UNIVERSITY OF PÉCS

Doctoral School of Physics

Laser physics, Nonlinear Optics and Spectroscopy Program

Low voltage Z-pinch plasmas and capillary X-ray lasers

PhD Thesis

Balázs Fekete

Supervisor:

Szergei Kuhlevsky, DSc

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1. Introduction

Capillary-discharge excited lasers have a relatively long history (in terms of today's technological advances), with such systems having been around for nearly 30 years. Initially (and often still today), research teams have used the scheme proposed by J. J. Rocca et al. [1] and then implemented in practice [2]. Although there are studies that aim a shorter (<15 nm) wavelength range than the system presented by Rocca [3], all devices that are stable and widely used in practice operate at 46.9 nm (or longer). At this wavelength range, important practical applications in both medicine and materials science are possible, but they are still mainly used in research. Popular research applications using soft X-rays are e.g. X-ray microscopy [4], X-ray lithography [5], or thermal ablation in polymers (PMMA) [6]. For capillary excitation, there are two main excitation schemes.

The first is recombination through electron impact pumping scheme, which uses the recombination of fully stripped hydrogen-like ions. Then, with sufficiently fast cooling, the population inversion of the energy levels associated with the Balmer-alpha transition can be achieved. Another way of amplifying spontaneous emission is based on electron impact ionisation pumping: this uses rapid excitation of Ne- or Ni-like ions to generate population inversions. In practice, this latter excitation scheme is the most commonly used by research groups, where high purity Ar gas is used as the active medium. In such systems, when properly excited, the laser emission occurs at the 46.9 nm wavelength transition of neon-like Ar+8 ions. For excitation, voltages of the order of 0.2 - 1 MV are applied (10 - 100 kA peak current), mostly using high voltage Marx generators. Such devices are large and expensive, so reducing (ideally minimising) the excitation voltage is essential to design small and relatively cheap systems that are practical to use.

2. Objectives

Over the past nearly 30 years, research groups have mostly used and improved the Rocca Marx generator-based C-C transfer mode system [7], [8], [9], [10], [11]. However, there are also some forward-looking researches, such as. further reduction of the wavelength, significant extension of the active medium length (with resonators or even longer capillaries) and miniaturisation [12], [13], [14]. The main obstacle of the latter is the still very high (0.2 - 1 MV) voltage excitation systems. Considering the current research opportunities, my main goal was to investigate and develop new excitation techniques.

My objective was to experimentally investigate an alternative possibility for the excitation of low current capillary discharge X-ray lasers and the realisation of bench-scale systems. For this purpose, I used an LC inversion power supply with a pulse transformer built in Szeged (originally for other purposes). My goal was to achieve laser operation with an excitation current of < 10 kA amplitude using a non-Marx-generator excitation system.

Marx generators are specifically designed to generate fast-ramping current pulses, but their use in capillary discharge X-ray lasers is more common in the C-C transition mode. In this arrangement, in practice, large peaking capacitors are used. By omitting the peaking capacitor, a significant size reduction could be achieved and the use of longer capillaries would be simplified. My goal was to investigate the possibility of Z-pinch discharges created in extreme (~1 m) long capillaries to achieve laser operation (with direct Marx-generator excitation).

Together with the SZTE, we have developed an LC inversion power supply (specifically designed for capillary discharge X-ray lasers) to generate high current (16 - 18 kA) discharges at extremely low excitation voltages of 40 - 50 kV. My goal was to design an experimental setup in which it is possible to achieve laser operation at 46.9 nm at low (< 50 kV) voltages without a Marx generator.

3. Methods

I used three different excitation systems to investigate my objectives. To generate low current Z-pinch discharges, I used an LC inversion power supply with a pulse transformer. The power supply is capable of generating current pulses with an amplitude of ~9 kA and a half-period of 150 ns at maximum excitation voltage (100 kV).

Direct Marx-generator excitation was used to investigate capillaries with a length of 95 cm, which is considered to be an extreme length in the field. In this setup, the capillary was connected to the output of the Marx generator without an intermediate storage (so-called peaking capacitor). In the experiments, I first used the Marx generator with 6 steps, later increasing the number of steps to 8. Thus the peak current achievable is in the order of 20 - 25 kA at the maximum excitation voltage of ~320 kV.

