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Population inversion due to charge-exchange interaction of plasma jets from plasma focus with residual gas

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Charge-exchange recombination is known to be an effective mechanism to obtain a population inversion in the extreme ultraviolet range. Theoretical estimates and preliminary experiments show that a plasma focus with a stored energy of several kJ can be used as a source of strong jets of plasma with highly ionized atoms of light elements $Z_n < 10$. In experiments with nitrogen as a working gas a kinetic energy of the jet was about 2–3 keV with initial radial dimension of a jet of about 2 mm. Velocity of the plasma jet starts to exceed a velocity of ''zippering'' when the point of initial plasma compression on the axis reaches a position of 8–10 mm from an anode. After that point the plasma jet interacts freely with a residual gas. An effective charge-exchange recombination of fully ionized nitrogen results in overpopulation of the n-4 level of the H-like ion N VII. [S1063-651X(98)01312-9]

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INTRODUCTION

Interaction of highly ionized atoms with neutral gas with subsequent charge-exchange (CE) recombination was proposed in [1] as a mechanism for a population inversion for transitions in a soft x-ray and vacuum ultraviolet (vuv) region and was discussed elsewhere [2,3]. Experiments have been made using laser produced plasma [4] expanding in a hydrogen or helium atmosphere. The idea to use for these purposes strong plasma jets from instabilities in high current axial discharges has been discussed in [5–7] and was applied for explanation of a lasing effect on the C VI (18, 2 nm) line in capillary discharge [8]. We presume that nonlinear effects of the anomalous intensities ratio for components of $n=4 \rightarrow n=3$ transitions in Li-like ions of elements with periodic number $Z_N < 10$, associated with neck type instabilities in Z pinches with current of about a few hundred kA [9,10], were a result of a CE reaction between plasma beams from instabilities and lower charged residual plasma as a pumping mechanism. Among different types of axial discharges the plasma focus geometry has evident advantages: (i) a fixed position of an instability—focus—appearance and (ii) a possibility to transport a highly ionized plasma jet to a specially prepared target.

In this paper we report results of experimental investigations of the proposed mechanism for creating population inversion in a plasma focus device. Observation of plasma compression dynamics and properties of a plasma jet originated at the moment of maximum compression are reported together with spectroscopic observation of level population in highly ionized ions.

PLASMA COMPRESSION DYNAMICS

Experiments have been done using a small Mather type plasma focus device PF3 described elsewhere [11] with a current of about 200 kA operated with pure nitrogen at pressure from 50 to 400 Pa. The main stages of plasma sheath dynamics are shown in Fig. 1. Comparatively cold current sheaths move in a radial motion, creating, as a result of thermalization of kinetic energy at the moment of stagnation on the axis, a hot focus plasma. Radial velocity of a plasma sheath prior to the final compression is indicated as V_{collapse}. Propagation of plasma sheaths along the discharge axis Z with a velocity V_{rundown} causes a so-called ''zippering'' effect—a movement of the position of a dense, hot focus along the axis with a velocity V_{zip}. Plasma jets from a plasma focus moving with a velocity V_{jet} are also shown.

Plasma compression dynamics has been investigated using visible and soft x-ray streak cameras and also a multiframe camera based on an open microchannel plate (MCP) with 5 ns frame duration.

Measurements using a visible streak camera were made with one-dimensional (1D) resolution in axial or radial resolution. ''Run down'' motion of comparatively cold plasma sheaths inhabiting temperatures of $kT \approx 10-20$ eV [11] (see Fig. 1) manifests itself by radiation mainly in the visible or uv region. Radial collapse prior to the moment of stagnation

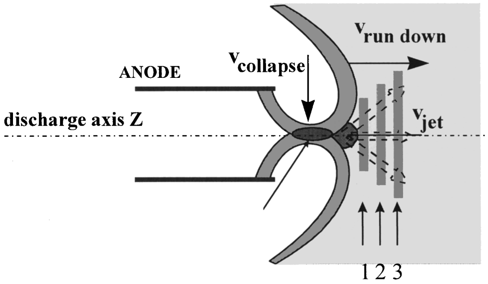

FIG. 1. The main stages of plasma focus development: ''run down'' motion—$V_{\text{run down}}$; collapse of plasma on axis with thermalization of a kinetic energy of radial motion—V_{collapse}; plasma jets from a hot plasma focus—V_{jet}.

