IOP PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion **52** (2010) 032001 (6pp) doi:10.1088/0741-3335/52/3/032001

BRIEF COMMUNICATION

Multiple pinch formations in small plasma-focus devices

M Barbaglia[1], **H Bruzzone**[2], **I Ríos**[3], **H Acuña**[2], **J González**[3] **and A Clausse**[1]

[1] CONICET-CNEA and Universidad Nacional del Centro, 7000 Tandil, Argentina
[2] IFIMAR, CONICET and Universidad Nacional de Mar del Plata, 7600 Mar del Plata, Argentina
[3] CNEA and Instituto Balseiro, 8400 Bariloche, Argentina

E-mail: pladema@exa.unicen.edu.ar

Received 3 July 2009, in final form 27 October 2009
Published 22 January 2010
Online at stacks.iop.org/PPCF/52/032001

Experimental observations of two or more pinches taking place with relatively large time separations ($\geqslant$ quarter of a period) within single discharges in two small plasma focus (PF) are reported. The first device is a 200J PF described in Barbaglia *et al* (2009), and was operated with a 6.2 mm outer diameter (OD), 9.1 mm insulator-free length bronze center electrode (anode), with a glass insulator and a grounded flat back plate (cathode) ending in a field intensifier edge surrounding the insulator. The insulator is a borosilicate tube 10.6 mm OD, 10.1 mm long measured from the field intensifier tip. The device is powered by eight capacitors of 0.1 μF and the total parasitic inductance of the assembly is 90 nH. The voltage between the anode base and the cathode, V_a, was measured with a calibrated fast resistive voltage divider and the time derivative of the discharge current, dI/dt, with a calibrated Rogowski coil surrounding the anode connection. A 5 cm thick plastic scintillator (EJ-200) coupled with a fast photomultiplier (PMT), located at 1.75 m from the pinch region, was used to detect hard x-ray pulses. No special filters were used; just the vacuum chamber wall (3 mm Pyrex glass) and 1 mm Al forming the metal encasement of the PMT assembly. All the signals were recorded using a four channel digital oscilloscope, 1 GHz BW and 0.8 ns digitalization time. The charging pressure (p_o) was measured by means of a differential vacuum oil manometer with a ±0.1 mbar uncertainty.

The second device is a compact PF powered by a single 2.5 μF capacitor and a total parasitic inductance of 50 nH. The discharge chamber is a sealed capsule filled with 4 mbar of deuterium, with the anode 10 mm in diameter and 25 mm in length, and the cathode 30 mm in diameter. The voltage between electrodes was measured with a calibrated fast resistive voltage divider and dI/dt from a calibrated Rogowski coil.

Several series of hundreds of discharges were performed in the first device with the capacitors charged at 18 kV and the filling pressure ranging from 0.5 to 40 mbar, using hydrogen or deuterium as the working gas. The purpose of this study was to observe the behavior of the device operation in a wide range of situations, including pressure ranges far from the expected optimum pinching conditions. A surprising outcome of this survey was the finding of more

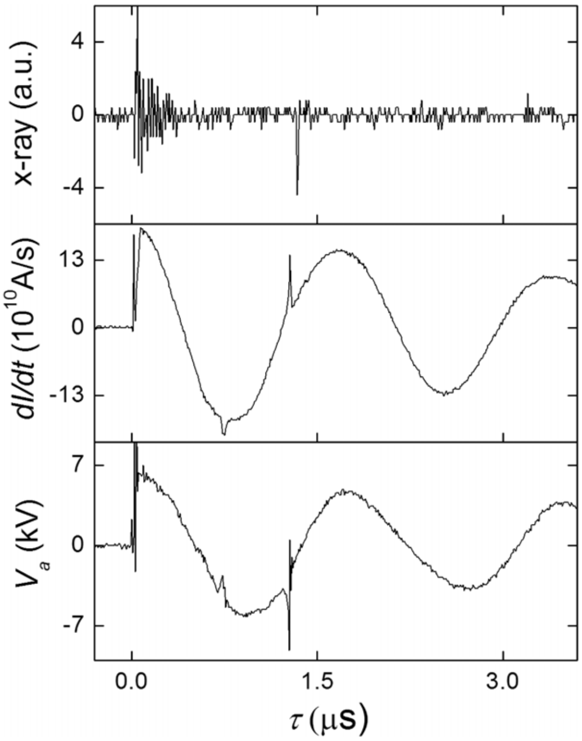

Figure 1. Signals of a discharge in the first device (14.3 mbar of H_2).

than one pinching action within the same shot and time separated by at least 1/4 of a period. Figures 1–3 show examples of the recorded traces of $V_a(t)$, dI/dt and the x-ray signal in three different shots performed at 14.3 and 16.4 mbar of H_2, and 36.8 mbar of D_2, respectively. It can be seen from these oscilograms that one can obtain one, two or even three pinches in successive half periods of the same shot, as indicated by the dips in dI/dt and peaks in $V_a(t)$. X-ray emissions were also observed in some of the pinches, and the relative frequency of the occurrence of more than one pinch was sometimes half of the shots. Figures 4 and 5 show traces of the voltage between electrodes and the current derivative in shots performed on the second device, charged at 8 kV and 7 kV, respectively. The formations of pinches in two subsequent periods of the signal are also clearly distinguished.

