DEVELOPMENT OF MILLIMETER-WAVE FEM FOR ELECTRON-POSITRON COLLIDERS[1].

A.A.Kaminsky, A.K.Kaminsky, S.N.Sedykh, A.P.Sergeev, JINR, Dubna, Russia
G.G.Denisov, N.S.Ginzburg, N.Yu.Peskov, A.S.Sergeev, IAP RAS, Nizhny Novgorod, Russia

Abstract

A free-electron maser (FEM) in oscillator configuration with a Bragg resonator was developed. It uses the electron beam of an induction linac LIU-3000 (0.8 MeV, 200 A, 200 ns). The highest FEM-oscillator's efficiency of 26% was achieved at a frequency of 31 GHz. Computer simulation showed the possibility of single-mode or multi-mode operation regimes depending on the resonator type and its Q-factor. Both regimes were realized experimentally. The radiation spectrum width of the oscillator in single-mode regime allows using it as a RF source for electron-positron colliders.

A 36.4 GHz FEM amplifier with an original RF input device is now at the stage of early beam experiments. The operation of the input device is based on the wave splitting in stepped waveguide. Its main features are the high efficiency, on-line control of the input power and absence of any elements in electron beam aperture. "Cold" measurements of the RF input efficiency are in good agreement with the simulation results.

Our nearest plans include also experimental registration of electron beam bunching inside and outside the interaction region using streak-camera.

1 INTRODUCTION

Two applications of millimeter-wave FEM for linear electron-positron colliders are studied by our team:

- as possible source of RF-power for high-gradient accelerating structures;
- as possible drive-beam buncher in two-beam configuration of collider.

For an estimation of the required radiation characteristics it is possible to be guided by parameters of project CLIC (CERN) [1]. Power of the individual device must be about 200 MW at the frequency of 30 GHz, spectrum width $\Delta\omega/\omega \leq 0.3\%$, and the pulse duration not less than 20 ns. The additional requirement is a precise phase correlation between all RF sources of the collider. For a long time it was considered, that only amplifying configuration of FEM was suitable to ensure necessary quality of the radiation [2]. However, some years ago a new scheme of two-beam accelerator was suggested, in which the microwave power was produced by a chain of oscillators (in particular, FEM-oscillators), mutually synchronized by the phase of bunched drive beam [3].

Most of our experiments were carried out using a linear induction accelerator LIU-3000 (0,8 MeV, 200 A, 200 ns). Because of the power of a beam was insufficient for achievement of required power of a microwave radiation, main efforts in ours researches were concentrated on improvement of the FEM characteristics (in particular, on increasing of the efficiency), and also on quality of the radiation. We develop both oscillator and amplifier configurations of the FEM.

FEM-amplifier is also a promising mean for bunching of intense electron beams with energies 1-10 MeV which can be used as drive beam of linear collider [4]. Our nearest plans include also experimental registration of electron beam bunching inside and outside the interaction region using streak-camera as it is already in use in CESTA [5].

2 FEM-OSCILLATOR WITH BRAGG RESONATOR

The main features of developed oscillator are Bragg resonator and configuration with reversed guide field [6], when cyclotron rotation of the beam electrons and their rotation imposed by helical wiggler have opposite directions. In these configuration the efficiency on the level of 26% - 27% was measured for both oscillator [7] and amplifier [8] schemes.

2.1 Computer Simulation

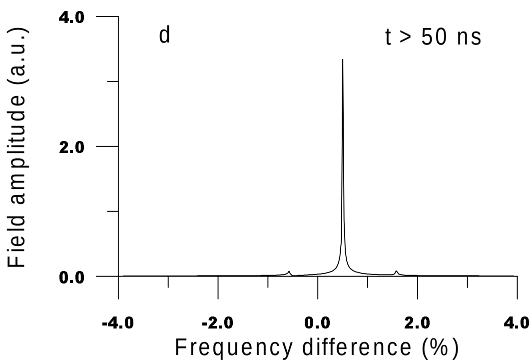
Dynamics of oscillation build-up in a FEM with a two-mirror Bragg resonator was studied theoretically. Time domain analysis taking into consideration the dispersion properties of the Bragg reflectors was used which allows us to investigate the both the transient process and stationary regime.

At the first time stage large oscillations of efficiency and output power occur. Such oscillations are caused by excitation of all longitudinal modes disposed at the zone of Bragg reflection.

For a low and moderate Q-factor resonator at the second stage one of the modes grows and suppresses other modes due to a nonlinear mode competition mechanism. This results in a single mode being established (Fig.1) and, consequently, stationary single frequency operation.

Figure 1. Output radiation spectrum of the oscillator in the single-mode operation regime.

[1] This work is supported by grants 97-02-16643 and 97-02-17379 of Russian Foundation for Basic Research.