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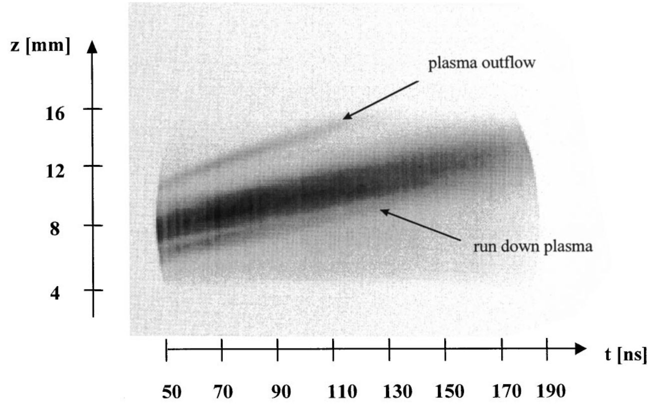

FIG. 2. Visible streak image of plasma propagation along the discharge axis in nitrogen at $p = 400$ Pa. Two different emitting plasma regions can be observed, one due to run down plasma, the second due to plasma outflow jet.

of plasma on the discharge axis can also be detected using visible radiation.

An example of 1D visible streak camera measurements with spatial resolution along the discharge axis is shown in Fig. 2. This streak starts about 50 ns after the moment of a plasma sheath stagnation on the discharge axis and shows a development of two zones radiating in a visible spectral range. The lower zone in Fig. 2 is associated with a plasma sheath run down movement, slowing down with time, and the upper is associated with a plasma jet in axial direction. Jet was originated at the moment of plasma stagnation on the axis.

Results of measurements of run down, ''collapse,'' and ''jet outflow'' velocities at the axial position $Z = 10$ mm from the anode surface are shown in Fig. 3 for different gas (nitrogen) pressure.

Soft x-ray radiation of a hot plasma is characteristic for the phase when a dense pinch is created on the axis. This radiation has been registered with 1D resolution along the discharge axis using an x-ray streak camera XRSC II [13]. An example of a streak for gas pressure $p = 250$ Pa is shown in Fig. 4(a).

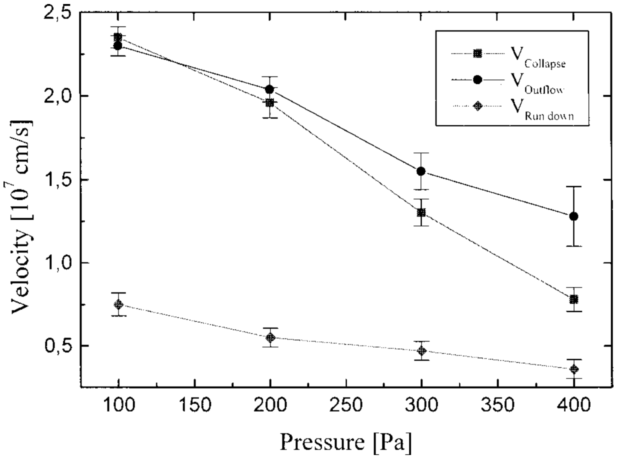

FIG. 3. Velocity of collapse—V_{collapse}, outflow—V_{jet}, and run down—$V_{\text{run down}}$ plasma motion evaluated from the streak measurements in the visible range for nitrogen at different gas pressures.

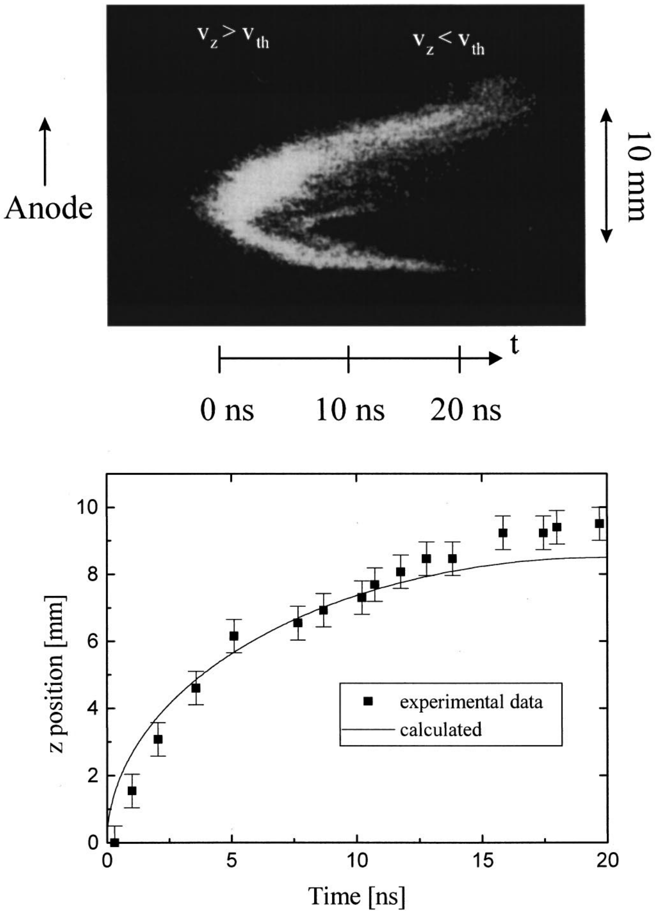

FIG. 4. (a) Soft x-ray streak image of plasma propagation along the discharge axis in nitrogen at $p = 250$ Pa. (b) Evaluation of experimental data from (a). Solid curve—position of x-ray radiation for zippering effect.

