OPTIMIZATION OF THE INJECTION SYSTEM FOR MICROTRON-BASED TERAHERTZ FEL*

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Abstract

A compact widely-tunable microtron-based terahertz Free Electron Laser (FEL) has been developed and during last few years operates for users. The laboratory-size, stable facility at the macro-pulse power of tens of W is attractive for application in research laboratories and universities. Reliability in operation and stability of such microtron-based FEL is determined generally by the microtron injection system. Main parameters of the injection system were studied on the base of 2-D tracking considering the frequency drift of the accelerating cavity as a result of variation of the beam loading caused by cathode overheating due to back bombardment with non-resonance electrons. The obtained results show that the injection system based on a thermionic single crystal LaB_6 2.5 mm-in diameter emitter provides operation of the microtron-based FEL with standard deviation of the macro-pulse lasing power less than 10% during long-time work. Experimental check of the FEL during more than five years confirmed stable and reliable operation of the microtron-based FEL with the macro-pulse power of tens of W in the terahertz range.

INTRODUCTION

The injection system of the accelerator intended to drive the terahertz FEL has to provide a suitable bunch current with appropriate transverse parameters of the beam. The qualities are well matched in the system using 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; the multi-turn motion of the electrons through the accelerating gap in the cavity provides good bunching of the beam. Worth to note that such system is simple and inexpensive in manufacturing but some drift of the beam loading during the macro-pulse is inherent to the system. The drift makes worse the intrapulse bunch repetition rate stability and the FEL operation as well because of the effective fluctuation of the FEL optical resonator length, detuning the resonator. The primordial source of the drift is a pulse overheating of the cathode emitting surface caused by back-streaming electrons.

To minimize the effect we optimized design and parameters of the microtron injecting system to operate with minimal acceptable cathode diameter. In this case the simplest and cheapest RF system employing the magnetron generator stabilized through the backward wave reflected from the accelerating cavity provides stable operation of the widely-tunable terahertz FEL based on the classical S-band microtron, [1]. For the optimization we calculated the accelerating cavity frequency drift caused by intrapulse variation of the beam loading as a function of the cathode diameter. The calculation was done for I-type injection, [2], basing on 2-D tracking in the microtron median plane. Comparison of the calculation with measured detuning curves of the FEL optical resonator showed that a single crystal LaB_6 emitter with diameter of 2.5 mm at a minimal acceptable detuning of the magnetron and the accelerating cavity can provide operation of the widely-tunable terahertz FEL with radiated macro-pulse power tens of W at a suitable stability and life time. Operation of the terahertz FEL during more than five years demonstrates that the optimized microtron injection system employing the thermionic cathode operating at the temperature of 1900^0 K at the strength of the electric field of > 10 MV/m provides reliable operation of the terahertz FEL. Results of simulations and measurements are presented and discussed in the article.

ANALYSIS OF THE EMISSION CURRENT IN THE MICROTRON WITH INTERNAL INJECTION

At operation of the high-current microtron with the internal injection the main part of electrons is emitted in non-resonance phases. The electrons could not reach the extracting channel, but they are participating in the process of acceleration and mainly hitting the cavity walls; a number of them hit the emitting surface making the back bombardment of the cathode. As was shown in [3], the back bombardment results in the pulse overheating of the emitting surface. This causes an additional emission including emission in resonance phases, thus the electron beam loading the cavity becomes increasing in time domain due to enhancement of number of synchronous electrons and non- synchronous as well.

To consider the effect of the back-streaming electrons hitting the cathode and increasing because of that the loading of the accelerating cavity we calculated the cathode overheats using 1-D analytic expression of the heat conduction along the emitter axis, [4]:

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

where: k_C is thermal conductivity, χ is thermal diffusivity coefficient, r_C is the cathode radius, and t_m is the pulse duration of the emission current in the microtron. The average power of the electrons heating the emitter per the RF period, $P_{bs}(T)$, was calculated using expression:

$$P_{bs}(T) = \frac{1}{2\pi} \cdot \int\limits_{\varphi_{bs}} \left[2\pi \cdot \int\limits_0^{r_C} i_C(T, r, \varphi) \cdot \varepsilon(r, \varphi) \cdot r\, dr \right] d\varphi, \qquad (2)$$

where: $\varepsilon(r,\varphi)$ is the energy of back-streaming electron emitted in point with a coordinate r and with an initial phase φ, the average value of ε is approximately of 8.9 keV; $i_C(T,r,\varphi)$ is the emission current density of LaB_6 single crystal emitter depending on emitting radius r and initial phase φ; the term was calculated considering Schottky effect through the expression:

