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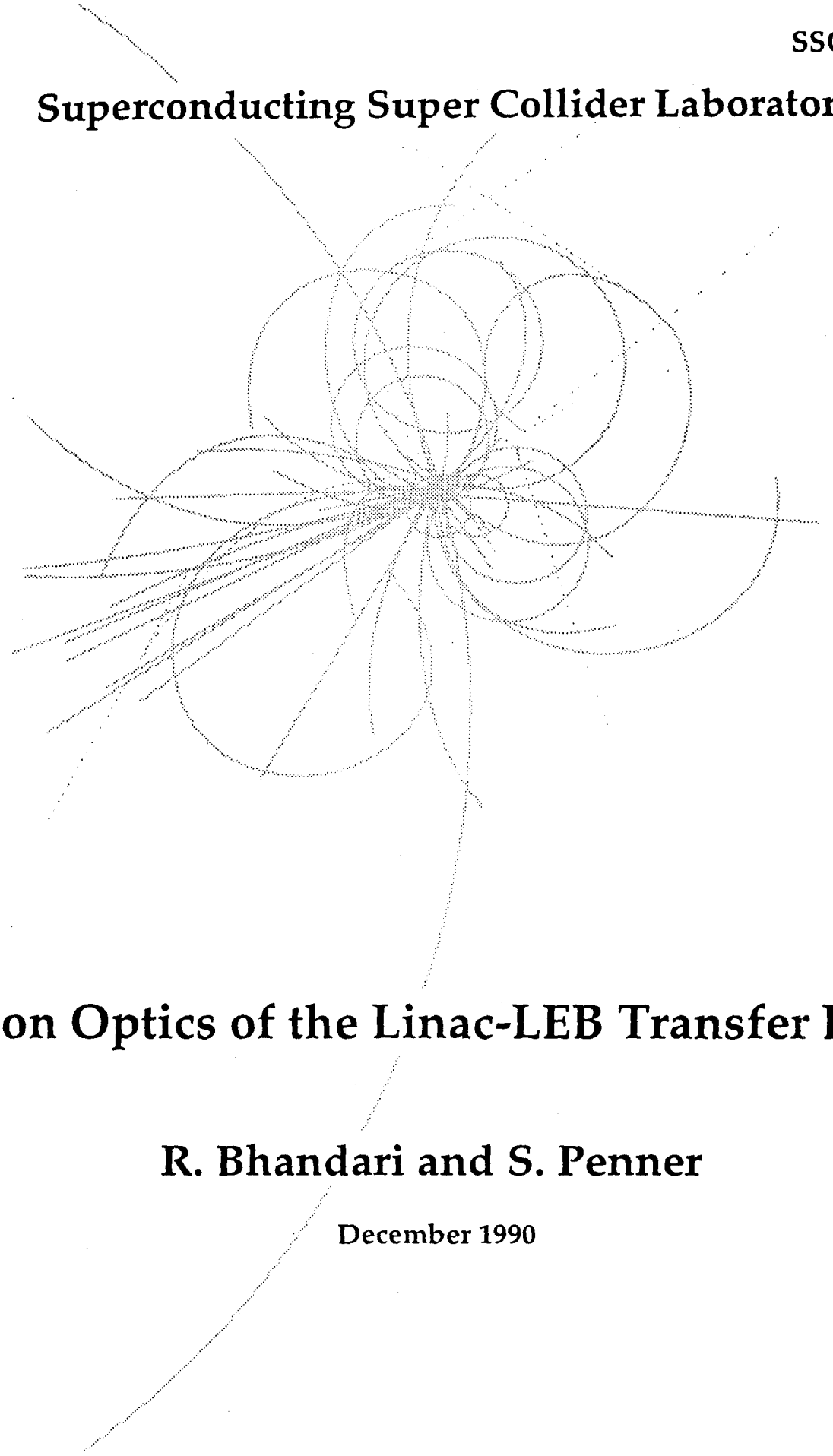

Ion Optics of the Linac-LEB Transfer Line

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* Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

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Abstract

This report describes the ion optical properties of a proposed transfer line to inject a nominal 25 mA H^- beam at 600 MeV from the Linac into the Low Energy Booster (LEB) synchrotron. Ion optical investigations have been carried out in detail using the TRANSPORT, TURTLE and TRACE 3-D codes. The calculations take account of linear space charge effects of up to 50 mA average beam current. These effects have been found to be quite appreciable, especially on the longitudinal phase space. Procedures for their evaluation and optimization are described. Effects of some imperfections in the beam line magnets have been studied.

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1. INTRODUCTION

The linac-to-LEB transfer line must deliver a properly matched, stable beam of small momentum spread and small transverse emittance to the stripper foil in the LEB. The requirements are described in the SSC SCDR[1] in detail. Figure 1 shows the layout of the proposed line and Table 1 gives the properties of the beam[2] which is required to be transported. The table indicates that for all practical purposes the beam at the starting point has a waist in each phase plane. The horizontal waist has rms $x_o = 0.678$ mm and $x'_o = 0.217$ mrad and the vertical waist has rms $y_o = 1.264$ mm and $y'_o = 0.127$ mrad. In the longitudinal direction the rms bunch length = 0.682 mm corresponding to 1284 MHz Coupled Cavity Linac (CCL) frequency and $\beta = v/c = 0.79244$ while the rms energy spread is 202.15 keV. The design average beam current for collider filling is 25 mA although the rated value for the CCL is 50 mA. The pulse rate is 428 MHz which is the Drift Tube Linac (DTL) frequency. The beam macropulse length is 6.6 μs for collider ring filling operation and up to 35 μs for test beam operation.

The first segment of the line, as seen in Figure 1, is a FODO array which transports the beam 98 m from the linac exit. This distance is reserved for a possible future upgrade of the linac to 1 GeV. Within the FODO array, an RF cavity is provided in order to compress the energy spread to about 0.1 MeV (rms) as required for LEB injection. Beyond the FODO array, the beam is transported using quadrupole doublets Q1, Q2 and Q3, Q4 over a distance of 41 m, where the beam enters a 12° achromatic bending system consisting of two identical dipole magnets D1 and D1′ and four quadrupoles 2*(Q5, Q6). (If D1 is off, the beam enters the first beam dump, shown in Figure 1, which is useful for initial tune-up of the linac.) At the center of the achromat, where dispersion is largest, a beam scraper and energy stabilizing slits will be installed. Next, quadrupole doublet Q7, Q8 transports the beam through the 20 m long emittance measurement segment to the transverse phase space matching system consisting of two doublets Q9, Q10 and Q11, Q12. Downstream of Q12, the beam is transported onto the stripper in the LEB ring by a 5.6608° septum magnet

Table 1. Beam Properties

X-plane		
Emittance (n, rms)	:	0.191π mm-mrad
α_x	:	-0.0316
β_x	:	3.1250 m
Y-plane		
Emittance (n, rms)	:	0.208π mm-mrad
α_y	:	-0.0490
β_y	:	9.9714 m
Longitudinal		
Emittance	:	268.1π keV-deg
		(0.1854π mm-mrad, n, rms)
α_1	:	-0.0334
β_1	:	0.00657 deg/keV
Beam Current	:	25 mA (average) H^-

and a 2.4551° bump magnet. Looking in the direction of the beam, these two magnets bend to the left while the dipoles D1 and D1′ bend to the right.

The calculations presented here correspond to producing a double waist of an rms half size of 1.52 mm on the stripper, which matches to an LEB beta function of 10 m and normalized emittance of 0.3π mm-mrad (rms). However, the matching system of quadrupoles Q9–Q12 is flexible enough to match to wide ranges of α and β in both transverse planes. The RF cavity located inside the FODO array will be primarily used to adjust the longitudinal phase space, so that the beam can be efficiently captured by the LEB RF system. Further details are given in Reference 1.

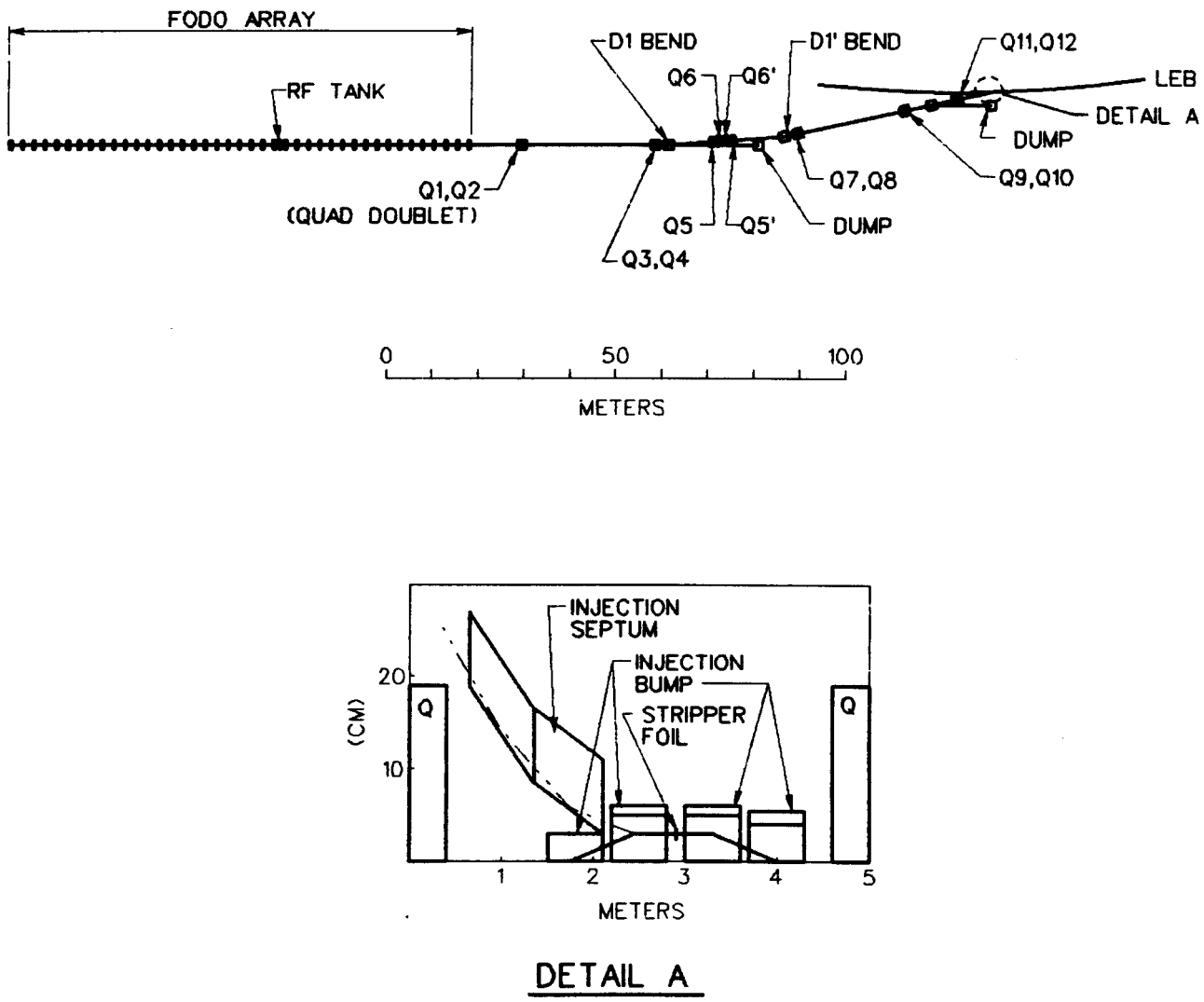

Figure 1. Layout of the Linac-LEB Transfer Line

2. DESCRIPTION OF THE TRANSFER LINE

2.1 FODO Array

This segment is made up of 21 D and 20 F quadrupole magnets alternately placed and separated by drift spaces of 2.38 m each. (As usual, D and F mean horizontally defocussing or focussing, respectively.) All quadrupole magnets are identical with an effective length of 70 mm and an aperture radius of 15 mm. Ion optically, there are 20 identical unit cells in the array, each starting at the center of a D quadrupole and ending at the center of the next D quadrupole. Each unit cell is thus 4.9 m long and the pole tip field is adjusted so that the phase advance per cell is 90 degrees. The starting point of the line, i.e. the virtual source provided by the CCL, is assumed to lie at the center of a D quadrupole. In this case, for the initial beam of Table 1, the ratio of matched beam sizes in x and y planes is approximately 1.7 at the center of every D quadrupole and 0.54 at the centers of the F quadrupoles.

