Fast collisional capillary discharge source for soft x-ray production and applications

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ABSTRACT

We report on a fast soft x-ray source consisting in a high temperature small diameter (4 mm) plasma column produced by electric discharge in a ceramic capillary. This source was developed to produce pulses of few hundred nanosecond duration for EUV lithography, x ray microscopy applications and also with the aim of developing a soft x ray amplifier. We obtained experimental results concerning the intensity and spectral analysis of the emitted x radiation pumped by a 30-40 kA, 100-200 ns, electric discharge at 1 Torr pressure in Ar gas. We refer also on the spectra obtained using CO_2, as plasma medium, after the optimization of the discharge setup and electrical parameters.

keywords: Capillary z-pinch discharges, soft x-ray sources.

1. INTRODUCTION

High-density plasmas devoted to the production of XUV radiation in the region of 1-50 nm are usually obtained by irradiation of solid targets by ultra-short powerful laser pulses[1, 2]. One alternative method for the production of such hot plasma sources is the capillary z-pinch discharge[3-7], which can be distinguished into ablative capillaries and gas filled discharges. In the first case, in which the discharge takes place into initially evacuated capillaries, the material ablated from the capillary channel generates the plasma column. In the second case the plasma is formed from a preionized gas initially filling the capillary channel. The first demonstration of a discharge pumped collisional soft X-ray laser on the transition 3p–3s of Ne–like Ar at 46.9 nm[6], and the identification of the appropriate conditions for lasing on the Balmer–α line of C^{+5} at 18.22 nm [3], stimulated a further investigation of this kind of sources.

In capillary discharge devices, current pulses with a peak value ranging from 10 to 100kA and a short rise time (less than 50 ns) represent the necessary condition for a fast and efficient heating of the plasma column. The high value of dI/dt ($dI/dt \sim 10^{12}$ A/s), allows the magnetic field to compress the plasma column and avoid its cooling by interaction of the plasma with the capillary walls. In the z-pinches, in which oscillating currents are generated by the direct discharge of a capacitor C through the channel, the relation $T \approx 2\pi(LC)^{1/2}$ determines the half cycle duration T of the current pulse, being L the total inductance of the circuit, including the inductance of the discharge channel.

Nowadays a great experimental effort is devoted to the realization of capillary discharge devices, with the aim to satisfy the requirements for applications in lithography. It means that they are aimed to produce x-ray emission in the region of the 10-14 nm utilizing discharges having lower input electrical energy per shot and high repetition rate[7,8]. More powerful sources are instead required to produce intense x-ray emission in shorter wavelength regions, as for example 2.2-4.3 nm range (which is of particular interest for microscopy of biological samples), up to 1 nm [9,10].

We have developed a high charging-voltage (up to 450 kV) fast electrical Z-pinch discharge in gas-filled capillary for the production of intense pulses of soft X-ray radiation in the spectral region of 1-50 nm. We report on the characterization of the device and its XUV emission, having a particular attention to the shorter wavelength regions. The experimental analysis of the X-ray emission, produced during the Z-pinch, is also discussed in comparison with a simplified MHD model.

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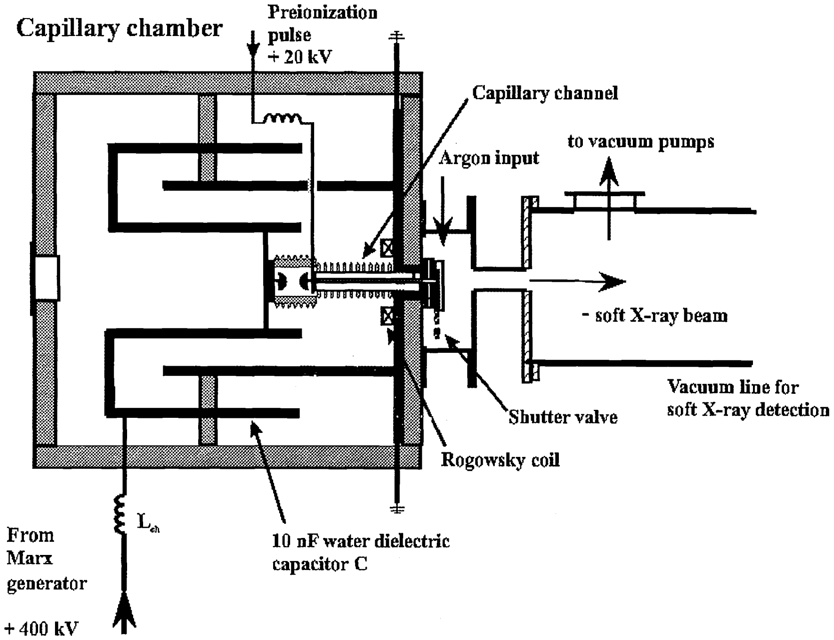


