DESIGN OF A 980-MEV ENERGY RECOVERY LINAC*

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Abstract

A 980-MeV energy recovery linac with radiofrequency (rf) of 1.5 GHz is designed. Electrons are accelerated by two passages through a 480-MeV superconducting linac, and decelerated by two subsequent passages. Recirculation is accomplished with six 60-degree bending magnets. The threshold current for beam breakup instability exceeds 100 mA. Gaussian bunches with normalized transverse emittances of 0.1 mm-mrad and rms length of 1.85 ps may be compressed by a factor of 180 (to a bunch length of 10 fs) with only a slight increase in transverse normalized emittance. Bunch charges up to 8 pC may be compressed at 980 MeV without excessive degradation from coherent synchrotron radiation, allowing operation with beam currents up to 12 mA.

INTRODUCTION

A 980-MeV energy recovery linac (ERL) may provide short pulses of bright synchrotron radiation with a high repetition rate. A "two-up/two-down" ERL accelerates 20-MeV bunches by two passages through a 480-MeV superconducting linac and decelerates by two subsequent passages. We describe the linac, recirculation arcs, beam spreader/combiner, and bunch compression in Ref. [1].

LATTICE DESIGN AND PERFORMANCE

We accelerate 20-MeV bunches from a high-performance electron gun and gunline that provides an average current ≤ 100 mA, repetition rate of 1.5 GHz and normalized emittances in both transverse directions of 0.1 mm-mrad. We accelerate with a superconducting linac composed of CEBAF/Cornell 5-cell cavities [2]. Quadrupole strengths are limited to values that are feasible with CEBAF magnets [2]: $|\partial B/\partial x|$ < 5.25 T/m for air-cooled quadrupoles in the linac and $|\partial B/\partial x|$ < 31.5 T/m for water-cooled quadrupoles in the recirculation arcs. We model sextupole magnets with zero length for tracking accuracy. Sextupoles of 0.1-m length can meet the CEBAF specification $|\partial^2 B/\partial x^2|$ < 1280 T/m^2. Dipole magnets are limited to 1.67 T.

The 20-MeV beam is accelerated to 500 MeV by a 480-MeV superconducting linac, recirculated in phase with the 20-MeV beam, and accelerated to 980 MeV. The 980-MeV beam is recirculated to arrive 180° out of phase with the 20-MeV beam. Two more passages through the linac decelerate the beam to 20 MeV.

In the graded-gradient linac, the focal lengths of all quadrupoles are equal when acting upon the lowest-energy beam [3]. Quadrupole fields are symmetric about the linac midpoint. We design recirculation arcs that are symmetric about their midpoint, with symmetric beta-functions. In this symmetric design, the beta-functions of the ERL are symmetric about the center of the 980-MeV recirculation arc.

The beam's transverse focusing is described with the traditional non-canonical beta-function parameterization of position and direction of propagation [4] that is used in the MAD-with-acceleration [5] and "elegant" [6, 7] codes. We begin with a 20-MeV beam with $\beta_x = \beta_y$ = 8 m and $\alpha_x = \alpha_y$ = 0. A quadrupole matches the beam to the linac entrance. The 480-MeV linac consists of 8 cryomodules separated by 2.2m. Each cryomodule contains eight 0.5-m cavities separated by 0.5 m; each cavity provides acceleration of 7.5 MeV. Focusing is provided by 0.2-m quadrupoles located between cryomodules and centered at locations 1.1-m before and after the linac. In the first half-passage through the linac, the horizontal betatron phase advances ~99° between horizontally focusing quadrupoles while the vertical phase advances ~95° between vertically focusing quadrupoles.

The two recirculation arcs have 180° isochronous achromatic bending arcs at each end. Each bending arc contains three identical 60° dipole sector magnets. In the 980-MeV and 500-MeV dipoles, the orbit's radii of curvature are 2 m and 1 m, respectively. We used eqs. (6)–(9) of Ref. [8] to find reasonable quadrupole strengths and drift lengths. We then computed the horizontal and vertical transfer matrices of each bending arc using MAD

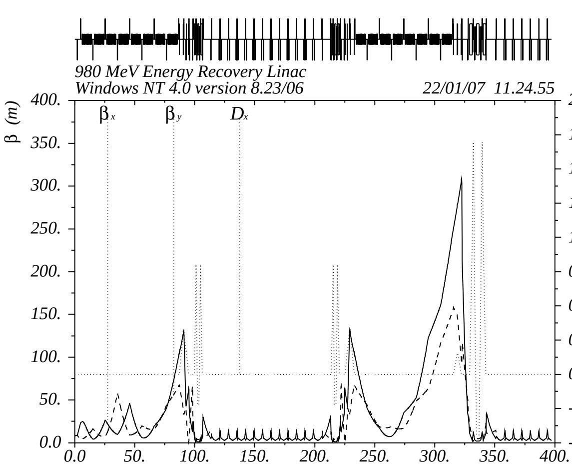

Figure 1: Lattice functions for one half of the 980-MeV energy recovery linac.

