HIGH-CURRENT SINGLE BUNCH ELECTRON LINEAR ACCELERATOR

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Abstract

An injector of an electron linear accelerator has been modified at ISIR of Osaka University in order to increase a single bunch charge from 14 nC to 60 nC. A 6th subharmonic prebuncher has been replaced with two 12th subharmonic prebunchers and a 6th subharmonic prebuncher which are newly constructed. A one-dimensional disk model has been used to calculate the bunching of the beam and to decide the optimum location of the subharmonic prebunchers. The subharmonic prebunchers are immersed in a solenoidal magnetic field so that the electron beam is confined during the travel through the drift region. The single bunch of 16 - 20 ps duration and up to 67 nC in charge, with the energy spread of 0.7 - 2.5 % over the range of 24 - 34 MeV, and a repetition rate from a single shot to 720 pps can be obtained. The energy spread depends on the charge and the minimum spread is 0.7 % at 33 nC. The single bunch of 25 - 45 nC in charge is used for the experiments in routine work.

Introduction

When a single bunch is accelerated by a conventional electron linear accelerator, a pulsed electron beam should be injected within an acceptance angle of a prebuncher. Therefore, the beam pulse shorter than 500 ps is required for L-band linear accelerators. It is difficult to generate a short-pulse and high-current beam by a triode gun. A subharmonic prebuncher makes it possible to generate a subnanosecond pulse beam by bunching a nanosecond beam. The subharmonic prebunchers driven by the 6th subharmonic frequency (f = 216 MHz) are utilized in the single bunch linear accelerators of the first generation.[1-3]

An increase in a peak current of the beam from the gun produces a single bunch of higher current. However, an increase in the peak current also requires the beam pulse wider than the 6th subharmonic prebuncher could bunch without producing satellite bunches. Exciting the subharmonic prebuncher by the lower frequency, the single bunch of higher current can be obtained with the wider pulse beam. On the other hand, a longer drift distance or a higher bunching voltage is required. As the final pulse width of the bunched beam is determined by the fundamental frequency, the space-charge effects increase with the single bunch charge. It is, therefore, desirable to bunch the beam with a couple of subharmonic prebunchers rather than a single subharmonic prebuncher alone.

The single bunch electron linear accelerators of the second generation utilize the subharmonic prebuncher system with multi-gaps. The new ANL injector[4] consists of a 12th subharmonic prebuncher with double-gaps, and the SLAC injector[5,6] consists of two 16th subharmonic prebunchers. The ISIR-Osaka linac supplies the single bunches for various kinds of experiments which require the single bunches from low-current to high-current. The space-charge effects depend on the beam parameters such as current, energy, beam radius and current waveform. The independent controll of both the rf-power and the rf-phase in each gap is desirable for the new subharmonic prebuncher system.[7]

Design Calculations for the New Injector

The computer simulation is required to select the frequencies, numbers and locations of subharmonic prebunchers, and to determine the optimum values of gap voltages and rf phases in the cavities. A one-dimensional disk model similar to that described in several papers[2,5,8] has been used to calculate the longitudinal space-charge debunching forces present in a high-current beam inside a cylindrical conducting tube.

The force acting on the i-th disk due to the j-th disk is basically calculated by the distance between two disks. As the energies of beam electrons are about 100 keV, a relativistic correction of the distance is required. In the one-dimensional disk models used in the previous works,[2,5,8] the force acting on the i-th disk is corrected by the total energy of an electron in the i-th disk, and then the change in energy of the i-th disk due to the j-th disk differs from that of the j-th disk due to the i-th disk. In the one-dimensional disk model utilized in the present calculations, the change in energy is corrected by the average total energies of two disks so as to conserve the total energies before and after the interaction.

For the purpose of design calculations, it is assumed that the initial beam pulse from the electron gun is a Gaussian shape with the following beam parameters: the pulse width t_p = 4.5 ns in FWHM, the peak current I_p = 15 A, and the initial beam energy E_0 = 120 keV. The beam is divided by 73 infinitely thin disks of equal charge. The program calculates both the longitudinal positions and energies of the disk by the following equations.