Figure 1: Schematic diagram of the experimental apparatus.

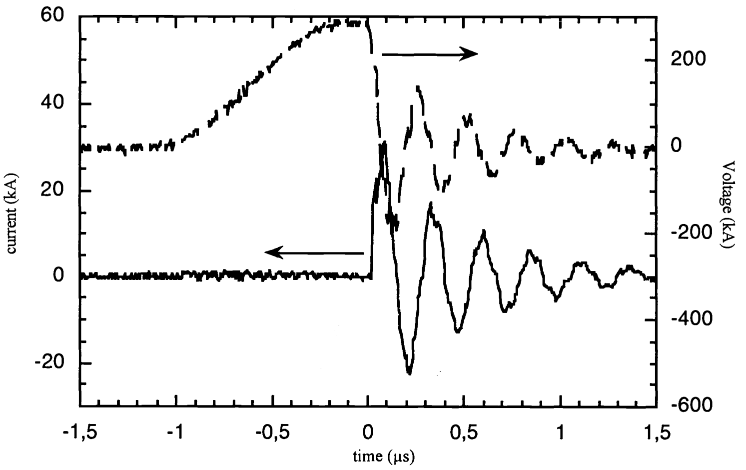


Figure 2: Volt-amperometric characteristics of the capillary discharge in a 4-mm-diam and 15 cm long capillary channel. Solid line represents the current pulse, dashed line the voltage on the capacitor.

2. EXPERIMENTAL SET-UP

In our experiment the high current pulse is generated by directly discharging through the capillary channel a 10 nF water dielectric capacitor, which is initially charged to high voltage by an six stage Marx generator (Figure1). The electrical discharge through the capillary channel is produced by the self-breakdown of a spark gap (having deionized water as insulator) when the voltage on the capacitor *C* reaches approximately the maximum value (200 and 400 kV). A Rogowsky coil measures the discharge current, while suitable resistive high voltage dividers record the voltage on the Marx generator and the capacitor *C*. The electrical signals from both, the Rogowsky coil and the voltage dividers are monitored by a 400 MHz digital oscilloscope (Tektronix TDS 380).

With such an electrical set-up, a current pulse with a peak value up to 40 kA and an half cycle duration of 125 ns can be produced through a 15 cm long, 4 mm in diameter ceramic (Al_2O_3) capillary channel. The peak value of the current pulse and its half cycle duration correspond to a circuit inductance of about 200 nH. Figure 2 shows the volt-amperometric characteristics of the capillary discharge.

During the experiments, the filling pressure of the argon gas was adjustable in an interval from 0.1 to 1 torr. The x-ray radiation was measured utilizing a fast, calibrated silicon PIN diode, having a detection area and a time resolution of 100 mm^2 and 5 ns respectively, coupled with different absorbers. The PIN diode signal is monitored on the Tektronix TDS 380 together with the current pulse. Such diode detector, having a sensitivity of 0.27 A/W (referred to the radiation, which reaches the junction after crossing 0.3 μm Si dead layer), allows an immediate estimation of the intensity of the soft X-rays emitted by the source. The PIN diode was positioned at 100 cm from the capillary output. A shutter valve was used to divide the capillary channel from the detection chamber, which is evacuated up to a pressure of 10^{-5} torr by a turbomolecular pump. The valve is opened roughly 1 ms before the starting of the current pulse.

