WAKE-FIELD COMPENSATION IN ENERGY RECOVERY LINACS

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Abstract

Problems created by the correlated energy spread that wake fields can produce are strongly enhanced in Energy Recovery Linacs (ERLs), as compared to conventional linacs. This is due to the fact that in ERLs the spent beam is decelerated by a potentially large factor, which increases the relative energy spread proportionally. We show how severe this problem is for the impedance budget of the x-ray ERL that Cornell plans to build, and we analyze several different possibilities to compensate the correlated energy spread involving de-phasing linac components, linear and nonlinear time-of-flight terms in different accelerator sections, or high frequency accelerating cavities. Because of the particular design, which has a turn-around loop between two sections of the linac, there are many options for these techniques, which we compare and evaluate.

INTRODUCTION

Energy Recovery Linacs (ERLs) accelerate high-current particle beams to high energy in a linac. These are then used in x-ray, FEL or nuclear physics experiments. Subsequently, the beams are sent into the same linac at a decelerating phase to recover the particles' energy. This energy is then used to accelerate new bunches of particles. Only with such energy-recycling does it become feasible to accelerate high-current beams to high energies in a linac.

One of the problems ERLs face is the wake-field-driven energy spread that builds up during a pass through the ERL. The energy spread is relevant because it limits the bandwidth of the x-ray radiation. And even more importantly, it is multiplied during deceleration by the ratio between high energy and dump energy, which is approximately 500 in the case of the Cornell ERL [1]. Decelerated bunches must be decoupled from accelerated bunches, via magnetic fields, in a demerger region before the dump. Here, particles with too large an energy are not bent sufficiently to reach the dump; similarly, particles with too little energy hit the beam pipe before the dump, or are even decelerated to zero energy before leaving the superconducting linac, and are then lost in the cryogenic environment. Therefore, the energy spread that bunches have at the end of their deceleration has to be limited.

Non-linear time-of-flight terms within the linacs can be used to reduce this correlated energy spread [2]. This paper explains how time-of-flight terms can be used and how they need to be chosen, and why two turn-around arcs are necessary. One can describe the propagation of a bunch's

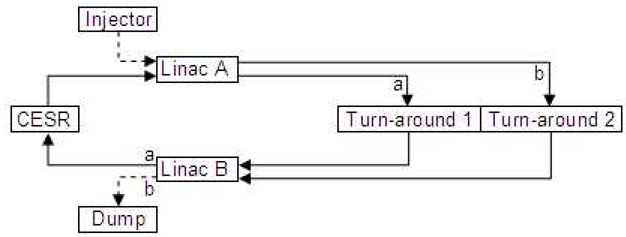

Figure 1: Schematic of the Cornell ERL. The linac is split into the sections with two turn around bends between the linac, one for the accelerating and one for the decelerating beam.

longitudinal phase-space distribution through the ERL via transformations for separate ERL components. These calculations have been performed for the Cornell ERL and the results are described below. In this accelerator, shown schematically in Fig. 1, the bunch is created in the Injector, accelerated in Linac A, taken through Turn-around 1 to accelerate in Linac B, bent back in CESR to decelerate in Linac A, then through Turn-around 2 to decelerate in Linac B and finally ending in the dump.

Source	Number	Max (kV/pC)
7 Cell RF Cavity	800	-11.32
Higher Mode Load (78 mm)	400	-0.89
Higher Mode Load (106 mm)	400	-0.50
Expansion Joint	356	-0.74
Beam Position Monitor (Button)	664	-0.35
Beam Position Monitor (Stripline)	20	-0.01
Flange Joint	356	-0.90
Clearing Electrode	150	-0.18
Gate Valve	68	-0.71
1 m Resistive Wall (12.7 mm)	2500	-4.00
1 m Roughness (12.7 mm)	2500	-14.00
Undulator Taper (3 mm)	18	-0.61
1 m Resistive Wall (3 mm)	144	-0.98
1 m Roughness (3 mm)	144	-3.60

Table 1: Sources and magnitudes of wake-driven energy spread [3]. The bunch in Cornell's ERL is 77pC.

SOURCES OF ENERGY SPREAD

In an ERL, having a beam with a bunch length of order of 1mm, there are three major sources for the beam's energy spread, the curvature of the RF accelerating voltage, wake fields and coherent synchrotron radiation (CSR.) In

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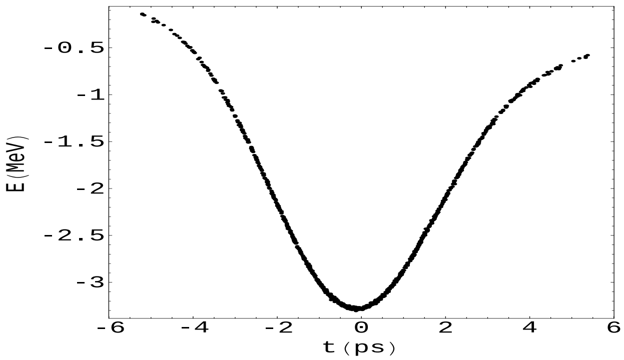

Figure 2: Accumulated longitudinal wake potential of the Cornell ERL.