$$\frac{d\gamma_i}{dz} = \frac{2 e Q_i}{\epsilon_0 m_0 c^2 \pi r^2} \sum_{\substack{j=1 \\ j\neq i}}^{N} \sum_{n=1}^{\infty} \frac{[J_1(j_{0n}\frac{r}{a})]^2}{[j_{0n} J_1(j_{0n})]^2} e^{-\left|\frac{j_{0n}}{a}\frac{(\gamma_i+\gamma_j)}{2}\beta_0(\theta_i-\theta_j)\frac{\lambda}{2\pi}\right|}$$

$$+ \frac{e E_{rf}}{m_0 c^2} \sin\theta_i \tag{1.1}$$

$$\frac{d\theta_i}{dz} = \frac{2\pi}{\lambda}\left(\frac{1}{\beta_0} - \frac{\gamma_i}{\sqrt{\gamma_i^2-1}}\right) \quad . \tag{1.2}$$

where $J_1(x)$ is the 1st Bessel function, j_{0n} is the n-th zero of the 0-th Bessel function, r is the radius of the disk, a is the radius of the drift tube, Q_i is the charge in the i-th disk, γ_i is the total energy of electron in the i-th disk, θ_i is the phase of the i-th disk relative to a wave with phase velocity β_0 and wavelength λ, and E_{rf} is the electric field in a gap.

Results of Calculations

The pulse width of the beam should be shorter than a half period of the subharmonic frequency. The rf frequency of the subharmonic prebuncher settled at the downstream of the gun is, therefore, determined from both the required charge in the single bunch and the peak current of the pulse beam available from the gun. In the present case, the 12th subharmonic (f = 108.3 MHz, 1/f = 9.2 ns) is an optimum frequency in order to obtain a single bunch up to 60 nC, since

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the pulse beam of 20 A peak is available from the gun.

The design calculations have been performed for three basic systems: a single, a tandem and a triple subharmonic prebuncher systems. In these systems, the first subharmonic prebuncher settled at the downstream of the gun is driven by the 12th subharmonic frequency, and the beam of 4.5 ns pulse duration is utilized for producing a single bunch.

The first system consists of a 12th subharmonic prebuncher with a single gap. The space-charge effect between the disks located at a center of the beam pulse is larger than that between the disks at the edge of the pulse, since the electron density is maximum at the center of the pulse. As the gap voltage is a sinusoidal field, the electric field act on the disks at the center of the beam pulse is lower than the field act on the disks at both the head and the tail of the beam pulse. When the current is higher than 5 A, the inner disks tends to debunch toward the outer disks. The beam pulse both with a rectangular like waveform and with pulse length longer than the one period of the fundamental frequency is produced at the focal distance. As shown in Fig. 1-a, it is found that the single 12th subharmonic prebuncher is not suitable to obtain a single bunch higher than 25 nC without satellite bunches.

The second system consists of two 12th subharmonic prebunchers. The second 12th subharmonic prebuncher is located at the focal point of the beam, which is modulated by the first 12th subharmonic prebuncher. The length of the pulse beam at the focal point (l = 32 - 50 cm) is more than ten times as long as the gap distance (d = 3.4 cm). When the beam is modulated by gap voltage, the time delay in modulation between disks located at the head and the tail of the beam pulse gives rise to the noneffective bunching. Figure 1-b shows that some of the disks escape from the one period of the fundamental frequency. In order to bunch the beam into the one period of the fundamental frequency, additional subharmonic prebuncher is required.

The third system consists of three subharmonic prebunchers. The third subhrmonic prebuncher is driven by the 6th subharmonic frequency, since the shorter wavelength provides higher modulating field to the beam. It has been found that a triple subharmonic prebunchers are suitable for the ISIR-Osaka single bunch linear accelerator. Figure 1-c shows that the disks in the phase angle within 180° of the 12th subharmonic frequency can be bunched into the single bunch.

Triple Subharmonic Prebunchers

The injector consists of a 12th subharmonic prebuncher followed by a 180 cm drift tube, a 12th subharmonic prebuncher followed by a 120 cm drift tube and a 6th subharmonic prebuncher with a 80 cm drift tube as shown in Fig. 2. These subharmonic prebunchers are coaxial single-gap cavities, with 3.4 cm gap at one end of the inner conductor. The loaded figure of merit Q_l are estimated to be 4,400 for the 12th subharmonic cavities and 1,970 for the 6th subharmonic cavity. The inner conductors of the cavities are made of copper solid tubes and the outer conductors are made of copper clad by a stainless steel cylinder.

