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Subject: **Partial design of a 980-MeV Energy Recovery Linac (ERL)**	**Author(s):** **R. A. Bosch, M. D. Medley and J. J. Bisognano**	
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ABSTRACT

We describe the partial design of a 980-MeV energy recovery linac (ERL) with radiofrequency (RF) of 1.5 GHz. We model the linac, recirculation arcs, beam spreader/combiner, and beam compression. The electron gun, gunline, and beam dump are not modeled.

We consider a one-up/one-down design in which 20-MeV bunches are accelerated and decelerated by a 960-MeV superconducting linac. We also consider a two-up/two-down design in which 20-MeV bunches are accelerated by two passages through a 480-MeV superconducting linac and decelerated by two subsequent passages. For both designs, which incorporate graded-gradient linac focusing with cavity gradients of 15 MeV/m, the beam breakup (BBU) thresholds exceed 100 mA.

In the two-up/two-down design, we achieved a large degree of longitudinal compression in both recirculation arcs by accelerating and decelerating off-crest in the linac. For low current operation with normalized emittances in both transverse directions of 0.1 mm-mrad, this high-compression design was studied by tracking without consideration of synchrotron radiation using two codes. In tracking with the MAD-with-acceleration code, bunches with initial rms bunchlength σ_t = 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. In tracking with the elegant code, bunches with initial rms bunchlength σ_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.

Incoherent synchrotron radiation (ISR) was then included in tracking with elegant, indicating a slight increase in the compressed bunch lengths and horizontal emittance. The effect of coherent synchrotron radiation (CSR) was also studied by tracking with elegant. For bunch charge of 1 pC (corresponding to average ERL current of 1.5 mA), the CSR has a small effect, while for bunch charges of 2 and 4 pC, the longitudinal bunch compression and horizontal focusing are both significantly worsened by CSR. For isochronous transport at 500 MeV and high compression (factor of ~180) at 980 MeV, bunch charges $\leq$ 2 pC suffered little degradation from CSR. With isochronous transport in both recirculation arcs, bunch charges $\leq$ 10 pC suffered little degradation from CSR. The tracking results suggest that average ring currents in the tens of milliamperes will be strongly affected by CSR, degrading high-current operation.

For ring currents of several mA, high performance operation with a large degree of longitudinal compression is expected from our design.

1. Introduction

A 980-MeV energy recovery linac (ERL) may provide short pulses of synchrotron radiation with a high (1.5 GHz) repetition rate. The average brightness of its synchrotron radiation and undulator radiation may exceed that of a 3rd-generation electron storage ring. However, a free electron laser (FEL) user facility appears to offer more advantages to SRC, so our ERL design work has been discontinued. We summarize our partial ERL design in this note.

2. Linac focusing

We study ERL designs that accelerate 20-MeV low-emittance bunches provided by the photocathode of a high-performance electron gun and gunline. The gun provides an average current ≤ 100 mA, repetition rate of 1.5 GHz and normalized emittances in both transverse directions of 0.1 mm-mrad. In these studies, we do not consider the electron gun, the gunline, the beam dump, the bending magnet that directs the 20-MeV beam down the linac, or the bending magnet that directs the spent 20-MeV beam exiting the linac to the dump.

We base our design upon a superconducting linac that utilizes the CEBAF/Cornell 5-cell cavity design [1]. A cavity of 0.5-m length accelerates electrons by 7.5 MeV, for a gradient of 15 MeV/m. The quadrupole strengths are limited to values that are feasible with CEBAF magnets [1]: $|\partial B/\partial x| < 5.25$ T/m for air-cooled quadrupoles in the linac and $|\partial B/\partial x| < 31.5$ T/m for water-cooled quadrupoles used in the recirculation arcs and for focusing the 20-MeV beam upstream of the linac. We model sextupoles with zero length for tracking accuracy. Sextupole magnets of 0.1-m length are able to provide the required fields while meeting the CEBAF specification that $|\partial^2 B/\partial x^2| < 1280$ T/m^2. The dipole magnets in our design are limited to the strength of Aladdin dipole magnets (1.67 T), bending 500-MeV electrons with a 1-m radius of curvature, and bending 980-MeV electrons with a 2-m radius of curvature.

The 20-MeV beam may be accelerated to 980 MeV by a single 960-MeV superconducting linac, and then recirculated to the linac entrance so that the 980-MeV bunches arrive 180° out of phase with 20-MeV bunches. A second pass through the linac reduces the beam energy to 20 MeV while recovering 960 eV of energy per electron. We refer to this as a one-up/one-down design.

Alternatively, the 20-MeV beam may be accelerated to 500 MeV by a 480-MeV superconducting linac, recirculated so that the 500-MeV bunches arrive in phase with 20-MeV bunches, and then accelerated to 980 MeV. The bunches are then recirculated to arrive 180° out of phase with 20-MeV bunches, so that two more passages through the linac recover 960 MeV per electron while decelerating the beam to 20 MeV. We refer to this as a two-up/two-down design.

We design a graded-gradient linac, in which the focal lengths of all quadrupoles are equal when acting upon the lowest-energy beam present at any given location [2]. In graded-gradient focusing, the quadrupole magnet fields are symmetric about the linac midpoint. We design recirculation arcs that are symmetric about their midpoint, with symmetric beta-functions. With our symmetric design, the beta-functions of the ERL are mirror-symmetric about the midpoint of the machine — the center of the 980-MeV recirculation arc. To achieve bunch compression and decompression without changing the beta-functions in the linac, the quadrupole strengths in the recirculation arcs are modified to satisfy constraints on the first-order transfer map. Sextupoles are added to the design to satisfy constraints on the second-order transfer map.

To describe the beam's transverse dimensions at a given energy, we use the traditional non-canonical beta-function parameterization that describes the beam's transverse position and direction of propagation. Non-symplectic transfer matrices and decreasing beam emittance describe the beam's acceleration [3].

This beta-function parameterization is used in the MAD-with-acceleration code [4] that we use for our low-current modeling, as well as the DIMAD [5] and "elegant" [6, 7] codes.

Transverse beam breakup (BBU) may limit the maximum current that may be transported. To determine the BBU threshold currents, the transfer matrix of the recirculating arcs is required. For recirculating arcs with reflection symmetry, we simplify the modeling by representing the arcs as symmetric triplets with symmetric beta-functions. To represent any symmetric recirculating arc, we consider the transfer matrix given by $T_2 \times T(\Delta\psi_x, \Delta\psi_y) \times T_1$, 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 [8].

The lattice functions of a one-up/one-down design called Model 1IC are shown in fig. 1(a). We begin with a 20-MeV beam that has been manipulated by the gunline to obtain $\beta_x = \beta_y = 5$ m and $\alpha_x = \alpha_y = 0$. Two quadrupoles then match the beam to the linac entrance. The linac consists of 16 cryomodules separated by 2.2 m. Each cryomodule, utilizing the CEBAF/Cornell 5-cell cavity design [1], consists of eight 0.5-m cavities separated by 0.5-m drifts, where each cavity provides acceleration of 7.5 MeV (for a gradient of 15 MeV/m). Focusing is provided by 0.2-m quadrupoles located midway between cryomodules. Two additional 0.2-m quadrupoles are centered at the locations 1.1 m before and after the cryomodules. A symmetric triplet with symmetric beta-functions represents the recirculating arc.

During acceleration in the graded-gradient focusing, the beam dimensions oscillate during the first half of the linac and expand in the second half of the linac. In the first half of the linac, the focusing gives a horizontal betatron phase advance of ~108° between pairs of horizontally focusing magnets and a vertical betatron phase advance of ~118° between vertically focusing magnets.

The lattice functions of a two-up/two-down design called Model D8 are shown in fig. 1(b). We begin with a 20-MeV beam that has been manipulated by the gunline to obtain $\beta_x = \beta_y = 8$ m and $\alpha_x = \alpha_y = 0$. A single quadrupole matches this beam to the linac entrance. The 480-MeV linac consists of 8 cryomodules separated by 2.2m. Again, each cryomodule consists of eight 0.5-m cavities separated by 0.5-m drifts, where each cavity provides acceleration of 7.5 MeV. Focusing is provided by 0.2-m quadrupoles located midway between adjacent cryomodules, as well as 0.2-m quadrupoles centered at locations 1.1-m before and after the string of cryomodules. In the first half of the linac, the focusing gives a horizontal betatron phase advance of ~99° between pairs of horizontally focusing magnets and a vertical betatron phase advance of ~95° between vertically focusing magnets.

A symmetric triplet with symmetric beta-functions represents the 500-MeV recirculation arc. The beam again passes through the linac, at which point another symmetric triplet with symmetric beta-functions represents the 980-MeV recirculation arc. Then deceleration occurs; the beta-functions of the ERL are symmetric about the middle of the 980-MeV recirculation arc.

3. Beam breakup instability

To determine the maximum beam currents that can propagate without exciting transverse beam breakup instability, we use the TDBBU code [9] to model equal bunches with 1.5-GHz repetition frequency. We model the CEBAF/Cornell 5-cell cavity design with one higher order mode (HOM) per cavity with transverse impedance of 22.2 Ω (linac definition) [1]. 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 1888 and 1889 MHz with a uniform distribution [1]. By studying different random number seeds, we found that the computed threshold currents have only a slight dependence upon the seed.

For horizontal BBU instability, figure 2(a) shows the computed threshold currents for the Model 1IC one-up/one-down design versus the phase advance of the recirculating arc. Vertical BBU instability in the one-up/one-down design is shown in Figure 2(b). Error bars show the uncertainty in computed threshold currents according to our study of different random number seeds.

Figure 2(c) shows the computed threshold current of horizontal BBU instability for the Model D8 two-up/two-down design versus the phase advance of the two recirculating arcs. Vertical BBU instability in the two-up/two-down design is shown in Figure 2(d).

For optimal phase advances of the recirculation arcs, the one-up/one-down design has BBU threshold current of 665 mA while the two-up/two-down has BBU threshold current of 310 mA. Threshold currents exceed 100 mA for all recirculation arc phase advances.

4. Bending arc design

We design recirculation arcs with identical 180° isochronous achromatic bending arcs at each end. Each bending arc contains three identical 60° dipole sector magnets. For a 980-MeV bending arc, the electron orbit’s radius of curvature is 2 m in the bending magnets, while for a 500-MeV bending arc, the radius of curvature is 1 m.

For each bending arc, we use a Mathcad [10] program incorporating eqs. (6)–(9) of Ref. [11] to determine reasonable quadrupole strengths and drift lengths that provide isochronous transport. We then compute the horizontal and vertical transfer matrices of the bending arc using MAD [4]. Using these transfer matrices and eqs. (C.8) and (C.9) from Appendix C of Ref. [11], we determine reasonable lattice functions $(\beta_x, \alpha_x, \beta_y, \alpha_y)$ that are symmetric about the center of the bending arc.

Fig. 3 displays the lattice functions of the bending arcs used in our Model 1IC and Model D8 designs. The locations of sextupoles, which will be used for bunch compression/decompression, are also shown.

5. Back straight section and matching regions.

The portion of the ERL recirculation arc between the bending arcs is the region where users may extract radiation using insertion devices. In the absence of known user requirements, we represent this region with a straight section opposite the linac. In our Model 1IC design, this back straight section consists of 24 identical triplets separated by 5.457654-m drifts, where the center of the drifts have $\beta_x = \beta_y = 2$ m and $\alpha_x = \alpha_y = 0$. The bending arc is then matched to the linac and the back straight section by triplets with lengths chosen so that the recirculated beam enters the linac 180° out of phase with the 20-MeV bunches.

In our Model D8 design, the 500-MeV and 980-MeV back straight sections each consist of 12 identical triplets separated by 5.4165424–m drifts, where the center of the drifts have $\beta_x = \beta_y = 2.5$ m and $\alpha_x = \alpha_y = 0$. The bending arcs are matched to the back straight section by two quadrupole doublets; this provides more flexibility than a matching triplet when compressing the beam.

The back straight section triplets are shown in fig. 4 for the one-up/one-down and two-up/two-down designs. The matching sections between the bending arcs and back straight sections are show in fig. 5.

A triplet that matches the linac to the bending arc of the one-up/one-down design is shown in fig. 6.

6. Spreader/recombiner

In the two-up/two-down design, a beam spreader and beam combiner match the linac to the bending arcs. The focusing in our initial two-dipole spreader design was overly dependent upon the beam energy, performing horribly with the chirped beam used for compression. With an asymmetric chicane spreader, we obtained better performance, but the R56 contribution from our first design caused too much beam compression in the first half of the recirculation arc. We reduced the spreader's R56 contribution by 75% with our subsequent Mark1 design. In the Mark1 spreader, the 500-MeV electrons traverse an asymmetric chicane followed by two quadrupole doublets for matching, in which the dipole bending angles are 5.624°. The 980-MeV electrons traverse a 4-dipole symmetric chicane without quadrupoles followed by two quadrupole doublets for matching; the dipole bending angles are 2.866°. The spreader/combiner dipoles are rectangular dipole magnets with pole faces perpendicular to the linac axis. The 500-MeV and 980-MeV magnets are staggered so that they don't occupy the same space. Lattice functions for the 500-MeV and 980-MeV electrons traversing the spreader/recombiner are shown in fig. 7.

7. Symmetric ERL lattice functions

By concatenating the ERL pieces described above, we obtain symmetric ERL designs with symmetric lattice functions. The lattice functions of the one-up/one-down and two-up/two-down designs are shown in fig. 8.

In these designs, the beam dynamics are not optimized. We consider these symmetric designs to be starting points for designs that compress a beam that is accelerated off-crest in the linac.

8. Bunch compression/decompression in the two-up/two-down design Model D8: low current behavior.

To obtain bunch compression with acceptable transverse dynamics, quadrupole strengths are modified for first-order compression while sextupoles in the bending arcs are powered for second-order compression. For the two-up/two-down design Model D8, we studied the longitudinal compression/decompression of bunches that are accelerated 10° off-crest (where the RF voltage peaks 10° after the bunch center passes through a cavity). We compress the chirped bunches in the first half of both recirculation arcs to obtain short bunch lengths with energies of 500 MeV and 980 MeV in the back straight sections. We decompress in the second half of the recirculation arcs to restore the original bunchlength at the linac entrance.

To compress/decompress the chirped beams to first order in the transfer map, we vary the strengths of the quadrupole families in the arcs, the quadrupoles in the spreader/combiner and the quadrupoles in the two-doublet sections that match the bending arc to the back straight. In our matching constraints, we maintain the lattice function values at the ends of 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.

To achieve compression, one approach is to constrain the transfer map from the linac exit to the middle of the back straight section. The transfer map terms R_{56} and T_{566} may be constrained to calculated values that give bunch compression [12], while the terms R_{16}, R_{26}, T_{166} and T_{266} may be constrained to zero so that off-energy bunch slices remain centered on the origin in phase space.

Our approach is to constrain the transfer map from the beginning of our ERL model (where the beam energy is 20 MeV) to the center of the back straight sections, using the MAD-with-acceleration code. We maximize compression in both recirculation arcs by constraining the linear transfer map by $R_{55} = R_{15} = R_{25} = 0$, and constrain the second order map by $T_{555} = T_{155} = T_{255} = 0$. For decompression, we constrain the transfer map of the accelerated beam from the beginning of our ERL model to the entrance of the linac at the end of the 500-MeV and 980-MeV recirculation arcs. We achieve decompression by constraining the linear transfer map by $R_{55} = 1$, $R_{15} = R_{25} = 0$, and constrain the second order map by $T_{555} = T_{155} = T_{255} = 0$.

To evaluate the compression/decompression for low-current operation, we track electrons lying on the emittance ellipse at the beginning of our ERL model for normalized horizontal and vertical emittances of 0.1 mm-mrad. To study an initial rms bunchlength of 1.85 ps (1° measured in linac phase), we consider electrons that enter the linac with phases (in MAD convention) of −11°, −10.5°, −10°, −9.5° and −9°. Synchrotron radiation is not included in the tracking by the MAD-with-acceleration code. A good compression/decompression scheme should achieve longitudinal compression and decompression with a good transverse beam profile. The transverse beam profile is considered good when the tracked emittance ellipses nearly lie on top of each other.

In our second-order matching, we use a subset of the sextupole locations shown in figs. 3(b) and 3(c). The choice of sextupole locations has a large effect on the quality of a compression/decompression scheme, as determined by tracking. By trying various subsets of the sextupole locations and limiting the sextupole excitations with various regularization parameters according to the method of Tikhonov [13], we achieved acceptable performance in our "2_21_06_mark1_#7" design. The resulting lattice functions are shown in fig. 9. The lattice functions for bunch compression/decompression are no longer symmetric in the recirculation arcs, but their values in the linac are unchanged from the symmetric ERL of fig. 8(b).

In fig. 10, MAD tracking results show the emittance ellipses of 20-MeV electrons at the beginning of our ERL model and the tracked values at the middle of the 980-MeV recirculation arc. Fig. 10(a) shows the longitudinal compression. According to MAD tracking of Gaussian bunches (truncated at 3 sigma) with rms length equaling one degree of RF phase (1.85 ps), compression produces a bunch with length of 15 fs ($\sigma_z \approx$ 4.5 μm) and energy spread $\sigma_E / E = 0.003$. This is comparable to the rough estimate of $\sigma_z \approx$ 10 μm obtained by neglecting the third-order transfer map term in the approximation given by eq. (5) of Ref. [12], and an estimated relative energy spread of 0.003 from eq. (2) of Ref [12].

Figure 10(b) shows the horizontal phase space and fig. 10(c) shows the vertical phase space in the middle of the 980-MeV recirculation arc. In the vertical phase space, energy-dependent focusing causes two of the 980-MeV emittance ellipses to be slightly rotated. A further improvement in compression that reduces the energy-dependent vertical focusing may be feasible by optimizing sextupole locations and excitations.

MAD tracking of Gaussian bunches also quantifies the bunch compression in both passages through the 500-MeV recirculation arc. On the first pass, the tracked bunchlength is σ_t = 22 fs ($\sigma_z \approx$ 6.6 μm) and energy spread $\sigma_E / E = 0.003$; on the second pass σ_t = 32 fs ($\sigma_z \approx$ 9.6 μm) and energy spread $\sigma_E / E = 0.003$. This is comparable to the rough estimate of $\sigma_z \approx$ 10 μm obtained by neglecting the third-order transfer map term in the approximation given by eq. (5) of Ref. [12], and an estimated energy spread of 0.003 from eq. (2) of Ref [12].

The bunch decompression in the second half of the recirculation arcs successfully restores the bunchlength to that of the 20-MeV injected bunches. However, according to tracking, the spent 20-MeV bunches have lengths nearly double that of the injected 20-MeV bunches.

Using eq. (D.15) in Appendix D of Ref. [11], we estimate that incoherent synchrotron radiation from each half of the 500-MeV recirculation arc will increase the horizontal normalized emittance by 1% (0.001 mm-mrad). The incoherent synchrotron radiation from each half of the 980-MeV recirculation arc is expected to increase the horizontal normalized emittance by 30% (0.03 mm-mrad).

The MAD files describing our ERL designs and the matching file for compression/decompression of our D8 two-up/two-down design are given in the Appendices.

9. Bunch compression/decompression in the two-up/two-down design Model D8: high current behavior.

The passage of compressed bunches through bending magnets may produce a large amount of coherent synchrotron radiation, thereby spoiling the bunch-compression process. We studied 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 bending magnets. The shielding of long-wavelength synchrotron radiation by the vacuum chamber is not considered in the elegant code. The study indicated that MAD and elegant tracking without ISR differ slightly in the zero-current limit. This may result from different approximations for higher-order terms of the transport matrix, which dominate the behavior of the highly compressed bunches.

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 (in MAD convention) of –10°. The rms bunchlength corresponds to one degree of linac phase. The tracked bunch was observed in the centers of the recirculation arcs for the "2_21_06_mark1_#7" design that maximizes compression in both recirculation arcs. In the elegant tracking of zero-current bunches without ISR, the compressed bunchlength is 8.46 fs in the first passage through the 500-MeV arc, 9.15 fs in the 980-MeV arc, and 47.9 fs in the second passage through the 500-MeV arc.

Tracking with ISR and CSR was performed by elegant for bunch charges of 0 pC, 1 pC, 10 pC and 100 pC. For zero bunch charge, we compared tracking results with and without ISR. With ISR, the compressed bunchlength is slightly increased to 8.53 fs in the first passage through the 500-MeV arc, 10.2 fs in the 980-MeV arc, and 49.1 fs in the second passage through the 500-MeV arc. In the center of the 980-MeV recirculation arc, the ISR increases the horizontal bunch width by 8% and the horizontal divergence by 17%, indicating an approximate emittance increase of 25%. This agrees with our analytic estimate of a 30% emittance increase.

Figure 11 shows the tracking of longitudinal phase space in the 980-MeV arc for bunch charges of 0 pC, 1 pC, 10 pC and 100 pC. For charges of 10 and 100 pC, the phase space is strongly modified by CSR. For the 100 pC bunch, the "Derbenev criterion" value of 0.5 computed by elegant indicates that the accuracy of the CSR modeling is reduced from use of elegant's one-dimensional approximation. Figures 12 and 13 show tracking of the bunch density histogram and horizontal phase space. As in Fig. 11, CSR has a strong impact for bunch charges of 10 and 100 pC (i.e., average currents of 15 mA and 150 mA). According to the tracking results, the vertical phase space is barely affected by the CSR.

With larger transverse emittances of 0.3 μm and 1 μm, the effect of CSR is slightly reduced. However, the 10 pC and 100 pC bunch charges are still strongly impacted by CSR. Figures 11–13 suggest that for maximum bunch compression in both recirculation arcs, CSR will limit the ERL average current to several milliamperes.

To further study the CSR for initial normalized transverse emittance of 0.1 μm and initial bunchlength of σ_t = 1.85 ps, tracking was performed for additional values of the bunch charge. We found that 1 pC is approximately the maximum bunch charge that could be tracked with little degradation from CSR; this corresponds to an average ring current of 1.5 mA. For a bunch charge of 2 pC, the compressed bunchlength in the 980-MeV arc exceeded the value at 0 pC by 37% while the horizontal size exceeded the zero-charge value by 51%. For a bunch charge of 4 pC, the compressed bunchlength in the 980-MeV arc exceeded the value at 0 pC by 78% while the horizontal size exceeded the zero-charge value by 120%.

We also considered a lesser degree of bunch compression. From the beginning of our MAD ERL model to the center of the 500-MeV recirculation arc, we changed the R_{55} matching constraint from R_{55} = 0 to R_{55} = 1. We maintained the constraint R_{55} = 0 from the beginning of our ERL model to the center of the 980-MeV recirculation arc. This provides an ERL with isochronous transport at 500 MeV and maximal compression (factor of 180) at 980 MeV. The maximum charge that could be tracked with little degradation from CSR was doubled to 2 pC, corresponding to an average ERL current of 3 mA. For higher bunch charges, the horizontal phase space was significantly degraded. The longitudinal phase space was degraded from CSR for bunch charges exceeding 20 pC.

The maximum charge that could be tracked with little degradation from CSR was further increased when the constrained value of R_{55} from the beginning of our ERL model to the center of the 980-MeV recirculation arc was increased to 0.05, 0.1 or 1. For these cases, there is isochronous transport at 500 MeV, while the 980-MeV bunch compression factors are 20, 10 and 1 (isochronous transport). In these cases, modification of the horizontal phase space limited the maximum charge that could be tracked with little degradation from CSR. For compression factors of 20 and 10, the maximum bunch charge that suffered little horizontal degradation from CSR was 4pC, while for isochronous transport, the maximum bunch charge was 10 pC. For compression factors of 20 and 10, the maximum bunch charge that suffered little longitudinal degradation from CSR was approximately 20 pC, while for isochronous transport, the maximum bunch charge was 40 pC.

For isochronous transport, a vacuum chamber with height ≤ 10 mm is expected to partially shield the coherent synchrotron radiation, so that the CSR effects for isochronous transport may be overestimated in the elegant tracking.

Table I summarizes the maximum bunch charges that could be tracked with little degradation from CSR. The ERL appears capable of high-performance operation with present-day e-gun currents of several mA. However, the low maximum charge values will prevent taking advantage of e-gun currents in the tens of milliamperes expected from future photocathode improvements.

10. Summary

The partial design of a 980-MeV energy recovery linac has been described. The two-up/two-down Model D8 design gives effective bunch compression/decompression, providing a 980-MeV bunchlength of $\sigma_t \approx$ 10–15 fs ($\sigma_z \approx$ 3–5 μm) at an average current of several milliamperes. Coherent synchrotron radiation is expected to increase the bunch dimensions for currents in the tens of milliamperes, even when the bunches are not compressed. This will prevent taking advantage of e-gun currents in the tens of milliamperes expected from future photocathode improvements. High performance in our ERL design appears limited to average currents of several mA.

