The Booster-to-Storage Ring Transfer Line: Preliminary Design Study

CLS DESIGN NOTE – 4.2.69.1 Rev. 0

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REVISION HISTORY

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A	2000-08-10	Original Draft	J.C. Bergstrom
Rev. 0	2000-10-10	Preliminary Design (# change from 2.1.46 → 4.2.69.1)	J.C. Bergstrom

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1. DESIGN GOALS

The Booster-to-Storage Ring (BTS) transfer line, as the name implies, carries the beam from the Booster to the Storage Ring. The optical design is constrained by the fact that the beam Twiss parameters entering and leaving the transfer line are specified. For example, the Twiss parameters of the beam at the *Booster extraction point* are:

$$\begin{array}{ll} \beta_x = 9.91\ \mathrm{m} & \alpha_x = 3.02 \\ \beta_y = 7.24\ \mathrm{m} & \alpha_y = -1.68 \\ \eta_x = 0.331\ \mathrm{m} & \eta_x^{\prime} = -0.05 \end{array} \tag{1}$$

as defined at the *entrance* to the Booster extraction septum magnet. The corresponding parameters at the *Storage Ring injection point*, defined as the *exit* of the final injection septum magnet, are:

$$\begin{array}{ll} \beta_x = 8.78\ \mathrm{m} & \alpha_x = -0.17 \\ \beta_y = 5.09\ \mathrm{m} & \alpha_y = -0.32 \\ \eta_x = 0.15\ \mathrm{m} & \eta_x^{\prime} = 0 \end{array} \tag{2}$$

The aim was to devise a transfer line that would match the beam parameters of Eq. (1) to those of Eq. (2) at the entrance and exit points, respectively. We also require some tuning flexibility. For example, one might improve the injection efficiency by reducing β_x by a factor of 2 and setting $\alpha_x = 0$ [as compared to the nominal parameters of Eq. (2)] as suggested to us by others.

2. DESIGN PHILOSOPHY

The BTS transfer line is illustrated in Fig. 1. The Booster extraction and Storage Ring injection points are connected by a deflecting arc consisting of 4 dipole magnets, each identical to the Booster dipole magnets. Each dipole has a deflecting angle of 18°, an arc length of 2.28 m, field strength B = 13.33 kg, and bending radius R = 7.26 m. Additional deflections are provided by the Booster extraction septum magnet (7.62°), and by the pair of Storage Ring injection septum magnets (8.38°, 7.62°). Note that the latter pair gives a total deflection of 16.0° in the same sense as the dipoles, while the extraction septum provide a reverse deflection. In other words, the two septa of identical but opposite deflection (7.62°) cancel each other as far as the total arc-angle is concerned, leaving the 8.38° septum to provide the angular matching. This addresses the required angular deflections. Now we address the focussing requirements.

Since the dipole magnets have zero-gradient, a common-sense approach to the design suggests bracketing each dipole by a pair of quadrupole magnets in a sort of F O D O arrangement. In fact, however, we propose a set of four cells each consisting of a D–bend–F arrangement (D = defocussing, F = focussing, in the horizontal plane.) The argument is as follows:

The Twiss parameters of the beam leaving the Booster [Eq. (1)] lead to a rapid growth in β_y with distance from the extraction point, while β_x develops rather slowly. We therefore insert a vertically-focussing quadrupole (i.e. a D-quad) as the first element following extraction, to clamp down on β_y. This is followed by an

F-quad to prevent a subsequent blow-up of β_x. So, we necessarily start with a D–F doublet (Fig. 1).

This initial D–F polarity now dictates the polarity of the first quadrupole of the first cell: clearly this must be defocussing, and leads to the D-bend–F arrangement as noted above.

