m^{-3}. It is interesting that the energy density parameter E/V_p and the ion density n are of the same order for devices operating from tens of joules to megajoules. Now, the energy per ion, which is proportional $E/(V_p n)$, is also of the same order in all operating devices regardless their energy. As the energy per ion is essentially the temperature, the mentioned invariance suggests that, given the proper scale, most nuclear and atomic reactions occurring in large plasma foci should be also expected in a miniaturized PF.

Another relevant conserved magnitude is the drive parameter ($I_o/ap^{1/2}$), I_o being the peak current and p the gas filling pressure for the maximum neutron yield. For devices in the energy range 50 J–1 MJ operating in deuterium, the drive parameter is 77 ± 7 kA cm^{-1} mbar$^{-1/2}$ [7, 8]. Moreover, it has been shown that the axial, v_a, and radial velocity, v_r, of the current sheath are proportional to this parameter, which are about (0.8–1) $\times 10^5$ m s^{-1} and (2–2.5) $\times 10^5$ m s^{-1}, respectively [7].

2. Design considerations

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

Let us consider a charging energy of 0.25 J. To conserve $28E/a^3 \sim 5 \times 10^{10}$ J m^{-3}, the anode radius should be $a \sim 0.5$ mm. Assuming a capacity of 5 nF, an inductance of 5 nH and a charging voltage 10 kV (0.25 J), the peak current results in $I_o = 10$ kA. To produce a good ionization over the insulator, a 3 mbar filling pressure can be used, which gives $a = 0.8$ mm to ensure $I_o/ap^{1/2} = 77$ kA cm mbar$^{1/2}$.

The effective anode length, z_a, is determined so as to ensure that the peak current is coincident with the pinch. Using the relation $z_a/v_a + a/v_r = T/4$ [7] (T being the period of the discharge), and assuming $v_a = 1 \times 10^5$ m s^{-1}, $v_r = 2 \times 10^5$ m s^{-1} and $T \sim 32$ ns, the required anode length results in $z_a \sim 0.5$ mm.

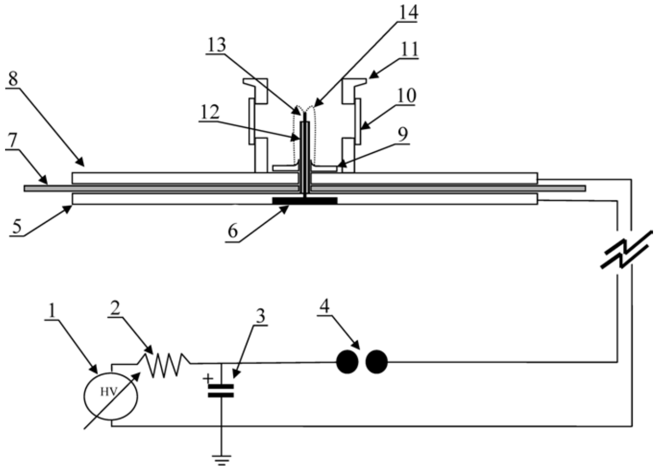

Figure 1. Sketch of the nanofocus discharge device. 1: power supply, 2: charging resistance 100 MΩ, 3: capacitor 28 nF, 4: spark gap, 5: anode, 8 cathode, 5 and 8: pair of 200 mm diameter brass electrodes forming the capacitor to drive the discharge ($\sim$5 nF), 6: anode, 7: dielectric, four PVDF films of 80 μm thickness, 9: cathode, 10: optical windows, 11: discharge chamber, 12: alumina tube, 13: anode, 14: plasma sheath between anode and cathode. A primary capacitor of 28 nF (3) charges, by means of a pulse, the driven capacitor ($\sim$5 nF) formed by the parallel plates 5 and 8.