Some issues that have not been addressed in our partial design are:

a) Whether or not the 500-MeV arc will be utilized by users. If so, it may be desirable to place the 500-MeV and 980-MeV arcs on opposite sides of the linac. If not, there is no apparent advantage in compressing the bunch in the 500-MeV arc.
b) Optimal sextupole locations for second-order compression/decompression.
c) The 20-MeV gunline, including the electron gun and the dipole magnet which directs the 20-MeV electrons into the linac.
d) The 20-MeV beam dump, including the dipole magnet that extracts the spent 20-MeV beam downstream of the linac.
e) The possible deleterious effects of space charge.

f) Sensitivity to magnetic-field errors, injection-timing jitter and RF-voltage variation.
g) Transit-time effects arising because bunches travel through the linac at less than the speed of light.
h) The inclusion of a phase trombone for adjustment of betatron phase advances in the arcs.
i) Improved modeling of CSR by including its effects in drift regions or using a different code.
j) The design of recirculation arcs with provision for insertion devices and users.

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[13] Y. N. Tang and S. Krinsky, in *Proceedings of the 1993 Particle Accelerator Conference, Washington, D. C.* (IEEE, Piscataway, NJ, 1993), p. 492; in *Orbit Correction and Analysis in Circular Accelerators*, edited by E. S. Bozoki, A. Friedman, A. U. Luccio and J. A. Niederer, AIP Conf. Proc. No. 315 (AIP, New York, 1994), p. 87.

Table I. Maximum bunch charge $Q_{\max}$ that could be tracked by "elegant" with minimal degradation from CSR, for transverse normalized emittance of 0.1 μm. Results are shown for different constraints upon the values of R_{55} from the beginning of the accelerator model to the centers of the 500-MeV and 980-MeV recirculation arcs. All results include ISR.

R_{55} @ 500 MeV	R_{55} @ 980 MeV	σ_t [fs] @ 980 MeV for $Q = 0$	σ_x [μm] @ 980 MeV for $Q = 0$	980-MeV compression factor for $Q = 0$	$Q_{\max}$ [pC]	$\langle I\rangle_{\max}$ [mA]	σ_t [fs] @ $Q = Q_{\max}$	σ_t [fs] @ $Q = 2Q_{\max}$
0	0	10.2	12.8	180	1	1.5	11.9	14.0
1	0	10.2	12.5	180	2	3	10.1	10.0
1	0.05	93.3	12.5	20	4	6	93.8	94.6
1	0.1	183	12.5	10	4	6	184	185
1	1	1810	12.1	1	10	15	1810	1810

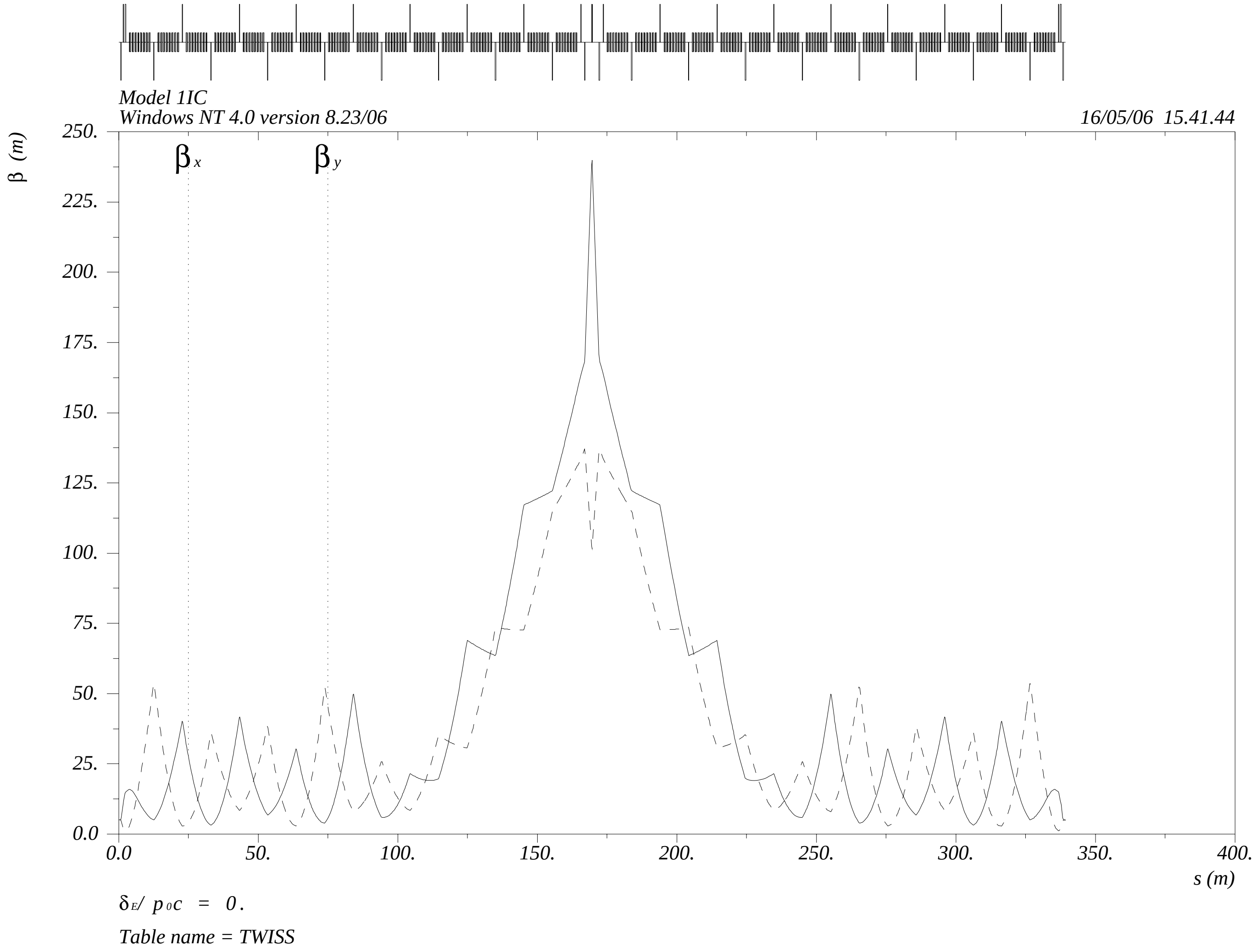

Figure 1(a). Beta functions for the one-up/one-down Model 1IC ERL with a symmetric triplet representing the recirculation arc.

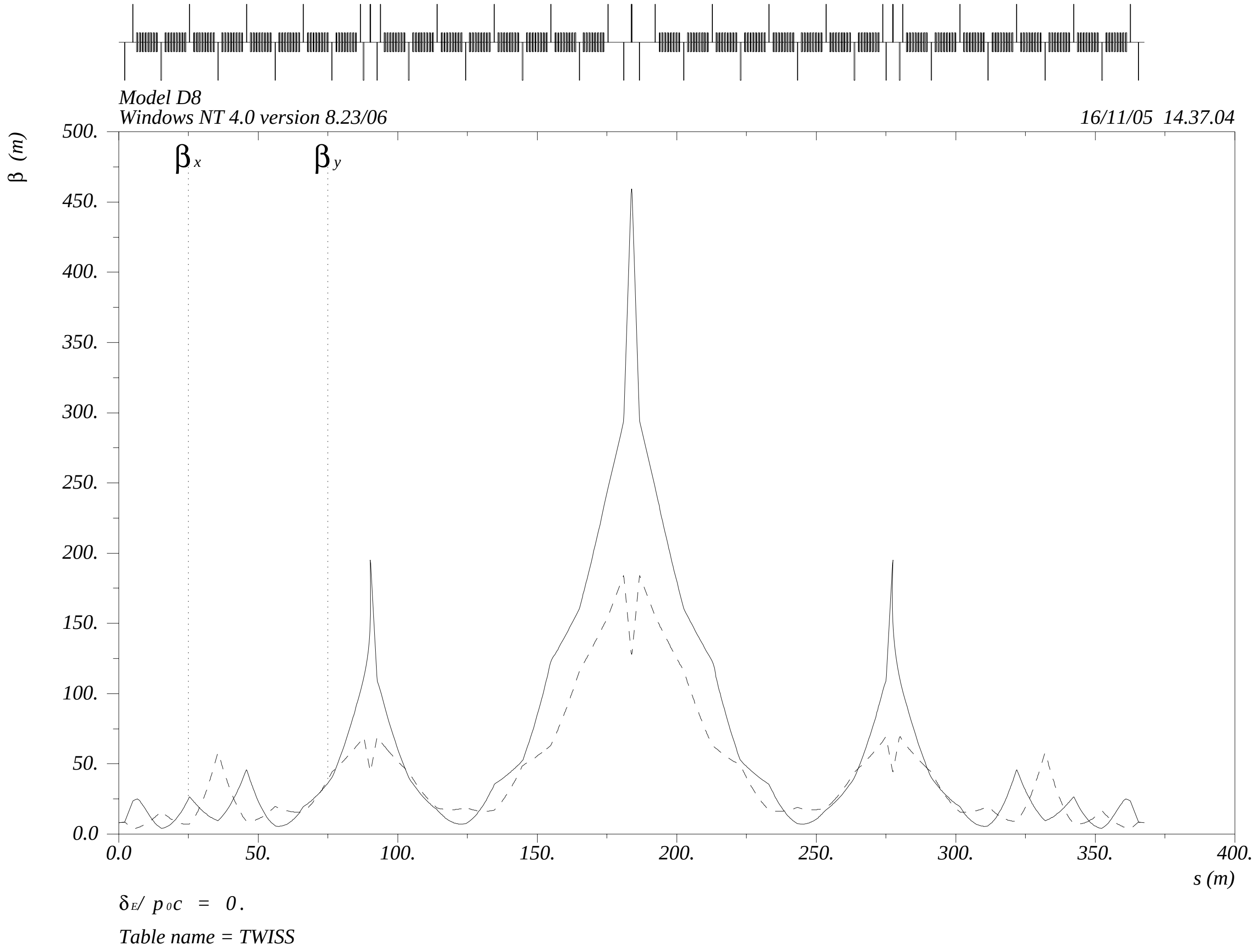

Figure 1(b). Beta functions for the two-up/two-down Model D8 ERL with symmetric triplets representing the recirculation arcs.

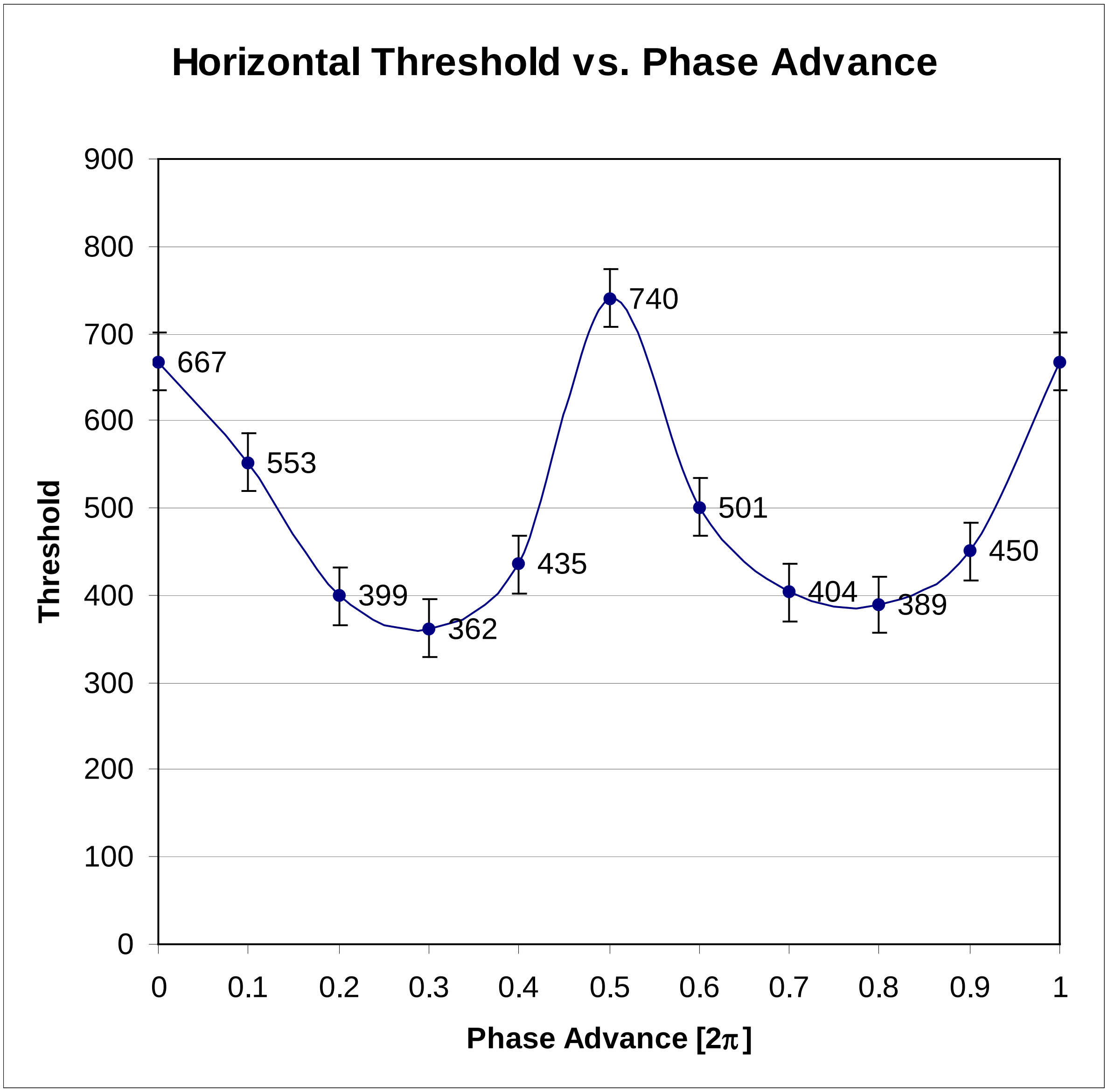

Figure 2(a). Horizontal beam breakup (BBU) threshold current vs. recirculation-arc phase advance in the one-up/one-down ERL design Model 1IC. Error bars show the uncertainty in computed threshold currents according to our study of different random number seeds.

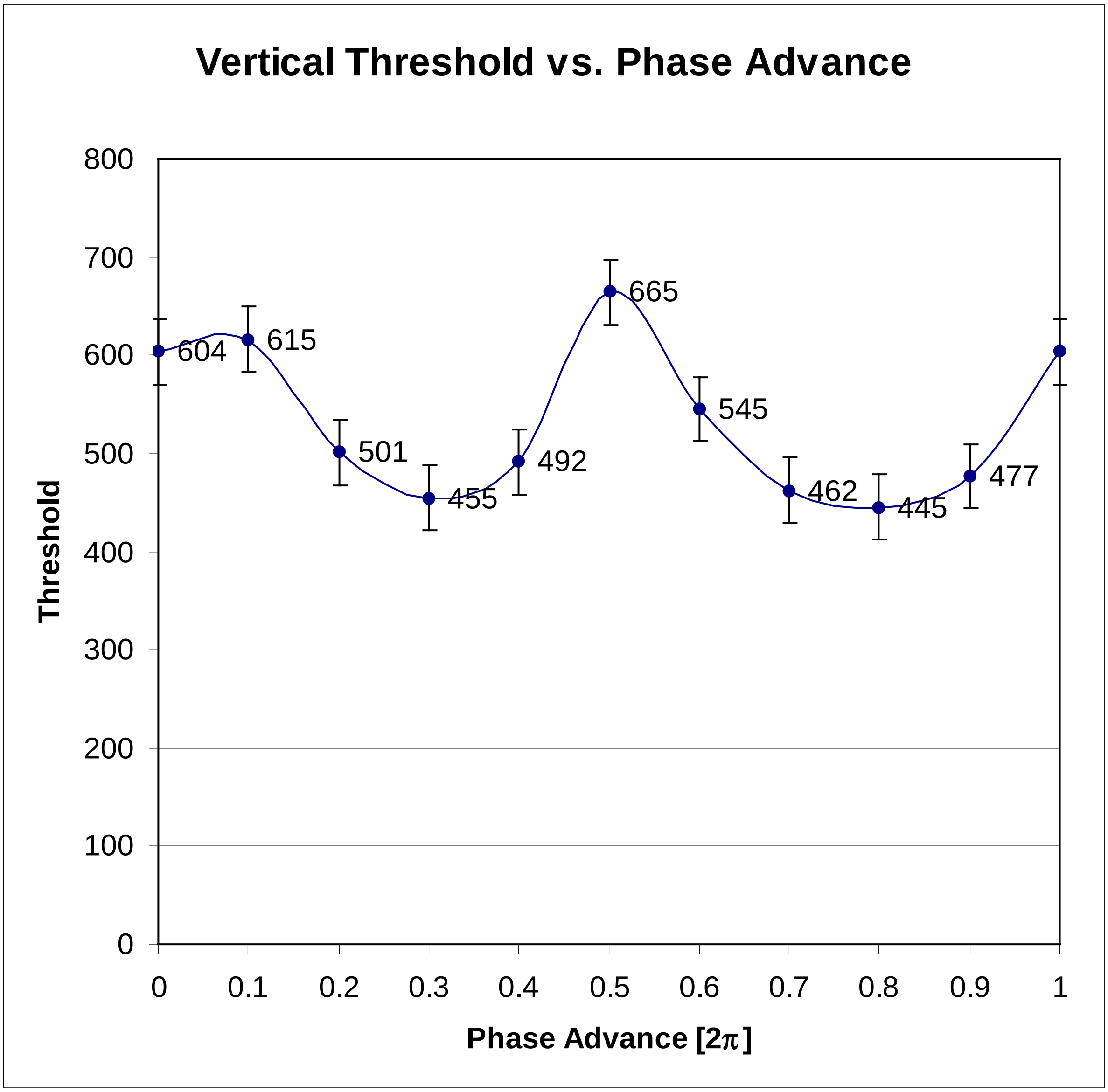

Figure 2(b). Vertical beam breakup (BBU) threshold current vs. recirculation-arc phase advance in the one-up/one-down ERL design Model 1IC. Error bars show the uncertainty in computed threshold currents according to our study of different random number seeds.

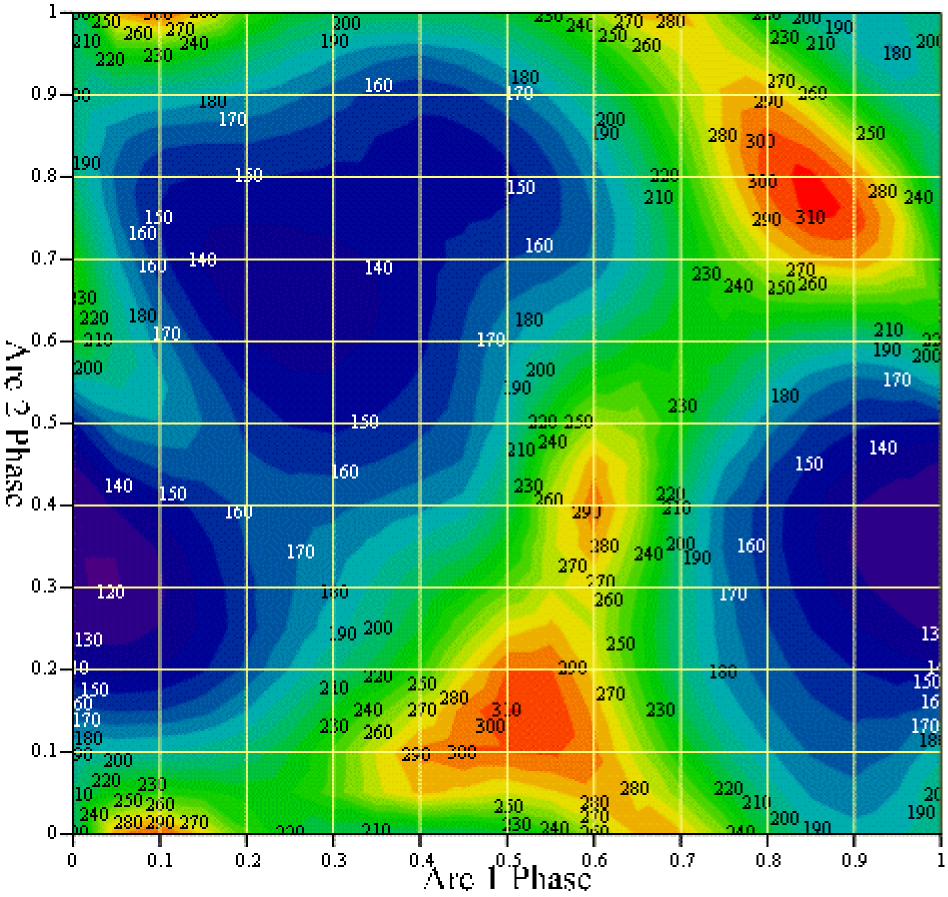

Figure 2(c). Horizontal beam breakup (BBU) threshold current vs. recirculation-arc phase advances in the two-up/two-down ERL design Model D8. Arc 1 is the 500-MeV arc. Arc 2 is the 980-MeV arc.

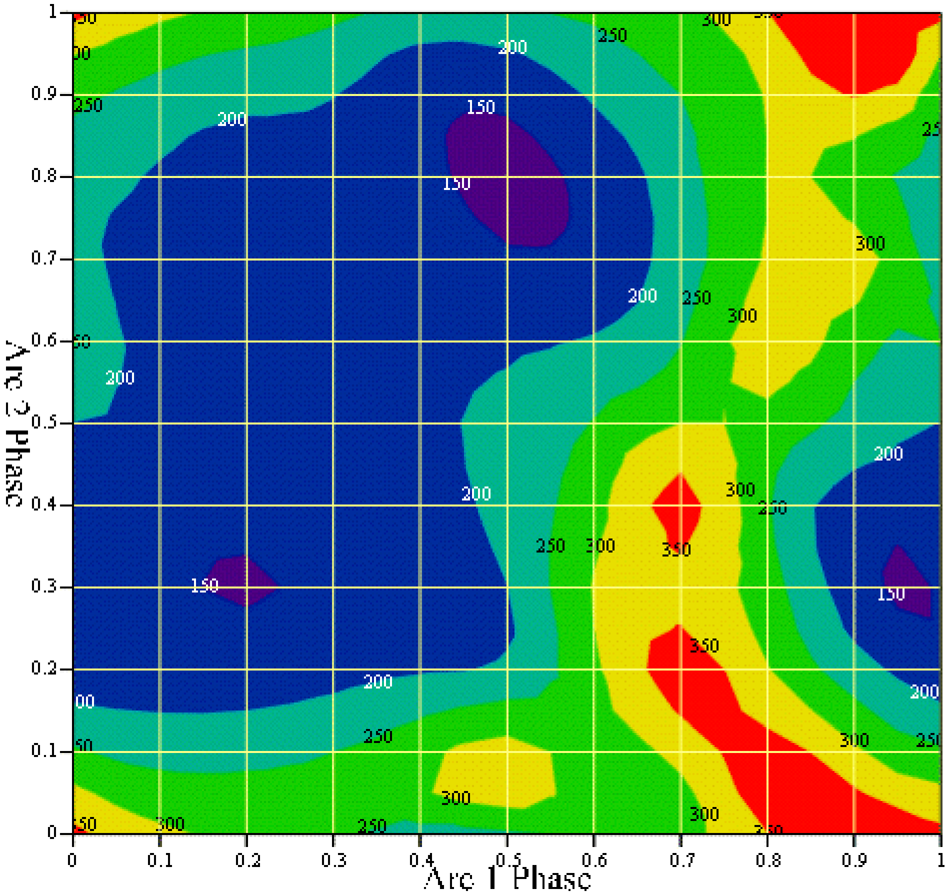

Figure 2(d). Vertical beam breakup (BBU) threshold current vs. recirculation-arc phase advances in the two-up/two-down ERL design Model D8. Arc 1 is the 500-MeV arc. Arc 2 is the 980-MeV arc.