3. OPTICAL ARRANGEMENT

By extension, the preceding argument suggests that all four cells should be of the D–bend–F configuration. To summarize, the proposed BTS line consists of a D-F quadrupole doublet followed by four cells each in a D-bend-F configuration. All studies suggest the quadrupole–dipole separation should be minimal: we propose 40 cm. The physical arrangement illustrated in Fig. 1 is capable of satisfying all the Design Goals as specified above. This is hardly surprising: we have 10 quadrupole “knobs” to satisfy 6 constraints. Exactly how one meets the constraints is another matter. There are several options. For example, the D and F quads of *each cell* can be chosen to be equal in strength. Conversely, the D-quads and the F-quads can be coupled separately. Or, all symmetries can be abandoned yielding 10 independent knobs. The basic design is sufficiently flexible to cover many tuning options. The particular choice of the tuning algorithm is, however, not arbitrary. It must be such that the maximum excursions of the β-functions, especially β_x, and the dispersion function η_x, are not excessive. The former dominates the horizontal beam size, while the latter determines the energy-acceptance window. The contribution of η_x to the beam size is minimal since the energy-spread from the Booster is expected to be about ± 0.1 % (at 1-sigma). Excursions of β_y are of less concern since the vertical emittance from the Booster is small compared to the horizontal emittance.

Preliminary studies have identified two operating modes of the BTS line that maintain a certain degree of symmetry with respect to the tuning of the F and D quadrupoles. In the first mode, the β-functions are small everywhere, but η_x tends to get large after the third dipole. In the second mode, η_x is minimized, but β_x gets a bit large, but not excessive. For convenience, we denote these as Mode 1 (Large η) and Mode 2 (Large β). The corresponding Twiss parameter envelopes are illustrated in Fig. 2 and Fig 3, respectively. The corresponding TRANSPORT files are included in Appendix A, Tables I and II respectively, where one can ascertain the different quadrupole symmetries between the two modes.

4. QUADRUPOLE MAGNETS

The BTS line contains 10 physically-identical quadrupole magnets. Each is 300 mm long, with an aperture radius of 17.5 mm, and a maximum pole-tip field of 0.4 Tesla. The rather small aperture is dictated by the rather large field gradients required (up to 23 T/m). Unfortunately, the small aperture impacts on the energy-acceptance window of the transfer line, and this will require careful study to achieve the optimal optical configuration.

5. SEPTUM MAGNETS

The beam passes through three septum magnets between the Booster extraction and Storage Ring (SR) injection:

(i) Booster extraction thin septum, -7.62°;
(ii) SR injection thick septum, $+8.38^\circ$;
(iii) SR injection thin septum, $+7.62^\circ$.

All have identical arc lengths of 1.655 m. The thick septum will run in a D.C. mode, while the thin septum magnets will both be pulsed. All magnets will be situated in air and therefore must accommodate vacuum chambers. This makes the interface between the injection thin septum and the Storage Ring rather tricky, since the “effective” septum thickness (actual septum, vacuum pipe, and SR wall) can not exceed about 3 mm.

The aperture of the thick septum magnet is 20 mm. The aperture of the thin septum magnet is still under review, but will probably lie in the 13-15 mm range. Other details can be found in Design Report 2.1.41.

6. STEERING MAGNETS

Steering doublets for both the horizontal and vertical planes are situated immediately following the Booster extraction septum magnet, and immediately in front of the SR thick septum magnet. Each doublet consists of a pair of steering magnets separated by about 2 m, thus permitting both angular shifts and lateral position shifts. In particular, this provides independent angular and position control at the SR injection point. Intermediate horizontal and vertical correctors are also be deployed between the 2nd and 3rd dipoles, since the current plan envisages the four dipole magnets to be powered in series. The deflecting strength of each steerer is roughly 1.6 mrad maximum.

7. STRAIGHT-THROUGH TUNEUP LINE

The first dipole has a special cut in the yoke to permit a straight-through beam transit when this dipole is passive. This line terminates in a beam dump, and can be used during those occasions when, for example, the Booster is being tuned and injection into the SR is to be avoided.

8. BEAM MONITORS

There are 3 kinds of beam monitors in the BTS line: beam profile monitors, beam position monitors, and beam current monitors.

a) Position Monitors

These are similar to the BPM's in the LTB line, and are stripline antennas tuned to the 500 MHz frequency of the Booster R.F. Two BPM's are deployed in the BTS line:

BPM1 – in front of the first D-Bend-F cell.
BPM2 – exit of the 3rd D-Bend-F cell, adjacent to TRM4, where the dispersion function η_x is a maximum (Fig. 2).

b) Profile Monitors

These are identical to the Transition Radiation Monitors (TRM's) deployed in the LTB line. Seven TRM's are deployed in the BTS line. In abbreviated notation, they are located as follows:

TRM1 - exit of the Booster extraction septum
TRM2 - between the 1st and 2nd quadrupoles
TRM3 - directly in front of the first D-Bend-F cell
TRM4 - exit of the 3rd D-Bend -F cell
TRM5 - entrance of the “thick” injection septum
TRM6 - between the “thick” and “thin” septum magnets
TRM7 - exit of the “thin” septum magnet. This serves a dual purpose: to observe the injected beam from the BTS line, or the circulating beam in the Storage Ring.

