ELECTRON LINAC INJECTOR DEVELOPMENTS*

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Summary

There is a continuing demand for improved injectors for electron linacs. Free-electron laser (FEL) oscillators require pulse trains of high brightness and, in some applications, high average power at the same time. Wakefield-accelerator and laser-acceleration experiments require isolated bunches of high peak brightness. Experiments with alkali-halide photoemissive and thermionic electron sources in rf cavities for injector applications are described. For isolated pulses, metal photocathodes (illuminated by intense laser pulses) are being employed. Reduced emittance growth in high-peak-current electron injectors may be achieved by linearizing the cavity electric field's radial component and by using high field strengths at the expense of lower shunt impedance. Harmonically excited cavities have been proposed for enlarging the phase acceptance of linac cavities and thereby reducing the energy spread produced in the acceleration process. Operation of injector linacs at a subharmonic of the main linac frequency is also proposed for enlarging the phase acceptance.

Introduction

The continuing demand for electron injectors with higher brightness comes from a variety of applied disciplines. FEL oscillators require linac injectors capable of delivering pulse trains of electron bunches with high charge density.[1] Wakefield accelerators operated at high repetition rates also require pulse trains with high peak brightness. Laser acceleration experiments[2] need essentially isolated or low repetition-rate pulses of very small charge. For some of these applications, experiments are being carried out on alkali-halide and III-V compound semiconductor photoemitters[3] and on thermionic electron sources[4] in rf cavities. For isolated pulses, short-wavelength, intense laser pulses are used to illuminate metal photocathodes.

In addition to novel sources of electrons for high-quality beams, injector linac performance is being improved. The end use of a linac beam may require a high peak-brightness beam, as does an FEL. Peak brightness can be increased by bunching, provided that the emittance growth that inevitably occurs is not too large. However, emittance growth is excessive if the beam is too tightly bunched at a low energy. Hence, the trend in improved injector linac design is toward initial acceleration of a partly bunched beam in a low-frequency (subharmonic) linac section. Because electrons become relativistic very rapidly in a typical linac, further bunching at moderate energies can only be done with the magnetic bunching method.[5] An additional improvement can be made by the addition of the third harmonic of the accelerator frequency, thus flattening the top of the rf waveform. This facilitates the acceptance of longer bunches in an accelerating field that is nearly constant during the transit of the bunch through the cavity.

Limitations to Emittance and Brightness

In comparing emittance and brightness, it is essential to state one's definitions at the outset to avoid confusion. In this paper, emittance refers to a phase-space area,[6] the action integral of classical mechanics. Furthermore, the inclusion of the factor π in the emittance helps to confirm that one is dealing with a phase-space area. The rms emittance formulation,[7] which is convenient to use in accelerator discussions, is defined as $E = 4\pi[<x^2><x'^2> - <xx'>^2]^{1/2}$. In this formulation, the rms emittance is equal to the total phase space area for a K-V distribution.[7] In analogy with the definition of brightness introduced in electron microscopy,[8] the normalized peak brightness of a charged particle beam is defined as $B_n = I/(E_x E_y)$, where I is the peak current and E_x and E_y are the normalized transverse phase-space areas of the beam.

The emittance of an electron beam is limited at its source by the radius of the electron emitting surface and by the temperature of the emitter. More precisely, the lower limit of the normalized rms transverse emittance of a beam from a thermionic emitter of radius r_c at a uniform temperature T is $E_n = 2\pi r_c [kT/m_0c^2]^{1/2}$, (units: m · rad). For a typical thermionic emitter at 1160 K, for which the thermal energy of the emitted electrons is about 0.1 eV, the minimum emittance of a beam with total current I (amperes) and current density J (amperes/cm²) is $E_n = 5.0 \times 10^{-6}\pi (I/J)^{1/2}$.

