Long-life Injection System for Microtron-based Terahertz Free Electron Laser*

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A long-life injection system of the widely tunable microtron-based terahertz Free Electron Laser (FEL) has been developed and during few years provides stable operation of the FEL for users. The system is based on the thermionic cathode assembly using monocrystalline LaB_6 emitter, heated by the tungsten filament with the power consumption of ≈50 W. The cathode emits the macro-pulse current up to 1.4 A, and in ordinary regime provides operation of the terahertz FEL with extracted macro-pulse power of 30-50 W during of ≈1000 h. The cathode assembly is installed on the cover of the microtron accelerating cavity in position providing an efficient injection for the acceleration with variable number of orbits. This variation widely changes the energy of the electron beam and allows on-the-fly retuning of the FEL in the range of 1-3 THz. Pulse-signal system stabilizing the emission current allows to maximize the cathode assembly life time, prevents randomized break-downs in the accelerating cavity and decreases fluctuations of the power of the FEL radiation. The standard deviation of the fluctuations was measured to be less than 9% during long-time operation.

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I. Introduction

Like in the RF-gun, the cathode intended for the microtron with an internal injection operates in the field with strength of ≈ tens of MV/m. Polycrystalline or single crystal LaB_6 emitters providing by the temperature of 1600 ^{o}C in one-two order lower electric fields the current density approximately of 8 and 20-22 A/cm^2, respectively, successfully operate by such field strength [1]. Usual disadvantage of such emitters for the high-current microtron is insufficient current density which one can compensate with higher operating temperature of the emitter. This way causes limited operation time of the cathode with the range of tens-hundred h. Main reasons for such limitation are: limited time operation of heater, destruction of the emitter holder due to the boron diffusion, and evaporation of the cathode material. The attempt to increase the accelerated current enlarging the emitting area in the microtron increases the vertical oscillations in the beam, decreasing the capture into acceleration, and makes worse parameters of the beam which are essential for FEL operation.

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For the high-current microtron-injector of the widely tunable terahertz FEL has been developed reliable and long time operating an injection system based on the LaB_6 emitter heated by tungsten filament. In this development we minimized the temperature of the filament and emitter supporting details using multi-layer heat shield, surrounding the filament. Moreover we minimized the emitter temperature choosing respective operating regimes of the microtron. Suppressing of the boron diffusion was done through clamping of the emitter in a graphite holder.

Results of the injection simulations, description and measured parameters of the injection system providing reliable and stable operation of the terahertz FEL and having life-time approximately of 1000 h. are presented and discussed in this article.

II. Simulation of the injection

The operating conditions of the cathode were determined for first type acceleration [2] in a cylindrical cavity having radius of 40.8 mm and height of 17.8 mm. The emitter center coordinate R_C, radius r_C and the emitter deepening d_C are 30 mm, 1.25 mm and 0.5 mm respectively. The E_{010} mode electric field at the emitter surface with an initial phase φ one can express as:

$$E_{CS}(r,\varphi) \cong E_0 \cdot J_0(k_0 \cdot R_C) \cdot \cos(\varphi) \cdot \frac{J_0(k_r \cdot r)}{\mathrm{ch}(k_z \cdot d_C)},$$

Here: E_0 is maximal field on the cavity axis, $k_0 = 2\pi/\lambda_0$, $k_r = \chi_{01}/r_C$, J_0 is the first kind Bessel function, $\chi_{01} = 2.405$ is the first square of the Bessel function and $k_z = \sqrt{k_r^{\,2} - k_0^2}$. Calculated value of maximal field on the cavity axis of $E_0 =$ 35.527 MV/m corresponds to operation parameters of the microtron (the cavity with operating frequency of 2.801 GHz is situated in the homogeneous magnetic field having value of 0.1065 T). Corresponding maximal value of the electric field in the center of the emitter surface is:

$E_0 \cdot J_0(k_0 \cdot R_C)/\mathrm{ch}(k_z \cdot d_C) = 8.5933$ MV/m.

