FEATURES OF THE FORMATION OF AN ELECTRON BEAM IN A LINEAR ACCELERATOR ON PARALLEL-COUPLED STRUCTURE

Yu. D. Chernousov†, I.M. Ikryanov, I.V. Shebolaev,
Voevodsky Institute of Chemical Kinetics and Combustion SB RAS, Novosibirsk, Russia

Abstract

The highest possible, close to 100%, rate of electron capture into acceleration mode has been achieved in an electron linear accelerator based on a parallel-coupled accelerating structure (PCS). High capture rate has been achieved by using an electron gun with high-frequency beam current control, entrance PCS resonators focusing the beam, and in-built into the PCS magnetic periodic focusing system of the solenoidal type based on permanent magnets (MPFS). This study investigates beam dynamics in the developed gun and PCS. The electron gun forms a cylindrical weakly-converging beam in the first resonator of the PCS as a sequence of short pulses with the accelerating frequency, the first and following resonators of the PCS focus, group and accelerate the beam and MPFS focuses and transports electrons to the PCS exit.

INTRODUCTION

Reaching high efficiency of capturing electrons into the acceleration mode is an important problem in the development of a low-energy electron accelerator. The capturing efficiency is usually 30-40% [1, 2]. By forming a sequence of electron bunches at the frequency of the following acceleration from a continuous beam using velocity pre-modulation and grouping, the capturing efficiency can be raised to 70% [2]. The capturing can be further improved by the effects of ultrahigh frequency (RF) focusing as a low-energy beam is flying through the accelerating cavities [1, p. 201]. To focus and transport the beam, an external magnetic field is used, which is generated by solenoids placed over the accelerating structures.

In order to achieve high capturing efficiency, the designed accelerator uses all the mentioned beam formation and focusing techniques on its parallel-coupled structure (PCS). A three-electrode electron gun with RF current control injects the beam into the PCS as a sequence of short pulse bunches at the frequency of the following acceleration, which are shorter than the half-period of the accelerating field. The electron gun optics forms a cylindrical, weakly convergent beam with a diameter close to that of the input port of the first cavity. This form is optimal for the efficient focusing of the electrons by the RF fields of the input and further cavities of the PCS. The PCS has an integrated permanent magnet-based magnetic periodic focusing system (MPFS) [3], which further focuses the accelerated beam and transports it to the PCS outlet.

Due to the techniques and devices used in the PCS accelerator, an extremely high, nearly 100%, efficiency of capturing into the acceleration mode was achieved [4].

† chern@catalysis.ru

Below, the dynamics and details of the beam formation in the electron gun, the first cavities, and the accelerator as a whole are discussed.

FORMING THE BEAM IN THE GUN

Grid-controlled electron guns have been proposed for and used in microwave generators, or klystrods, and they are used in the injection systems of electron accelerators [5-8]. This kind of a gun forms a beam which contains a sequence of electron pulse bunches at the frequency of the following acceleration with beam duration within half of the accelerating field period. The pulse current is formed by a cathode grid cavity with a concentrated grid-cathode capacitance. A microware power applied to the cavity generates a microwave voltage at the grid-cathode gap, and current pulses with duration close to the microwave half-period are injected in the grid-cathode gap under a negative cathode potential relative to the grid (π-injection). The microwave power is applied to the cathode grid cavity by two antennas, one grounded and the other under the injection voltage [5, 6].

Under microwave control, the current varies across the entire range from zero to the maximum within a short generated pulse; therefore, electron beam shape must be made weakly dependent from current. This quality of the beam can be achieved by a focusing electrode with an optimal aperture angle of 135°, while the anode electrode should be flat. Then, the electron beam in the gap between the electrodes will have a parallel cylindrical shape, diverging in a relatively small angle beyond the anode in a wide current range [8, p. 150].

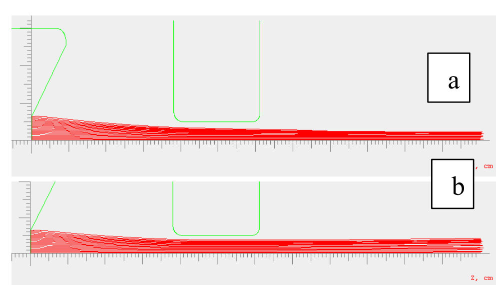

Figure 1: Shape of gun electrodes and beam trajectories. a - beam current ~0.6 A, b - beam current ~1 A.

A similar shape of the electrodes is used in this work. To adjust the beam divergence beyond the anode port, the aperture angle of the focusing electrode was chosen equal to 128°. A cathode grid assembly of the GS-34 lamp is used, which has emitting surface diameter 13 mm and transit ports diameter in the accelerating cavities 10 mm, therefore the diameter of the flat anode electrode port was made

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10 mm. The grid-anode gap is 38 mm. In the current range up to 1 A, this geometry of the focusing electrodes is optimal for the formation of a converging beam in the grid-anode gap, which is almost parallel beyond the anode subject to the defocusing effect of the anode lens.