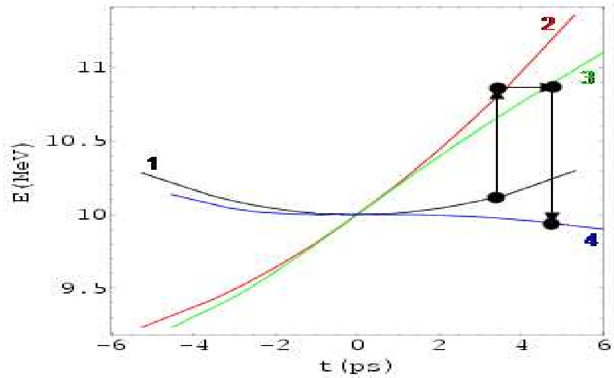

Figure 3: Illustration of curvature change in $E(t)$ by off-crest acceleration and nonlinear time-of-flight terms.

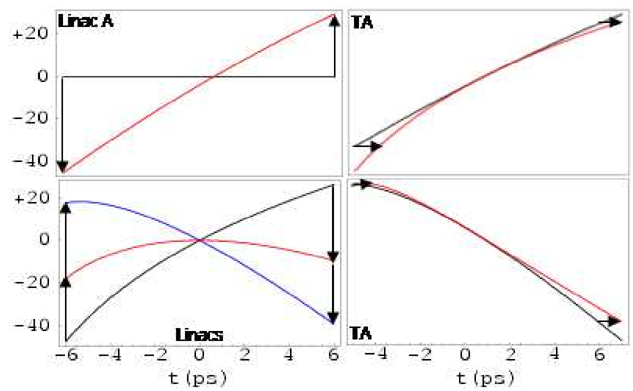

Figure 4: Illustration of curvature cancellation in $E(t)$ by time-of-flight terms in a common turn-around loop for accelerating and decelerating beams. Ordinate: energy relative to the bunch center in MeV.

the Cornell ERL, CSR is important for bunch lengths significantly less than 0.6mm, so this effect on energy spread should not be important. Table 1 lists the sources and magnitudes of wake fields for 0.6mm bunches passing through the different vacuum chamber components. The structure of the wake field from the entire ERL and its effect on the energy spread of the bunch in the Cornell ERL is estimated in Fig. 2.

COMPENSATION METHODS FOR WAKE-DRIVEN ENERGY SPREAD

A bunch's correlated energy spread may be reduced by decreasing its slope and curvature in time-energy phase space. This can be done by accelerating the bunch off-crest in the linacs, choosing an energy-dependent time of flight, and then further accelerating the bunch off-crest. We sketch this procedure in Fig. 3. There, arrows show the phase-space motion of a particle. Curve 1 shows the initial bunch profile; curve 2 shows the bunch after acceleration by the linacs; curve 3 shows the bunch after application of time-of-flight terms; curve 4 shows the bunch after further acceleration, where the bunch's initial curvature, i.e. second-order correlation between time and energy, is eliminated. The arrows follow one particle of the bunch through this process.

There are several different options for how the time-of-flight correction can be created: a) in CESR, b) in one turn-around used for both the accelerated and decelerated beams, and c) with separate turn-arounds and time-of-flight corrections for the accelerated and decelerated beams. When time-of-flight in CESR is used (a) to reduce the slope and curvature of the longitudinal phase space distribution, the beam must accelerated off-crest and admitted into CESR with a first order phase space energy correlation. Consequently, the bunch entering CESR must have a large energy spread, which undesirably broadens the bunch's x-ray spectrum, rendering it unfeasible to use time-of-flight terms in CESR for wake compensation. For possibility (b) with a common turn-around loop to make use of the second linac to eliminate the energy slope of the phase space distribution in CESR by operating the two linacs $\pm\Delta\Phi$ off of the RF crest. However, as explained in Fig. 4, this produces no curvature change in the phase space distribution at the dump. First, linac A accelerates off-crest to produce a correlated energy spread here with positive slope. Second, the turn-around loop adds a second order time-of-flight shift, here to the right and thus effectively to the bottom of the bunch. In the second pass through the turn-around loop, the slope is negative, so that the second order time-of-flight terms shift effectively to the top of the bunch, compensating the curvature change in the first pass. The curvature from the first turn-around loop is counter-balanced by the curvature from the second turn-around loop. Evidently, this method cannot change the curvature or any other even-order time-energy correlation. This leads to the conclusion that the compensation of the bunch energy spread can be feasibly carried out in neither CESR nor a single turn-around loop.