Superposition of the pinched plasma regions—a zippering effect—causes a spread of the ionization front along the discharge axis in both directions. At the beginning the zippering velocity is very high (of about 3×10^8 cm/s) but slows down with time. Figure 4(b) shows results of measurements together with results of their evaluation. Numerical simulation of a zippering front position is shown as a solid line in Fig. 4(b). One can see that during the first 10 ns there is a good agreement between calculated and measured position of a hot plasma front propagation. Nevertheless after approximately 10–12 ns from the moment of initial plasma constriction on the axis, when a zippering velocity slows down to a value of $(1-2) \times 10^7$cm/s, an additional acceleration of an x-ray front plasma image is noticeable. We attribute this part of the curve to an observation of a strong plasma jet flowing out from the foci region. When a zippering velocity is higher than the velocity of a jet, originated by pinch, the jet meets on its way the next portion of a compressed dense plasma and dissipates in it. After the moment when the speed of a zippering propagation starts to be lower than plasma jet speed ($V_{\text{jet}} > V_{\text{zip}}$) a plasma jet moves free. These measurements agree well with an observation of the same phenomena with the help of a visible streak technique.

It is important to notice that the point on the axis after which plasma jet velocity exceeds the velocity of a zippering

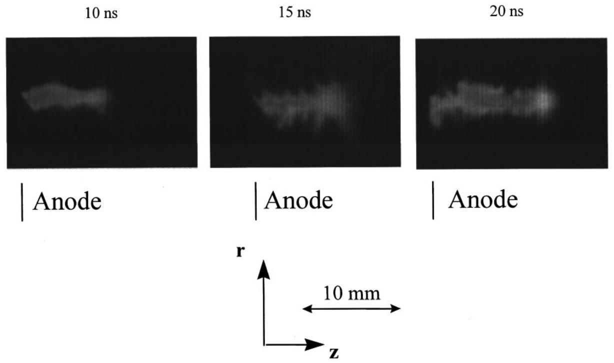

FIG. 5. Time gated (5 ns) pin-hole images of pinch plasma in soft x-ray and vuv radiation at 10, 15, and 20 ns after initial compression on the discharge axis.

front corresponds to a position between 7 and 9 mm from the anode surface—a sort of plasma jet ''taking off'' point. One can expect that after this moment, ions in a plasma jet can interact with neutral and low ionized atoms of a residual gas (plasma) in a discharge chamber.

This interaction was detected on pin-hole images of plasma with the help of a time gated multiframe open MCP camera, sensitive to soft x-ray and vuv radiation. Pin-hole images of plasma corresponding to moments of pinch development at 10, 15, and 20 ns after initial compression on the axis are shown in Fig. 5. Gating time was 5 ns.

At the frame corresponding to the 10 ns moment one can see a column expansion for a plasma close to the anode and deeper compression for position of about 6–7 mm from the anode (zippering effect). At the moment $t = 15$ ns propagation of a position of a dense focus is terminated, plasma has a strong neck type structure and starts to expend at all lengths of the focus. Five ns later a new source of radiation appears at a distance of about 12 mm from the anode. As one can see from Fig. 4(a) zippering of plasma sheaths does not reach this point on the axis and we presume that this radiation is a result of interaction of plasma jets from the focus with residual gas.

These plasma jets are moving with a kinetic energy $E_{\mathrm{kin}} = 2-3$ keV per ion [corresponding to $(1-2)\times 10^7$ cm/s ion velocity]. As will be demonstrated below, the jet plasma mainly consists of fully ionized nitrogen or [H]-like ions of this element. For the expected range of ion kinetic energy between 500 and 5 keV the charge-exchange recombination [8,12] is the most important, having more than two orders of magnitude higher cross sections than other processes like Coulomb scattering and/or impact ionization.

POPULATION OF EXCITED LEVELS OF H-LIKE ION N VII

Spectra radiated by nitrogen plasma were registered with space (along axis) resolution with the help of two grazing incident spectrographs—a flat field spectrograph with a gold grating 1200*l*/mm and an ''off Rowland'' spectrograph with gold grating of 300, 600, and 1200*l*/mm, both spectrographs with 1 m radius of curvature of gratings. The flat field spectrograph focuses the spectrum in a spectral range 5–20 nm into a plate area of 2×2 cm which allows us to use film or a charge coupled device (CCD) camera as detector. The ''off Rowland grazing incident spectrograph'' allows us to detect radiation in a region from 3 to 100 nm using film or a time gated MCP detector.

