ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2023, Vol. 87, No. 5, pp. 573–579. © Allerton Press, Inc., 2023.
Russian Text © The Author(s), 2023, published in Izvestiya Rossiiskoi Akademii Nauk, Seriya Fizicheskaya, 2023, Vol. 87, No. 5, pp. 652–659.

Kiloampere Electron Beam of a Linear Induction Accelerator as a Driver for a Submillimeter Free Electron Laser

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Received November 28, 2022; revised December 15, 2022; accepted January 25, 2023

Abstract—A project for a submillimeter free electron laser (FEL) based on a relativistic electron beam (REB) generated in a linear induction accelerator (LIA) is proposed for the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, and the Institute of Applied Physics, Russian Academy of Sciences. A theoretical analysis shows that the electron beam generated in the LIA (energy E_e = 5–10 MeV, current I_b = 1–2 kA, normalized emittance $\varepsilon_n \sim 1100\,\pi$ mm mrad) is a suitable driver for generating subgigawatt pulses of coherent EM radiation in the submillimeter range of wavelengths (0.3–1 THz). The main proposals for developing a FEL based on the electron beam generated in a linear induction accelerator are presented, the main project tasks are outlined, and proposed ways of solving them are described. Results from electron-optical experiments on the formation of an electron beam intended for FEL applications are presented.

Keywords: free electron laser, relativistic electron beam, linear induction accelerator, subgigawatt pulses, coherent EM radiation, submillimeter radiation range

DOI: 10.3103/S1062873822701763

INTRODUCTION

A project for a high-power free-electron laser capable of generating coherent electromagnetic radiation pulses in the frequency range of 0.3–1 THz is currently being developed in cooperation between the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences (BINP SB RAS) (Novosibirsk) and the Institute of Applied Physics, Russian Academy of Sciences (IAP RAS) (Nizhny Novgorod) [1, 2]. This project is based on a new linear induction accelerator (LIA) built recently by the Budker Institute of Nuclear Physics and the Russian Federal Nuclear Center—Zababakhin All-Russia Research Institute of Technical Physics [3–5]. This LIA allows us to form relativistic electron beams (REBs) with energies up to 10 MeV and current strengths as high as 2 kA, having durations up to 100 ns and normalized emittances around 1100 π mm mrad [4, 5].

A distinctive feature of the new LIA, relative to similar foreign facilities [6–13], is its use of a discrete focusing magnetic system. This magnetic system helps simplify adjusting the LIA to bring it to the optimum operating mode and allows us to ensure conditions for beam travel that prevent beam corkscrew motion [14]. Such a magnetic system also ensures sufficient stability of the beam with respect to transverse instability (beam breakup instability, BBU) [15–17].

The use of an electron beam with the above parameters in combination with a highly selective electrodynamic FEL system with a diameter of ~40–50 λ, where λ is the wavelength of the generated radiation, should allow us to implement long-pulse FEL generators in the subterahertz and terahertz ranges at a subgigawatt power level and peak energy content per pulse radiation totalling 10–100 J [1].

Developing such a source of THz radiation is of undoubted interest on the part of researchers in such scientific fields as physics, chemistry, biology and medicine, where the effect of THz radiation fluxes have on organic and inorganic substances, along with biological objects, are studied. The high spectral power density of the radiation, and the possibility of varying the frequency of radiation, should allow us to use such a generator to study new phenomena and important patterns in the subTHz and THz ranges [18, 19].

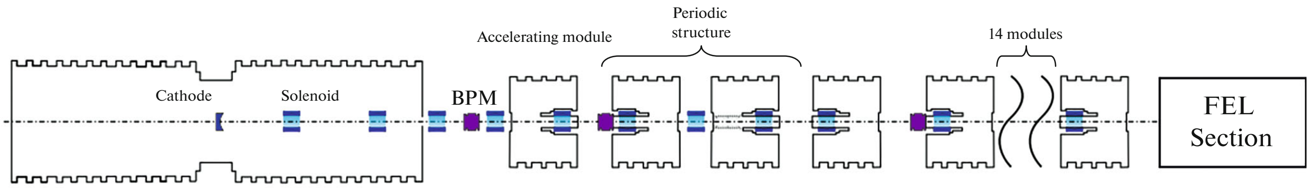

Fig. 1. General outline of the LIA accelerating system for obtaining a beam with electron energies up to 10 MeV. The accelerating modules and the injector are shown in black, the sensors of beam position (beam position monitor, BMP) are shown in purple, and the discrete system of pulsed magnetic lenses is shown in blue.

