HIGH-FREQUENCY ELECTRON GUNS – CURRENT STATUS

V.A. Kushnir
NSC KIPT, Kharkov, Ukraine

INTRODUCTION

During the past decades the development of physics and technique of linear electron accelerators (linacs) has been marked by increased requirements to the quality of electron beam. For carrying out scientific investigations and solving the numerous applied problems the bright electron beams with small particle energy spread are needed.

Now injector systems, based on using high-frequency sources of electrons (RF-guns) have obtained the great prevalence [1]. The RF-gun generally is a microwave-cavity with electric modes (for example, E_{010}) turned on accelerator frequency or its sub-harmonic. The cathode emitting surface is arranged in the cavity, where the electric field strength is about (10^7-10^8) V/m. This creates the necessary condition to form the high-energy (10^5-10^6 eV) electron bunches and to obtain the small beam emittance. The typical pulse current length at the exit of RF-guns with thermoionic cathode [2 - 6] is 1.5-8.0 μs and the pulse current of 0.5-1.5 A. When using the photocathode the pulse length is determined by the pulse length of laser radiation. It can average the several picoseconds and even hundreds of femtoseconds, and the current in the bunch amounts to hundreds of amperes. The frequency range, where the high-frequency electron sources are used, extends from 10^8 to 10^{10} Hz.

Many scientific publications deal with the problems related to the development and investigation of RF-guns. The researches concerned with design of photocathode RF-guns are described in the most of them. A number of detailed reviews (see, for example, [9, 10]) have been devoted to the current status in this sphere. In the present work we analyze the state of investigations in the field of engineering the high-frequency electron sources with the thermoionic cathodes (TC) and give information about one of the new RF-gun types.

RF GUNS WITH THERMIONIC CATHODE

The first high-frequency gun with thermoionic cathode was constructed in 1983-1985 years at Stanford High Energy Physics Laboratory (HEPL) by G.A. Westenskow and J.M.Madey [2]. The gun was a cylindrical E_{010} cavity with LaB_6 cathode placed in it. This high-frequency gun was designed to use it in the Mark III accelerator [11, 12]. Just the successful experiments allowing to design a free electron laser on the base of this accelerator created the basis for wide use of RF-guns in linacs. Unlike the photo-RF-guns the guns with TC do not require the unique and expensive laser devices and, moreover, they have good performances. On the other hand, in spite of simple design the thermoionic RF-guns are quite complex objects in the context of physical processes which occur in it. Now we shall consider qualitatively the main processes.

1. In the RF-guns with TC the emission occurs during the whole accelerating half-period of the high-frequency field. This fact leads to the following:

1.1. The portion of electrons (for the most of guns over the range of initial phase of 90°-180°) has not enough time to leave the cavity during the accelerating half-period. These electrons are braked and, accelerating to the back direction, bombard the cathode. This phenomenon is the significant range limitation of RF-guns use in linacs [3, 13, 14]. The cathode bombardment leads to heating its surface during the time of pulse current and to increasing the average temperature. So the pulse length and repetition rate for the most of guns designed do not exceed 4μs and 25Hz, respectively, without using any special equipment.

1.2. Every electron emitted by the cathode surface in different times will have different values of longitudinal and transverse pulses at the exit of gun by virtue of the time dependence of high-frequency field.

2. In connection with the fact that field intensity on the cathode surface is about (10^7-10^8) V/m, the current density of emission varies according to the Richardson-Deshmen low and Schottky effect [15]. This condition plays an important part in forming the beam in the gun cavity system. The degree of the current variation as a function of the electric field intensity depends on characteristics of the gun cathode material under other equal conditions. First of all, it depends on the value of work function. The work function becomes less as the current density increases during the half-period of high-frequency field. As follows from the simulation of particles dynamics (see, for example, [16]) for the monocavity guns, the electrons leaving the cathode at the moment of field maximum (phase of 90°) have a low energy and considerable spread at the exit of the gun. So, in the context of energy homogeneity beam development with the small emittance the Schottky effect leads to the negative consequences in this case. It should be noted, that now the physics of thermoionic emission from the surface of a cathode placed in the high microwave fields is not investigated in detail. In particular, the consideration of this problem under condition of comparability between the RF period of oscillation and the representative time of electron-phonon interaction is of interest.

