

GENERAL EXPERIMENTAL TECHNIQUE

A Nanosecond Electron Accelerator with a Heterogeneous Transmission Line and a Gas-Filled Diode

V. F. Tarasenko^a, S. B. Alekseev^a, E. Kh. Baksht^{a,*}, A. G. Burachenko^a, and M. I. Lomaev^a

^a Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences,
Tomsk, 634055 Russia

*e-mail: beh@loi.hcei.tsc.ru

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Abstract—This paper describes the design and parameters of a nanosecond accelerator with an additional transmission line that has variable wave impedance and a gas-filled diode. The possibility of controlling the beam current parameters by changing the air pressure in the diode is shown. Behind the anode foil, at a half-maximum pulse width of ≈ 1.3 ns and an electron energy of up to 350 keV, the beam current amplitude was ≈ 700 A. Vavilov–Cherenkov radiation spectra and oscillograms were recorded when were excited by the electron beam of this accelerator. quartz, sapphire, and synthetic diamond were excited by the electron beam of this accelerator.

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INTRODUCTION

Electron accelerators are used in various fields of science and technology [1, 2] and continue to improve [3, 4]. Electron beams are usually formed in vacuum diodes and thin foil anodes are used in most accelerators to output the beam current to air and other gases. Since the last century, accelerators of electron beams of nanosecond and picosecond durations with energies of hundreds of kiloelectron-volts, as well as sources of bremsstrahlung X-ray radiation based on such accelerators, have been developed and studied [5–21].

In the development of nanosecond small accelerators and x-ray machines, various high-voltage pulse generation schemes are used. The most common devices use pulse transformers [5], a Marx circuit [8] and inductive energy storage devices [14, 21]. To reduce the voltage pulse duration, sharpeners of various designs are used based on high-pressure [15, 20] and solid-state switches. All this allows the creation of accelerators with various parameters and adjustment of the amplitude and duration of beam current pulses.

In recent years, additional lines with ferrite rings have been used to increase the amplitude of the voltage pulse and reduce its duration [21–23]. However, such lines must be placed in a magnetic field. For this, cylindrical magnets are needed, whose length is equal to the length of the line, which significantly complicates the design of the accelerator.

In this paper, it is shown that other approaches can be used to increase the electron energy and adjust the duration of the beam current pulse, which allow creating electron accelerators of a relatively simple design. Accordingly, the aim of this work was to develop and

study an accelerator with an open circuit voltage of 500 kV, an electron energy of up to 350 keV, a beam current pulse duration of ~ 1 ns, and a current density behind the foil of more than 200 A/cm².

An additional line with variable wave impedance was used to increase the electron energy in the accelerator and the diode was filled with air to pressures of 0.1–10 Torr to control the beam current pulse duration and electron energy. We note that the possibility of controlling the duration of the beam current pulse and its amplitude in gas-filled diodes was studied in [24–26].

INSTALLATION AND METHODS OF MEASUREMENTS

The design of the high-voltage accelerator block, which consists of two sections and a gas-filled diode, is shown in Fig. 1.

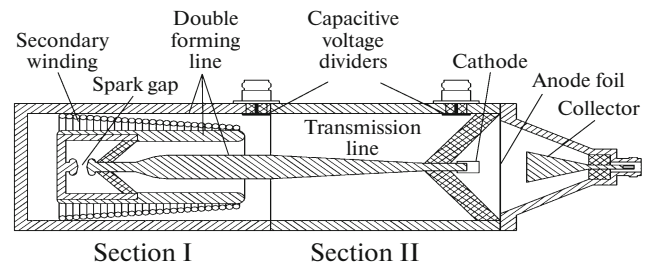


Fig. 1. The scheme of the high-voltage block of the accelerator, consisting of two sections and a gas-filled diode, to which a conical collector is connected. Both sections of the accelerator are filled with transformer oil.

