Powerful Long-Pulse FEL based on Linac LIU: Simulations and Optimization of Parameters for Initial Experiments at 0.3 THz Range

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***Abstract*—Project of sub-THz/THz band FEL driven by induction linac LIU is under development in collaboration between BINP RAS (Novosibirsk) and IAP RAS (N.Novgorod) and aimed to achieve sub-GW power and a record pulse energy content of ~ 10 -100 J in these frequency band. Two alternative electrodynamic systems were proposed for this FEL to provide stable narrow-band generation regime: (1) advanced Bragg resonators with quasi-cutoff feedback waves and (2) quasi-optical resonators of the Talbot-type. Present paper is devoted to the results of simulations and optimization of parameters of the FEL with such resonators for conducting initial experiments at the 0.3 THz range.**

Keywords—free-electron laser, linear induction accelerator, powerful long-pulse THz radiation, high-selective oversized electrodynamic systems, Bragg resonators, Talbot-type resonators

I. Introduction

Project of ultra-high power long-pulse free-electron laser (FEL) operating from sub-THz to THz frequency range is under development in collaboration between BINP RAS (Novosibirsk) and IAP RAS (N.Novgorod) [1]. This FEL is based on the induction linac LIU, which was elaborated in recent years at BINP RAS [2]. This project is aimed to achieve sub-GW to GW powers and a record energy content of ~ 10 - 100 J in radiation pulses with 100-ns duration at the specified frequencies.

Initial proof-of-principle experiments are planned to start at the 0.3 THz frequency range, with prospects of transition to 0.6 THz range and higher frequencies after positive results would be demonstrated. The 0.3 THz FEL is currently under assembling at the LIU-5 accelerating complex forming 5 MeV electron beam with kA - level current and up to 200 ns duration. In the electron-optical experiments carried out at the LIU-5 accelerator, the formation of an electron beam with about 7 - 10 mm in diameter and energy/velocity spread acceptable for operation in the sub-THz range was demonstrated. An undulator with a period of 10 cm was constructed for pumping the operating bounce-oscillations in the beam. To transport intense electron beam formed by the LIU-5 accelerator through the FEL interaction space (taking into account its bounce-oscillations in the undulator), the cavity diameter would be Ø ≈ 20 mm, i.e. oversize parameter is Ø/λ ~ 20 in the selected frequency range.

In order to provide stable narrow-band generation regime in this FEL-oscillator, we elaborate two types of electrodynamic systems: (1) advanced Bragg resonators based on coupling of quasi-cutoff and propagating waves [3, 4] and (2) quasi-optical Talbot-type resonators [5]. At the current stage, additional simulations of the FEL-oscillator exploiting proposed high-selective electrodynamic systems in the selected frequency range were performed, aimed at optimizing the FEL parameters and the resonators geometry in order to enhance the efficiency of electron-wave interaction and the stability of establishing a narrow-band generation regime in such strongly-oversized conditions.

II. FEL with Advanced Bragg Resonator

For operation in the selected frequency range, a two-mirror resonator scheme with two Bragg reflectors of the advanced type was chosen, which allows reducing the Ohmic losses associated with the excitation of the quasi-cutoff waves in the interaction space. Simulations of dynamics of the FEL with advanced Bragg resonators of such type were carried out using an original quasi-optical non-stationary model of electron-wave interaction within the framework of the coupling waves approach. Based on the theoretical analysis carried out, the following optimal resonator geometry was selected: the up-stream (cathode-side) mirror $L_{in} \approx 15$ - 20 cm providing power reflection $R_{in} \approx 0.9$ - 0.95, the down-stream (collector-side) mirror $L_{out} \approx 7$ - 10 cm with

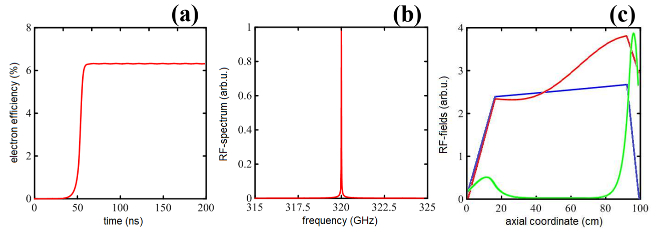

Fig. 1. Results of simulations of 0.3 THz FEL with a two-mirror advanced Bragg resonator under conditions of the planned experiments at the LIU-5 accelerator: (a) time-dependence of the electron efficiency, (b) spectrum of the radiation and (c) longitudinal structure of the partial waves in the stationary regime (red curve corrswponds to the synchronous with the electrons forward-propagating wave, blue curve - to the backward feedback wave, green curve - to the quasi-cutoff wave).

