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Evolution of the small ball-like structures in the plasma focus discharge

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Abstract. The experiments were carried out in the PF-1000 plasma-focus device at the maximum current reaching about 2 MA, at the deuterium or neon filling and with deuterium injected from a gas-puff nozzle placed on the axis of the anode face. Ball-like structures of diameters of 1–12 mm were identified in interferometric and XUV pinhole camera frames. We made the statistical description of their parameters. A lifetime of the ball-like structures was in the range from 30 to 210 ns, and in some cases even more. These structures appeared mostly at the surface of the imploding plasma shell and they did not change their position in relation to the anode end. During the evolution of these structures, interferometric fringes were observed near the surfaces of the structures only, and their internal parts were initially chaotic (without noticeable) fringes. Subsequently the number of interferometric fringes increased (the internal 'chaotic' area was filled with fringes too) and later on it decreased. The radii of the ball-like structures were mostly increasing during their existence. The maximum electron density reached the value of 10^{24} to 10^{25} m^{-3}. The ball-like structures decayed by absorption inside the expanded pinch column and/or gradually expired in rare plasma outside of the dense plasma column.

Key words: dense plasma focus • interferometric diagnostics • organized structures in plasma • plasmoids

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Introduction

The ball-like structures were observed on the PF-1000 device at the shots with the deuterium or neon filling and deuterium puffing usually outside of the dense-pinched plasma column. The short description of the ball-like structures observed in shot #10080 and #10122 was presented in a paper [1]. In that paper, it was observed that the ball-like structures occurred at the imploding plasma shell boundary, the lifetime of the structures could be longer than 200 ns, the maximum electron density in the center of such structures was about 10^{25} m^{-3}. The ball-like structures had an internal region without clear interferometric fringes at the very beginning of their existence. During the existence of the ball-like structures, their internal regions were filled by interferometric fringes step by step, before they started to decay. The author suggested that the internal region without clear pattern of fringes was caused by internal turbulent behavior with velocities determined by the duration of the diagnostic laser beam above 10^6 m/s. Structures decayed by absorption in the expanding column with the decreasing of the electron density or by ejection of a plasma jet [1].

In this paper, the more detailed characteristics formulated from 15 shots (i.e., electron density profiles and total electron number of the ball-like struc-

Table 1. Parameters of the ball-like structures observed in the PF-1000 experiments

No. of shot	Maximum electron density n_e [m^{-3}]	Maximum total number of electrons	Maximum diameter [mm]	Lifetime [ns]
#10099	10.0×10^{24}	40.0×10^{16}	12.0	>210
#10122	11.0×10^{24}	55.0×10^{16}	9.0	>210
#10124	5.7×10^{24}	4.0×10^{16}	5.0	>210
#10125 first	4.5×10^{24} (it could reach a higher value)	3.8×10^{16} (it could reach a higher value)	3.7 (it could reach a higher value)	>210
#10125 second	4.0×10^{24}	0.2×10^{16}	1.8	100
#10125 third	8.0×10^{24}	0.1×10^{16}	1.1	30
#10126	7.4×10^{24} (it could reach a higher value)	1.6×10^{16} (it could reach a higher values)	2.5 (it could reach a higher value)	>120
Common range	$(4.0–11.0) \times 10^{24}$	$(0.1–55) \times 10^{16}$	1–12	30 ns and above 210 ns

tures in different times of the existence) are shown. The uncertainty of estimated electron density of the ball-like structures (from the Abel transformation of the interferometric image) includes an error that is caused mostly by nonideal spherical symmetry of the considered structure. The final electron density profile is presented as an average density profile of four profiles estimated from the left, right, upper, and lower-side of the structure. The uncertainty of those computations was estimated to be about 20%.

Most of the ball-like structures occurred at the dense plasma column's surface. These structures did not have interferometric fringes in the internal region. Their diameter and maximal electron density value increased. Later, after the filling of the internal region with fringes, the considered structures started to decay. The maximal values of electron density were decreased and their diameter changed until these structures disappeared.

It should be noted that such ball-like structures were observed in two experimental campaigns when we also observed many fine filamentary structures in the dense plasma column [1]. Further more detailed descriptions of the ball-like structures are in the following sections: experimental results, evolution of the ball-like structures, discussions, and conclusions.

Experimental arrangement

The experiments were carried out on the PF-1000 plasma focus facility equipped with the Mather-type coaxial electrodes of 48 cm length. The anode diameter was 23 cm. The cathode of 40 cm in diameter was composed of twelve stainless-steel rods of 82-mm in diameter each, which were distributed symmetrically around the anode circumference. The condenser bank was charged to the initial voltage of 23 kV, which corresponded to stored energy of 350 kJ. The maximal discharge current amounted to 1.7–1.9 MA. The initial pressure in the discharge chamber with a deuterium filling was about 200 Pa [2].

