**UNIVERSITY OF PÉCS**

Doctoral School of Physics

# Capillary discharge $Ar^{8+}$ soft X-ray lasers

PhD Thesis

János Péter Szász

Supervisor:

Dr. Szergej Kuhlevszkij

Professor

PÉCS, 2016

# 1. Introduction

Coherent soft X-ray sources with wavelengths in the range $\lambda \approx 0.1$–50 nm are required in many areas of science and technology. Synchrotrons, free-electron lasers, laser-induced plasmas and high-harmonic generators are examples of effective soft X-ray sources [1], [2], [3], but such sources are usually very expensive and complex. Hence many small laboratories, universities and institutes are interested in more practical, simpler, compact (table-top) and inexpensive sources of soft X-rays. One of the most practical soft X-ray lasers is currently considered to be the $Ar^{8+}$ laser excited by a capillary discharge z-pinch [4], [5], [6], [7], [8], [9], [10], [11], [12].

Z-pinch discharges, which previously have been investigated mainly as drivers for thermonuclear fusion, are used in $Ar^{8+}$ lasers for generation and excitation of the hot (temperature $T_e \sim 0.1$ keV) and dense ($N_e > 10^{18}$ cm$^{-3}$) argon plasma as the active laser medium. In this laser pumping scheme a hot and highly ionized plasma active medium with a diameter of about 50 μm is produced by high-current electric pulses with short rise times (a few tens of nanoseconds) flowing axially through a capillary channel filled with low pressure argon. The plasma temperature and density increase through fast radial compression of the plasma column by the magnetic field created by the current itself. The lasing takes place in the 46.9 nm line of $2p^53p$ ($J = 0$) – $2p^53s$ ($J = 1$) transition of neon-like argon ($Ar^{8+}$) through collisional excitation of the ion by hot electrons. Recently, considerable effort has been devoted to reducing the laser size from laboratory to table top. In the laboratory-size laser, a capillary z-pinch with a peak current $I \sim 40$ kA is produced by a water capacitor with $C \sim 5$ nF that is charged to a high voltage of up to about 150 kV by a pulsed Marx generator. The output pulse energy of such a laser is up to about 1 mJ. Table-top lasers have been developed by using low-inductance coaxial discharge configurations that decrease the voltage and current necessary for the laser excitation [4]. In order to achieve this, a water or ceramic capacitor is charged to a relatively low voltage (150–300 kV) by a Marx-generator or a simple single-stage power unit providing the peak current (12–20 kA) required for saturated laser operation. Laser amplification in the most compact and effective $Ar^{8+}$ laser was obtained in a 2 cm long aluminium oxide ceramic capillary with inside diameter 3.2 mm filled with pre-ionized argon at a pressure of about 0.9 mbar. Laser pulses with energy around 1 μJ were generated at repetition rates of up to 12 Hz. The laser beam profile typically had an annular shape with an angular divergence of about 7 mrad [5].

The present thesis concentrates on research and development of a practical, table-top $Ar^{8+}$ laser excited by relatively low current (< 22 kA) and voltage (< 200 kV) capillary z-pinch discharges. In accordance with previous studies, the main motivation in the research and development of table-top $Ar^{8+}$ lasers is the reduction of the overall size from laboratory to table top. Other important motivations include the peculiarities of the physics of capillary $Ar^{8+}$ lasers in the different operation regimes. Laboratory size lasers excited by capillary z-pinches with a peak current of around 40 kA using a high voltage of about 600 kV can produce laser pulses with high energy, up to ~ 1 mJ, but with low beam quality. The beam profiles are typically annular with divergences of around 7 mrad and low transverse coherence. Most laser applications require a transversely coherent beam with a Gaussian intensity distribution and angular divergence less than about 1 mrad. Laser beams with such parameters can be obtained by using small apertures, but the energy of the laser pulse will be low. The energy of such a coherent, low-divergence beam would be ~10 μJ. A laser beam with such parameters could be obtained directly by using a relatively low voltage (150-200 kV) and peak current (14-22 kA).