It should be noted that studies aimed at developing high-power FEL generators in the THz range are underway at scientific laboratories and centers in many countries, e.g., Germany, Great Britain, the United States, Korea, China, Japan, and Russia [20–26]. Despite fierce competition in the field of achieving the maximum values of peak and average radiation power in the studied range of frequencies, the world leader today is the Novosibirsk FEL (Novo-FEL), developed and manufactured at the BINP SB RAS [27, 28]. At beam electron energies of 12 MeV, this FEL generates radiation in the 1.2–2.5 THz range of frequencies in the form of pulses with durations of 30–100 ps at a peak power of 1 MW with intervals between pulses of around 180 ns.

The principal difference between the FEL system we have proposed and the FEL systems created earlier is the use of intense REBs formed in the LIA with much longer durations of the beam current pulses, up to several hundred nanoseconds. The combination of this pulse duration and a kiloampere level of beam current ensures the potential of making a long-pulse FEL generator of coherent THz radiation with a relatively narrow spectral line at a subgigawatt power level and pulse energies of 10 to 100 J [2, 29].

The aim of this work was to study the current state of the development and manufacturing of such a FEL generator. Results from electron-optical experiments on forming an intense REB for use in a FEL are presented. The main components of the FEL magnetic system with magnetic lenses and a leading magnetic field solenoid are described. These components should ensure magnetic compression of the beam's cross section and its subsequent passage in a compressed state through an electrodynamic system where an electromagnetic wave is pumped by the beam under conditions of the beam's motion in the undulator's magnetic field.

FORMATION OF INTENSE RELATIVISTIC ELECTRON BEAMS IN THE LIA SYSTEM

A schematic diagram of a linear induction accelerator with discrete focusing [4, 5, 30, 31] that ensures the formation of a kiloampere electron beam suitable for generating terahertz radiation in a FEL is shown in Fig. 1. The beam-forming structure includes three main elements: an electron injector, an accelerating structure, and a magnetic focusing system.

Electrons with a maximum current of 2 kA are emitted from the surface of an incandescent porous metal-oxide cathode 180 mm in diameter, mounted in the injector under the conditions of external magnetic field screening. The electric field generated by the accelerating system of the injector brings the energy of electrons at the output of the injector to a level of 2 MeV. The electron beam formed within the injector then enters the LIA accelerating structure, which consists of a periodic sequence of 20 accelerating modules. The beam focusing in this structure is ensured by a set of 34 pulsed magnetic lenses, each around 200 mm long.

The maximum magnetic field in the lenses can be as high as 0.08 T. The accelerating voltage in the modules can vary in the range of 100 to 400 kV, depending on the needs of the experiment. This LIA allows us to obtain a high-current REB with energies up to 10 MeV and currents up to 2 kA at the output. It should be noted that the diameter of the electron beam changes smoothly from 8 cm at the input to 4 cm at the output when transporting and accelerating the REB in the accelerating structure of the LIA, in accordance with the parameters of the focusing system chosen upon tuning the accelerator.

In this work, we describe the modes of LIA operation in obtaining an electron beam with an energy of 5 MeV and a current strength of around 1 kA, since these parameters are the ones most suitable for conducting the first series of experiments on using the LIA beam as a driver for the FEL generator.