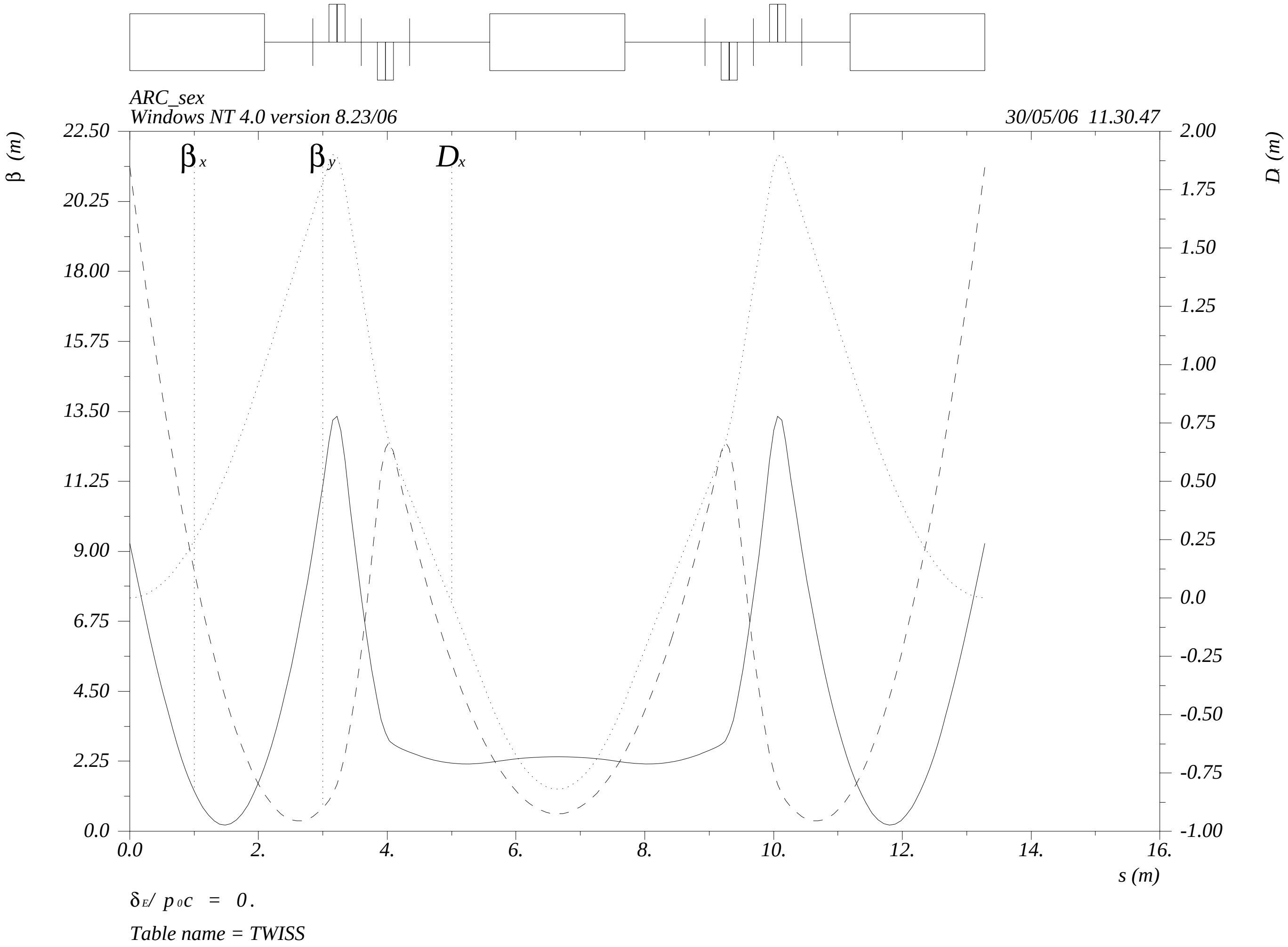

Figure 3(a). Lattice functions are shown for the isochronous bending arc of the one-up/one-down design Model 1IC.

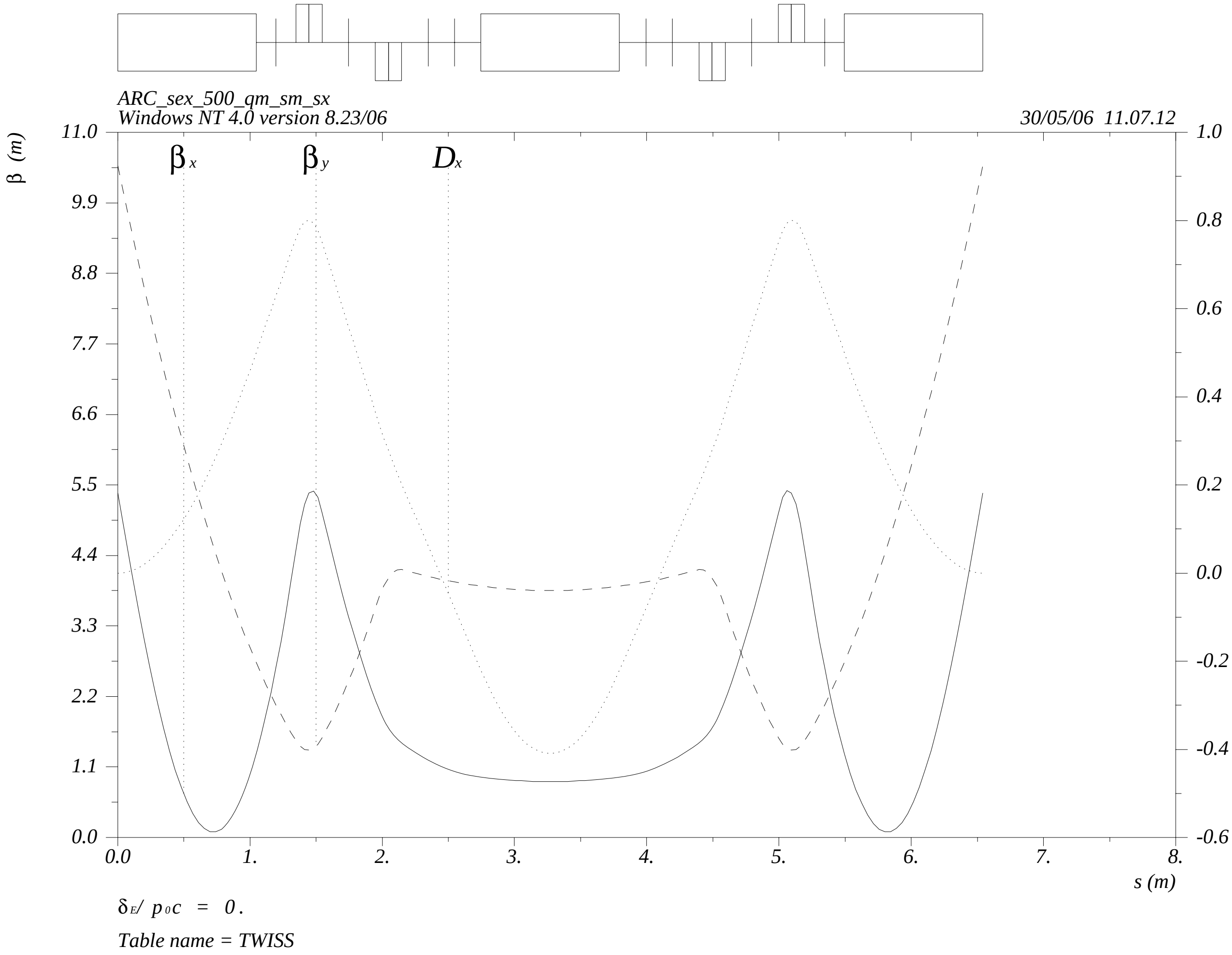

Figure 3(b). Lattice functions are shown for the 500-MeV isochronous bending arc of the two-up/two-down design Model D8.

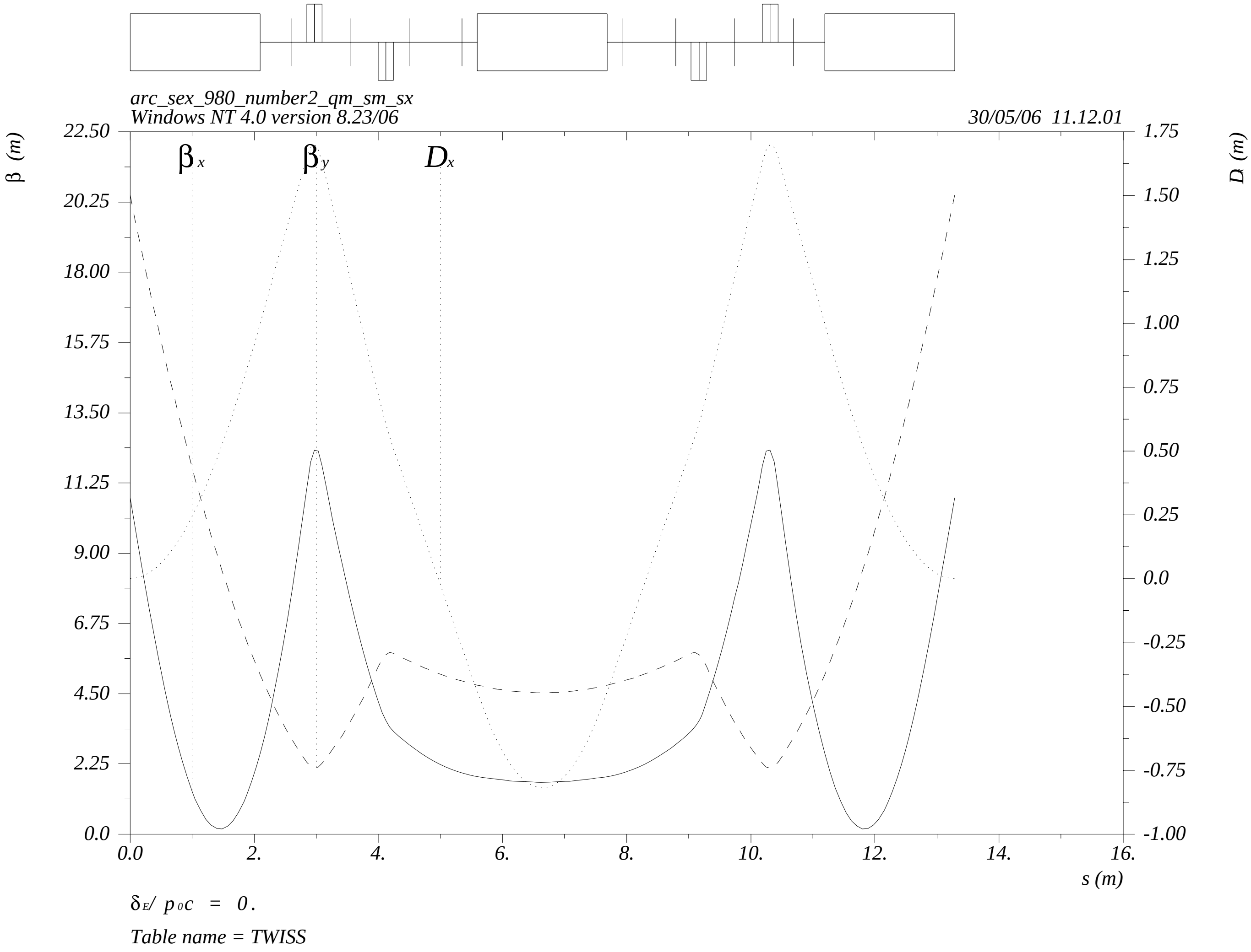

Figure 3(c). Lattice functions are shown for the 980-MeV isochronous bending arc of the two-up/two-down design Model D8.

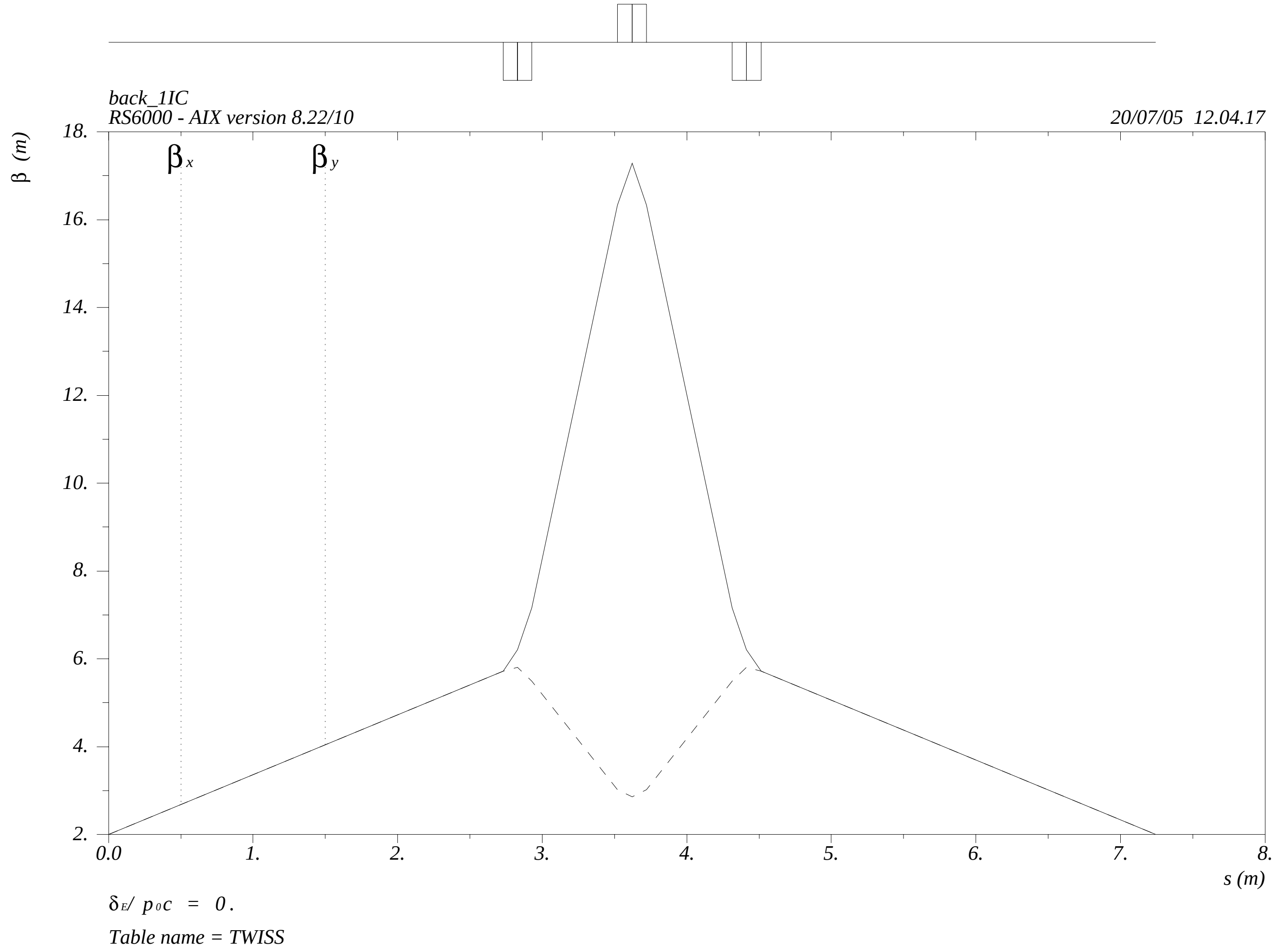

Figure 4(a). Lattice functions are shown for one period of the back straight section of the one-up/one-down design Model 1IC.

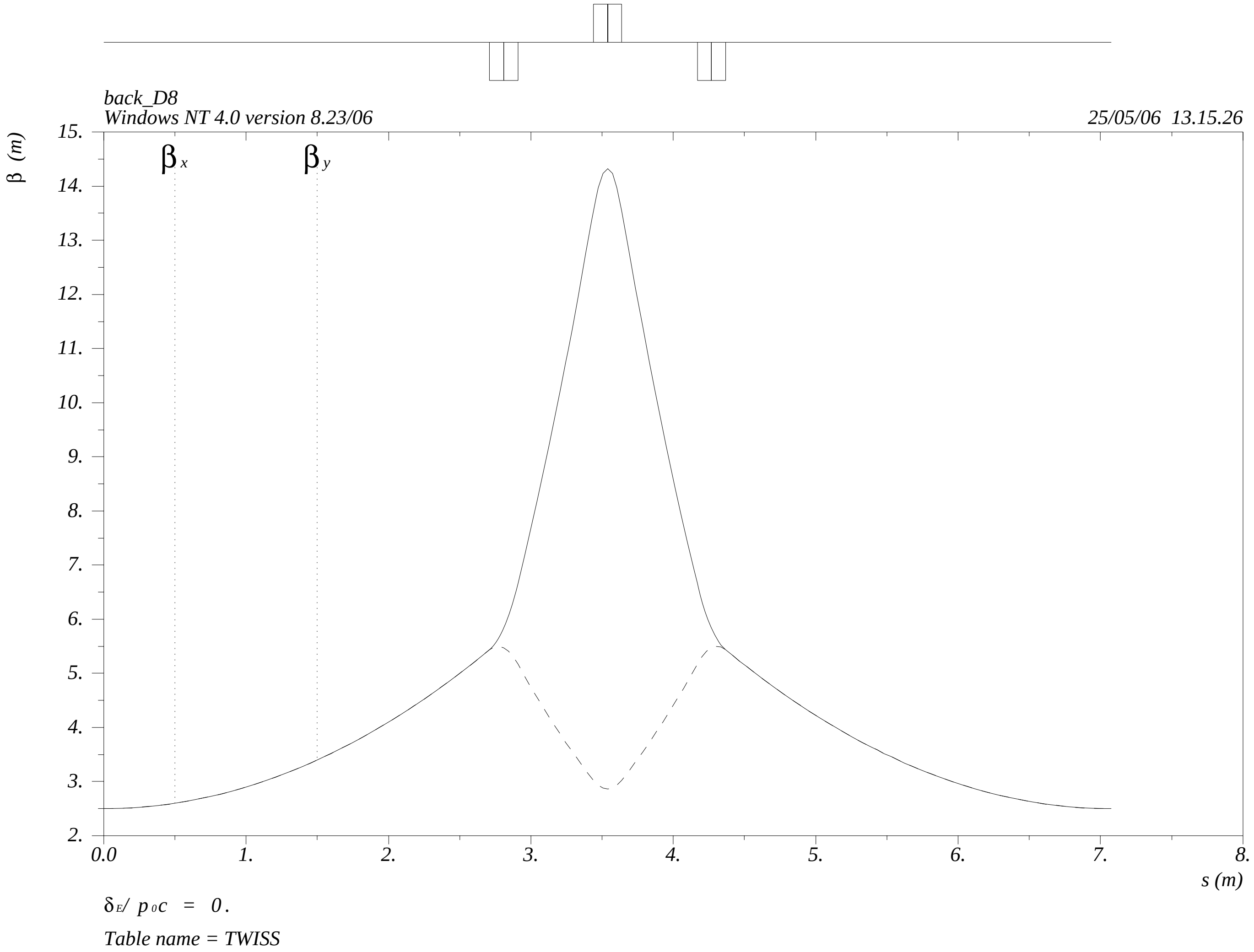

Figure 4(b). Lattice functions are shown for one period of the back straight sections of the two-up/two-down design Model D8.

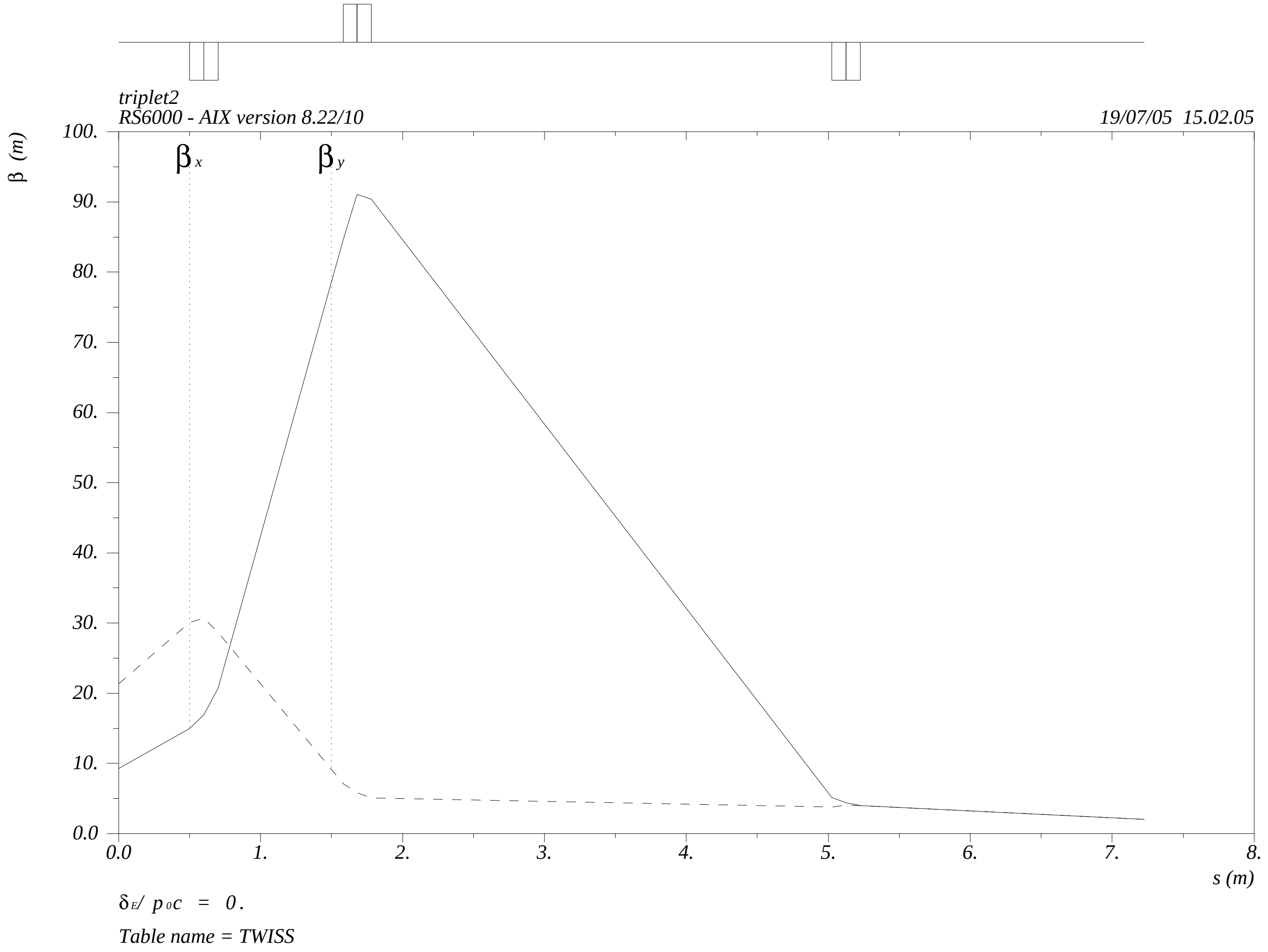

Figure 5(a). Lattice functions for the triplet matching the bending arc to the back straight section of the one-up/one-down design Model 1IC.