3. When considerable emission current occurs, the large part of electromagnetic energy stored in the cavity is transmitted to the beam particles. In this case, reduction of the electric field strength and variation of the field phase during the pulse by beam loading effect have a great influence on the dynamics of electrons.

It is evident that the amount, energy and angle distribution of electrons returning to the cathode is determined by the electric field distribution. On the other hand, the same field defines the beam characteristics at the exit of the gun. So, the forming of optimum field distribution, which would satisfy the various and sometime antilogy requirements, is a complex problem. For instance [17] is shown that it is impossible to achieve the considerable lowering the power of the back electron current without losing the beam quality and primarily the degradation of the beam emittance. One of the ways to reduce the effect of back bombardment is to choose the appropriate cathode material and its form. In this connection it is important to study all the factors determining the variation of the cathode temperature as well as the change of the emission density depending on the cathode surface. The investigation results obtained for the non-steady temperature processes on the cathode surface under the influence of the back flue electrons are given in [18]. It is shown, that the temperature variation during the pulse caused by the electron bombardment is determined by the depth of electron penetration into the cathode material and, consequently, by the energy spectrum of electrons. This condition should be taken into account, when choosing the cathode. Generally speaking, at present the problem of the cathode type selection for thermoionic RF-gun is not yet studied in detail. As the analysis shows, "the most acceptable cathode" for a RF-gun with a typical beam characteristic (the pulse current of 1-2 A, the field strength on the cathode of 30-50 MV/m, the pulse length up to 10 μs) should have:

- the high emission density of 15-20 A/cm^2 that allows to design a cathode of small size (diameter of 1.5-2 mm) and, consequently, to have the potential possibility for obtaining the low emittance of the beam. Besides, the high emission density allows fixing up the effectiveness of using the cross magnetic field method to reduce the amount of electrons bombarding the cathode [19];
- the work function not less than 2.5-2.8 eV for reducing the influence of the Shottky effect;
- rather high operating temperature (not less than 1700 K) to reduce the effect of temperature variation on the emission density;
- the cathode stability to the sputtering;
- the small sublimation rate of emitting substrate (not more than 10^{-7} g/cm^2s);
- the possibility of multiple exposure in atmosphere under the air-pressure.

Now the different types of oxide cathodes (pressed, impregnated and so on) or LaB_6 cathodes, traditionally used in the accelerator technique, are employed in RF-guns. The temperature of their surface is 1000-1800 K; the work function is 1.7-2.8 eV. The application of the monocrystal LaB_6 cathode is the most preferable one in spite of some difficulties connected with heating. However, such a choice is not, apparently, the only one. In particularly, the use in RF-guns of high-temperature cathodes on the base of alloys of iridium, rhenium and osmium with the elements of lanthanide's group (IrCe, IrLa etc.) seems to be rather preferable [20]. By our means it is advisable to use directly heated metal cathode, when the RF-guns with a small pulse current (less than 1mA) and with a large repetition rate are designed. The use of a special cathode form can reduce the influence of bombardment on the gun characteristics. For example, the circular pressed BaNi cathode was used for this purpose in the one of the LUE-60 accelerator RF-gun modifications [21, 22]. It is apparently possible to propose such a cathode form that the electrons will not reach the emitting surface at all. In particularly, one of the possible cathode variants is a cylinder with the emitting layer disposed on its element. On the other hand, the coming back electrons can be used for heating the cathode surface. In this context the results of experiments carried out in 1992 on the LUE-60 accelerator are very interesting. The possibility of stable operation of the RF-gun with BaNi-cathode was shown in this experiment, when the source of cathode heating was turned off. The results of this experiment are important since they allow to study the problem connected with the design of a new RF-gun type with the thermoionic cathodes.