In my work a transversally coherent beam with a Gaussian intensity distribution, angular divergence less than about 1mrad and energy ~ 10 μJ was generated using a long (45 cm) capillary; $Ar^{8+}$ lasers are usually excited by z-pinch discharges in short (≈ 20 cm) capillaries. The longer plasma column provides a gain-length product $G{\cdot}l$ of about 16, as required for saturated laser operation, at a relatively low gain of $G \approx 0.3\ \mathrm{cm}^{-1}$. Such a low gain can be produced at relatively low plasma temperature and density using a low voltage and current. For comparison, $Ar^{8+}$ lasers excited by capillary z-pinches in short (21 cm) capillaries by using a peak current of 22 kA and a voltage of 100 kV are saturated at high gains, $G \approx 0.7\ \mathrm{cm}^{-1}$. Such gains require high plasma temperature and density, meaning high voltage and current. The refraction of amplified radiation by radial electron density gradients in the high density column of radius

$R_{pl} \approx 0.15$mm results in the high divergence (≈ 7 mrad) and annular profile of the laser beam. The advantage of the low-density long plasma column is the potential decrease of beam divergence and increased transverse coherence. Indeed, the use of a long ($L \approx 0.5$m) plasma column of radius $R_{pl} \approx 0.25$ mm with low electron density and radial gradients would provide almost refraction-free laser operation in the super-fluorescent mirror-less mode, where the beam angular divergence $\varphi$ ($\varphi \sim R_{pl}/L \approx 0.5$mrad) is determined by the radius $R_{pl}$ and length $L$ of the plasma column rather than by the refraction of amplified rays.

It is generally accepted that the operation of $Ar^{8+}$ lasers requires the use of an external low-current circuit to provide pre-ionization of the argon gas before the main excitation current of about 20 kA. The crucial role of the pre-ionization current, of ≈ 20 A and duration ≈ 5 μs generated by the external circuit, has been demonstrated previously [13]. The present thesis demonstrates $Ar^{8+}$ laser operation without using any external low-current pre-ionization circuit. Instead, the pre-ionization of the argon gas was provided by automatic pre-ionization via the so-called gliding discharge on the internal surface of the capillary driven by the main excitation circuit. Such a technique considerably simplifies the laser device; we can use relatively low voltage (200 kV) of the main excitation pulse. The reduction of the voltage and current of the main excitation pulse also reduced the ablation of the electrodes and capillary walls increasing their lifetimes.

# 2. Aims and Methods

The main aim of the experiments was to reduce the size of $Ar^{8+}$ lasers from laboratory size to table top. The experiments concentrated on research and development of practical table-top $Ar^{8+}$ lasers excited by relatively low current (< 22 kA) and voltage (< 200 kV) capillary z-pinch discharges. The technical realization of the laser was based on the use of a long ($l \approx 0.5$m) capillary. The MHD codes showed that the long plasma column would provide the gain-length product $Gl \approx 16$, as required for saturated laser operation, at a relatively low gain, $G \approx 0.3\text{cm}^{-1}$. Such a low gain could be produced at relatively low plasma temperature and density, with correspondingly low voltage and current. The advantage of a low density, long plasma column is the possibility to decrease the laser beam divergence thereby increasing the transverse coherence of the beam.

Another experimental aim was to demonstrate laser operation without using any external low current pre-ionization circuit. The role of the circuit that generated the pre-ionization current with amplitude about 20 A and duration about 3.4 μs has been stated to be crucial in previous studies [13]. For the circuit-less operation, the argon gas was automatically pre-ionized by a so-called gliding discharge on the internal surface of the capillary driven by the main excitation circuit. Such a technique considerably simplifies the laser device.

## 3. Experimental Arrangement and Diagnostics

In our experiments the laser active medium was generated by discharging a 5.9 nF water dielectric capacitor, initially charged to high voltage by a custom built six stage Marx voltage ($U \approx 200$ kV) through a low inductance circuit which contained a water insulated spark gap and the capillary channel. The energy stored by the discharge capacitor was about 0.2 kJ. The lasing was obtained in an aluminium oxide ceramic capillary of length 0.45 m. The excitation current pulse, monitored by a custom built Rogowsky coil, had a peak value of 14–22 kA and half cycle duration of about 165-175 ns. In laser schemes using an external low current pre-ionization circuit the main discharge pulse is preceded by a 3.4 μs long current pulse with amplitude of about 20 A, which pre-ionizes the argon and assures uniform initial conditions for the z-pinch plasma compression. The lasing is obtained using 3.1 mm diameter $Al_2O_3$ capillary channels, filled with continuously flowing argon gas at a pressure in the region of 0.2–0.4 mbar.