Increasing the reflectivity of the Bragg mirrors above the optimal value led to lower electron efficiency and an increase in the width of the radiation spectrum. In this case the excitation of several longitudinal resonator modes takes place (Fig.2), and beating between these modes causes the modulation of the output power in the final stage of evolution.

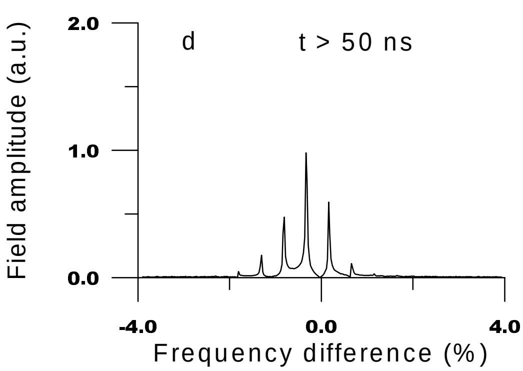


Figure 2. Output radiation spectrum of the oscillator in the multi-mode operation regime.

2.2 Experimental Results

An experimental study of the FEM was performed on the linac LIU-3000 (JINR, Dubna) which generated electron beam with parameters (0.8 MeV, 200 A, 200 ns) at a repetition rate up to 1 Hz. The helical wiggler with period of 6 cm and the transverse magnetic field up to 3.5 kG was used to drive the electron transverse oscillations. The wiggler was immersed in a uniform axial magnetic field generated by a solenoid. The strength of this field could be varied from –7 to 7 kG (minus sign corresponds to the configuration with reversed guide field).

In the oscillator a two-mirror Bragg resonator was used to provide a selective feedback loop. The resonator was designed for $TE_{1,1}$ operating mode with three possible feedback modes: $TE_{1,1}$, $TM_{1,1}$ and $TM_{1,2}$ at the frequencies near 29 GHz, 31 GHz and 38 GHz respectively.

In the experiments, radiation at the designed circularly polarized $TE_{1,1}$ wave and separate frequencies bands corresponding to all the feedback waves mentioned above were detected. Changing both the wiggler and guide fields performed selection of the feedback regime.

Accordingly to theoretical predictions for the cavity configuration with a high Q factor, multi-mode operation of the oscillator was detected by the modulation of the output power in the frequency band of 31 and 38 GHz. Modulation period coincides very well with the calculated beating period taking into account the distance between mirrors and the phase velocity of backward mode. The oscillator efficiency in this configuration was from 5 to 10%.

For high efficiency operation with optimal Q-factors about 450 no modulation of output signal was observed. The highest radiation power as well as the narrowest bandwidth were obtained at a frequency of 31 GHz. Maximum output power of 37 MW corresponding to a record FEM-oscillators efficiency of 26% was achieved. Diffraction spectrum width in this configuration (0.25%) is small enough for using such radiation for feeding the accelerating structure of collider.

3 RF-INPUT FOR THE FEM-AMPLIFIER

Drawing of RF-input for the FEM-amplifier is presented in Fig.3. The operating principle of the RF-input is based on the effect of microwave beams multiplication [9]. A narrowly directed monochromatic wave beam with cross-section a, when injected into a wide waveguide with its cross-section $A > a$, excites such a set of eigenmodes with certain definite amplitudes and phases that at distance $L = A^2 / p\lambda$ from the input of the wide waveguide the field looks like a set of p split wave beams with amplitude profiles identical to the injected beam. The new unit makes it possible to separate microwave and electron beams and to provides a high (up to 100%) transformation of the input signal into the operating wave of an oversized waveguide without any elements on electron beam aperture. Moreover, this high transformation is possible in rather wide (about 10%) frequency range.

The RF-input was designed with a 85% input signal transformation into the operating $TE_{1,1}$ mode of a circular waveguide in the frequency region from 32 to 37 GHz. Results of "cold" microwave measurements are presented in Fig.4. Channel 1 corresponds to transformation into the interaction region and channel 2 (the rest 15% of the input signal) is designed to use for on-line control.

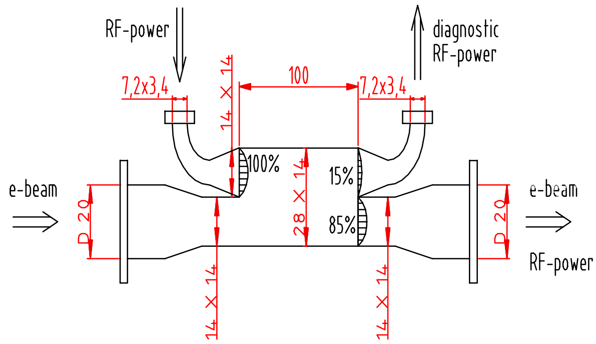


Figure 3. Scheme of the RF-input for the FEL-amplifier.