PF shots having two or more pinches separated by up to tens of or even one hundred nanoseconds are not rare to find in PF devices (and are associated with several pinches within the same plasma column), but to the best of our knowledge, this is the first report on repeated pinching action in separate half time periods, which implies that this repeated pinching is not taking place in the same plasma column. Actually, the phenomenon of multipinch in single PF discharges could be more frequent than one might think, because the standard procedure in PF research is to record only the first half period of dI/dt or thereabout.

The finding of several consecutive pinches in different periods of the same discharge suggests the occurrence of several consecutive current sheaths (CSs). Actually, experimental evidence on the formation of more than one CS within the same shot was reported in the past (Soto 2005, Mohammadi 2009), but to the best of our knowledge, the underlying physical problems of such a situation have not been discussed in the literature. The basic question to

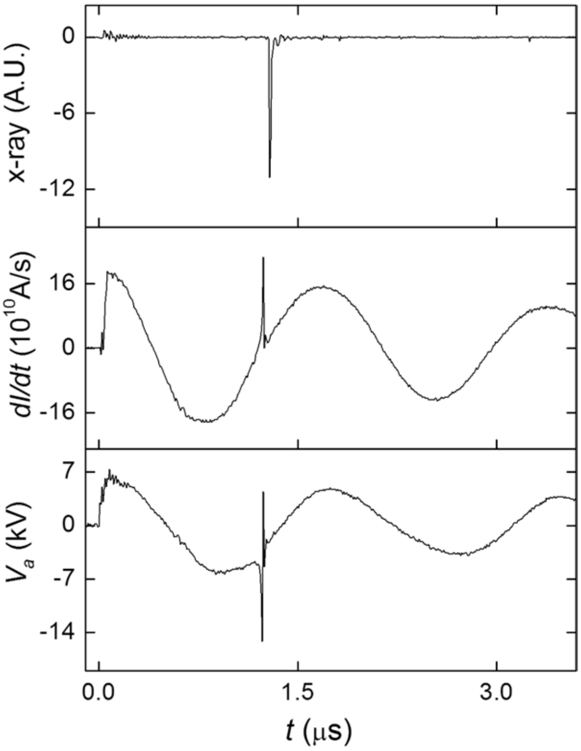

Figure 2. Signals of a discharge in the first device (16.4 mbar of H_2).

address is this: if the snowplow description of the discharge evolution within the electrodes is valid, and therefore the gas filling the interelectrode space is swept by the CS, on what material (gas or plasma) does a secondary sheet form?

A somewhat naïve answer to this question could be produced by noting that throughout the literature there are many references to 'mass sweeping efficiencies' or terms to that effect, which were introduced from the very beginning of coaxial guns research. However, it should be recalled that such 'sweeping efficiencies' were introduced for parameter fitting the kinematics predicted by plane 1D snowplow models to the experimental data (Bruzzone *et al* 1976, Lee 1989, Moreno *et al* 2000, González *et al* 2004, Siahpoush *et al* 2005, Goudarzi *et al* 2008). Since actual CS are not plane but bullet shaped, its kinematics involves both axial and radial velocities (the motion is physically that of a swelling balloon); therefore it is not surprising that the equivalent swept mass required to adjust the experimental observations is smaller than the total mass calculated using the filling gas density. Actually, Gratton and Vargas (1975) have deduced an analytical method to assess the shape of the CS in a plasma-focus discharge, from which it is possible to calculate the ratio between the mass swept by a curved and a planar snowplow CS. Table 1 shows as examples this ratio for different gun geometries. It can be seen that, since the 'sweeping' efficiency is actually a shape factor effect, one can hardly support a real mass leakage in the CS evolution on this ground. Moreover, it is well known that the propagating speed of the CS in plasma-focus discharges is highly supersonic from the very beginning, which is contradictory to the assumption of a leaking front.