EXPERIMENTS FOR ENSURING ELECTRON BEAM STABILITY IN THE LIA AND ITS COMPRESSION IN THE FEL SYSTEM

A necessary condition for achieving the maximum efficiency of generating THz radiation in a FEL is ensuring the minimum amount of dispersion in the longitudinal velocity of the beam electrons as the beam travels within the electrodynamic system. According to our estimates, the allowable amount of dispersion in the longitudinal velocity of electrons can be determined using the relation [31]

$$\Delta\beta_z < \Gamma_{\text{rad}}\lambda \approx \frac{\sqrt{3}}{2}\left[4\pi\frac{I_{\text{b}}}{I_{\text{A}}}\left(\frac{\lambda}{r_{\text{t}}}\right)^2\frac{1}{\gamma_0^5}\right]^{\frac{1}{3}}, \quad (1)$$

where Γ_{rad} is the spatial increment of the instability that generates radiation with wavelength λ in the FEL, I_{b} is the beam current, $I_{\text{A}} = \frac{mc^3}{e}$ is the Alfvén current, r_{t} is the radius of the drift tube, $\gamma_0 = \gamma_z\left(1+\left(\frac{eA_{\text{u}}}{mc^2}\right)^2\right)^{1/2}$ is the gamma factor in the FEL cross-section, A_{u} is the amplitude of the vector potential of the undulator magnetic field, m is the electron mass, c is the speed of light, $\gamma_z = 1\Big/\sqrt{1-\beta_z^2}$.

With the energy and angular dispersion of electron velocities, their contributions to the amount of dispersion in longitudinal velocities can be estimated according to the relations

$$\Delta\beta_z^{(1)} \approx \frac{\Delta E}{\gamma_0\left(E_0 + mc^2\right)}, \quad (2)$$

$$\Delta\beta_z^{(2)} \approx \frac{\varepsilon_{\text{n}}^2}{2r_{\text{b}}^2\gamma_0^2}, \quad (3)$$

where ΔE is the dispersion of electron energy in the beam, ε_{n} is the normalized beam emittance, and ε_{n} is the beam radius in the FEL section. Estimating the values of these contributions for a beam with a current of 1 kA and energies of 5 to 7 MeV, whose energy dispersion $\frac{\Delta\gamma}{\gamma_0}$ does not exceed 1–2%, and whose normalized emittance is ~ 1000π mm mrad at r_{t} ~ 10 mm and λ ~ 0.5–1 mm, it is quite easy to verify that condition (1) is fully met.

Such a beam can therefore be used as a FEL driver with a maximum efficiency of radiation generation of 2–3% at the existing parameters of the electron beam generated in the LIA [1, 29]. It should be noted that much work has already been done [31] to adjust the operating modes of the accelerator to provide the required quality of beam transportation, in order to reduce the energy and angular dispersion of beam electrons in the LIA.

Let us consider one aspect of this work on the stability of the beam during its transportation and acceleration within the LIA structure. There are a number of instabilities of high-current electron beams in LIAs that affect the process of the beam transportation and acceleration. They are transverse electron beam instability (BBU-instability) [15–17]; corkscrew beam motion [14], ion-hose instability [32]; and beam instability caused by charge image displacement [33]. The most hazardous of these for guiding the beam in our LIA is transverse instability.

Transverse instability deteriorates the characteristics of a microscopic beam, and the beam could be lost on the walls of the drift chamber at high values of the instability increment. The excitation of this instability is due to the interaction between a high-current REB and the fields of dipole modes excited by the REB in the resonators of accelerator modules [15, 16, 30].

As a result of this interaction, the electron beam begins to oscillate in the cross-section of the vacuum chamber with an amplitude that grows exponentially as the beam moves along the accelerator's structure. With an LIA that has a continuously focusing magnetic field, the generalized relationship for the amplitude of oscillation of the beam centroid (the center of the charge density distribution in the beam's cross section), results obtained using the Neil–Cooper–Hall theory can be described by the relations [16]:

$$\xi_N = \xi_0\left[\frac{\gamma_0}{\gamma_N}\right]^{1/2}\exp(\Gamma N), \quad (4)$$

$$\Gamma \propto \frac{I_{\text{b}}Qk}{B}, \quad (5)$$

$$k = \frac{\left(\int B_{\perp}dz\right)^2}{2U}, \quad (6)$$

where ξ_0 is the initial amplitude of oscillation of the beam centroid, N is the number of the accelerator module, γ_0 and γ_N are the gamma factors of the beam at the injector output and after the Nth accelerator module, Γ is the increment of transverse instability, I_{b} is the beam current, B is the average magnetic field of the focusing system, k is the coefficient of coupling between this mode and the beam, U and Q are the time-averaged energy of this mode and the mode's quality factor, and $B_{\perp}$ is the transverse component of the dipole mode magnetic field with respect to the accelerator's axis.