The method of transverse magnetic field proposed in [19] is the most common way to reduce the power of the back electrons in the monocavity RF-guns. The idea of this method is that the transverse magnetic field is set up near the cathode by means of a special magnetic system. The intensity of the transverse field decreases rapidly along the longitudinal coordinate. The maximum field is only hundreds of oersteds at the cathode plane in first experiments. However, the possibility arises to increase the current pulse length of the Mark III accelerator RF-gun from 1.2 μs to 6 μs [19]. According to the calculation given in [6], the use of this method makes it to reduce the quantity of back electrons to 75% and to increase the pulse length to 10 μs with the optimum magnetic field distribution. The transverse magnetic field method has been used in the RF-gun of Beijing FEL accelerator-injector [13, 23]. The increase of the current pulse length to 5.0 μs has allowed obtaining the saturation regime of FEL generation [14, 24]. The main drawback of this technique is the influence of the magnetic field on the track of the "useful" particles escaping the cavity. Therefore, the special correcting magnet elements are set up at the exit of the RF-gun. However, generally, in these devices the beam emittance increases because of the large energy spread of particles.

The output beam characteristics of the RF gun are changing during the pulse because of the back-bombardment effect. Besides, the particles have the considerable energy and phase spread even at the fixed time moment. The typical amount of the energy and phase spread is 60 -70% and 60°, respectively, for 80% of particles. So, for application of monocavity RF-gun in the precise accelerator the beam is additionally formed at the special magnetic systems (α-magnet) [25, 26, 27]. Owing to these magnet systems the energy spread does not exceed 1% and the current in the bunch achieves the tens of amperes at the accelerator exit of the injector system containing RF-gun with TC and α-magnets. Such accelerators are successfully used as injectors of electrons in FEL [12, 24] and as injectors for sources of synchrotron radiation [22].

The application of the more complex, specially optimized resonance systems consisting, in particularly, of the several cavities is the alternative of using the outside forming devices. As a simple variant such resonance systems consist of two cylindrical cavities with electric and magnetic couplings [4, 28, 29] and π - type mode. The optimum field distribution is determined by means of particle dynamics simulation and calculation of beam characteristics at the exit of the gun (see, for example, [30]). The design of some guns gives the possibility to change the frequency of each cavities and thereby to vary quickly the accelerator field distribution along the gun axis. Such gun [4] is used now as an electron source of the LIC facility [31,32]. The diameter of BaNi cathode is 5mm. The beam has the following characteristics at the exit of the RF-gun: particle energy of 0.7-0.9 MeV, pulse current of 1.5 A, phase bunch length equal or less than 50°, current pulse length of 0.7 - 1.5μs, normalized emittance not more than 12π·mm·mrad.

The multicavity S-band RF-guns, designed in the Beijing University and IHEP, China [33] and in NSC KIPT, Ukraine [34,35] can serve as an example of using the most complex resonance systems. These guns operate as injector systems with beam characteristics allowing to use them both in precise accelerators, and in technological accelerators. The RF-gun of NSC KIPT serves for operation in the regime of high average beam intensity. The gun resonance system consists of three cavities connected by means of coupling cavities. The mode of oscillations is $\pi/2$. The LaB_6 circular cathode has been used in the gun. The pulse power of the back flow electrons is 21kW, when the beam pulse current at the exit of the gun is 0.5A and the energy of particles is 0.8 MeV. This power is five times less, than in the case of a usual monocavity gun with similar output beam characteristics. The phase bunch length does not exceed 43°, and the normalized beam emittance is 11 π·mm·mrad. The high average beam intensity at the exit of the gun (up to 0.5 mA) allows to use it in technological linacs.