Commonly used dispenser cathodes are limited to a current density $J \leqq 10$ A/cm². Semiconductor photoemitters, on the other hand, are capable of delivering[9] over 200 A/cm², and their effective temperature may be low enough to produce low-emittance beams of high intensity. Measurements at low currents[10] yielded an average energy spread of less than 0.2 eV. An additional advantage of the photoemissive electron source is the possibility of controlling the temporal profile of the electron bunch by tailoring the laser pulse used to generate the current pulse. These capabilities of the photoemissive electron source are being exploited in an injector-linac experiment at the Los Alamos National Laboratory.

Even higher current densities have been reported from cesiated thin films illuminated by an intense laser beam[10]. The temporal profile of the electron emission lags that of the laser pulse, indicating a thermionic rather than a photoelectric emission process.

Brightness can, in principle, be increased by emittance filtering. The rms emittance of a beam is strongly influenced by the particles in the beam halo. If the halo is selectively scraped off by a beam aperture in the middle of a lens (where the beam diameter is at a maximum in a periodic transport line), the rms emittance may be more strongly attenuated than is the beam current[11] so that an increase in brightness can be realized.

Jones and Peter[12] have suggested a method of reducing emittance growth for an "rf gun" cavity. It is to be expected that the charge density in the bunch will be nearly uniform as the bunch leaves the photocathode, provided the laser pulse is ideally square; the space-charge force in the bunch will in this case be linear. Jones and Peter derived a cavity shape based on equipotential surfaces near the beam axis that produces a linear radial electric field. The superposition of the linear space-charge force and the radially linear external electric field should result in minimum emittance growth in an accelerated bunch. Indeed, an ISIS[12] code simulation of a 100-ps-long, 10-nC bunch accelerated to 1 MeV in a 100-MHz cavity 4 cm long had a normalized emittance growth of only $5\pi\ 10^{-6}$ m·rad.

Conventional Injector-Linac Systems

In the recent past, conventional injectors for high peak-current linacs have used electronically pulsed dispenser cathodes with one or more subharmonic buncher cavities.[5,13–15] This arrangement permits the

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compression of a bunch, which initially straddled many (up to 10) rf cycles of the main linac frequency, into a single rf bucket. Bunching by the velocity-modulation, or klystron, method becomes increasingly difficult as the mean velocity of the electrons approaches the velocity of light. Therefore, the electron gun voltage is restricted to about 500 kV or less. In contrast to ion bunching systems in which linearizing the velocity profile through the bunch can be done to advantage, a linear voltage variation over the electron bunch as it passes through a buncher cavity will fail to produce linear bunching because the velocity profile along the bunch is nonlinear,[5,13] a result of relativistic kinematics. A second subharmonic buncher can be used to partially compensate for the asymmetric bunching. A second buncher may also be effective in correcting for distortions from space charge. Young* has suggested using a second buncher cavity at the third harmonic of the first cavity to correct for such asymmetries.

After the bunch passes through the buncher cavity and a drift space, further bunching can occur in the first few cells of an injector linac. These first few cells can either be graded-beta cells of a standing-wave linac or a tapered phase-velocity section of a traveling-wave linac. Until bunching is complete, the accelerating gradient should be moderate at first and then ramped up gradually to the final gradient of the main linac.

In an rf accelerating cavity, the radial force on a particle crossing the gap depends, in part, on the rf phase angle of the particle. Using a thin-lens approximation for an rf gap, Weiss[16] has shown that the increase in rms emittance, when a bunch of particles of finite size crosses an rf gap, is $\Delta E_{rms} \propto (x^2/\lambda)^2$. The emittance growth is due to the rf radial forces that depend on the phase and radial coordinate of a particle. Clearly, rms emittance growth in an rf gap is minimized with a small beam radius as well as with a low-frequency cavity.

The optimum choice of frequency for the injector linac is a subharmonic of the main-linac frequency. This choice allows a longer bunch to be accelerated to a moderate energy before bunching is complete, thereby minimizing the space-charge density in the bunch while the energy is subrelativistic. When the beam energy reaches 10 MeV or so, further bunching can be effected by the magnetic phase-compression method (see below).