The interferometric measurements were performed with a Nd:YLF laser operated at the second harmonics (527 nm). The laser pulse (shorter than 1 ns) was split by a set of mirrors into 15 separate beams, which passed through a Mach-Zehnder interferometer with strictly parallel mirrors. These beams probed the plasma region at 10–20 ns intervals during the period of 210 ns [3]. The time scale was adjusted in such a way that the instant $t = 0$ corresponded to the minimum of the current's derivative. The uncertainty in timing of different signals was about 2–3 ns.

The gated microchannel plate (MCP) was used to obtain four time-resolved XUV frames using four separate pinholes. The polystyrene filters of 5 μm in thickness were placed in front of the pinholes. The transmission range of these filters was above 700 eV, with the window in the range 150–300 eV. A gold photo-cathode of MCP produced electrons from photons above 10 eV. The exposure time of frames was approx. 2 ns and we obtained four images with 10 ns delay between frames. The diameter of the pinholes was 80 μm and the magnification ratio was equal to 10. Therefore, the spatial inaccuracy of the gained frames was about 0.8 mm [1, 2]. The angle between the optical axis of the MCP detector and the main interferometric beam was 45°. The schematic location of MCP is shown in Fig. 1.

More detailed information about diagnostics applied at the PF-1000 facility was given in earlier papers [1, 2].

Experimental results

The total neutron yield registered in the shots with the deuterium gas-puff and the neon/deuterium fill-

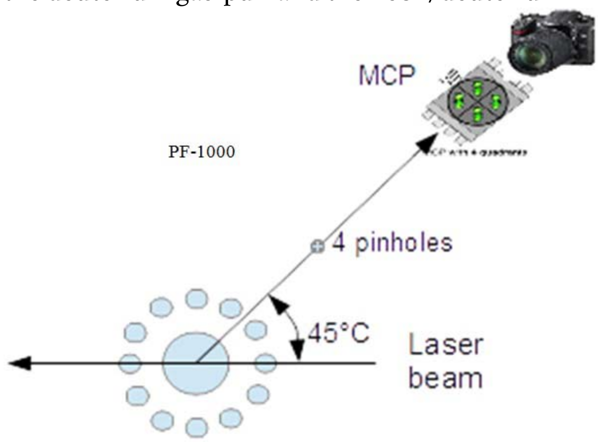

Fig. 1. Radial position of MCP and interferometric diagnostics at the PF-1000 facility.

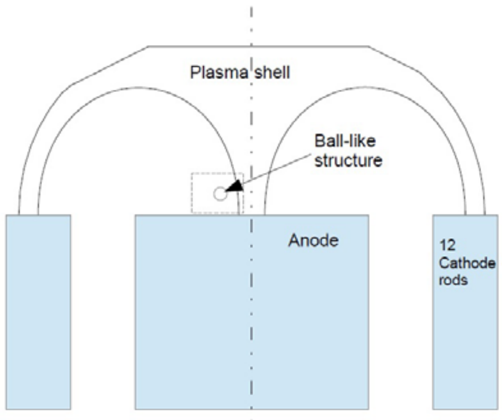

Fig. 2. Schematic location of the ball-like structures during a PF-1000 discharge.

ing in the chamber reached 10^{10}–10^{11}. We observed the ball-like structures in six shots performed with the deuterium filling in the chamber and in nine shots with the neon filling of the chamber. Those structures were seen on the MCP and interferometric frames. It should, however, to mention that it was possible to observe such structures in the shots with the deuterium gas-puff only. Observations of the ball-like structures were possible at the initial pressure of the neon filling in a range of 66–80 Pa, as well as at the initial pressure of the deuterium filling equal to 200 Pa and the deuterium puffing under pressure of 150 kPa. A schematic place of the ball-like structure during the plasma focus discharge is shown in Fig. 2.