The placement of the TRM's facilitates the measurement of the beam emittance, the energy spectrum, and determination of the Twiss parameters at the Storage Ring injection point, as described later.

c) <u>Current Monitors</u>

These are manufactured by the Bergoz company of France. Two types of monitor are deployed, an Integrating Current Transformer (ICT), and a Fast Current Transformer (FCT). The ICT integrates the total charge in the train of bunches (1-68), while the FCT provides a measure of the relative bunch-bunch fill. The single FCT is situated just before the first D-Bend-F cell. Two ICT's are deployed, just before the first cell, and at the exit of the final (4th) cell. These provide a measurement of beam-loss through the BTS line, as well as the average current.

9. EMITTANCE MEASUREMENT

As noted, the BTS line starts with a D-F quadrupole doublet, with an inter-element spacing of 1 m. The drift to the first (D) quad of the first cell is roughly 5 m. This arrangement provides, almost for free, the ability to measure both the horizontal and the vertical beam emittance. For a coupling of 10%, the emittances are expected to be $\varepsilon_x = 0.52$ mm-mr and $\varepsilon_y = 0.052$ mm-mrad.

To complete the emittance monitor, we insert beam profile monitors (of the transition-radiation variety) between the quads of the doublet, and also downstream in front of the first quad of the first cell. Call these two profile monitors M1 and M2. The D-F quads of the doublet are used independently (i.e. one or the other is shut off) to minimize the beam size at M2, first in the horizontal plane, than in the vertical plane. These minimum profiles, in conjunction with the profiles at M1, yield the emittances factors ε_x and ε_y directly (see, e.g., Design Report 2.1.23).

10. ENERGY SPECTROMETER

The BTS line can be used as a spectrometer to measure the energy, and the energy spread, of the beam emerging from the Booster. This requires a particular set-up of the quadrupoles to provide a large η_x, and a small β_x, at some convenient location where the beam profile (centroid and width information) can be determined. We have identified one such mode (η_x = 3.4 m, β_x = 5.9 m, corresponding to an energy resolution of roughly 1.5 MeV for a beam energy of 2900 MeV). This is the Mode 1 referred to in Sect. 3 and illustrated in Fig. 2. The required profile information is measured following the third dipole magnet. Judging from the experience of other facilities, there is some merit in having energy information independent of the Booster dipole calibrations.

11. PHYSICAL DIMENSIONS

The dimensions of the transport line can be discerned from Fig. 1 and the TRANSPORT files in Appendix A.

