First Lasing of Volume FEL (VFEL) at Wavelength Range $\lambda \sim 4 - 6$ mm ⋆

V. Baryshevsky, K. Batrakov, A. Gurinovich, I. Ilienko,
A. Lobko,V.Moroz, P.Sofronov, V. Stolyarsky

22050, Bobruyskaya 11, Minsk, Belarus, Research Institute of Nucler Problem, Belorussian State University

Abstract

First lasing of volume free electron laser (VFEL) is described. The generating system consists of two metal diffraction grating with different spatial periods. The first grating creates the conditions for Smith Purcell emission mechanism. The second grating provides the distributed feedback for emitted wave. The length of diffraction grating is 10 cm. Electron beam pulse with a time duration $\tau \sim 10$ ms has a sinusoidal form with the amplitude varied from 1 to 10 kV. The measured microwave power reached the value of about 3-4 W in mm wavelength range. The generation stops at threshold current value. When the current tends to the threshold value, the region of generation tends to a narrow band near to 5 kV. At higher current values the radiation appears in electron energy range 5 - 7.5 KeV.

Key words: Volume Free Electron Laser (VFEL), Volume Distributed Feedback (VDFB), diffraction grating, Smith-Purcell, electron beam instability
PACS: 41.60.C, 41.75.F, H, 42.79.D

1 Introduction

The most essential feature of FEL and other types of generators is a feedback, which is formed by a system of mirrors, or distributed feedback based on diffraction in spatially periodic medium, when wave vectors of transmitted and reflected waves are colinear. The distinction of volume FEL (VFEL) is non-one-dimensional multi-wave volume distributed feedback (VDFB). VDFB performs two basic functions simultaneously:

⋆ This work is carried out with financial support of private joint-stock company BelTechExport, Belarus

1) it provides more effective interaction of an electromagnetic wave with an electron beam due to new dispersion law;
2) it forms volume distributed mirror retaining radiation in interaction region.

It is well known that each radiative system is defined by its eigenmodes and by the so-called dispersion equation, which in the case of small perturbations (linear regime) describes possible types of waves in system and relation between frequency and wave number of system eigenmodes. Thorough analysis of properties of FEL dispersion equation is done in [1]. It is shown there that
1. dispersion equation for FEL in collective regime coincides with that for conventional travelling wave tube amplifier (TWTA) [2];
2. FEL gain (increment of electron beam instability) is proportional to $\rho^{1/3}$, where ρ is the electron beam density.

For the first time the possibility of essential change of instability of an electron beam moving in a spatially periodic medium was indicated in [3]. In this paper the dispersion equations are obtained and investigated for conditions of multi-wave diffraction. It is shown that there is a new law of electron beam instability in the points of diffraction roots degeneration. The amplification and generation gain of electromagnetic wave are sharply changed in these points. In [3] this statement is derived from the fact that the instability increment in the point with s-times degeneration is proportional to $\rho^{1/(3+s)}$ (here ρ is the electron beam density and it is supposed that the point in which s roots coincide is the point with (s-1)-times degeneration). This increment differs from the relevant increment for one-wave system which is proportional to $\rho^{1/3}$. This result is also valid for electron beam which moves in vacuum close to the surface of spacially periodic medium [4] (or in a vacuum slot made inside a periodic medium). Explicit expressions for dependence of starting current j on interaction length L are obtained in degeneration points [5]: $j_{start} \sim 1/\{(kL)^3(k\chi_\tau L)^{2s}\}$. The advantages of VFEL are exhibited in wide spectral range from microwaves to X-rays [5–7]. In [7] the experimental simulation of electrodynamic processes in the volume diffraction grating was performed for a millimeter wavelength range. The possibility of obtaining of extremely high Q-factor for a system with two strongly coupled waves is experimentally confirmed.

In the present work the first lasing of VFEL in millimeter wavelength range is reported. The main parts of VFEL are two flat diffraction gratings with different spatial periods. The first diffraction grating is used for radiation generation due to Smith-Purcell radiating mechanism [8]. The second grating provides distributed feedback using Bragg dynamical diffraction [9], the grooves of diffraction grating are oriented at the nonzero angle to the direction of electron beam velocity. It should be noted, that generation in nonrelativistic TWT devices in similar conditions is impossible at single harmonic, since the wavelength of emitted radiation considerably exceeds period of TWT spiral (or corrugation period). Lasing of considered VFEL type for the first time was described in [10], where the theoretical model of its operation was presented.

2 Experimental setup and results

Block-scheme of the experimental setup is illustrated in fig.1.