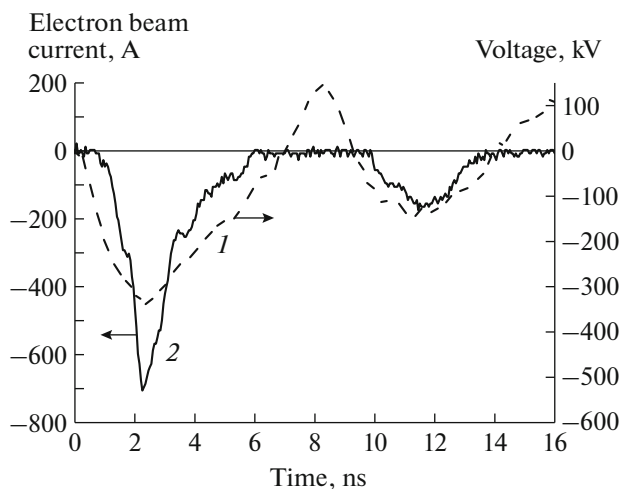


Fig. 2. Oscillograms of the voltage pulse on the diode (1) and the beam current behind the foil (2) with interelectrode gap $d = 11.5$ mm and the air pressure in the diode $p \approx 0.8$ Torr.

In the first section of the accelerator, as in [15], a double forming line is used. However, instead of an spark gap with an adjustable gap, which is located between the middle and grounded coaxial electrodes, an industrial two-electrode high-pressure switch R-49 was used, which was connected to the internal electrode.

The wave impedances of each of the two forming lines of the first section were $\approx 20 \Omega$. That of the short transmission line was 50Ω . A second accelerator section was installed after a short transmission line, which consisted of an inhomogeneous transmission line 20 cm long, whose wave impedance gradually varied from 50 to 100Ω . The use of the second section provides a simple way to increase the amplitude of the voltage pulse. The diameter of the inner electrode at the inlet of the inhomogeneous line into the gas-filled diode was 8 mm and the inner diameter of the outer cylinder of the coaxial line was 102 mm. This provided a relatively high strength insulator gas diode.

A tubular cathode with an inner diameter of 8 mm was made of stainless steel foil with a thickness of $100 \mu\text{m}$. The interelectrode gap could vary from 2 to 13 mm. The beam current was extracted through $40\text{-}\mu\text{m}$ -thick AlMg foil. The beam current was recorded using a conical collector with a time resolution of no worse than 0.1 ns [27]. Measurements of voltage pulses at the output of the first and second sections of the accelerator were carried out using capacitive dividers.

The double forming line was charged from the secondary winding of a pulse transformer, which was located between two coaxial cylinders with built-in magnetic cores, when the capacitor was discharged through the primary winding of the transformer (not shown in the figure). Further, when the R-49 high-pressure spark gap was triggered, a nanosecond voltage pulse with an amplitude of ≈ 190 kV was formed in sec-

tion I, which was supplied to the tubular cathode along a short transmission line and a line with a variable wave impedance. This made it possible to obtain voltage pulses with a duration of 2.5 ns with an amplitude at idle of ≈ 500 kV. The air pressure in the diode could vary from 0.1 to 760 Torr. As was shown in [24, 28], the optimal pressure in the diode to obtain the maximum amplitudes of the beam current in helium, hydrogen, and nitrogen is different. In this accelerator, air was used to fill the gas diode.

Signals from capacitive dividers and a collector were fed to a Keysight DSO-X6004A digital oscilloscope (6 GHz and 20 samples/ns) via 5D-FB PEEG high-frequency cables (Radiolab) 1.2 m long. To attenuate the signals, 142-NM attenuators (Barth Electronics, 30 GHz) were used, which made it possible to register voltage pulses with a front duration of up to 20 ps without significant distortion.

RESULTS OF STUDIES ON THE BEAM CURRENT PARAMETERS

Oscillograms of voltage pulses and the beam current are shown in Fig. 2. These oscillograms were recorded in a regime close to optimal for conducting experiments on the study of the Vavilov–Cherenkov radiation parameters [29]. The amplitude of the voltage pulse across the diode was ≈ 350 kV and the current recorded by a collector with a receiving diameter of 15 mm was ≈ 700 A. The beam current density behind the foil from the central site 3 mm in diameter was ≈ 220 A/cm². Oscillograms of voltage pulses and beam current in this mode consisted of two pulses. The duration of the first (main) pulse at the half maximum was ≈ 1.3 ns.

The second beam current pulse had a smaller amplitude and was detected only when the pressure in the gas-filled diode decreased and/or the interelectrode gap increased. It arose due to differences in the resistances of the generator and the gas-filled diode, which increased with increasing resistance of the diode. However, due to this mismatch, it was possible to increase the gap voltage and, accordingly, the electron energy.