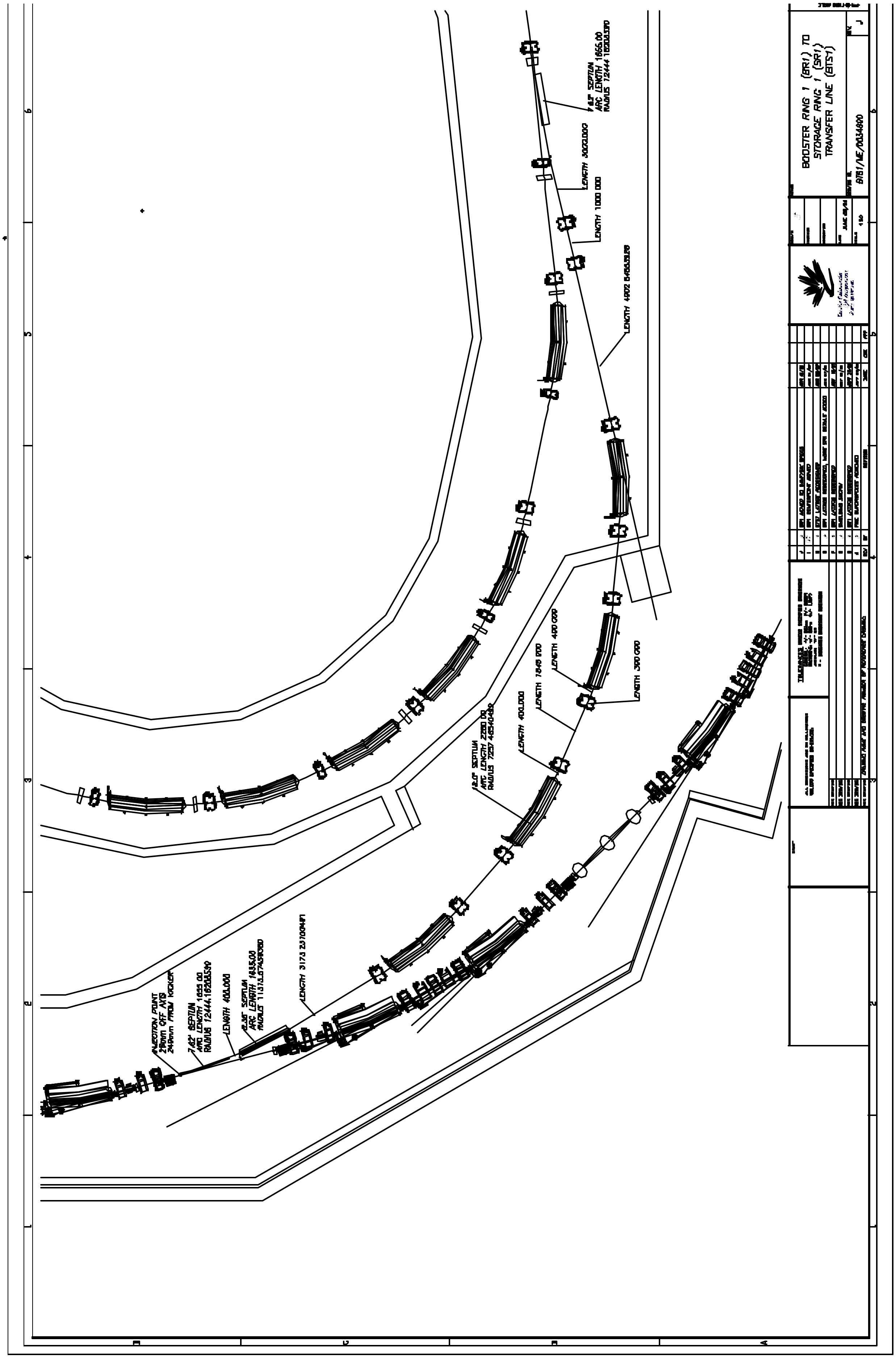
BOOSTER RING 1 (BR1) TO
STORAGE RING 1 (SR1)
TRANSFER LINE (BTS1)
BTS1/ME/0034800
REV. J
JUNE 03/00
1:50
7.8° SEPTUM
ARC LENGTH 1656.00
RADIUS 12444.16200.5390
LENGTH 3000.000
LENGTH 1000.000
LENGTH 4902.84563.520
18.0° SEPTUM
ARC LENGTH 2280.00
RADIUS 7257.465404.92
LENGTH 400.000
LENGTH 1848.000
LENGTH 400.000
LENGTH 300.000
INJECTION POINT
28mm OFF AXIS
24.9mm FROM KICKER
7.62° SEPTUM
ARC LENGTH 1655.00
RADIUS 12444.16200.5390
LENGTH 400.000
8.36° SEPTUM
ARC LENGTH 1655.00
RADIUS 11375.67458060
LENGTH 3173.237004.81