A second linac stage with a higher subharmonic frequency could be used and followed by a second phase compression. Thus, the bunching and preliminary acceleration can be accomplished in several subharmonic frequency stages with the phase width of the bunch being the same in all stages. The constancy of the phase width is easily realized by having the phase-compression factor equal to the frequency ratio between the two stages.

The energy spread impressed on a bunch by the sinusoidally varying field in an accelerating cavity can be significantly reduced by adding a third harmonic to the fundamental wave in the correct proportion to flatten the wave crest.[17,18] This reduction occurs when the third-harmonic amplitude is one-ninth of the fundamental and its phase such that the third harmonic field decelerates the beam when the fundamental accelerating field is at a maximum. Obviously, the rf cavity must be appropriately designed to be resonant at both the fundamental and the third harmonic.[18] In addition, there is an increased complexity in a second rf power supply with its amplitude and phase controls. The result may be, in some cases, well worth the additional complication because the phase acceptance at the wave crest is considerably enlarged. For example, the phase range for an amplitude variation less than 0.1% goes from 5° for the fundamental alone to 37° for the harmonically resonant cavity.[18]

An additional advantage accrues from the use of the third harmonic. For a limited radial distance from the cavity axis, the rf field remains flat-topped to the extent that the ratio of the third harmonic field to the fundamental field remains 1:9. The range of the flat-topped field from the axis depends on the design of the cavity. Emittance growth is also reduced because nonlinear radial forces arising from the off-axis azimuthal magnetic field are approximately zero for the phase range of interest.

One of the advantages offered by the harmonically resonant cavity can be realized by using two separate cavities, one at the fundamental frequency and the other adjacent to it at the third harmonic. If the third-harmonic cavity is phased correctly to subtract one-ninth the peak energy gained in the fundamental cavity, the energy variation off the peak is largely canceled. The energy-spread reduction can also be done effectively, for fundamental cavities grouped together in a tank, by using a single third-harmonic cavity. Figure 1(a) shows a PARMELA simulation of an electron bunch accelerated from 10 to 19 MeV in nine 1.3-GHz cavities. The curvature in the phase-energy scatter plot is removed by decelerating the bunch by 1 MeV (at the centroid) in 3.9-GHz cavities Fig. 1(b). Detailed simulations are needed to study the effects on emittance growth by separated fundamental and third-harmonic cavities.

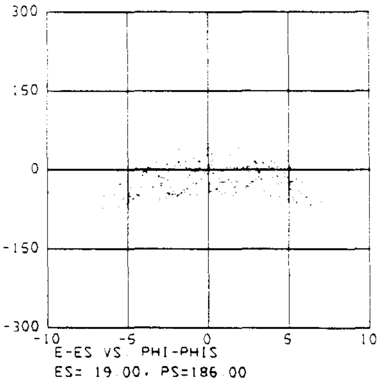

Fig. 1 (a). Scatter plot in longitudinal phase space for a beam accelerated from 10 to 19 MeV in a 1.3-GHz tank.

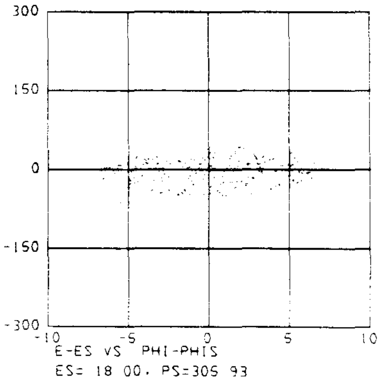

Fig. 1 (b). Correction of the curvature of Fig. 1 (a) by a third-harmonic cavity subtracting 1.0 MeV at the centroid of the bunch.

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*L. Young, Informal Workshop on High-Current Electron Injectors, Los Alamos National Laboratory, February 19-20, 1986.