Since relationships (4)–(6) give only an approximate estimate for the amplitude of beam oscillations, depending on the main parameters of the LIA, we have developed the IRBIS (Investigating Relativistic Beam Instability) software package for modeling transverse instability in an LIA with discrete focusing [34]. The IRBIS software package allows us to model the development of instability for each operating mode of the accelerator. Several modifications of the geometry of the accelerator modules that allow us to largely reduce the increment of transverse instability have been calculated and then tested in experiments [30].

These measures allowed us to reduce this increment by approximately an order of magnitude at the first stage of constructing an LIA consisting of 8 accelerating modules. We succeeded in achieving stable

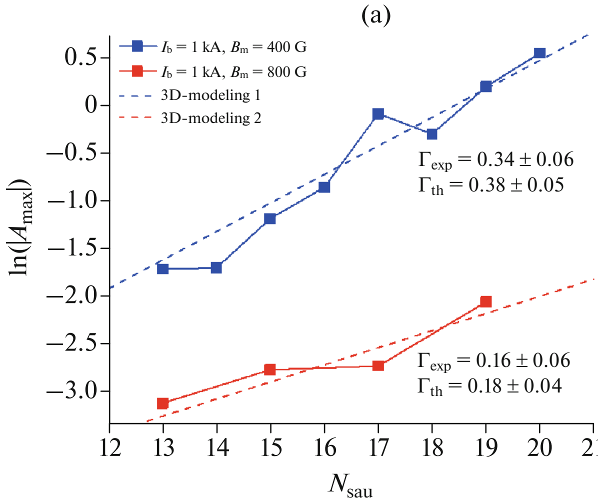

Fig. 2. Logarithm of the maximum oscillation amplitude of mode fields depending on the number of the LIA module in the three modes of LIA operation: (a) the modes with the same beam current of 1 kA and different fields in the LIA focusing system, B_m = 0.04 T and B_m = 0.08 T; (b) modes with the same field in the LIA focusing system, B_m = 0.08 T, and at different beam currents of 1 and 1.4 kA. The dotted line corresponds to a linear approximation of the experimental points.

electron beam transportation with a current of 2 kA and an energy of 5 MeV at an amplitude of transverse beam oscillations not exceeding 0.1 mm at the output of the accelerator [4, 34].

At the next stage, the accelerating structure of the LIA was extended from 8 to 20 modules; the magnetic focusing system, to 34 magnetic lenses with a maximum field of 0.08 T on the axis. The total length of the accelerator was 30 m. To further reduce the increment of transverse instability, which was proportional to the quality of the modes according to (5), we calculated and used a set of mode energy absorbers based on a radiation-absorbing material in the accelerator modules. The quality factors of the most unstable dipole modes in the 700–850 MHz range of frequencies that have the highest coupling coefficients with the beam were reduced to a level of 15–20, except for one mode with a frequency of 450 MHz whose quality factor was 30–35.

In order to compare the results from modeling and experimental data, we registered signals taken from the fast current transformers of each accelerator module that were proportional to the fields of the beam and the dipole modes excited by it [34]. Since the harmonic with a frequency of 450 MHz predominates in the spectra of these signals, we analyzed the maximum amplitude of signal oscillations taken from the current transformer with this frequency during the shelf of a current pulse ~100 ns long, depending on the number of the accelerator module.

A comparative analysis of the increments of instability obtained with our calculations and experiments is presented in Fig. 2, where the dots correspond to the logarithmic dependence of the maximum amplitude of signal oscillations registered using fast current transformers. Increment Γ_{exp} itself was determined from the slope of the linear approximation of the registered data. The numbers in Fig. 2 show the calculated Γ_{th} and experimental Γ_{exp} values of the increment of transverse instability for different LIA operating modes.

We can see from Fig. 2 that the increments of the transverse instability of the beam with a current of 1–1.4 kA obtained with our calculations and experimental measurements are consistent with the accuracy of measuring this quantity (20%). Thus we have shown that the increment of transverse beam instability in an LIA with a discrete magnetic configuration falls as the magnetic field in the lenses grows and rises along with the current, which is similar to the results registered for an LIA with focusing based on a continuous magnetic field [17].