Considering the Schottky effect one can express the current density of LaB_6 single crystal emitter depending on r, φ as:

$$i_C(T, r, \varphi) = AT^2 \cdot \exp\left[\frac{-e\phi_C + 3.79 \cdot 10^{-4} \cdot \sqrt{E_{CS}(r, \varphi) \cdot 10^6}}{k \cdot T}\right].$$

Here: $A = 73$ A / grad^2·cm^2 and $e\phi_C = 2.66$ eV are the Richardson constant and the work function for LaB_6, respectively, k is the Boltzmann constant and T is the emitter temperature in Kelvin deg. Corresponding value of the maximal current density by the emitter temperature of 1900 ^{o}K is: $i_{C\,max} = i_C(1900^0\mathrm{K}, 0, 0) \approx 46$ A / cm^2.

Then the initial value of the emission cathode current will be equal to:

$$I_C(T) = \frac{1}{2\pi} \cdot \int_0^{2\pi} \left[2\pi \cdot \int_0^{r_C} i_C(T, r, \varphi) \cdot r\, dr\right] d\varphi \cdot$$

The tracking of injection of the electrons in the microtron was performed using 2-D motion equation in the median plane considering E_{010} mode electric and magnetic components of the cavity accelerating field and the microtron magnetic field. The result of the simulation of the first orbit is shown in Fig. 1(a). Fig. 1(b) shows in details the trajectories of the back-streaming electrons emitted in non-resonance phases from the edge point of the emitter and hitting the emitter surface.

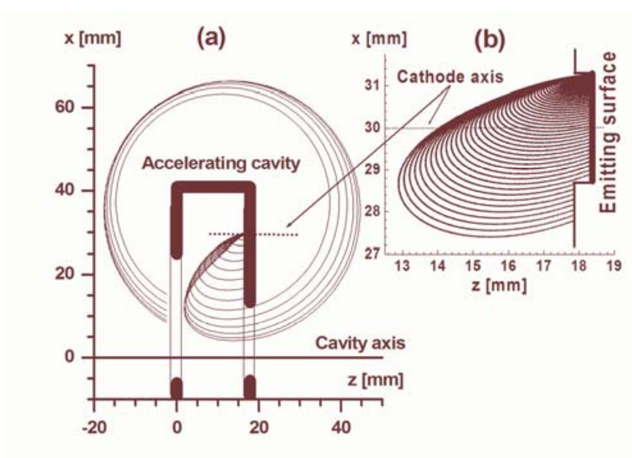

Fig. 1. (a)-2-D tracking of the first orbit. (b)-2-D tracking of the back-streaming electrons hitting the emitter.

The current of the electron back-stream one can calculate as:

$$I_{bs}(T) = \frac{1}{2\pi} \cdot \int_{\varphi_{bs}} \left[2\pi \cdot \int_0^{r_C} i_C(T, r, \varphi) \cdot r\, dr\right] d\varphi.$$

Here φ_{bs} - all initial phases of the electron back-stream. The integral is taking over all phases of the back-streaming electrons. Total power of the electrons heating the emitter was calculated as:

$$P_{bs}(T) = \frac{1}{2\pi} \cdot \int_{\varphi_{bs}} \left[2\pi \cdot \int_0^{r_C} i_C(T, r, \varphi) \cdot \varepsilon(r, \varphi) \cdot r\, dr\right] d\varphi,$$

here $\varepsilon(r, \varphi)$ is the energy of back-streaming electron emitted in point with a coordinate r and with an initial phase φ.

Calculated spectrum of the back-streaming electrons and spectral distribution of power of the back-streaming electrons hitting the emitter are presented in Fig. 2.

