Internal injection for microtron driving the terahertz FEL*

Grigory M. Kazakevich**, Viatcheslav M. Pavlov***, Gennady I. Kuznetsov

Budker Institute of Nuclear Physics RAS, Academician Lavrentyev 11, Novosibirsk, 630090, Russia

Young Uk Jeong, Seong Hee Park and Byung Cheol Lee

Korea Atomic Energy Research Institute, P. O. Box 105, Yusong, Taejon, 305-600, South Korea

A terahertz Free Electron Laser (FEL) driven by a high-current classical S-band 12-orbit microtron with an internal injection and magnetron-based RF-system has been developed and during few years operates for users. The laboratory-size, inexpensive facility, widely-tunable in the terahertz range, is attractive for application in research laboratories and universities. Stability and reliability in operation of such microtron-based FEL is determined generally by the microtron injection system. Operation of the injection system employing a thermionic cathode has been analyzed. The analysis was performed using 2-D tracking simulations in which we considered bombardment of the cathode emitting surface with the back-streaming electrons. The analysis showed that the bombardment causes pulse overheating of the emitting surface and as result increase of a beam loading of the accelerating cavity during the micro-pulse. The phenomenon affects the intrapulse stability of the accelerated current and the FEL operation. The analysis and the measurements showed how to optimize the microtron operation minimizing affects of the back-streaming electrons. The developed injection system based on LaB$_6$ thermionic cathode provides operation of the widely-tunable terahertz FEL in ordinary regime with radiated macro-pulse power of 40-50 W at the pulse duration of 2-4 µs. The standard deviation of the lasing macro-pulse energy is less than 10% for long-time operation. PACS codes: 41.60.Cr; 07.57.Hm; 29.20.-C

Introduction

The RF accelerator intended to drive the terahertz FEL has to provide a suitable bunch current with appropriate transverse parameters and bunch properties of the beam. The qualities are well matched in the classical high-current microtron with an internal injection. In this case the acceleration starts in a high-gradient electric field that allows getting small beam emittance [1]; the multi-turn motion of the electrons through the accelerating gap in the cavity provides good bunching of the beam [2]. Worth to note that such injection system is simple in manufacturing but the intrapulse variation of the beam loading caused by bombardment of the cathode with the back-streaming electrons is inherent to the system. The variation causes significant drop of the accelerated current during the macro-pulse longer than 2-3 µs. To keep few µs duration of the lasing macro-pulse in the FEL based on the magnetron-driven microtron we compensated increase of the accelerating cavity loading through incremental RF power feeding the cavity. This was done using incremental magnetron current during the macro-pulse. Concurrently, to avoid the frequency pushing in the magnetron, the auto generator was stabilized employing the frequency pulling through the backward wave reflected from the accelerating cavity, [3].

These methods allowed to obtain lasing with the microtron-based terahertz FEL, [4], employing simple and inexpensive both key systems: the magnetron-based RF system and the internal injection systems using the thermionic LaB$_6$ cathode. We analyzed how the back-streaming electrons affect the lasing in the microtron-based FEL. The analysis was performed for I-type acceleration, [5], basing on 2-D simulation of acceleration in the microtron and measured results. Minimization of affects of the back-streaming electrons and optimization of the microtron injection system parameters in accordance with the analysis allowed to reach required for users macro-pulse energy in the lasing and stability in operation of the FEL. The developed injection system provides long-time stable operation of the microtron-based terahertz FEL in wide wavelength range at radiated macro-pulse power of tens of W and r.m.s. deviation of the lasing macro-pulse energy less than 10%. Developed thermionic cathode has life-time approximately of 1000 h. at optimized for the FEL parameters of the microtron. The terahertz FEL driven by classical microtron demonstrates stability and reliability during more than six years of operation. Results of the simulations and measurements, design and description of the microtron long-life cathode and main concepts of the optimization are presented and discussed in the article.