The electrical discharges in $Al_2O_3$ capillaries are characterized by low wall material ablation, which is important for uniform compression and efficient heating of the plasma in the capillary z-pinch. The spectra were recorded on a Jobin–Yvon spectrometer with a phosphor film. The system was also used to analyze the spatial intensity distribution of the laser beam. The output energy and time characteristics of the laser pulse were measured by a vacuum photodiode (XRD) and a calibrated photodiode (SXUV-100Al). To attenuate the laser intensity radiation several aluminium foils with calibrated thicknesses were used. A 350 MHz digital oscilloscope monitored the signal from the photodiode. The far-field intensity distributions of the laser pulses were recorded by a two dimensional imaging detector consisting of a phosphor film coupled to a CCD camera. In the saturation detection regime the phosphor detector was screened by aluminium foils.

# 4. New scientific achievements (Thesis points)

**1.** I modeled the electrical pumping with concentraded parameters for the capillary discharge $Ar^{8+}$ soft X-ray laser, containing Marx generator and the fast discharge transmission line. I determined the values of each electrical components (resistors, capacitors and inductances) that make up the model of the pumping scheme for the built laser. By using this model, I determined the maximum peak current for a given voltage setting (free of electric breakdowns) in the pumping scheme to achieve the lowest rise time for the current pulse related to the capacitance of the capillary discharge loop, the inductance nessesary for C-C charge transfer, and a method to adjust the spark gap in the fast discharge loop [S1].

**2.** I developed an enclosed coaxial discharge loop and the output of a 45 cm long capillary, a small form factor, capillary discharge $Ar^{8+}$ soft X-ray laser system. This build implementation constitutes simplicity compared to the previously constructed systems. In this completed construct, I determined the argon gas pressure-region, where lasing is achieved. For the developed system, I determined the change of the pulse energy and the divergence of the laser as a function of the capillary peak and the initial gas pressure [S1], [S3].

**3.** I defined the parameter settings that result in Gaussian-like, 10 μJ output pulse energy and 0.8 mrad divergence laser beam without outer ring shaped beam. Although publications reporting higher pulse energy values are available in the literature they refer to ring shaped beams with 4-7 mrad divergence, or they describe the coexistence of a central Gaussian-like beam with 0.5-1 mrad divergence and a surrounding ring [S1], [S3].

**4.** I determined the specific parameters for obtaining maximum energy and spatial coherence. The inital argon gas pressure for maximal cumulated output pulse energy and for the lowest possible beam divergence is not the same. For maximum pulse energy the necessary gas pressure is 0.1-0.3 mbar higher than the pressure where the beam profile is favorable [S1].

**5.** I confirmed experimentally that the capillary discharge $Ar^{8+}$ soft X-ray laser system can be made without an external preionization unit. My experiments confirm the concept that, owing to the effect of the coaxial line designed and realized by me, a transverse electric field is formed in the capillary that creates a „gliding discharge" and contributes to the stabilization of the plasma column, to the Z-pinch formation. [S2], [S3].

**6.** In order to synchronize the 1.8 ns wide pulse of the capillary discharge $Ar^{8+}$ soft X-ray laser, the underwater spark gap was triggered by an external optical laser. This resulted in less temporal uncertainty of the laser pulses and the shot-after-shot stability in energy was improved significantly. I have shown that in this system, compared to the external electrical starting pulse, the temporal uncertainty of the output pulse is less than 10 ns [S4].