Figure 1

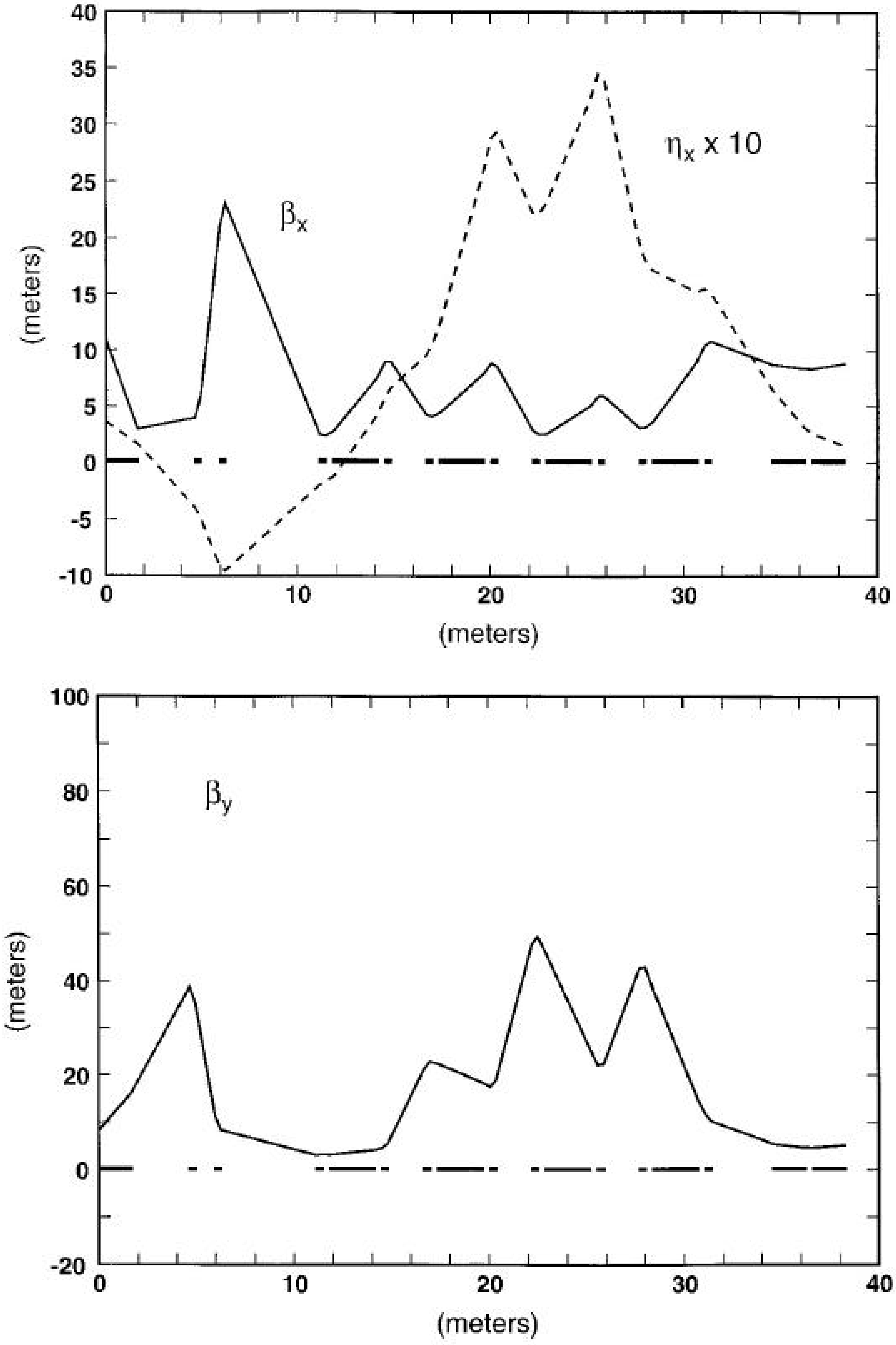

Figure 2: Mode 1 - Twiss Parameters

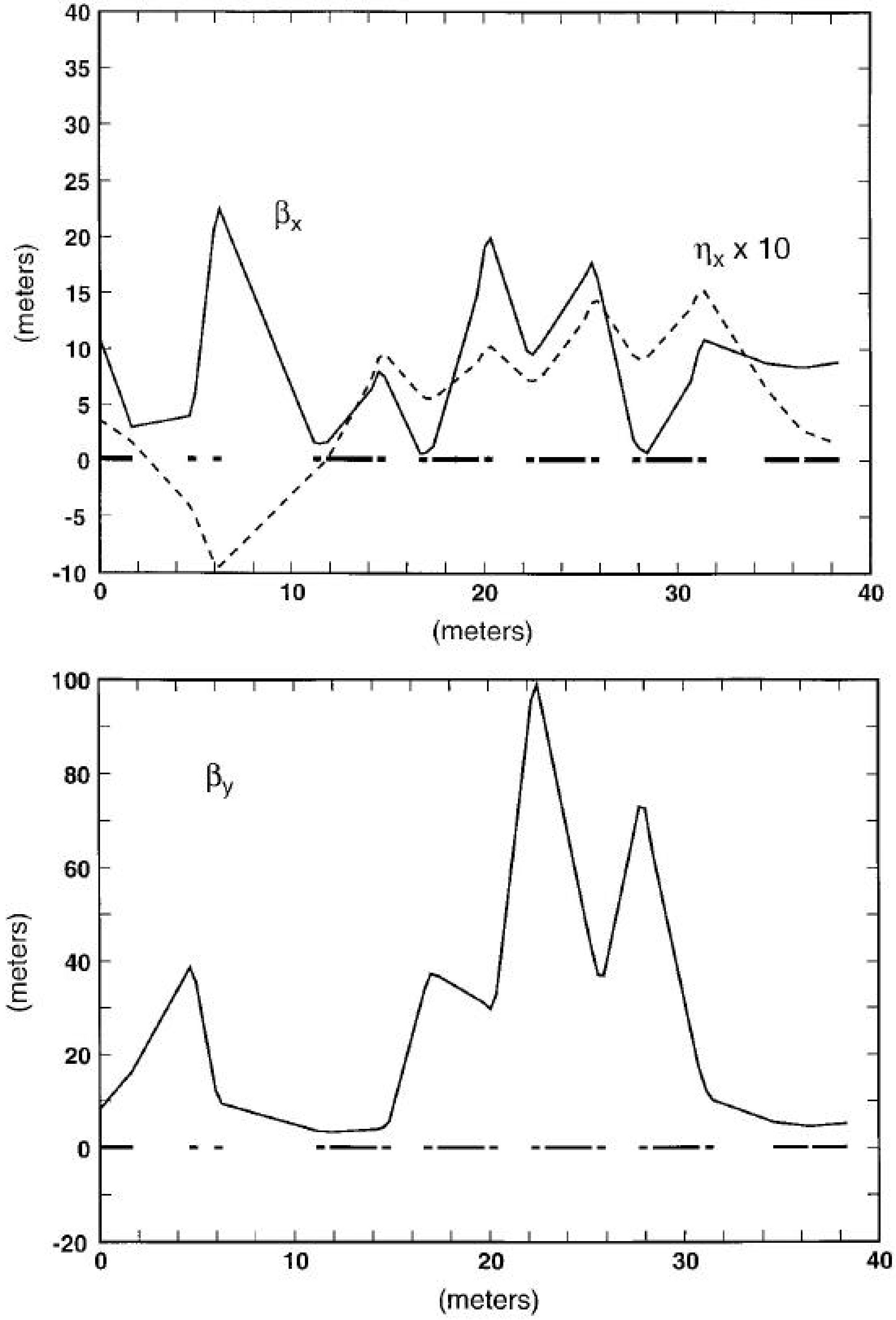

Figure 3: Mode 2 – Twiss Parameters

APPENDIX A – Transport Input Files

TABLE I - MODE 1

```
' BOOSTER  - TO - SYNCHROTRON TRANSFER LINE'
( SMALL-BETA  BUT  LARGE-ETA SOLUTION )
( TWISS PARAMETERS )
( NOTE: MULTIPLY BETAS BY 10 TO GET METERS )
(     : DIVIDE ETA-PRIMES BY 10 TO GET STANDARD UNITS )
0
15. 11. 'mev' 0.001;
13. 7. 'twis';
13. 3. 'sigm';
13. 13.;
1.0 0.991 3.02 0.724  -1.68 0. 0. 2900. 'bm';
14. 1. 0. 0. 0. 0. 0.331 1.;
14. 0. 1. 0. 0. 0. -0.51 2.;
13. 48. 'deg';
16. 2. 0.00 'k0';
16. 7. 0.500 'k1';
16. 5. 1.60 'gap';
20. 180.;
4.0 1.655 7.62 0.0 'extr';
20. -180.;
3.0 3.00;
5.01 0.30 -3.011 1.75 'q1';
3.0 1.00;
5.01 0.30 3.403 1.75 'q2';
3.0 4.90265;
5.01 0.30 -2.199 1.75 'qd1';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0. 'ben1';
2.0 9.00;
3.0 0.40;
5.0C 0.30 2.200 1.75 'qf1';
3.0 1.845;
5.0A 0.30 -1.628 1.75 'qd2';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0. 'ben2';
2.0 9.00;
3.0 0.40;