Low resolved time integrated spectra were realized utilizing a 100 μm pinhole transmission grating having 1000 l/mm. This grating was positioned at 100 cm from the capillary output, axially centered with the capillary channel. In this configuration we had a resolution of about 1 nm, which allows a rough determination of the spectra selected by the filters. More accurate spectroscopic measurements were conducted using a 1m grazing incidence spectrometer (Jobin- Yvon LHT 30), having a resolution of 2 A when an entrance slit of 100 μm is utilized.

The spectrometer has been calibrated utilizing as references the absorption edge of Al (17.2 nm) and He (50.4nm).

3. MEASUREMENTS OF THE SOFT X–RAY RADIATION

3.1 Soft x-ray intensity dependence on initial gas pressure

We first focused our attention on the study of the soft x-ray emission as a function of the initial pressure of the gas, by changing it in the interval of 100–1000 mtorr, all other external parameters, such as the capillary diameter and current pulse, remaining fixed. At this stage, we used Ar as initial filling of the capillary channel. The study was conducted employing the PIN diode coupled with different kind of filters (aluminum, polypropylene, and nickel), so realizing spectrally integrated measurements of the XUV emission in three distinct spectral regions.

Figure 3 shows the time evolution of the soft x-ray emission selected by a 1.6 μm thick aluminum filter together with the current pulse. This filter gives a transmission of 2– 4% in the window 18-20 nm. A greater transmission is only obtained at wavelengths shorter than 2.5 nm, but, in our measurements, we verified that, with that Al filter, the range 18-20 nm strongly dominates the signal of the PIN diode.

As a result of the plasma compression, the XUV emission reaches its maximum value at 100 ns from the starting of the current pulse. This time also corresponds to the time of the compression τ_c predicted by the model calculation[11]. In the figure it can be seen that there is a second compression of the plasma column during the negative second half-period of the current.

While the amplitude of the first peak remains unchanged for the different gas pressure analyzed, the amplitude of the second peak decreases, by increasing the initial gas pressure. The reduction of the x-ray emission in the second compression indicates the reduction of the plasma temperature as the pressure increases. This is confirmed by the theoretical predictions[11].

In order to characterize shorter wavelength radiation, a 2-μm thick polypropylene foil combined with 0.4 μm of Al and a 1 μm Ni filter were utilized. The first filter strongly attenuates the radiation with wavelengths longer than 6 nm and has a transmission of 1-2 % in the window of $\approx$ 4-5 nm (Figure 4), the second one attenuates radiation with wavelength shorter than 3nm (Figure 5). In these cases, we obtain emission only during the first half cycle duration of the current. The radiation intensity decreases when higher-pressure values are used. As a result of the calculations we can expect that the plasma temperature maintains lower than around 60 eV for the initial pressure higher than 0.6 torr. Below this value of temperature the population of the highly charged ions (Ar IX, Ar X, ...) that emit x-rays with wavelength of shorter than 4 nm becomes negligible[12]. Using the low-resolution transmission grating, we have clearly shown the emission of lines at 4 nm typical of highly ionized Ar ions at pressure below 0.4 torr. More accurate measurements have been performed with the high-resolution spectrometer in the range of 18-26 nm. The spectrum reported in Figure 6, obtained with a pressure of 0.2 torr and a 36-kA current pulse, shows in fact the presence of ionization stages up to Ar XIII.