# 5. List of Publications

## I. Publications related to this thesis


[S1] J. Szasz, M. Kiss, I. Santa, S. Szatmari, S. V. Kukhlevsky
Critical parameters of the pumping scheme of $Ar^{+8}$ lasers excited by z pinches in long capillaries
***CONTRIBUTIONS TO PLASMA PHYSICS*** 52:(9) pp. 770-775. (2012)

[S2] J. Szasz, M. Kiss, I. Santa, S. Szatmari, S. V. Kukhlevsky
Magnetoelectric Confinement and Stabilization of Z Pinch in a Soft–x-Ray $Ar^{+8}$ Laser
***PHYSICAL REVIEW LETTERS*** 110:(18) Paper 183902. 4 p. (2013)

[S3] J. Szasz, M. Kiss, I. Santa, S. Szatmari, S. V. Kukhlevsky
Table-Top Soft X-ray $Ar^{+8}$ Lasers Excited By Capillary z-pinches
In: Bleiner D, Costello J, Dortan F, O'Sullivan G, Pina L, Michette A (szerk.) Short Wavelength Laboratory Sources: Principles and Practices. London: The Royal Society of Chemistry, 2015. pp. 85-101. (ISBN:978-1-84973-456-1)

***Patent:***

[S4] Almasi G., Kiss M., Kuhlevszkij Sz., Santa I., Szatmari S., Szasz J.
Method and apparatus for syncronized starting of soft X-ray laser
Lajstromszám: US 8,792,522 B2 Benyújtás éve: 2011. Közzététel éve: 2014
Benyújtás helye: Amerikai Egyesült Államok
Oltalmi formák /USA szabadalom /Tudományos


## II. Non-referred publications related to this thesis


Szász János, Kiss Mátyás, Kuhlevszkij Szergej, Sánta Imre, Szatmári Sándor
Magnetoelektromos z-pinch stabilizálás kapilláris kisüléssel gerjesztett $Ar^{+8}$ lágyröntgen-lézerben.
In: Kvantumelektronika 2014: VII. Szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Konferencia helye, ideje: Budapest, Magyarország, 2014.11.28p. P17.

Szasz J., Kiss M., Santa I., Szatmari S., Kuhlevszkij Sz.
A lézerparaméterek vizsgálata z-pinch gerjesztésű $Ar^{+8}$ lágyröntgen-lézerben
In: Ádám Péter, Mechler Mátyás Illés (szerk.) "Új fények a fizikában": Fizikus vándorgyűlés. 99 p. Konferencia helye, ideje: Pécs, Magyarország, 2010.08.24 -2010.08.27. Budapest: Eötvös Loránd Fizikai Társulat, pp. 24-27

J. Szász, G. Almási, M. Kiss, Sz. Kuhlevszkij, A. Mérő, I. Sánta, S. Szatmári, R. Told
Kapilláris kisülés elektromos paramétereinek optimizálása z-pinch gerjesztésű $Ar^{+8}$ lágyröntgenlézerben In: Ádám P., Kiss T., Varró S. (szerk.) Kvantumelektronika 2008: VI.szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Konferencia helye, ideje: Budapest, Magyarország, 2008.10.17 Budapest: MTA SZFKI, 2008. Paper P-56. (ISBN:978-963-06-5922-2)

J. Szász, M. Kiss, G. Almási, J. Hebling, I. Sánta, S. Szatmári, Sz. Kuhlevszkij
A lézerműködés és a plazmaparaméterek kísérleti és elméleti vizsgálata z-pinch gerjesztésű $Ar^{+8}$ lágyröntgenlézerben
In: Ádám P., Kiss T., Varró S (szerk.)
Kvantumelektronika 2008: VI.szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Konferencia helye, ideje: Budapest, Magyarország, 2008.10.17 Budapest: MTA SZFKI, 2008. Paper P-57. (ISBN:978-963-06-5922-2)

S. V. Kukhlevsky, J. Szász, M. Kiss, G. Almási, J. Hebling, I. Sánta
Experimental and Theoretical Studies of Lasing and Plasma Processes in a Soft X-Ray $Ar^{+8}$ Laser Excited by Capillary Z-Pinches
Konferencia helye, ideje: Siófok, Magyarország, 2008.09.13-2008.09.18.
2008. International conference. Advanced Laser Technologies 2008 (ALT9´08)

S. V. Kukhlevsky, J. Szász, M. Kiss, G. Almási, J. Hebling, I. Sánta, S. Szatmári
Experimental and Theoretical Studies of Lasing and Plasma Processes in a Soft X-Ray $Ar^{+8}$ Laser Excited by Capillary Z-Pinches

In: Proceedings of Advanced Laser Technology '08 Conference. Konferencia helye, ideje: Siófok, Magyarország, 2008.09.13 -2008.09.16. p.