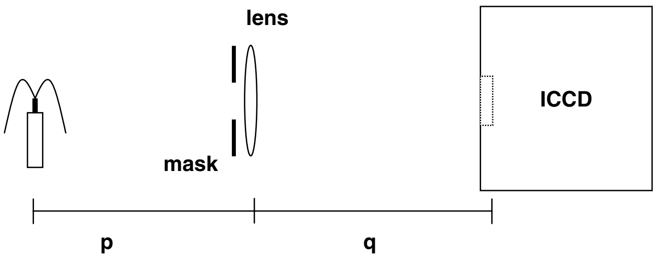

Figure 2. Optical system. For imaging the plasma over the microchannel plate in the ICCD camera, a regular bi-convex lens with 17.5 cm focal length and 5 cm diameter was used. A mask with an open circle of 0.8 cm diameter was attached to the lens in order to increase the field depth, resulting in an optical number $F \cong 22$. Value of other magnitudes: $p = 35$ cm, $q = 35$ cm, magnification $m = 1$.

3. The apparatus and diagnostics

A device with the characteristics deduced in the preceding section have been constructed at the Chilean Nuclear Energy Commission, CCHEN. The schematics of the apparatus is shown in figure 1. A pair of 200 mm diameter brass electrodes act as a capacitor to drive the discharge. A 1.6 mm Cooper tube covered with alumina is attached to the center of the anode plate and passes through a small hole in the cathode center. Four dielectric PVDF films, 80 μm thick, were placed between both plates. The measured capacity is 4.9 nF. The total dimensions of the device are 20 cm$\times$20 cm$\times$5 cm. A primary capacitor of 28 nF charges the driven capacitor by means of a pulse.

The current temporal derivative was measured using a Rogowski coil; the charging voltage was controlled using a resistive divider. Discharges at high pressure in hydrogen, $\geqslant$20 mbar, were performed to induce a short-circuit over the insulator. From the electrical signals a period of 30 ns was

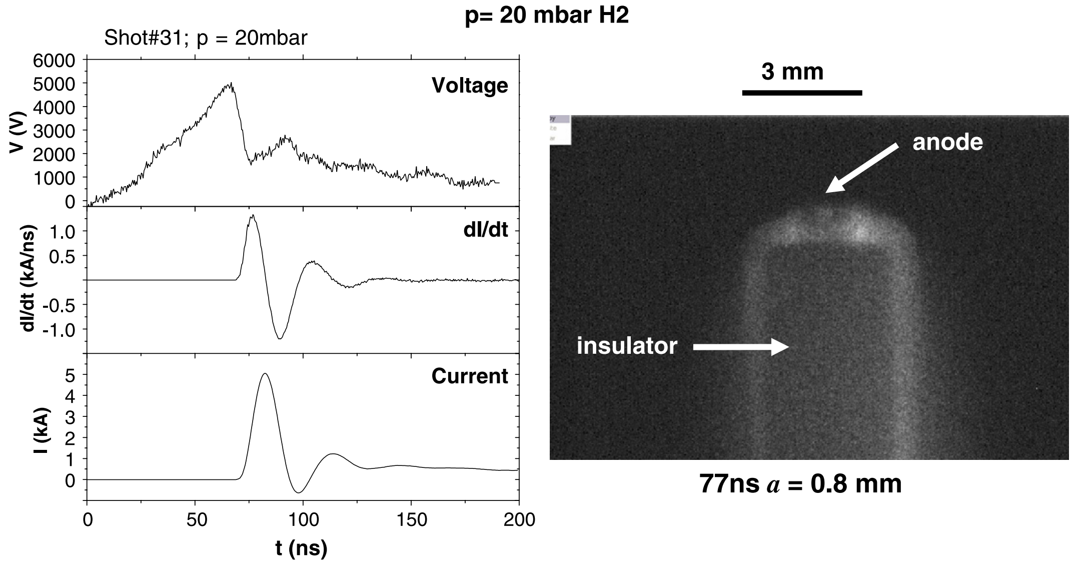

Figure 3. Electrical signals during a discharge in hydrogen at 20 mbar, with an initial charge of 5 kV. Also a photograph of the plasma at a later time of the discharge is shown. It can be seen that the plasma remains attached to the insulator, which is consistent with the behavior of PF discharges at high pressures.

obtained and the inductance of the device was measured to be $L = 4.8$ nH.