Intrinsically Bright Electron Sources

The use of photoemissive electron sources for polarized beams in linacs[19] and for other uses[3] has given rise to their application in FEL linacs and wakefield-acceleration experiments.[20] For rf-linac-driven FELs, the required electron pulse train is naturally produced by a mode-locked laser illuminating a photoemitter. A laser-illuminated photocathode can be used in a dc gun configuration in much the same way that it is employed in the laser-klystron[21] or lasertron.[22] On the other hand, a more rapid acceleration rate can be achieved if the photocathode is placed in the rf field of a resonant cavity because an rf cavity can sustain a higher surface field than can a dc diode.[23] The rf gun, shown schematically in Fig. 2, forms the heart of an experimental program at the Los Alamos National Laboratory to develop an intrinsically bright electron source for linacs. If the transverse electron velocities in the photoelectron beam do not increase too rapidly with beam current, a bright beam should be obtainable. Early simulation calculations with the ISIS code at Los Alamos, however, showed that the leading and trailing edges of the bunch contained higher emittance components than did the midsection.[12] It follows that although a completely bunched beam can be produced by a laser illuminating a photoemitter, a penalty is paid in emittance. Therefore, a compromise is adopted in which an rf gun delivers to an injector linac a bunch that is longer than the optimum bunch length in the main linac. After acceleration to several million electron volts, a magnetic phase compressor shortens the bunch.

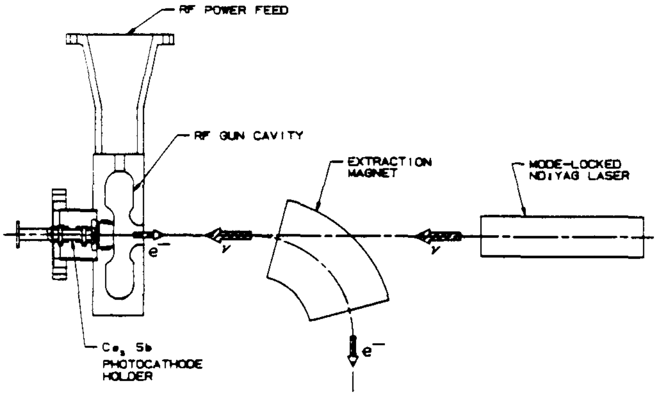

Fig. 2. The rf gun cavity.

The Los Alamos FEL operates at 1300 MHz. A logical choice for the frequency of the subharmonic injector linac is 433.3 MHz, a frequency for which a suitable klystron for low duty-factor operation is available. Figure 3 is a schematic diagram of a staged injector linac proposed for the Los Alamos FEL linac. The first section at 433 MHz comprises an rf gun and four accelerating cavites. The first two cavities are separately excited, whereas the final three are coupled through two off-axis cavities, the group of three coupled cavities being operated in the $\pi/2$ mode. Next is a 1.3-GHz cavity whose function is to flatten the top of the effective accelerating field; the mean beam energy is reduced in the process from 6 to 5.3 MeV. Finally, a bunching or energy-ramping cavity in the first section prepares the bunch for magnetic compression in a quartet of dipoles. The 90-ps pulse with a phase width of 16° at 433 MHz is compressed to 30 ps or 16° of phase in the second injector stage operated at 1.3 GHz. After acceleration to about 15 MeV, the flat-topping and magnetic-compression functions are repeated. A final magnetic compression could be carried out at the end of the main linac.

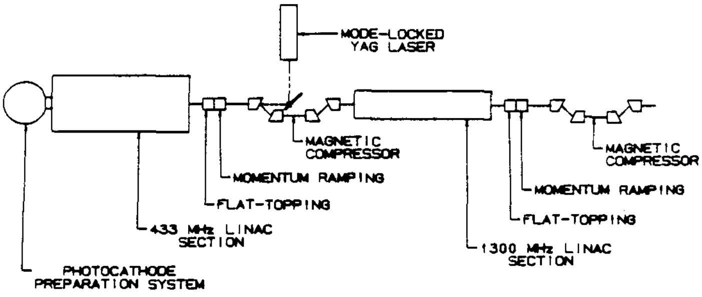

Fig. 3. Block diagram of a staged injector linac comprising a photoelectric rf gun source, a subharmonic linac, a magnetic phase compression system followed by a second injector linac at the main linac frequency and a second magnetic compressor.