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[5]. With these transfer matrices and eqs. (C.8) and (C.9) of Ref. [8], we found reasonable lattice functions (β_x, β_y) that are symmetric about the center of the bending arc. Sextupoles are added for beam compression.

A beam spreader and beam combiner match the linac to the bending arcs. The 500-MeV electrons traverse an asymmetric chicane followed by two quadrupole doublets; the dipole bending angles are 5.624°. The 980-MeV electrons traverse a 4-dipole symmetric chicane followed by two quadrupole doublets; the dipole bending angles are 2.866°. A back straight section parallel to the linac is matched to the bending arcs to complete each recirculation arc. In the back straight section, the beam is periodically focused, with $\beta_x = \beta_y = 2.5$ m and $\alpha_x = \alpha_y = 0$ at the center of each recirculation arc.

The lattice functions from the gunline to the center of the 980-MeV recirculation arc are shown in Fig. 1.

This symmetric design is a starting point for designs that compress bunches accelerated at a linac phase that precedes the peak by 10°. We can compress the chirped bunches in the first half of each recirculation arc to obtain short bunches with energies of 500 MeV and 980 MeV. We decompress in the second half of each recirculation arc to restore the original bunchlength at the linac entrance. We can also compress and decompress the 980-MeV bunches while the 500-MeV bunches undergo isochronous transport.

To compress/decompress to first order using the MAD-with-acceleration matching, we vary the strengths of the quadrupole families in the bending arcs, and the quadrupoles in the spreader/combiner and the two-doublet sections that match the bending arc to the straight section. We constrain the lattice functions at the ends of the linac and back straight sections, and require mirror-symmetry in the bending arcs. To satisfy constraints on the second-order transfer map, some sextupole strengths are varied.

We constrain the transfer map from the beginning of our model (where the energy is 20 MeV) to the center of each recirculation arc. We maximize compression in each recirculation arc by constraining $R_{55} = R_{15} = R_{25} = 0$ and $T_{555} = T_{155} = T_{255} = 0$. For decompression, we constrain the transfer map from the beginning of our model to the linac entrance at the end of each recirculation arc, constraining $R_{55} = 1$, $R_{15} = R_{25} = 0$ and $T_{555} = T_{155} = T_{255} = 0$. For compression at 980 MeV and isochronous transport at 500 MeV, we change the R_{55} matching constraint from the beginning of our model to the center of the 500-MeV recirculation arc from $R_{55} = 0$ to $R_{55} = 1$.

We achieve a high degree of longitudinal compression in both recirculation arcs. For low current operation with normalized emittances in both transverse directions of 0.1 mm-mrad, tracking was performed without synchrotron radiation. In tracking with the MAD-with-acceleration code, bunches with initial rms bunchlength of 1.85 ps are compressed to 22 fs in the 500-MeV arc, to 15 fs in the 980-MeV arc, and to 32 fs in the second passage through the 500-MeV arc. The compressed bunch transverse dimensions are slightly larger than those given by conservation of the normalized emittance. With the elegant code, bunches with initial $\sigma_t =$ 1.85 ps are compressed to 8.5 fs in the 500-MeV arc, to 9.2 fs in the 980-MeV arc, and to 48 fs in the second passage through the 500-MeV arc. When incoherent synchrotron radiation is included in elegant tracking, the compressed bunch lengths and horizontal sizes are slightly increased.

BBU INSTABILITY

Transverse beam breakup (BBU) may limit the beam current that may be transported. To determine the threshold currents, the transfer matrix of the recirculation arcs is required. For a symmetric recirculation arc, we find a symmetric triplet with symmetric beta-functions that equal those of the arc at the endpoints. We represent the transfer matrix of any symmetric recirculation arc by the matrix $T_2 \times T(\Delta\psi_x, \Delta\psi_y) \times T_1$, where T_1 is the transfer matrix of the first half of the triplet, T_2 is the transfer matrix of the second half of the triplet, and $T(\Delta\psi_x, \Delta\psi_x)$ is a transfer matrix giving phase advances in x and y of $\Delta\psi_x$ and $\Delta\psi_y$ without changing the lattice functions.

To determine the maximum beam currents that can propagate without exciting transverse BBU instability, we use the TDBBU code [9] to model bunches with 1.5-GHz repetition frequency. We consider the CEBAF/Cornell 5-cell cavity with one higher order mode (HOM) per cavity whose transverse impedance is 22.2 Ω (linac definition) [2]. This corresponds to transverse impedance of 11.1 Ω in the "standard" definition where a pillbox cavity of length L and radius b has transverse impedance of 96.7(L/b) Ω. The HOMs have quality factor of 3200, with resonant frequencies randomly distributed between