Trajectory calculations using the POISSON software [9] were performed for the selected geometry of the focusing electrodes in the range from zero current to 1 A at 60 kV. Figure 1 shows the typical electron beam shape. At a current of ~0.6 A (Fig. 1a), a weakly divergent beam with an input diameter of about 6 mm is formed in the grid-anode gap and beyond the anode near the input of the first accelerating cavity; when the current is ~1 A (Fig. 1b), the beam beyond the anode is almost parallel, with a diameter of 8 mm. For the chosen geometry of the electron gun optics, beam shape is almost independent of current, and beam diameter is comparable to the input diameter for beam transit in the first cavity, the space-charge density being minimal.

BEAM DYNAMICS IN PCS CAVITIES

The beam dynamics in the PCS cavities was calculated by a program developed by V. M. Pavlov [10]. The program does not take into account the beam loading of the microwave power applied to the cavity. The calculations showed that the beam was effectively focused by either external MPFS magnetic field or the microwave field of the accelerating cavities.

Figures 2-4 show the trajectory shapes for electrons accelerated from PCS cavity 1 to PCS cavity 5. Input electron energy was 60 keV, accelerating field period was 0.4 nsec, operating frequency was 2.45 GHz. The calculations were performed for a cylindrical parallel beam with the first cavity input diameter 6 mm without (Figs. 2, 3) or with (Fig. 4) external magnetic field.

Figure 2 shows the focusing effect of the microwave fields on various parts of the pulse at low current. The dynamics of short, shorter than accelerating field period, current pulses was calculated with the input phase φ varied from ~–π/2 to ~+ π/2. The microwave focusing is most optimal for electrons flying in the first cavity at the start of the rise of the accelerating field.

The Table 1 shows quality factor Q, gap L, and applied power P for cavities 1-5.

The relative magnitude of the electric field in the cavities is shown at the top of Figs. 2, 4. Figure 4 also shows magnetic field values.

Table 1: Cavity Parameters

Cavity No.	1	2	3	4	5
Q,10^3	3.4	12.3	14.5	14.5	14.5
L, mm	19	32	42	42	42
P, kW	60	250	250	250	250

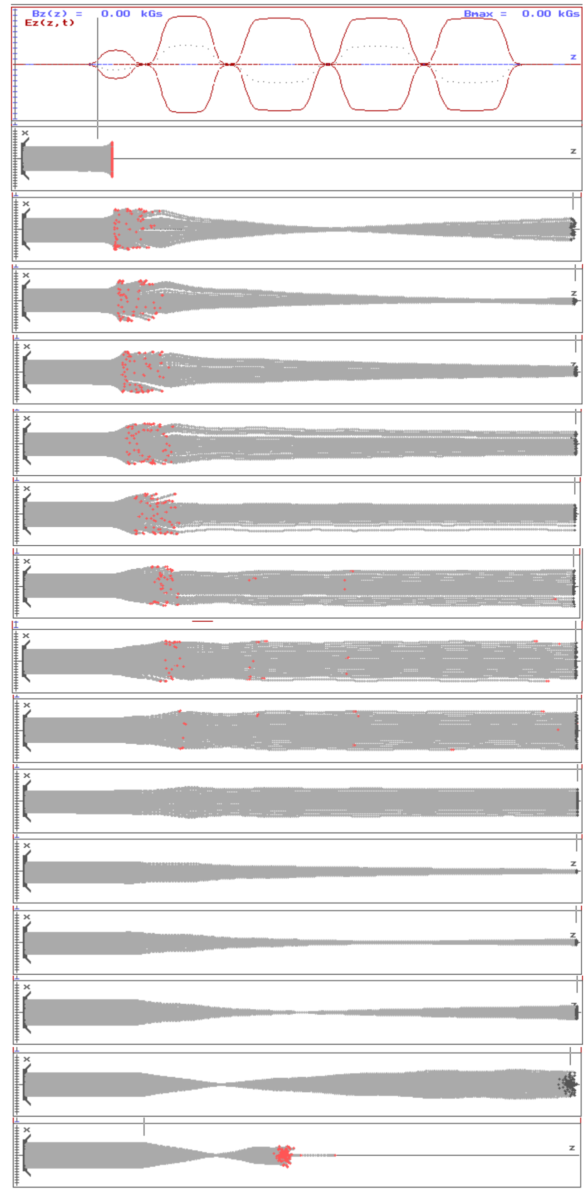

Figure 2: Beam trajectories in PCS. Input phase is varied. Pulse duration is 0.01 nsec, beam current is 0.1 A, magnetic field is off.

