Comparison of Energy Spreads Induced by a Longitudinal Wakefield in a Cavity*

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Abstract

The energy spread of a beam bunch induced in a linear accelerator can be reduced to a minimum if the amplitude and the phase of the RF voltage are optimized. The energy spread is induced by the longitudinal wakefield and by the sinusoidal profile of the accelerating voltage acting on the beam. The cavity shape, the bunch profile, and the charge in the bunch determine the wake function. Aiming to have an approximately constant net voltage acting across the beam bunch, we optimize the amplitude and the phase of the RF voltage. The minimum energy spread, the required RF voltage, and the required RF phase are calculated as a function of the net charge and the length of the bunch. To find out the effect of cavity shape on the minimum energy spread, the optimization was performed for several types of cavities.

Introduction

When a beam bunch passes accelerator cavities, it experiences nonuniform acceleration over the bunch; the energy gained at the head differs from the energy gained at the tail of the bunch. Ideally, the beam maintains the energy spread if the net energy gained at each part of the beam is constant. However, an additional energy spread is induced by the sinusoidal RF voltage acting on the beam bunch. The energy spread is also induced because the longitudinal wakefield generated by the beam bunch acts on itself nonuniformly. Each part of the beam bunch is affected by the accelerating field and the wakefield. To accelerate the beam bunch to a given voltage without increasing the energy spread, we optimize the amplitude and the phase of the RF voltage so that the net acceleration as a sum of the wakefield and the sinusoidal profile of the RF is nearly the constant voltage over the bunch. In the least square optimization, we weight with the Gaussian beam charge distribution. This is an improvement of the optimization algorithm used in Ref. 2.

The longitudinal wake function depends on the cavity shape, the bunch profile, and the bunch charge. We calculate the longitudinal wake function for several cavity shapes using the code TBCI.[1] Then, the sum of the wake function and the accelerating voltage is fitted to a constant voltage over a range where the beam bunch effectively interacts with a free-electron laser (FEL); the low charge density at the beam head and at the tail do not contribute to the laser amplification. To simplify the argument, we limit the fitting range to $\pm 1.2\sigma$ from the center of the Gaussian bunch in the calculation. Although a better fit can be achieved by introducing odd harmonics of RF,[2] we limit accelerating voltage to only the fundamental RF frequency of 433.3 MHz. We consider four types of cavities: (1) the ERX-type cavity,[3] (2) the MCTD-type cavity,[4] (3) the elliptic-type cavity, and (4) the ERX/elliptic-type cavity. The profiles of the cavities are shown in Figs. 1a through 1d in the above order. In the following calculation, we fit the RF such that each cavity accelerates 1.0 MeV on average over the bunch.

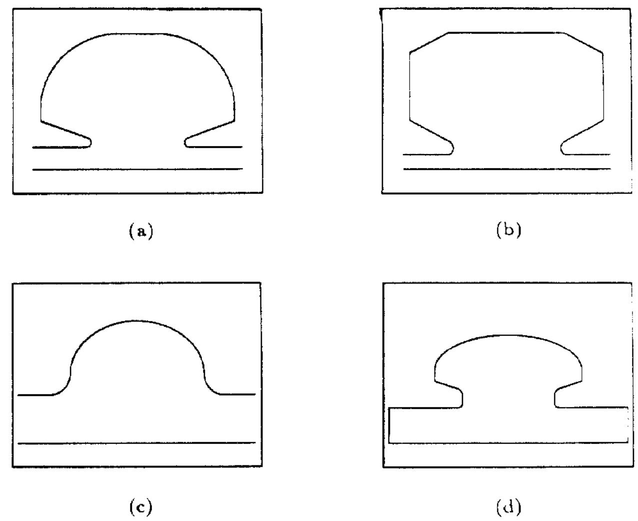

Fig. 1. (a) ERX-type cavity, (b) MCTD-type cavity, (c) elliptic cavity, and (d) ERX/elliptic-type cavity.

The RF Voltage Boost and RF Phase Offset for a 1-MeV Net Acceleration

Assuming that the center of the beam bunch is at the origin of the z axis, a 45-ps bunch (i.e., full width 2σ) and a 10-nC charge, Fig. 2 shows the net voltage acting on the beam as a solid curve for the elliptic cavity. The voltage is approximately constant from -1 cm to $+1$ cm. The origin is set to 1 MV. The wake potential for 10 nC is shown as a dashed curve.