The effect of air pressure in a gas-filled diode on the amplitude of voltage pulses and current of the first pulse of the beam, as well as on the duration of the beam current at half maximum, is shown in Fig. 3.

It can be seen that under these conditions a significant increase in the voltage amplitude in the gap begins at an air pressure of less than 2 Torr and maximum stresses are recorded at pressure of less than 0.5 Torr. Accordingly, to obtain beam electrons with maximum energies, one must work in this pressure range. However, the duration of the beam current pulse with decreasing pressure increases and to obtain pulses with a duration at the half maximum $\tau_{0.5} < 1$ ns the air pressure in the gas diode must exceed 1 Torr.

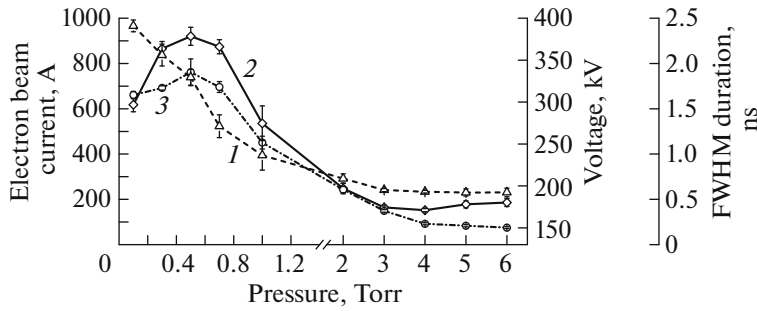


Fig. 3. The dependences of the amplitude of the voltage pulse on the diode (1), as well as the amplitudes (2) and duration (3) beam current behind the foil, from air pressure. The interelectrode gap $d = 11.5$ mm.

As can be seen from Fig. 3, the maximum amplitude of the beam current at an optimal pressure and an electrode gap of 11.5 mm was 900 A. An increase in the pressure in the diode to 2 Torr led to a decrease in the amplitude of the beam current to ≈ 250 A. To obtain the pulse duration $\tau_{0.5} \approx 0.1$ ns the air pressure in the diode should be increased to 100 Torr or more. However, this led to a significant decrease in the amplitude of the beam current.

At an air pressure of 400 Torr in the diode, the beam current amplitude was 3 A, while at atmospheric pressure it was 1.3 A. The amplitude of the voltage pulse at air pressures of 400 and 760 Torr was ≈ 135 kV. The low beam currents at elevated pressures under these conditions were due to the duration of the voltage pulse front, which was ≈ 2 ns.

When the voltage pulse front duration was ≈ 0.3 ns at the SLEP-150 generator with a tubular cathode with a diameter of 6 mm, the amplitude of the beam current at atmospheric air pressure and the voltage amplitude at the 180 kV diode (140 kV in the incident voltage wave) was 10 A [30]. The transition to a mesh cathode with a diameter of 40 mm made it possible to obtain the amplitude of the beam current behind the foil ≈ 100 A with a pulse duration at the half maximum of 0.1 ns using an SLEP-150 generator with a voltage of 200 kV in the incident wave [17].

The effect of the interelectrode gap on the amplitude of the voltage and beam current of the first and second pulses, as well as on the beam-current duration at half maximum, is shown in Fig. 4.