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**Corresponding author. E-mail: gkazakevitch@yahoo.com Current affiliation: Fermi National Accelerator Laboratory P.O. Box 500, Batavia, IL, 60510, USA

***Current affiliation: University of Strathclyde, Dept. of Physics The John Anderson Building 107, Glasgow, G4 0NG, UK.
Analysis of the emission process in the microtron with internal injection

Operating parameters of the cathode with the LaB₆ emitter were analyzed for first type acceleration in a cylindrical cavity having radius of 40.8 mm and height of 17.8 mm. The cavity with operating frequency of 2.801 GHz is situated in the homogeneous microtron permanent magnetic field $B=0.10-0.11 \ T$. The cavity has two radial narrow slits in both cavity covers employed for input-output of the electrons. The emitter is located in a hole with a center coordinate of $R_e=30 \ mm$, the emitter deepening relatively the cavity cover surface is: $d_e=0.5 \ mm$, the hole radius is: $r_H=2 \ mm$.

The $E_{010}$ mode electric field with an initial phase $\varphi$ at the emitter surface one can express as:

$$E_{CS}(r,\varphi) \equiv E_0 \cdot J_0(k_0 \cdot R_e) \cdot \cos(\varphi) \cdot \frac{J_0(k_z \cdot r)}{\cosh(k_z \cdot d_e)}. \quad (1)$$

Here: $E_0$ is maximal field on the cavity axis, $k_0=2\pi/\lambda_0$, $k_z=\sqrt{k^2-k_0^2}$. Calculated value of the maximal field on the cavity axis of $E_0=35.53 \ MV/m$ corresponds to ordinary operating parameters of the microtron. Corresponding maximal value of the electric field in the center of the emitter surface is:

$$E_0 \cdot J_0(k_0 \cdot R_e) / \cosh(k_z \cdot d_e) = 10.35 \ MV/m.$$ 

Considering the Schottky effect one can express the current density of LaB₆ single crystal emitter depending on $r, \varphi$ as:

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

Here: $A=73 \ A/\text{grad}^2\cdot\text{cm}^2$ and $e\phi_c=2.66 \ eV$ are the Richardson constant and the work function for LaB₆, respectively, $k$ is the Boltzmann constant and $T$ is the emitter temperature in Kelvin deg. Corresponding value of the maximal current density at the emitter temperature of 1900 K is: $i_{c_{\max}} = i_c(1900K,0,0) \approx 49.5 \ A/cm^2$.

Then the initial value of the emission current at the emitter radius of $R_e$ should be equal to:

$$I_c(T) \approx \frac{1}{2\pi} \int_0^{2\pi} \left[2\pi \cdot \int_0^{\varphi_c} i_c(T,r,\varphi) \cdot r \ dr \right] d\varphi. \quad (3)$$

To calculate contribution of the back-streaming electrons in the emitter heating we performed tracking of the electrons inside the accelerating cavity. The tracking was done using 2-D Lorentz equation in the microtron median plane considering $E_{010}$ mode electric and magnetic components of the cavity accelerating field and the permanent magnetic field for several values of cathode diameter and the microtron parameter: $\varepsilon_0 = E_0 / cB$, where $c$ is light velocity.

The result of the tracking of the first orbit and a schematic layout of the accelerating cavity in the median plane of the microtron are 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. With numbers 1 and 2 are marked the narrow slits directed along the x axis and used for input-output of the electrons. (b) 2-D tracking of the back-streaming electrons hitting the emitter.

The average power of the electrons heating the emitter per the RF period was calculated as:

$$P_{h\epsilon}(T) = \frac{1}{2\pi} \int_0^{\varphi_c} \left[2\pi \cdot \int_0^{\varphi_c} i_c(T,r,\varphi) \cdot \varepsilon(r,\varphi) \cdot r \ dr \right] d\varphi, \quad (4)$$

where: $\varepsilon(r,\varphi)$ is the energy of back-streaming electron emitted in point with a coordinate $r$ and with an initial phase $\varphi$, $\varphi_c$ - all initial phases of the electron back-stream. The integral is taking over all phases of the back-streaming electrons; there are considered only the electrons hitting the cathode emitting surface.

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/d$\varepsilon$) and the power (dP/d$\varepsilon$) in the electron back-stream. 