$$i_C(T, r, \varphi) = AT^2 \cdot \exp\left[\frac{-e\phi_C + 3.79 \cdot 10^{-4} \cdot \sqrt{E_{CS}(r,\varphi) \cdot 10^4}}{k \cdot T} \right], \qquad (3)$$

where $A = 73$ 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; $E_{CS}(r,\varphi)$ is the electric field strength at the emitting surface with an initial phase φ. For cylindrical accelerating cavity employed in the microtron the E_{010} mode electric field strength was calculated for the emitting surface deepened relatively the cavity cover surface by d_C = 0.5 mm and emitter located in the center of the cathode hole, made in the cavity cover. The hole radius r_H is 2 mm; coordinate of the emitter center R_C is 30 mm. The $E_{CS}(r,\varphi)$ values were calculated using the expression:

$$E_{CS}(r,\varphi) = E_0 \cdot J_0(k_0 \cdot R_C) \cdot \cos(\varphi) \cdot \frac{J_0(k_r \cdot r)}{\mathrm{ch}(k_z \cdot d_C)}. \qquad (4)$$

Here: $E_0 \approx$ 35.53 MV/m is maximal field on the cavity axis corresponding to the microtron optimal regime, $k_0 = 2\pi/\lambda_0$, $k_r = \chi_{01}/r_H$, J_0 is the first kind Bessel function, $\chi_{01} = 2.405$ is the first square of Bessel function and $k_Z = \sqrt{k_r^2 - k_0^2}$.

Calculated maximal value of the current density at the emitter temperature of 1900^0 K is: $i_{C\max} = i_C(1900^0\ \mathrm{K}, 0, 0) \approx$ 49.5 A / cm^2. At this temperature the developed thermionic cathode with a single-crystal LaB_6 emitter, [3], has a life time approximately of 1000 h. The initial value of the emission cathode current was calculated using following expression, [3], for several values of the cathode diameter:

$$I_C(T) = \frac{1}{2\pi} \cdot \int\limits_0^{2\pi} \left[2\pi \cdot \int\limits_0^{r_C} i_C(T, r, \varphi) \cdot r\, dr \right] d\varphi. \qquad (5)$$

To calculate the loading current of the accelerating cavity we performed tracking of the electrons in the microtron using 2-D Lorentz equation in the median plane. The E_{010} mode electric and magnetic components of the cavity accelerating field and the permanent microtron magnetic field were considered. The electrons hitting the cavity walls (inside or outside the cavity) were non-participating in the tracking. The 2-D Lorentz equations were integrated up to last (12-th) orbit. The tracking in the microtron was done for several values of cathode diameter and the microtron parameter $Eps = E_0 / cB$, where: B - is the value of the microtron permanent magnetic field (for our microtron the optimal value of $B =$ 0.1065 T).

Results of calculation of the cathode overheats vs. the cathode diameter for the microtron operating condition at the initial emitter temperature of 1900^0 K for several values of *Eps* parameter and the emission macro-pulse current having duration of 6 μs are presented in Fig 1. The values of k_C and of χ for LaB_6 at the high temperature were taken from [5].

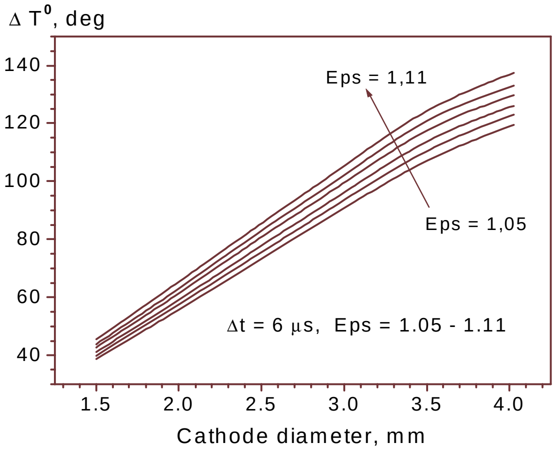

Fig. 1. Cathode overheats caused by back-streaming electrons during 6 μs macro-pulse vs. cathode diameter at the initial temperature of 1900^0 K. The arrow shows variation of the parameter Eps.

Note that we did not consider the heat losses caused by thermo-conductivity of the emitter holder and radiation of heat from the emitter. Because of that the $\Delta T°$ values and the overheating effects are overestimated.

Calculated values of the initial emission current at the initial temperature of 1900^0 K vs. the cathode diameter are plotted in Fig. 2.