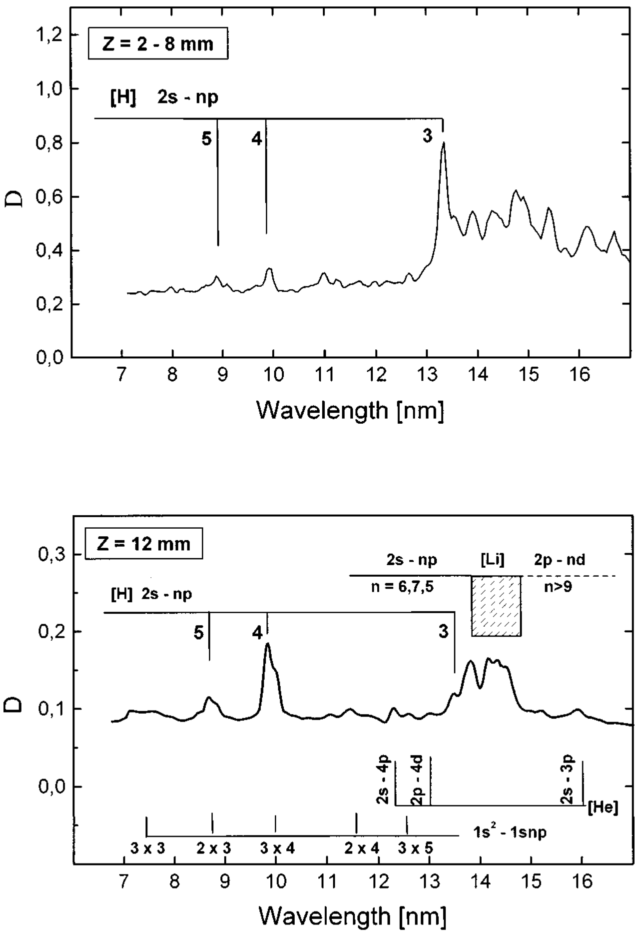

FIG. 6. (a) vuv spectra emitted by a nitrogen plasma at a distance between 2 and 8 mm from the anode. (b) The same as (a) for a plasma at a distance of 12 mm from the anode.

Examples of time integrated spectra in the range from 7 to 17 nm for a plasma region with axial coordinate z between 2 and 7 mm and for a region with $z = 12$ mm are shown in Figs. 6(a) and 6(b), correspondingly. Both spectra show strong emission of $n\rightarrow 2$ transition of hydrogenlike ions N VII and some lines of lithiumlike ions N V. The main dif-

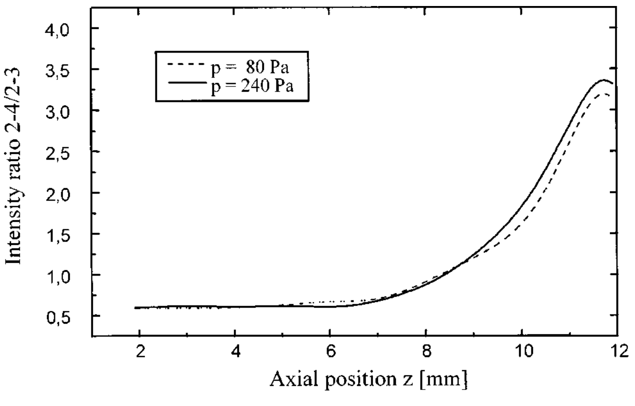

FIG. 7. Relative intensity ratio of 4-2 and 3-2 transition of N VII line emission.

ferences in the two spectra can be described as follows. For the spectra registered for the plasma region behind the jet take off point ($z > 8-10$mm) one can detect a strong increase of a relative intensity of 4→2 transition in H-like ion N VII spectra.

Figure 7 shows a ratio of intensities of 4→2 (99.13 A) and 3→2(133.82 A) transitions in N VII as a function of the position of the radiating plasma on a discharge axis for two different pressures of a working gas in a plasma focus chamber. It is important to note that the ratio changes drastically in the vicinity of a take off point after which the plasma jet directly interacts with neutral or weakly ionized residual gas.

CONCLUSION

It was shown that interaction of plasma jets from plasma focus discharge in a nitrogen atmosphere results in a population inversion between levels with principal quantum numbers $n=4$ and 3 of H-like ions N VII. A charge-exchange recombination was considered as the most probable pumping mechanism.

ACKNOWLEDGMENT

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