MINIMUM BEAM-ENERGY SPREAD OF A HIGH-CURRENT RF LINAC*

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Abstract

Energy spread is an important parameter of an electron linac and, usually, is determined by the time dependence of the external rf accelerating field. By using a combination of fundamental and higher harmonic frequencies, the accelerating field can be maintained approximately constant over a beam bunch with the resultant energy spread approximately zero. This technique is no longer adequate when the longitudinal wake field of the beam bunch is taken into account. The wake-field variation along the bunch length introduces an energy spread that cannot be exactly compensated for with the use of fundamental and higher harmonic frequencies. The achievable minimum energy spread including the wake-field effect is therefore limited. In this paper, we report the minimum energy spreads achievable using the fundamental and third-harmonic frequencies, calculated using a least-squares algorithm, for some typical structures in use at Los Alamos National Laboratory. The dependence of these results on bunch shape, bunch charge, and structure frequency is discussed. Also included are discussions of schemes for implementing the third-harmonic frequency and their effectiveness.

I. Introduction

A small energy spread is required for almost all accelerator operations. In high-energy electron linacs, there are two major contributions to energy spread. The first is the external rf accelerating field in the cavities. Electrons in a bunch of finite length traversing an accelerating cavity will acquire a cosine-like energy variation along the bunch length. This energy spread can be effectively eliminated by the use of additional rf fields at higher harmonics.[1,2] For example, the use of a combination of third-harmonic and fundamental frequencies can allow the acceleration of a 37° bunch with only 0.1% energy spread.[2] The second contribution to energy spread is the longitudinal wake field induced by charges in a beam bunch, thereby modifying the energy of charges in the same bunch: that is to say, single bunch beam loading. Most of the wake field in a linac is generated in accelerating cavities; for a beam bunch with high charge density, a significant energy spread can be introduced.[3] Although this energy spread usually can be minimized by phasing the external rf voltage, it cannot be completely eliminated because it does not have the simple sinusoidal shape of the external voltages. In this paper, we describe a study of the minimum energy spread achievable with consideration of the wake fields produced in accelerating cavities. A typical 1300-MHz cavity at Los Alamos National Laboratory is used as an example. In Sec. II, the minimum energy spreads were calculated using a least-squares fitting procedure that has shown good agreement with experiments and with particle-tracking simulations.[4] The dependence of the minimum energy spread on beam parameters is discussed, and the improvement obtained by adding a third-harmonic component field is shown. In Sec. III, ways of adding a third-harmonic voltage are discussed.

II. Minimum Energy Spread with Wake Field

Figure 1 shows the energy-difference percentage along the bunch introduced by the bunch's wake field for an accelerator that consists of three successive stages: A, B, and C. The beam parameters are listed in Table I. Beam bunches are assumed to have Gaussian shapes with

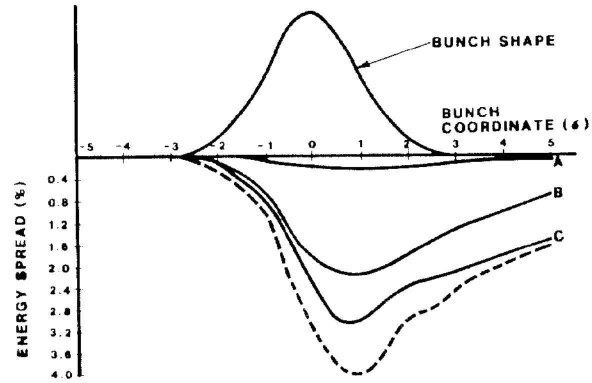

Fig. 1. Energy spreads introduced by single-bunch beam loading. The abcissa is the position along the Gaussian bunch in units of σ as given in Table I for curves A, B, C.