Typical diameters of the observed ball-like structures reached values of 1–12 mm. We have often observed several ball-like structures per shot, and in one shot with the deuterium filling in the chamber, there were recorded even above 70 such structures. These structures could appear at the surface of the imploding plasma shell of the pinch column. A lifetime of the ball-like structures was in the range from several tens to 200 nanoseconds, and in some cases, it was even longer (see Table 1). They could also appear without any visible external influence, but their maximal diameter did not exceed few mm and their lifetime did not exceed 100 ns. All structures did not change their position during their existence (with a visible inaccuracy), but their sizes and shapes were changed. The typical value of electron density maximum inside the considered structures reached of (3–11) $\times$ 10^{24} m^{-3}. The typical maximum total number of electrons reached the value from (1–2) $\times$ 10^{15} in structures of 1–2 mm in diameter – to 5.5 $\times$ 10^{17} in structures of 10–12 mm in diameter. The observed ball-like structures decayed inside an expanding pinch column, also when there was no visible effect. Their diameters were increased or decreased, but their electron density decreased in time.

Some statistical parameters of the ball-like structures are shown in Table 1. The most often observed structures had small diameter, one to two fringes, and short lifetime (as in shots #10125 second and #10125 third). That was a reason why the detailed characteristics were assumed approximately to be the same for structures with diameter less that 3 mm.

Evolution of the ball-like structures

For a detailed description, we chose two convenient ball-like structures from shots #10122 and #10099 performed with the neon filling in the chamber. In shot #10122, the ball-like structure was observed at the increasing phase of the ball-like structure evolution. In shot #10099, the ball-like structure was observed during the decay phase of the ball-like structure evolution.

Data from shot #10122

In shot #10122, the ball-like structure occurred at outer surface of the imploding plasma shell at the instant t = –90 ns (see Fig. 3). A distance of the considered ball-like structure from the pinch axis, which was estimated from XUV and interferometric frames, amounted to 47 ± 9 mm, and the distance between this structure and the anode face was approximately 7 mm.

The diameter of the described structure was 1.9 mm at the instant t = –90 ns (see Fig. 3). During subsequent 160 ns from this instant, that is, until the instant t = 70 ns, the diameter of the structure grew up to 6 mm, the number of interferometric fringes was gradually increased from 0.5 to 4.5, and the central chaotic circle field was gradually filled up by such fringes. At the instant t = +100 ns, the form of the interferometric fringes showed some interaction of the observed ball-like structure with the expanding dense plasma column. The number of fringes rapidly increased to almost 9. The diameter of the structure reached about 10 mm. And then, during next 20 ns, the structure started to gradually decay, and the shape of the fringes was changed to the more unsymmetrical form. The number of the fringes started to decrease after the instant t = 100 ns, and the diameter of the observed structure decreased to about 8 mm.

We do not know the accurate electron density value in the central part of the ball-like structure during at the period ranging from –90 ns to +100 ns because its inner part was not filled with interferometric fringes. Probably, in that region there occurred very quick plasma transformations (turbulences). It was assumed that electron temperature was equal

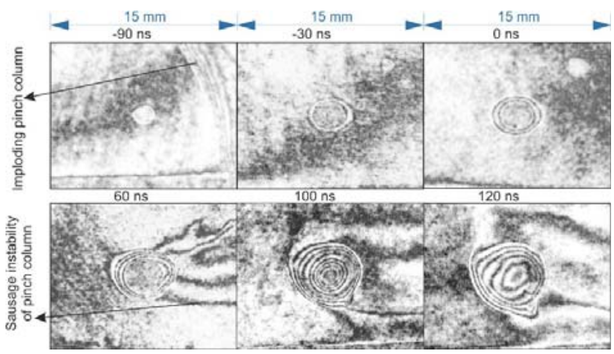

Fig. 3. Shot #10122 (neon filling in the chamber and deuterium puffing from valve). Interferometric frames of the evolution of the ball-like structure.

to 30 eV, electron density 3×10^{24} m^{-3} at the beginning of the existence of the ball-like structure. The atomic mass was equal to 2. Hence, the temperature equilibration time of electrons and ions was approximately 10 ns, according to the known relation given in [4]. Consequently, at this temperature, density, and dimensions of the structure, we could assume the temperature equilibrium inside the ball-like structures. It was enough for alignment of pressure and temperature values in the center of the ball-like structures (when they were filled with fringes). Hence, we assumed that the values of the electron densities for this region were equal to the electron density of the inner fringe's zone of the structure.

The maximum of the electron density in the center of the ball-like structure was approximately 2×10^{24} m^{-3} (see Fig. 4a) at the instant t = –30 ns. Later on, in the period from –20 ns to 100 ns, this density was increased up to 11×10^{24} m^{-3}. During last 20 nanoseconds of observation, the maximum electron density decreased to about 6×10^{24} m^{-3}.

The value of the total number of electrons in the observed ball-like structure increased in the considered period (from –90 ns to 100 ns) from the value of 0.5×10^{17} to about 3.8×10^{17}, and later on it decreased to 3.2×10^{17} (at the instant t = 120 ns).