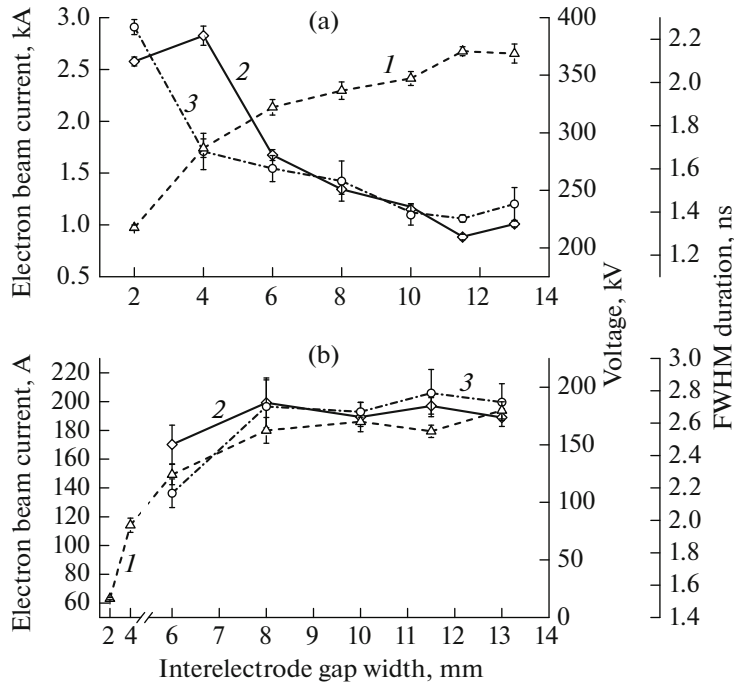


Fig. 4. The influence of the interelectrode gap on the amplitude of the first (a) and the second (b) voltage pulses (1) and beam current (2), as well as the pulse width of the beam current at the half maximum (3). The air pressure in the diode $p \approx 0.8$ Torr.

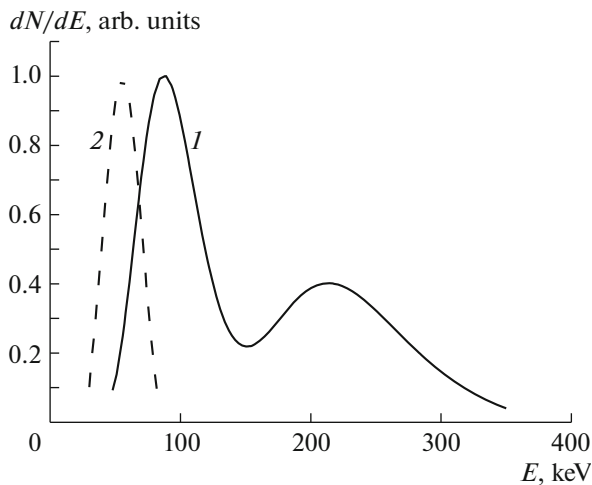


Fig. 5. The energy distribution of electrons for the first (1) and the second (2) current pulses of the electron beam. $d = 11.5$ mm, $p \approx 0.8$ Torr. Both distributions are normalized to unity.

When these dependences were obtained the pressure in the diode during continuous pumping by the foreline pump through a small-diameter hose was ≈ 0.8 Torr. This pressure at a pulse width at the half maximum of ≈ 1.3 ns corresponded to the region of the largest amplitudes of the beam current in the first pulse for $d = 11.5$ mm. With a decrease in the interelectrode gap, the amplitude of the beam current increased, while the voltage across the diode decreased. The duration of the beam current pulse at the half maximum also increased. The second pulse of the beam current under small gaps was not recorded, which is associated with a decrease in the diode resistance and, accordingly, the voltage across it. The electrons of the second-pulse beam under small gaps were absorbed by the anode foil.

Testing of an accelerator with a cathode with a diameter of 4 mm from a foil 100 μm thick, which was also made of stainless steel, gave a similar dependence. With a decrease in the interelectrode gap from 8 to 4 mm the gap voltage decreased and the amplitude of the beam current and its duration increased. The amplitude of the beam current at $d = 2.75$ mm was ≈ 3.2 kA, but the amplitude of the voltage pulse was ≈ 230 kV. At the same pressure in the gas diode and the same d the cathode diameter did not significantly affect the amplitude of the beam current.

To determine the spectra of the beam current behind the foil, we used a technique that uses the attenuation curves of the beam current by filters, which was described in [31, 32]. Aluminum foils of various thicknesses were installed between the foil and the collector and the amplitudes and durations of the beam current pulses were measured. Then, from the obtained attenuation curve, the electron spectrum was

restored. Figure 5 shows the electron beam spectra for the first and second pulses at $p \approx 0.8$ Torr and $d = 11.5$ mm.

According to the calculations, for the first pulse in the electron energy distribution there were two groups with 50–150 and 180–350 keV. In the second pulse, under the same conditions, the electron energy did not exceed 100 keV and the distribution had one maximum.