2.2 Emittance Scraper Segment

The function of the scraper is to remove extreme tails from the beam profile—at most, a few percent of the beam current. Two apertures, separated by approximately 90 degrees of betatron phase, provide the desired emittance limit. The first aperture will be placed at the exit of the last quadrupole of the FODO segment. The quadrupole doublet Q1, Q2, 9.85 m downstream, provides the desired betatron phase advance. The second aperture is placed within the 28 m drift following this doublet. At the end of this drift space, the doublet Q3, Q4 refocusses the beam into the following spectrometer. All quadrupole magents beyond the FODO segment have an effective length of 300 mm and an aperture radius of 37.5 mm.

2.3 Achromatic Spectrometer

This system is mirror symmetric about its center point where the energy stabilizing and scraper slits will be located. The system is made doubly achromatic

(i.e., zero dispersion and zero angular dispersion at its exit, $\eta = 0$ and $\eta' = 0$ in accelerator notation) by setting the angular dispersion coefficient (R_{26} element of the transfer matrix in TRANSPORT notation) to zero here. The dipoles are rectangular, uniform field magnets, with an effective length of 2 meters.

Optical aberrations in the spectrometer are minimized when there is a beam waist at the symmetry plane for both transverse planes. Energy resolution is maximized by minimizing the horizontal-plane waist size. The smaller the waist size, the larger the beam size in the dipoles. Constraining the vertical beam size in D1 to be about 2.8 mm (rms), we achieve the desired waist conditions by adjusting gradients of the quadrupoles Q1 through Q4. The monoenergetic horizontal waist size is 0.63 mm. For a still smaller horizontal waist, the beam size at the entrance of D1 increases sharply. Dispersion of the system at the symmetry plane is 1.534 m, and thus the momentum resolution is about 0.041% (rms).

Since there is only one constraint on the settings of Q5 and Q6, we have chosen to excite them to the same pole tip field but with opposite polarity. This results in a doubly achromatic beam exiting the spectrometer, and a nearly achromatic beam on the stripper foil. The dispersion (η) can be adjusted by changing the ratio fields in Q5 and Q6, while maintaining the condition $R_{26} = 0$ at the symmetry plane. Angular dispersion can be changed by breaking the symmetry, i.e., by setting Q5′ and/or Q6′ differently from Q5 and/or Q6.

Two sextupole magnets SX1 and SX2 have been introduced in this system in order to correct for the second order field inhomogeneity in the dipole magnets. They are symmetrically placed at 35 cm upstream of D1 and 35 cm downstream D1′. Design calculations and further details are described in Section 5.1.

2.4 Emittance Measurement Range

Following the achromatic spectrometer, quadrupole doublet Q7, Q8 is used to produce a double waist about 11 m downstream, near the mid-point of a 20 meter long emittance measurement range. Three wire beam profile monitors will be

used for emittance measurement, the central one being at the double waist location. Since the beam is drifting freely in this region, and space charge forces are very small because the beam has expanded longitudinally, the emittance can be accurately determined with a single measurement (of all three scanners) as long as the beam goes through a local minimum size somewhere within the measurement range.

2.5 Matching Segment

This segment guides the beam through the injection segment to match at the stripper location in the LEB ring. Two quadrupole doublets, Q9, Q10 and Q11, Q12, separated by an 11 m drift space provide flexible capability to match to a variety of input and output conditions even for beams with high space charge effects, as will be shown later.

A dipole magnet midway between the two doublets is pulsed on to guide the beam to the second beam dump, so that no beam enters the LEB during tune-up of the linac or between LEB fills. This magnet is geometrically identical to D1 but operates at twice the field to give a 12° bend.

2.6 Injection Segment

About 2.8 m downstream of Q12, the beam enters the injection septum. It is a rectangular magnet of length 1.407 m and bending angle 5.6608°. The edge rotation angles at the entrance and exit are 8.1159° and −2.4551°, respectively. The injection bump magnet follows 10 cm downstream of the septum magnet. The bump magnet is 0.6 m long and bends the beam by −2.4551°. The rotation angle at its entrance is also 2.4551°. The stripper is located 10 cm downstream of the exit of the bump magnet.

3. TRANSPORT CALCULATIONS

The transfer line was initially designed and optimized using the first order TRANSPORT code[3], which ignores space charge effects. Table 2 compares the

Table 2. Comparison Listing of Maximum Beam Sizes in Unique Transfer Line Segments for Calculated Output Admittance

Transfer segment	Maximum half beam size			
	x-plane		y-plane	
	size (mm)	location	size (mm)	location
FODO Array	1.270	Middle of F Quad	1.264	Middle of D Quad
Emittance Scraper Section	8.038	Exit of Q4	3.935	Exit of Q2
Achromatic Spectrometer	7.444	Entry of D1 and Exit of D1′	2.045	Entry of Q5 and Exit of Q5′
Emittance Measurement Range	8.040	Entry of Q7	2.058	End of second 10 m drift
Matching Section	6.048	Entry of Q9	3.042	Exit of Q10
Injection Segment	1.582	Exit of Q12	1.568	Exit of Q12
	($\epsilon_x = 0.191\pi$ mm-mrad, n, rms)			
	($\epsilon_y = 0.208\pi$ mm-mrad, n, rms)			

maximum beam sizes which occur in different segments of the transfer line, for the calculated linac output emittance[2]. Since beam sizes scale like the square

root of the emittance, we see that more than six times the rms emittance can be transported within 75% of the quadrupole aperture (37.5 mm radius).

It is convenient to use TRANSPORT to test for the sensitivities of the system to variations in input emittance, virtual source parameters, and matching requirements at the stripper. Small adjustments of doublets Q3, Q4, or Q7, Q8 produce double waist conditions at the locations described above. Similarly, quadrupoles Q9 to Q12 can easily match the transverse phase space on the stripper.

Location of the energy-compressor RF cavity is strongly dependent on the space charge effects and other constraints as will be seen in a later section. In the TRANSPORT calculations, it has been included mainly to obtain realistic values of the momentum spread in the achromatic spectrometer segment and beyond. The value used corresponds to the energy spread required for proper matching into the longitudinal phase space in the LEB ring. The transverse focussing effects of the cavity are very weak. Its final location has been determined using the TRACE 3-D code.

TRANSPORT calculations for the entire transfer line have been carried out to second order. Second order aberrations are found to be negligible, except for the effect of the sextupole component of the dipole fields, mentioned above.

Output of the TRANSPORT code for the transfer line is presented in Appendix 1. Details of various beam line elements, their parameters and the phase space ellipses are available in this output.

4. SPACE CHARGE CALCULATIONS

Linear space charge effects have been estimated and beam line parameters reoptimized for space charge using the TRACE 3-D[4] interactive code. This code is particularly good for linear accelerators and their variations in addition to the usual beam line components. Like TRANSPORT, this code uses matrix method for calculating the optics. Graphical output, consisting of beam envelopes and phase space ellipses, is convenient and useful. Figure 2 shows these plots for the

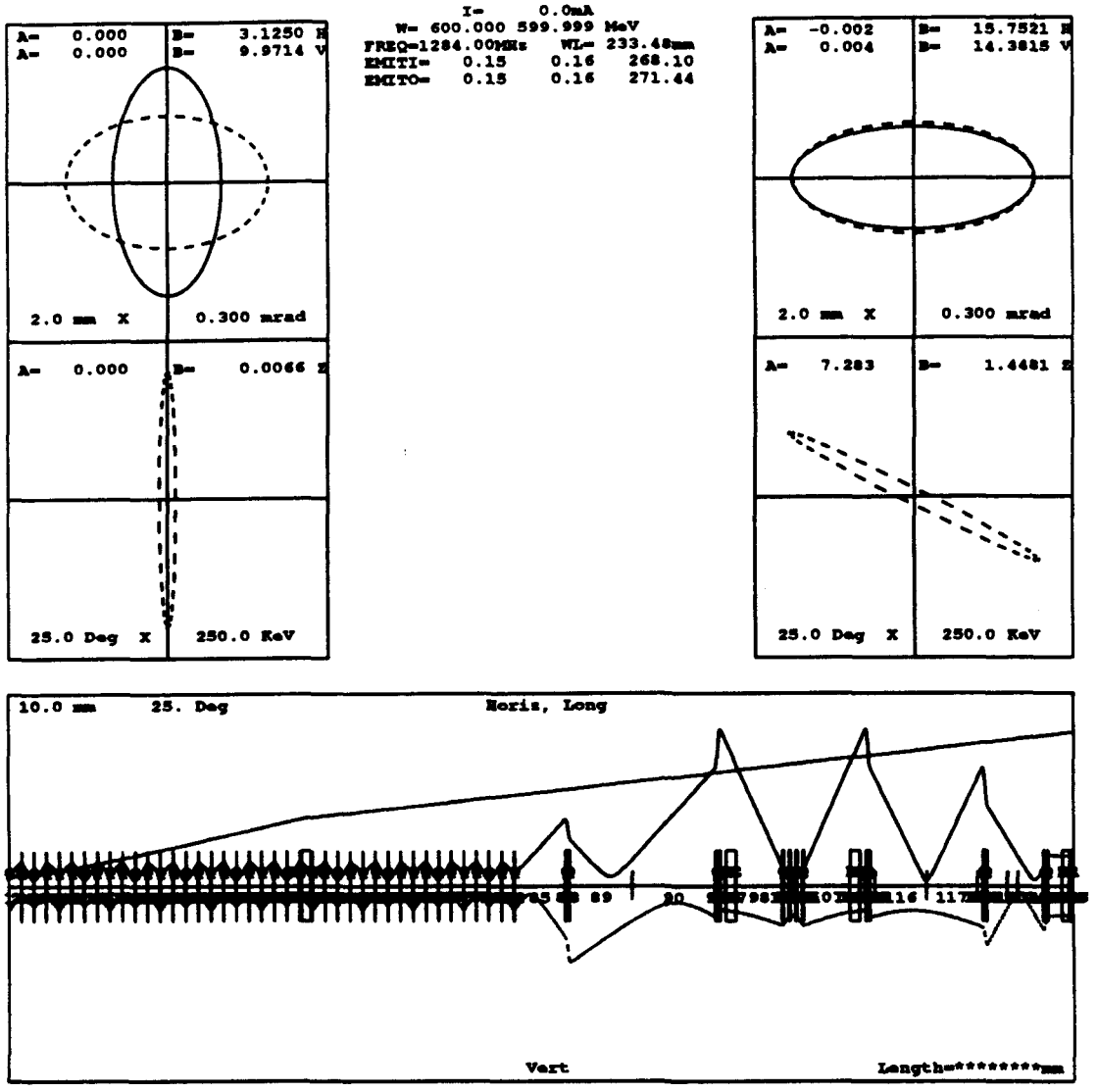

Figure 2. RMS beam profiles and phase space ellipses plots in the transfer line for zero beam current. Input and output emittances (EMITI and EMITO) in the transverse as well as longitudinal phase spaces are shown. In the upper diagrams the initial (left) and final (right) phase space ellipses in the horizontal direction (full lines) and vertical direction (broken lines) are shown. Initial and final phase space ellipses for the longtitudinal motion are shown separately. In all these cases, A is the twiss parameter α and B is β for the corresponding phase ellipses. Scales for different plots have been given. WL is the RF wavelength.

complete transfer line for zero beam current for the initial beam described in Table 1. In the zero-current case, agreement with TRANSPORT is excellent.