To estimate the overheating of the emitting surface with the back-streaming electrons one can assume that the
average energy of the hitting electrons is approximately of 8.9 keV, Fig. 2. The tracks of the electrons with such energy in LaB$_6$ crystal are less than 1 µm. Calculation of the overheating of the emitting surface caused by back-streaming electrons during the macro-pulse was performed in a simplified 1-D model, assuming that the process is stationary with constant power of the electron back stream ($P_0 = P_{bs} (T_0^*) = \text{const}$; $T_0^*$ is an initial emitter temperature) and using exact solution of 1-D equation for the heat conduction along the emitter axis [6]. The model gives the following analytic expression to estimate the overheating of the emitting surface with the electron back-stream during time $t$:

$$\Delta T_0^*(t) = \frac{P_{bs0}}{\pi \cdot r_c^2} \cdot \frac{1}{k_c} \cdot \sqrt{\frac{4 \cdot \chi \cdot t}{\pi}}.$$  

(5)

Here: $k_c$ is thermal conductivity, and $\chi$ is thermal diffusivity coefficient.

Note that used model does not consider cooling of the emitting surface caused by the heat conduction along the emitter axis and then through the emitter holder. Some part of the heat is loosed through radiation. The employed model non-considering the cooling overestimates the emitter overheating caused by the electron back-stream and the overheating effects as well. Moreover the model gives averaged overheated and does not consider space distribution of the temperature along the emitter, while the small part of the emitter area located close to the microtron median plane has higher temperature. This effect also contributes in overestimation of the emitter overheating.

Results of calculation of the cathode overheats vs. the cathode diameter for the microtron operating condition at the initial emitter temperature of 1900 K for several values of the $\varepsilon_0$ and duration of the emission current of $t = t_{bs} = 6$ µs are presented in Fig 3. The values of $k_c$ and of $\chi$ for LaB$_6$ at the high temperature were taken from [7].

Calculated dependence of the emission current $I_F(t_{bs})$ on the cathode diameter at the final temperature increased because of the overheating during the 6 µs- electron back-stream macro-pulse and at the initial emitter temperature of 1900 K is plotted in Fig. 4. Calculated plot of the initial emission current $I_0$ at the temperature of 1900 K obtained using expression (3) is presented in this figure as well.

![Graph](image)

Fig. 4. Initial and final values of the emission current vs. cathode diameter at the macro-pulse duration of 6 µs, the initial emitter temperature of 1900 K and various values of $\varepsilon_0$.

**Frequency deviations in a high-current microtron with internal injection.**

The considered increase of the emission current during the macro-pulse causes variation of the beam loading of the accelerating cavity and concurrently leads to the intrapulse frequency deviation in the cavity, [8].

The maximal estimate of the frequency deviation in the accelerating cavity caused by variation of the beam loading was obtained using following expression:

$$\Delta F(t_{bs}) \approx \frac{1}{2 \pi} \cdot \eta_{e0} \cdot \omega_{oc} \cdot \tan \varphi_w \cdot \left( \frac{I_F(t_{bs})}{I_0} - 1 \right),$$  

(6)

where: $Q_{oc} = 9800$ is the accelerating cavity wall quality factor (measured value), $\omega_{oc}$ is the circular eigen frequency of the cavity, and $\eta_{e0}$ is the initial beam loading coefficient. The value of $\eta_e$ is determined as a ratio of the beam power $P_e$ to the cavity wall loss power $P_{cw}$:

$$\eta_e = \frac{P_e}{P_{cw}} = \frac{I \cdot V_c \cdot \cos(\varphi_w)}{\left[ \frac{V_c^2}{R_{sh}} \right]} \cdot \frac{R_{sh} \cdot I}{W \cdot \cos(\varphi_w)}.$$  

Here: $R_{sh} = 1.08$ MOhm is the effective shunt impedance of the accelerating cavity, $I$ - is the averaged emission macro-pulse current, $W$ and $\varphi_w$ are dimensionless first harmonic current amplitude and the harmonic phase, respectively, depending on the cavity voltage amplitude, $V_c$. ($V_c$ is equal to 0.586 MV for $\varepsilon_0 = 1.08$). The value of
\( V_c \) is a constant (in steady-state); the values of \( W \) and \( \varphi_w \) are constants as well.