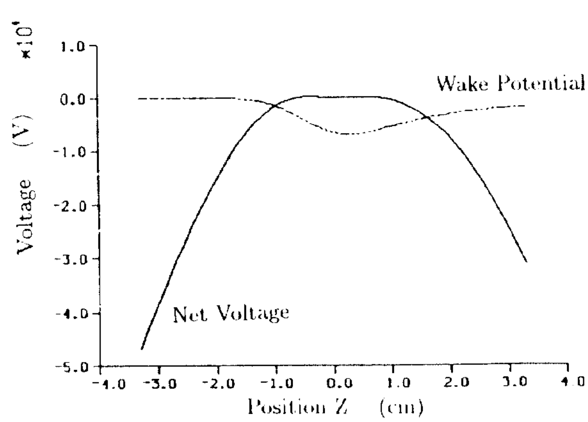

Fig. 2. Net voltage acting on the bunch with 10 nC and an induced wake potential.

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The optimized RF voltage must compensate for two effects: one is for reduced voltage acting on the particle caused by the optimized RF phase displaced from maximum accelerating phase. This is to cancel the leading slope of the wake function. The other is for nullifying the reduced net voltage caused by the energy loss due to the longitudinal wakefield. Because the wakefield is proportional to the charge of the beam bunch, the needed RF voltage boost must increase as the charge increases.

The voltage boost δV determined by the optimization is calculated as a function of the net charge in the beam bunch. The voltage boosts are shown in Fig. 3a for each type of cavity. Solid curves represent bunch full length ($= 2\sigma$) at 15-ps. With a 15-ps bunch full length ($= 2\sigma$) and a 30-nC charge, the ERX cavity required a 300 kV voltage boost. The depth of the wake function is about 37 kV at the center of the bunch. But the voltage boost decreases rapidly as the bunch length increases. The optimized phase offset, 37°, itself requires a 260-kV boost. Figure 3b shows the optimized phase offsets for the different

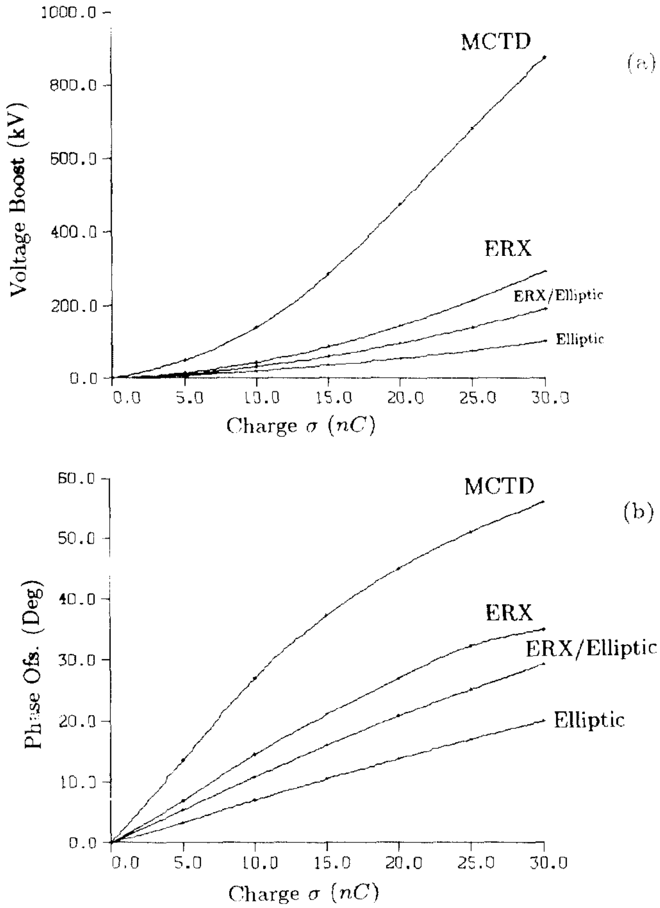

Fig. 3. (a) Required RF voltage boosts δV at a minimum energy spread for a fundamental and (b) phase offsets ϕ.

bunches. For the MCTD cavity, we must boost the voltage by 900 kV for the same bunch to accelerate 1 MeV. The optimized phase offset is 56°, which accounts for the 840 kV. The remaining 60 kV is the depth of the wake function at the center of the bunch. The ERX elliptic-type cavity requires 190 kV of voltage boost for the same bunch. The phase offset is 29.4°, which accounts for the 150 kV. The remaining 40 kV comes from the depth of the wake function. The elliptic-type cavity requires only a 105-kV voltage boost. The phase offset is 20°, and the wake function is 70 kV.

