ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-TUC03

DEVELOPMENT OF POWERFUL LONG-PULSE THz-BAND FEL DRIVEN BY LINEAR INDUCTION ACCELERATOR*

N. Yu. Peskov†, V. I. Belousov, N. S. Ginzburg, D. I. Sobolev and V. Yu. Zaslavsky,
Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia
A. V. Arzhannikov, D. A. Nikiforov, E. S. Sandalov, S. L. Sinitsky,
D. I. Skovorodin, A. A. Starostenko, and K. I. Zhivankov
Budker Institute of Nuclear Physics, Russian Academy of Sciences, Novosibirsk, Russia

Abstract

Project of high-power long-pulse sub-THz to THz-band FEL is under development based on the linac "LIU" of the new generation forming 5 - 20 MeV / 2 kA / 200 ns electron beam. The aim of this project is to achieve a record sub-GW power level and pulse energy content up to 10 - 100 J at the specified frequency ranges. In the present paper, results of electron-optical experiments on the formation of an electron beam with parameters acceptable to drive the FEL are discussed. Helical pulse undulators were elaborated for pumping operating transverse oscillations of the beam electrons. As a key component of the electrodynamic system of the FEL-oscillator, the possibility of using advanced Bragg resonators based on the coupling of propagating and quasi-cutoff waves, which are capable to provide stable narrow-band generation under conditions of substantial oversize of the interaction space, is analyzed.

INTRODUCTION

Project of free-electron laser (FEL) is under development in collaboration between BINP RAS (Novosibirsk) and IAP RAS (Nizhny Novgorod) based on a new generation of induction linac "LIU" 5 - 20 MeV / 2 kA / 200 ns implemented in recent years at BINP RAS [1]. The use of such beam makes it possible to realize ultra-high power long-pulse FEL operating from sub-THz to THz frequency range [2]. Principal problems in realization of this generator include: (a) formation of the relativistic electron beam (REB) with parameters acceptable for operation in the short-wavelength ranges, (b) development of undulator for pumping operating transverse oscillations in the beam, and (c) elaboration of electrodynamic system that can provide stable narrow-band oscillation regime in a strongly oversized interaction space.

Initial proof-of-principle experiments are planned to start at the "LIU-5" accelerator in the 0.3 THz frequency range, with prospects of transition to 0.6 THz range and higher frequencies after positive results would be demonstrated. In the paper, the design parameters of the FEL project are discussed. Results of electron-optical experiments on the beam formation are presented. Structural elements of the FEL magnetic system based on helical undulator and a guide solenoid that provides intense beam transportation were elaborated. An electrodynamic system was proposed exploiting a new modification of oversized Bragg structures, so-called advanced Bragg structures, which have significantly improved selective properties. Structures of such type were designed with the diameter of 20 and 40 wavelengths for operation in specified frequency ranges.

RESULTS OF ELECTRON-OPTICAL EXPERIMENTS AT THE LINAC "LIU"

The experimental basis for realization of the novel FEL scheme is the "LIU-5" accelerator complex [1] comprising a 2 MeV thermionic injector and the induction accelerating sections (total number of 8 with the acceleration of ~ 0.4 MeV each), which finally provide formation of 5 MeV beam with the current of up to 2 kA, duration of 200 ns and diameter of ~ 4 cm at the output. Beam focusing between these sections is provided by the pulsed magnetic lenses of ~ 0.2 T.

To conduct experiments on sub-THz /THz generation in the FEL, it is necessary to perform a significant compression over the beam cross-section from the size given above to the required diameter D_{beam} ~ 5 - 7 mm and further transportation of the beam along the interaction region of about 1 - 1.5 m without loss of current. Based on the existing electron-optical system of the "LIU-5", the beam injection into the undulator was designed using magnetic lens of the accelerator and focusing pulsed solenoid of ~ 0.4 T. Simulations of the beam dynamics in this magnetic system were carried out using WARP code (which takes into account the electric and magnetic fields of an intense REB) and demonstrated possibility to compress the beam with measured emittance to the diameter needed to drive the FEL (see Fig. 1).