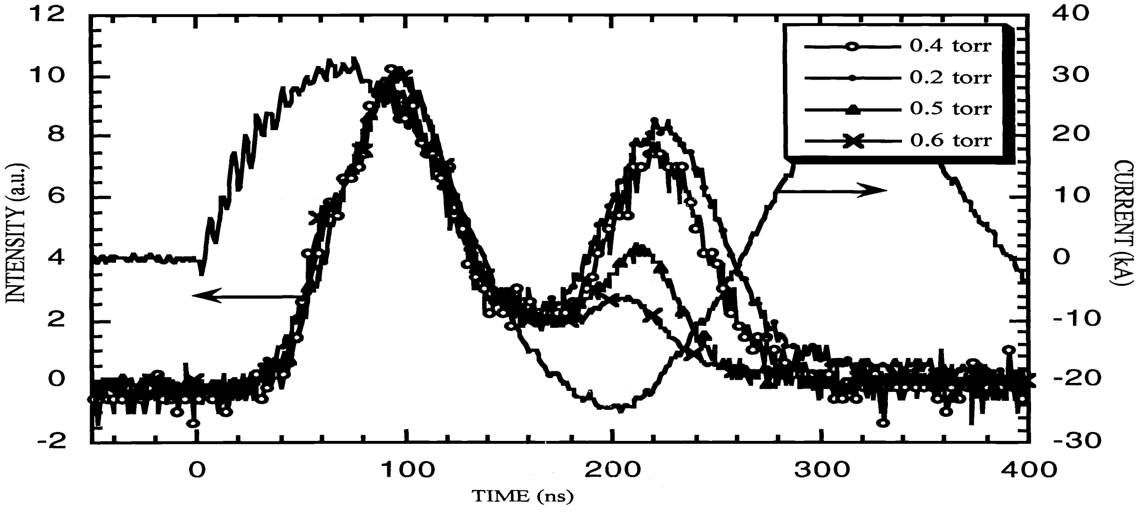


Figure 3: PIN diode signal measured with 1.6 μm thick Al foil at different initial pressure of Ar. The solid line represents the current pulse. The discharge is generated into a 4-mm-diam, 15 cm long capillary channel.

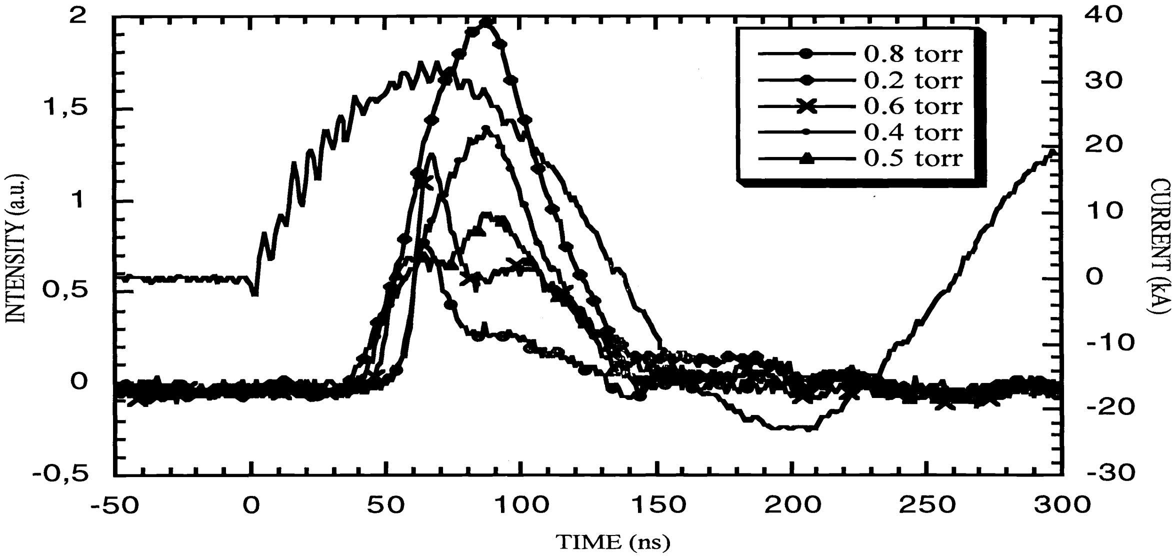


Figure 4: PIN diode signal measured with a 2μm thick polypropylene combined with 0.4 μm of Al at different pressure of Ar. The discharge is generated into a 4-mm-diam, 15 cm long capillary channel.