In order to calculate the linear space charge effects, TRACE 3-D postulates that the beam has uniform charge distribution in real space. Electric field components, and resulting impulse components, due to a uniformly charged ellipsoid are calculated. It has been shown in Reference 4 that the 'equivalent uniform beam' should have, in each plane, five times the rms emittance of the real beam so that evolution of the beam envelopes depends almost exclusively on the linearized part of the space charge forces. Thus, the beam envelopes generated by TRACE 3-D are approximately $\sqrt{5}$ times the rms envelopes in each plane.

Space charge effects for a bunched beam depend only on the charge per bunch, and not on the bunch repetition frequency. TRACE 3-D uses the RF frequency and the average current to calculate the charge per bunch, assuming every RF cycle contains a charge bunch. In our case, because the CCL operates at three times the RF frequency of th4e RFQ and DTL, only every third cycle contains a bunch. In order to obtain the correct space charge effect, it is only necessary to input three times the actual average current to the code along with the actual CCL frequency of 1284 MHz. (These modified currents appear in some of the computer-generated figures, e.g., $I = 75\,\mathrm{mA}$ in Figure 7 corresponds to an actual 25 mA beam.)

Due to rather long flight paths in the transfer line, space charge effects depend strongly on the energy spread in the beam. They are more pronounced in the case of short bunches like those emerging from the CCL. In view of this, location of the energy compressor cavity in the beam line is very important. In the next section, we shall discuss the considerations and procedures for locating the cavity properly in the transfer line.

4.1 Location of the Energy Compressor RF Cavity

The energy compressor is a coupled cavity tank operating at 1284 MHz and consisting of 20 identical cells, each $\beta\lambda/2$ in length. The total length is thus 1.85 m

for 600 MeV H^- beam. The reference particle has energy E_s and synchronous phase $\phi_s = -90°$. Ions with energy $E_s + \Delta E$ arrive at the cavity before the reference particle, and thus see a decelerating field while those with energy $E_s - \Delta E$ see an accelerating field. The rate of change of energy of ions with charge q arriving at the cavity at phase ϕ is given by:

$$\frac{dw}{dz} = |q| E_o T \cos \phi_o$$

where, E_oT is the effective peak accelerating field in the cavity. It is required to locate and operate the energy compressor such that:

(1) Energy spread at the stripper in the LEB ring is compressed to about 100 keV (rms) to match the injection requirement.

(2) Half bunch length of the 95% (6σ) beam at the tank entrance should be approximately 60° so that most particles see the linear part of the RF waveform.

(3) The value of E_oT is minimized.

This has been done using the coupled cavity tank element (type code 13) of the TRACE 3-D code. Parameters of this element are the value of E_oT, total length of the tank, synchronous phase ϕ_s and the number of cells in the tank. In the first step the tank is placed in one of the drift spaces of the FODO array. It is moved back and forth along the array until a location is found which satisfies condition (2) above. Space charge effects for the desired beam current are turned on while carrying out this process. It is to be noted that shorter bunch lengths (i.e. the tank nearer to the linac exit) require higher E_oT for a given energy spread condition at the stripper.

The next step of the procedure is to adjust E_oT in order to obtain the desired energy spread, 100 keV (rms) for the cases discussed here, at the stripper location. For consistency with the other parameters, half bunch lengths for the rms beam rather than 95% beam will be compared in the following discussion. In the case of 25 mA average beam current, calculations show that the tank entrance

should be situated at 56.65 m downstream of the linac exit, midway between the F quadrupole of the 12th cell and the next D quadrupole of the FODO array. Half bunch length at the tank entrance is 24.9° (rms) which corresponds to about 61.1° for the 95% beam. The required E_oT to obtain 100 keV energy spread at the stripper is 0.825 MV/m. The corresponding location for the tank for 50 mA average beam current is 41.95 m from the linac exit. Here the half bunch length is 24.3° (rms). However, it is not possible to find an E_oT value which yields 100 keV energy spread at the stripper in this case. This is due to the fact that reduction in the energy spread caused by the tank is cancelled by space charge effects in the subsequent flight path. The increased space charge effects are due to a rather small bunch length for the larger beam current as well as due to the longer flight path to the stripper. The minimum energy spread which could be obtained in this case at the stripper is approximately 158 keV (rms) for an E_oT of 1.3 MV/m. For a lower E_oT value, the energy compression due to the tank is not sufficient, while for the higher E_oT the bunch length is further reduced downstream of the tank, as compared to at its entrance, giving rise to increased space charge effects. The tank was shifted downstream by one cell length, i.e. at 46.85 m from the linac exit. At this location the half bunch length at its entrance for 50 mA beam current is 27.65° and the minimum energy spread obtainable at the stripper is about 102.4 keV (rms) for an E_oT of 1.227 MV/m. In the case of 25 mA average beam current, with the tank at this location, the half bunch length is 20.04° and the energy spread at the stripper is 99.75 keV for an E_oT of 1.13 MV/m. Table 3 summarizes various parameters of the tank and the beam for 25 mA and 50 mA cases.

Some further studies were carried out for the 25 mA case. In Figure 3, the effect of variation of E_oT on the rms energy spread at the stripper is shown. Figure 4 shows the corresponding half bunch lengths. For each E_oT value plotted in these figures, quadrupoles Q9 through Q12 were adjusted for transverse phase space matching as specified earlier. There are two settings of the tank voltage which yield the same energy spread at the stripper. Corresponding half bunch

Table 3. Summary of Parameters of Tank and Beam for 25 mA and 50 mA

Average beam current	Linac-to-tank distance	E_oT	At tank entrance		At the stripper	
			rms bunch length	rms energy spread	rms bunch length	rms energy spread
(mA)	(m)	(MV/m)	(deg)	(keV)	(deg)	(keV)
25	56.65	0.825	24.95	673.5	31.69	100.0
25	46.85	1.130	20.04	662.2	22.87	99.8
50	56.65	0.852	34.42	927.1	39.40	99.9
50	46.85	1.227	27.65	913.9	22.41	102.4
50	41.95	1.302	24.31	905.0	28.88	157.6

lengths are, however, different for these settings. Minimum obtainable energy spread, which corresponds to a unique value of E_oT, depends on the tank location for a given beam current. This behavior can be understood in the light of the competing effects of energy compression due to the tank, and energy spread due to the space charge effects, as explained in the previous paragraph.

We have studied the effect of fine tuning of the tank voltage on beam bunch parameters at the stripper for two representative cases from Table 3. In the case of a 25 mA beam with the tank located 56.65 m from the linac exit, the energy spread changes by -4.9 keV per percent increase in tank voltage, while the half bunch length at the stripper changes by -0.66 degrees/percent. In the case of a 50 mA beam with the tank at 46.85 m, the half bunch length changes by -0.84 degrees/percent. However, in this case there is a quadratic minimum in the energy spread at the stripper for $E_oT = 1.227$ MV/m and the energy spread increases by 0.05 keV for a voltage change of $\pm 0.5\%$.

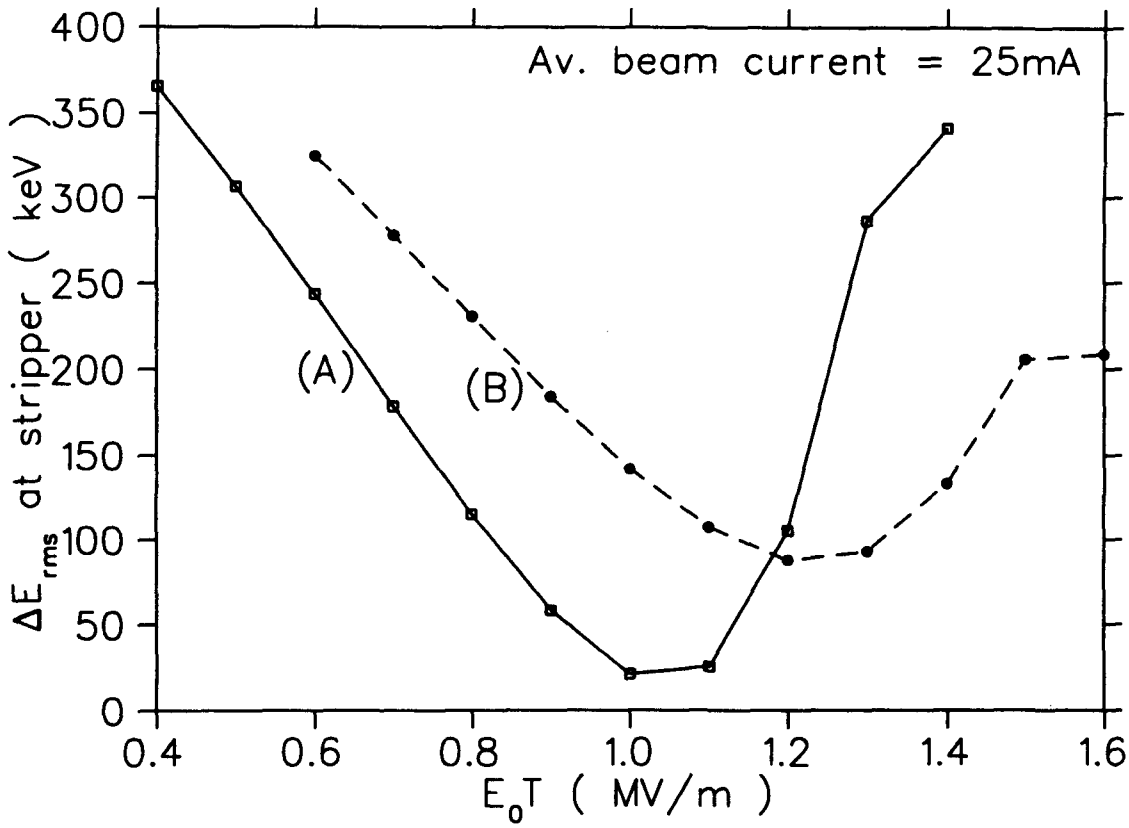

Figure 3. Effect of variation of E_oT on the RMS energy spread at the stripper when the energy compressor tank is located at, (A) 56.65 meters from the linac exit, and (B) 46.85 meters from the linac exit.