Schematic of experiments on the injection of an electron beam formed by the linac "LIU-5" into the FEL electron-optical system and its further transportation is shown in Fig. 1. As a result of the experiments, the required beam compression was realized. Beam current transmission through the vacuum channel was obtained with an efficiency of about 90%, which, however, was accompanied by reduction in the beam pulse duration to 80 - 100 ns due to the cutting of its leading and trailing edges. Currently, additional tuning of the accelerator and the magnetic system is being carried out, which should allow transportation of the compressed beam through the FEL interaction space to be close to 100% without beam pulse shortening. In this case, according to the simulation, energy spread in the beam is expected to be less than 1%.

* Work supported by the Russian Science Foundation, grant 19-12-00212
† peskov@ipfran.ru

ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-TUC03

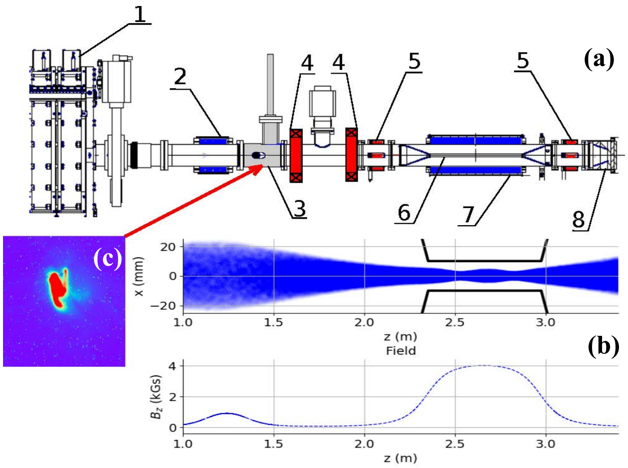


Figure 1: (a) Scheme of beam compression experiment: 1 - output accelerating module of the linac "LIU-5", 2 - matching pulsed magnetic lens, 3 - transient radiation detector, 4 - dipole correctors, 5 - beam position detectors, 6 - vacuum chamber, 7 - guide solenoid and 8 - beam collector. (b) Results of simulations of the beam dynamics in the compression system using the WARP code (the beam envelope is shown). (c) The image of the beam on the transient radiation detector at the entrance of the compression system.

DESIGN OF PULSED HELICAL UNDULATOR AND GUIDE SOLENOID

Constructing the pulsed undulators, we applied our experience accumulated in the previous FEM experiments, which were successfully realized up to now in the millimeter wavelength bands in collaboration between IAP RAS and JINR (Dubna) [3]. To improve the uniformity of the transverse magnetic field distribution over the undulator cross-section and increase the ratio: magnetic field amplitude to current in the windings, we exploited a bifilar helical configuration composed of the four conductors (see Fig. 2a), in which the conductors with the same current direction are positioned at an azimuthal angle of $\varphi \sim 60°$ to each other [4]. For pumping operating bounce oscillations in magnetically-guided REBs, undulators with adiabatically up-tapered section are traditionally applied at the entrance. For realization of such an input (and output) section of the undulator, an "optimized" tapered configuration was developed, based on the simultaneous application of two methods: (i) increasing the distance of the conductors from the axis using a conical section, and (ii) approaching the conductors with the currents of opposite directions in the winding. Sample of the undulator, which implements the proposed "optimized" profiling, is shown in Fig.2a. Results of 3D simulations demonstrate that an undulator with such an input section provides smooth rise of the magnetic field amplitude with no parasitic spatial "spikes", which was confirmed by the "cold" magnetic measurements (Fig. 2b).

The so-called reverse guide field regime [5, 6] was chosen for the FEL operation, which, according to the simulation [3], possesses a low sensitivity to the initial spread of the REB parameters and provides a high-quality helical beam formation in the slowly up-tapered undulator entrance. Simulations demonstrated that in this regime amplitude of "parasitic" cyclotron oscillations never exceeded 2 - 3% of the operating bounce oscillations acquired by the electrons in the entire range of designed values of the guide and the undulator fields. As the theoretical analysis shows, these beams allow for implementation of the sub-THz/THz FEL with relatively high electron efficiency.

DESIGN AND TESTING OF ADVANCED BRAGG RESONATORS

One of the key problems in realization of the FEL-oscillator is development of an electrodynamic system that can provide stable narrow-band oscillation regime in a strongly oversized interaction space. Moreover, for transportation of intense electron beam, which is realized currently at the "LIU-5" accelerator, the resonator diameter D should in orders exceeds the radiation wavelength λ when operating from sub-THz to THz band, i.e. $D/\lambda \sim 20$ to 50.