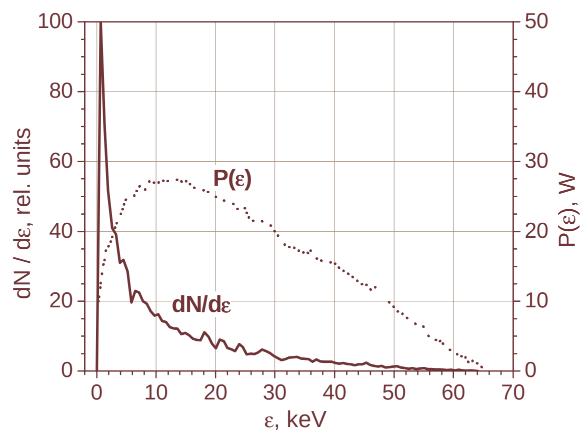

Fig. 2. Spectral distributions of the electrons (dN/dε) and the power (P(ε)) in the electron back-stream.

For estimation of the overheating of the emitting surface with the back-streaming electrons one can assume the average energy of the electrons approximately of 20 keV, Fig. 2. The range of the electrons with such energy in LaB_6 crystal is approximately of few μm. Calculation of the pulsed overheating of the emitting surface caused by back-streaming electrons was performed in a simplified 1-D model, assuming that the process is stationary with constant power of the electron back stream ($P_{bs0} = P_{bs}(T_0^0) = const$; T_0^0 is an initial emitter temperature) and using the exact solution of 1-D equation for the heat conduction along the emitter axis [3]. This model gives the following analytic expression for estimation of overheat of the emitting surface with the back-streaming electrons:

$$\Delta T^0(t_m) = \frac{P_{bs0}}{\pi \cdot r_C^2} \cdot \frac{1}{k_C} \cdot \sqrt{\frac{4\chi \cdot t_m}{\pi}}.$$

Here: k_C is thermal conductivity, χ is thermal diffusivity coefficient, and t_m is the pulse duration of the emission current in the microtron.

Results of calculations for the microtron operating condition and values of k_C and of χ for the considered temperature range [4] are presented in Tab. I. The last column shows calculated value of the increment of the emission current $\Delta I_C\left(\Delta T^0\right)$ caused by back-streaming electrons.

Table I: Results of calculations

Initial emitter temperature T_0^0	Initial emission current I_C	Back-stream power P_{bs0}	ΔT^0 (6μs)	Emission current increment $\Delta I_C\left(\Delta T^0\right)$
1873 ^{o}K	0.617 A	1.04 kW	48 ^{o}K	0.35 A
1900 ^{o}K	0.783 A	1.33 kW	61 ^{o}K	0.59 A
1923 ^{o}K	0.989 A	1.68 kW	78 ^{o}K	0.98 A

III. Choice of the microtron operating parameters

Operation in a neighborhood of main maximum of the microtron volt-ampere characteristic (on the left slope) provides maximal value of the capture coefficient and for given value of the accelerated current allows minimizing the emission current, i.e. the emitter temperature. This increases the life-time of the cathode assembly. However, operation close to the maximum of the volt-ampere characteristic increases risk of stripping of the acceleration and leads to break-downs in the accelerating cavity. Developed computer-controlled stabilizing system [5] using pulse-signal stabilization of the emission current allows operation of the microtron in such working point practically without risk of randomized stripping of the acceleration and break-downs in the accelerating cavity. The stabilizing system decreases pulse-to-pulse instability of the accelerated current to the value of ≈1% during long-time operation and improves stability in lasing power by operation of the terahertz FEL.

IV. Cathode assembly construction

The layout of the developed cathode assembly is shown in Fig. 3. The 2.5 mm-in diameter [100]-face LaB_6 single crystal tablet-shape emitter, 1, is fixed in the graphite holder, 2, with an outside diameter of 4 mm. The emitter thickness is 1.1 mm. The cathode sleeve, 3, is welded with a precisely fitted mount to the carrying base, 6, whose width and thickness are 7 mm and 0.3 mm respectively. The cylindrical filament, 4, is made from 0.5 mm in-diameter tungsten wire and consists of 8.5 turns with a 0.75-mm step. One lead of the filament is fixed in the cathode sleeve, 3, by the tight fit of the enlarged-diameter turn; the other lead is attached to the tantalum plate, 7, which is insulated from the base with ceramic insulators, 8. The cathode sleeve is surrounded with 8 heat shields, 5, providing considerable reduction of heat losses through the side walls of the heater chamber.