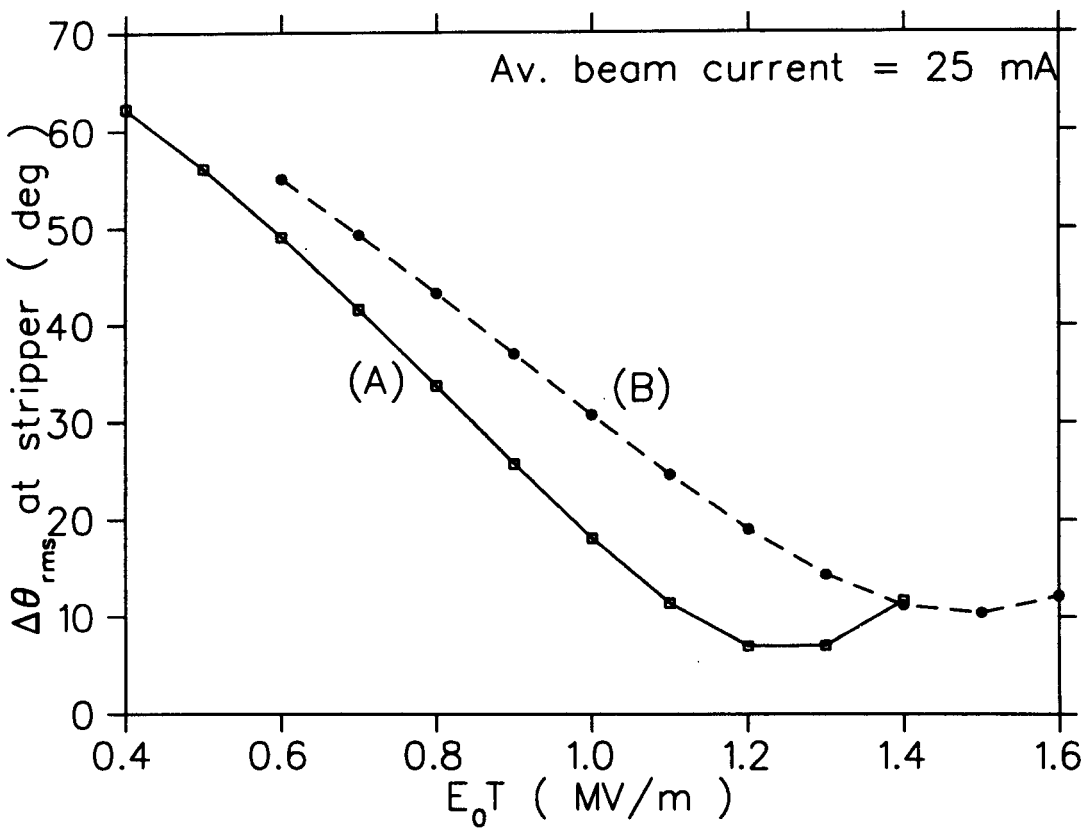

Figure 4. Variation of the half bunch length (RMS) at the stripper with E_oT for the cases of Figure 3. RMS half bunch length at the tank entrance for case (A) is 24.95° and for (B) 20.04°.

4.2 Space Charge Effects in the Transfer Line

Space charge effects have been calculated in the transverse direction for average beam current of 25 mA and 50 mA, corresponding to the first and fourth rows of Table 3. For convenient comparison with the space charge beam envelopes, Figures 5 and 6 show the beam envelopes and phase space ellipses for the case of zero beam current but 5 times the rms emittance in the total transfer line and the FODO array segment, respectively.

Starting with the zero beam current case shown in Figure 5, we turned on the space charge effects without changing any other parameter. It was found that for the 25 mA beam current the rms half beam sizes in x and y planes at the stripper location are 1.24 mm and 1.45 mm, respectively (compared to 1.52 mm in both x and y planes in the zero current case). The corresponding values for the 50 mA beam are 0.73 mm and 1.48 mm. However, it is easy to match to the desired double waist condition at the stripper with the help of matching quadrupoles Q9 to Q12. Figures 7 and 8 show the beam line plots for the case of 25 mA average beam current, with all the beam line parameters unchanged from the zero current case, except that field strengths of the quadrupoles Q9 to Q12 are adjusted to produce the desired double waist of 1.52 mm half size at the stripper. It can be seen that the beam sizes are very much under control throughout the line and the matching at the stripper is also very good. Similarly, the space charge effects of 50 mA average beam current are shown in Figure 9 for the total transfer line. Interestingly, the beam sizes in general are notably smaller than in the 25 mA case. This may partly be due to the fact that the 50 mA beam emerging from the FODO segment is converging in the x-plane, while the 25 mA beam is diverging. Also, the total angular spread at this point is smaller in the 50 mA case. These differences can be seen by comparing Figures 8 and 10. Table 4 compares the pole tip fields of the matching quadrupoles for zero, 25 mA and 50 mA average beam currents.

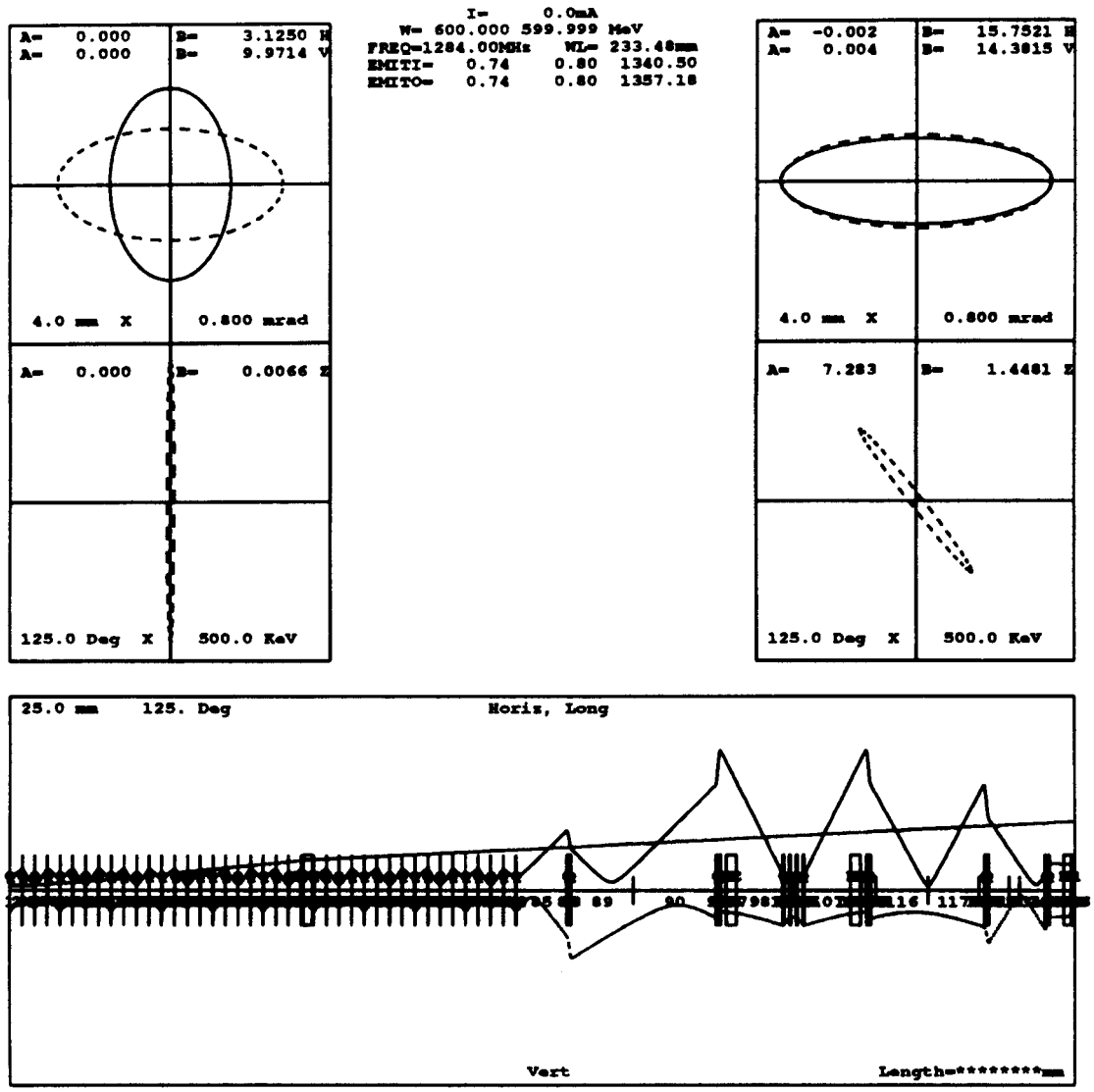

Figure 5. Beam envelopes and phase space ellipses plots in the transfer line for zero beam current with the initial emittance 5 times the rms emittance as explained in the text. E_oT for the tank $= 0.3655\,\mathrm{MV/m}$.

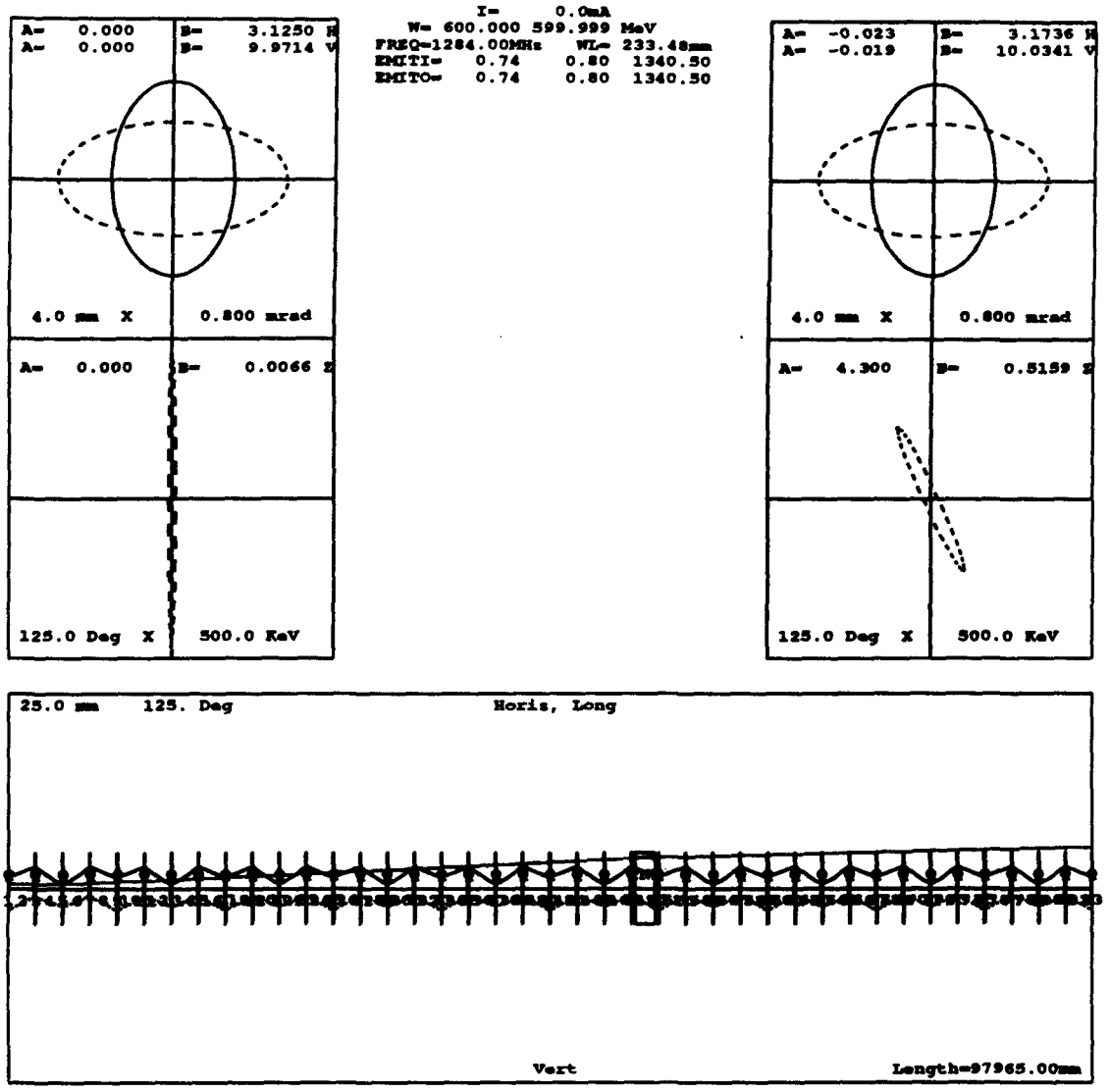

Figure 6. Beam envelopes and phase ellipses for the FODO array segment for 5 times the rms emittance and zero beam current. (This figure corresponds to Figure 5.)