5.0C 0.30 2.200 1.75 'qf2';
3.0 1.845;
5.0A 0.30 -1.628 1.75 'qd3';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0.0 'ben3';
2.0 9.00;
3.0 0.40;
5.0C 0.30 2.200 1.75 'qf3';
3.0 1.845;
5.0A 0.30 -1.628 1.75 'qd4';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0.0 'ben4';
```

```
2.0 9.00;
3.0 0.40;
5.01 0.30 1.258 1.75 'qf4';
3.0 3.17323;
2.0 0.00;
4.0 1.655 8.38 0.0 'sept';
2.0 0.00;
3.0 0.40;
2.0 7.62;
4.0 1.655 7.62 0.0 'inj';
2.0 0.00;
10. 1. 1. 0.878 .001 'betx';
10. 2. 2. -0.17 .001 'alfx';
10. 3. 3. 0.509 .001 'bety';
10. 4. 4. -0.32 .001 'alfy';
10. -1. 6. 0.15 .001 'r16';
10. -2. 6. 0. .001 'r26';
SENTINEL
SENTINEL
```

TABLE II - MODE 2

```
' BOOSTER - TO - SYNCHROTRON TRANSFER LINE'
( LARGE-BETA  BUT  SMALL-ETA SOLUTION )
( TWISS PARAMETERS )
( NOTE: MULTIPLY BETAS BY 10 TO GET METERS )
(     : DIVIDE ETA-PRIMES BY 10 TO GET STANDARD UNITS )
0
15. 11. 'mev' 0.001;
13. 7. 'twis';
13. 3. 'sigm';
13. 13.;
1.0 0.991 3.02 0.724 -1.68 0. 0. 2900. 'bm';
14. 1. 0. 0. 0. 0. 0.331 1.;
14. 0. 1. 0. 0. 0. -0.51 2.;
13. 48. 'deg';
16. 2. 0.00 'k0';