For the investigation of low (<50 kV) voltage capillary discharge X-ray lasers, an LC inversion power supply was developed in collaboration with SZTE to generate current pulses with amplitudes of 16 - 18 kA. For this purpose, the previously used power supply with pulse transformer was further developed, where the main aspect was to maximise the peak current available. A spark gap and a pulse forming circuit were also incorporated in the improved power supply.

4. Results

We have successfully created capillary Z-pinch discharges with the LC inversion pulse transformer power supply developed by the SZTE High Intensity Laser Laboratory. In parallel to this research, we have also investigated the possibility of generating Z-pinch plasmas in extreme (~1 m) long capillaries, in line with our objective. My task in these studies was to build the laser tube and to perform the measurements. In both studies, we have demonstrated new types of excitation methods where strong spontaneous emission has been produced. For the improved (pulse transformerless) LC inversion power supply, I modified the previously used laser tube design. I determined the ideal experimental parameters required for laser operation. Different inductance reduction techniques were used, of which the coaxial design was successful in producing laser operation. Laser operation was observed with an Al_2O_3 capillary of 22 cm length and 3.2 mm inner diameter at an excitation voltage of 23 - 27 kV and a preferred Ar gas pressure of 0.19 - 0.23 mbar. I measured the pulse energy (maximum ~4 μJ), pulse time (~1.6 ns), divergence (~1.9

mrad). I determined the beam profile, which was Gaussian in all cases, and also measured the spectrum, where the 46.9 nm wavelength line was dominant.

Experimentally, I have shown that it is possible to pump capillary-discharge soft-edge lasers efficiently with excitation systems below 50 kV peak voltage, so that these systems can be brought into the voltage range of nitrogen and excimer lasers. The fully coaxial design can be used to generate current pulses with fast (~15 ns) rise-up amplitudes of 16 - 18 kA, capable of laser operation at the 46.9 nm wavelength transition of Ar^{+8} ions. The fast rise-up is a consequence of the transient quenching of the intrinsic inductance of the system. By testing the system, which has been proven for capillaries with a length of 22 cm and an inner diameter of 3.2 mm, on a capillary with a length of 35 cm and an inner diameter of 3.2 mm, laser operation was also demonstrated without a significant decrease in current rise-up (~$1.5\text{-}2 \cdot 10^{12}$ A/s). This further demonstrates that with a significant increase in capillary length (and thus in the intrinsic inductance of the system), inductance quenching always occurs transiently due to the fully coaxial design. This raises the possibility of using even longer (0.5 - 1 m) capillaries. The characteristics of the current pulses generated by our own system with a fully coaxial design, i.e. >50% drop in current after a fast ~15 ns rise-up of 10-15 ns compared to the peak current, may also be suitable for recombination excitation.

5. New scientific results

1. Experimentally, I have shown that low current (< 9 kA) pulse transformer LC inversion power supplies can be used to generate capillary Z-pinch discharges, where strong spontaneous emission was achieved in 22 cm long capillaries with an inner diameter of 3.2 mm [E3], [P1].

2. Experimentally, I have shown that capillaries of extreme (~1 m) length can be used to excite capillary-discharge X-ray lasers directly from a Marx generator without C-C transitions. Direct evidence of this is the strong spontaneous emission detected [E1], [E2].

3. I have experimentally shown that it is possible to create soft X-ray lasers with capillary discharges below 50 kV peak voltage, which can be classified in the operating voltage range of conventional nitrogen and excimer lasers [S1].

4. I have experimentally demonstrated that laser operation at 46.9 nm is feasible with a Z-pinch plasma created in capillaries 22 cm long and 3.2 mm inner diameter using our low voltage (< 50 kV) excitation system. The resulting beam has a Gaussian profile and a pulse energy of 4 μJ [S1].

5. Experimentally, I have demonstrated that with low voltage (< 50 kV) LC inversion power supplies, excitation currents of 16-18 kA amplitude with fast ~15 ns rise-up in longer (l > 22 cm) capillaries can only be generated if the capillary is coaxially shielded at both ends with a well-grounded, conductive sheath. This solution could open a new path towards further size reduction (even semiconductor-based switching techniques) [S2], [S3].