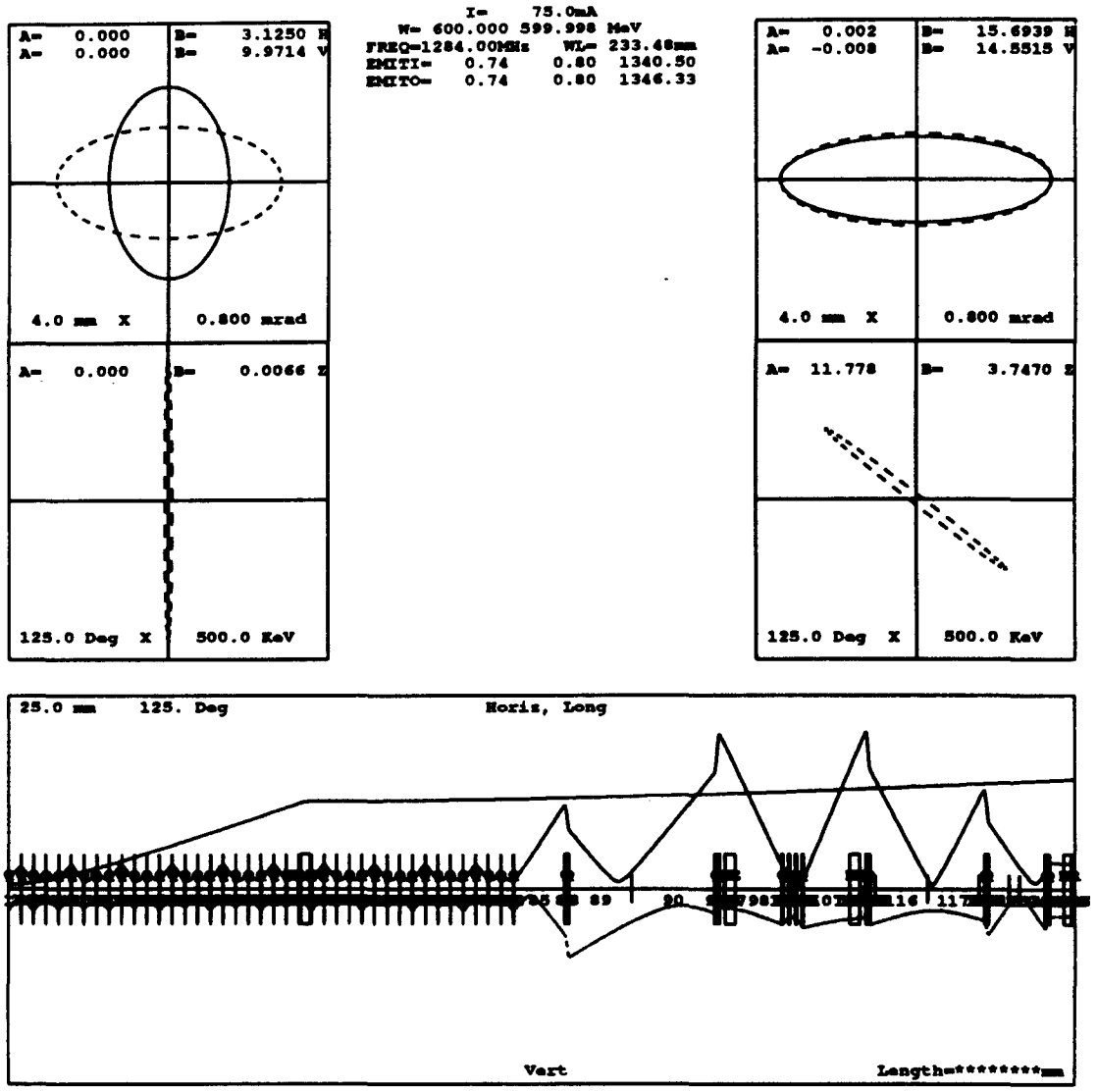

Figure 7. Average beam current 25 mA in the transfer line. Plots of the beam envelopes and phase space ellipses. $E_oT = 0.825\,\mathrm{MV/m}$ for the RF tank. Matching quadrupoles adjusted to match double waist of half size 1.52 mm at the stripper in the LEB ring. Initial emittance 5 times the rms emittance as explained in the text.

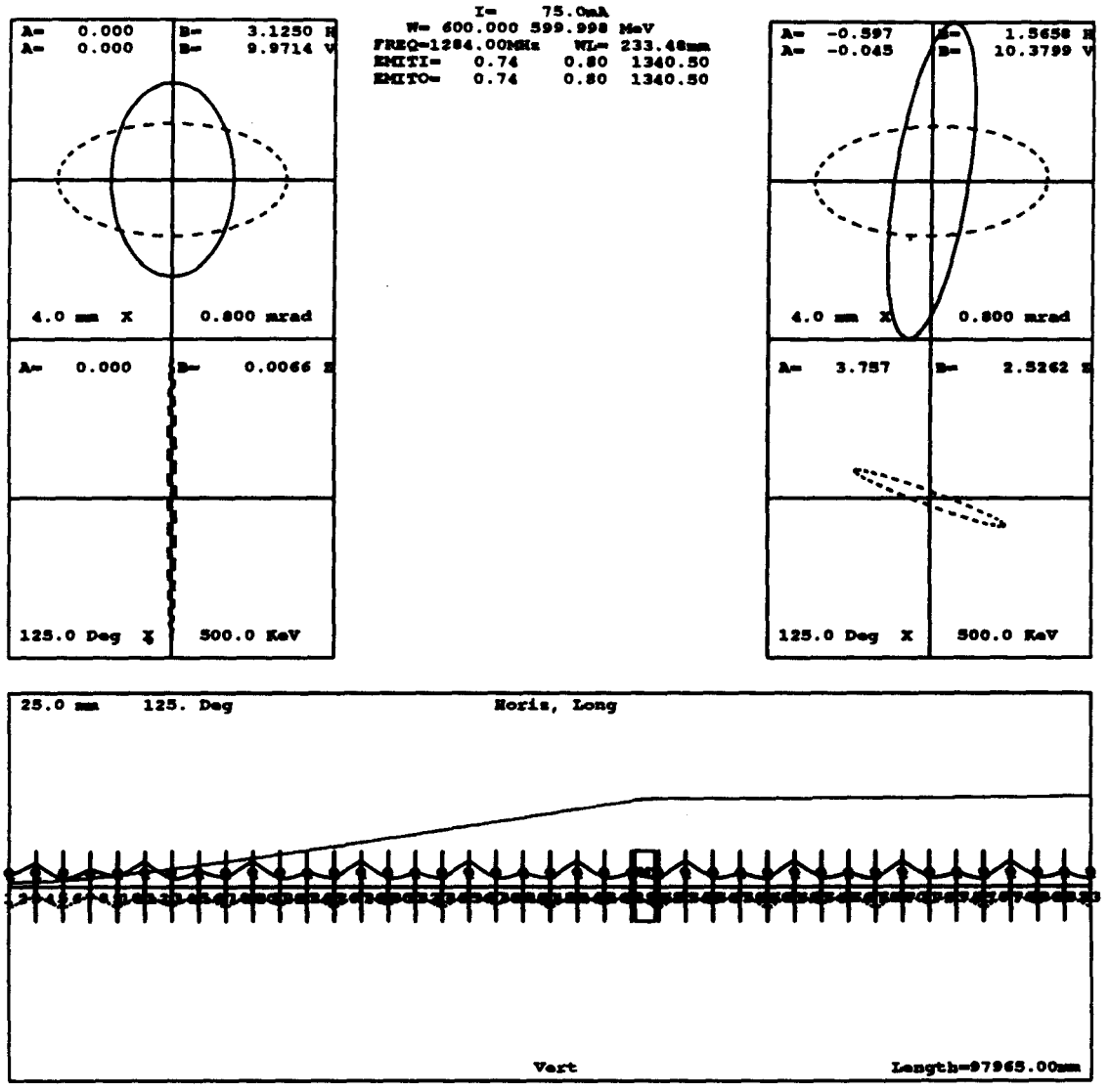

Figure 8. Average beam current 25 mA. Plots of the beam envelopes and phase space ellipses for the FODO array segment. Initial emittance 5 times the rms emittance.

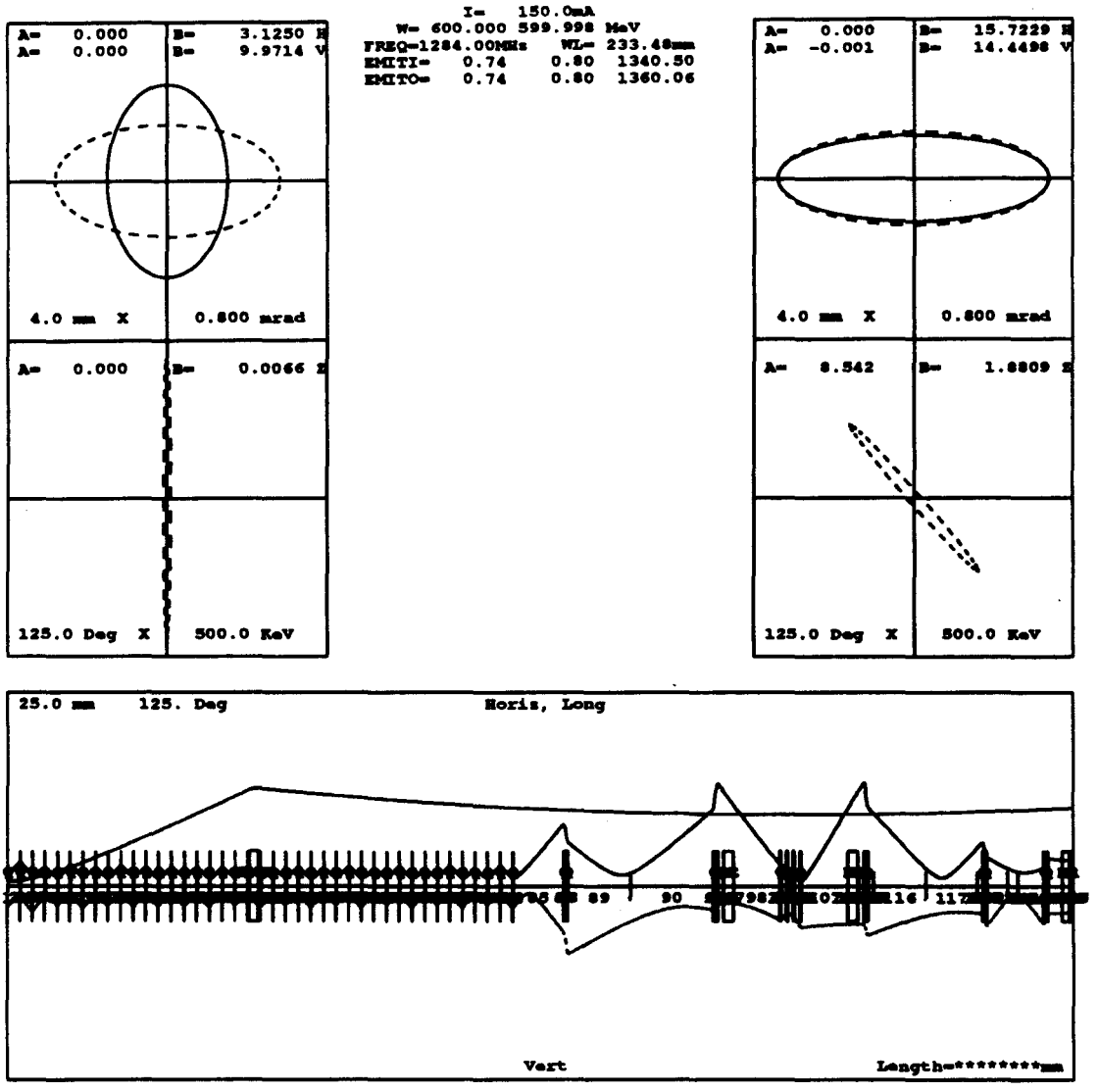

Figure 9. Plots of the beam envelopes and phase space ellipses in the full transfer line for 50 mA average beam current. E_oT for the RF tank is 1.227 MV/m. Matching quadrupoles adjusted for a 1.52 mm half size double waist at the stripper. Initial emittance is 5 times the rms emittance.