Performing the 2-D tracking of the electrons for all 12 orbits in the microtron we calculated velocities of the electrons as well. That allowed us to determine the amplitude and phase of the fist harmonic cavity loading current. Note that the used method allows considering the cavity loading through all accelerated particles, synchronous and non-synchronous as well. We determined the \( W \) and \( \varphi_w \) for various values of \( \varepsilon_0 \) parameter. For optimal value of \( \varepsilon_0 = 1.08 \), \( W = 2.607 \), \( \varphi_w = 20.9^\circ \), and for \( I = 1.0 \, \text{A} \) a calculated value of the beam loading coefficient is: \( \eta_e \approx 4.5 \).

Strictly speaking used 2-D tracking without consideration of the vertical motion of the electrons gives overestimation of the contribution of the synchronous electrons in the beam loading. Because of that the calculated \( \eta_e \) value is higher by 10-20% than one obtains from the measurements. Fig. 5 shows calculated maximal estimate for the frequency deviation caused by overheating of the emitting surface with the electron back-stream vs. the cathode diameter at the initial emitter temperature of 1900 K and \( \varepsilon_0 = 1.08 \).

![Graph showing the accelerating cavity frequency deviation caused by overheating of the electron emitter with the electron backstream vs. cathode diameters at the initial emitter temperature of 1900 K and various values of \( \varepsilon_0 \).](image)

Presented plot shows stronger than linear dependence of the frequency deviations in accelerating cavity on the emitter area. The described deviation of the frequency in the accelerating cavity itself does not affect the microtron operation, but, because of the feedback stabilizing the magnetron through the wave reflected from the accelerating cavity, it causes the intrapulse deviation of the magnetron frequency, i.e. makes worse stability of the bunch repetition rate during the macro-pulse. Additional contribution in the bunch repetition rate instability causes artificial increase of the magnetron current during the macro-pulse (to keep constant accelerated current at the incremental beam loading of the accelerating cavity) at a finite value of the frequency stabilization coefficient. Resulting bunch repetition rate deviation during the macro-pulse in fact leads to intrapulse detuning of the FEL optical resonator.

The developed terahertz microtron-based FEL employs a confocal free-space mode in horizontal plane and waveguide mode in vertical plane optical resonator [4]. The resonator was formed with two cylindrical mirrors mounted on the ends of a rectangular waveguide installed in the 2-meter long undulator; one of the mirrors has a coupling hole to extract the FEL radiation. Tuning of the FEL optical resonator is provided by precise motion of the outcoupling mirror through a stepping motor.

The length \( L \) between the mirrors was chosen using the expression:

\[
L = 52 \cdot \frac{\lambda_b}{2} = 52 \cdot \frac{c}{2 \cdot F_b},
\]

were: \( \lambda_b \) is the wavelength of the accelerating voltage, \( F_b \) is the bunch repetition rate of the accelerated current. For \( F_b \approx 2.801 \, \text{GHz} \), \( \lambda_b = c / F_b \approx 10.7 \, \text{cm} \). From (7) follows: \( |\Delta F| = 26 \lambda_b \cdot \frac{\Delta F_b}{F_b} \). The expression shows that increase of the bunch repetition rate deviations is an equivalent to increase detuning of the FEL optical resonator with given length \( L \); that leads to drop of the power radiated by the FEL. This points at necessity to minimize the deviations of the bunch repetition rate in the microtron driving the terahertz FEL. This problem was solved through optimization of detuning in the system magnetron-accelerating cavity and minimization of the increment of the emission current caused by the pulse overheating. For the last the microtron was tuned to provide maximal efficiency of acceleration that minimized the emission current; moreover we employed 2.5 mm-in diameter emitter, though the emitter with larger diameter provides higher accelerated current at the same cathode life time. The developed cathode assembly based on LaB\(_6\) single crystal emitter is described in following chapter.

**Cathode assembly construction**

Design of the cathode assembly is presented in Fig. 6.

![Design of the cathode assembly](image)
The 2.5 mm-in diameter [100]-face LaB₆ 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 graphite holder prevents diffusion of boron inside tantalum components of the assembly; that significantly increases the assembly life time.