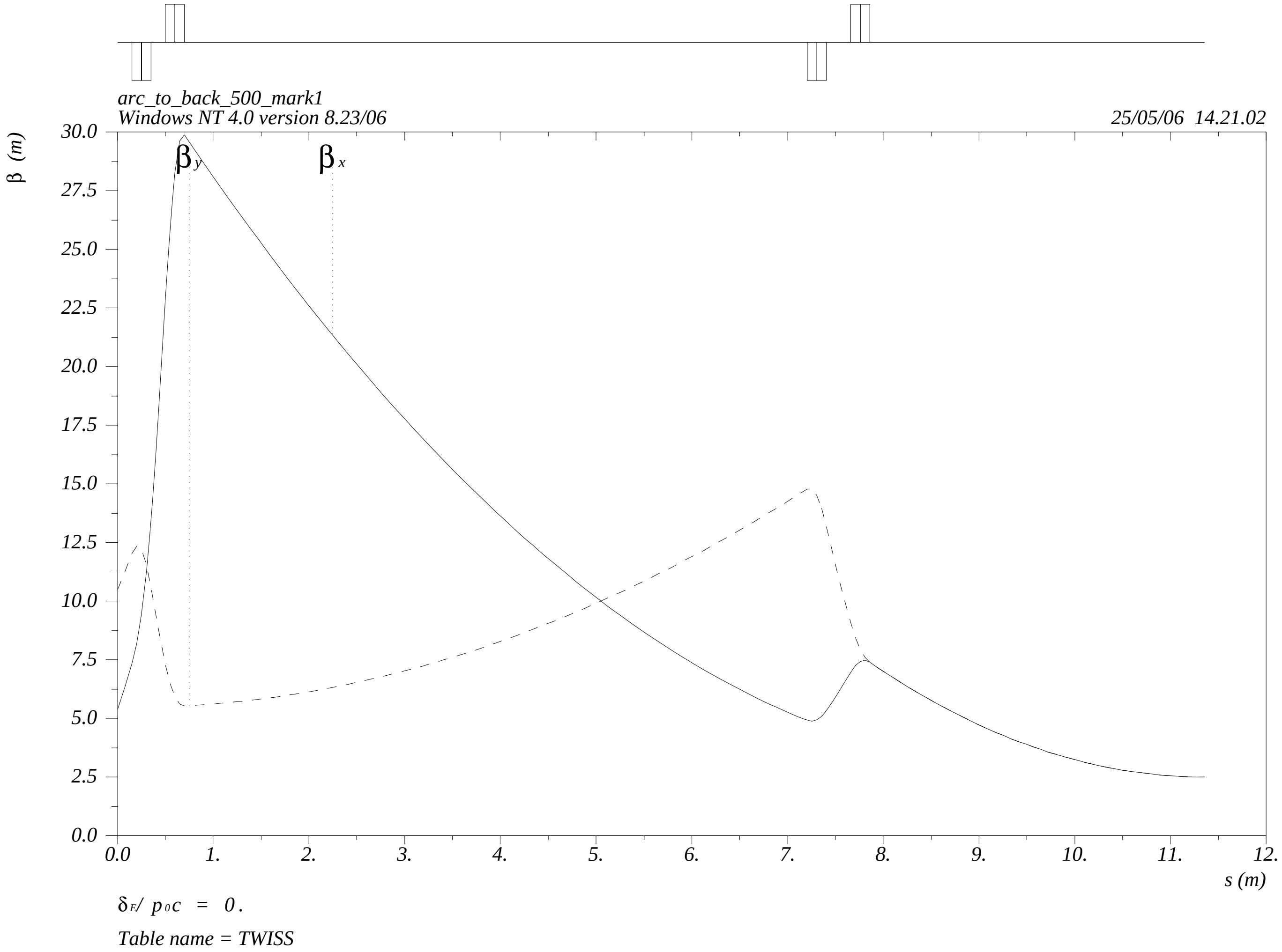

Figure 5(b). Lattice functions of the two quadrupole doublets that match the 500-MeV bending arc to the back straight section of the two-up/two-down design Model D8.

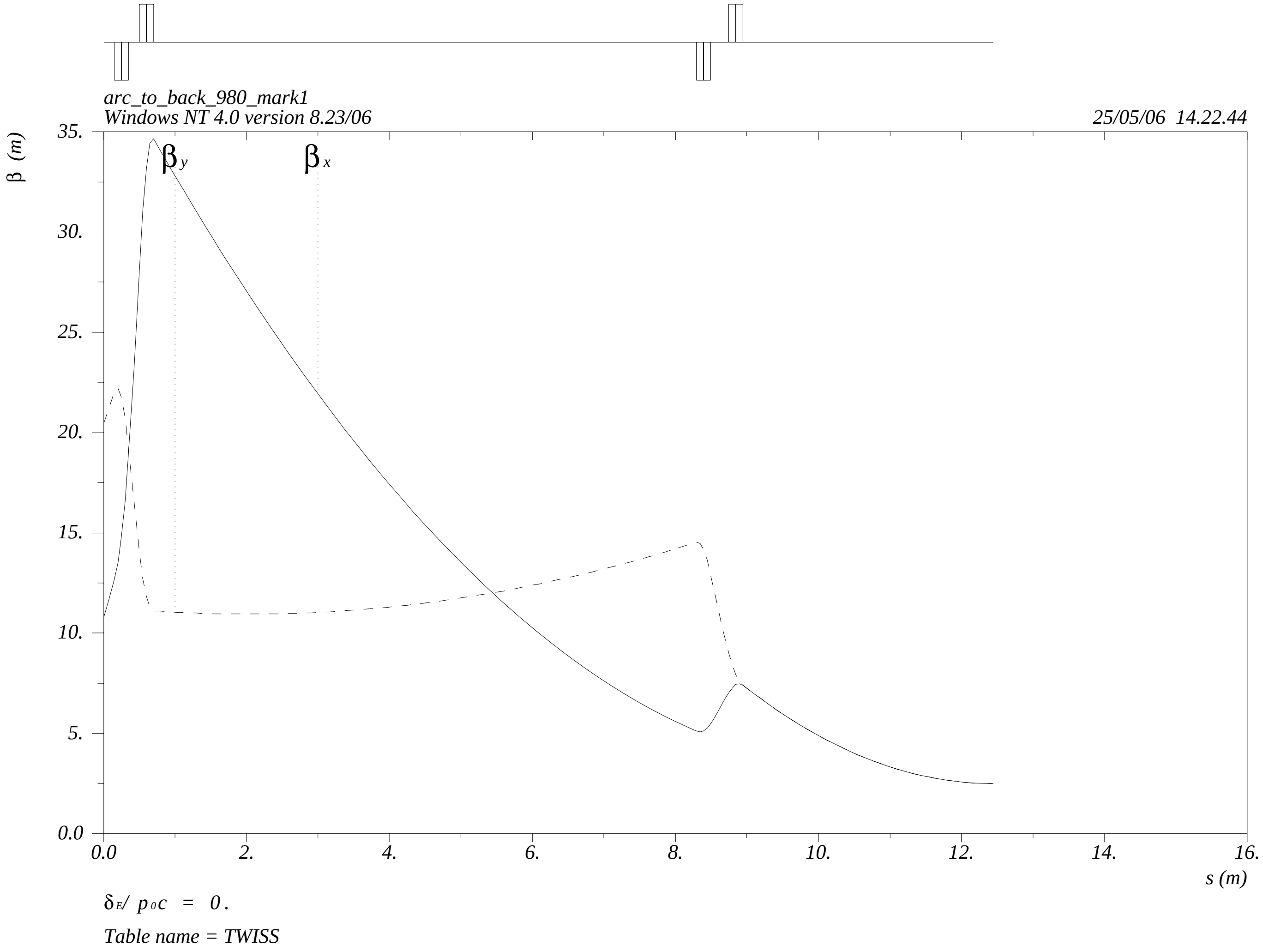

Figure 5(c). Lattice functions of the two quadrupole doublets that match the 980-MeV bending arc to the back straight section of the two-up/two-down design Model D8.

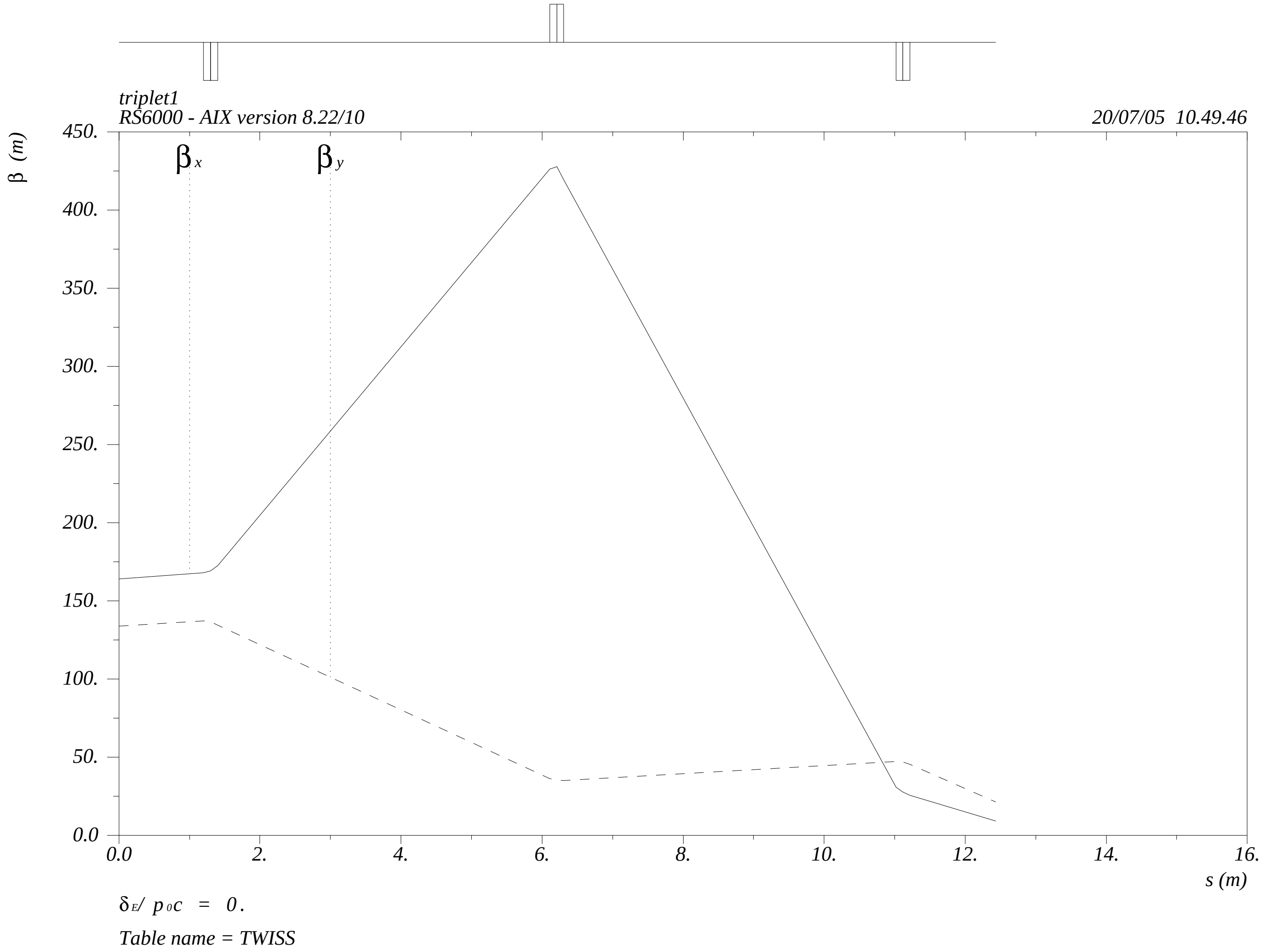

Figure 6. Lattice functions of the triplet that matches the linac to the bending arc of the one-up/one-down design Model 1IC.

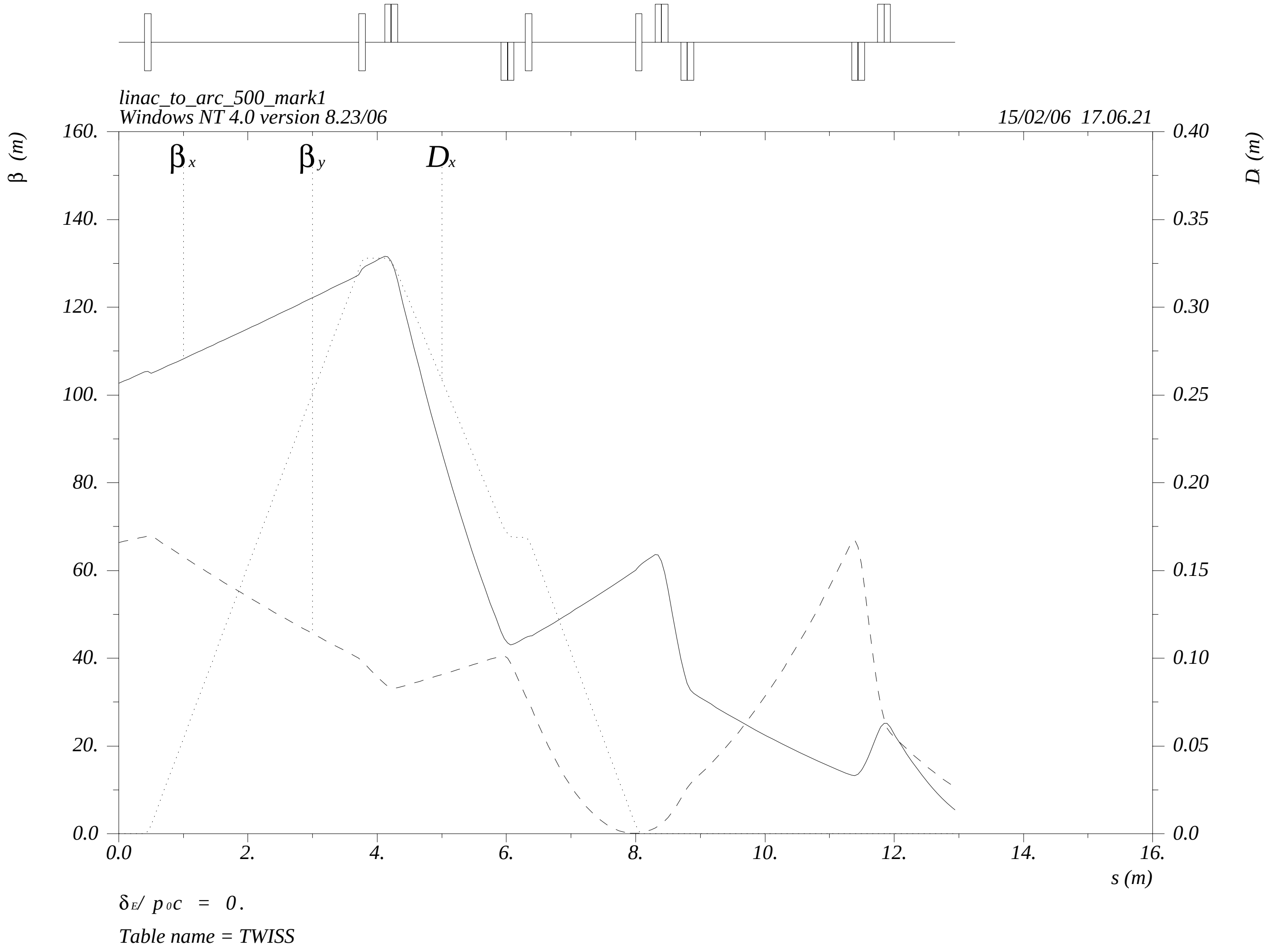

Figure 7(a). Lattice functions of the 500-MeV orbit through the asymmetric chicane of the spreader in the two-up/two-down design Model D8.

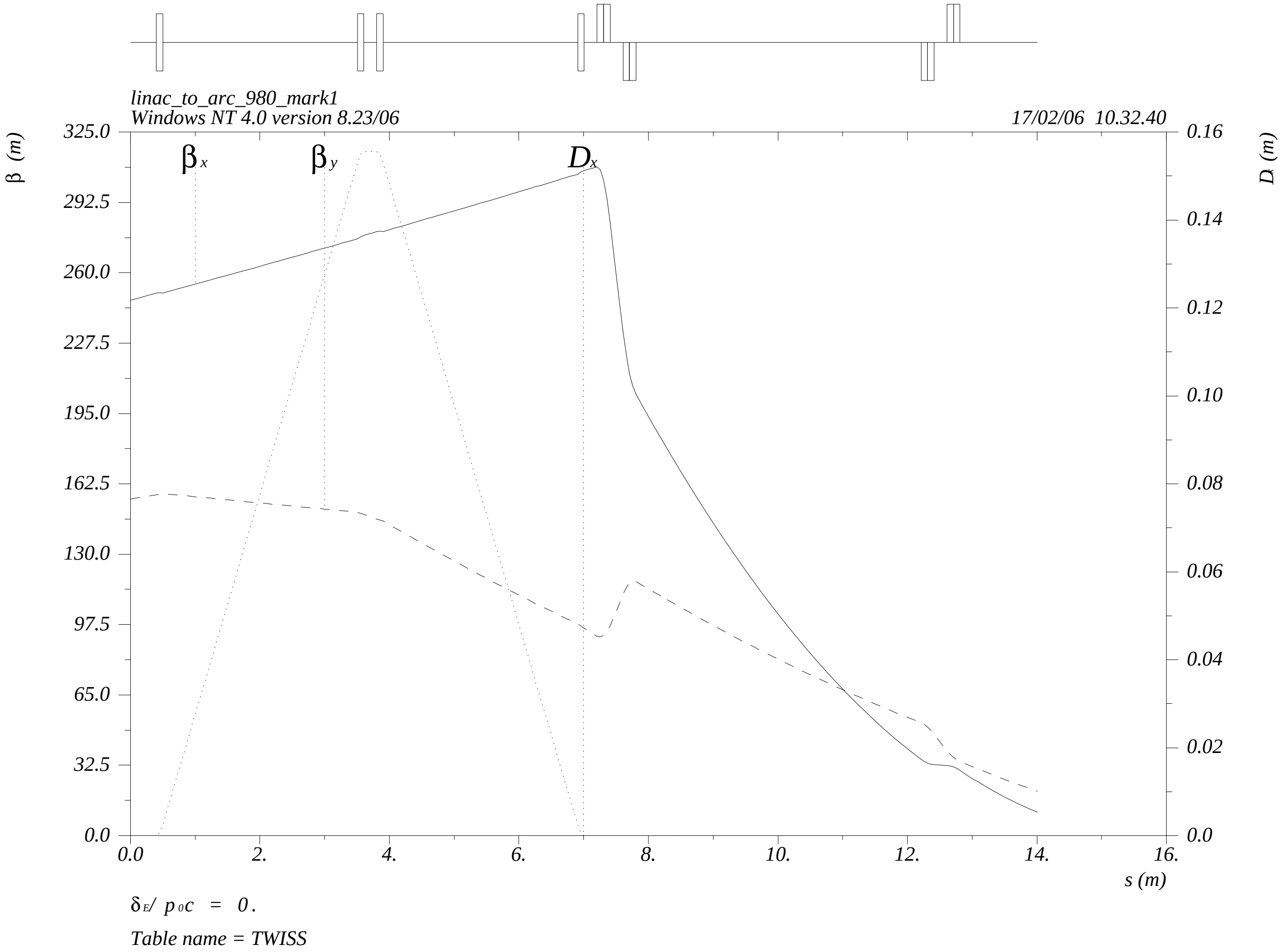

Figure 7(b). Lattice functions of the 980-MeV orbit through the symmetric chicane of the spreader in the two-up/two-down design Model D8.

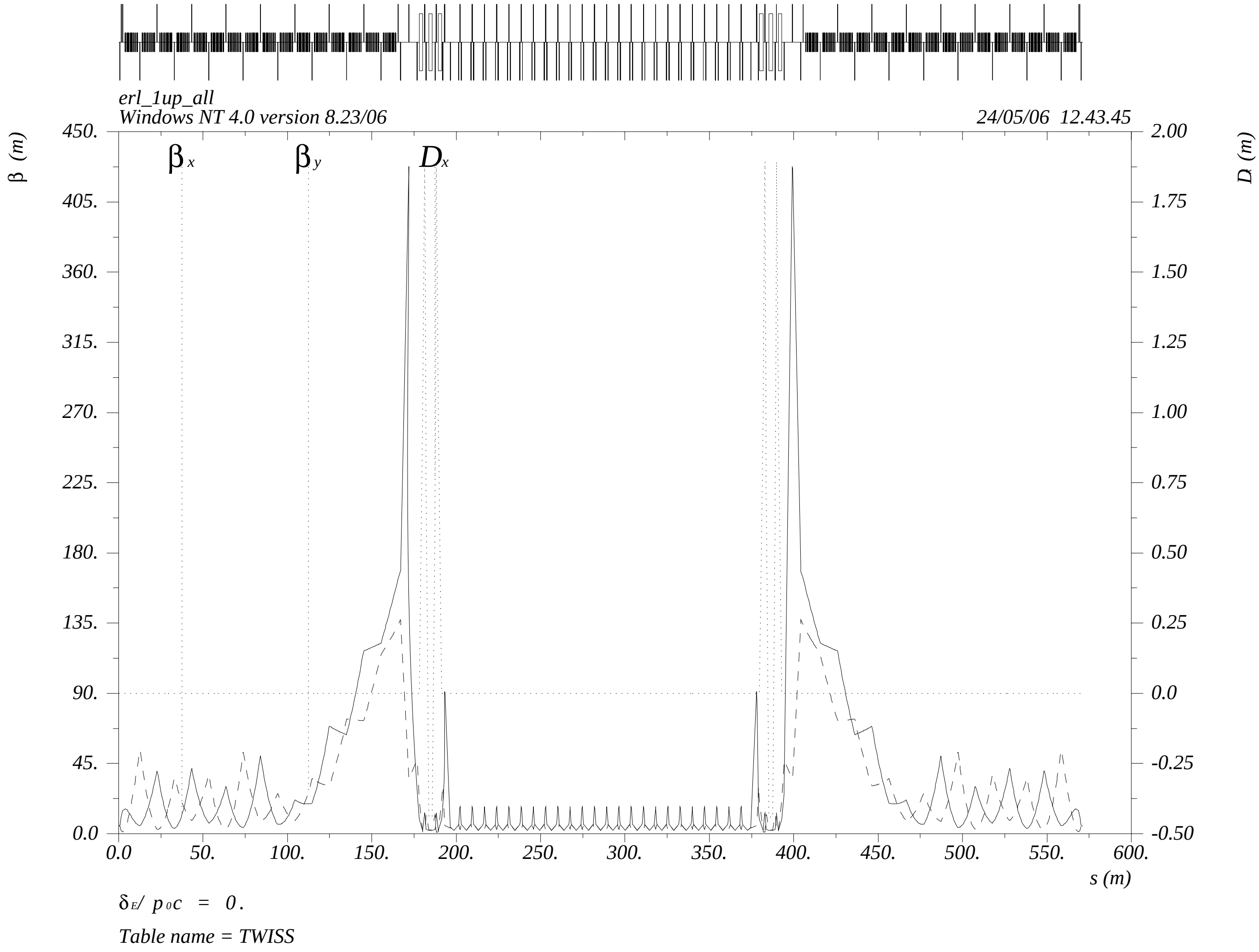

Figure 8(a). Lattice functions for the symmetric one-up/one-down Model 1IC ERL design.

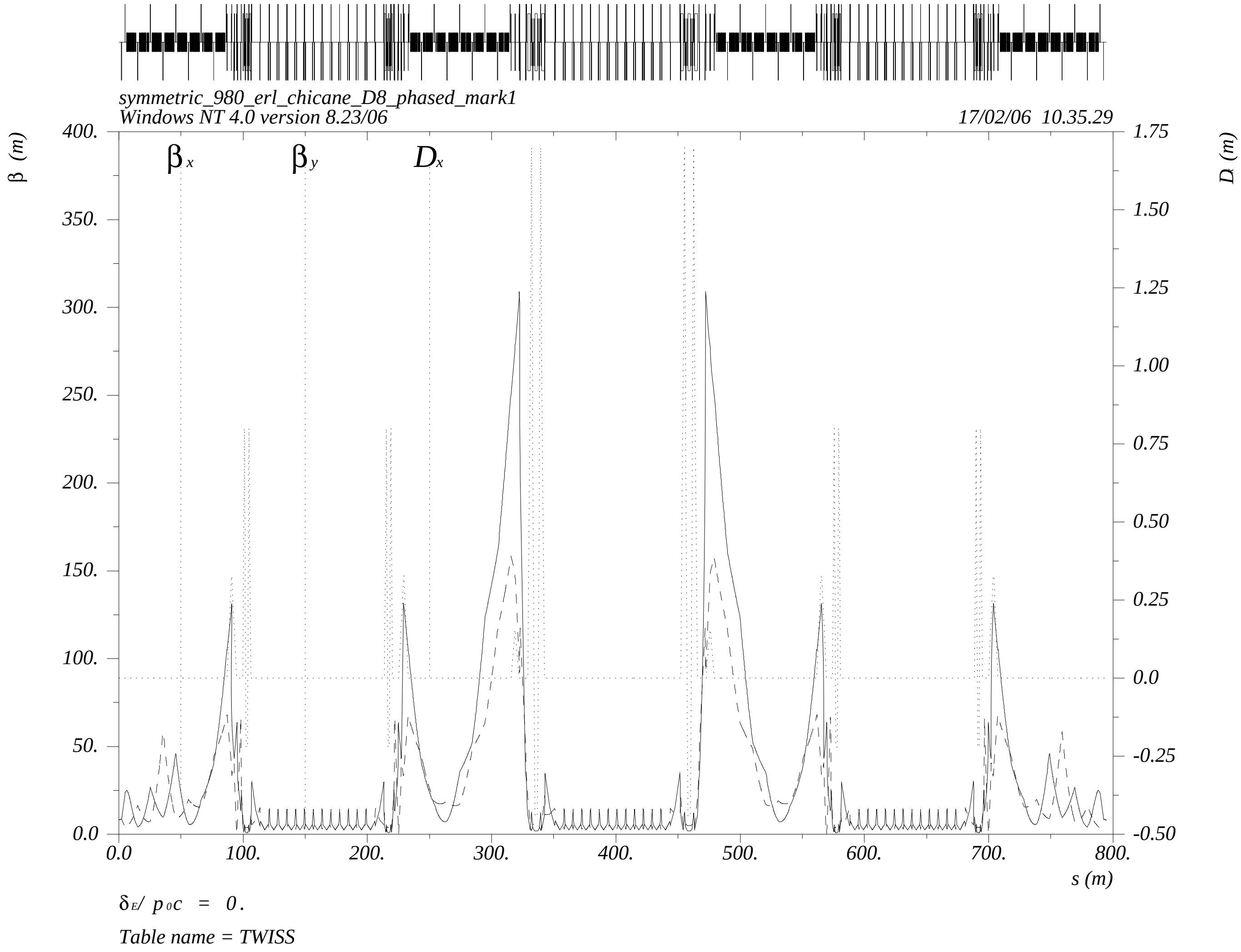

Figure 8(b). Lattice functions for the symmetric two-up/two-down Model D8 ERL design.