An intensified CCD camera (ICCD) gated at 4 ns exposure time and synchronized with the discharge was used to obtain side view images of the visible light emitted from the plasma. For imaging the plasma over the microchannel plate in the ICCD camera, a regular bi-convex lens with a focal length of 17.5 cm and diameter of 5 cm was used. In order to increase the field depth, a mask with an open circle of 0.8 cm diameter was attached to the lens, resulting in an optical number $F = 0.8/17.5 \cong 22$. A magnification $m = 1$ was used. The resolution of the camera for magnification $m = 1$ is 23 μm. The depth field for $F = 22$ and for the distances used in this optical system is 0.9 cm. Figure 2 shows the optical system.

4. Results

According to our experience, fast deuterium PF devices with a hybrid aspect ratio $z/a \sim 1$ can produce pinches in hydrogen discharges, provided that the pressure is adjusted to compensate for the pinch time. In the present case, hydrogen gas was used to test and characterize the discharge. In order to electrically characterize the device, discharges in hydrogen at pressures $\geqslant$20 mbar were performed. Figure 3(*a*) shows the electrical signals during a discharge in hydrogen at 20 mbar, with an initial charge of 5 kV. Figure 3(*b*) shows an image from the plasma obtained with a visible ICCD camera gated at 4 ns exposure time for the discharge at 20 mbar. It can be seen that the plasma remains attached to the insulator, which is consistent with the behavior of PF discharges at high pressures. Essentially, this discharge is a short-circuit, and therefore it can be used to calculate the electrical characteristics of the effective LC system, which works out to be $C = 4.9$ nF, $T = 30$ ns, $L = 4.8$ nH. The first quarter of the period was 16 ns, which suggests that the time to create the current sheath is of the order of 8 ns.

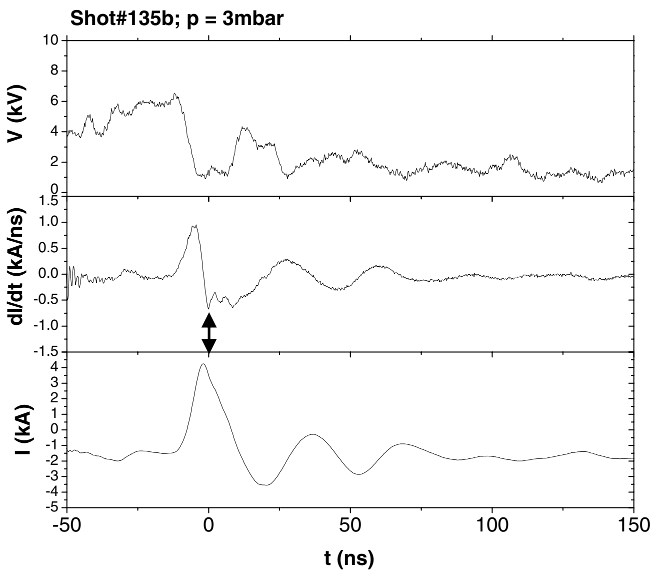

Figure 4. Electrical signals during a discharge in hydrogen at 3 mbar, with an initial charge of 6.5 kV (i.e. 0.1 J). The anode radius is $a = 0.8$ mm. A current peak of 4.5 kA was obtained. Clear evidence that a radial compression (pinch) actually occurred is the dip observed in the current derivative signal (it is the frequency change in the dI/dt oscillation and has been used as time zero in the graph, indicated by the arrow), coinciding with a drop in the electrical current.

Figure 4 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. Figure 5 shows the sequence of photographs of the evolving plasma. The following phenomena can be extracted from the observation of the picture series: (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 and (d) finally the plasma separates from the anode in the axial direction. The