The elliptic-type cavity was designed to minimize wakefield effects by increasing the size of the beam pipe. In doing so, the shunt impedance of the cavity was reduced by a factor of 2. Results show that much of this loss of power efficiency in the elliptic-type cavity compared to other cavity types is recovered when an optimized energy spread is considered. The large voltage boost required for the high shunt-impedance cavities is not required in the case of the elliptic-type cavity.

The Optimized rms Energy Spread

We calculate rms energy spreads induced at each cavity at the optimized voltage and phase. The rms energy spreads are calculated in a range $\pm 1.2\sigma$ of the charge distribution. Figure 4 shows the rms energy spreads for various charge and bunch lengths for the ERX cavity. The full rms energy is much smaller than the depth of the wake function. The fitting for the 15-ps bunch is near perfect. As a result, the calculated energy spread for the 15-ps bunch is better than the 20-ps or the 25-ps bunch. The energy spread is approximately linear with the charge of the bunch except for the long bunch with the low-charge state. The shape of the wake function for the long bunch with low charge differs significantly: the cancellation of the RF voltage and the wake function are poor and increased the energy spreads. For the MCTD-type cavity, the energy spread is approximately linear with the charge (Fig. 5). The elliptic-type cavity shows the same feature as the ERX cavity: the energy spread increases at low charge and long bunch. At other conditions, the rms energy spread is approximately linear with the charge (Fig. 6). The energy spread is linear with the charge for the ERX elliptic-type cavity (Fig. 7).

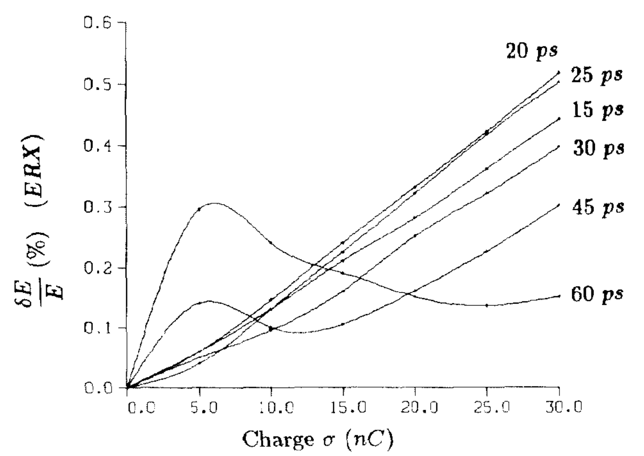

Fig. 4. Minimized rms energy spreads at various bunch full lengths (2σ of Gaussian bunch) (ERX cavity).

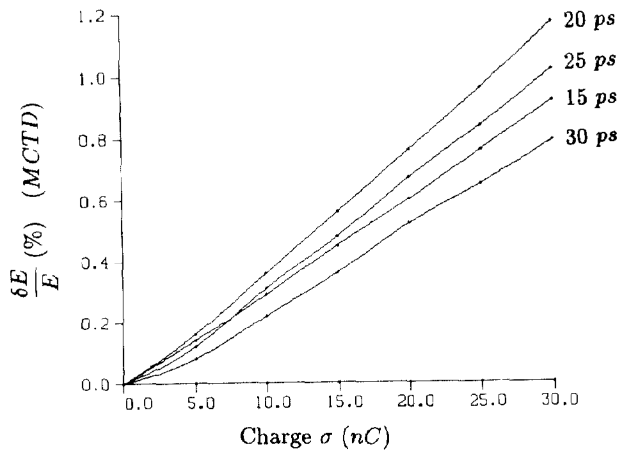

Fig. 5. Minimized rms energy spreads at various bunch full length (MCTD cavity).