TABLE I

Beam Parameters of a Proposed Three-Stage Electron Accelerator at the Los Alamos National Laboratory[a]

Accelerator stage	A	B	C
Frequency (MHz)	433	1300	1300
Bunch charge (nC)	6	6	6
σ (ps)	90	30	15
Field gradient (MV/cavity)	1.5	0.6	0.6

[a]See Ref. 4.

bunch rms half-width of σ. These curves have been calculated using the computer code TBCI[5] with a typical cavity shape similar to the 1300-MHz cavity used at Los Alamos (Fig. 2). The curves in Fig. 1 show the general shape of the energy spread along the bunch. Energy spreads of up to 2.9% are introduced. They also show the typical scaling behavior of cavity wake fields: higher wake fields for higher frequency cavities and for shorter bunch lengths. The wake-field-induced energy spreads are usually reduced by advancing the phase of the bunch so that the increase of the wake field toward the end of the bunch can be compensated for by the still-rising external voltage. The best compensation lies in an amplitude and phase of the external rf field that best fits the wake-field shape. Numerically, one can fit the wake-field shape with a sinusoid of the fundamental frequency using a least-squares algorithm. The residual energy spread is then reduced to the difference between the best fit and the wake-field shape. This least-squares fitting method for obtaining the minimum energy spread has been compared to experimental measurement and particle-tracking simulations. In both cases, good agreement has been obtained.[4]

We have done this fitting for accelerator stages B and C. The difference between these two stages is only in the bunch length. The fitting variables were the amplitude and phase of the sinusoidal shape, and the field gradient at the middle of the bunch was constrained to the required accelerating field gradient as shown in Table I. Fits were obtained for two regions defined as between $\pm 1\sigma$ and between $\pm 2\sigma$. These two regions correspond, respectively, to regions containing 68 and 95% of the beam charge. Figure 3 shows typical fits for stage C. The

*Work performed under the auspices of the U. S. Department of Energy and supported by the U. S. Army Strategic Defense Command.

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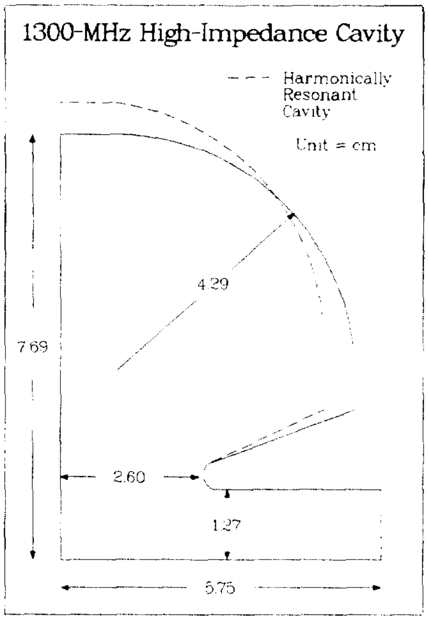

Fig. 2. A typical cavity shape used in the Los Alamos free-electron laser accelerator. The dashed curve is the modified shape that will support, in addition to the fundamental voltage, the third-harmonic frequency of 3900 MHz.

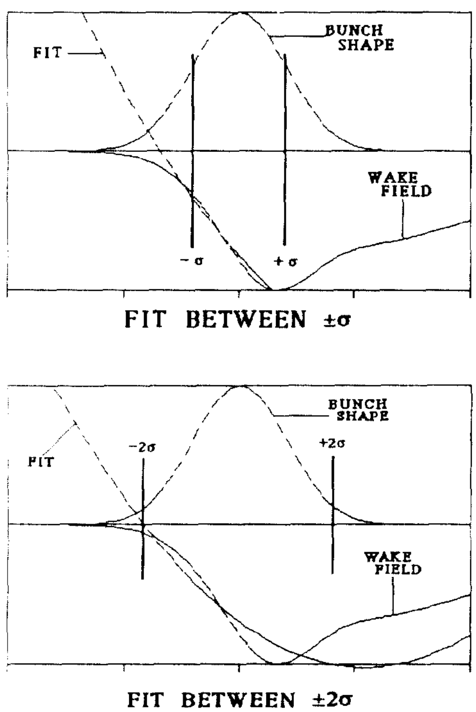

Fig. 3. Typical least-squares fits of the wake-field shape.