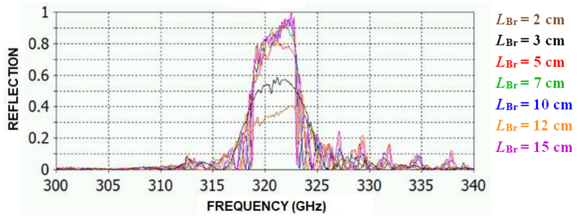

Fig. 2. Results of the CST-simulations of advanced Bragg structures for the 0.3 THz FEL. Frequency dependence of the reflection coefficient at different lengths of the structures L_{Br} (waveguide diameter Ø ≈ 20.7 mm, corrugation period 0.93 mm, corrugation depth 0.4 mm).

$R_{out} \approx 0.7$ and the regular section of $L_0 \approx 70$ - 80 cm. Results of simulations of 0.3 THz FEL-oscillator with a resonator of the specified configuration are shown in Fig. 1. Geometry of the reflectors was optimized in the 3D simulations using the CST Microwave Studio software (Fig. 2). According to the simulations, the chosen resonator geometry allows for stable establishment of the single-mode generation regime under the conditions of planned experiments. Herewith, the electron efficiency reaches more than 6%, which corresponds to the output radiation power of up to 0.5 GW. Rather high efficiency of the electron-wave interaction is provided by the field structure of the synchronous partial wave, favorable for the extraction energy from the beam, which is formed in the selected resonator geometry by a relatively short output advanced Bragg reflector with a moderate reflection. At the same time, sectioning of the interaction space and the relatively short length of this mirror reduce the Ohmic losses in the system down to the level of 15 - 20% of the radiated power. The oscillation rise time is about 50 - 70 ns, which is acceptable for the beams formed by the LIU accelerator.

III. FEL BASED ON TALBOT-TYPE RESONATOR

It should be noted that the use of quasi-optical principles in such resonators makes it possible to operate up to the oversize Ø/λ ~ 50 - 100 and, thus, to prospect the FEL into the THz range and up to the IR range. At the same time, the transverse size Ø/λ ~ 20, planned in the initial experiments in the 0.3 THz, is relatively low for the resonators of this type and leads to a Talbot repetition length $L_{Talbot} \approx Ø^2/\lambda \approx 40$ cm. According to the simulations, this length is insufficient to ensure effective energy extraction from the beam under the conditions of the planned experiments. Thus, the possibility of using a novel scheme of Talbot-type resonator with a "doubled" length (corresponding to the length of the second Talbot repetition $2L_{Talbot}$) to implement the FEL in the specified frequency range was studied.

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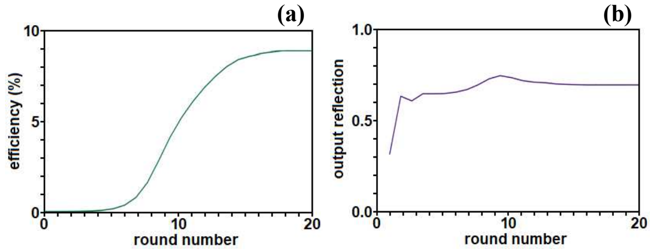

Fig. 3. Results of simulation results of 0.3 THz FEL with a Talbot-type resonator of "doubled" length at the LIU-5 accelerator (original averaged model): (a) electron efficiency and (b) "hot" reflection coefficient of the operating supermode from the output mirror, depending on the number of the supermode passes along the resonator.

Results of simulation of the FEL with Talbot-type resonator of "doubled" length are shown in Fig. 3. Simulation showed that in the designed 10-cm period undulator for the operating supermode, the optimal detuning of electron-wave (undulator) synchronism is realized near 0.34 THz. In this frequency range, the operating supermode is formed by partial waves, in which the lower wave of the $TE_{1,1}$ - type prevails. In the resonator with a mirror (a ring inside the waveguide) of 2.5 - 3 mm in size, the stationary generation regime is onset after about 20 passes of the supermode along the resonator (which corresponds to about 50 - 70 ns). It is important that in the resonator having a double Talbot-length, the operating supermode has a favorable longitudinal structure of the "klystron-type", which leads to a sufficiently high electron efficiency of ~ 8 - 10% and, as a result, the possibility of achieving output power of a GW-level (Fig. 3a). Taking into account the influence of intense beam on the transverse structure of the amplified supermode, the "hot" reflection coefficient of this supermode from the output mirror decreases in comparison with the value obtained in the "cold" resonator (see Fig. 3b), while the reflection coefficient from the input mirror remains the same as in the "cold" system at a level of about 92% in power. As a result, the transverse structure of the operating supermode formed by the electron beam leads to almost single-directional radiation output through the down-stream edge of the Talbot-resonator.

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