SECONDARY EMISSION RF-GUNS

The first works on design and research of RF-guns with secondary emission cathodes were executed by F.M. Mako and W. Peter [36, 37] in USA. In these guns the high-current pulses are generated by multipacting the electrons from the walls of the microwave cavity. The experiments were carried out both in S- and L-bands. The resonant system consists of one cavity (cylindrical E_{010}-mode cavity in L-band and rectangular H_{101}-mode cavity in S-band). On one of the walls of the cavity is the emitting surface (cathode), on the contrary wall the metallic grid is mounted. This grid has a high transmittance and as a cathode it is the source of secondary electrons. In essence, in these guns the well-known two-electrode high frequency resonance discharge is used (see, for example [38]). The possibility to obtain a high-current beam during long time is shown experimentally. The macropulse current of 18 A, e.g. in experiments at S-band (2.85 GHz), was obtained. The corresponding peak current is 360 A. This gun operates at a repetition rate of 50-300 Hz with a macropulse length of 2.25 μs. The analysis of beam dynamic and experimental data shows the possibility of obtaining the short electron bunches (about 5 % of the RF period). Unfortunately, in the literature there is no information about any experimental researches on a beam emittance and energy spread behavior. This problem is a key for determining the application area of these guns.

The similar operational mode of a gun was observed in KIPT on the two-cavity universal RF-gun of the accelerator LIC [4]. In this case the source of secondary electrons was thermoionic BaNi cathode bombarded by "return" electrons. The temperature of the cathode was below the threshold for the significant thermoionic emission. The gun was operating at a pulse duration of 2.8μs with a pulse current of about 1.5 A. The researches on this operationing mode are continued.

There is one more type of electron sources, which application in RF-guns on our opinion can be promising. It is a so-called magnetron secondary emission gun with the cold cathode [39 - 41]. This electron source is a magnetron diode with smooth cylindrical electrodes. The basic mechanism of diode operation is the secondary emission multiplication in crossed electric and magnetic fields. The pulse current up to hundreds of amperes have been obtained experimentally. One of advantages of such a source is the large service life (on some evaluations up to 10^5 hours).

CONCLUSIONS

The high-frequency guns with thermoionic cathode are effective sources of electrons for linear accelerators. The work on perfecting these sources of electrons actively proceeds now in many laboratories of the world. The direction of these researches is connected first of all with increase of the average beam intensity and reaching the homogeneity of performances of a beam during pulse. Together with traditional thermoionic and photocathode RF-guns the new variants of guns with the use of various types of cathodes are offered and investigated.

REFERENCES

1. C.Travier RF-guns: review. – Orsay cedex (France): 1990. – 38 c. (Preprint / Laboratorie de l'Accelerateur Linearie; RT 98-13). // SERA/90-219/RFG, RFG Note 07. LAL, 1990.
2. G.A. Westenskow, J.M. Madey // Laser and Particle Beams. 1984. Vol. 2. Part 2. P. 223-225.
3. G.A. Westenskow, J.M. Madey // HEPL Technical Note, TN-86-1, 1986.
4. M.I. Ayzatsky, E.Z. Biller, A.N. Dovbnya, V.A. Kushnir, V.V. Mitrochenko // Pribory i technika experimenta, 1997. №1. P. 34-38. (in Russian).
5. N.V. Demidov, V.C. Demin, A.N. Dovbnya et al.// VANT, 1992. Vol. 4(25). P. 80-83 (in Russian).
6. C.B.McKee and John M.J. Madey // NIM, 1991. A304. P. 386-391.
7. C. Travier // Proc. of the EPAC'94. Vol. 1, P. 317-321.
8. A. Endo, T. Nori, K.Kobayashi et al //Proc. of the EPAC'96, Vol. 2, P.1562-1564.
9. C.Travier // NIM, A340, (1994), №1, P. 26-39.
10. J.E. Clendin // Proc. of the LINAC'96, P.298-302.
11. S.V.Benson, J.M.J.Madey, J.Schultz et al. // NIM, A250, (1986), №12, P.39-43.
12. S.V.Benson, W.S. Faim, B.A.Hooper et. al. //NIM. 1990. A296. P.110-114.
13. J. Gao and J.L.Xie //NIM, 1991. A304. P. 357-363.