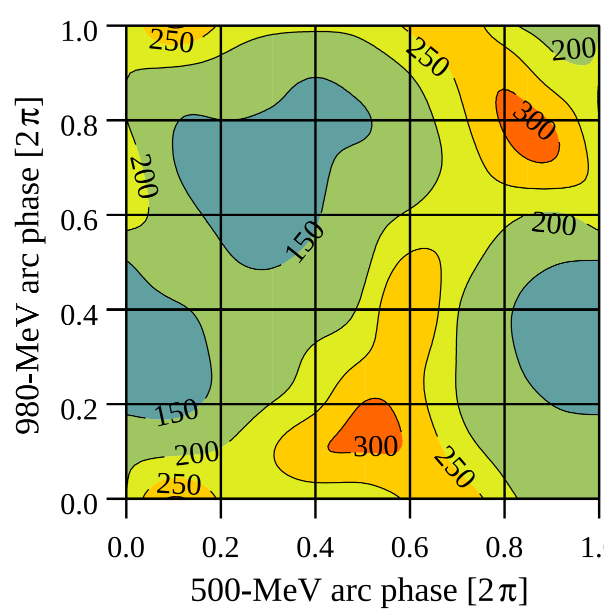


Figure 2: Horizontal beam breakup (BBU) instability threshold current (in mA) determined by the "TDBBU" code, versus betatron phase advance in the 500-MeV and 980-MeV recirculation arcs.

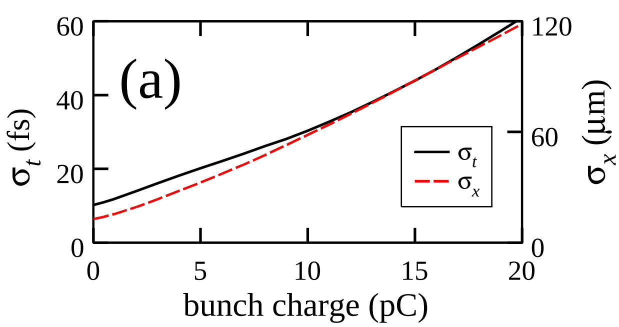
1888 and 1889 MHz with a uniform distribution [2]. By studying different random number seeds, we found that the computed threshold currents have only a slight dependence upon the seed.

Figure 2 shows the computed threshold current of horizontal BBU instability versus the phase advance of the two recirculation arcs. Threshold currents exceed 100 mA for all recirculation arc phase advances; this is also the case for vertical BBU instability [1].

COHERENT SYNCHROTRON RADIATION

The passage of compressed bunches through bending magnets may produce a large amount of coherent synchrotron radiation, thereby spoiling the bunch-compression process. We study this effect with the tracking code "elegant" [6, 7], in which the "csrcsbend" element models coherent synchrotron radiation (CSR) and incoherent synchrotron radiation (ISR) in the dipole magnets. The shielding of long-wavelength synchrotron radiation by the vacuum chamber is not considered.

In our elegant tracking, a Gaussian bunch with 0.1 μm normalized transverse emittance and bunchlength σ_t = 1.85 ps (σ_z = 555 μm) is represented by 100,000 macroparticles in a distribution truncated at $3\sigma_t$, centered at the linac phase that precedes the crest by 10°. The rms bunchlength corresponds to one degree of linac phase.



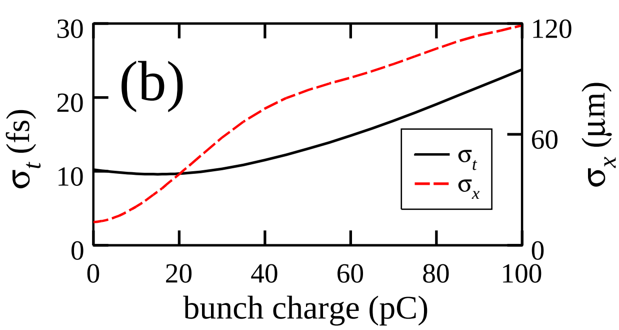


Figure 3: The compressed 980-MeV bunch's longitudinal and horizontal dimensions versus bunch charge, when coherent synchrotron radiation in the dipole magnets is simulated by the code "elegant". (a) Maximal compression in both the 500-MeV and the 980-MeV recirculation arcs. (b) Maximal compression in the 980-MeV recirculation arc with isochronous transport at 500 MeV.

The tracked bunch is observed in the centers of both recirculation arcs.

Fig. 3(a) shows the effect of CSR upon the bunch's longitudinal and horizontal dimensions in the center of the 980-MeV recirculation arc, when the bunches are maximally compressed in both recirculation arcs. The bunchlength and horizontal width are increased by 50% for bunch charges of 2.5 pC and 2 pC, respectively.

Fig. 3(b) shows the effect of CSR when bunches are maximally compressed in the 980-MeV recirculation arc, while undergoing isochronous transport in the 500-MeV recirculation arc. The bunchlength and horizontal width are increased by 50% for bunch charges of 60 pC and 8 pC, respectively. By operating with 8-pC bunches in all rf buckets, a beam current of 12 mA may be provided.

We did not investigate the possibility of compensating the CSR effects to improve performance at high currents.

SUMMARY

A two-up/two-down 980-MeV energy recovery linac gives effective bunch compression/decompression, providing 980-MeV bunches with bunchlength $\sigma_t \approx$ 10–15 fs with repetition rate of 1.5 GHz. Bunch charges up to 8 pC may be compressed at 980 MeV without excessive degradation from coherent synchrotron radiation, allowing operation with beam currents up to 12 mA.

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