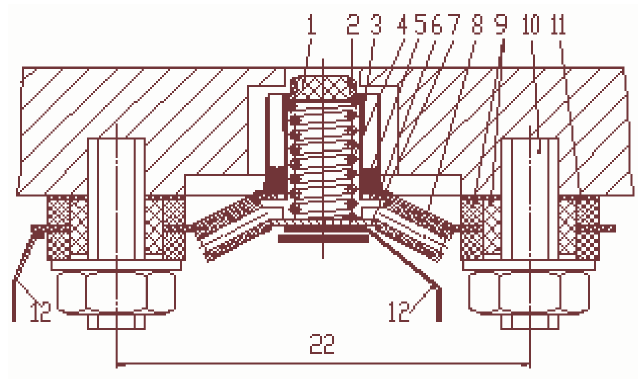

Fig. 3. Layout of the microtron cathode assembly.

The carrying base is insulated from the cover of the accelerating cavity with a set of ceramic tubes and spacers, 9, which are mounted on two titanium studs, 10, screwed into the cavity cover with the distance of 22 mm, so that the cathode assembly is disposed in the deepening of the cavity cover. The depth to which the cathode is embedded one can adjust with the spacers, 11. The tantalum strips, 12, were used to feed the current to the cathode heater; the strips are welded to the heater-fixing plate and the carrying base. Total height of the cathode assembly is 8.5 mm.

V. Experimental results

Operation of the terahertz FEL optimized for radiated macro-pulse power of 30-50 W in the range of 2.73-1.76 THz, requires the accelerated current of 43-46 mA during the macro-pulse at the 12-th orbit of the microtron [5]. Required average value of the emission current providing the accelerated current is of 1.05-1.08 A, Fig. 4. This value corresponds to initial emission current of ≈ 0.9A.

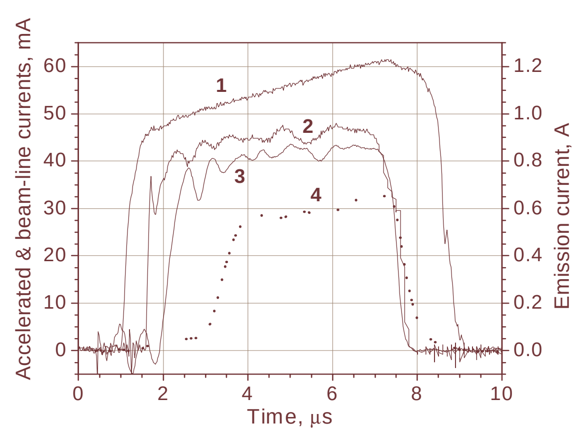

Fig. 4. Measured pulse shapes of the terahertz FEL: 1-the emission current, 2-the accelerated current at the 12-th orbit, 3-the beam-line current at the entrance of undulator, 4-the lasing macro-pulse power signal (in relative units).

Plotted in this figure the accelerated current was measured using the internal movable target inserted in 12-th orbit; the beam-line current was measured with a wide-band calibrated current transformer; the terahertz lasing signal was measured using a quasi-optical Schottky-barrier detector [6].

Operation of the FEL with lower frequency (in the range of 1.85-0.9 THz) is providing by extraction of the accelerated electrons with lover energy, varying the number of orbits in the microtron [7]. This is possible due to precisely-controlled motion of the accelerating cavity through a moving stage driven by a stepping motor. Measured efficiency of the beam extraction from 11-th - 9-th orbits is approximately of 95-97%. The microtron provides the beam current required for a lasing at the entrance of undulator of the terahertz FEL, Fig. 5, with approximately same value of the initial emission current.