6. List of publications related to the thesis

Journal articles

[S1] B. Fekete, M. Kiss, A.A. Shapolov, S. Szatmari and S.V. Kukhlevsky, „Soft x-ray Ar+8 laser excited by low-voltage capillary discharge", Optics Express, vol. 31, no. 21, pp. 34381-(doi: 10.1364/OE.498927) 2023.

[S2] B. Fekete, M. Kiss, A. A. Shapolov, S. Szatmari, and S. V. Kukhlevsky, „Low-voltage capillary Z-pinches with short rise times and high currents for portable soft X-ray Ar+8 lasers", Transactions on Plasma Science, 2023, Sent for publication.

[S3] B. Fekete, M. Kiss, A. A. Shapolov, S. Szatmari, and S. V. Kukhlevsky, „Short rise and decay time z-pinch currents for soft-x-ray laser excitation", Physical Review Letters, 2023. Sent for publication

Presentations

[E1] Fekete Balázs, Sapolov Anatolij, Kiss Mátyás, Szatmári Sándor, Kuhlevszkij Szergej „1m Hosszú Kapilláris Röntgenlézer Közvetlen Marx-generátoros Gerjesztéssel” In: (dof)φ - Fizikus Doktoranduszok Konferenciája (DOFFI 2019). Conference place: Balatonfenyves, Hungary, 2019.06.13-16. p. 9-10.

[E2] Fekete Balázs, Sapolov Anatolij, Kiss Mátyás, Kuhlevszkij Szergej, Szatmári Sándor „Preliminary Experiments for 1m Long Capillary Discarge Ar+8 X-ray Lasers and Waveguides” In: VIII. Interdiszciplináris Doktorandusz Conference place: Pécs, Hungary, 2019.05.24-25. p. 14.

[E3] Fekete Balázs, Sapolov Anatolij, Kiss Mátyás, Kuhlevszkij Szergej, Szatmári Sándor „Developing Low Current Impulse Transformer for Capillary Z-Pinch Ar+8 Lasers And Waveguides” In: XVI. János Szentágothai Multidiszciplinary Conference and Student Competition. Conference place: Pécs, Hungary, 2019.02.14-15. p. 37

[E4] <u>Fekete Balázs</u>, Sapolov Anatolij, Kiss Mátyás, Szatmári Sándor, Kuhlevszkij Szergej „Impulzus-transzformátor fejlesztése alacsony áramú kapilláriskisüléssel gerjesztett lágyröntgen-lézerekhez” in: (dof)φ - Fizikus Doktoranduszok Konferenciája (DOFFI 2018). Conference place: Balatonfenyves, Hungary, 2018. Június 14. - Június 17.

Posters

[P1] <u>B. Fekete</u>; M. Kiss; A. A. Shapolov; S. Szatmári; S. V. Kukhlevsky „Soft X-ray Ar+8 lasers and wake-field electron accelerators by using low-current capillary Z-pinches” In: Kvantumelektronika: IX. Szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Conference place: Szeged, Hungary, 2020, (doi: 10.14232/kvantumelektronika.9.7). pp. 39-44.

[P2] <u>B. Fekete</u>, M. Kiss, A.A. Shapolov, S. Szatmari, S.V. Kukhlevsky „Development of soft X-ray Ar+8-lasers excited by low-current capillary Z-pinch discharges” In: The 3rd EMN Meeting on Photonics. Conference place: Kaohsiung, Taiwan, 2018.10.21-2018.10.25. p. 36.

[P3] B Fekete, A A Shapolov, M Kiss, S Szatmari, S V Kukhlevsky, „Impulse Transformer for Sub 9 kA Capillary Z-Pinch Ar+8 Lasers and Waveguides" In: V Aubrecht, V Celedova Plasma Physics and Technology. Conference place: Prague, Czech Republic, 2018.06.18-2018.06.21. Prague: Czech Technical University in Prague, 2018. p. 30. 48 p.

[P4] Fekete Balázs, Sapolov Anatolij, Kiss Mátyás, Szatmári Sándor, Kuhlevszkij Szergej „Röntgenlézer Gerjesztése Impulzus-Transzformátorral" In: Kvantumelektronika 2018: VIII. Szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Conference place: Budapest, Magyarország, 2018.06.15. pp. 48-49. (ISBN: 978-963-429-250-0)

[P5] B Fekete, A A Shapolov, M Kiss, S Szatmári, S V Kukhlevsky „Capillary Z-pinch plasma generated by impulse transformer" In: 45th IOP PLasma Physics Conference: Programme and Abstract Book. Conference place: Belfast, United Kingdom / Northern Ireland, 2018.04.09-2018.04.12. p. 45. 61 p.