During our experiments on the passage of the beam through the LIA, we established that parameter $\xi_0 \sim 1$ μm. In order to use the beam as a driver for a FEL generator, we must satisfy the requirement for limiting the amplitude of beam oscillations at the output of the LIA, expressed by relation $\xi_N < 1$ mm. Based on these values of the parameters and relation (4), we can set a boundary for the maximum value of transverse instability increment Γ, at which the amplitude of oscillation of the beam centroid does not exceed 1 mm at the output from an LIA consisting of 20 accelerating modules. This boundary can be given by relationship $\Gamma \leq 0.38$.

Along with studying the stability of the beam in the LIA, we also performed test experiments on the compression and passage of the electron beam in a compressed state through a FEL section 0.6 m long. These experiments are important for evaluating the prospects

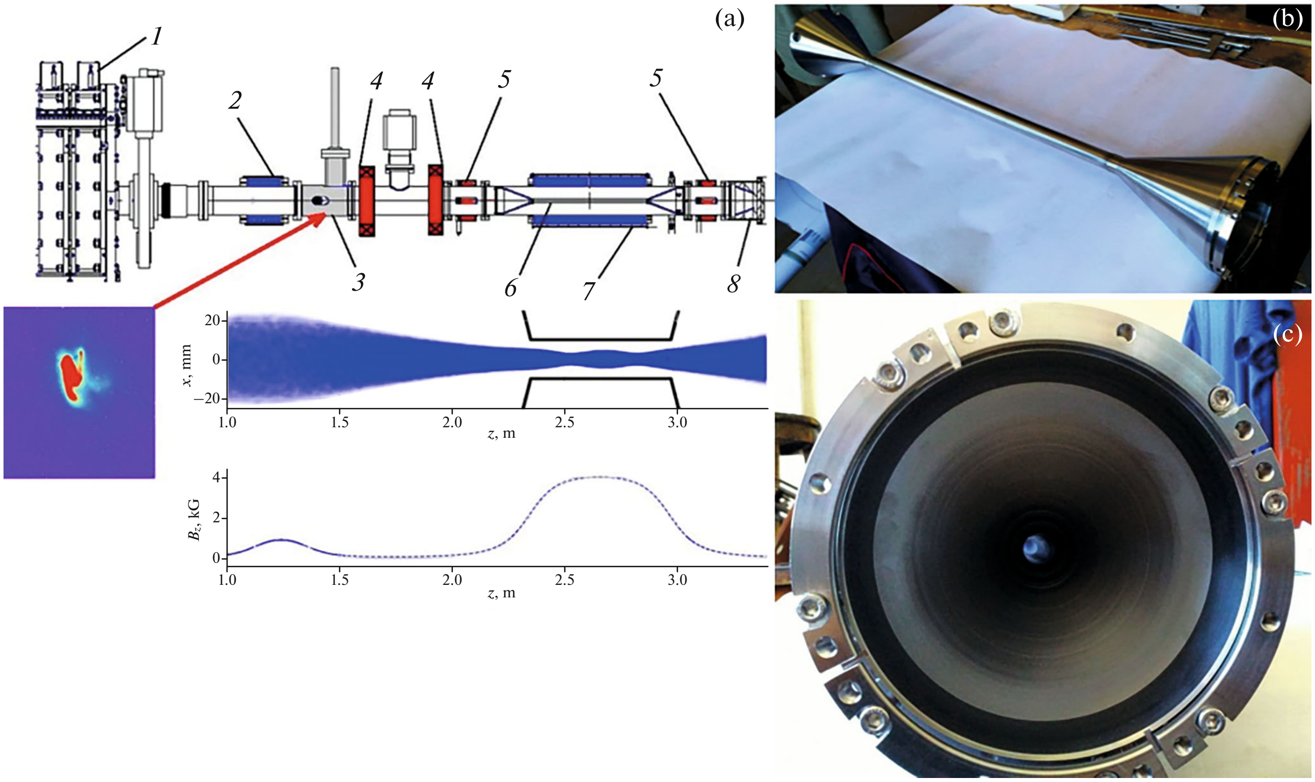

Fig. 3. Beam compression experiment: (a) schematic diagram of an experiment where (*1*) is the output accelerating module, (*2*) is the matching magnetic lens, (*3*) is a transient radiation sensor, (*4*) are dipole correctors, (*5*) are beam position sensors, (*6*) is the vacuum channel for transporting the compressed beam, (*7*) is an impulse solenoid, and (*8*) is a beam collector. The blue color shows a calculated envelope of the electron beam when it is injected into the FEL section; (b) and (c) are photographic images of the vacuum channel (*6*).