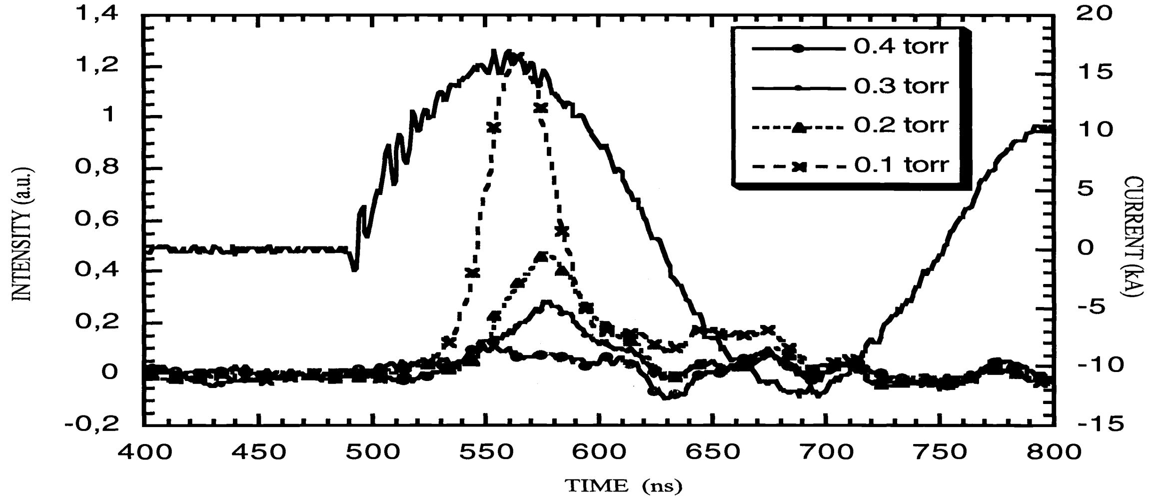


Figure 5: PIN diode signal measured with a 1 μm thick Ni-foil at different pressure of Ar. The discharge is generated into a 4-mm-diam, 15-cm long capillary channel.

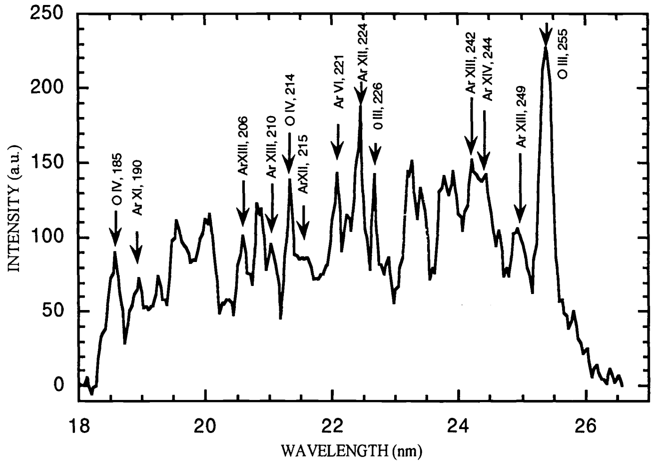


Figure 6: Ar time integrated spectrum of soft –x-ray emission from a 4- mm-diameter capillary excited by a 34 kA current. Pressure in the capillary channel was 0.2 torr

Concerning the emitted fluence of x-ray radiation, we have found, in the optimized pressure conditions an x-ray intensity of 6.8 mJ/sr/eV at 18 nm, an intensity of about 1.3 mJ/sr/eV at 5 nm and 0.3 mj/sr/eV at 4 nm.

3.2. Emission spectra of a CO_2 plasma

To improve emission in shorter wavelength region other gases were analyzed like airs, nitrogen, $C0_2$. Results will be published elsewhere. It is evident, also in this case, that lower pressure of the gas are needed to obtain a greater plasma temperature and a significant emission of radiation. In this context highly resolved spectra were obtained utilizing a focusing spectrograph with spherically bent crystal (Faenov et al[13,14]). Figure 7 shows the spectra obtained with an initial gas pressure of 0.1 torr of CO_2 and 1.8-mm-diam, 10-cm long capillary channel. The current pulse was 34 kA. We can distinguish OVII emission lines ($1s^2$–1s4p at 1.776 nm and $1s^2$–1s5p at 1.74). This spectra allows the detemination of the plasma temperature and electron density. From the relative amplitude of the lines and from the model calculation an electron temperature of 90 eV and an electron density of about 9 10^{17} cm^{-3} were estimated.