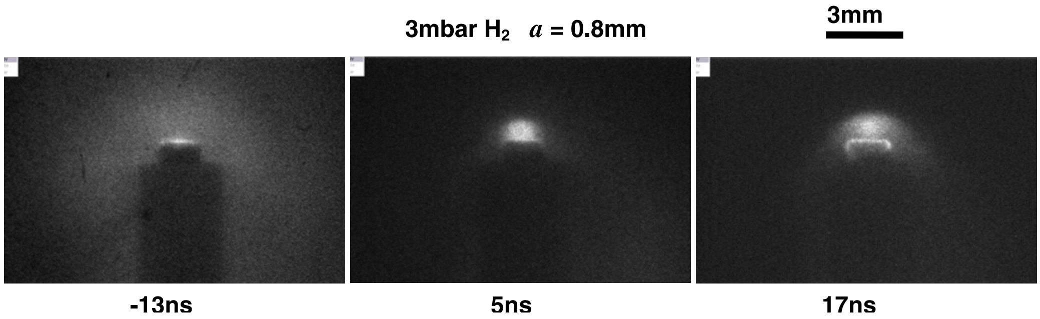

Figure 5. Sequence of photographs of the evolving plasma. The anode radius is $a = 0.8$ mm. The following phenomena can be extracted from the observation of pictures: (*a*) the plasma is initiated over the insulator, (*b*) the plasma covers the anode, (*c*) there is a radial compression of the plasma 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.

time from stages (a) to (d) is about 30 ns. According to the scaling rules for the pinch size and duration for PF discharges in deuterium [7], the expected pinch length is $z_p = 0.8a$ and the expected pinch radius is $r_p = 0.12a$, i.e. 0.64 mm and 0.1 mm, respectively, for this device. The expected pinch duration is $t_p[\mathrm{s}] = 2 \times 10^{-6}a$ [m], i.e. 1.6 ns for this device. Even though the experiments were performed in hydrogen, it is reasonable to expect the pinch size and pinch duration in this experiments to be of the same order of magnitude. It is clear that 4 ns exposure time is not enough to trace the plasma dynamics, and therefore the pictures correspond to time-integrated photographs produced during 4 ns. This explains the apparently wide plasma column over the anode observed close to the pinch moment. Taking into account these considerations it is reasonable to conclude that the dynamics observed from the set of photographs is similar to that observed in PF devices operating with larger energies (from 50 J to 1 MJ).

Clear evidence that a radial compression (pinch) actually occurred is the dip observed in the current derivative signal in figure 4 (it is the frequency change of the $\mathrm{d}I/\mathrm{d}t$ oscillation and was 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. In larger PF devices the mentioned effect occurs later, yet closer to, the maximum plasma compression and it has been attributed to the production of a plasma diode in the pinch, resulting in an anomalous plasma resistance [11]. Although in our case the temporal response of the voltage monitor is not sufficiently fast to properly follow the rapid voltage variations, the frequency change in $\mathrm{d}I/\mathrm{d}t$ and the drop in the current is a conclusive evidence of the pinch.

The characteristic parameters of the miniaturized PF operating with hydrogen at 3 mbar were $E/V_p = 5.6 \times 10^9\,\mathrm{J\,m^{-3}}$ and $I_o/(p^{1/2}a) = 33\,\mathrm{kA\,mbar^{-1/2}\,cm^{-1}}$. To increase these parameters either the current should be increased or the anode radius should be decreased.

A set of experiments with a smaller anode radius ($a = 0.21$ mm) was also performed. The signals and photographs of a 9 kV (∼0.2 mJ) discharge are shown in figures 6 and 7. A pinch evidence is also observed in the electrical signals in this case (i.e. frequency change of $\mathrm{d}I/\mathrm{d}t$ and current drop). The measured peak current was 4.5 kA. In addition, the same dynamics observed in previous experiments with an anode of 0.8 mm radius is observed when an anode of only 0.21 mm of radius is used (figure 7). In this last case the energy density parameter has the value of