16. 7. 0.500 'k1';
16. 5. 1.60 'gap';
20. 180.;
4.0 1.655 7.62 0. 0 'extr';
20. -180.;
3.0 3.00;
5.01 0.30 -2.954 1.75 'q1';
3.0 1.00;
5.01 0.30 3.502 1.75 'q2';
3.0 4.90265;
5.01 0.30 -0.884 1.75 'qd1';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0. 'ben1';
2.0 9.00;
3.0 0.40;
5.00 0.30 4.000 1.75 'qf1';
3.0 1.845;
5.0A 0.30 -1.844 1.75 'qd2';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0. 'ben2';
2.0 9.00;
3.0 0.40;
5.0C 0.30 2.559 1.75 'qf2';
3.0 1.845;
5.0A 0.30 -1.844 1.75 'qd3';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0.0 'ben3';
2.0 9.00;
3.0 0.40;
5.0C 0.30 2.559 1.75 'qf3';
3.0 1.845;
5.0A 0.30 -1.844 1.75 'qd4';
3.0 0.40;
2.0 9.00;
4.0 2.28 18.0 0.0 'ben4';
2.0 9.00;
```

```
3.0 0.40;
5.01 0.30 2.325 1.75 'qf4';
3.0 3.17323;
2.0 0.00;
4.0 1.655 8.38 0.0 'sept';
2.0 0.00;
3.0 0.40;
2.0 7.62;
4.0 1.655 7.62 0.0 'inj';
2.0 0.00;
10. 1. 1. 0.878 .001 'betx';
10. 2. 2. -0.17 .001 'alfx';
10. 3. 3. 0.509 .001 'bety';
10. 4. 4. -0.32 .001 'alfy';
10. -1. 6. 0.15 .001 'r16';
10. -2. 6. 0. .001 'r26';
SENTINEL
SENTINEL
```