S. V. Kukhlevsky, J. Szász, M. Kiss, G. Almási, J. Hebling, I. Sánta, S. Szatmári
Lasing and Plasma Processes in a Soft X-Ray $Ar^{8+}$ Laser Excited by Capillary Z-Pinches
In: The 7th International Conference on Dense Z-pinches 18th - 21st August 2008 Alexandria. Konferencia helye, ideje: Alexandria, Amerikai Egyesült Államok, 2008.08.18 -2008.08.21. pp. 1-7.

S. V. Kukhlevsky, J. Szász, G. Almási, J. Hebling, I. Sánta, S. Szatmari
Soft-x-ray $Ar^{8+}$ lasers by non-ablative slow Z-pinches in 0.5-m capillaries: Experiment and theory
In: 23rd Summer School and International Symposium on the Physics of Ionized Gases: Experiment and theory. Konferencia helye, ideje: Kopaonik, Szerbia és Montenegro, 2006.08.28 -2006.09.01. p. 1.

## 6. References


[1] L. B. Da Silva, J. E. Trebes, S. Mrowka, T. W. Barbee, Jr., J. Brase, J. A. Koch, R. A. London, B. J. MacGowan, D. L. Matthews, D. Minyard, G. Stone, T. Yorkey, E. Anderson, D. T. Attwood, and D. Kern, Opt. Lett. **17**, 754 (1992).

[2] J. Nejdl, I. D. Howlett, D. Carlton, E. H. Anderson, W. Chao, M. C. Marconi, J. J. Rocca, and C. S. Menoni, IEEE Photon. J. **7**, 1 (2015).

[3] A. Ritucci, A. Reale, P. Zuppella, L. Reale, P. Tucceri, G. Tomassetti, P. Bettotti, and L. Pavesi, J. Appl. Phys. **102**, 034313 (2007).

[4] J. J. Rocca, D. C. Beethe, and M. C. Marconi, Opt. Lett. **13**, 565 (1988).

[5] J. J. Rocca, V. Shlyaptsev, F. G. Tomasel, O. D. Cortazar, D. Hartshorn, and J. L. A. Chilla, Phys. Rev. Lett. **73**, 2192 (1994).

[6] I. A. Artyukov, B. R. Benware, A. V. Vinogradov, Y. S. Kas'yanov, V. V. Kondratenko, C. D. Macchietto, A. Ozols, J. J. Rocca, and J. L.-A. Chilla, Quantum Electron. **30**, 328 (2000).

[7] C. A. Tan and K. H. Kwek, J. Phys. D Appl. Phys. **40**, 4787 (2007).

[8] A. Ritucci, G. Tomassetti, A. Reale, L. Palladino, L. Reale, F. Flora, L. Mezi, S. V. Kukhlevsky, A. Faenov, and T. Pikuz, Appl. Phys. B **78**, 965 (2004).

[9] G. Niimi, Y. Hayashi, M. Nakajima, M. Watanabe, A. Okino, K. Horioka, and E. Hotta, J. Phys. Appl. Phys. **34**, 2123 (2001).

[10] A. Ben-Kish, M. Shuker, R. A. Nemirovsky, A. Fisher, A. Ron, and J. L. Schwob, Phys. Rev. Lett. **87**, 015002 (2001).

[11] Y. Zhao, Y. Cheng, B. Luan, Y. Wu, and Q. Wang, J. Phys. Appl. Phys. D **39**, 342 (2006).

[12] S. Heinbuch, M. Grisham, D. Martz, and J. J. Rocca, Opt. Express **13**, 4050 (2005).

[13] S. V. Kukhlevsky, Europhys. Lett. **55**, 660 (2001).