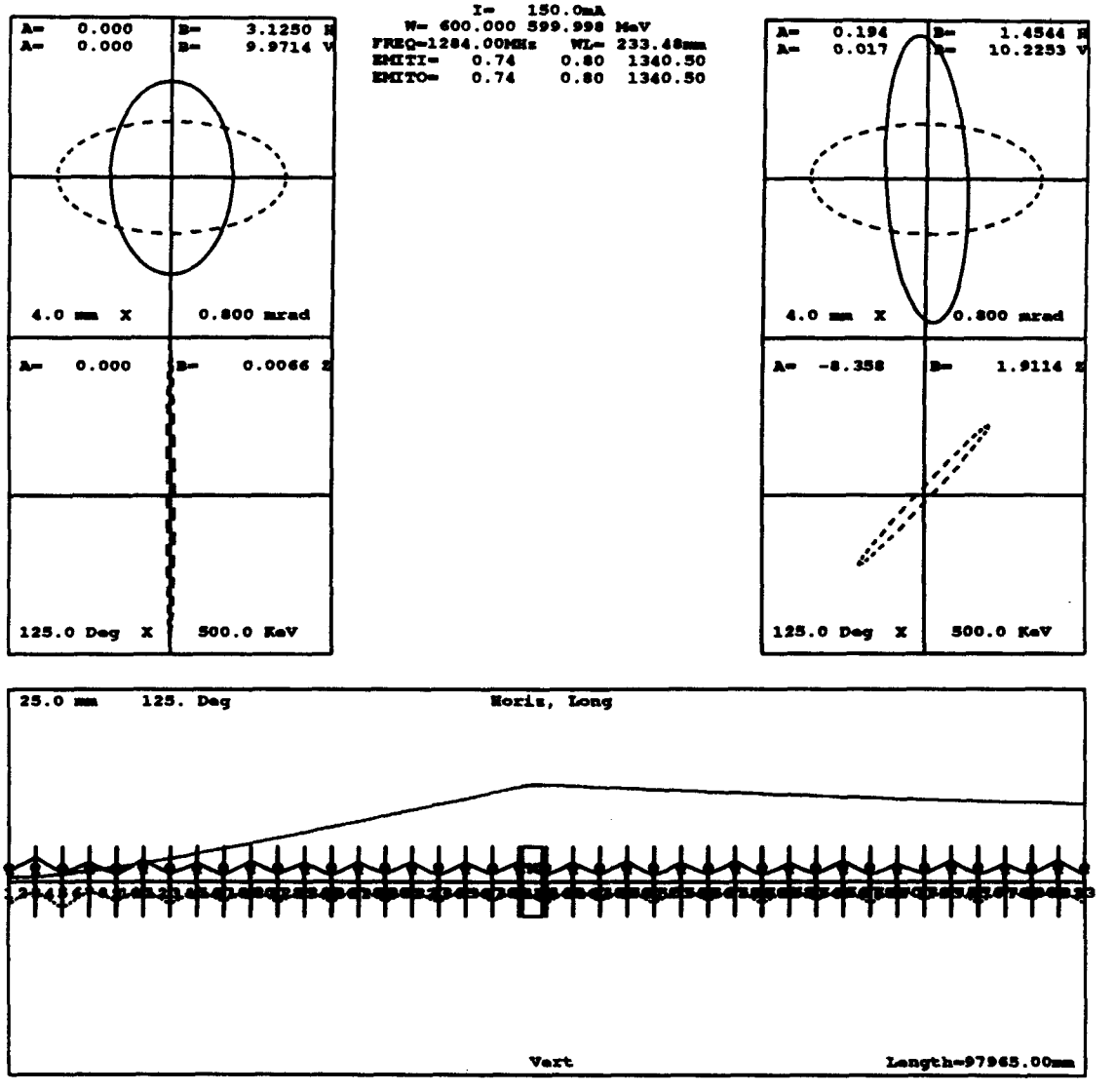

Figure 10. Plots of the beam envelopes and phase space ellipses for 50 mA average beam current in the FODO array segment. Initial emittance 5 times the rms emittance.

Table 4. Comparative Listing of Pole Tip Fields of Matching Quadrupoles for 0.0 mA, 25 mA, and 50 mA Average Beam Currents

	Pole tip fields (Tesla)		
Quadrupole	0 mA	25 mA	50 mA
Q9	0.3335	0.3468	0.3636
Q10	−0.3462	−0.3609	−0.3678
Q11	−0.3968	−0.3829	−0.3355
Q12	0.3923	0.3806	0.2998

The rms half beam sizes at the center of the achromat, i.e. at the high dispersion location, are 0.33 mm, 0.61 mm and 0.95 mm for zero, 25 mA and 50 mA beam current cases, respectively. Since the dispersion is not affected by the current, the obtainable resolution deteriorates from about two parts in 10^4 at zero current to about 6 parts in 10^4 at 50 mA.

As a special case, we have analyzed the space charge effects of the 25 mA beam in the transfer line when the initial beam emittance doubles in each plane. The system was first optimized by the procedure described in Section 3. Subsequently, the space charge effects were calculated without changing the RF tank location (56.65 meters from the linac exit). It required $E_oT = 0.841$ MV/m to obtain 100 keV energy spread (rms) at the stripper. Figures 11 and 12 show the beam profiles for this case in the total line and the FODO array segment, respectively. Approximately 90% of the quadrupole aperture will be filled by 95% of the beam at two locations, as can be seen in Figure 11. Some optimization of the system will be necessary in order to contain the envelopes below 75% of the aperture. Matching at the stipper is, however, easy to achieve. The pole tip fields for the matching quadrupoles Q9 to Q12 are 0.3348 (0.3278), −0.3467 (−0.3382), −0.4459 (−0.4455) and 0.4646 (0.4515) Tesla, respectively; where the quantities in parentheses are the corresponding values for zero beam current.

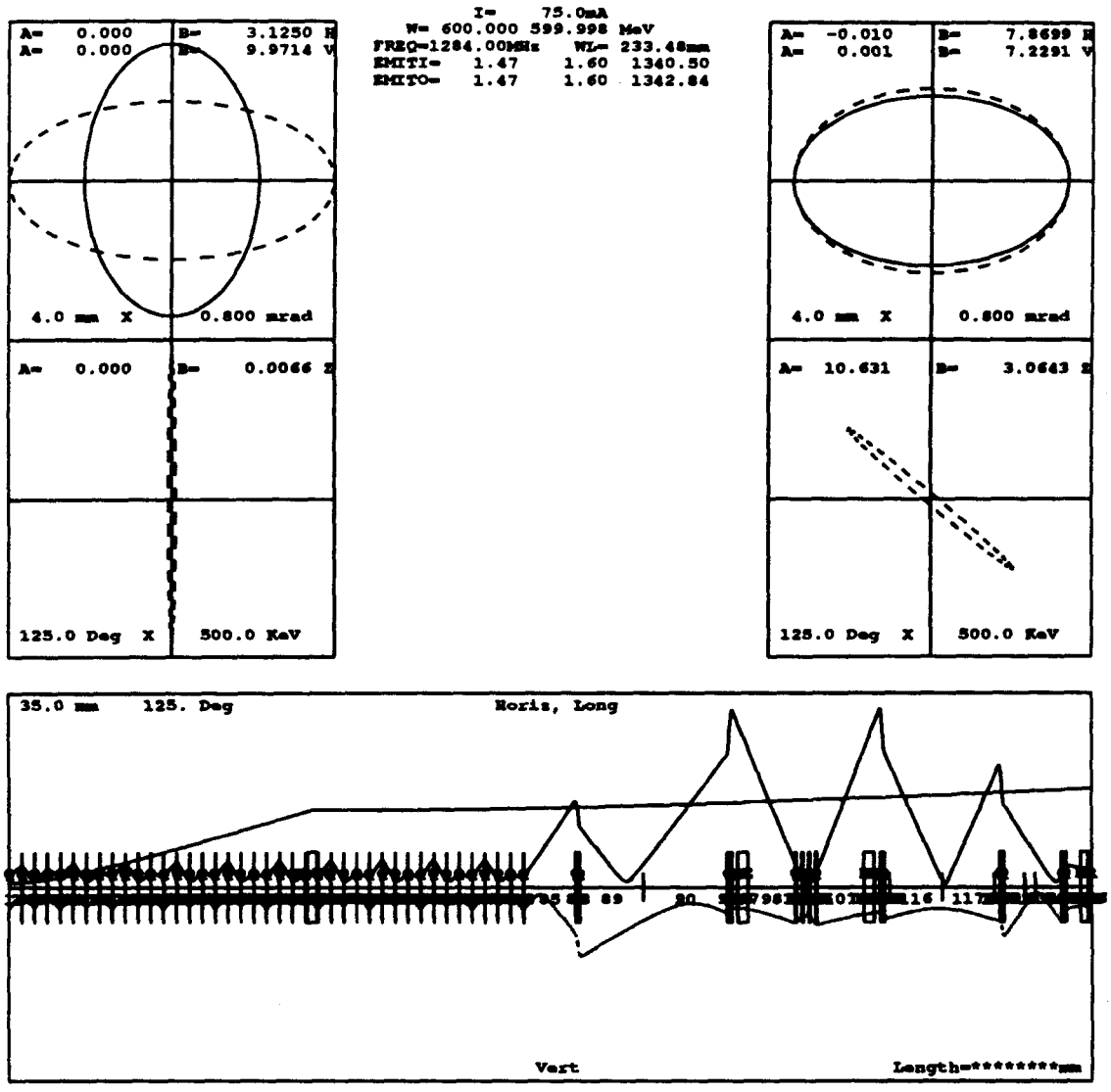

Figure 11. Beam envelopes and phase space ellipses for 25 mA average beam current in the transfer line for the case when the rms emittance at the exit of the linac doubles in the transverse planes. The E_oT value for the RF tank is 0.841 MV/m in order to obtain 100 keV rms energy spread at the stripper. Matching quadrupoles have been adjusted as in the case of Figure 7 and 9.