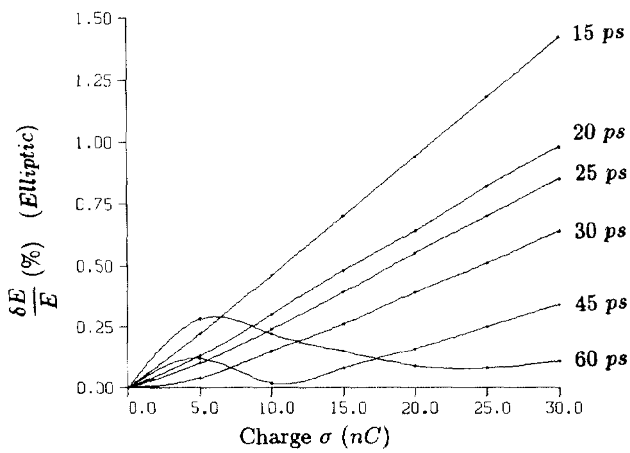

Fig. 6. Minimized rms energy spreads at various bunch full length (elliptic cavity).

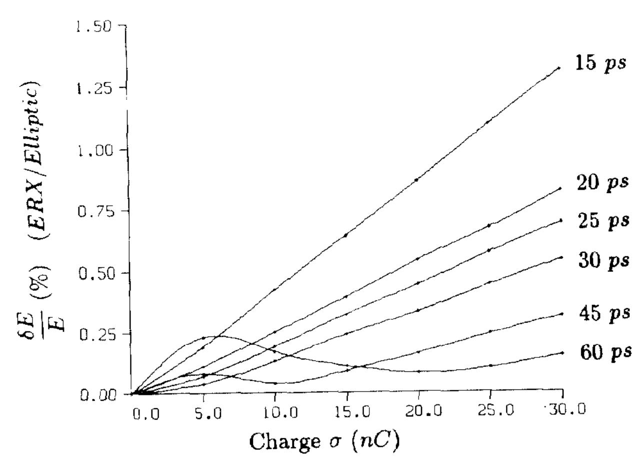

Fig. 7. Minimized rms energy spreads at various bunch full length (ERX/elliptic).

Energy Spread Improvements

Calculating the full energy spread within the $\pm 1.2\sigma$ of the Gaussian beam without optimization and comparing to the energy spread with the optimized voltage and phase, the energy spread reduction factors are calculated. The ratios of energy spreads with optimization and without optimization are plotted against the charge of the bunch in Fig. 8. The improvement strongly depends on the cavity type and it depends weakly on the charge.

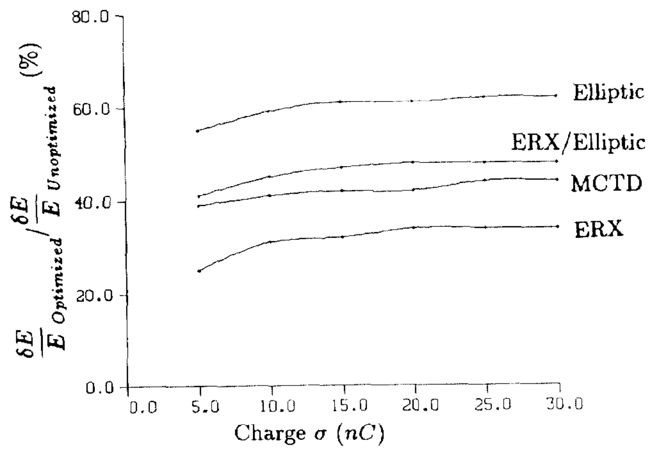

Fig. 8. Ratio of an energy spread with optimization to an energy spread without optimization for a 20-ps pulse; energy spreads are extreme to extreme.

Conclusion

To accelerate to the same 1 MeV for each cavity, the phase offset of the RF determines the largest part of the increase of the RF voltage required to minimize the beam energy spread. The optimization shows that the energy spread can be reduced by a factor of 3 for the ERX-type cavity and the MCTD-type cavity by adjusting the amplitude and the phase of the RF voltage. This is done by increasing RF voltage and phase. However, the ERX-type cavity is superior because it requires a third of the voltage of the MCTD to attain the same energy spread. The reduction of energy spread achieved by the optimization depends strongly on the cavity shape, but not on the beam charge.

References

1. T. Weiland, "Transverse Beam Cavity Interaction, Part I: Short Range Forces," Deutsches Elektronen Synchrotron report DESY 82-015 (1982).

2. K. C. D. Chan and J. S. Fraser, "Minimum Beam-Energy Spread of a High-Current RF Linac," 1987 Particle Accelerator Conference, IEEE Catalog No. 87CH2387-9, Vol. II, p. 1075.

3. The ERX-type cavity was used for the Energy Recovery Experiment at the Los Alamos Free-Electron Laser Facility.

4. The MCTD-type cavity was designed for the Modular Component Technology Development project at Boeing Corp., Seattle.