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 sidewalls of the heater chamber. This allows to decrease the filament temperature and noticeably increases life time of the filament.

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 of 8.5 mm.

Optimization of the microtron for terahertz FEL operation

Optimization of the microtron for the FEL operation includes tuning the magnetron power to work in the neighborhood of the general maximum of the microtron Volt-Ampere characteristic. At that the modulator charging line is tuned to provide flat top of the accelerated current during the macro-pulse compensating the incremental beam loading. The optimization provides highest efficiency of acceleration and for given accelerated current allows minimizing the emission current. However random decrease of the emission current and/or the accelerated current in this case can initiate stripping of acceleration and discharges in the accelerating cavity. To avoid this, we developed computer-controlled pulse stabilization of the emission current, [3], allowing operation on the left slope in the neighborhood of general maximum of the microtron Volt-Ampere characteristic practically without risk of discharges, in fact with minimized emission current. Note that minimization of the emission current for the internal injection provides minimization of the emitter temperature that prolongs the cathode life time.

Moreover, optimizing the microtron operation we tune the magnetron frequency to work with minimal acceptable detuning for the system magnetron-accelerating cavity keeping operation on the left slope of the frequency characteristic of the accelerating cavity.

Experimental results

Measurements of the microtron and the terahertz FEL parameters were done at the LaB₆ emitter temperature of 1900±10 K. The value was determined by measurements of the emitter brightness temperature on the cathode bench at the same filament power consumption.

Measured pulse shapes of the microtron emission current, accelerated current, beam current at the entrance of the FEL undulator and the lasing power are shown in Fig. 7. The shape of the incremental magnetron pulse current is shown in this figure as well. The measurements were done in the optimized regime of the microtron; electron beam, transported to the FEL undulator was extracted from 12-th orbit.

![Fig. 7. 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 the FEL undulator, 4-the lasing macro-pulse power signal (in relative units), 5-the magnetron pulse current.](image-url)

Plotted in Fig. 7 time-dependent value of the emission current was obtained through measurements of the voltage on a calibrated non-inductive load. The accelerated current was measured using the internal movable target inserted on 12-th orbit; the beam-line current was measured with a calibrated wide-band current transformer; the terahertz lasing signal at the wavelength of 113 µm was measured using a quasi-optical Schottky-barrier detector [9], and the magnetron pulse current was measured using calibrated wide-band current transformer.

Note that the back-streaming electrons hitting the emitting surface can not directly contribute to the measured emission current. As follows from tracking, the non-synchronous electrons are emitted in the phase angle of ≈60°. However the electrons hitting the emitting surface cause a secondary emission, which contributes to the measured current. For La atoms the averaged secondary emission coefficient is ~ 1 in relatively wide range of the energy of back-streaming electrons [10]. Due to that the measurement of the emission current through measurement of the voltage on the non-inductive load provides quite correct value for this parameter.

Presented in Fig. 7 plots show that the incremental magnetron current allows keeping flat top of the accelerated current and the current at the entrance of FEL
undulator. This provides the lasing macro-pulse duration of 3-4 µs in the range of 2.73-1.76 THz. Measured with calibrated pyro-electric detectors radiated macro-pulse energy of lasing in the range of 0.12-0.2 mJ gives value of the lasing macro-pulse power of 40-50 W in the terahertz range.

Measured value of the initial emission current, Fig. 7, curve 1, of ≈ 0.91 A with good accuracy coincides with data calculated using (3) at initial emitting surface temperature of 1900 K and the emitter diameter of 2.5 mm, Fig. 4. The agreement demonstrates also adequate correction of the measured emission current with the secondary emission caused by the back-streaming electrons. Measured value of the averaged emission current at the optimized regime is ≈ 1.07A.