However, passing the bunch through different turn-around loops before and after CESR allows different time-of-flight contributions and thus enables the curvature re-

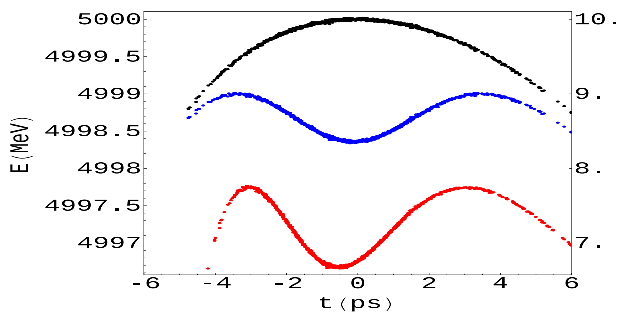

Figure 5: Bunch profiles after nonlinear-wake correction with separate turn-around loops for each ERL beam. Left ordinate: energy at CESR, right ordinate: energy at dump. Black-top: Cosine-like correlated longitudinal phase space from accelerating on crest with a $\sigma_t = 2$ps bunch length. Blue-middle: Longitudinal profile after suffering half the Cornell ERL's wake field. Red-bottom: Longitudinal profile at dump with residual energy spread due to higher-order correlations.

duction of the bunch's energy spread in CESR and the dump separately. The results of an optimization for the parameters of turn-around loops leads to the results found in Fig. 5 where the maximum energy difference within the bunch has been reduced from 3.2MeV to 1.1MeV. The third alternative (c) minimizes the phase-space curvature at the bunch center before the dump by adding energy to the bunch-center to flatten its longitudinal phase-space distribution. We simulate this by inserting a cavity with period T approximately six times as large as σ_t, the rms temporal bunch length, immediately after CESR. T is chosen to ensure the cavity is a multiple of the linac frequency, so subsequent bunches have the same phase at the cavity. This can be implemented using a single turn-around loop and results in a reduction in the energy difference between particles in the bunch from 3.2MeV and 0.60MeV. However, this solution would require a cavity frequency of approximately 80 GHz, where high power RF sources are not available.

Still using a single turn-around loop, this may be remedied by increasing the bunch length approximately a factor of 7 to utilize a cavity powered by an RF source at 11.7 GHz and then re-compressing immediately before passing into any of the linac sections to avoid increasing the energy spread from the curvature of the accelerating field. When the beam passes through the turn-around for the second time during deceleration, the bunch is first compressed and then decompressed. For this case the energy difference within the bunch decreases to 0.72MeV. Although this is a respectable result, it requires the bunch to be over-compressed during the second pass through the turn-around producing a very short bunch length and exacerbating CSR damage to the beam. A last alternative is to use harmonic correction with separate turn-around loops result-

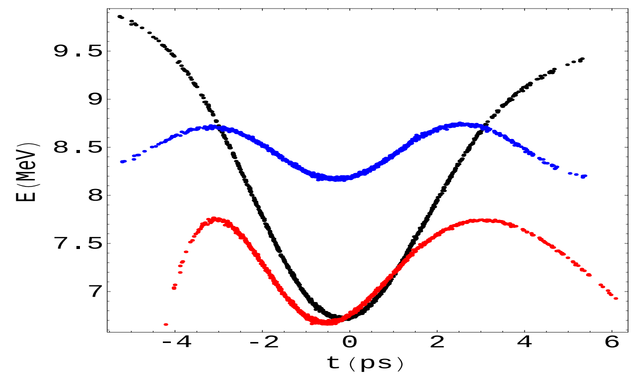

Figure 6: Black-top: Longitudinal profile at dump without wake-correction. Blue-middle: Dump profile with high frequency harmonic wake-correction. Red-middle: Dump profile with nonlinear time-of-flight wake-correction. Harmonic wake-correction reduces energy spread more but is less feasible than nonlinear wake-correction.

ing a reduction of the energy differences within the bunch to 0.69MeV. Figure 6 gives the energy distribution at the dump using harmonic correction from two separate turn-arounds in comparison with the uncorrected wake field and with non-linear time-of-flight compensation.

CONCLUSIONS

This paper reports that wake fields in ERLs can produce a large energy spread at the beam dump, representing a potential source of lost particles from the beam. For the Cornell ERL design we have learned that the use of non-linear time-of-flight transport in CESR or in a single turn-around arc will not succeed with a practical method for significantly reducing the energy spread of the beam at the dump. However, employing non-linear time-of-flight transport in two separate turn-around arcs and harmonic RF cavity compensation yields a practical method to reduce the beam's energy spread. Also the latter correction requires separate turn around arcs. Cornell's ERL design therefore contains two turn around arcs in between two linacs.

REFERENCES

[1] G.H. Hoffstaetter et al., Challenges for beams in an ERL extension to CESR, published in these proceedings of EPAC08, Genoa/IT (2008)

[2] G.H. Hoffstaetter, Yang Hao Lau, Compensation of wake-field-driven energy spread in Energy Recovery Linacs, arXiv:0805.2637v1 (2008)

[3] M. Billing, Wakes and Energy Spread During Energy Recovery, in Review of ERL@CESR, Cornell University (August 2007)