Calculated values of the final emission current increased because of the overheating through the electron back-stream during the 6 μs- macro-pulse are plotted in this figure as well.

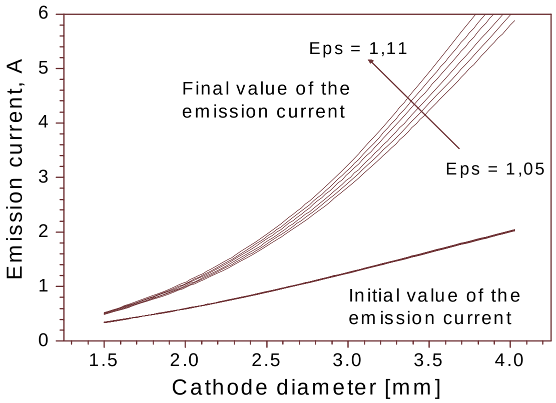

Fig. 2. Initial and final values of the emission current vs. cathode diameter at the initial emitter temperature of 1900^0 K and the macro-pulse duration of 6 μs. The arrow shows variation of the parameter *Eps*.

ESTIMATIONS OF THE FREQUENCY DRIFT IN A HIGH-CURRENT MICROTRON WITH INTERNAL INJECTION

Obtained data allow calculating the intrapulse variation of the accelerating cavity beam loading; that results in frequency drift of the cavity. Performing 2-D tracking of the electrons 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.

The highest possible frequency drift of the accelerating cavity caused by variation of the beam loading was calculated using following expression, [6]:

$$\Delta F \approx \frac{1}{2\pi}\cdot\frac{\eta_{e0}\cdot\omega_{0C}}{2Q_{0C}}\cdot\tan\varphi_W\cdot\left(1-\frac{I_F}{I_0}\right), \qquad (6)$$

where: I_0 - initial emission current at the temperature of 1900^0 K, I_F - final value of the emission current increased because of additional heating of emitting surface through back-streaming electrons during 6 μs macro-pulse, Q_{0C} = 9800 is the accelerating cavity wall quality factor (measured value), ω_{0C} is the circular eigen frequency of the cavity, η_{e0} is the initial beam loading coefficient, and φ_W is the phase of the cavity loading current.

The value of η_e is determined as a ratio of the beam power P_e and the cavity wall loss power P_C:

$$\eta_e=\frac{P_e}{P_C}=\frac{\left[I\cdot V_C\cdot W\cdot\cos(\varphi_W)\right]}{\left[\dfrac{V_C^2}{R_{sh}}\right]}=\frac{R_{sh}\cdot I}{V_C}\cdot W\cdot\cos(\varphi_W)\cdot \qquad (7)$$

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 φ_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 $Eps = 1.08$). The value of V_C is a constant (in steady-state); the values of W and φ_W are constants as well.

Note that using 2-D tracking without consideration of the vertical motion of the electrons causes overestimation of the contribution of the synchronous electrons in the beam loading; for the contribution of the non-synchronous electrons the 2-D tracking gives some underestimation.

From the tracking we determined the values of W and φ_W for various values of Eps parameter. For optimal value of Eps =1.08, W =2.607, φ_W =20.9º, and for I ≈1.07 A the calculated beam loading coefficient η_e ≈ 4.8. The value is higher by 10-20% than obtained from the measurements because of overestimation of the accelerated current as was noted above. Fig. 3 shows calculated maximal estimation for the frequency drift caused by overheating of the emitting surface with the electron back-stream vs. the cathode diameter.

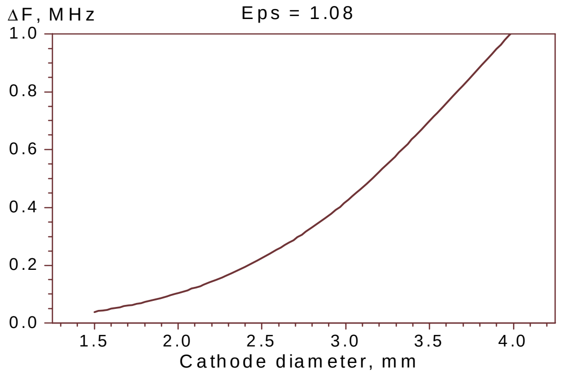

Fig. 3. The cavity frequency drift caused by overheating of the electron emitter with the electron back stream vs. cathode diameters at the initial emitter temperature of 1900^0 K and the value of *Eps* parameter of 1.08.