Calculated value of the emission current at the ending of the 6 µs macro-pulse for the above mentioned initial emitter temperature is ≈ 1.8 A, Fig. 4. Presented in Fig. 7 plot, curve 1, shows increase of the measured emission current approximately up to 1.23 A during of 6 µs. Note: from expression (2) for considered temperature range of the LaB₆ emitter follows: \( \frac{\Delta i_e(T)}{i_e(T)} \approx 20 \frac{\Delta T}{T} \); i.e. variation of the emitter temperature by few percents causes significant relative variation of the emitted current. Because of that the agreement of the calculated and measured results one can assume as a satisfactory for simplified model of calculation of the emitter overheating without consideration of heat losses and distribution of the temperature on the emitting area as was noted above.

Operation of the FEL with lower frequency (in the range of 1.85-0.9 THz) is provided by extraction of the accelerated electrons with lower energy, varying the number of orbits in the microtron [11]. 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 with the lower frequency at the entrance of the FEL undulator with approximately same value of the emission current as plotted in Fig. 7. Measured radiated macro-pulse power in the range of 1.85-1.5 THz was in the range of 40-50 W at operation in the optimized regime. The measurements were done using calibrated pyro-electric detector measuring the lasing macro-pulse energy and the wide-band Schottky barrier detector measuring the lasing macro-pulse shape and the pulse duration.

The intrapulse bunch repetition rate deviations in the range of ≈ 0.25 MHz at the optimized regime were measured transporting the electron beam through low Q-factor measuring cavity employing the heterodyne method, [12]. Increase of the bunch repetition rate deviations decreases duration of saturation in the lasing macro-pulse because of the FEL optical resonator detuning and as result decreases the macro-pulse energy of lasing. The detuning characteristics were measured at various wavelength of the FEL generation in optimized regime of the microtron providing radiated lasing macro-pulse energy of ≈ 0.2 mJ at maximum of the detuning curve. During the measurements the FEL radiation was transported to a user bench as a quasi-parallel beam; the lasing macro-pulse energy was measured by calibrated pyro-electric detector. Detuning of the FEL resonator was performed by precise motion of the outcoupling mirror through stepping motor.

Typical measured detuning characteristic of the FEL optical resonator is shown in Fig. 8.

Fig. 8. Detuning curve of the FEL optical resonator measured at the wavelengths of 113 µm (2.655 THz).

From this plot follows that detuning by 0.2-0.25 mm, corresponding to variation in bunch repetition rate by 0.2-0.25 MHz, expression (7), decreases the FEL macro-pulse energy at most by few tens of percents. This allows to obtain the abovementioned value of the lasing energy, radiated in the far infrared range at the power of tens of W, and quite stable operation of the terahertz FEL.

Direct measurements of the instability in lasing energy during long-time operation of the FEL facility were performed at various wavelengths of the terahertz FEL. The measurements were done employing optimized regime of the microtron and demonstrated relatively low instability.

Fig. 10 shows measured deviations in the lasing macro-pulse energy at the wavelength of 110 µm during approximately 3 h. The standard deviation of the lasing energy during this measurement is of 8.8%.

Fig. 9. Fluctuations of the lasing macro-pulse energy during long-time operation.
Very slow deviations of the lasing energy shown in this figure are correlated with deviations of the temperature of water, cooling the accelerating cavity and the microtron magnet.

Operation of the microtron-driven terahertz FEL during more than 6 years demonstrates stability and reliability of the developed facility employing simple in manufacturing system of the internal injection. Developed cathode assemblage based on the LaB₆ single crystal emitter at the temperature of 1900 K has the life time approximately of 1000 h. providing radiated macro-pulse power of 40-50 W in wide range of the FEL operation. The cathode life time is determined by allowable decrease of thickness of the LaB₆ emitter because of the tablet evaporation.

Summary

Process of the internal injection in the classical microtron driving the terahertz FEL has been analyzed basing on 2-D tracking of the acceleration. The analysis considering back-streaming electrons, causing pulse overheat of the emitter, explains affects of the electron back stream in operation of the microtron and the FEL. Results of analysis are in agreement with experimental data obtained at the FEL facility. Concepts allowing to minimize affects of the back-streaming electrons and according to the analysis results were realized in the terahertz FEL, which was developed as a laboratory-size, inexpensive, stable and reliable source of the coherent far-infrared radiation, tunable in wide range and providing the lasing macro-pulse power of tens of W.

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