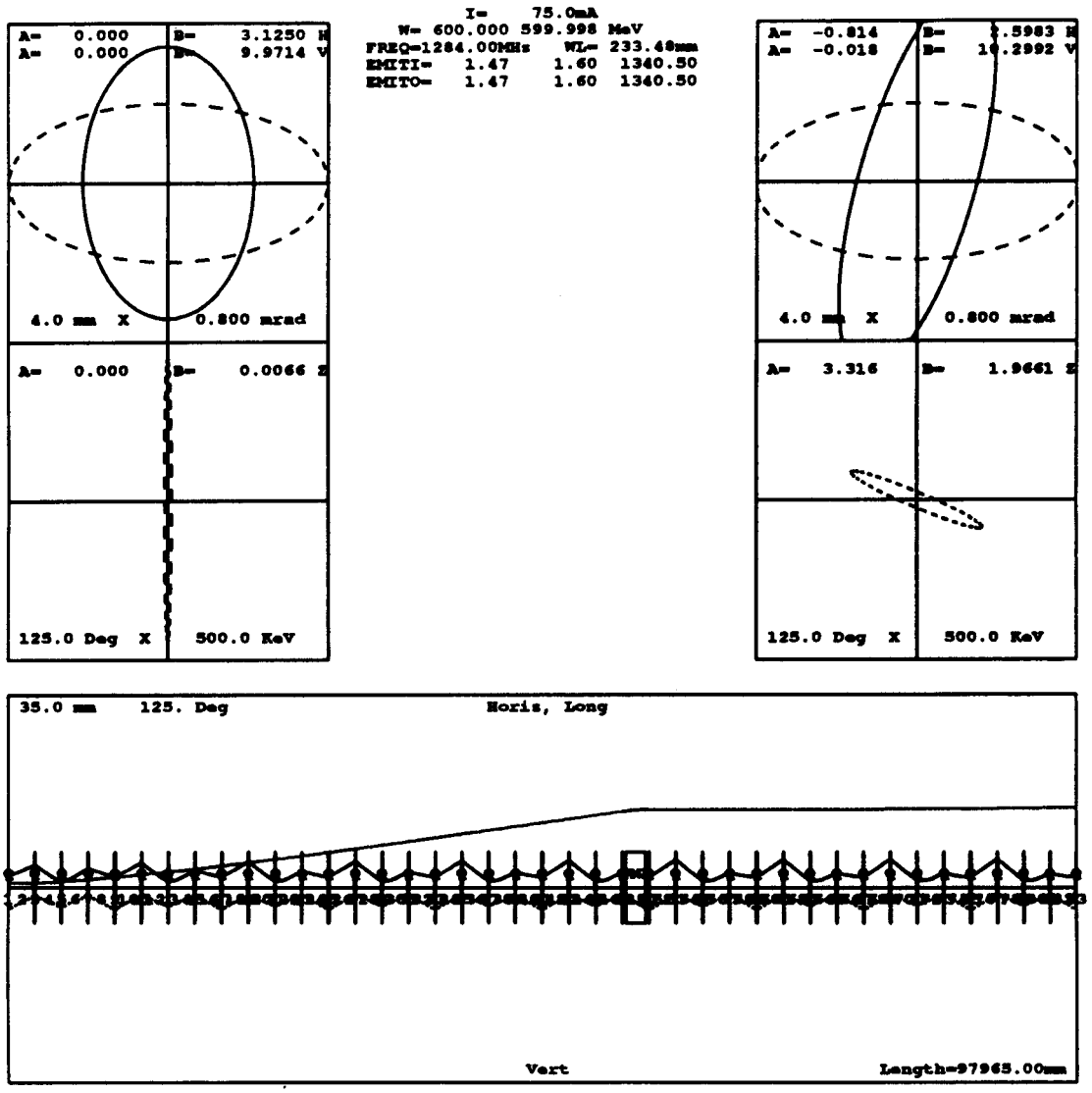

Figure 12. Beam envelopes and phase space ellipses in the FODO array segment shown expanded for the case of Figure 11.

5. RAY TRACING CALCULATIONS

These calculations were carried out using the TURTLE code[5] obtained from D.C. Carey. The desired number of rays originating from within the boundaries of the initial phase space ellipse are individually traced throught various elements of the line. A matrix approach is used and various higher order aberration coefficients are included. Each traced ray is collected at the desired location in the beam line and histograms generated to exhibit the effect on the phase space explicitly. Aberrations like the chromatic effects, geometric effects, magnetic field imperfections, etc. can be studied. Data for the final beam line from TRANSPORT, as described in Section 3, is used as input to TURTLE. In the first step, a correspondence between the phase space ellipses given by TRANSPORT and the histograms generated by TURTLE was established. Subsequently, the effects described in the following sections were studied. All results have been compared at the stripper location for 6σ (95%) beam. In Figure 13, histograms at the stripper are shown as reference for the "ideal case" of a zero-current beam with no aberrations present. In each case 5000 rays have been traced. A "standard rectangle" has been superimposed over the x, x' histograms in the relevant figures. This rectangle covers an area enclosed by $x = -3.75$ to $+3.75$ mm and $x' = -0.250$ to $+0.250$ mrad and corresponds very closely to the desired waist at the stripper location. Over 98% of the rays fall within the area of this rectangle in the ideal case. In order to make an estimate of the phase space deformation, a mismatch factor (MF)[6] has been arbitrarily defined as follows:

$$\mathrm{MF} = 1 - \frac{n \times n'}{n_o \times n'_o}$$

where, n is the number of rays falling within the rectangle in the x direction, n' is the number of rays falling within the rectangle in the x' direction, and n_o and n'_o are the corresponding numbers in the ideal case (in which MF = 0).

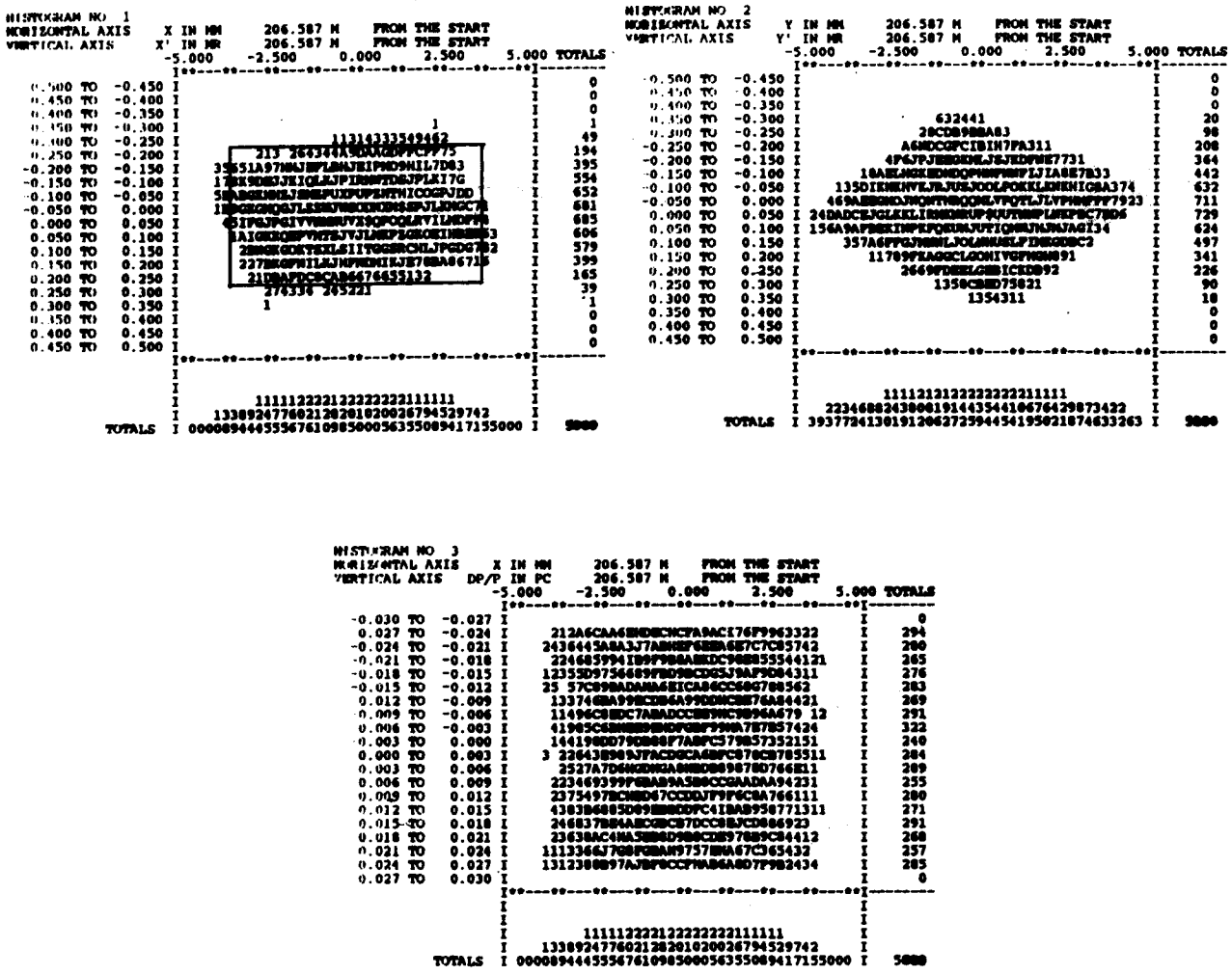

Figure 13. Beam histograms at the stripper in the LEB ring in an ideal case. Top: (x, x') phase plane; Middle: (y, y') phase plane and Bottom: $(x, \Delta p/p)$ phase plane. The number of rays at any point are shown by numerals 1–9, letters A–Z for 10 to 35 rays and sign \$ for more than 35 rays. The rectangle drawn on the x, x' histogram covers an area enclosed by $x = -3.75$ to $+3.75$ mm and $x' = -0.25$ to $+0.25$ mrad and very closely corresponds to the desired waist at the stripper. About 98% of the rays fall within this rectangle in an ideal case. This standard rectangle is drawn on all the x, x' histograms in the subsequent figures as a reference.

5.1 Magnetic Field Inhomogeneity in the Dipole Magnets

The field expansion in the median plane of the dipole magnet is given by:

$$B(x) = B(o)\left\{1 - n\left(\frac{x}{\rho_o}\right) + \beta\left(\frac{x}{\rho_o}\right)^2 - \ldots\right\}$$

where, $B(o)$ is the field on the reference trajectory, x is the displacement from this trajectory in the median plane and ρ_o is the radius of curvature of this trajectory. D1 and D1$'$ have uniform magnetic field ($n = 0$ and $\beta = 0$) in the ideal case. Effects on the beam of a second order field inhomogeneity of 1×10^{-3} per centimeter of displacement from the central trajectory has been estimated. The effect of equal errors of this magnitude in both dipoles (D1 and D1$'$) of the achromatic spectrometer is shown in Figure 14. It is seen that the (x, x') phase space is very severely deformed at the analyzing slit. About half of the beam passes through a slit of width 1.75 mm, which is the second order beam size for a momentum spread of 0.027% ($= \sqrt{6} \times 0.011\%$) at this location. However, if the slit is kept wide open all rays reach the stripper and the (x, x') phase space is undeformed compared to the ideal case. This implies that the aberration is cancelled beyond D1$'$ due to the symmetry. However, in practice it is quite possible that the field errors in the two dipoles are different. Figure 15 shows three situations where the effect of the field errors on the beam at the stripper is very severe. The worst case found is when the errors in D1 and D1$'$ are of opposite sign. This figure also shows cases when the error in both dipoles is an order of magnitude smaller. It is clear that even an error of 10^{-4} per cm may be serious. This accuracy may be very difficult to achieve in practice.

While an effort should be made to shape the dipole fields to a reasonable accuracy, the problem can also be overcome by introducing two sextupole magnets in the achromatic spectrometer segment. They are optimized using TRANSPORT. Each sextupole has an effective length of 15 cm and an aperture radius