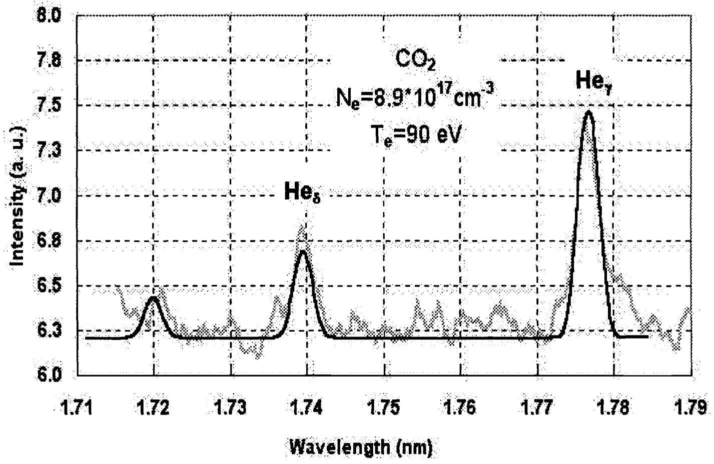


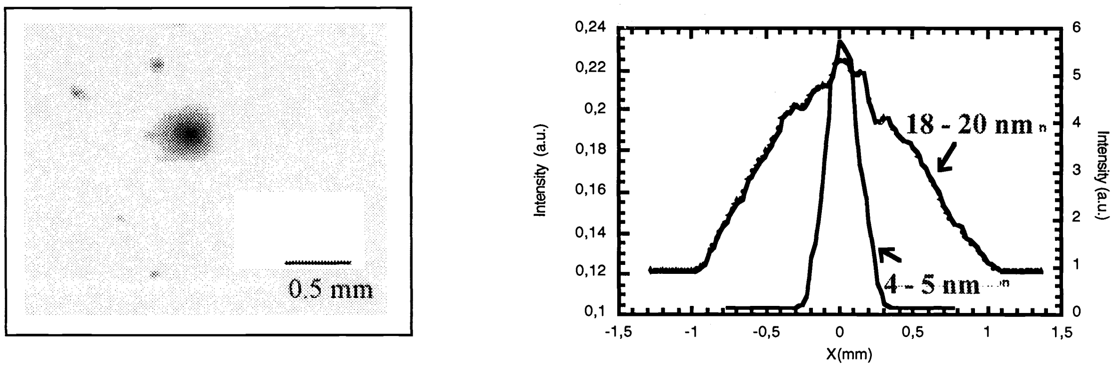
Figure 7: Spectrum obtained with 0.1 torr of CO_2 and a 34 kA current pulse using the spherical crystal spectrograph. The measurement was performed in a 1.8-mm-diam, 10-cm long capillary channel.

3.3. Source dimension

Concerning the dimension of the source, this has been studied at different wavelengths using different filters. In Figure 8a we report a time-integrated image of the plasma source relatively to the spectral range of 4-5 nm, obtained by a pinhole having a dimension of 100 μm, which was positioned to produce a X 1 magnified image of the source. The images, which were recorded also for other spectral regions, were recorded on Ilford Q-plate films. When the plasma was created initially filling the capillary channel with 0.4 torr of Ar and utilizing a 32 kA current pulse, the dimension of the source resulted about 200 μm at λ= 4-5 nm, and 1.5 mm at wavelengths of 18-20 nm (Figure 8b).

5. CONCLUSIONS

In conclusion, an apparatus for production of high-current (up to 40 kA) fast Z-pinch electrical discharges gas filled capillaries has been developed. Experimental analysis of the soft x-ray emission was performed utilizing a fast PIN diode, and performing time-integrated measurements of the dimension of the plasma source and time-integrated spectroscopic measurements. A preliminary study of the parameters necessary to maximize the emission in the spectral region from 1 nm to 20 nm is performed and compared with the results of a theoretical MHD model. The measured intensity resulted of 68 mJ/sr/eV at 18 nm, of about 1.3 mJ/sr/eV at 5 nm and 0.3 mj/sr/eV at 4 nm. We are also considering how to utilize this source for x-ray contact and projection microscopy. This applications will be possible being our x-ray source a debris-free one. Attempts have been done both in the water window region and at about 700 ev using Faenov spherical crystals as mirrors.



a) b)

Figure 8: a) image of the source measured with the polypropilene filter and a 100 µm- pinhole with a 1:1 magnification; b) dimension of the source at 4-5 nm and 18-20 nm. The measurements were performed in Ar with a current pulse of 32 kA, a gas pressure of 0.4 torr in a 4-mm-diam, 15 cm long capillary channel.