calculated minimum energy spreads are shown in Part 1 of Table II with the required operating peak fields and phases. Compared to the 600 kV required without wake-field compensation, there is an increase of rf power required because the bunch centroid is not at the maximum accelerating phase, a small penalty one pays to get better energy spread. In Part 2 of Table II, we show the results of using, in addition to the fundamental voltage, a third-harmonic rf voltage. A further decrease in energy spread by at least a factor of 2 is obtained. Compared to the 675- and 75-keV fundamental and third-harmonic voltages required[2] to compensate for the sinusoidal variation of the external rf voltage, the rf requirements are similar. In this latter fitting, we first use a sinusoidal shape for the fundamental frequency to fit without requiring a particular field gradient; then we use a combination of fundamental and third-harmonic frequencies to bring the field gradient to the required level afterwards. The operating phase of the third-harmonic voltage is restricted to zero degrees. We did not include the phase and amplitude of the third-harmonic voltage as fitting parameters because, with too many free parameters, such a fit usually gave a very high third-harmonic voltage and consequently does not represent a practical approach.

TABLE II

Least-Squares Fitting Results for the Minimum Energy Spread and the Required Peak Voltages and Phases[a]

		SYSTEM B 30 ps		SYSTEM C 15 ps	
		$\pm 1\sigma$	$\pm 2\sigma$	$\pm 1\sigma$	$\pm 2\sigma$
Part 1: No Third-Harmonic Voltage					
Energy Spread	(%)	0.28	1.42	0.45	1.10
V_1	(kV)	613	614	628	619
ϕ_1	(°)	-3.85	-2.4	-12.11	-7.86
Part 2: With Third-Harmonic Voltage					
Energy Spread	(%)	0.10	0.50	0.20	0.70
V_1	(kV)	650	662	522	560
ϕ_1	(°)	-3.91	-2.61	-14.01	-8.43
V_3	(kV)	-38.0	-51.4	108.9	60.9
Part 3: With Third-Harmonic Voltage					
Energy Spread	(%)	0.18	0.66	0.33	1.05
V_1	(kV)	637	655	504	524
ϕ_1	(°)	-4.79	-3.02	-20.36	-11.80
V_3	(kV)	-21.4	-41.0	147.0	106.0

[a] V_1 and ϕ are for the fundamental frequency and V_3 is for the third-harmonic frequency. The third-harmonic voltage is operated at zero phase.

To investigate the scaling of the minimum energy spread, one can perform the least-squares procedure analytically. By expanding the wake function and sinusoidal curves to third order at the beam bunch center, one finds that the minimum energy spread is proportional to $\phi^2[1 + M_1/E]$ for cases with fundamental frequency only and to $\phi^2(M_2/E)$ for cases with fundadmental plus the third-harmonic, where ϕ is the range of phase where fitting is done, E is the accelerating field gradient, and M_1 and M_2 are factors that depend on the frequencies and energy-loss parameters of the cavity modes. These formulae show that the energy spread

1. decreases with the accelerating gradient, approaching a limit in the case of fundamental voltage alone;
2. increases rapidly if a higher fraction (larger ϕ) of the beam is included; and
3. increases with M_1 and M_2; like other wake-field effects, both M_1 and M_2 increase with high bunch charge density, shorter bunch, higher cavity frequency, and higher cavity shunt impedance.

III. Method of Adding a Third-Harmonic Voltage

In the previous section, a third-harmonic voltage was used to reduce energy spread without specifying how it was produced. One can, in principle, add a separate, third-harmonic cavity. One example of this scheme (Fig. 4)

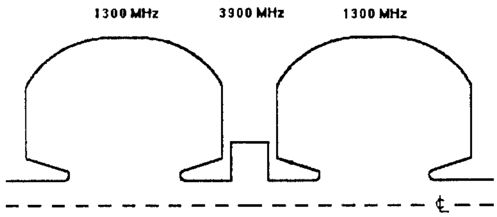

Fig. 4. A combination geometry of two 1300-MHz and one 3900-MHz cavities.

includes a third-harmonic cavity added between pairs of fundamental frequency-accelerating cavities.[6] The minimum energy spreads are summarized in Part 3 of Table II. Although there are improvements over the energy spreads compared to those in Part I, the energy spreads are higher than those in Part 2 because the wake field generated by the third-harmonic cavity has increased the energy spread from 3 to 4% (see dashed curve in Fig. 1) and introduced more higher frequency components in the wake fields.