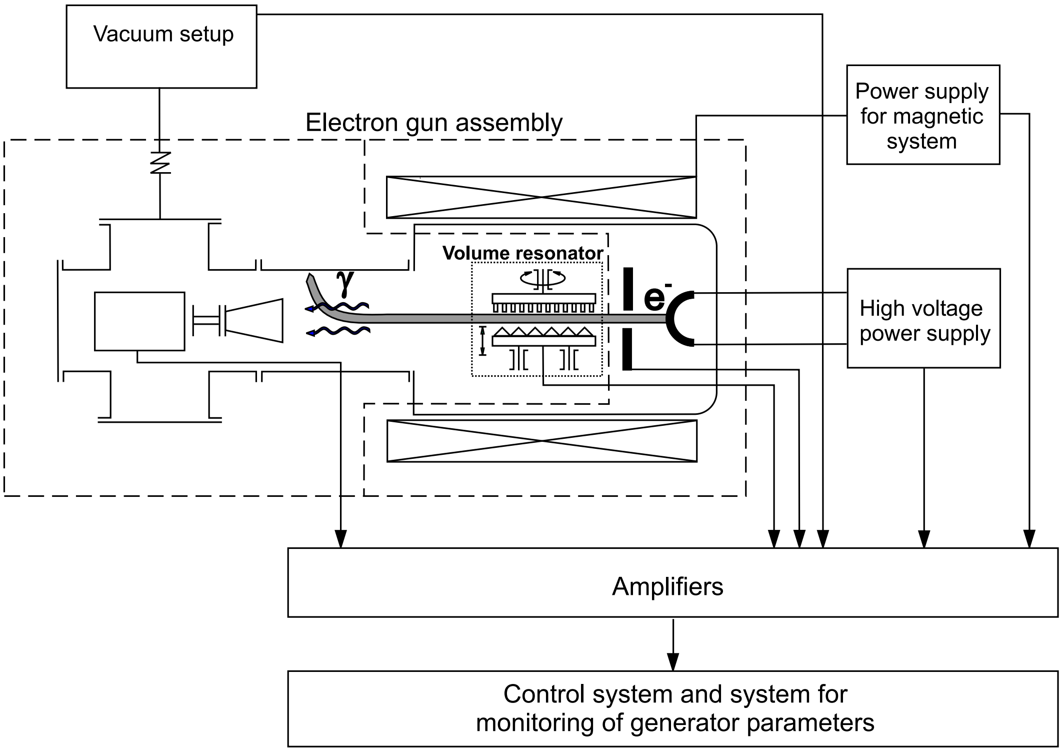

Fig. 1. Block scheme of experimental setup for studing of VFEL generation.

Volume resonator is the basic functional part of VFEL (see Fig.2). In considered setup it is formed by two diffraction gratings with different periods and two smooth side walls. Cross section of the resonator is rectangular and constant along all its length. But the distance between diffraction gratings can be varied in different experiments. Radiation is output from the resonator through end-wall.

The interaction of the first diffraction grating (exciting grating) with the electron beam arouses generation of Smith-Purcell radiation. The second (resonant) grating provides distributed feedback of generated radiation with electron beam. The distance between grooved surface of exciting grating and electron beam can be varied during experiment that allows to encrease efficiency of generation process. Rotation of resonant diffraction grating provides the

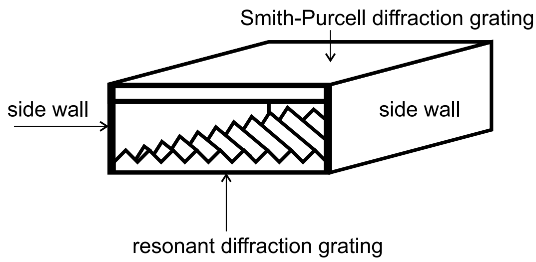

Fig. 2. Block scheme of experimental setup for studing of VFEL generation.

possibility to change radiation frequency by varying the orientation of grating grooves with respect to electron beam velocity. Mechanical tuning of the radiation frequency is also provided by the adjustment of distance between gratings.

The sheet electron beam emitted by the thermal cathode (tungsten labilized by barium or calcium iridate) is formed in cylindrical Peirce gun. It is guided in the VFEL resonator by the magnetic field $\sim 3\ KGs$. Electrons are emitted in pulsed regime (unipolar pulse with sinusoidal shape and pulse duration $\sim 10\ ms$) in sequence of two or three voltage pulses (voltage amplitude can vary from 1 to 10 KeV).

Generated radiation is output through a radiotransparent window (plexiglas) to a radiation detector (thermistor detector M5-50 or power meter M3-22A) with a bandwidth of detected radiation 54-78 GHz.