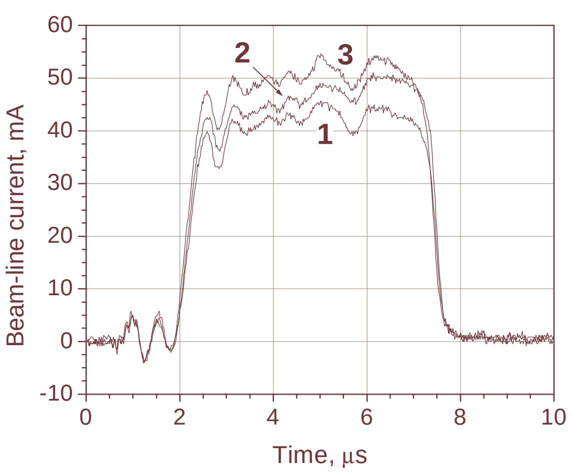

Fig. 5. Measured beam-line macro-pulse current extracted from 11-th, 10-th and 9-th orbits of the microtron, curves 1, 2, 3 respectively.

Presented in Fig. 4 plot shows increase of the emission current from approximately of 0.91 A to 1.23 A, i.e. by ≈0.32 A during of 6 μs. Approximately same is the emission current increment by operation with lower number of the orbits. Calculated value of the initial emission current is of ≈0.8÷1 A at the temperature of 1900÷1923 ^{o}K at the emitting surface, Tab. 1. This is in a good agreement with measured result. Calculated increment of the emission current for this temperature range is of ≈0.59÷0.98 A. The agreement one can consider as a satisfactory because of addition losses in the emitter overheat due to heat conductance of the emitter holder and some loss due to radiation. So, one can assume that the emitter operates with the average temperature of ≈1900÷1923 ^{o}K. Note that more exact calculation has to be based on a 2-D model of the heat conductance considering distribution of the heat along the emitting surface.

Measured brightness temperature of the emitter surface versus the heater power consumption [8] showed that the heater feeding power of ≈50 W is enough to provide the initial value of the macro-pulse emission current required for stable operation of the terahertz FEL.

The long-time stability of the described injection system was checked by generation of the terahertz FEL at various wavelengths and demonstrated good stability. Fig. 6 shows measured relative deviations in the lasing pulse energy at the frequency of 2.73 THz during long-time operation. The standard deviation of the lasing energy fluctuations is of 8.8%.

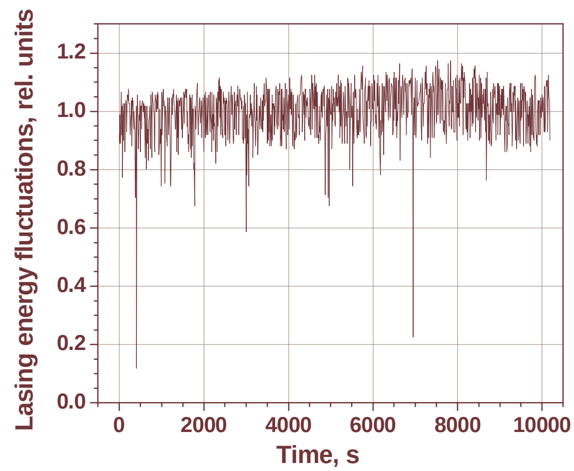

Fig. 6. Relative fluctuations of the lasing macro-pulse energy during long-time operation.

The life-time of the developed LaB_6 cathode assembly is determined by evaporation of the emitting surface. At the emitter temperature of 1900 ^{o}K the evaporation velocity is approximately of 10^{-4} mm/h. [9]. The allowable range of evaporation of the emitting tablet is ≈0.12 mm. That corresponds to the stable operation of the cathode assembly during the life-time of ≈1000 h. Reliable and stable operation of the terahertz FEL during more than 5 years confirms this value.

VI. Summary

Reliable injection system employing the thermionic cathode assembly based on the single-crystal LaB_6 emitter was developed for S-band microtron-terahertz FEL injector. The life-time of the assembly operating with ordinary regime of the terahertz FEL is ≈1000 h. The system provides good stability of the terahertz FEL. The standard deviation of the lasing macro-pulse energy is less than 9% during long-time operation.

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