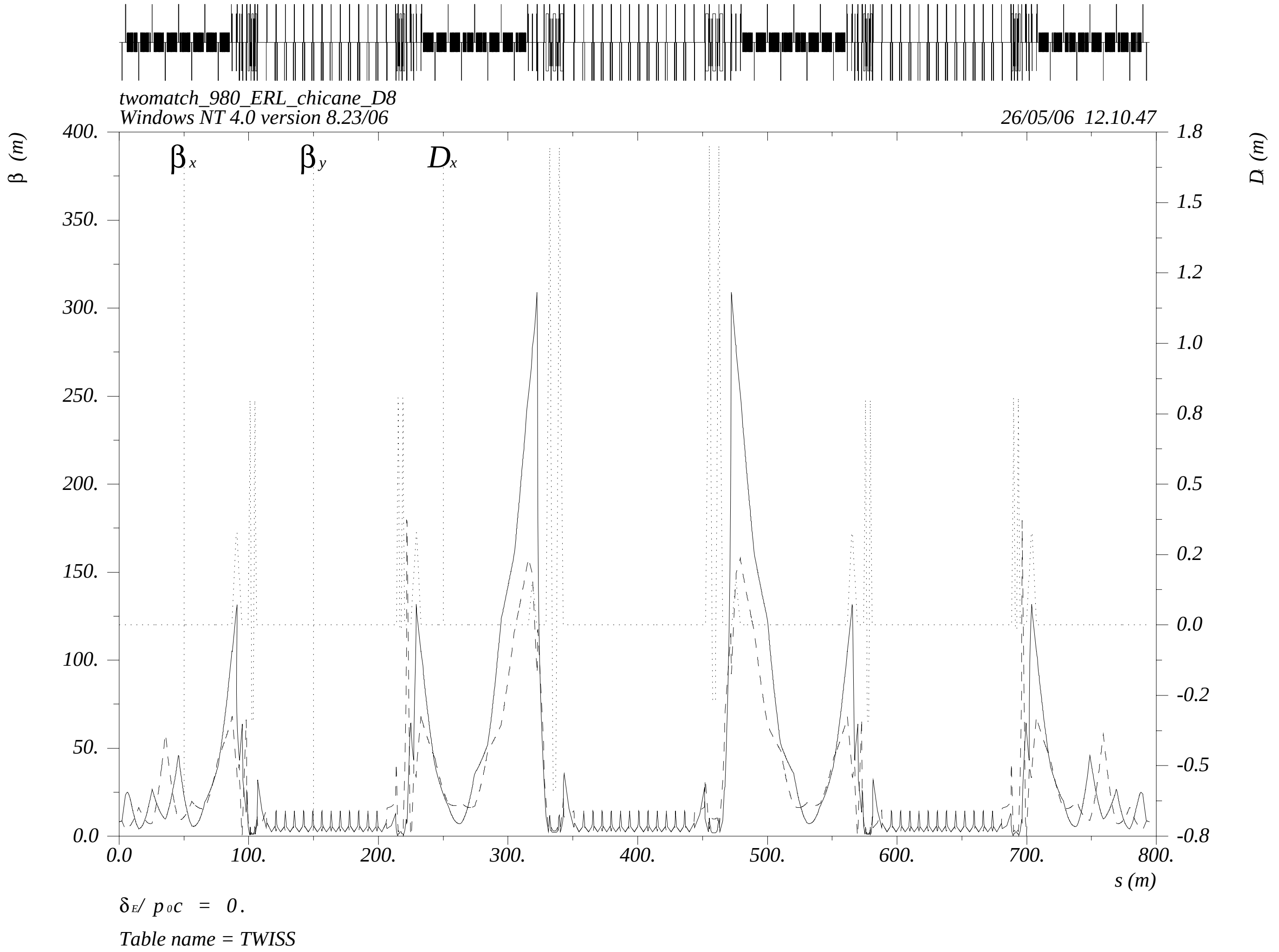

Figure 9. Lattice functions for the two-up/two-down Model D8 ERL with bunch compression/decompression.

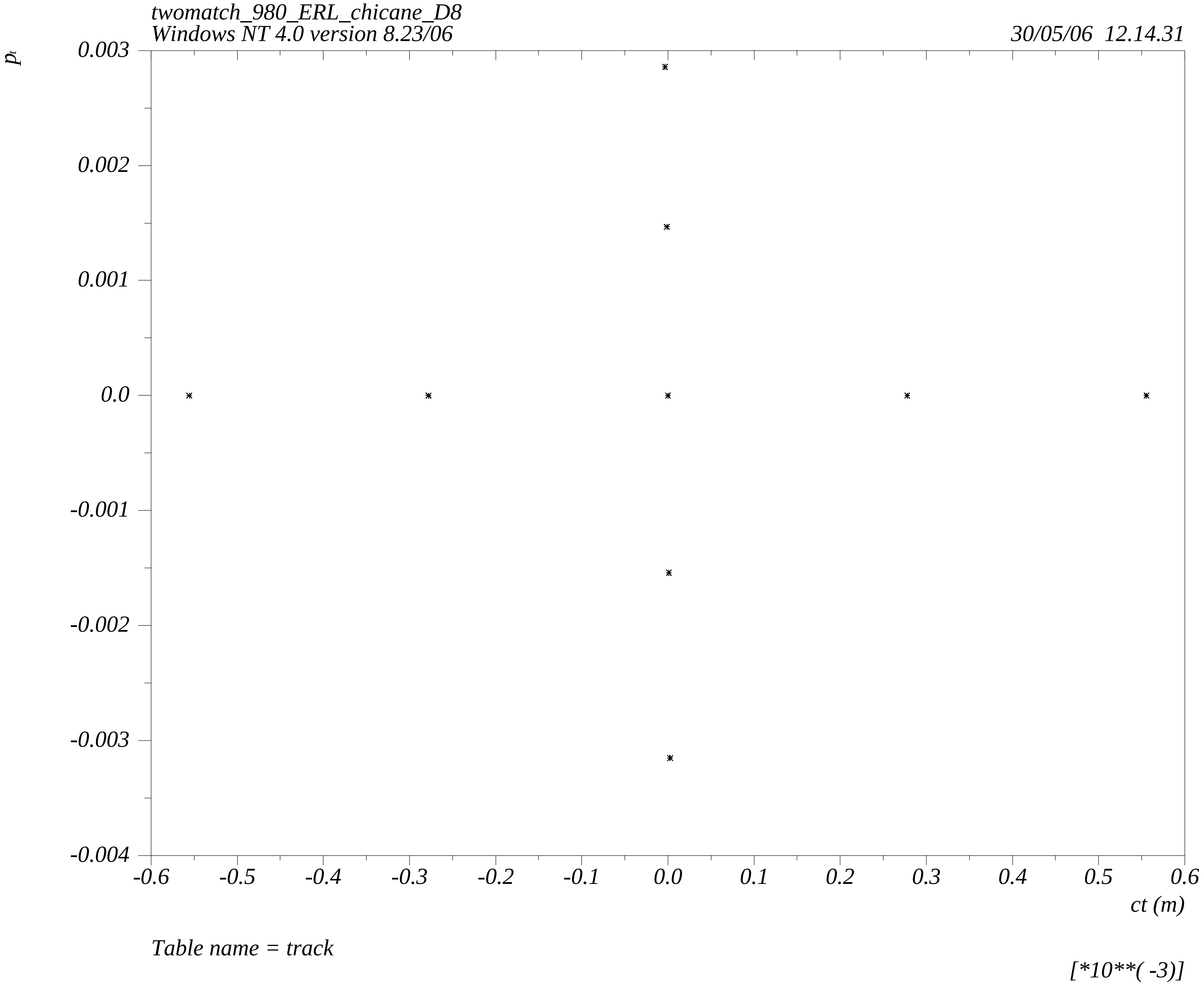

Figure 10(a). Longitudinal tracking of emittance ellipses that enter the linac with phases of –11°, –10.5°, –10°, –9.5° and –9° and undergo longitudinal compression/decompression on each recirculation arc. The 20-MeV ellipses are shown at the start of our ERL model while the 980-MeV ellipses are shown in the center of the 980-MeV recirculation arc.

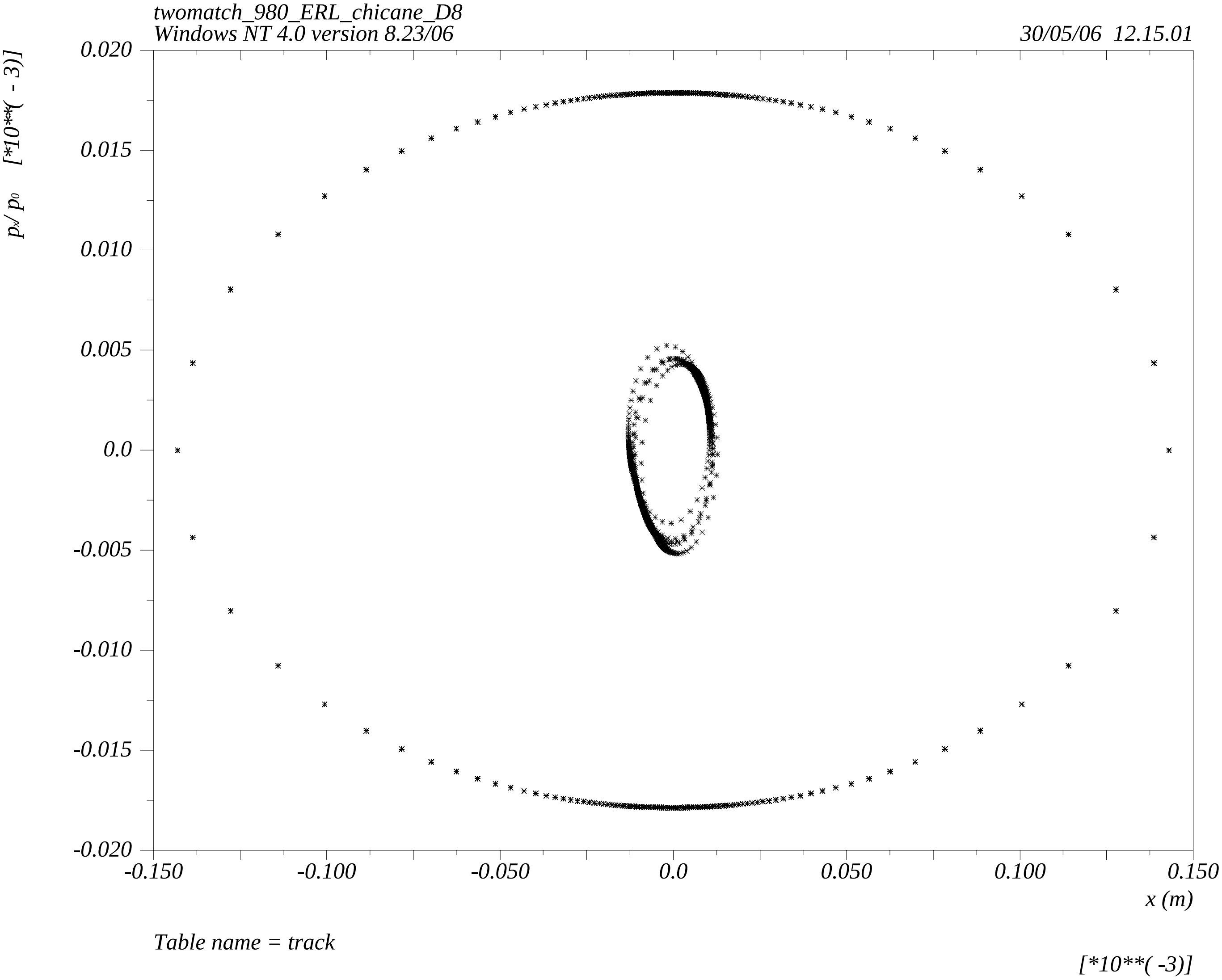

Figure 10(b). Horizontal tracking of emittance ellipses that enter the linac with phases of –11°, –10.5°, –10°, –9.5° and –9° and undergo longitudinal compression/decompression on each recirculation arc. The 20-MeV ellipses are shown at the start of our ERL model while the 980-MeV ellipses are shown in the center of the 980-MeV recirculation arc.

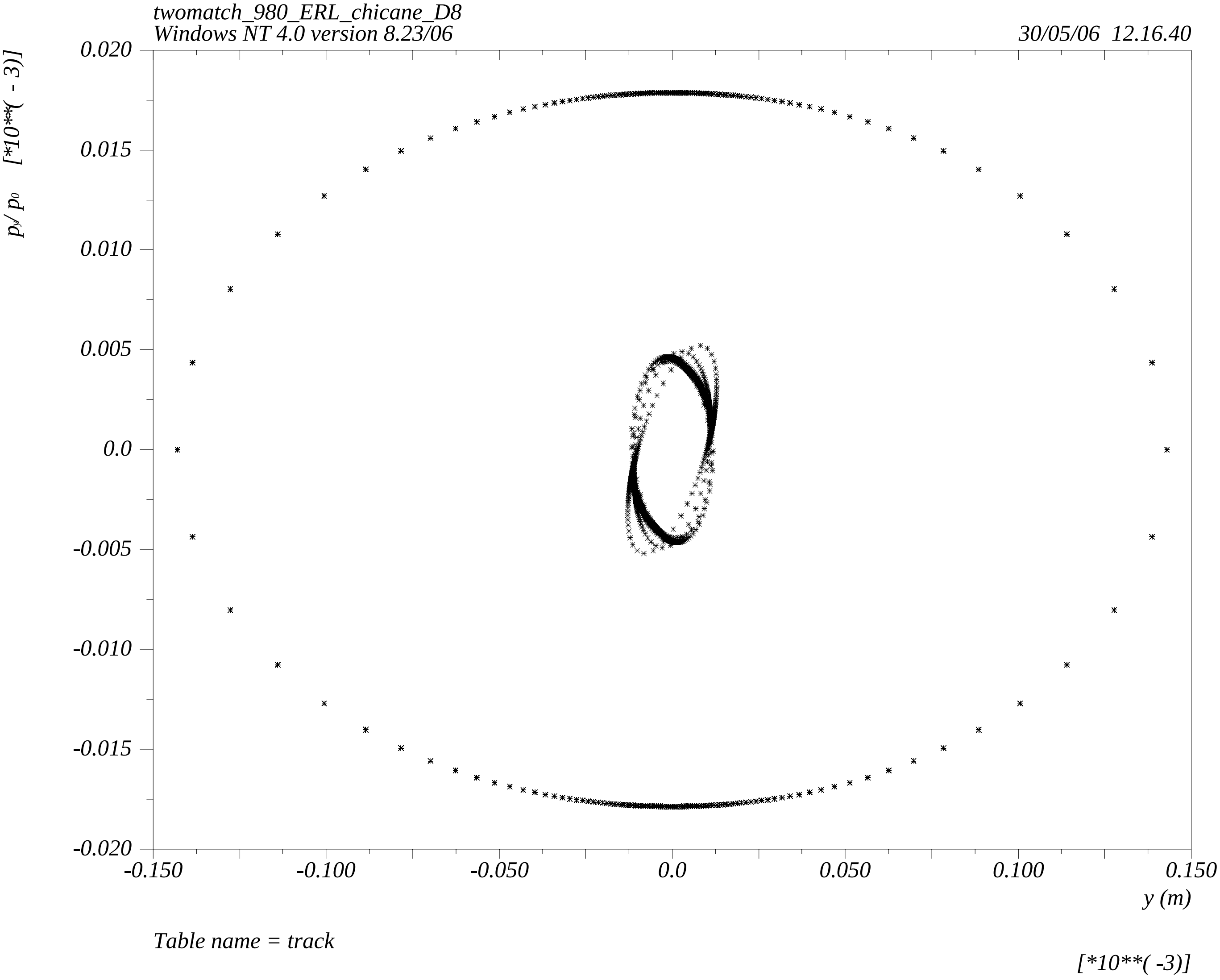

Figure 10(c). Vertical tracking of emittance ellipses that enter the linac with phases of –11°, –10.5°, –10°, –9.5° and –9° and undergo longitudinal compression/decompression on each recirculation arc. The 20-MeV ellipses are shown at the start of our ERL model while the 980-MeV ellipses are shown in the center of the 980-MeV recirculation arc.

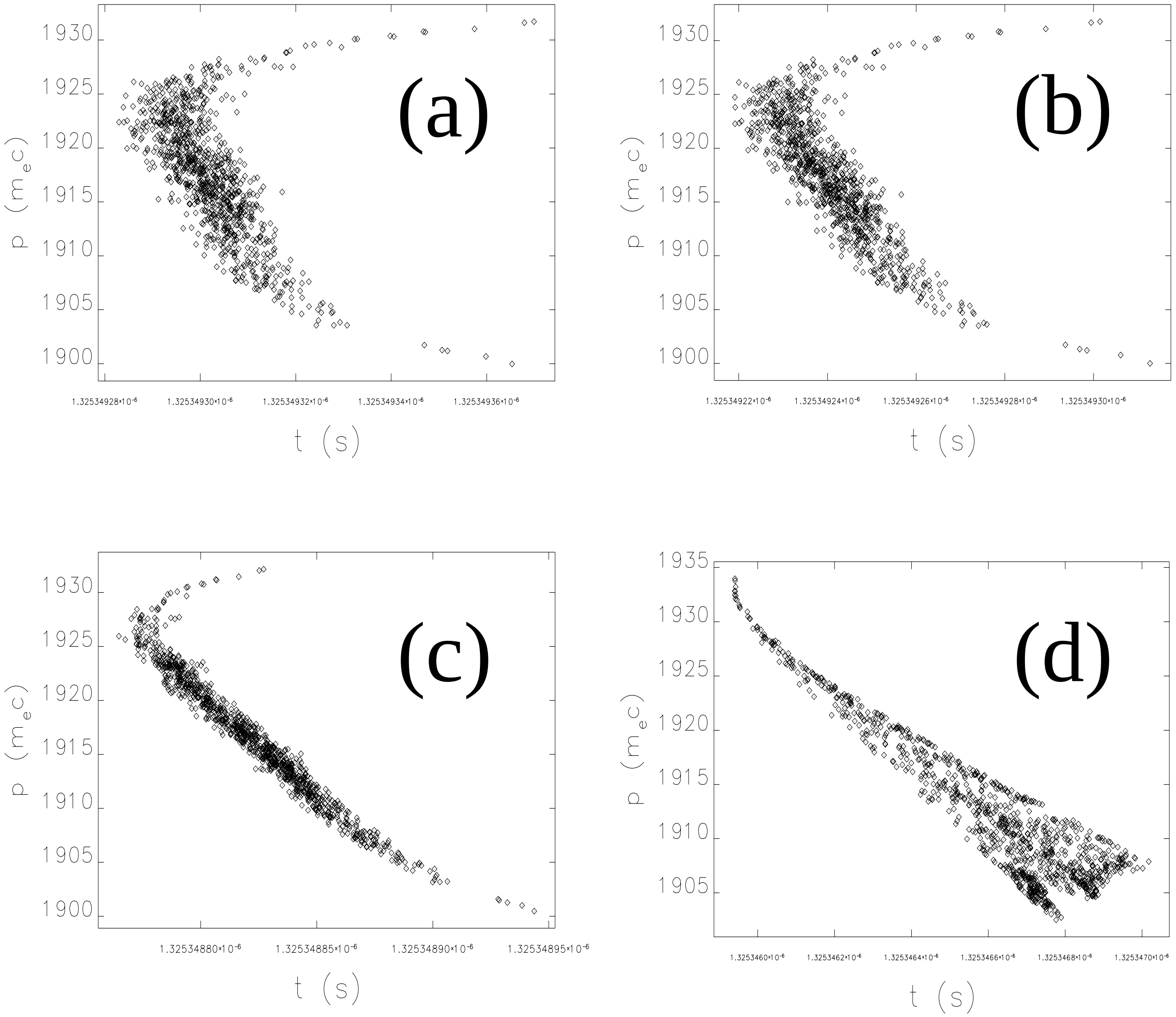

Figure 11. Longitudinal tracking by the code "elegant" of a Gaussian bunch whose uncompressed rms bunchlength is σ_t = 1.85 ps (σ_z = 555 μm), corresponding to 1 degree of linac phase. Incoherent and coherent synchrotron radiation are included in the bending magnets. The compressed bunch is shown in the center of the 980-MeV recirculation arc. (a) Bunch charge = 0. (b) Bunch charge = 1 pC. (c) Bunch charge = 10 pC. (d) Bunch charge = 100 pC.

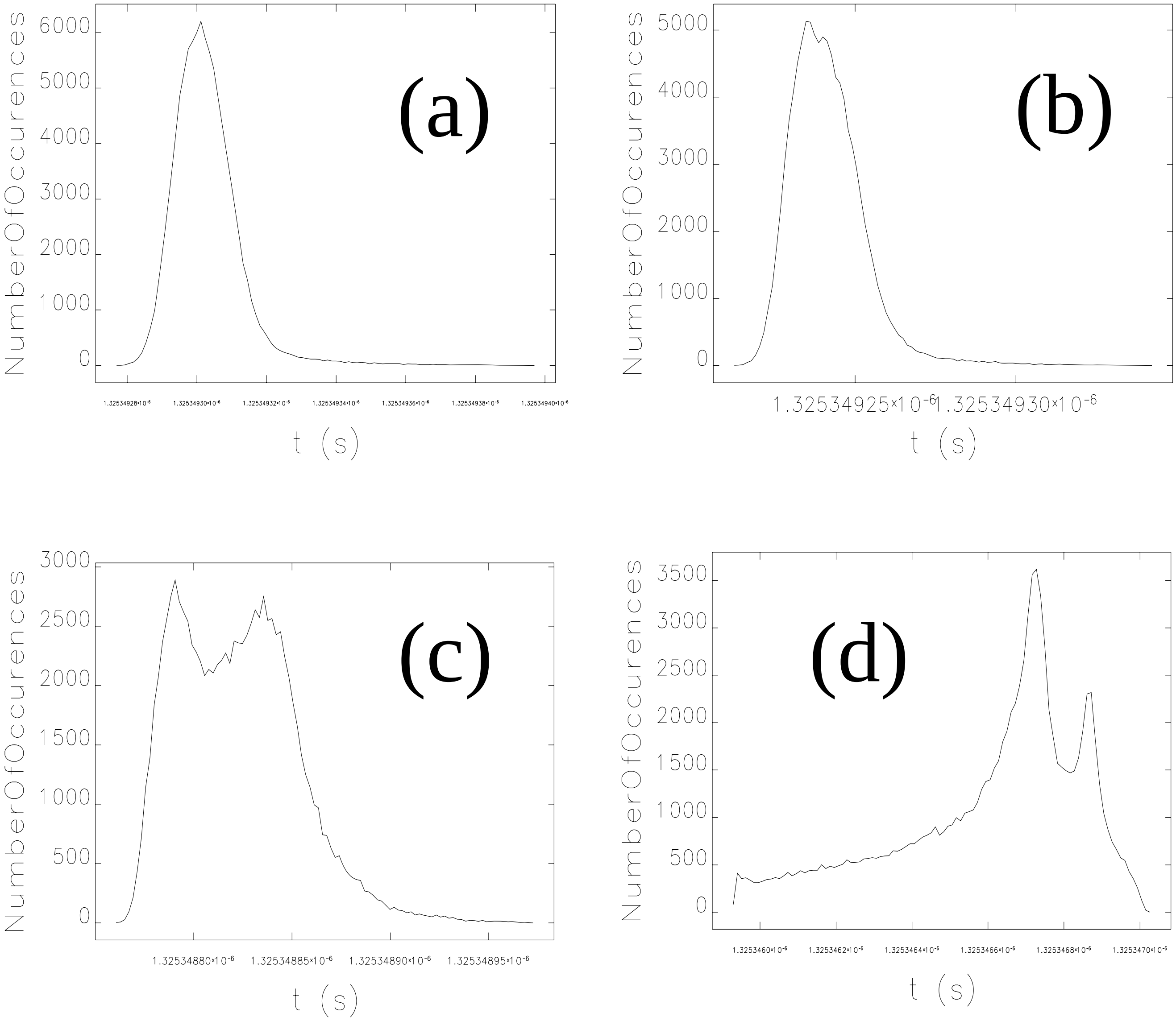

Figure 12. Bunch charge histograms from the code "elegant" of a Gaussian bunch whose uncompressed rms bunchlength is σ_t = 1.85 ps (σ_z = 555 μm). Incoherent and coherent synchrotron radiation are included in the bending magnets. The compressed bunch is shown in the center of the 980-MeV recirculation arc. (a) Bunch charge = 0. (b) Bunch charge = 1 pC. (c) Bunch charge = 10 pC. (d) Bunch charge = 100 pC.