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REFERENCES

1. S. Suckewer, C.H. Skinner, H. Milchberg, C. Keane, and D. Voorhees: *Phys. Rev. Lett.* **55**, 1753, 1985
2. R.C. Elton: *X-ray Lasers*, Academic Press, New York, 1990.
3. C. Steden and H.-J. Kunze, "Observation of gain at 18.22 nm in the carbon plasma of capillary discharge", *Phys. Lett. A* **151**, 534–537, 1990.
4. S.V. Kukhlevsky, Cs. Vér, J. Kaiser, L. Kozma, L. Palladino, A. Reale, G. Tomassetti, F. Flora and G. Giordano, "Generation of pure, high-density metal-vapor plasma by capillary discharge", *Appl. Phys. Lett.* **74** 2779–2881, 1999.
5. D. Hong, R. Dussart, C. Cachoncinlle, W. Rosenfeld, S. Gotze, J. Pons, R. Viladrosa, C. Fleurier and J.–M. Pouvesle "Study of a fast ablative capillary discharge dedicated to soft X-ray production", *Rev. of Sci. Instr.*, **71**,15–19, 2000
6. J.J. Rocca, V. Shlyaptev, F.G. Tomasel, O.D. Cortazar, D. Hartshorn and J.L.A. Chilla, "Demonstration of a discharge pumped table–top soft-X-ray laser", *Phys. Rev. Lett.* **73**, 2192–2195, 1994.
7. M. A. Klosner and W.T. Silvfast, "Intense xenon capillary discharge extreme ultraviolet source in 10-6 nm wavelength region", *Opt. Lett.* **23**, 1608–1611, 1998.

8. K.Bergman, G.Schriever, O.Rosier, M.Muller, W.Neff and R.Lebert, "Highly repetitive, extreme-ultraviolet radiation source based on a gas-discharge plasma", *Applied optics*, **38**, 5413-5417, 1999.

9. R.B. Spielman, D.L.Hanson, M.A.Palmer, M.K.Matzen; T.W.Hussey, and J.M.Peek, "Efficient x-ray production from ultrafast gas-puff Z pinches", *J. Applied Phys.,* **57**, 830-833, 1985

10. K.L.Wong,P.T.Springer, J.H.Hammer, C.A.Iglesias, A.L.Osterheld, M.E.Foord, H.C.Bruns, J.A.Emig, C.Deeney "Spectrocopic characterization of an argon-neon z-pinch plasma at stagnation", *Phys. Rev. Lett.*, **80**, 2334-2337, 1998:

11. S.V. Kukhleevsky, A. Ritucci, J. Kaiser, G. Tomassetti, A. Reale, L. Palladino, I. Z. Kozma, F. Flora, L. Mezi, O. Samek, M. Liska, "Study of plasma evolution in argon filled capillary Z-pinch devoted to X-ray production", *Plasma Souces Sci. & Techn.,* (accepted for publication).

12. B:R:Benware, C.D. Macchietto, C. Moreno and J.J. Rocca, "Demonstration of high average power tabletop soft x-ray laser", *Phys. Rev. Lett.,* **81**, 5804-5807, (1998)

13. I.Yu. Skobolev, A.Ya.Faenov, B.A.Bryunketkin et al., *Zh. Eksp.Teor.Fiz.*, **108**, 1263, 1995.

14. J.Abdallah Jr, R.E.H. Clark, A.Ya.Faenov, L.Karpinski, S.A.Pikuz, V.M.Romanova, M.Sadowsky, M.Scholz, A.Szydlowsky, "Electron beam effects on the spectroscopy of multiply charged ions in plasma focus experiments", *J.Quant. Spectr. & Rad. Transf.* **62**, 85-96, 1999