of using the proposed system of a terahertz radiation generator. As it has been already mentioned in the Introduction, the diameter of the FEL electrodynamic system based on modified Bragg reflectors [35], in the case of which the system retains its highly selective properties and ensures a stable level of single-mode radiation generation, should not exceed ~ 40 λ.

For characteristic radiation wavelength $\lambda = 0.5$ mm in the working region of the FEL, the diameter of the electrodynamic system must not exceed 20 mm. In order to efficiently transport a beam in a drift tube with such a diameter over a distance of 1–2 m under the conditions of transverse oscillations in the undulator's magnetic field, the beam must be compressed from its initial diameter $d_1 = 4$ cm at the output of the LIA to the bean diameter in the FEL resonator, $d_2 = 5$–10 mm.

To perform a test experiment on beam cross-section compression (see the schematic diagram in Fig. 3), the LIA electron-optical system was supplemented with a pulsed solenoid (*7*) 0.65 m long with a magnetic field of 0.4 T on the axis to ensure transport of the compressed beam, along with magnetic lens (*2*) that matches the beam size at the output of the LIA to the one required at the input to solenoid (*7*) [5, 31]. It should be noted that the magnetic field profile on the axis of the system we chose ensures the minimum amplitude of pulsation of the beam radius (<1) mm in vacuum channel (*6*). A detailed description of the experimental results is presented in [31].

During our experiments we found that the level of current transmission of a beam with an energy of 5 MeV and a current of 900 A through the vacuum channel of the beam's cross-section compression system while keeping the current at a constant level under the conditions of a negligible change in the electron energy was 85–90%. However, a substantial drop in this parameter was observed at the leading and trailing edges of the beam pulse, due possibly to a large change in the electron energy.

GENERAL FEL OUTLINE

After the successful series of demonstration experiments on beam compression described above, we designed the FEL section whose general view and outline are shown in Fig. 4 as the first stage of creating an FEL generator based on an LIA beam. The FEL section consisted of

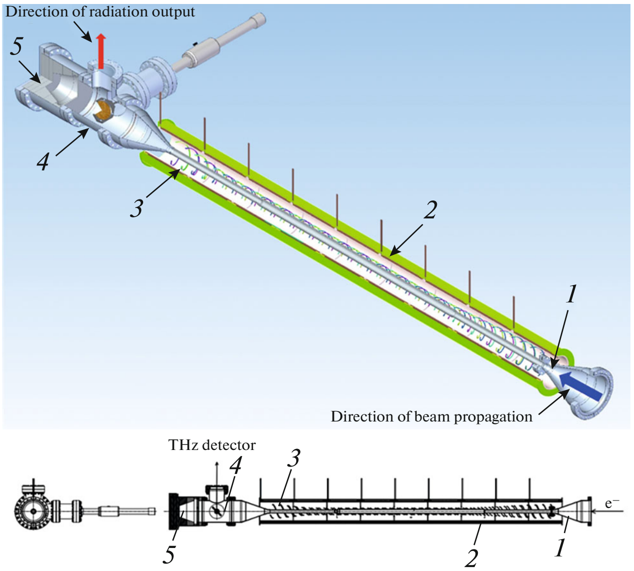

Fig. 4. FEL section: (a) a three-dimensional view of the FEL section including the beam cross-section compression system, the system for beam ejection onto the collector, and the radiation output system; (b) general outline of the FEL section, where (*1*) is a vacuum chamber with conical extensions at the ends, (*2*) are magnetic lenses, (*3*) is a helical winding of the undulator, (*4*) is a radiation output system at an angle of 90 degrees with respect to the beam motion direction, (*5*) is a beam ejection repository. The blue arrow shows the direction of electron beam propagation, the red arrow shows the direction of radiation output.