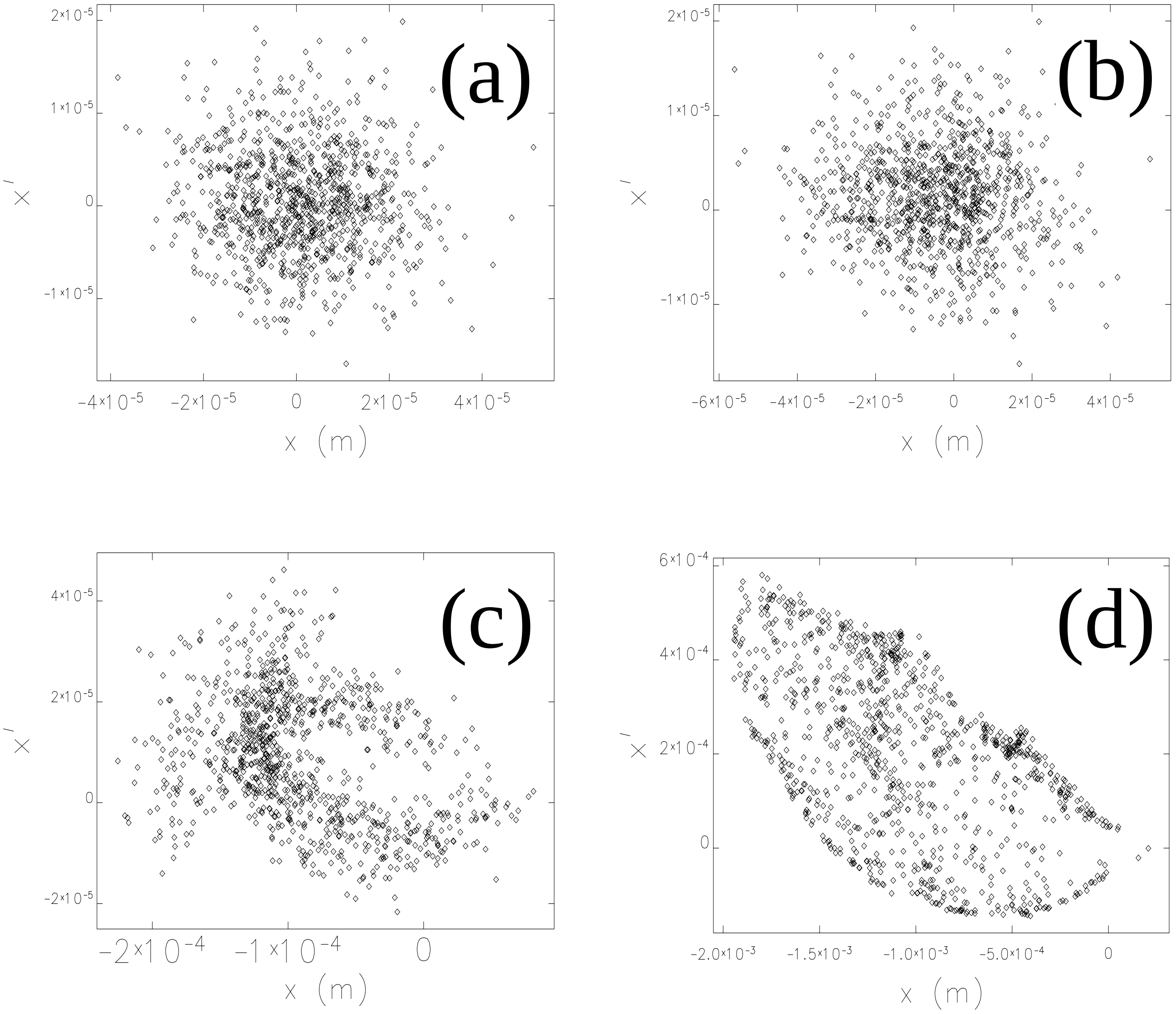

Figure 13. Horizontal tracking by the code "elegant" of a Gaussian bunch whose normalized emittance is 0.1 μm, with uncompressed rms bunchlength of σ_t = 1.85 ps (σ_z = 555 μm). Incoherent and coherent synchrotron radiation are included in the bending magnets. The compressed bunch is shown in the center of the 980-MeV recirculation arc. (a) Bunch charge = 0. (b) Bunch charge = 1 pC. (c) Bunch charge = 10 pC. (d) Bunch charge = 100 pC.

Appendix A. MAD files for the Model 1IC one-up/one-down ERL with a triplet representing the recirculation arc

```
TITLE, "Model 1IC" ! 980-MeV one-up/one-down ERL with triplet "recirculation arcs"
call Lcavity_linac_980MeV.mad
TITLE, "Model 1IC"
beam, energy = .020 ! total (KE and mc**2), otherwise the default is 1 GeV
lens0: lens, k1= 1.
lens00: lens, k1 = -2.587628
drift1_20MeV: drift, L= .6793619
drift2_20MeV: drift, L= .6668337
drift3_20MeV: drift, L= .5802200
drift1_980: drift, L = 1.2
drift2_980: drift, L = 2.4
lens1_980: lens, k1=-.3265966
lens2_980_half: lens, L = .1, k1=.6359837
ring_up: line = (drift1_20MeV,lens00,drift2_20MeV,lens0,drift3_20MeV, &
  linac_up,drift1_980,lens1_980,drift2_980,lens2_980_half)
ring_down: line = (lens2_980_half,drift2_980,lens1_980,drift1_980, &
  linac_down,drift3_20MeV,lens0,drift2_20MeV,lens00,drift1_20MeV)
ring: line = (ring_up,ring_down)
use, ring
!twiss, betx = 5., alfx = 0., bety = 5., alfy = 0. &
!   mux = 0., muy = 0., dx = 0., dpx = 0., dy = 0., dpy = 0.,save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
return

TITLE, "Lcavity_linac_980MeV" ! Lcavities (instead of RFcavities) model acceleration
k1_1:=.75
lens: quadrupole, L=.2, k1 = k1_1
lens1: lens
lens2: lens, k1=-lens[k1]
lens3: lens, k1=lens[k1]
lens4: lens, k1=-lens[k1]
lens5: lens, k1=lens[k1]
lens6: lens, k1=-lens[k1]
lens7: lens, k1=lens[k1]
lens8: lens, k1=-lens[k1]
lens9: lens, k1=lens[k1]
lens10: lens, k1=-lens[k1]*(60.*7.+20.)/(60.*9.+20.)
lens11: lens, k1=lens[k1]*(60.*6.+20.)/(60.*10.+20.)
lens12: lens, k1=-lens[k1]*(60.*5.+20.)/(60.*11.+20.)
lens13: lens, k1=lens[k1]*(60.*4.+20.)/(60.*12.+20.)
lens14: lens, k1=-lens[k1]*(60.*3.+20.)/(60.*13.+20.)
lens15: lens, k1=lens[k1]*(60.*2.+20.)/(60.*14.+20.)
lens16: lens, k1=-lens[k1]*(60.*1.+20.)/(60.*15.+20.)
lens17: lens, k1=lens[k1]*(60.*0.+20.)/(60.*16.+20.)
drift_p25: drift, L=0.25
drift_1: drift, L=1.
bbu_kick: marker
rf_half: Lcavity, L=0.25, deltae =7.5/2., phi0=0., freq=1500.
rf_unit: line = (drift_p25,rf_half,bbu_kick,rf_half,drift_p25)
cryostat: line = (8*rf_unit)
linac_up: line = (lens1,drift_1,cryostat,drift_1, &
       lens2,drift_1,cryostat,drift_1, &
```

```
       lens3,drift_1,cryostat,drift_1, &
       lens4,drift_1,cryostat,drift_1, &
       lens5,drift_1,cryostat,drift_1, &
       lens6,drift_1,cryostat,drift_1, &
       lens7,drift_1,cryostat,drift_1, &
       lens8,drift_1,cryostat,drift_1, &
       lens9,drift_1,cryostat,drift_1, &
       lens10,drift_1,cryostat,drift_1, &
       lens11,drift_1,cryostat,drift_1, &
       lens12,drift_1,cryostat,drift_1, &
       lens13,drift_1,cryostat,drift_1, &
       lens14,drift_1,cryostat,drift_1, &
       lens15,drift_1,cryostat,drift_1, &
       lens16,drift_1,cryostat,drift_1, &
       lens17)
rf_down_half: Lcavity, L=0.25, deltae = -7.5/2., phi0=0., freq=1500.
rf_down_unit: line = (drift_p25,rf_down_half,bbu_kick,rf_down_half,drift_p25)
cryostat_down: line = (8*rf_down_unit)
linac_down: line = (lens17,drift_1,cryostat_down,drift_1, &
             lens16,drift_1,cryostat_down,drift_1, &
             lens15,drift_1,cryostat_down,drift_1, &
             lens14,drift_1,cryostat_down,drift_1, &
             lens13,drift_1,cryostat_down,drift_1, &
             lens12,drift_1,cryostat_down,drift_1, &
             lens11,drift_1,cryostat_down,drift_1, &
             lens10,drift_1,cryostat_down,drift_1, &
             lens9,drift_1,cryostat_down,drift_1, &
             lens8,drift_1,cryostat_down,drift_1, &
             lens7,drift_1,cryostat_down,drift_1, &
             lens6,drift_1,cryostat_down,drift_1, &
             lens5,drift_1,cryostat_down,drift_1, &
             lens4,drift_1,cryostat_down,drift_1, &
             lens3,drift_1,cryostat_down,drift_1, &
             lens2,drift_1,cryostat_down,drift_1, &
             lens1)
return
```

Appendix B. MAD files for the Model D8 two-up/two-down ERL with triplets representing the recirculation arcs

```
TITLE, "Match7_triplets" ! symmetric triplets with symmetric betafunctions represent
! recirculation arcs
call Lcavity_linacs.mad
title, "Model D8"
beam, energy = .020 ! total (KE and mc**2), otherwise the default is 1 GeV
lens0: lens, k1= -0.93934317
drift1_20MeV: drift, L=2.09944577
drift2_20MeV: drift, L=2.62727244
lens00: lens, k1 = -.543544353
lens000_half: quadrupole, L=0.1, k1 = 1.051001382
drift_500MeV_1: drift, L = 0.92480307
drift_500MeV_2: drift, L = 2.24220286
injection: line = (drift1_20MeV,lens0,drift2_20MeV)
linacs_up: line = (linac1, &
     drift_500MeV_1,lens00,drift_500MeV_2,  &
     lens000_half, &
     lens000_half,drift_500MeV_2,lens00, &
     drift_500MeV_1,linac2)
linacs_down: line = (linac3, &
     drift_500MeV_1,lens00,drift_500MeV_2,  &
     lens000_half, &
     lens000_half,drift_500MeV_2,lens00, &
     drift_500MeV_1,linac4)
lens1_980: lens, k1 = -0.380792640
lens2_980_half: quadrupole, L=0.1, k1 = 0.732380117
drift_980_1: drift, L = 5.50064564
drift_980_2: drift, L = 2.57415568
arc_980: line = (drift_980_1,lens1_980,drift_980_2, &
      lens2_980_half, &
      lens2_980_half,drift_980_2,lens1_980, &
      drift_980_1)
ring: line = (injection,linacs_up,arc_980,linacs_down,-injection)
!use, ring
!twiss, betx = 8., alfx = 0., bety = 8., alfy = 0., &
!   mux = 0., muy = 0., dx = 0., dpx = 0., dy = 0., dpy = 0., &
!   save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
return

TITLE, "Lcavity_linacs"
k1_1:=0.63730192 ! quadrupole strength of first lens
lens: quadrupole, L=.2, k1 = k1_1
lens1: lens
lens2: lens, k1=-lens[k1]
lens3: lens, k1=lens[k1]
lens4: lens, k1=-lens[k1]
lens5: lens, k1=lens[k1]
lens6: lens, k1=-lens[k1]*(60.*3.+20.)/(60.*5.+20.)
lens7: lens, k1=lens[k1]*(60.*2.+20.)/(60.*6.+20.)
lens8: lens, k1=-lens[k1]*(60.*1.+20.)/(60.*7.+20.)
lens9: lens, k1=lens[k1]*(60.*0.+20.)/(60.*8.+20.)
drift_p25: drift, L=0.25
drift_1: drift, L=1.
```

```
bbu_kick: marker
rf_half: Lcavity, L=0.25, deltae =7.5/2., phi0=0., freq=1500.
rf_unit: line = (drift_p25,rf_half,bbu_kick,rf_half,drift_p25)
cryostat: line = (8*rf_unit)
linac1: line = (lens1,drift_1,cryostat,drift_1, &   ! accelerate to 500
       lens2,drift_1,cryostat,drift_1, &
       lens3,drift_1,cryostat,drift_1, &
       lens4,drift_1,cryostat,drift_1, &
       lens5,drift_1,cryostat,drift_1, &
       lens6,drift_1,cryostat,drift_1, &
       lens7,drift_1,cryostat,drift_1, &
       lens8,drift_1,cryostat,drift_1, &
       lens9)
lens1a: lens, k1=lens[k1] *(60.*0.+20.)/(60.*8.+20.)
lens2a: lens, k1=-lens[k1]  *(60.*1.+20.)/(60.*9.+20.)
lens3a: lens, k1=lens[k1]  *(60.*2.+20.)/(60.*10.+20.)
lens4a: lens, k1=-lens[k1]  *(60.*3.+20.)/(60.*11.+20.)
lens5a: lens, k1=lens[k1]  *(60.*4.+20.)/(60.*12.+20.)
lens6a: lens, k1=-lens[k1]*(60.*3.+20.)/(60.*13.+20.)
lens7a: lens, k1=lens[k1]*(60.*2.+20.)/(60.*14.+20.)
lens8a: lens, k1=-lens[k1]*(60.*1.+20.)/(60.*15.+20.)
lens9a: lens, k1=lens[k1]*(60.*0.+20.)/(60.*16.+20.)
linac2: line = (lens1a,drift_1,cryostat,drift_1, &   ! accelerate to 980
       lens2a,drift_1,cryostat,drift_1, &
       lens3a,drift_1,cryostat,drift_1, &
       lens4a,drift_1,cryostat,drift_1, &
       lens5a,drift_1,cryostat,drift_1, &
       lens6a,drift_1,cryostat,drift_1, &
       lens7a,drift_1,cryostat,drift_1, &
       lens8a,drift_1,cryostat,drift_1, &
       lens9a)
rf_down_half: Lcavity, L=0.25, deltae = -7.5/2. , phi0=0., freq=1500.
rf_down_unit: line = (drift_p25,rf_down_half,bbu_kick,rf_down_half,drift_p25)
cryostat_down: line = (8*rf_down_unit)
linac3: line = (lens9a,drift_1,cryostat_down,drift_1, &  ! decelerate from 980
       lens8a,drift_1,cryostat_down,drift_1, &
       lens7a,drift_1,cryostat_down,drift_1, &
       lens6a,drift_1,cryostat_down,drift_1, &
       lens5a,drift_1,cryostat_down,drift_1, &
       lens4a,drift_1,cryostat_down,drift_1, &
       lens3a,drift_1,cryostat_down,drift_1, &
       lens2a,drift_1,cryostat_down,drift_1, &
       lens1a)
linac4: line = (lens9,drift_1,cryostat_down,drift_1, &  ! decelerate from 500
       lens8,drift_1,cryostat_down,drift_1, &
       lens7,drift_1,cryostat_down,drift_1, &
       lens6,drift_1,cryostat_down,drift_1, &
       lens5,drift_1,cryostat_down,drift_1, &
       lens4,drift_1,cryostat_down,drift_1, &
       lens3,drift_1,cryostat_down,drift_1, &
       lens2,drift_1,cryostat_down,drift_1, &
       lens1)
return
```

Appendix C. MAD files for the Model 1IC one-up/one-down symmetric ERL with a symmetric recirculation arc

```
title "erl_1up_all_sex"  ! sextupoles with zero excitation included in arcs
beam, energy = .020 ! total (KE and mc**2), otherwise the default is 1 GeV
call injection_20MeV.mad
call triplet1.mad
call triplet2.mad
call Lcavity_linac_980MeV.mad
call arc_sex.mad
call back_half.mad
title "erl_1up_all"
erl_half_up: line = (injection,linac_up,triplet1,iso,triplet2,back_half)
erl_half_down: line = (back_half,-triplet2,iso,-triplet1,linac_down,-injection)
erl_1up_all: line = (erl_half_up,erl_half_down)
use, erl_1up_all
!twiss, betx = 5., alfx = 0., bety = 5., alfy = 0. &
!   mux = 0., muy = 0., dx = 0., dpx = 0., dy = 0., dpy = 0., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
return

TITLE, "injection_20MeV" ! injection region for MAD with acceleration
lens0: quadrupole, L=.2, k1= 1.
lens00: quadrupole, L=.2, k1 = -2.587628
drift1_20MeV: drift, L= .6793619
drift2_20MeV: drift, L= .6668337
drift3_20MeV: drift, L= .5802200
injection: line = (drift1_20MeV,lens00,drift2_20MeV,lens0,drift3_20MeV)
return

TITLE, "triplet1" ! linac to arc matching triplet
qd1_half_1: quadrupole, L = 0.1, k1 = -.5603724
qd2_half_1: quadrupole, L = 0.1, k1 = -1.427259
qf_half_1: quadrupole, L = 0.1, k1 = 1.155261
d1_1: drift, L = 1.2
d2_1: drift, L = 4.708682
d3_1: drift, L = 1.216136
triplet1: line = (d1_1,qd1_half_1,qd1_half_1,d2_1, &
      qf_half_1,qf_half_1,d2_1,qd2_half_1,qd2_half_1,d3_1)
return

TITLE, "triplet2" ! arc to back matching triplet
qd1_half_2: quadrupole, L = 0.1, k1 = -4.356699
qd2_half_2: quadrupole, L = 0.1, k1 = -3.984100
qf_half_2: quadrupole, L = 0.1, k1 = 3.964882
d1_2: drift, L = .5
d2_2: drift, L = 0.8813233
d3_2: drift, L = 3.244376
d4_2: drift, L = 2.
triplet2: line = (d1_2,qd1_half_2,qd1_half_2,d2_2, &
    qf_half_2,qf_half_2,d3_2,qd2_half_2,qd2_half_2,d4_2)
return

TITLE, "Lcavity_linac_980MeV"  ! uses Lcavities to model acceleration
k1_1:=0.75 ! quadrupole strength of first lens
```

```
lens: quadrupole, L=.2, k1 = k1_1
lens1: lens
lens2: lens, k1=-lens[k1]
lens3: lens, k1=lens[k1]
lens4: lens, k1=-lens[k1]
lens5: lens, k1=lens[k1]
lens6: lens, k1=-lens[k1]
lens7: lens, k1=lens[k1]
lens8: lens, k1=-lens[k1]
lens9: lens, k1=lens[k1]
lens10: lens, k1=-lens[k1]*(60.*7.+20.)/(60.*9.+20.)
lens11: lens, k1=lens[k1]*(60.*6.+20.)/(60.*10.+20.)
lens12: lens, k1=-lens[k1]*(60.*5.+20.)/(60.*11.+20.)
lens13: lens, k1=lens[k1]*(60.*4.+20.)/(60.*12.+20.)
lens14: lens, k1=-lens[k1]*(60.*3.+20.)/(60.*13.+20.)
lens15: lens, k1=lens[k1]*(60.*2.+20.)/(60.*14.+20.)
lens16: lens, k1=-lens[k1]*(60.*1.+20.)/(60.*15.+20.)
lens17: lens, k1=lens[k1]*(60.*0.+20.)/(60.*16.+20.)
drift_p25: drift, L=0.25
drift_1: drift, L=1.
bbu_kick: marker
rf_half: Lcavity, L=0.25, deltae =7.5/2., phi0=0., freq=1500.
rf_unit: line = (drift_p25,rf_half,bbu_kick,rf_half,drift_p25)
cryostat: line = (8*rf_unit)
linac_up: line = (lens1,drift_1,cryostat,drift_1, &
       lens2,drift_1,cryostat,drift_1, &
       lens3,drift_1,cryostat,drift_1, &
       lens4,drift_1,cryostat,drift_1, &
       lens5,drift_1,cryostat,drift_1, &
       lens6,drift_1,cryostat,drift_1, &
       lens7,drift_1,cryostat,drift_1, &
       lens8,drift_1,cryostat,drift_1, &
       lens9,drift_1,cryostat,drift_1, &
       lens10,drift_1,cryostat,drift_1, &
       lens11,drift_1,cryostat,drift_1, &
       lens12,drift_1,cryostat,drift_1, &
       lens13,drift_1,cryostat,drift_1, &
       lens14,drift_1,cryostat,drift_1, &
       lens15,drift_1,cryostat,drift_1, &
       lens16,drift_1,cryostat,drift_1, &
       lens17)
rf_down_half: Lcavity, L=0.25, deltae = -7.5/2., phi0=0., freq=1500.
rf_down_unit: line = (drift_p25,rf_down_half,bbu_kick,rf_down_half,drift_p25)
cryostat_down: line = (8*rf_down_unit)
linac_down: line = (lens17,drift_1,cryostat_down,drift_1, &
             lens16,drift_1,cryostat_down,drift_1, &
             lens15,drift_1,cryostat_down,drift_1, &
             lens14,drift_1,cryostat_down,drift_1, &
             lens13,drift_1,cryostat_down,drift_1, &
             lens12,drift_1,cryostat_down,drift_1, &
             lens11,drift_1,cryostat_down,drift_1, &
             lens10,drift_1,cryostat_down,drift_1, &
             lens9,drift_1,cryostat_down,drift_1, &
             lens8,drift_1,cryostat_down,drift_1, &
             lens7,drift_1,cryostat_down,drift_1, &
             lens6,drift_1,cryostat_down,drift_1, &
             lens5,drift_1,cryostat_down,drift_1, &
```

```
             lens4,drift_1,cryostat_down,drift_1, &
             lens3,drift_1,cryostat_down,drift_1, &
             lens2,drift_1,cryostat_down,drift_1, &
             lens1)
return

TITLE, "ARC_sex" ! bending arc for symmetric ERL with unpowered sextupoles
sf: multipole, K2L = 0.
sm: multipole, K2L = 0.
sd: multipole, K2L = 0.
L1a: drift, L = 0.75
L1b: drift, L = 0.25
L2_half: drift, L = 0.25
L3a: drift, L = 0.25
L3b: drift, L = 1.25
qf_half: quadrupole, L = 0.125, K1 = 5.501647
qf: line = (qf_half,qf_half)
qd_half: quadrupole, L = 0.125, K1 = -5.372879
qd: line = (qd_half,qd_half)
BD: sbend, angle = 1.04719755, L = 2.094395
iso: line = (BD,L1a,sf,L1b,qf,L2_half,sm,L2_half,qd,L3a,sd,L3b,BD, &
    L3b,sd,L3a,qd,L2_half,sm,L2_half,qf,L1b,sf,L1a,BD)
!use, iso
!twiss, betx = 9.259, alfx = 5., bety=21.344, alfy=8., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
return

TITLE, "back_half"
qd_half_b: quadrupole, L = 0.1, k1 = -3.417051
qf_half_b: quadrupole, L = 0.1, k1 = 5.617534
d1_b: drift, L = 2.728827
d2_b: drift, L = 0.592361
tripletback: line = (d1_b,qd_half_b,qd_half_b,d2_b, &
      qf_half_b,qf_half_b,d2_b,qd_half_b,qd_half_b, d1_b)
back_half: line = (12*tripletback)
return
```