This problem can be solved using advanced Bragg structures based on coupling of the propagating and quasi-cutoff waves. For realization of such coupling, the corrugation period should be approximately twice as long as in "conventional" structures. Involvement of a quasi-cutoff wave in the feedback loop, similarly to gyrotrons or orotrons, results in significant purification of transverse mode spectrum of the resonator under the substantial oversize parameter and improvement of selective properties in comparison with the Bragg structures of "conventional" type. Thus, FELs based on advanced Bragg resonators combine the advantages of the gyrotrons (high selectivity over the transverse mode index) with those of relativistic oscillators (operation at short wavelength

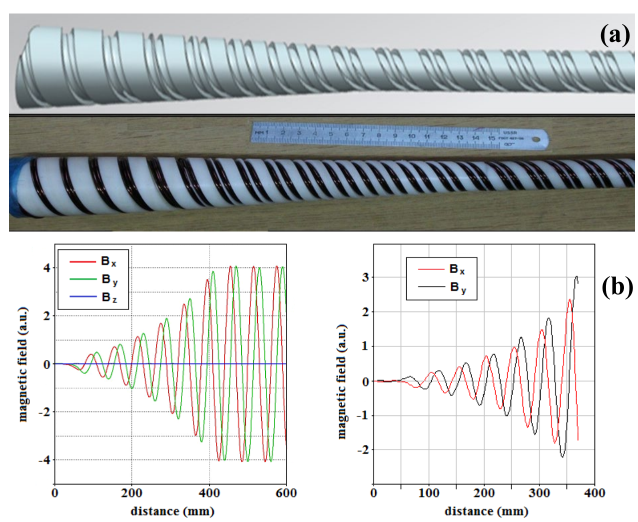
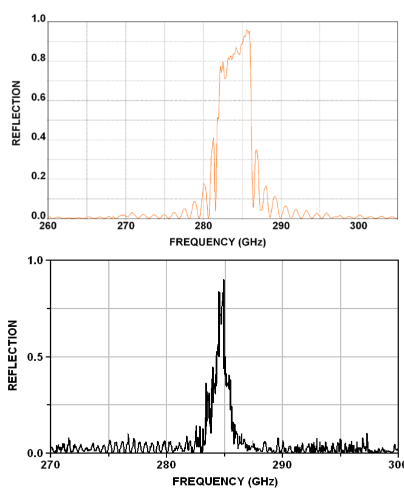


Figure 2: (a) Photograph of 3D model (top) and experimental prototype (bottom) of the "improved" undulator with a period d_u = 6 см, and (b) results of 3D simulations (left) and "cold" measurements (right) of longitudinal structure of magnetic field at the undulator entrance.

ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-TUC03

bands with high pulsed power level). According to the theoretical analysis carried out in the frame of averaged models as well as to the 3D simulations, advanced Bragg structures allow selective excitation of the operating mode at the transverse sizes sufficient for realization of FELs up to THz frequencies [7].

Results of 3D simulations (code CST Microwave Studio) of cylindrical advanced Bragg structures in the ranges of 0.3 THz and 0.6 THz are shown in Fig. 3a and Fig. 4. These structures have approximately the same diameter of ~ 20 mm acceptable for transportation of the beam formed at the "LIU-5" accelerator. The oversize factor D/λ of these structures is about 20 and 40, respectively and their feedback loop is formed by two counter-propagating $TE_{1,1}$ waves (the forward propagating wave of this type is chosen to be an operating one) and cutoff waves of $TE_{1,20}$ and $TE_{1,40}$ types. Simulations demonstrate that even with such large transverse dimensions, novel Bragg structures provide selective reflection for the operating mode with an efficiency of ~ 80 - 90% in power. Results of "cold" electrodynamic tests of advanced Bragg structure carried out at 0.3 THz band coincide with the simulations and confirm the existence of effective narrow-band reflection in the designed frequency range (Fig. 3b).