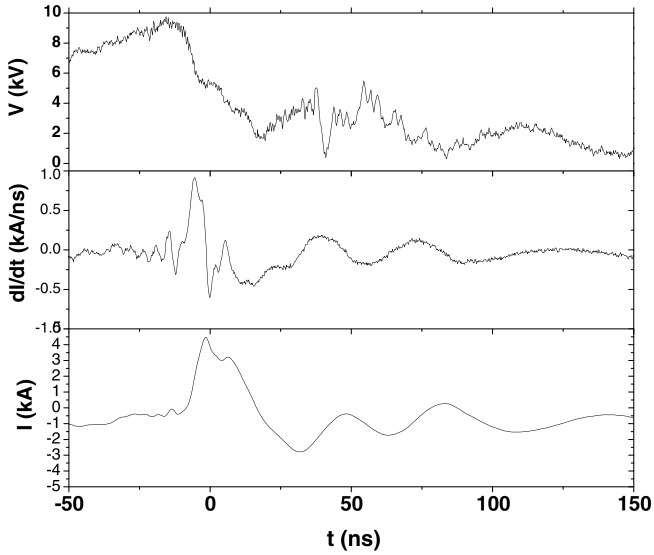

Figure 6. Electrical signals during a discharge in hydrogen at 3 mbar, with an initial charge of 9 kV (i.e. 0.2 J) using a 0.21 mm anode radius. A current peak of 4.5 kA was obtained. Evidence of a radial compression (pinch) is the dip observed in the current derivative signal (it is the frequency change in the $\mathrm{d}I/\mathrm{d}t$ oscillation and has been used as time zero in the graph), coinciding with a drop in the electrical current.

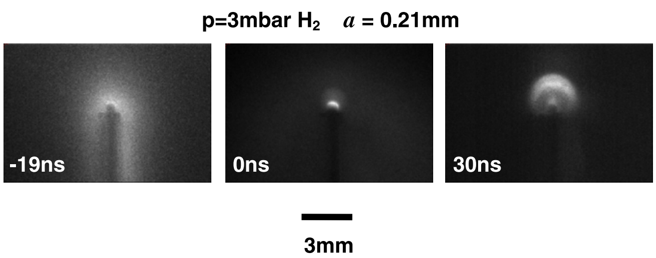

Figure 7. Sequence of photographs of the evolving plasma for discharges on anode radius $a = 0.21$ mm. The plasma dynamics is similar to that observed in conventional PF discharges.

$E/V_p = 3 \times 10^{11}\,\mathrm{J\,m^{-3}}$ and the value of the drive parameter is $I_0/(p^{1/2}a) = 126\,\mathrm{kA\,mbar^{-1/2}\,cm^{-1}}$.

Similar results have been observed in preliminary discharges performed in deuterium at 2–4 mbar of pressure; thus a similar drive parameter for discharges in deuterium is expected.

5. Conclusions

A PF operating with energy of the order of ∼0.1–0.2 J has been designed and constructed. Results using an anode radius of 0.8 mm showed pinch evidence; however, the values of the plasma energy density parameter and drive parameter turned out to be lower in comparison with the values observed in devices operating in the range 50 J–1 MJ. To increase the plasma energy density and drive parameters, experiments with an anode of only $a = 0.21$ mm radius were performed. Pinch evidence has also been observed under these conditions in discharges in hydrogen and in preliminary discharges in deuterium. The energy density parameter has a value of the order of $E/V_p \sim 3 \times 10^{11}\,\mathrm{J\,m^{-3}}$, i.e. one order of magnitude greater than the value observed in devices operating in the range 50 J–1 MJ. The value of the drive parameter is $I_o/(p^{1/2}a) \sim 126\,\mathrm{kA\,mbar^{-1/2}\,cm^{-1}}$, which is also greater than the value observed in the 50 J–1 MJ energy range. There are theoretical conjectures that suggest that the thermonuclear component of the neutron emission can be increased drastically when the drive parameter is increased [8, 10]. Future works include the study of the x-ray emission using mixtures of gases. Currently the neutron emission is being studied in discharges in deuterium using a system for measurement of low yield neutron pulses from D–D fusion reactions based upon a ^{3}He proportional counter in current mode [9]. A neutron yield of the order of 10^3 neutrons per shot is expected in 10 kA discharges. Improvements in the device are being developed in order to operate it at repetitive rate from 10 to 100 Hz.

Acknowledgments

This work is supported by the Chile Bicentennial Program in Science and Technology grant ACT 26, Center of Research and Applications in Plasma Physics and Pulse Power Technology (P^4-Project). C Pavez is supported by CCHEN and grant PSD-01, PBCT. The authors acknowledge the fruitful discussions with L Altamirano of Dicontek, Chile.

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