Magnetic Phase Compression

Relativistic particles can be bunched by utilizing the path length difference in a system of bending magnets for particles of different momenta. The longitudinal phase space occupied by an ensemble of particles must be elongated and rotated so that a correlation exists between energy and phase. In this respect, a magnetic phase compressor system is similar to the energy compression system used with some intermediate-energy electron linacs to reduce the energy spread of the beam.[24–27] A magnetic phase compressor differs from an energy compressor only in rotation of the phase space of the bunch to produce a narrow phase spread rather than a narrow energy spread. Figure 4 (a) is a longitudinal phase-space diagram such as would be produced by an rf cavity operated as a buncher to put an energy ramp on the bunch but with the centroid unchanged in energy. In a system of dipole magnets (see Fig. 3), the path length difference produced for particles with differing momenta is represented in TRANSPORT notation by the R_{56} matrix element. For a positive R_{56} element, bunching will occur if the phase-energy diagram is as shown in Fig. 4 (a); for a negative R_{56} element, the slope of the scatter plot of Fig. 4 (a) must be reversed. Figure 4 (b) shows the bunching effect of a set of magnets with R_{56} = 0.24 cm/%.

The energy spread that makes the magnetic phase compression possible can be reduced if the bunching is left incomplete, as in Fig. 4 (b). Segall[28] has suggested the use of a second rf cavity to compress the energy spread impressed on the bunch by the first cavity. Figure 5 shows the result of a final set of cavities, which put a reversed energy ramp on the bunch to reduce the energy spread.

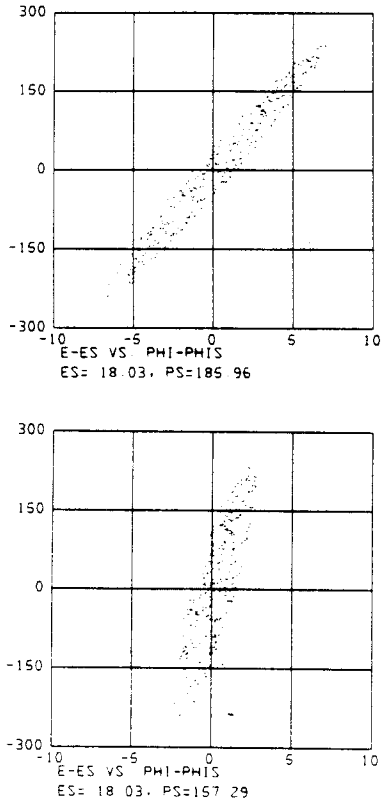

Fig. 4 (a). Energy ramp impressed on the bunch by an rf cavity and
(b) partial phase compression after passing through a set of magnets with R_{56} = 0.24 cm/%.

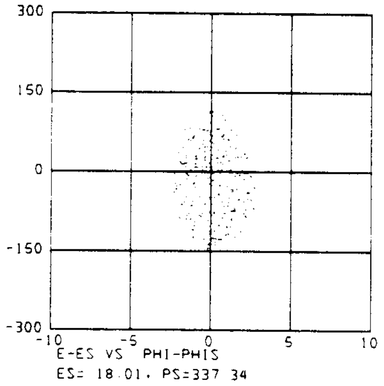

Fig. 5. Energy spread reduced from that of Fig. 4 (b) by an energy ramp of reversed slope to that of Fig. 4 (a).

Conclusions

An improvement in the performance of conventional injector linacs can be realized if the bunching process is done more gradually than is usually the case and at a lower (hence, subharmonic) frequency than the main linac frequency. It follows that only the first of several bunchers can be of the klystron or velocity modulation type. After an initial acceleration stage in a subharmonic-frequency linac, magnetic bunching is carried out before further acceleration in a higher frequency linac.

A potential improvement in electron guns, especially for high-average-current applications, lies in the rf gun, based on a mode-locked laser-illuminated photocathode in the first rf cavity of the injector linac.

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