(a)
(b)

Figure 3: Results of (a) 3D simulations and (b) "cold" tests of advanced Bragg structure having oversize factor Ø/λ ~ 20 and operating at 0.3 THz band (feedback loop $TE_{1,1} \leftrightarrow TE_{1,20\text{ - cutoff}} \leftrightarrow TE_{1,1}$, length l_{ad} = 10 cm, corrugation period d_{ad} = 1.05 mm and depth r_{ad} = 0.3 mm).

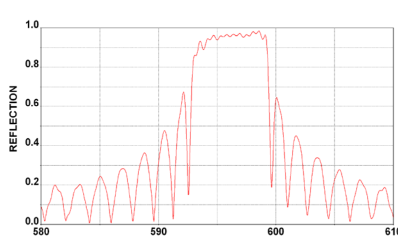


Figure 4: Results of 3D CST simulations of advanced Bragg structure with oversize factor D/λ ~ 40 in the frequency band of 0.6 THz (l_{ad} = 7.5 см, d_{ad} = 0.5 мм, r_{ad} = 0.3 мм, feedback loop $TE_{1,1} \leftrightarrow TE_{1,40\text{-cutoff}} \leftrightarrow TE_{1,1}$).

CONCLUSION

Summarizing, theoretical studies of electrodynamic, magnetic, and electron-optical systems, simulations of processes of formation of intense REBs and their interaction with RF-waves in new high-selective electrodynamic systems allowed developing the project of powerful FEL operating from sub-THz to THz bands based on the linac "LIU". The key components for experimental realization of these FEL-oscillators have been designed and studied in "cold" tests. Assembly of the installation components was started for their full-scale tests.

It is important to underline that operability of novel components of electron-optical ("optimized" helical undulator) and electrodynamic (advanced Bragg structures) systems were studied in the proof-of-principle experiment carried out in collaboration between IAP RAS and JINR (Dubna) based on the induction linac "LIU-3000" 0.8 MeV / 200 A / 200 ns. In these experiments [8], high-efficiency FEM-oscillator was realized at W-band, and stable narrow-band operation was demonstrated under the transverse oversize factor D/λ ~ 5. Increase in the radiation frequency in the JINR-IAP FEM was limited by the electron beam energy at this accelerator and the achievable undulator periods. Meanwhile, this FEM-oscillator can be considered as a prototype for the FEL project, which is in progress in the frame of BINP - IAP cooperation based on linacs of the new generation.

REFERENCES

[1] D.A. Nikiforov *et al*, "High-current electron-beam transport in the LIA-5 Linear Induction Accelerator", *Phys. of Particles and Nuclei Lett.*, vol.17(2), pp.197-203, 2020.

[2] A.V. Arzhannikov *et al*, "Powerful long-pulse THz-band Bragg FEL based on linear induction accelerator", in *Proc. of the 44th Int. Conf. on Infrared, Mm and THz Waves (IRMMW-THz 2019)*, Paris, France, Sept. 2019, p.5864231.

[3] N.Yu. Peskov *et al*, "Powerful narrow-band Free-Electron Masers based on linear induction accelerators", *Radiophys. and Quant. Electron.*, vol.63, no.12, pp.1032-1081, 2020.

[4] N.Yu. Peskov *et al*, "Powerful FEM-oscillators with advanced Bragg resonators operating in a single mode regime from Ka- to W-band", *Proc. of the 41th Int. Conf. on Infrared, Mm and THz Waves (IRMMW-THz 2016)*, Copenhagen, Denmark, Sept. 2016, p.F2E.01.

[5] A.A. Kaminsky *et al*, "Experiments on the efficiency increase of FEL amplifier on the base of LIU-3000", *Particle Accelerators*, vol.33, pp.189-195, 1990.

[6] M.E. Conde and G. Bekefi, "Experimental study of a 33.3 GHz free electron laser amplifier with a reversed axial guide magnetic field", *Phys. Rev. Lett.*, vol.67, no.22, pp.3082-3085, 1991.

[7] N.Yu. Peskov *et al*, "Oversized advanced bragg resonators for powerful long-pulse FEL of subteraherts frequency range", *Radiophys. and Quant. Electr.*, vol.63, no.5-6, pp.542-546, 2020.

[8] N.Yu. Peskov *et al*, "Powerful oversized W-band FEM with advanced Bragg resonator based on coupling of propagating and cutoff waves", *Appl. Phys. Lett.*, vol.116, p.213505, 2020.