Notwithstanding the above, there are at least two experimental observations of coaxial CS that might leave behind the CS part of the gas contained within the electrodes. One

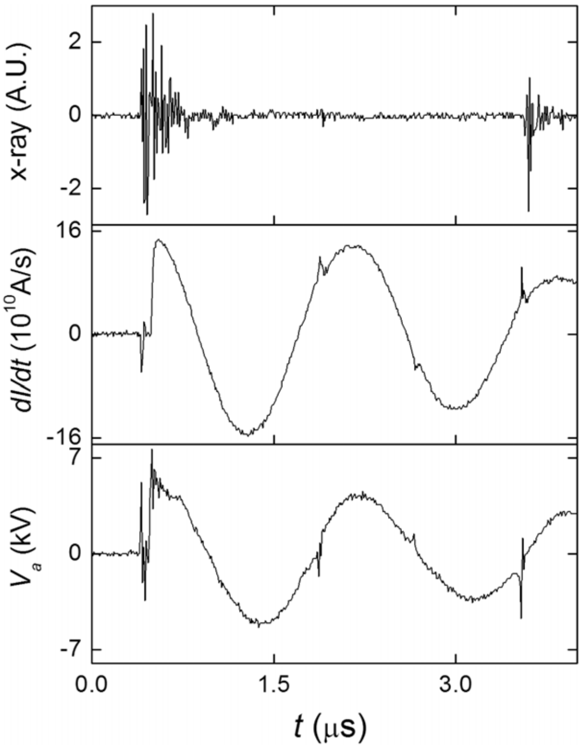

Figure 3. Signals of a discharge in the first device (36.8 mbar of D_2).

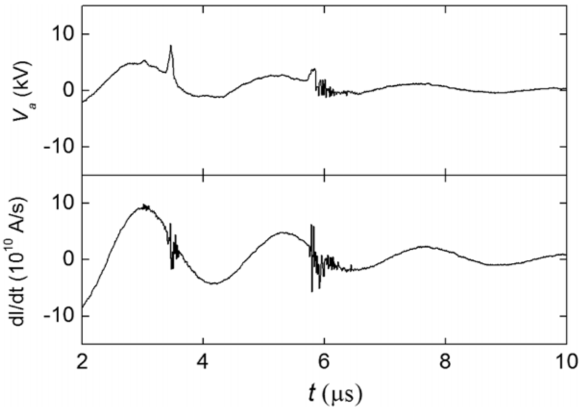

Figure 4. Signals of a discharge in the second device (8 kV).

of them is the so-called 'deflagration' regime, which was reported in gas puff filled coaxial guns (Cheng 1970). This regime in principle can also occur in uniform filling devices with stagnated gas where an ionizing front moves carrying the current, but without mass motion. In a pure deflagration mode it is difficult to conceive of the formation of a pinch on the axis, but evidence exists that deflagration modes can switch to snowplow modes within the length of the gun (Woodall 1985), which would leave unswept gas within the gun. The other

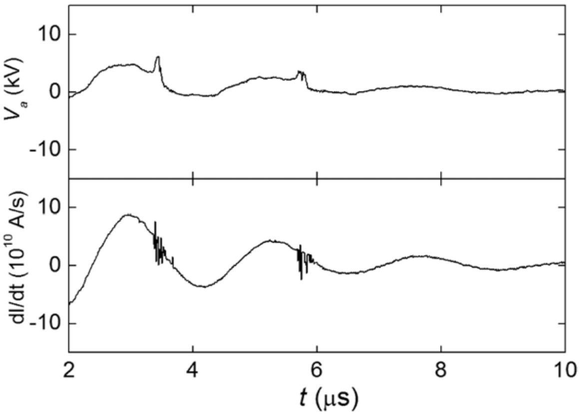

Figure 5. Signals of a discharge in the second device (7 kV).

Table 1. Ratio between the mass swept by a curved and a planar snowplow CS at the end of the rundown (r_1: anode radius, r_2: cathode radius, L: anode length).

	L/r_1		
r_2/r_1	3	4	5
2	0.40	0.55	0.64
1.8	0.53	0.65	0.72
1.5	0.69	0.77	0.81

possible explanation for the presence of unswept gas behind the CS is the formation of a radially filamented traveling CS. Such phenomena have been observed in the past (Bostick 1972, Bernard 1975, Bruzzone 1976), but no systematic work has been done to determine the conditions that favor its occurrence. Studies related to the breakdown stage of PF discharges have shown, however, that initial filamentary CS form when operating at relatively high filling pressure values (Bruzzone 1993). Therefore, had filamentary CS been generated during the initial stage of the discharges at certain filling pressures, it is not unreasonable to expect the presence of filamentary CS at relatively higher operating pressures.