• vacuum chamber (*1*) 2 m long, in which an electrodynamic system with an internal diameter of 20 mm is mounted;

• magnetic beam compression system (*2*), consisting of nine pulsed magnetic lenses with built-in dipole correctors. Each lens is a pulsed axially symmetrical solenoid spaced at a distance of 5 mm from the neighboring lens. Each solenoid is 0.22 m long with a diameter of 0.15 m, 120 turns, and a maximum magnetic field strength of 0.6 T along the axis;

• helical winding of the undulator (*3*), which generates the helical field required for pumping transverse oscillations of the beam electrons [33];

• radiation output system (*4*), inside of which there is a rotating mirror in the form of a thin foil inclined at an angle of 45° with respect to the direction of the beam motion;

• beam ejection system (*5*), needed to substantially reduce the power of the X-ray flux that makes it difficult to register parameters of the beam and the THz radiation flux.

CONCLUSIONS

Measures were developed and implemented to ensure stable electron beam transport to an LIA. It was shown that modifying the accelerating modules and increasing the magnetic field in the focusing system of the LIA allows us to suppress the transverse instability of an electron beam with a current as high as 1 kA and an energy of 10 MeV by reducing its increment to $\Gamma < 0.16$.

Test experiments showed that under the conditions of a leading magnetic field we can compress a beam with a diameter of 40 mm to a diameter of 10 mm at an electron energy of 5 MeV and a current of 1 kA, followed by beam transport in a compressed state over a distance of 0.6 m inside a FEL vacuum channel with a diameter of 20 mm.

A design of an FEL section with magnetic and vacuum systems for beam compression and transportation was developed along with a system for radiation output. Details of the design of the helical undulator were worked out. Technical documentation is now under way, and the main components of the FEL generator are being manufactured. Our results confirm it is quite possible to create a high-power FEL generator in the 0.3–1 THz range of frequencies, based on the beam generated by an LIA accelerator.

ACKNOWLEDGMENTS

The authors express their gratitude to A.V. Burdakov, N.A. Vinokurov, and E.K. Kenzhebulatov for their useful remarks and discussions during our research.

FUNDING

Most of our investigations were performed at the Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Scienes. The results presented in sections III and IV were obtained as part of project no. 19-12-00212 of the Russian Science Foundation. Our experiments on generating an electron beam with a current of 1 kA and an energy of 5–8.5 MeV in an LIA were been performed in collaboration with the Russian Federal Nuclear Center—Zababakhin All-Russia Research Institute of Technical Physics.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Arzhannikov, A.V., Ginzburg, N.S., Malkin, A.M., et al., *Proc. 44th Int. Conf. on Infrared, Millimeter, and Terahertz Waves*, Paris, 2019, p 5864231.
2. Peskov, N.Yu., Arzhannikov, A.V., Ginzburg, N.S., et al., *Proc. SPIE*, 2020, vol. 11582, p. 1158207.
3. Logachev, P.V., Kuznetsov, G.I., Korepanov, A.A., et al., *Instrum. Exp. Tech.*, 2013, no. 6, p. 42.
4. Nikiforov, D.A., Blinov, M.F., Fedorov, V.V., et al., *Phys. Part. Nucl. Lett.*, 2020, vol. 17, p. 197.