The created accelerator will be used to study Vavilov–Cherenkov radiation in KU-1 quartz, sapphire and synthetic type IIa diamond obtained by gas-phase deposition. In preliminary experiments, as in [29], Vavilov–Cherenkov radiation was detected using a standard spectrometer. The intensity of this radiation in the ultraviolet and visible regions of the spectrum increased in the transparency region of the samples with decreasing wavelength. In addition, the Vavilov–Cherenkov radiation pulses coincided in duration and shape with the duration and shape of the beam current. In contrast to [29], in which an accelerator with a pulse duration at the half maximum of 12 ns was used, this accelerator with a similar electron energy distribution had $\tau_{0.5} \approx 1.3$ ns.

CONCLUSIONS

An electron accelerator with an open circuit voltage of 500 kV has been created, which has a relatively simple design. The parameters of the beam current and the voltage across the gap with a change in the air pressure in the diode are presented and the possibility of controlling these parameters is shown. At a diode voltage of 350 kV and a beam current amplitude of 700 A, the beam current pulse duration at a half maximum of 1.3 ns was obtained. It has been demonstrated that an additional line with a variable wave impedance makes it possible to increase the gap voltage and, accordingly, the electron energy. Vavilov–Cherenkov radiation was detected in KU-1 quartz, sapphire and synthetic diamond using a standard spectrometer, whose intensity in the ultraviolet and visible regions of the spectrum increased with decreasing wavelength.

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REFERENCES

1. Martin, T.H., *IEEE Trans. Nucl. Sci.*, 1973, vol. 20, no. 3, p. 289.
<https://doi.org/10.1109/TNS.1973.4327103>
2. Mehnert, R., *Nucl. Instrum. Methods Phys. Res., Sect. B*, 1996, vol. 113, nos. 1–4, p. 81.
[https://doi.org/10.1016/0168-583X\(95\)01344-X](https://doi.org/10.1016/0168-583X(95)01344-X)
3. Zheltov, K.A., *Pikosekundnye sil'notochnyye elektronnyye uskoriteli* (Picosecond High-Current Electron Accelerators), Moscow: Energoatomizdat, 1991.