7. References

[1] J. J. Rocca, D. C. Beethe and M. C. Marconi, "Proposal for soft-x-ray and XUV lasers in capillary discharges," *Optics Letters,* vol. 13, no. 7, pp. 565-567, 1988.

[2] J. J. Rocca, V. N. Shlyaptsev, F. G. Tomasel, O. D. Cortázar, H. Hartshorn and J. L. A. Chilla, "Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser," *Phys. Rev. Lett.,* vol. 72, no. 16, pp. 2192 - 2195, 1994.

[3] K. Kolacek, J. Schmidt, V. Prukner, O. Frolov and J. Straus, "Ways to discharge-based soft X-ray lasers with the wavelength λ<15 nm," *Cambridge University Press,* vol. 26, no. 2, pp. 167-178, 2008.

[4] D. L. Silva, J. E. Trebes, S. Mrowka, J. T. Barbee, J. Brase, J. A. Koch, R. A. London, B. J. Macgowan and D. L. Matthews, "Demonstration of x-ray microscopy with

an x-ray laser operating near the carbon K edge," *Opt. Lett.,* vol. 17., no. 10., pp. 754-6, 1992.

[5] A. Ritucci, A. Reale, P. Zuppela, E. Reale, P. Tucceri, G. Tomasetti, P. Bettotti and L. Pavesi, "Interference lithography by a soft x-ray laser beam: Nanopatterning on photoresists," J. Appl. Phys., vol. 102., 2007.

[6] O. Frolov, K. Kolacek, J. Straus, J. Schmidt, V. Prukner and A. Shukurov, "Generation and application of the soft X-ray laser beam based on capillary discharge," Journal of Physics: Conference Series 511, 2014

[7] Y. Zhao, Y. L. Cheng, Q. Wang and D. W. Yang, "Device of capillary discharge with pre-pulse and main pulse to excite soft X-ray laser," High Power Laser and Particle Beams, vol. 16, no. 6, pp. 732-6, 2004.

[8] C. A. Tan and H. K. Kwek, "Development of a low current discharge-driven soft x-ray laser," Journal of Physics D: Applied Physics, vol. 40, pp. 4787-92, 2007.

[9] Y. Sakai, Y. Kakuya, X. Yifan, T. Hiroaki, H. Yasushi, G. Hamid, W. Masato, O. Akitoshi, H. Kazuhiko and H.

Eiki, “Performance of soft x-ray laser pumped by capillary discharge,” International Atomic Energy Agency, pp. 39-42, 2005.

[10] M. Nevrkla, A. Jancarek, P. Vrba and M. Vrbova, “Capillary discharge apparatus for intense XUV radiation generation,” in Pulsed Power Conference, 2009 IET European, Svájc, 2009

[11] M. Vrbova, A. Jancarek, P. Vrba, M. Nevrkla and P. Kolar, “XUV Radiation Emitted by Capillary Pinching Discharge,” in X-Ray Lasers, Springer, 2010, pp. 257-62.

[12] S. Heinbuch, M. Grisham, D. Martz and J. J. Rocca, “Demonstration of a desk-top size high repetition rate soft x-ray laser,” Optics Express, vol. 13, no. 11, pp. 4050-55, 2005.

[13] S. Barnwal, S. Nigam, K. Aneesh, R. S. Prasad, M. I. Sharma, P. K. Tripathi, S. A. Joshi, P. A. Naik, S. H. Vora and P. D. Gupta, “Exploring X-ray lasing in nitrogen pinch plasma at very high and fast discharge current excitation,” Appl. Phys. B., vol. 123, no. 178, 2017.

[14] M. Nevrkla, J. Hubner, J. Sisma, P. Vrba, M. Vrbova, N. Bobrova, P. Sasorov and A. Jancarek, “A Study of Current Controlled Discharge in a Nitrogen Filled Tube,” Applied Sciences, vol. 11, 2021.