A better approach is to support both the fundamental and third-harmonic frequencies in the accelerating cavity.[2] A high-shunt-impedance cavity, such as is represented in Fig. 2 by the solid lines, can be modified to become harmonically resonant at the fundamental and third harmonic, as shown by the dashed line in Fig. 2. The shape was adjusted using the computer code URMEL[7] so that the TM_{010}- and TM_{020}-like modes have frequencies of 1300 and 3900 MHz, respectively. For a harmonically excited cavity, it is important to have a capability to tune, independently at least, one of the two harmonically excited modes for simple frequency control during operation. The modified cavity was adjusted so that a region around point A (Fig. 5) has very weak magnetic and electric fields for the TM_{020}-like mode, allowing a tuner to be installed at this region for tuning primarily the TM_{010}-like mode frequency. The tuner sensitivities for the TM_{010}- and TM_{020}-like modes are, respectively, 0.9 and 0.05 MHz/cm.[3] If necessary, a second tuner can be installed at location B, which has a tuning sensitivity for the TM_{010}- and TM_{020}-like modes of 0.7 and 3.6 MHz/cm^3, respectively. Both tuners are accessible radially. The shunt impedance of the fundamental frequency is 6.4 MΩ/cavity, not significantly different from that of the original shape. The TM_{020}-like mode has a shunt impedance of 0.76 MΩ/cavity. Using the typical voltages required for third-harmonic voltages in Table II, the power dissipation in the cavity is increased by 10% over that required for the fundamental frequency alone.

IV. Conclusion

Although the energy spread in a low-current linac beam can be made less than 0.1% by flattening the rf field with the addition of a third-harmonic component, the reduction in energy spread at high current is limited when the longitudinal wake field is taken into account. However, the residual energy spread, including the wake field effect, can be minimized by proper choices of the external rf-field amplitude and phase. It is also better if only a small fraction of the bunch is considered. Third-harmonic voltages can further decrease the energy spread, and a preferred method of improvement is the use of a harmonically excited cavity supporting both the fundamental and third-harmonic frequencies. Such a cavity with high shunt impedance has been shown to be feasible.

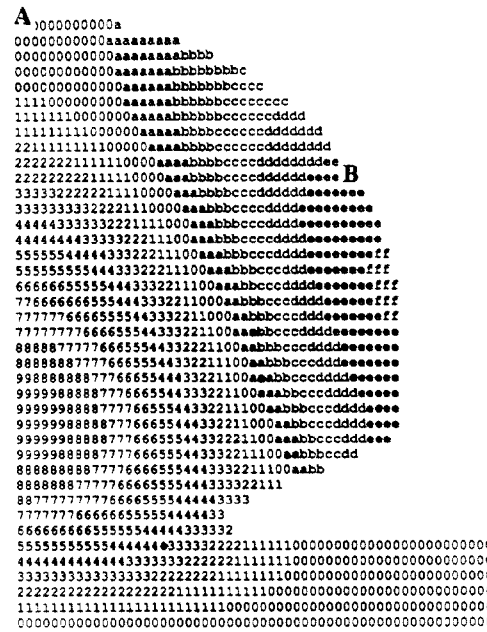

Fig. 5. An $(H_\phi * r)$ plot for the harmonically resonant cavity. The magnitude of $(H_\phi * r)$ is from negative to positive in the order of: f, e, d, ..., 0, ..., 6, 7, 8. Positions A and B are possible locations for tuners.

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