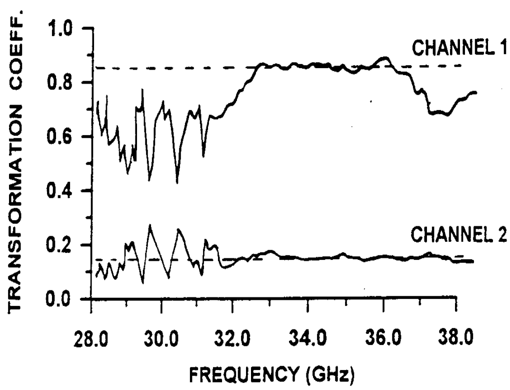


Figure 4. Results of «cold» microwave measurements of the RF-input: transformation coefficient versus frequency.

Experimental study of the amplifier on LIU-3000 is under progress now. A magnetron with the frequency of 36.4 GHz was used to drive the amplifier. At the present stage of the experiment amplification of 20 dB and output power of 5 MW were obtained when the beam of current of 110 A is utilized. We expect that at the next stage an improvement in the beam transportation through the new unit and the use of full beam current produced by the accelerator (about 180 – 200 A) will increase the amplification and output power.

4 PREPARATION TO EXPERIMENTAL OBSERVATION OF BEAM BUNCHING

Most preparation for experimental observation of beam bunching inside- and outside of the FEM interaction region using the Cherenkov radiation registration by the streak-camera have been fulfilled. We have tested various types of the Cherenkov radiators, assembled and tuned a streak-camera "Imacon 500", prepared the equipment for digitizing of its output image. This experimental technique can be used both for FEM improvement and for investigation of possible drive beam buncher for colliders.

5 CONCLUSION

- Both theoretically predicted operating regimes of FEM-oscillator with Bragg resonator - multi-mode and single-mode - were realized in the experiment by means of proper choice of the Q-factor. In single-mode regime the spectrum width of the radiation ($\Delta\omega / \omega \leq 0.25\%$) allows using it as a RF source for high-gradient accelerating structure of the electron-positron colliders. Under optimal resonator configuration at the frequency of 31 GHz the output power of 37 MW and efficiency of 26% were obtained.
- A new original RF input device for FEL-amplifier was designed and tested. The input efficiency of the $TE_{1,1}$ mode is about 85% in frequency range from 32 to 37 GHz. The rest 15% of the input signal were used for on-line control of input power.
- Most preparation for experimental observation of beam bunching inside- and outside of the FEM interaction region using the Cherenkov radiation registration by the streak-camera have been fulfilled. This experimental technique can be used both for FEM improvement and for investigation of possible drive beam buncher for colliders.

6 REFERENCES

[1] W. Schnell, "Radio-frequency acceleration for Linear Colliders", CERN-LEP-RF/86-27, 1986, "The drive linac for a two-stage RF linear collider", CERN-LEP-RF/88-59, 1988.

[2] A.M. Sessler, AIP Conf. Proc.#91,-"The free electron laser as a power source for a high-gradient accelerating structure.- American Institute of Physics, New York, p.154-159, 1982.

[3] G.G. Denisov, V.L. Bratman, A.K. Krasnykh et al., "Problems of autobunching and phase stability for the TBA-driver: calculations and design for a modeling experiment" -Nuclear Instrum. and Meth., A358, p.528-531, 1995.

[4] H.D.Shay, R.A.Jong, R.D.Ryne et al., "Use of a FEL as a buncher for a TBA scheme", Nuclear Instrum. and Meth., A304, p.262-267, 1991.

[5] J.Gardelle, J.Labrouche, J.L.Rullier, "Direct Observation of Beam Bunching Produced by a High Power Microwave Free-Electron Laser", Phys. Rev. Letters, v.76, #24, p. 4532-4535, 10 June 1996.

[6] 13. A.K. Kaminsky, A.A. Kaminsky, V.P. Sarantsev et al., "High efficiency FEL-oscillator with Bragg Resonator operated in the reversed guide field regime." - Nuclear Instrum. and Meth., A375 p. 215-218, 1996.

[7] A.K.Kaminsky, A.A.Kaminsky, S.N.Sedykh et al., "Efficiency Optimization of the JINR-IAP Narrow-band Millimeter Wavelength FEL-oscillator". - FREE ELECTRON LASERS 1996. G.Dattoly, A.Renieri (eds.) Elsevier Science B.V. - II-81, 1997.

[8] M.E.Conde and G.Bekefi. "Experimental Study of a 33.3 GHz Free Electron-Laser Amplifier with a Reversed Axial Guide Magnetic Field". Phys. Rev. Lett., 67 3082, 1991.

[9] G.G. Denisov, D.A. Lukovnikov, M.Yu. Shmelyov «Microwave system based on the effect of image multiplication in oversized waveguides», Proc. of SPIE, Edit. by J.R. Birch and T.J. Parker, vol.2104, pp.485-486, 1993.