In order to flow the image current of the high-current beam, the drift tube is made of copper clad by stainless steel. The conducting drift tubes of smaller diameter are required to reduce the forces due to space-charge debunching. On the other hand, the tubes of larger diameter are preferable for the effective vacuum pumping. The inner diameter of the conducting tube is decided to be 5 cm. Two additional vacuum stations are installed to ensure the sufficient pumping of the subharmonic prebunchers. The vacuum stations are connected with the drift tubes through the conducting slits which reduce the inductance for the flow of the image current.

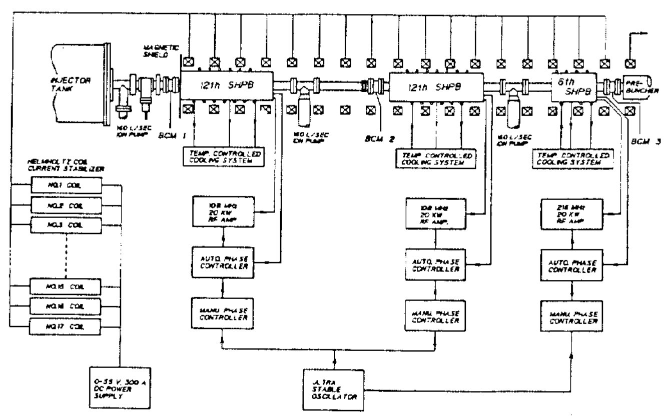


Fig. 2. Block diagram of the triple subharmonic prebunchers (108 MHz + 108 Mhz + 216 MHz).

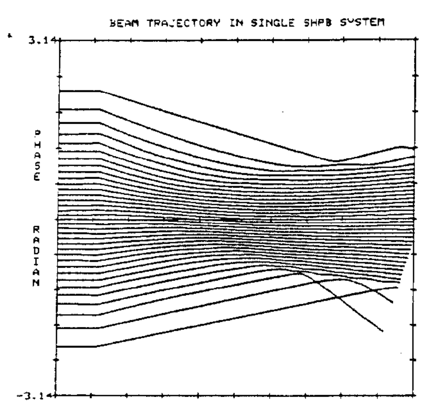


Fig. 1-a. Beam trajectory by a 12th subharmonic prebuncher.
E_0 = 120 keV, I_p = 15 A,
t_p = 4.5 ns, Q = 72 nC,
V_1 = 20 kV.

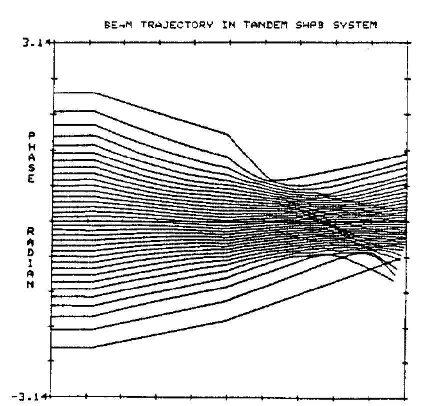


Fig. 1-b. Beam trajectory by two 12th subharmonic prebunchers.
E_0 = 120 keV, I_p = 15 A,
t_p = 4.5 ns, Q = 72 nC,
V_1 = 20 kV, V_2 = 20 kV.

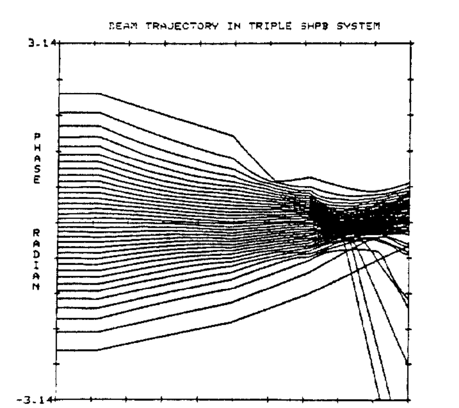


Fig. 1-c. Beam trajectory by three subharmonic prebunchers.
E_0 = 120 keV, I_p = 15 A,
t_p = 4.5 ns, Q = 72 nC,
V_1 = 20 kV, V_2 = 20 kV, V_3 = 30 kV.

Helmholtz Coils

The subharmonic prebunchers and the drift tubes are confined by the Helmholtz coils, which are independently connected with the power supplies. The axial magnetic field is tapered from 150 Gausses at the entrance to 450 Gausses at the output in order to keep the beam at Brillouin flow condition as the charge density increases due to beam bunching. The electron gun should be placed in a magnetic shield, while the beam should be focused at the place where the field strength is about 60 % of the Brillouin field. The beam from the gun is focused by two magnetic lenses in order to controll both the radius and the convergence of the beam at the entrance to the magnetic confined region. The locations of lenses with respect to the axial magnetic fields are selected to obtain the optimum point of beam focusing. When the beam of 4.5 ns is accelerated without bunching by the subharmonic pre-bunchers, the axial magnetic field (Fig. 3) is constant along the axis. The axial magnetic fields (Fig. 4) for the single bunch accelerations should be increased along the axis where the beam is bunched by the subharmonic prebunchers.