Data from shot #10099

For this shot, the interferometric pictures of the ball-like structure (see Fig. 5a) were recorded during its decay after the SXR, HXR, and neutron peaks (observed in the period from 166 to 376 ns).

The diameter of the considered structure (Fig. 5a) reached 9 mm at the instant t = 166 ns. At this time, the central part of the structure was quite a nonsymmetrical one. During next 210 ns, that is, in the period from 166 to 376 ns, the diameter of the structure grew up to about 12 mm, but the number of fringes decreased gradually from 6 to 1.5.

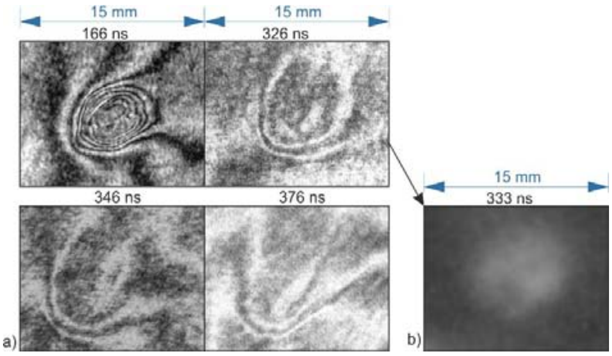

Fig. 5. Shot #10099 (neon filling in the chamber and deuterium puffing from valve). Interferometric (a) and XUV (b) frames of the ball-like structure.

The maximum electron density in the center of the observed structure was approximately 6×10^{24} m^{-3} (see Fig. 6a) at the instant t = 166 ns. Later on, at the instant t = 196 ns the electron density increased even up to 10×10^{24} m^{-3}. During the subsequent period from 196 ns to 376 ns, the maximum electron density decreased gradually to about 1.3×10^{24} m^{-3}.

The value of the total number of electrons in the structure gradually decreased from 4×10^{17} to 2.3×10^{17} during the period from 166 to 376 ns (see Fig. 6b). The uncertainty of the curve shown in Fig. 6b was raised at later times (about $\pm 0.7 \times 10^{17}$) because the surface of the analyzed structure was not clearly identified as in earlier period.

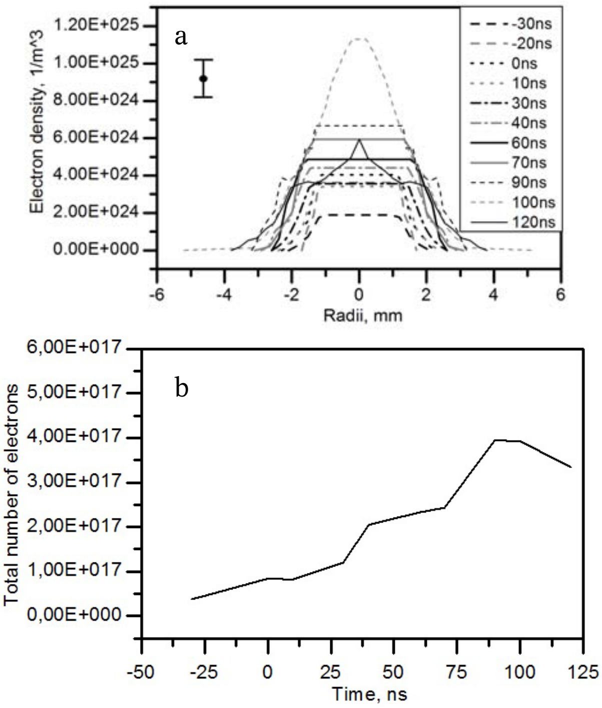

Fig. 4. Shot #10122. (a) The electron density profiles of the ball-like structure in different times. (b) The evolution of the total number of electrons in the ball-like structure.