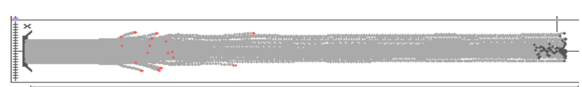

Figure 3: Beam trajectories in PCS. Magnetic field is off. Pulse duration is 0.2 nsec, beam current is 0.4 A. Capturing efficiency is 80%.

For optimal-phase π-injection, the capturing efficiency is ~80% (Fig. 3). The area of capturing electrons into the acceleration mode is close to π; however, near the limits of the area some of the most off-axis electrons fail to transit from the first cavity to the second one within the available time, and they settle on the walls of the transfer channel.

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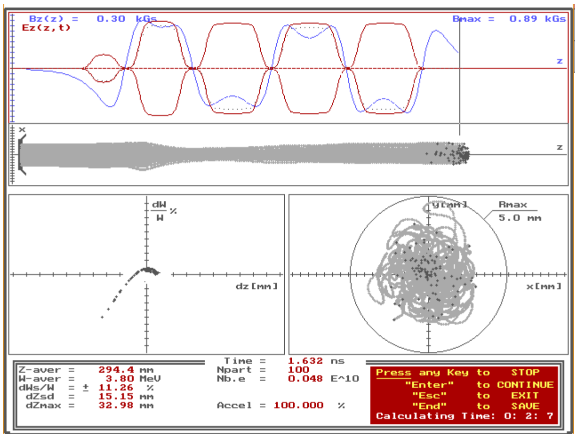

Figure 4: Beam trajectories in PCS. Magnetic field is on. Pulse duration is 0.2 nsec, beam current is 0.4 A. Capturing efficiency is 100%.

MPFS and π-injection bring the trajectories of the outmost particles into a maximum diameter of 10 mm, and the microwave fields of the PCS and the magnetic field of the MPFS effectively focus electrons to form an electron beam of almost parallel shape (Fig. 4), thus increasing capturing efficiency.

According to an experimental test, π-injection in a linear electron accelerator with a 9-cavity accelerating structure with an integrated MPFS generates an output beam of less than 3 mm in diameter with a capturing efficiency of about 100% [4], the average current over a microwave pulse being up to 0.2 A.

CONCLUSION

An electron beam with high efficiency of capturing into the acceleration mode was generated at a linear electron accelerator with a PCS. This was achieved due to the combination of the following devices and techniques:

1. An electron gun with microwave current control was used to inject the beam. The gun forms an electron beam consisting of a sequence of current pulse bunches with duration within the half-period of the accelerating field.
2. The electron optics of the gun is designed to generate a cylindrical, weakly-converging beam. The diameter of the beam is close to the input port diameter in the first PCS cavity, and the space-charge density is minimal.
3. The beam is focused by the RF fields of the accelerating structure. The electrons are exposed to a transversal force, which is proportional to the distance off the cavity axis; the force is directed towards the axis in the first half of the cavity and away from the axis in its second half. Velocity of the electrons grows; they pass the second half of each cavity faster than the first half. The difference in the transit time, i.e. the time of exposure to the transverse force, focuses the beam as a whole, reducing its diameter.
4. PCS has an integrated MPFS, a focusing system based on permanent magnets, which generates a solenoid-type alternating-sign magnetic field. This kind of a system applies a focusing force which is proportional to the squared intensity of the longitudinal field and directed towards the symmetry axis of the system; the magnetic field is applied almost exclusively near the axis of the accelerating cavities; the weight of the magnets is minimal. The MPFS effectively focuses and transports the beam to the accelerator output.

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REFERENCES

[1] Th. P. Wangler RF Linear Accelerators. WILEY-VCH, 2008.
[2] Shi-Lun Pei, Bin Gao. Nucl. Instrum. Methods in Phys. Res. A 888, p.64, 2018.
[3] Yu. D.Chernousov, Parallel Coupled Accelerating Structure. Russian Federation Patent № 2605949, 2017.
[4] Yu.D. Chernousov, I. V. Shebolaev, I. M.Ikryanov. Tech. Phys. Lett., Vol. 44, No. 1, p.50, 2018.
[5] A. S. Bogomolov, E. M. Zakutov, I. V. Shebolaev, Yu. D. Chernousov, Instruments and Experimental Techniques, vol.2, p. 210, 1983.
[6] S. H. Gold Phys. Rev. ST AB 16, 083401, 2013.
[7] A. M. Barnyakov, Yu. D. Chernousov, et.al, JINST 10, P06004, 2015.
[8] S. I. Molokovskii and A. D. Sushkov, High-Intensity Electron and Ion Beams. Energoatomizdat, Moscow, 1991 [in Russian].
[9] V.Ya. Ivanov. Computational methods, optimization and synthesis in electron optics. Palmarium Acad. Publ. 2016.
[10] O. N. Brezhnev, P. V. Logatchev, V. M. Pavlov, et al. Proceedings of LINAC’2002, Gyeongju, Korea, p. 213.

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