4. Mesyats, G.A., *Impul'snaya energetika i elektronika* (Pulse Power and Electronic Engineering), Moscow: Nauka, 2004.
5. Zelenskii, K.F., Troshkin, I.A., and Tsukerman, V.A., *Prib. Tekh. Eksp.*, 1963, no. 2, p. 140.
6. Charbonnier, F.M., Barbour, J.P., Brewster, J.L., Dyke, W.P., and Grundhauser, F.J., *IEEE Trans. Nucl. Sci.*, 1967, vol. 14, no. 3, p. 789.
<https://doi.org/10.1109/TNS.1967.4324658>
7. Belkin, N.V., Komyak, N.I., Peliks, E.A., and Tsukerman, V.A., *Prib. Tekh. Eksp.*, 1972, no. 2, p. 194.
8. Koval'chuk, B.M., Mesyats, G.A., and Shpak, V.G., *Prib. Tekh. Eksp.*, 1976, no. 6, p. 73.
9. Belkin, N.V., Tarakanov, M.Yu., and Tarasov, M.D., *Prib. Tekh. Eksp.*, 1987, no. 6, p. 133.
10. Zagulov, F.Ya., Kotov, A.S., Shpak, V.G., Yurike, Ya.Ya., and Yalandin, M.I., *Prib. Tekh. Eksp.*, 1989, no. 2, p. 146.
11. Zheltov, K.A., Korobkov, S.A., Petrenko, A.N., and Shalimanov, V.F., *Prib. Tekh. Eksp.*, 1990, no. 1, p. 37.
12. Aduiev, B.P. and Shpak, V.G., *Prib. Tekh. Eksp.*, 1990, no. 2, p. 49.
13. Gubanov, V.P., Korovin, S.D., Pegel, I.V., Roitman, A.M., Rostov, V.V., and Stepchenko, A.S., *IEEE Trans. Plasma Sci.*, 1997, vol. 25, no. 2, p. 258.
<https://doi.org/10.1109/27.602497>
14. Kotov, Yu.A. and Sokovnin, S.Yu., *Instrum. Exp. Tech.*, 1997, vol. 40, no 4, pp. 513–515.
15. Yalandin, M.I. and Shpak, V.G., *Instrum. Exp. Tech.*, 2001, vol. 44, no 3, pp. 285–310.
16. Hasegawa, D., Kamada, K., Kuraku, A., Ando, R., and Masuzaki, M., *Jpn. J. Appl. Phys.*, 2001, vol. 40, no. 2B, p. 944.
<https://doi.org/10.1143/JJAP.40.944>
17. Kostyrya, I.D., Rybka, D.V., and Tarasenko, V.F., *Instrum. Exp. Tech.*, 2012, vol. 55, no. 1, pp. 72–77.
<https://doi.org/10.1134/S0020441212010071>
18. Sokovnin, S.Yu., Balezin, M.E., and Shcherbinin, S.V., *Instrum. Exp. Tech.*, 2013, vol. 56, no. 4, pp. 411–413.
<https://doi.org/10.1134/S0020441213040106>
19. Kumar, R., Chandra, R., Mitra, S., Beg, M.D., Sharma, D.K., Sharma, A., and Mittal, K.C., *J. Instrum.*, 2014, vol. 9, no. 4, p. 04017.
<https://doi.org/10.1088/1748-0221/9/04/P04017>
20. Avilov, E.A., Belkin, N.V., Dudin, A.V., Zykov, A.P., Kanunov, M.A., and Razin, A.A., *Prib. Tekh. Eksp.*, 1973, no. 1, p. 137.
21. Rukin, S.N., *Rev. Sci. Instrum.*, 2020, vol. 91, no. 1, p. 011501.
<https://doi.org/10.1063/1.5128297>
22. Romanchenko, I.V., Rostov, V.V., Gunin, A.V., and Konev, V.Y., *Rev. Sci. Instrum.*, 2017, vol. 88, no. 2, p. 024703.
<https://doi.org/10.1063/1.4975182>
23. Gusev, A.I., Pedos, M.S., Rukin, S.N., and Timoshenkov, S.P., *Rev. Sci. Instrum.*, 2017, vol. 88, no. 7, p. 074703.
<https://doi.org/10.1063/1.4993732>
24. Burachenko, A.G. and Tarasenko, V.F., *Tech. Phys. Lett.*, 2010, vol. 36, no. 12, pp. 1158–1161.
<https://doi.org/10.1134/S1063785010120278>
25. Alekseev, S.B., Rybka, D.V., and Tarasenko, V.F., *Instrum. Exp. Tech.*, 2013, vol. 56, no 5, pp. 571–575.
<https://doi.org/10.1134/S0020441213040131>
26. Lomaev, M.I., Tarasenko, V.F., and Baksht, E.Kh., *Tech. Phys.*, 2019, vol. 64, no. 8, pp. 1200–1204.
<https://doi.org/10.1134/S1063784219080115>
27. Tarasenko, V.F. and Rybka, D.V., *High Voltage*, 2016, vol. 1, no. 1, p. 43.
<https://doi.org/10.1049/hve.2016.0007>
28. Tarasenko, V.F., Baksht, E.Kh., Burachenko, A.G., Lomaev, M.I., and Sorokin, D.A., *IEEE Trans. Plasma Sci.*, 2010, vol. 38, no. 10, p. 2583.
<https://doi.org/10.1109/TPS.2010.2041474>
29. Tarasenko, V.F., Oleshko, V.I., Erofeev, M.V., Lipatov, E.I., Beloplotov, D.V., Lomaev, M.I., Burachenko, A.G., and Baksht, E.Kh., *J. Appl. Phys.*, 2019, vol. 125, no. 24, p. 244501.
<https://doi.org/10.1063/1.5094956>
30. Kostyrya, I.D., Tarasenko, V.F., Baksht, E.Kh., Burachenko, A.G., Lomaev, M.I., and Rybka, D.V., *Tech. Phys. Lett.*, 2009, vol. 35, no. 11, pp. 1012–1015.
31. Baksht, E.H., Burachenko, A.G., Kozhevnikov, V.Yu., Kozyrev, A.V., Kostyrya, I.D., and Tarasenko, V.F., *J. Phys. D: Appl. Phys.*, 2010, vol. 43, no. 30, p. 305201.
<https://doi.org/10.1088/0022-3727/43/30/305201>
32. Kozyrev, A.V., Kozhevnikov, V.Yu., Vorobyev, M.S., Baksht, E.Kh., Burachenko, A.G., Koval, N.N., and Tarasenko, V.F., *Laser Part. Beams*, 2015, vol. 33, no. 2, p. 183.
<https://doi.org/10.1017/S0263034615000324>