14. V.A.Kushnir, V.V.Mitrochenko, Wang Gang. // Sbornik docladov 14 Soveshania po uskoritelyam zarazennyx chastic, Protvino, 1994. Vol 3, P. 97-102 (in Russian).
15. A.M.Brodsky, Yu.Ya. Gurevich Theoriya electronoi emissii iz metallov- M. Nauka 1973. (in Russian).
16. Honghin Liu. // NIM, 1991. A304. P. 371-373.
17. V.V.Mitrochenko // PhD Tesis, Kharkov, 1999. (in Russian).
18. M.I. Ayzatsky ,V.V. Gann , A.N. Dovbnya et al.. //Radiotechnika i electronika 1998. Vol 43. № 1. P. 112 – 117. (in Russian).
19. C.B. McKee and John M.J Madey // NIM, 1990. A296. P. 716-719.
20. G.Kuznetsov // NIM–1994. A340. No.1. P. 204-208.
21. A.N.Dovbnya, V.A.Kushnir, V.V.Mitrochenko et al. // Proc. of Workshop on JNR c-tay factory, Dubna, 1992.
22. Yu.I. Akchurin, V.I. Beloglasov, E.Z. Biller et al. //VANT, 1989. Vol. 5(5). P. 3 - 10. (in Russian).
23. Jialin Xie, Jiejia Zhuang et al. // NIM, 1990. A296. P. 224-250.
24. Jalin Xie, Juieia Zhuang, Yonghang Huang et al. // NIM, 1995. A358 (1-3). P. 256-259.
25. H.A. Enge // Rev. Sciens. Instru. 1963. Vol.34. P.385-389.
26. A.N.Dovbnya, A.I. Kosoi, A.E. Tolstoy et al. // VANT, 1992. Vol.4(25). P. 7-11.(in Russian).
27. G.A. Westenskow, J.M. Madey. Application for a patent USA No.632757. 1984.
28. M. Borland // Proc. of the 1993 IEEE Particle Accelerator Conference. Washington (USA). 1993. P. 3015 - 3017.
29. J.N.Weawer, R.D.Genin, P. Golceff et. al. //Proc. of the 1993 IEEE Particle Accelerator Conference. – Washington (USA). 1993. P. 3018 - 3020.
30. V.A.Kushnir, V.V.Mitrochenko // Proc. of the fifth European Particle Accelerator Conference. 1996. vol. 2, P. 1414-1416.
31. M.I. Ayzatsky, E.Z. Biller, V.N. Boriskin, et al. // Plasma Physics Report, 1994. Vol. 20. № 7, 8. P. 603-605.
32. M.I. Ayzatsky, E.Z. Biller, A.N. Dovbnya et. al. // Proc. of the EPAC'96, Vol.1,P.795-797.
33. J. Xie // Proc. 1995 Particle Accelerator Conff. – Dallas (USA). 1995. P.162 – 166.
34. V.V. Mitrochenko // VANT, 1997. Vol. 2,3 (30,31). P. 195-197, (in Russian).
35. V.V. Mitrochenko // Proc. of the 17th Particle Accelerator Conference.– Vancouver (Canada). – 1997. Vol. 3. P.2817 - 2819.
36 .F. Mako and W. Peter // Proc. of the 1993 IEEE Particle Accelerator Conference. –Washington (USA). 1993. Vol.4. P. 2702-2704.
37. L.K. Len and Frederick M. Mako // Proc. of the 1999 Particle Accelerator Conference. (in print).
38. I.N. Slivkov. Processes under high voltage in vacuum. M. 1986. (in Russian).
39. A.N. Dovbnya, V.V. Mitrochenko, N.G. Reshetnyak et al // Proc. of the 17th Particle Accelerator Conference. Vol. 3. Vancouver (Canada). 1997. P. 2820 – 2822.
40. M.I. Ayzatsky, A.N. Dovbnya, P.I. Gladkikh et al // Proc. of the BEAMS'98, (in print).
41.Y.M Saveliev, W. Sillett, D.M. Darkes //Proc. of the 11 IEEE Int. Pulse Power Conf., Maryland, USA, 1997, P.340-345.