Appendix D. MAD files for the Model D8 two-up/two-down symmetric ERL with symmetric recirculation arcs

```
TITLE, "symmetric_980_erl_chicane_D8_phased_mark1" ! D8 symmetric 980-MeV ERL
!  asymmetric-chicane spreader for 500 MeV; 4-dipole no-quad chicane for 980 MeV
beam, energy = .020 ! total (KE and mc**2), otherwise the default is 1 GeV
call injection.mad
call Lcavity_linacs_split_phased.mad ! linacs phased for bunch at -10 degrees
call linac_to_arc_500_mark1.mad
call arc_sex_500_qm_sm_sx.mad
call arc_to_back_500_mark1.mad
call back_500.mad
call linac_to_arc_980_mark1.mad
call arc_sex_980_number2_qm_sm_sx.mad
call arc_to_back_980_mark1.mad
call back_980.mad
TITLE, "symmetric_980_erl_chicane_D8_phased_mark1"
half_ring_up: line = (injection,linac1,linac_to_arc_500,arc1_500, &
  arc_to_back_500,6*back_500)
half_ring_down: line = (6*back_500, &
  back_to_arc_500,arc2_500,arc_to_linac_500,linac4,-injection)
half_ring: line = (half_ring_up,half_ring_down)
end_500MeV: line = (half_ring_up,6*back_500,back_to_arc_500, &
  arc2_500,arc_to_linac_500)
ring_up: line = (end_500MeV,linac2,linac_to_arc_980,arc1_980, &
  arc_to_back_980,6*back_980)
end_980MeV: line = (ring_up,6*back_980,back_to_arc_980, &
  arc2_980,arc_to_linac_980)
second_pass_500: line = (end_980MeV,linac3,linac_to_arc_500, &
  arc1_500,arc_to_back_500,6*back_500)
end_second_pass_500MeV: line = (second_pass_500,6*back_500, &
  back_to_arc_500,arc2_500,arc_to_linac_500)
ring: line = (end_second_pass_500MeV,linac4,-injection)
use, ring
!twiss, betx = 8., alfx = 0., bety = 8., alfy = 0. &
!   mux = 0., muy = 0., dx = 0., dpx = 0., dy = 0., dpy = 0., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
return

TITLE, "injection" ! injection regions for 2-up ERL, Match7 design
lens_20MeV: quadrupole, L = 0.2, k1=-0.93934317
drift1_20MeV: drift, L=2.09944577
drift2_20MeV: drift, L=2.62727244
injection: line = (drift1_20MeV,lens_20MeV,drift2_20MeV)
return

TITLE, "Lcavity_linacs_split_phased" ! Lcavities split up to limit acceleration
k1_1:=0.63730192 ! quadrupole strength of first lens
lens: quadrupole, L=.2, k1 = k1_1
lens1: lens
lens2: lens, k1=-lens[k1]
lens3: lens, k1=lens[k1]
lens4: lens, k1=-lens[k1]
lens5: lens, k1=lens[k1]
lens6: lens, k1=-lens[k1]*(60.*3.+20.)/(60.*5.+20.)
```

```
lens7: lens, k1=lens[k1]*(60.*2.+20.)/(60.*6.+20.)
lens8: lens, k1=-lens[k1]*(60.*1.+20.)/(60.*7.+20.)
lens9: lens, k1=lens[k1]*(60.*0.+20.)/(60.*8.+20.)
drift_p25: drift, L=0.25
drift_1: drift, L=1.
bbu_kick: marker
RF_tenth: LCAVITY, L=0.05, DELTAE=0.75/.984807753,  &
  PHI0=-10./360., FREQ=1.5E3
rf_half: line = (5*rf_tenth)
rf_unit: line = (drift_p25,rf_half,bbu_kick,rf_half,drift_p25)
cryostat: line = (8*rf_unit)
linac1: line = (lens1,drift_1,cryostat,drift_1, &   ! accelerate to 500
       lens2,drift_1,cryostat,drift_1, &
       lens3,drift_1,cryostat,drift_1, &
       lens4,drift_1,cryostat,drift_1, &
       lens5,drift_1,cryostat,drift_1, &
       lens6,drift_1,cryostat,drift_1, &
       lens7,drift_1,cryostat,drift_1, &
       lens8,drift_1,cryostat,drift_1, &
       lens9)
lens1a: lens, k1=lens[k1] *(60.*0.+20.)/(60.*8.+20.)
lens2a: lens, k1=-lens[k1]  *(60.*1.+20.)/(60.*9.+20.)
lens3a: lens, k1=lens[k1]  *(60.*2.+20.)/(60.*10.+20.)
lens4a: lens, k1=-lens[k1]  *(60.*3.+20.)/(60.*11.+20.)
lens5a: lens, k1=lens[k1]  *(60.*4.+20.)/(60.*12.+20.)
lens6a: lens, k1=-lens[k1]*(60.*3.+20.)/(60.*13.+20.)
lens7a: lens, k1=lens[k1]*(60.*2.+20.)/(60.*14.+20.)
lens8a: lens, k1=-lens[k1]*(60.*1.+20.)/(60.*15.+20.)
lens9a: lens, k1=lens[k1]*(60.*0.+20.)/(60.*16.+20.)
linac2: line = (lens1a,drift_1,cryostat,drift_1, &   ! accelerate to 980
       lens2a,drift_1,cryostat,drift_1, &
       lens3a,drift_1,cryostat,drift_1, &
       lens4a,drift_1,cryostat,drift_1, &
       lens5a,drift_1,cryostat,drift_1, &
       lens6a,drift_1,cryostat,drift_1, &
       lens7a,drift_1,cryostat,drift_1, &
       lens8a,drift_1,cryostat,drift_1, &
       lens9a)
RF_DOWN_tenth: LCAVITY, L=0.05, DELTAE=0.75/.984807753, &
  PHI0=-190./360.,FREQ=1.5E3
rf_down_half: line = (5*rf_down_tenth)
rf_down_unit: line = (drift_p25,rf_down_half,bbu_kick,rf_down_half,drift_p25)
cryostat_down: line = (8*rf_down_unit)
linac3: line = (lens9a,drift_1,cryostat_down,drift_1, &  ! decelerate from 980
       lens8a,drift_1,cryostat_down,drift_1, &
       lens7a,drift_1,cryostat_down,drift_1, &
       lens6a,drift_1,cryostat_down,drift_1, &
       lens5a,drift_1,cryostat_down,drift_1, &
       lens4a,drift_1,cryostat_down,drift_1, &
       lens3a,drift_1,cryostat_down,drift_1, &
       lens2a,drift_1,cryostat_down,drift_1, &
       lens1a)
linac4: line = (lens9,drift_1,cryostat_down,drift_1, &  ! decelerate from 500
       lens8,drift_1,cryostat_down,drift_1, &
       lens7,drift_1,cryostat_down,drift_1, &
       lens6,drift_1,cryostat_down,drift_1, &
       lens5,drift_1,cryostat_down,drift_1, &
```

```
       lens4,drift_1,cryostat_down,drift_1, &
       lens3,drift_1,cryostat_down,drift_1, &
       lens2,drift_1,cryostat_down,drift_1, &
       lens1)
return

TITLE, "linac_to_arc_500_mark1" ! reduce R56 with smaller separation and angles
! drifts are the same in linac_to_arc_500 and arc_to_linac_500, and denoted by "LA"
Lstraight2_500LA := 2.475 ! qf-qd straight
Lstraight4_500LA := 4.85 - 0.007726505 ! tweaked for an integral no. of RF periods
d_p4m_500LA: drift, L = 0.4  ! between LINAC and 1st spreader dipole
d1_500LA: drift, L = 3.215477978
d2_500LA: drift, L = .3
d3_500LA: drift, L = 1.6
d4_500LA: drift, L = Lstraight2_500LA-.4-d3_500LA[L]-d2_500LA[L]
d5_500LA: drift, L = d1_500LA[L]/2.
! drifts below are in the matching section straight4
d6_500LA: drift, L = .2
d7_500LA: drift, L = .2 ! 1st doublet spacing
d9_500LA: drift, L = .2 ! 2nd doublet spacing
d10_500LA: drift, L = 1.
d8_500LA: drift, L = Lstraight4_500LA - 0.8 &
   -d6_500LA[L]-d7_500LA[L]-d9_500LA[L]-d10_500LA[L]
! rectangular bending magnets
! NOTE: bend magnet names must not exceed 16 characters
bend_5p624_e1_0: sbend, angle=.098157547, L=0.10016076, e1=0., e2= .098157547
bend_m5p624_e2_0: sbend, angle=-.098157547, L=0.10016076, e1=-.098157547, e2=0.
bend_5p624_e2_0: sbend, angle=.098157547, L=0.10016076, e2=0., e1=.098157547
bend_m5p624_e1_0: sbend, angle=-.098157547, L=0.10016076, e2=-.098157547, e1=0.
! linac_to_arc_500 quadrupole strengths
qf_half_500LA: quadrupole, L = 0.1, K1 = 1.35968132 ! |K1| < 19 for CEBAF-type quads
qf_500LA: line = (qf_half_500LA,qf_half_500LA)
qd_half_500LA: quadrupole, L = 0.1, K1 = -2.57174033 ! |K1| < 19 for CEBAF-type quads
qd_500LA: line = (qd_half_500LA,qd_half_500LA)
q1_half_500LA: quadrupole, L = 0.1, K1 = 4.09341374  ! 1st doublet in straight4
q1_500LA: line = (q1_half_500LA, q1_half_500LA)
q2_half_500LA: quadrupole, L = 0.1, K1 = -4.18013210  ! 1st doublet in straight4
q2_500LA: line = (q2_half_500LA, q2_half_500LA)
q3_half_500LA: quadrupole, L = 0.1, K1 = -6.52694120  ! second doublet in straight4
q3_500LA: line = (q3_half_500LA, q3_half_500LA)
q4_half_500LA: quadrupole, L = 0.1, K1 = 6.72947543  ! second doublet in straight4
q4_500LA: line = (q4_half_500LA, q4_half_500LA)
linac_to_arc_500: line = (d_p4m_500LA,bend_5p624_e1_0,d1_500LA, &
  bend_m5p624_e2_0,d2_500LA,qf_500LA,d3_500LA,qd_500LA, &
  d4_500LA,bend_m5p624_e1_0,d5_500LA, bend_5p624_e2_0, &
  d6_500LA,q1_500LA,d7_500LA,q2_500LA,d8_500LA,q3_500LA, &
  d9_500LA,q4_500LA,d10_500LA)
! arc_to_linac_500 quadrupole strengths
qf_half_500AL: quadrupole, L = 0.1, K1 = 1.35968132 ! |K1| < 19 for CEBAF-type quads
qf_500AL: line = (qf_half_500AL,qf_half_500AL)
qd_half_500AL: quadrupole, L = 0.1, K1 = -2.57174033 ! |K1| < 19 for CEBAF-type quads
qd_500AL: line = (qd_half_500AL,qd_half_500AL)
q1_half_500AL: quadrupole, L = 0.1, K1 = 4.09341374  ! 1st doublet in straight4
q1_500AL: line = (q1_half_500AL, q1_half_500AL)
q2_half_500AL: quadrupole, L = 0.1, K1 = -4.18013210  ! 1st doublet in straight4
q2_500AL: line = (q2_half_500AL, q2_half_500AL)
q3_half_500AL: quadrupole, L = 0.1, K1 = -6.52694120  ! second doublet in straight4
```

```
q3_500AL: line = (q3_half_500AL, q3_half_500AL)
q4_half_500AL: quadrupole, L = 0.1, K1 = 6.72947543  ! second doublet in straight4
q4_500AL: line = (q4_half_500AL, q4_half_500AL)
arc_to_linac_500: line = (d10_500LA,q4_500AL,d9_500LA,q3_500AL, &
 d8_500LA,q2_500AL,d7_500LA,q1_500AL,d6_500LA,bend_5p624_e1_0, &
 d5_500LA,bend_m5p624_e2_0,d4_500LA,qd_500AL,d3_500LA, &
 qf_500AL,d2_500LA,bend_m5p624_e1_0,d1_500LA,bend_5p624_e2_0, &
 d_p4m_500LA)
!use, linac_to_arc_500
!twiss, betx =102.636, alfx =-3.256, bety =66.382, alfy =-1.589, save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=Dx,style=100,spline
!use, arc_to_linac_500
!twiss, betx =5.377071, alfx =-6., bety =10.482558, alfy =-5., save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=Dx,style=100,spline
return

TITLE, "ARC_sex_500_qm_sm_sx" ! 500-MeV bending arc with unpowered sextupoles and qm
!quadrupoles.  The qm quadrupoles are not used.
! Quad and sextupole strings are broken up
! The 500-MeV arc differs from the 980-MeV arc.
! drifts and dipoles are the same in both 500-MeV bending arcs
L1a_500arc: drift, L = 0.15
L1b_500arc: drift, L = 0.15
L2a_500arc: drift, L = 0.1
L2b_500arc: drift, L = 0.1
L3a_500arc: drift, L = 0.2
L3b1_500arc: drift, L = 0.2
L3b2_500arc: drift, L = 0.2
BD_500arc: sbend, angle = 1.04719755, L = 1.04719755
!arc1:
sf1_500arc1: multipole, K2L = 0.
sf2_500arc1: multipole, K2L = 0.
sd1_500arc1: multipole, K2L = 0.
sd2_500arc1: multipole, K2L = 0.
sm1_500arc1: multipole, K2L = 0.
sm2_500arc1: multipole, K2L = 0.
sx1_500arc1: multipole, K2L = 0.
sx2_500arc1: multipole, K2L = 0.
qm1_half_500arc1: quadrupole, L = 0.1, K1 = 0.
qm1_500arc1: line = (qm1_half_500arc1,sm1_500arc1,qm1_half_500arc1)
qm2_half_500arc1: quadrupole, L = 0.1, K1 = 0.
qm2_500arc1: line = (qm2_half_500arc1,sm2_500arc1,qm2_half_500arc1)
qf1_half_500arc1: quadrupole, L = 0.1, K1 = 11.620516
qf1_500arc1: line = (qf1_half_500arc1,qf1_half_500arc1)
qd1_half_500arc1: quadrupole, L = 0.1, K1 = -4.55524
qd1_500arc1: line = (qd1_half_500arc1,qd1_half_500arc1)
qf2_half_500arc1: quadrupole, L = 0.1, K1 = 11.620516
qf2_500arc1: line = (qf2_half_500arc1,qf2_half_500arc1)
qd2_half_500arc1: quadrupole, L = 0.1, K1 = -4.55524
qd2_500arc1: line = (qd2_half_500arc1,qd2_half_500arc1)
arc1_500: line = (BD_500arc,L1a_500arc,sf1_500arc1,L1b_500arc, &
  qf1_500arc1,L2a_500arc,qm1_500arc1,L2b_500arc,qd1_500arc1, &
  L3a_500arc,sd1_500arc1,L3b1_500arc,sx1_500arc1,L3b2_500arc, &
  BD_500arc,L3b2_500arc,sx2_500arc1,L3b1_500arc, &
  sd2_500arc1,L3a_500arc, &
  qd2_500arc1,L2b_500arc,qm2_500arc1,L2a_500arc,qf2_500arc1, &
  L1b_500arc,sf2_500arc1,L1a_500arc,BD_500arc)
```

```
!arc2:
sf1_500arc2: multipole, K2L = 0.
sf2_500arc2: multipole, K2L = 0.
sd1_500arc2: multipole, K2L = 0.
sd2_500arc2: multipole, K2L = 0.
sm1_500arc2: multipole, K2L = 0.
sm2_500arc2: multipole, K2L = 0.
sx1_500arc2: multipole, K2L = 0.
sx2_500arc2: multipole, K2L = 0.
qm1_half_500arc2: quadrupole, L = 0.1, K1 = 0.
qm1_500arc2: line = (qm1_half_500arc2,sm1_500arc2,qm1_half_500arc2)
qm2_half_500arc2: quadrupole, L = 0.1, K1 = 0.
qm2_500arc2: line = (qm2_half_500arc2,sm2_500arc2,qm2_half_500arc2)
qf1_half_500arc2: quadrupole, L = 0.1, K1 = 11.620516
qf1_500arc2: line = (qf1_half_500arc2,qf1_half_500arc2)
qd1_half_500arc2: quadrupole, L = 0.1, K1 = -4.55524
qd1_500arc2: line = (qd1_half_500arc2,qd1_half_500arc2)
qf2_half_500arc2: quadrupole, L = 0.1, K1 = 11.620516
qf2_500arc2: line = (qf2_half_500arc2,qf2_half_500arc2)
qd2_half_500arc2: quadrupole, L = 0.1, K1 = -4.55524
qd2_500arc2: line = (qd2_half_500arc2,qd2_half_500arc2)
arc2_500: line = (BD_500arc,L1a_500arc,sf2_500arc2,L1b_500arc, &
  qf2_500arc2,L2a_500arc,qm2_500arc2,L2b_500arc,qd2_500arc2, &
  L3a_500arc,sd2_500arc2,L3b1_500arc,sx2_500arc2,L3b2_500arc, &
  BD_500arc,L3b2_500arc,sx1_500arc2,L3b1_500arc, &
  sd1_500arc2,L3a_500arc, &
  qd1_500arc2,L2b_500arc,qm1_500arc2,L2a_500arc,qf1_500arc2, &
  L1b_500arc,sf1_500arc2,L1a_500arc,BD_500arc)
!use, arc1_500
!twiss, betx = 5.377 , alfx = 6., bety=10.483, alfy=5., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
!use, arc2_500
!twiss, betx = 5.377 , alfx = 6., bety=10.483, alfy=5., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
return

TITLE, "arc_to_back_500_mark1"  ! for D8 ERL with chicane spreader with lower R56
!  drifts are the same in arc_to_back_500 and back_to_arc_500
d1_500AB: drift, L = .15
d2_500AB: drift, L = .15
d4_500AB: drift, L = .25
d5_500AB: drift, L = 3.5
d3_500AB: drift, L = 6.5073747  ! gives total length of 11.3573747
! arc_to_back_500
qd1_half_500AB: quadrupole, L = 0.1, k1 = -7.56738873 ! k1 < 19 for 500 MeV
qd2_half_500AB: quadrupole, L = 0.1, k1 = -3.71247596
qf1_half_500AB: quadrupole, L = 0.1, k1 =  7.49534511
qf2_half_500AB: quadrupole, L = 0.1, k1 =  3.41397101
qd1_500AB: line = (qd1_half_500AB,qd1_half_500AB)
qd2_500AB: line = (qd2_half_500AB,qd2_half_500AB)
qf1_500AB: line = (qf1_half_500AB,qf1_half_500AB)
qf2_500AB: line = (qf2_half_500AB,qf2_half_500AB)
arc_to_back_500: line = (d1_500AB,qd1_500AB,d2_500AB,qf1_500AB, &
   d3_500AB,qd2_500AB,d4_500AB,qf2_500AB,d5_500AB)
! back_to_arc_500
```

```
qd1_half_500BA: quadrupole, L = 0.1, k1 = -7.56738873 ! k1 < 19 for 500 MeV
qd2_half_500BA: quadrupole, L = 0.1, k1 = -3.71247596
qf1_half_500BA: quadrupole, L = 0.1, k1 =  7.49534511
qf2_half_500BA: quadrupole, L = 0.1, k1 =  3.41397101
qd1_500BA: line = (qd1_half_500BA,qd1_half_500BA)
qd2_500BA: line = (qd2_half_500BA,qd2_half_500BA)
qf1_500BA: line = (qf1_half_500BA,qf1_half_500BA)
qf2_500BA: line = (qf2_half_500BA,qf2_half_500BA)
back_to_arc_500: line = (d5_500AB,qf2_500BA,d4_500AB,qd2_500BA, &
   d3_500AB,qf1_500BA,d2_500AB,qd1_500BA,d1_500AB)
!use, arc_to_back_500
!twiss, betx=5.377071, alfx= -6., bety=10.482558, alfy= -5., save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
!use, back_to_arc_500
!twiss, betx = 2.5, alfx = 0., bety=2.5, alfy=0., save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
return

TITLE, "back_500" ! for 12 back straight sections
qd_half_500B: quadrupole, L = 0.1, k1 = -3.26010968
qf_half_500B: quadrupole, L = 0.1, k1 = 5.55513046
d1_length_500B := 2.7082712
d1_500B: drift, L = d1_length_500B
d2_500B: drift, L = (7.0766498 -.6 - 2.*d1_length_500B)/2.
back_500: line = (d1_500B,qd_half_500B,qd_half_500B,d2_500B, &
  qf_half_500B,qf_half_500B,d2_500B,qd_half_500B,qd_half_500B,d1_500B)
!use, back_500
!twiss, betx =2.5, alfx =0., bety =2.5, alfy =0., save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
return

TITLE, "linac_to_arc_980_mark1" ! use symmetric chicane for 980 MeV
! drifts and bends are the same in linac_to_arc(LA) and arc_to_linac(AL); labeled LA
Lstraight2_980LA := .2 ! straight doesn't need quadrupoles for a symmetric chicane
Lstraight4_980LA := 7.00456703 ! tweaked for a half-integral no. of RF periods
! Magnets have radius of curvature equalling 2 meter for 980 MeV
! NOTE: element names must not exceed 16 characters (or additional characters are
! truncated)
bend_2p866_e1_0: sbend, angle=.0500209, L = 0.10004171, e1=0., e2=.0500209
bend_m2p866_e2_0: sbend, angle=-.0500209, L = 0.10004171, e1=-.0500209, e2=0.
bend_2p866_e2_0: sbend, angle=.0500209, L = 0.10004171, e2=0., e1=.0500209
bend_m2p866_e1_0: sbend, angle=-.0500209, L = 0.10004171, e2=-.0500209, e1=0.
d_p4m_980LA: drift, L = 0.4  ! between LINAC and 1st spreader dipole
d1_980LA: drift, L = 3.00375705
d2_980LA: drift, L = .2
d3_980LA: drift, L = 3.00375705
! drifts below are in the matching section straight4
d4_980LA: drift, L = .2
d5_980LA: drift, L = .2 ! 1st doublet spacing
d7_980LA: drift, L = .2 ! 2nd doublet spacing
d8_980LA: drift, L = 1.2
d6_980LA: drift, L = Lstraight4_980LA - 0.8 &
   -d4_980LA[L]-d5_980LA[L]-d7_980LA[L]-d8_980LA[L]
! linac to arc
q1_half_980LA: quadrupole, L = 0.1, K1 = 2.33702579  ! 1st doublet in straight4
q1_980LA: line = (q1_half_980LA, q1_half_980LA)
q2_half_980LA: quadrupole, L = 0.1, K1 = -2.02763296  ! 1st doublet in straight4
```

```
q2_980LA: line = (q2_half_980LA, q2_half_980LA)
q3_half_980LA: quadrupole, L = 0.1, K1 = -1.48579497  ! second doublet in straight4
q3_980LA: line = (q3_half_980LA, q3_half_980LA)
q4_half_980LA: quadrupole, L = 0.1, K1 = 1.49385397  ! second doublet in straight4
q4_980LA: line = (q4_half_980LA, q4_half_980LA)
linac_to_arc_980: line = (d_p4m_980LA,bend_2p866_e1_0,d1_980LA, &
  bend_m2p866_e2_0,d2_980LA,bend_m2p866_e1_0,d3_980LA, bend_2p866_e2_0, &
  d4_980LA,q1_980LA,d5_980LA,q2_980LA,d6_980LA,q3_980LA, &
  d7_980LA,q4_980LA,d8_980LA)
! arc_to_linac
q1_half_980AL: quadrupole, L = 0.1, K1 = 2.33702579  ! 1st doublet in straight4
q1_980AL: line = (q1_half_980AL, q1_half_980AL)
q2_half_980AL: quadrupole, L = 0.1, K1 = -2.02763296  ! 1st doublet in straight4
q2_980AL: line = (q2_half_980AL, q2_half_980AL)
q3_half_980AL: quadrupole, L = 0.1, K1 = -1.48579497  ! second doublet in straight4
q3_980AL: line = (q3_half_980AL, q3_half_980AL)
q4_half_980AL: quadrupole, L = 0.1, K1 = 1.49385397  ! second doublet in straight4
q4_980AL: line = (q4_half_980AL, q4_half_980AL)
arc_to_linac_980: line = (d8_980LA,q4_980AL,d7_980LA,q3_980AL,d6_980LA, &
 q2_980AL,d5_980LA,q1_980AL,d4_980LA,bend_2p866_e1_0,d3_980LA, &
  bend_m2p866_e2_0,d2_980LA,bend_m2p866_e1_0,d1_980LA, bend_2p866_e2_0, &
  d_p4m_980LA)
!use, linac_to_arc_980
!twiss, betx =247.292, alfx =-4.021, bety =155.541, alfy =-2.468, save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=Dx,style=100,spline
!use, arc_to_linac_980
!twiss, betx =10.782534, alfx =-6., bety =20.475504, alfy =-5., save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=Dx,style=100,spline
return

TITLE, "arc_sex_980_number2_qm_sm_sx"  ! 980-MeV arc with unpowered sextupoles and qm
! quadrupoles.  The qm quadrupoles are not used.
!  980 and 500 arcs are on the same side of the linac.
! drifts and dipoles are the same in both 980-MeV bending arcs
L1a_980arc: drift, L = 0.5
L1b_980arc: drift, L = 0.25
L2a_980arc: drift, L = 0.325
L2b_980arc: drift, L = 0.325
L3a_980arc: drift, L = 0.25
L3b1_980arc: drift, L = 0.85
L3b2_980arc: drift, L = 0.25
BD_980arc: sbend, angle = 1.04719755, L = 2.*1.04719755
!arc1:
sf1_980arc1: multipole, K2L = 0.
sf2_980arc1: multipole, K2L = 0.
sd1_980arc1: multipole, K2L = 0.
sd2_980arc1: multipole, K2L = 0.
sm1_980arc1: multipole, K2L = 0.
sm2_980arc1: multipole, K2L = 0.
sx1_980arc1: multipole, K2L = 0.
sx2_980arc1: multipole, K2L = 0.
qm1_half_980arc1: quadrupole, L = 0.125, K1 = 0.
qm1_980arc1: line = (qm1_half_980arc1,sm1_980arc1,qm1_half_980arc1)
qm2_half_980arc1: quadrupole, L = 0.125, K1 = 0.
qm2_980arc1: line = (qm2_half_980arc1,sm2_980arc1,qm2_half_980arc1)
qf1_half_980arc1: quadrupole, L = 0.125, K1 = 4.46766868
qf1_980arc1: line = (qf1_half_980arc1,qf1_half_980arc1)
```

```
qd1_half_980arc1: quadrupole, L = 0.125, K1 = -2.00176426
qd1_980arc1: line = (qd1_half_980arc1,qd1_half_980arc1)
qf2_half_980arc1: quadrupole, L = 0.125, K1 = 4.46766868
qf2_980arc1: line = (qf2_half_980arc1,qf2_half_980arc1)
qd2_half_980arc1: quadrupole, L = 0.125, K1 = -2.00176426
qd2_980arc1: line = (qd2_half_980arc1,qd2_half_980arc1)
arc1_980: line = (BD_980arc,L1a_980arc,sf1_980arc1,L1b_980arc, &
  qf1_980arc1,L2a_980arc,qm1_980arc1,L2b_980arc,qd1_980arc1, &
  L3a_980arc,sd1_980arc1,L3b1_980arc,sx1_980arc1,L3b2_980arc, &
  BD_980arc,L3b2_980arc,sx2_980arc1,L3b1_980arc, &
  sd2_980arc1,L3a_980arc, &
  qd2_980arc1,L2b_980arc,qm2_980arc1,L2a_980arc,qf2_980arc1, &
  L1b_980arc,sf2_980arc1,L1a_980arc,BD_980arc)
!arc2:
sf1_980arc2: multipole, K2L = 0.
sf2_980arc2: multipole, K2L = 0.
sd1_980arc2: multipole, K2L = 0.
sd2_980arc2: multipole, K2L = 0.
sm1_980arc2: multipole, K2L = 0.
sm2_980arc2: multipole, K2L = 0.
sx1_980arc2: multipole, K2L = 0.
sx2_980arc2: multipole, K2L = 0.
qm1_half_980arc2: quadrupole, L = 0.125, K1 = 0.
qm1_980arc2: line = (qm1_half_980arc2,sm1_980arc2,qm1_half_980arc2)
qm2_half_980arc2: quadrupole, L = 0.125, K1 = 0.
qm2_980arc2: line = (qm2_half_980arc2,sm2_980arc2,qm2_half_980arc2)
qf1_half_980arc2: quadrupole, L = 0.125, K1 = 4.46766868
qf1_980arc2: line = (qf1_half_980arc2,qf1_half_980arc2)
qd1_half_980arc2: quadrupole, L = 0.125, K1 = -2.00176426
qd1_980arc2: line = (qd1_half_980arc2,qd1_half_980arc2)
qf2_half_980arc2: quadrupole, L = 0.125, K1 = 4.46766868
qf2_980arc2: line = (qf2_half_980arc2,qf2_half_980arc2)
qd2_half_980arc2: quadrupole, L = 0.125, K1 = -2.00176426
qd2_980arc2: line = (qd2_half_980arc2,qd2_half_980arc2)
arc2_980: line = (BD_980arc,L1a_980arc,sf2_980arc2,L1b_980arc, &
  qf2_980arc2,L2a_980arc,qm2_980arc2,L2b_980arc,qd2_980arc2, &
  L3a_980arc,sd2_980arc2,L3b1_980arc,sx2_980arc2,L3b2_980arc, &
  BD_980arc,L3b2_980arc,sx1_980arc2,L3b1_980arc, &
  sd1_980arc2,L3a_980arc, &
  qd1_980arc2,L2b_980arc,qm1_980arc2,L2a_980arc,qf1_980arc2, &
  L1b_980arc,sf1_980arc2,L1a_980arc,BD_980arc)
!use, arc1_980
!twiss, betx = 10.782534, alfx = 6., bety=20.475504, alfy=5., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
!use, arc2_980
!twiss, betx = 10.782534, alfx = 6., bety=20.475504, alfy=5., &
!   save
!plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
return

TITLE, "arc_to_back_980_mark1" ! for D8 ERL with chicane spreader, 2 sets of doublets
!  drifts are the same in arc_to_back_980 and back_to_arc_980; all are labeled "AB"
d1_980AB: drift, L = .15
d2_980AB: drift, L = .15
d4_980AB: drift, L = .25
d5_980AB: drift, L = 3.5
```

```
d3_980AB: drift, L = 7.59466823  ! gives total length of 12.44466823
! arc_to_back_980
qd1_half_980AB: quadrupole, L = 0.1, k1 = -5.73461997 ! k1 < 9.7 for 980 MeV
qd2_half_980AB: quadrupole, L = 0.1, k1 = -3.34389497
qf1_half_980AB: quadrupole, L = 0.1, k1 =  5.97650951
qf2_half_980AB: quadrupole, L = 0.1, k1 =  3.21104166
qd1_980AB: line = (qd1_half_980AB,qd1_half_980AB)
qd2_980AB: line = (qd2_half_980AB,qd2_half_980AB)
qf1_980AB: line = (qf1_half_980AB,qf1_half_980AB)
qf2_980AB: line = (qf2_half_980AB,qf2_half_980AB)
arc_to_back_980: line = (d1_980AB,qd1_980AB,d2_980AB,qf1_980AB, &
   d3_980AB,qd2_980AB,d4_980AB,qf2_980AB,d5_980AB)
! back_to_arc_980
qd1_half_980BA: quadrupole, L = 0.1, k1 = -5.73461997 ! k1 < 9.7 for 980 MeV
qd2_half_980BA: quadrupole, L = 0.1, k1 = -3.34389497
qf1_half_980BA: quadrupole, L = 0.1, k1 =  5.97650951
qf2_half_980BA: quadrupole, L = 0.1, k1 =  3.21104166
qd1_980BA: line = (qd1_half_980BA,qd1_half_980BA)
qd2_980BA: line = (qd2_half_980BA,qd2_half_980BA)
qf1_980BA: line = (qf1_half_980BA,qf1_half_980BA)
qf2_980BA: line = (qf2_half_980BA,qf2_half_980BA)
back_to_arc_980: line = (d5_980AB,qf2_980BA,d4_980AB,qd2_980BA, &
   d3_980AB,qf1_980BA,d2_980AB,qd1_980BA,d1_980AB)
!use, arc_to_back_980
!twiss, betx = 10.782534, alfx = -6., bety=20.475504, alfy=-5., save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
!use, back_to_arc_980
!twiss, betx = 2.5, alfx = 0., bety=2.5, alfy=0., save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
return

TITLE, "back_980" ! for 12 back straight sections, same as back_500
qd_half_980B: quadrupole, L = 0.1, k1 = -3.26010968
qf_half_980B: quadrupole, L = 0.1, k1 = 5.55513046
d1_length_980B := 2.7082712
d1_980B: drift, L = d1_length_980B
d2_980B: drift, L = (7.0766498 -.6 - 2.*d1_length_980B)/2.
back_980: line = (d1_980B,qd_half_980B,qd_half_980B,d2_980B, &
  qf_half_980B,qf_half_980B,d2_980B,qd_half_980B,qd_half_980B,d1_980B)
!use, back_980
!twiss, betx =2.5, alfx =0., bety =2.5, alfy =0., save
!plot,haxis=s,vaxis=betx,bety,style=100,spline
return
```