Another possibility for the formation of multiple CS is the emergence of a secondary 'atmosphere' from the inner electrode surface, due to gas desorption after the passage of a CS. It is well known that, on any material surface within a vacuum system, several layers of molecules of the filling gas exist (up to 10–15), with a packing density of one molecule every few Å^2. The passage of a CS implies a large current density flowing into the central electrode, which unavoidably heats its surface, ejecting several layers of gas molecules with speeds very likely exceeding $10^6\,\mathrm{cm\,s^{-1}}$. Furthermore, the plasma attached to the insulator for some hundred nanoseconds during the initial formation stage probably heats the insulator surface through thermal conduction, and can also liberate adsorbed gases from it. Hence, one should also expect that after the CS lift-off, desorbed gas would also appear in this region. The details of this process are not well known, and should depend on the central electrode and insulator diameter values, but it is not unlikely that in about 500 ns a 5 mm gas layer with particle densities of $\sim 10^{16}\,\mathrm{cm^{-3}}$ (0.2 mbar) forms over the insulator-central electrode. Had this happened, when the interelectrode voltage reaches a sufficiently large value the residual layer breaks down and forms a secondary plasma current sheet.

It can be seen from the above considerations that the whole problem is quite complex and not amenable to simple theoretical descriptions determining whether and when secondary CS would form. Experimental studies are possible but lengthy, because of the large number of parameters involved and the difficulties in performing diagnostics in the region behind the CS. In any case, the purpose of this discussion is to bring the attention of PF researchers on the existence of discharges with multiple pinches, which puts a considerable question mark on the indiscriminate use of simple snowplow models for the design of PF devices and on the interpretation of its functioning. To name but one, if two CS exist at pinch time, the current amplitude measured by an external Rogowski coil does not yield the actual current value circulating in the pinch, hence correlations of neutron yields with the current derived from this measurement could be misleading. There are PF models that include the formation of a 'leakage' current flowing behind the main CS (Lee 2008). However, it should be noted that such currents are assumed to exist during the whole duration of the discharge, which is certainly not granted.

References

Barbaglia M, Bruzzone H, Acuña H, Soto L and Clausse A 2009 Experimental study of the hard x-ray emissions in a Plasma Focus of hundreds of joules *Plasma Phys. Control. Fusion* **51** 045001

Bernard A, Coudeville A, Jolas A, Launspach L and de Mascureau J 1975 Experimental studies of the plasma focus and evidence for nonthermal processes *Phys. Fluids* **18** 180

Bostick W, Nardi V and Prior W 1972 X-ray fine structure of dense plasma in a co-axial accelerator *J. Plasma Phys.* **8** 7

Bruzzone H, Gratton R, Kelly H, Milanese M and Pouzo J 1976 Experimental results of a low energy Plasma Focus *Energy Storage Compression and Switching* ed W Bostick *et al* (New York: Plenum) pp 255–8

Bruzzone H and Vieytes R 1993 The initial phase in Plasma Focus devices *Plasma Phys. Control. Fusion* **35** 1745

Cheng D Y 1970 Plasma deflagration and the properties of a coaxial plasma deflagration gun *Nucl. Fusion* **10** 305–17

Gonzalez J, Florido P , Bruzzone H and Clausse A 2004 A lumped parameter model of plasma focus *IEEE Trans. Plasma Sci.* **32** 1383–91

Goudarzi S, Amrollahi R and Moghaddam R 2008 A model based on lumped parameters for Filippov-type Plasma Focus devices *J. Fusion Energy* **27** 195–99

Gratton F and Vargas M 1975 *Proc. VII Eurpoean Conf. on Controlled Fusion and Plasma Physics (Lausanne, Switzerland)* p 64

see also Gratton F and Vargas M 1983 Two-dimensional electromechanical model of the Plasma Focus *Energy Storage, Compression, and Switching* vol 2, ed V Nardi *et al* (New York: Plenum) pp 353–86

Lee S 1989 Technology of a small PF *Proc. Spring College on Plasma Physics* (Trieste, Italy: ICTP) pp 113–69

Lee S, Saw S, Lee P, Rawat R and Schmidt H 2008 Computing plasma focus pinch current from total current measurement *Appl. Phys. Lett.* **92** 111501

Mohammadi M, Sobhanian S, Wong C, Lee S, Lee P and Rawat R 2009 The effect of anode shape on neon soft x ray emissions and current sheath configuration in plasma focus devices *J. Phys. D: Appl. Phys.* **42** 045203

Moreno C, Bruzzone H, Martínez J and Clausse A 2000 Conceptual engineering of plasma focus thermonuclear pulsors *IEEE Trans. Plasma Sci.* **28** 1735–41

Siahpoush V, Tafreshi M, Sobhanian S and Khorram S 2005 Adaptation of Sing Lee's model to the Filippov type plasma focus geometry *Plasma Phys. Control. Fusion* **47** 1065–75

Soto L 2005 New trends and future perspectives on plasma focus research *Plasma Phys. Control. Fusion* **47** A361–381

Woodall D M and Len L K 1985 Observation of current sheath transition from snowplow to deflagration *J. Appl. Phys.* **57** 961