Control and measurement system provides output of registed data to PC display. Also the following parameters are recorded on a hard disk drive:

- Cathode voltage;
- Total electron beam current;
- Current in a guiding magnetic system windings;
- Grating current;
- Power of microwave radiation.

The generation of microwave radiation was detected at electron energy $\geq 5\ KeV$ in millimeter wavelength range ($\lambda \sim 4-6$ mm). Parameters of resonator are: the length of resonator is 100 mm;
the period of the exciting diffraction grating is 0.67 mm;
the period of the resonant diffraction grating is 3 mm.
The detected pulse power of generated radiation was about 3 - 4 W. Taking into account the fact, that only the part of the electron beam with cross size $\delta \sim \frac{\lambda u}{4\pi c} < 0.1\ mm$ interacts effectively with electromagnetic wave the efficiency of "working" part of a beam can be evaluated as $\sim 10\%$. The oscillogram of VFEL lasing is shown in fig. 3.

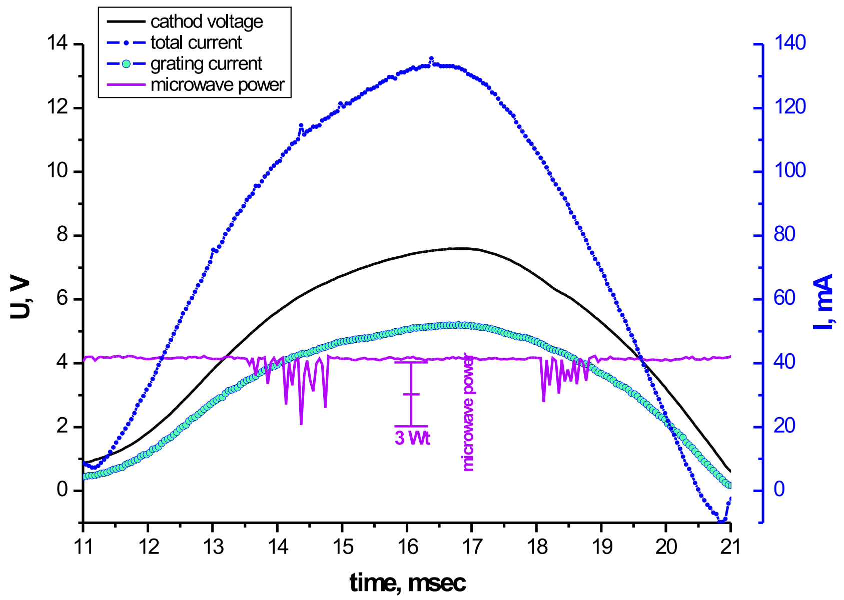

Fig. 3. The oscillogram of VFEL lasing.

The continuous generation of radiation was observed for electron beam currents higher than 35 mA . To define the threshold conditions the beam current was changed by the varying of the cathode heating voltage. Threshold conditions of generation are illustrated in fig.4, where the dependence of grating current and emitted microwave radiation on cathode heating voltage is shown. The decreasing of heat voltage from 178 V to 158 V does not cause the decreasing of the grating current because of saturation mechanisn due to Child-Langmuir law. But at $U_{heat} \leq 156V$ the grating current decreases. It is clear from fig. 4 that reduction of the current leads to decreasing of radiation power. And the peaks on radiation power curve concentrates near electron beam energy $\sim 5\ keV$ when the grating current tends to the threshold value. The peaks on radiation curve appears at minimum value of grating current $\sim 35\ mA$. The lasing starts from voltage $\sim 5\ kV$. This value is defined by the diffraction gratings period. As a result at the electron beam energy $\sim 5\ kV$ the mode with the highest Q-factor is excited. For this reason when the grating current tends to the threshold value, the region of generation tends to a narrow band near to 5 kV. At higher current values the radiation appears in electron energy range 5 - 7.5 KeV that demonstrates the excitation of the other modes with smaller Q-factor, for which the working current exceeds the starting that.