5. Sandalov, E.S., Sinitsky, S.L., Skovorodin, D.I., et al., *Proc. 2021 IEEE Int. Conf. on Plasma Science*, Lake Tahoe, 2021, p. 21360392.
6. Ekdahl, C., *IEEE Trans. Plasma Sci.*, 2022, vol. 30, no. 1, p. 254.
7. Ekdahl, C., Sinitsky, S.L., Skovorodin, D.I., et al., *IEEE Trans. Plasma Sci.*, 2006, vol. 34, p. 460.
8. Merle, E., Anthouard, Ph., Bardy, J., et al., *Proc. 5th European Conference EPAC 96*, Sitges, 1996, Report EPAC-1996-THP014G.
9. Ekdahl, C., Beam dynamics for ARIA, Tech. Rep. LA-UR-14-274454, Los Alamos: Los Alamos Natl. Lab., 2014.
10. Ekdahl, C., *IEEE Trans. Plasma Sci.*, 2015, vol. 43, no. 12, p. 4123.
11. Ekdahl, C., *IEEE Trans. Plasma Sci.*, 2021, vol. 49, no. 10, p. 3092.
12. Crawford, M. and Barraza, J., *Proc. 2017 IEEE 21st Int. Conf. on Pulsed Power*, Brighton, UK, 2017, p. 1.
13. Ekdahl, C., Beam dynamics for the Scorpius conceptual design report, Tech. Rep. LA-UR-17-29176, Santa Fe: Los Alamos Natl. Lab., 2017.
14. Ekdahl, C., *IEEE Trans. Plasma Sci.*, 2021, vol. 49, no. 11, p. 3548.
15. Panofsky, W.K.H. and Bander, M., *Rev. Sci. Instrum.*, 1968, vol. 39, p. 206.
16. Neil, V.K., Hall, L.S., and Cooper, R.K., *Part. Accel.*, 1979, vol. 9, no. 4, p. 213.
17. Ekdahl, C., Coleman, J.E., and McCuistian, B.T., *IEEE Trans. Plasma Sci.*, 2016, vol. 44, no. 7, p. 1094.
18. Faries, W., Gehring, K.A., Richards, P.L., et al., *Phys. Rev.*, 1969, vol. 180, no. 2, p. 363.
19. Morris, J.R. and Shen, Y.R., *Opt. Commun.*, 1971, vol. 3, no. 2, p. 81.
20. Gallerano, G.P., Doria, A., and Giovenale, E., *Terahertz Sci. Technol.*, 2014, vol. 7, no. 4, p. 160.
21. Jeong, Y.U., Lee, B.C., Kim, S.K., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2001, vol. 475, p. 47.
22. Byrd, J.M., Leemans, W.P., Loftsdottir, A., et al., *Phys. Rev. Lett.*, 2002, vol. 89, p. 224801.
23. Carr, G.L., Martin, M.C., McKinney, W.R., et al., *Nature*, 2002, vol. 420, p. 153.
24. Gover, A., Faingersha, A., Eliran, A., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2004, vol. 528, p. 23.
25. Van Der Meer, A.F.G., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2004, vol. 528, p. 8.
26. Prazeres, R., Glotin, F., Ortega, J.M., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2004, vol. 528, p. 83.
27. Shevchenko, O.A., Arbuzov, V.S., Vinokurov, N.A., et al., *Phys. Procedia*, 2016, vol. 84, p. 13.
28. Kulipanov, G.N., Bagryanskaya, E.G., and Chesnokov, E.N., *IEEE Trans. Terahertz Sci. Technol.*, 2015, vol. 5, no. 5, p. 798.
29. Sandalov, E.S., Sinitsky, S.L., Nikiforov, D.A., et al., *Proc. 46th Int. Conf. on Infrared, Millimeter and Terahertz Waves*, Chengdu, 2021, p. 1.
30. Sandalov, E.S., Sinitsky, S.L., Skovorodin, D.I., et al., *IEEE Trans. Plasma Sci.*, 2021, vol. 49, no. 2, p. 718.
31. Nikiforov, D.A., Petrenko, A.V., Sinitsky, S.L., et al., *J. Instrum.*, 2021, vol. 16, p. 11024.
32. Ekdahl, C., *IEEE Trans. Plasma Sci.*, 2019, vol. 47, no. 1, p. 300.
33. Godfrey, B.B. and Hughes, T.P., *Proc. 1989 IEEE Particle Accelerator Conference "Accelerator Science and Technology,"* Chicago, 1989, vol. 2, p. 1023.
34. Sandalov, E.S., Sinitskii, S.L., Skovorodin, D.I., et al., *Sib. Fiz. Zh.*, 2022, vol. 17, no. 1, p. 5.
35. Ginzburg, N.S., Zaslavskii, V.Y., Zotova, I.V., et al., *JETP Lett.*, 2010, vol. 91, p. 266.

Translated by O. Polyakov