The new type of current monitors without using the magnetic substances are required to observe the bunching beam inside the axial magnetic fields. The core-less current monitors with the fast response have been developed, and they are settled at the upstream of the second 12th subharmonic prebuncher and the the pre-buncher.

The rf Amplifiers

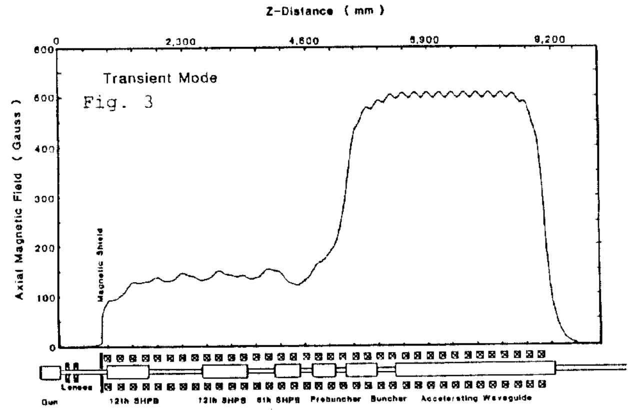
The subharmonic prebunchers are independently connected with the rf amplifiers. Each amplifier is supplied its excitation from a master oscillator that produces signals at 108.4 MHz and 216 MHz. The rf power of 20 kW peak and 20 μs pulse width is generated by the high-power vacuum tubes (RCA7651 and RCA7214) in each amplifier. The automatic phase controllers are installed in the amplifiers in order to lock the rf phase at the cavity gap. Consequently, the rf-phases and the rf-powers in the cavities can be independently controlled by the manual operation.

Status of the ISIR-Osaka Sigle Bunch Linac

The ISIR-Osaka Linac consists of a 120 keV electron gun, three subharmonic prebunchers, a pre-buncher, a buncher, a 3 m long accelerating waveguide and a beam transport system. The accelerating waveguide is driven by a 20 MW klystron, and both the buncher and the prebuncher are driven by a 5 MW klystron. In the transport system, a 12th subharmonic single bunch chopper has been installed in order to eliminate the satellite bunches at the beam window.

The single bunches of 16 - 20 ps duration and up to 67 nC in charge, with the energy spread of 0.7 - 2.5 % over the range of 24 -34 MeV, and the repetition rate from a single shot to 720 pps can be accelerated by the new injector system. The normal operating energy and the energy spread depends on the single bunch charge, since the energy spectrum is determined by both the accelerating fields and the longitudinal wake potential.[9] The single bunch of 67 nC, 16 -20 ps with a long bunch tail, 24 -28 Mev, 2.5 % in energy spread is obtained.[9] However, the single bunches of 25 - 45 nC in charge are used for the experiments in routinework, since the minimum energy spread of 0.7 % is obtained at 33 nC.[9] The beam emittance of π mm-mR is observed for the single bunch of 10 nC, 16 ps, 24 -34 MeV, 1 % in energy spread.

The 12th subharmonic single bunch chopper will be replaced with a new 24th subharmonic single bunch chopper. A single bunch compressor with dipole bending magnets[6] will be installed to controll the length of the single bunch.



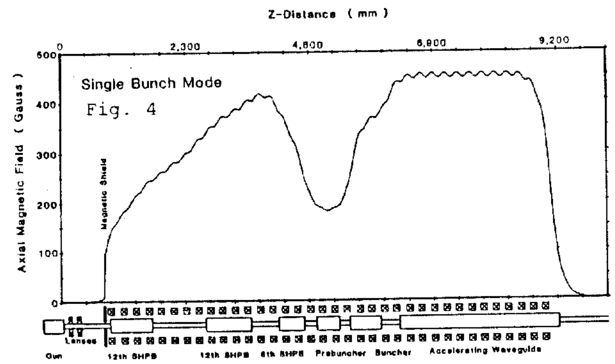


Fig. 3 - 4. The distribution of the axial magnetic fields for a transient mode and a single bunch mode.

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