References

[1] A.Gover, Z. Livni *Optics Communications* **26** (1978), 375;

[2] J.R.Pierci. *Travelling wave tubes* (Van Nostrand, Princeton 1950);

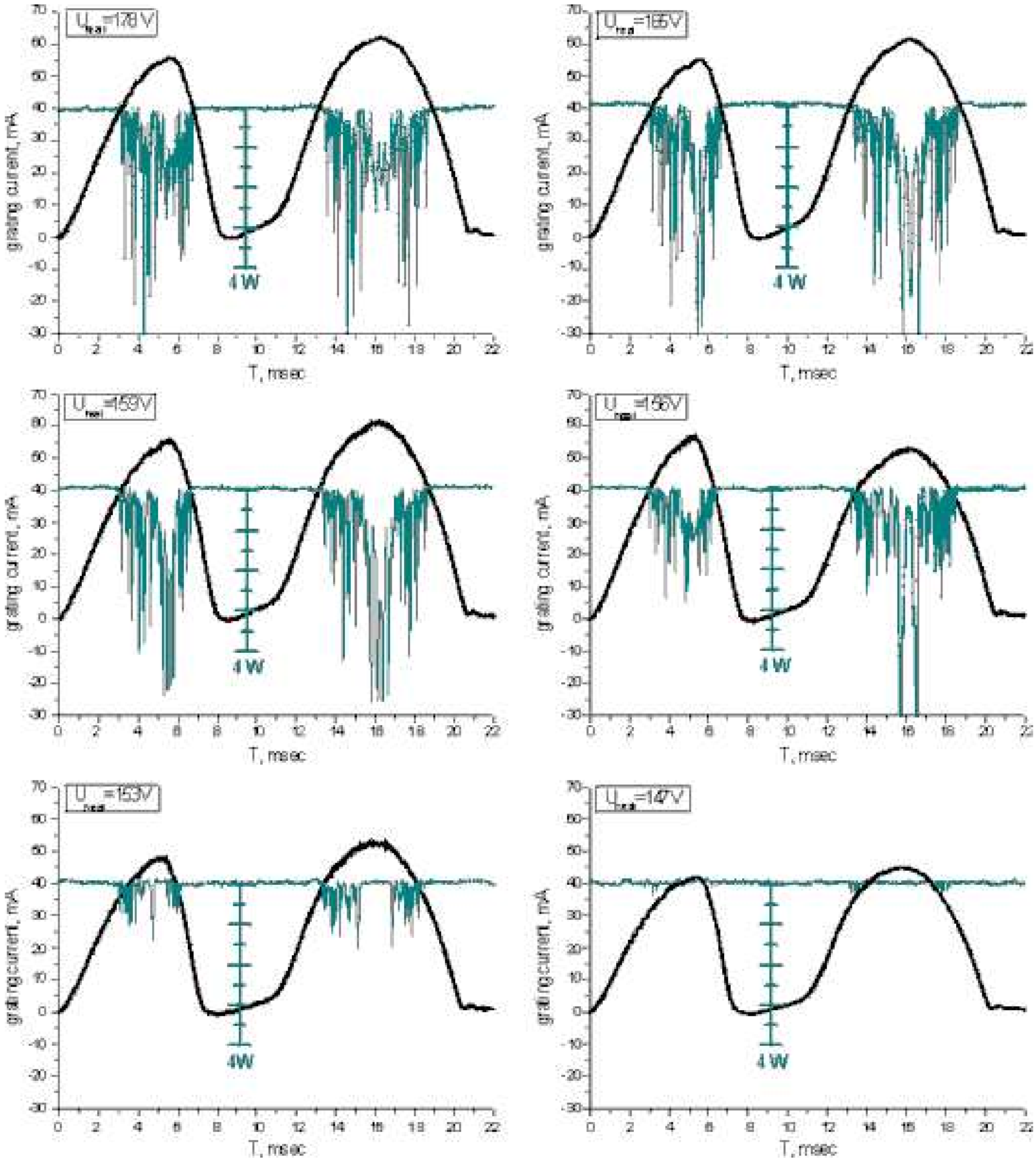

Fig. 4. The oscillograms of dependence of VFEL lasing on the cathode heating voltage.

[3] V.G.Baryshevsky, I.D.Feranchuk, *Phys.Lett.* **102A** 1984 141.

[4] V.G.Baryshevsky, *Doklady Akademii Nauk USSR* **299** 1988 19.

[5] V.G.Baryshevsky, K.G.Batrakov, I.Ya. Dubovskaya *Journ.Phys D.***24** 1991 1250.

[6] V.G.Baryshevsky, *NIM* **445A** 2000 281.

[7] V.G.Baryshevsky, K.G.Batrakov, I.Ya. Dubovskaya, V.A.Karpovich, V.M.Rodionova, *NIM* **393A** 1997 71-75.

[8] Smith S.L., Purcell E.M., *Phys. Rev.* 1953 **91** 1069.

[9] Shih-Lin Chang, *Multiple Diffraction of X-Rays in Crystals* (Springer-Verlag, 1984).

[10] V.G.Baryshevsky, K.G.Batrakov, V.I.Stolyarsky Proc. of the 21 International FEL Conference 1999 II-37.