EFFECT OF THE FREQUENCY DRIFT ON THE TERAHERTZ FEL OPERATION

The described drift of the frequency of the accelerating cavity makes worse stability of the bunch repetition rate because of the stabilizing feedback through reflected wave coming to magnetron. Additional contribution in the bunch repetition rate instability causes increase of the magnetron current during the macro-pulse at a finite value of the frequency stabilization coefficient. The intrapulse increase of the magnetron current and the magnetron power, respectively, is used to keep constant accelerating voltage and accelerated current at increase of the cavity loading, [1]. Both contributions result in the bunch repetition rate deviation during the macro-pulse; that effectively leads to intrapulse detuning of the FEL optical resonator.

Our terahertz FEL optical resonator, confocal free-space mode in horizontal plane and waveguide mode in vertical plane, was formed with two cylindrical mirrors mounted on the ends of a rectangular waveguide; one of the mirrors has a coupling hole to extract the FEL radiation.

The distance D between the mirrors was chosen using the expression:

$$D = 52 \cdot \frac{\lambda_b}{2} = 52 \cdot \frac{c}{2 \cdot F_b}, \qquad (8)$$

were: λ_b is the wavelength of the accelerating voltage, c is light velocity, F_b is the bunch repetition rate equal to the accelerating cavity frequency. For $F_b \approx 2.801$ GHz, $\lambda_b = \frac{c}{F_b} \approx 10.703$ cm. From expression (8) follows: $|\Delta D| = 26\lambda_b \cdot \frac{\Delta F_b}{F_b}$. I.e. for the optical resonator variation of the bunch repetition rate by 1 MHz approximately corresponds (in a signal level) to the detuning by 1 mm. Measured FEL optical resonator detuning curve at the lasing wavelengths of 113 μm is shown in Fig. 4.

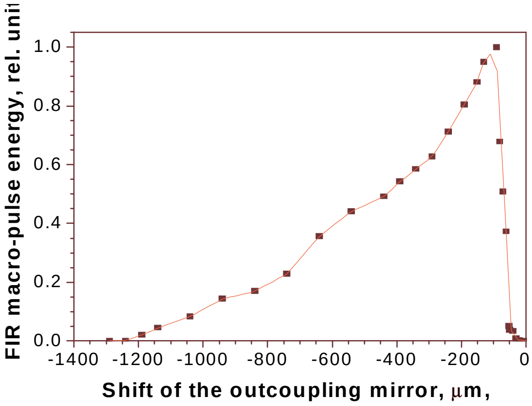

Fig. 4. Detuning curve of the FEL optical resonator measured at the wavelengths of 113 μm.

The measurements were done employing developed cathode assembly based on 2.5 mm-in diameter single crystal, face (100), LaB_6 emitter, operating at the initial temperature of ≈ 1900^0 K. The microtron operating parameters were chosen to provide the intrapulse bunch repetition rate deviations ≤ 0.25 MHz; that was measured using heterodyne method, [7]. At the measurements the microtron provided the beam current of 40 mA at the undulator entrance. The detuning of the FEL optical resonator was done by precise motion of the outcoupling mirror through a stepping motor.

The Fig. 4 curve shows that detuning by 0.2-0.25 mm, corresponding to variation in bunch repetition rate by 0.2-0.25 MHz, decreases the FEL macro-pulse energy by few tens of percents. The value can be used as an upper limit of the intrapulse bunch repetition rate deviations for the microtron intended driving the terahertz FEL. Considering curve plotted in Fig. 3, this points to a necessity in limitation of the emitter size though the emitter with larger diameter provides higher accelerated current at the same life time of the cathode.

Optimal diameter of 2.5 mm of the single crystal LaB_6 emitter for the microtron-terahertz FEL injector was chosen as a compromise considering requirements of reliable operation of the microtron and stable operation of the terahertz FEL. With the emitter at the microtron regime optimized for long-life operation of the cathode we obtained radiated macro-pulse lasing power of 40-50 W in the wavelength range of 100-200 μm. 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 width.

The thermionic cathodes with such emitters at optimized regime of the microtron have life time approximately of 1000 h, providing operation of the widely-tunable terahertz FEL with standard deviation of the lasing macro-pulse energy less than 10% during long-time work, [3].

SUMMARY

Effect of the back-streaming electrons bombarding the emitting surface of the thermionic cathode in a classical microtron with the internal injection on the lasing of the microtron-based FEL was analyzed. The results allow choosing the optimal size of the microtron thermionic cathode to provide stable and reliable operation of the microtron-based widely-tunable terahertz FEL with the macro-pulse lasing power few tens of W.

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