Appendix E. MAD matching file for the Model D8 two-up/two-down ERL with bunch compression/decompression in both recirculation arcs

```
title "twomatch_980_ERL_chicane_D8" ! quadrupoles and sextupoles matched separately:
! "twomatch".  The qm quadrupoles (in bending arcs) are not used.
beam, energy = .020, particle=electron ! total (KE and mc**2); the default is 1 GeV
call injection.mad
call Lcavity_linacs_split_phased.mad  ! each linac split into 10 pieces and phased
call linac_to_arc_500_mark1.mad
call arc_sex_500_qm_sm_sx.mad   ! quad and sextupole strings split up, sx included
call arc_to_back_500_mark1.mad
call back_500.mad
call linac_to_arc_980_mark1.mad
call arc_sex_980_number2_qm_sm_sx.mad ! quad and sextupole strings split, sx included
!call flip_arc_sex_980_number2_qm_sm_sx.mad ! bends in opposite direction as 500-MeV
! arc
call arc_to_back_980_mark1.mad
call back_980.mad
TITLE, "twomatch_980_ERL_chicane_D8"
half_ring_up: line = (injection,linac1,linac_to_arc_500,arc1_500, &
  arc_to_back_500,6*back_500)
half_ring_down: line = (6*back_500, &
  back_to_arc_500,arc2_500,arc_to_linac_500,linac4,-injection)
half_ring: line = (half_ring_up,half_ring_down)
end_500MeV: line = (half_ring_up,6*back_500,back_to_arc_500, &
  arc2_500,arc_to_linac_500)
ring_up: line = (end_500MeV,linac2,linac_to_arc_980,arc1_980, &
  arc_to_back_980,6*back_980)
end_980MeV: line = (ring_up,6*back_980,back_to_arc_980, &
  arc2_980,arc_to_linac_980)
second_pass_500: line = (end_980MeV,linac3,linac_to_arc_500, &
  arc1_500,arc_to_back_500,6*back_500)
end_second_pass_500MeV: line = (second_pass_500,6*back_500, &
  back_to_arc_500,arc2_500,arc_to_linac_500)
ring: line = (end_second_pass_500MeV,linac4,-injection)
half_500: line = (linac_to_arc_500,arc1_500,arc_to_back_500,6*back_500)
full_500: line = (half_500,6*back_500,back_to_arc_500,arc2_500,arc_to_linac_500)
half_980: line = (linac_to_arc_980,arc1_980,arc_to_back_980,6*back_980)
full_980: line = (half_980,6*back_980,back_to_arc_980,arc2_980,arc_to_linac_980)
second_half_ring_up: line = (linac2,full_980)

! Match 500-MeV quads to obtain 1st order bunch compression
b1:=5.377
a1:=6.
b2:=10.483
a2:=5.
use, half_ring_up
match, energy=.020, betx=8.,bety=8.
! linac to arc matching quads (for beta-matching):
vary, q1_half_500LA[k1], step=1.e-6
vary, q2_half_500LA[k1], step=1.e-6
vary, q3_half_500LA[k1], step=1.e-6
vary, q4_half_500LA[k1], step=1.e-6
! arc to back quads (for beta-matching)
vary, qd1_half_500AB[k1], step=1.e-6
vary, qd2_half_500AB[k1], step=1.e-6
```

```
vary, qf1_half_500AB[k1],  step=1.e-6
vary, qf2_half_500AB[k1],  step=1.e-6
! arc1 (for R matching)
qf2_half_500arc1, k1=qf1_half_500arc1[k1]
vary, qf1_half_500arc1[k1], step=1.e-6
qd2_half_500arc1, k1=qd1_half_500arc1[k1]
vary, qd1_half_500arc1[k1], step=1.e-6
! variable parameters for symmetrizing
vary, b1, step=1.e-6
vary, b2, step=1.e-6
vary, a1, step=1.e-6
vary, a2, step=1.e-6
rmatrix,range=#s/#e, RM(1,5)=0.,RM(2,5)=0., RM(5,5)=0.
constraint, range = #e, betx=2.5,bety=2.5,alfx=0.,alfy=0.
constraint, range = d10_500LA[1],betx=b1,bety=b2,alfx=a1,alfy=a2 ! d10 is the drift
! next to the arc
constraint, range = BD_500arc[3],betx=b1,bety=b2,alfx=-a1,alfy=-a2
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 500-MeV sextupoles to obtain 2nd order bunch compression
fweight:=1.e-9  ! weighting to minimize sextupole excitation
formula:= (sf1_500arc1[k2L]*sf1_500arc1[k2L]+sf2_500arc1[k2L]*sf2_500arc1[k2L] &
 + sd1_500arc1[k2l]*sd1_500arc1[k2l]+sd2_500arc1[k2l]*sd2_500arc1[k2l] &
 + sm1_500arc1[k2l]*sm1_500arc1[k2l]+sm2_500arc1[k2l]*sm2_500arc1[k2l] &
 + sx1_500arc1[k2l]*sx1_500arc1[k2l]+sx2_500arc1[k2l]*sx2_500arc1[k2l] &
 )*fweight
beam, energy=.020
use, half_ring_up
match, energy=.020, betx=8.,bety=8.
vary, sf1_500arc1[k2L], step = 1.e-6
vary, sm1_500arc1[k2L], step = 1.e-6
!vary, sd1_500arc1[k2L], step = 1.e-6
vary, sx1_500arc1[k2L], step = 1.e-6
vary, sf2_500arc1[k2L], step = 1.e-6
vary, sm2_500arc1[k2L], step = 1.e-6
!vary, sd2_500arc1[k2L], step = 1.e-6
vary, sx2_500arc1[k2L], step = 1.e-6
tmatrix,range=#s/#e, TM(5,5,5)=0., TM(1,5,5)=0. , TM(2,5,5)= 0.
constraint, range = #e, dx=0.,dpx=0.,betx=2.5,bety=2.5,alfx=0.,alfy=0.
global, formula = 0.  ! to reduce sextupole strengths
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 500-MeV quads to obtain 1st order bunch decompression
b1:=5.377
a1:=6.
b2:=10.483
a2:=5.
use, end_500MeV
match, energy=.020, betx=8.,bety=8.
! arc to linac quads:
vary, q1_half_500AL[k1], step=1.e-6
vary, q2_half_500AL[k1], step=1.e-6
vary, q3_half_500AL[k1], step=1.e-6
```

```
vary, q4_half_500AL[k1], step=1.e-6
! back to arc quads
vary, qd1_half_500BA[k1], step=1.e-6
vary, qd2_half_500BA[k1], step=1.e-6
vary, qf1_half_500BA[k1], step=1.e-6
vary, qf2_half_500BA[k1], step=1.e-6
! arc2
qf2_half_500arc2, k1 = qf1_half_500arc2[k1]
vary, qf1_half_500arc2[k1], step=1.e-6
qd2_half_500arc2, k1 = qd1_half_500arc2[k1]
vary, qd1_half_500arc2[k1], step=1.e-6
vary, b1, step=1.e-6
vary, b2, step=1.e-6
vary, a1, step=1.e-6
vary, a2, step=1.e-6
rmatrix,range=#s/#e, RM(1,5)=0.,RM(2,5)=0., RM(5,5)=1.
constraint, range = #e, betx =102.636, alfx =3.256, bety =66.382, &
  alfy =1.589
constraint, range = d1_500AB[2],betx=b1,bety=b2,alfx=a1,alfy=a2 ! d1 is the drift
! next to the arc
constraint, range = BD_500arc[6],betx=b1,bety=b2,alfx=-a1,alfy=-a2
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 500-MeV sextupoles to obtain 2nd order bunch decompression
fweight:=1.e-9 ! weighting to minimize sextupole excitation
formula:= (sf1_500arc2[k2L]*sf1_500arc2[k2L]+sf2_500arc2[k2L]*sf2_500arc2[k2L] &
 + sd1_500arc2[k2l]*sd1_500arc2[k2l]+sd2_500arc2[k2l]*sd2_500arc2[k2l] &
 + sm1_500arc2[k2l]*sm1_500arc2[k2l]+sm2_500arc2[k2l]*sm2_500arc2[k2l] &
 + sx1_500arc2[k2l]*sx1_500arc2[k2l]+sx2_500arc2[k2l]*sx2_500arc2[k2l] &
 )*fweight
use, end_500MeV
match, energy=.020, betx=8.,bety=8.
vary, sf1_500arc2[k2L], step = 1.e-6
vary, sm1_500arc2[k2L], step = 1.e-6
!vary, sd1_500arc2[k2l], step = 1.e-6
vary, sx1_500arc2[k2l], step = 1.e-6
vary, sf2_500arc2[k2L], step = 1.e-6
vary, sm2_500arc2[k2L], step = 1.e-6
!vary, sd2_500arc2[k2l], step = 1.e-6
vary, sx2_500arc2[k2l], step = 1.e-6
tmatrix,range=#s/#e, TM(5,5,5)=0., TM(1,5,5)=0. , TM(2,5,5)= 0.
constraint, range = #e, betx =102.636, alfx =3.256, bety =66.382, &
  alfy =1.589, dx=0.,dpx=0.
global, formula = 0.  ! to reduce sextupole strengths
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 980-MeV quads to obtain 1st order bunch compression
b1:= 10.782534
a1:=6.
b2:=20.475504
a2:=5.
beam, energy=.020
use, ring_up
```

```
match, energy=.020, betx=8.,bety=8.
! linac to arc quads:
vary, q1_half_980LA[k1], step=1.e-6
vary, q2_half_980LA[k1], step=1.e-6
vary, q3_half_980LA[k1], step=1.e-6
vary, q4_half_980LA[k1], step=1.e-6
! arc to back quads
vary, qd1_half_980AB[k1], step=1.e-6
vary, qd2_half_980AB[k1], step=1.e-6
vary, qf1_half_980AB[k1],  step=1.e-6
vary, qf2_half_980AB[k1],  step=1.e-6
! arc1
qf2_half_980arc1, k1=qf1_half_980arc1[k1]
vary, qf1_half_980arc1[k1], step=1.e-6
qd2_half_980arc1, k1=qd1_half_980arc1[k1]
vary, qd1_half_980arc1[k1], step=1.e-6
vary, b1, step=1.e-6
vary, b2, step=1.e-6
vary, a1, step=1.e-6
vary, a2, step=1.e-6
rmatrix,range=#s/#e, RM(1,5)=0.,RM(2,5)=0., RM(5,5)=0.
constraint, range = #e, betx=2.5,bety=2.5,alfx=0.,alfy=0.
constraint, range = d8_980LA[1],betx=b1,bety=b2,alfx=a1,alfy=a2 ! d8 is the drift
! next to the arc in mark1 980 spreader
constraint, range = BD_980arc[3],betx=b1,bety=b2,alfx=-a1,alfy=-a2
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 980-MeV sextupoles to obtain 2nd order bunch compression
fweight:=1.e-9 ! weighting to minimize sextupole excitation
formula:= (sf1_980arc1[k2L]*sf1_980arc1[k2L]+sf2_980arc1[k2L]*sf2_980arc1[k2L] &
 + sd1_980arc1[k2l]*sd1_980arc1[k2l]+sd2_980arc1[k2l]*sd2_980arc1[k2l] &
 + sm1_980arc1[k2l]*sm1_980arc1[k2l]+sm2_980arc1[k2l]*sm2_980arc1[k2l] &
 + sx1_980arc1[k2l]*sx1_980arc1[k2l]+sx2_980arc1[k2l]*sx2_980arc1[k2l] &
 )*fweight
beam, energy=.020
use, ring_up
match, energy=.020, betx=8.,bety=8.
vary, sf1_980arc1[k2L], step = 1.e-6
vary, sm1_980arc1[k2L], step = 1.e-6
!vary, sd1_980arc1[k2l], step = 1.e-6
vary, sx1_980arc1[k2l], step = 1.e-6
vary, sf2_980arc1[k2L], step = 1.e-6
vary, sm2_980arc1[k2L], step = 1.e-6
!vary, sd2_980arc1[k2l], step = 1.e-6
vary, sx2_980arc1[k2l], step = 1.e-6
tmatrix,range=#s/#e, TM(5,5,5)=0., TM(1,5,5)=0. , TM(2,5,5)= 0.
constraint, range = #e, dx=0.,dpx=0.,betx=2.5,bety=2.5,alfx=0.,alfy=0.
global, formula = 0.  ! to reduce sextupole strengths
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 980-MeV quads to obtain 1st order bunch decompression
b1:= 10.782534
a1:=6.
```

```
b2:=20.475504
a2:=5.
beam, energy=.020
use, end_980MeV
match, energy=.020, betx=8.,bety=8.
! arc to linac quads:
vary, q1_half_980AL[k1], step=1.e-6
vary, q2_half_980AL[k1], step=1.e-6
vary, q3_half_980AL[k1], step=1.e-6
vary, q4_half_980AL[k1], step=1.e-6
! back to arc quads
vary, qd1_half_980BA[k1], step=1.e-6
vary, qd2_half_980BA[k1], step=1.e-6
vary, qf1_half_980BA[k1],  step=1.e-6
vary, qf2_half_980BA[k1],  step=1.e-6
! arc2
qf2_half_980arc2, k1=qf1_half_980arc2[k1]
vary, qf1_half_980arc2[k1], step=1.e-6
qd2_half_980arc2, k1=qd1_half_980arc2[k1]
vary, qd1_half_980arc2[k1], step=1.e-6
vary, b1, step=1.e-6
vary, b2, step=1.e-6
vary, a1, step=1.e-6
vary, a2, step=1.e-6
rmatrix,range=#s/#e, RM(1,5)=0.,RM(2,5)=0., RM(5,5)=1.
constraint, range = #e, betx =247.292, alfx =4.021, bety =155.541, &
  alfy =2.468
constraint, range = d1_980AB[2],betx=b1,bety=b2,alfx=a1,alfy=a2 ! d1 is the drift
! next to the arc
constraint, range = BD_980arc[6],betx=b1,bety=b2,alfx=-a1,alfy=-a2
level, 0
lmdif, tolerance = 1.e-20, calls =10000
endmatch

! Match 980-MeV sextupoles to obtain 2nd order bunch decompression
fweight:=1.e-9 ! weighting to minimize sextupole excitation
formula:= (sf1_980arc2[k2L]*sf1_980arc2[k2L]+sf2_980arc2[k2L]*sf2_980arc2[k2L] &
 + sd1_980arc2[k2l]*sd1_980arc2[k2l]+sd2_980arc2[k2l]*sd2_980arc2[k2l] &
 + sm1_980arc2[k2l]*sm1_980arc2[k2l]+sm2_980arc2[k2l]*sm2_980arc2[k2l] &
 + sx1_980arc2[k2l]*sx1_980arc2[k2l]+sx2_980arc2[k2l]*sx2_980arc2[k2l] &
 )*fweight
use, end_980MeV
match, energy=.020, betx=8.,bety=8.
vary, sf1_980arc2[k2L], step = 1.e-6
vary, sm1_980arc2[k2L], step = 1.e-6
!vary, sd1_980arc2[k2l], step = 1.e-6
vary, sx1_980arc2[k2l], step = 1.e-6
vary, sf2_980arc2[k2L], step = 1.e-6
vary, sm2_980arc2[k2L], step = 1.e-6
!vary, sd2_980arc2[k2l], step = 1.e-6
vary, sx2_980arc2[k2l], step = 1.e-6
tmatrix,range=#s/#e, TM(5,5,5)=0., TM(1,5,5)=0. , TM(2,5,5)= 0.
constraint, range = #e, betx =247.292, alfx =4.021, bety =155.541, &
  alfy =2.468, dx=0.,dpx=0.
global, formula = 0.  ! to reduce sextupole strengths
level, 0
lmdif, tolerance = 1.e-20, calls =10000
```

```
endmatch

save, file = "match_980MeV_ERL.mad"

beam, energy=.020
use, ring
twiss, energy=.020, betx=8., alfx=0., bety=8., alfy=0., &
  dx=0.,dpx=0., save ! initial conditions
plot,haxis=s,vaxis1=betx,bety,vaxis2=dx,style=100,spline
return
```