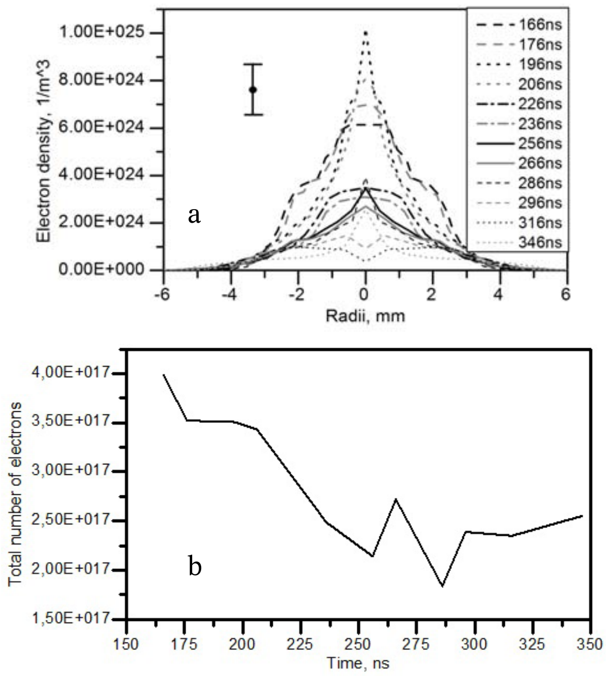

Fig. 6. Shot #10099. (a) The electron density profiles at different times. (b) The evolution of the total electron number in the ball-like structure.

Discussion

It is suspected that the plasma mass could flow between the ball-like structure and the surrounding plasma. Quite high stability of the ball-like structures could be explained by the following speculations. The higher electron density and electron temperature can induce a higher plasma pressure inside the ball-like structure than that appearing in the surrounding the plasma region. This higher pressure could also be explained by the influence of the filament current flowing around the ball-like structure. One can suspect that the almost ideal spherical form of the ball-like structures (seen as a circular object) can be explained by some surface tension caused by the internal closed currents [2]. In contrary to plasmoids observed in the dense pinch column [5], the ball-like structures were observed without noticeable plasma current of the electron density amounting to above 10^{23} m^{-3}, which could flow around the considered plasma structure.

Conclusions

The reported experimental studies can be summarized as follows:

1. The evolution of the ball-like structures can be divided into two phases: (a) phase of increase and (b) phase of decay.
2. The ball-like structures can appear at the surface of the imploding plasma shell and they appear without external influence during the pinch and stagnation phase of the plasma column.
3. During the (a) phase (lasting about 30–200 ns), the diameter of the ball-like structures usually increase. The maximum of electron density increases to the value of about 1.1×10^{25} m^{-3}. The total number of electrons increases also to about 4×10^{17}.
4. During the (b) phase (lasting about 30–200 ns), the visible diameter of the ball-like structures continues to increase up to about 12 mm and it decreases until the instant when the structure disappears. The electron density decreases gradually, and the total number of electrons also decreases. The observed mean lifetime of the ball-like structures ranges from several tens nanoseconds to about 200 ns (or even more).
5. The velocity of the expansion of ball-like structures amounts to (3–20) $\times 10^4$ m/s, but the ball-like structures do not change their position in relation to the anode face (with a spatial inaccuracy of ± 0.3 mm).
6. The ball-like structures have probably a temperature of several tens electrovolts (because they are observed in XUV frames), and the internal electron density can be quite high (ranging up to 10^{25} m^{-3}).
7. The ball-like structures decay usually during the explosion of a constriction of the pinch column, or disappear in the expanding plasma column, even with no noticeable external influence.

The future study should be aimed at searching of more favorable regimes, enabling to observe the ball-like structures or filamentary structures through the application of some gas admixtures in the gas--puff, because they might penetrate into the ball-like structures and make them more visible.

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References

1. Kubes, P., Paduch, M., Cikhardt, J., Kortanek, J., Cikhardtova, B., Rezac, K., Klir, D., Kravarik, J., & Zielinska, E. (2014). Filamentary structure of plasma produced by compression of puffing deuterium by deuterium or neon plasma sheath on plasma-focus discharge. *Phys. Plasmas*, *21*, 122706.
2. Kubes, P., Paduch, M., Cikhardt, J., Kortanek, J., Batobolotova, B., Rezac, K., Klir, D., Kravarik, J., Surala, W., Zielinska, E., Scholz, M., Karpinski, L., & Sadowski, M. J. (2014). Neutron production from puffing deuterium in plasma focus device. *Phys. Plasmas*, *21*, 082706.
3. Zielinska, E., Paduch, M., & Scholz, M. (2011). Sixteen-frame interferometer for a study of a pinch dynamics in PF-1000 device. *Contrib. Plasma Phys.*, *51*(2/3), 279–283.
4. Ryutov, D. D. (2015). Characterizing the plasmas of dense Z-pinches. *IEEE Trans. Plasma Sci.*, *43*(8), 2363–2384.
5. Kubes, P., Klir, D., Kravarik, J., Rezac, K., Kortanek, J., Krauz, V., Mitrofanov, K., Paduch, M., Scholz, M., Pisarczyk, T., Chodukowski, T., Kalinowska, Z., Karpinski, L., & Zielinska, E. (2013). Scenario of pinch evolution in a plasma focus discharge. *Plasma Phys. Control. Fusion*, *55*, 035011.