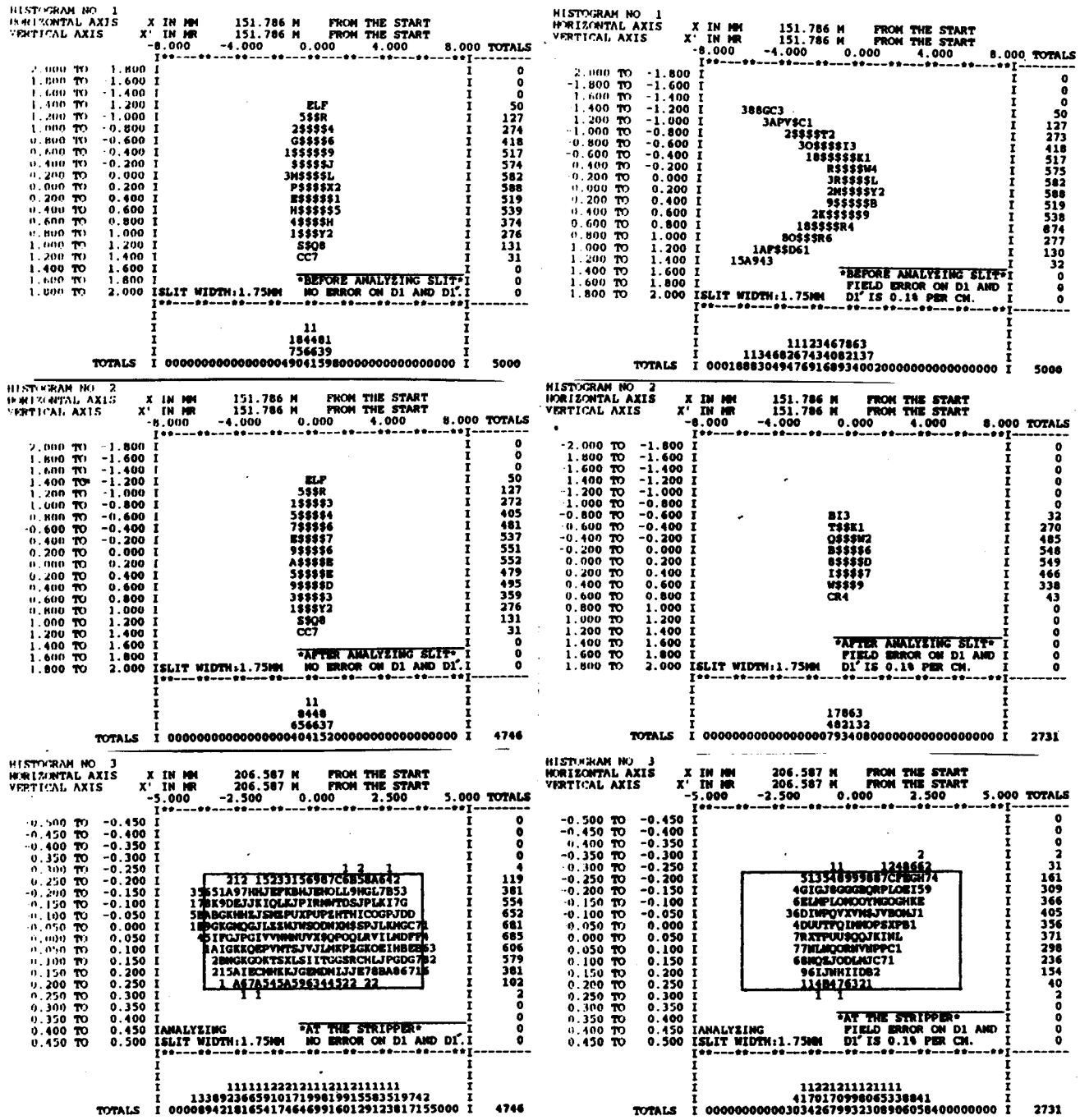

Figure 14. Distortion of the (x, x') phase space at the analyzing slit location after the D1 dipole magnet for a second order field inhomogeneity of $\Psi = 1 \times 10^{-3}$ per cm. Ideal case ($\Psi = 0$) histograms also shown for comparison. Top: Just before the slit; Middle: Just after the slit and Bottom: At the stripper. Started with 5000 rays. Analyzing slit width = 1.75 mm.

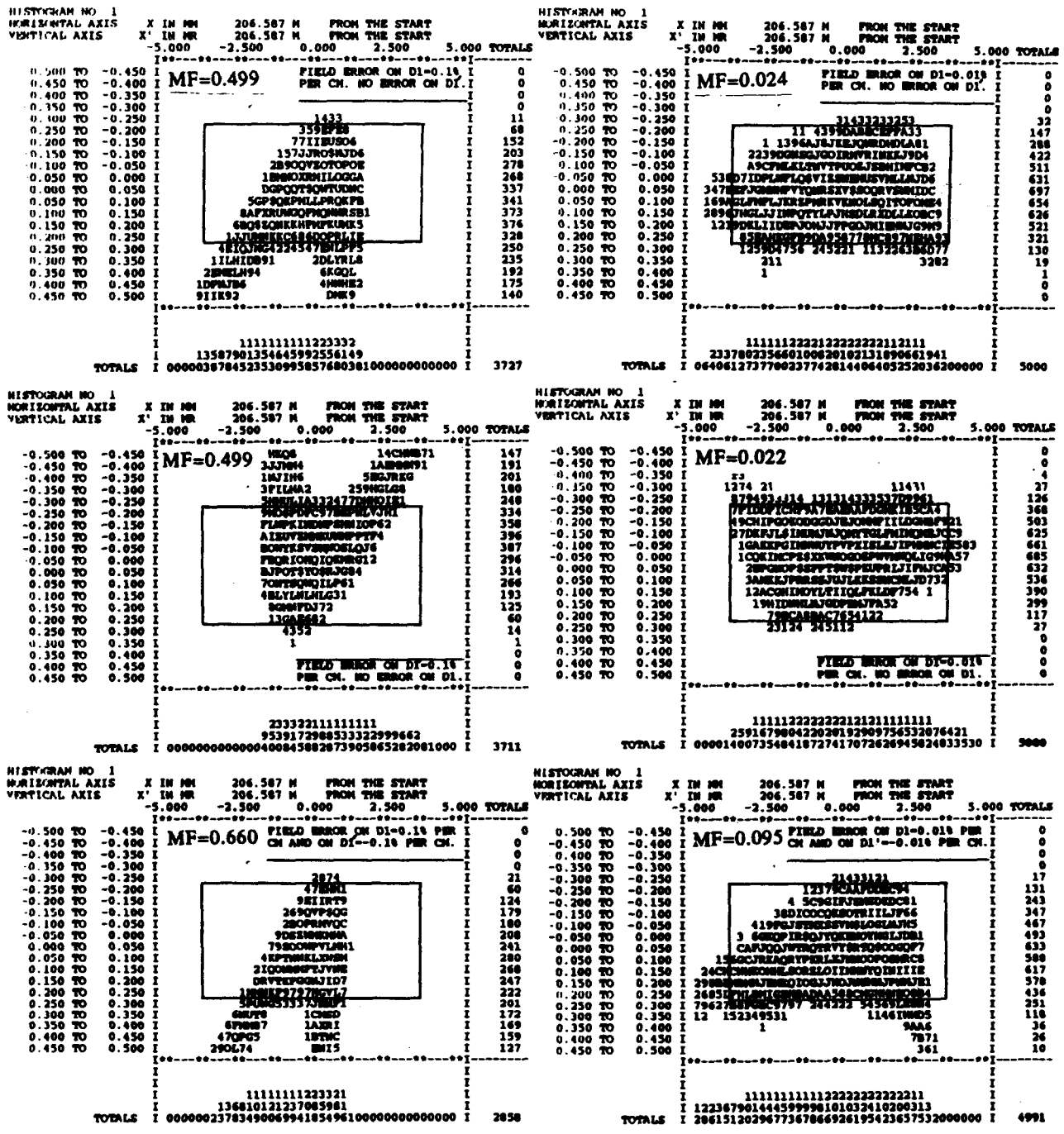

Figure 15. Distortion of the (x, x') phase space at the stripper location due to second order field inhomogeneity errors of different magnitudes on the dipoles of the achromatic spectrometer.

of 37.5 mm. They are symetrically placed in the segment, 35 cm before D1 and 35 cm after D1′. Their strengths are optimized such that the net contribution of second order effects on the x beam size due to the field errors is minimized at the analyzing slit and at the stripper location. This condition is very nearly satisfied, for example, when the error in D1 is $+1 \times 10^{-3}$ per cm and the error in D1′ is -1×10^{-3} per cm, with the pole tip field -0.0284 T for the upstream sextupole and $+0.0283$ T for the downstream sextupole. Second order effects are almost elminated except for a minor centroid shift in the x and x' directions. For an error in D1, only the upstream sextupole needs to be excited, and vice versa for D1′. Figure 16 shows the TURTLE ray tracing results for the above example. It is seen that for a slit opening of 2.8 mm all the rays pass through. The x, x' histogram at the stripper shows little effect due to these errors when corrected by the sextupoles. The (y, y') phase space remains relatively unaffected by any field errors that do not violate the midplane symmetry of the dipoles. In the above calculations no field error was applied to the septum and bump magnets. However, we have shown that errors of the order of 1×10^{-3} per cm in these magnets need no correction.

5.2 Multipole Aberrations in the Quadrupoles

The effects of sextupole, octupole and decapole components have been studied individually for different ratios of the multipole to the quadrupole field. One parameter of importance is $B_N/\left(ga^{N-1}\right)$, where B_N is the pole tip field of the $2N$ multipole (e.g. $N = 3$ for sextupole), g is the quadrupole field gradient and a is its aperture radius. This parameter can also be written R_N/a^{N-2}, where R_N is the ratio of the multipole and quadrupole pole tip fields. The other significant parameter is the phase angle (α_N) of the multipole, where the magnetic scaler potential giving rise to the multipole is $r^N \times \sin(N\theta - \alpha_N)$ (see Reference 5). The multipole effects have been evaluated for $\alpha_N = 0°$ and $180°$. Figure 17 shows the effects of various multipole fields on the (x, x') phase space at the stripper location, for a strength of 1% of the quadrupole field, applied to all the

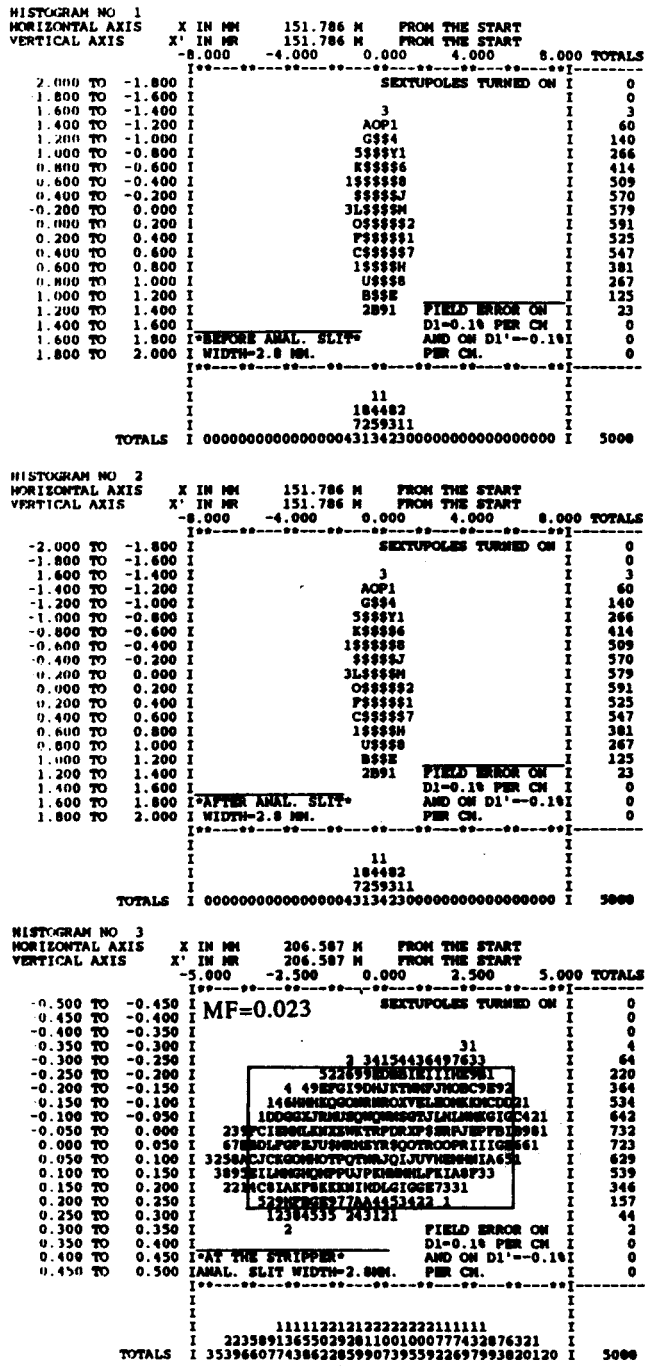

Figure 16. Cancellation of the second order field inhomogeneity error of 0.1% on D1 and −0.1% on D1′ when the sextupole magnets are turned on. Improvements are shown in the histograms; Top: Just before the slit; Middle: Just after the slit and Bottom: At the stripper. Pole tip fields for SX1 and SX2 are −0.0284T and 0.0283T, respectively.

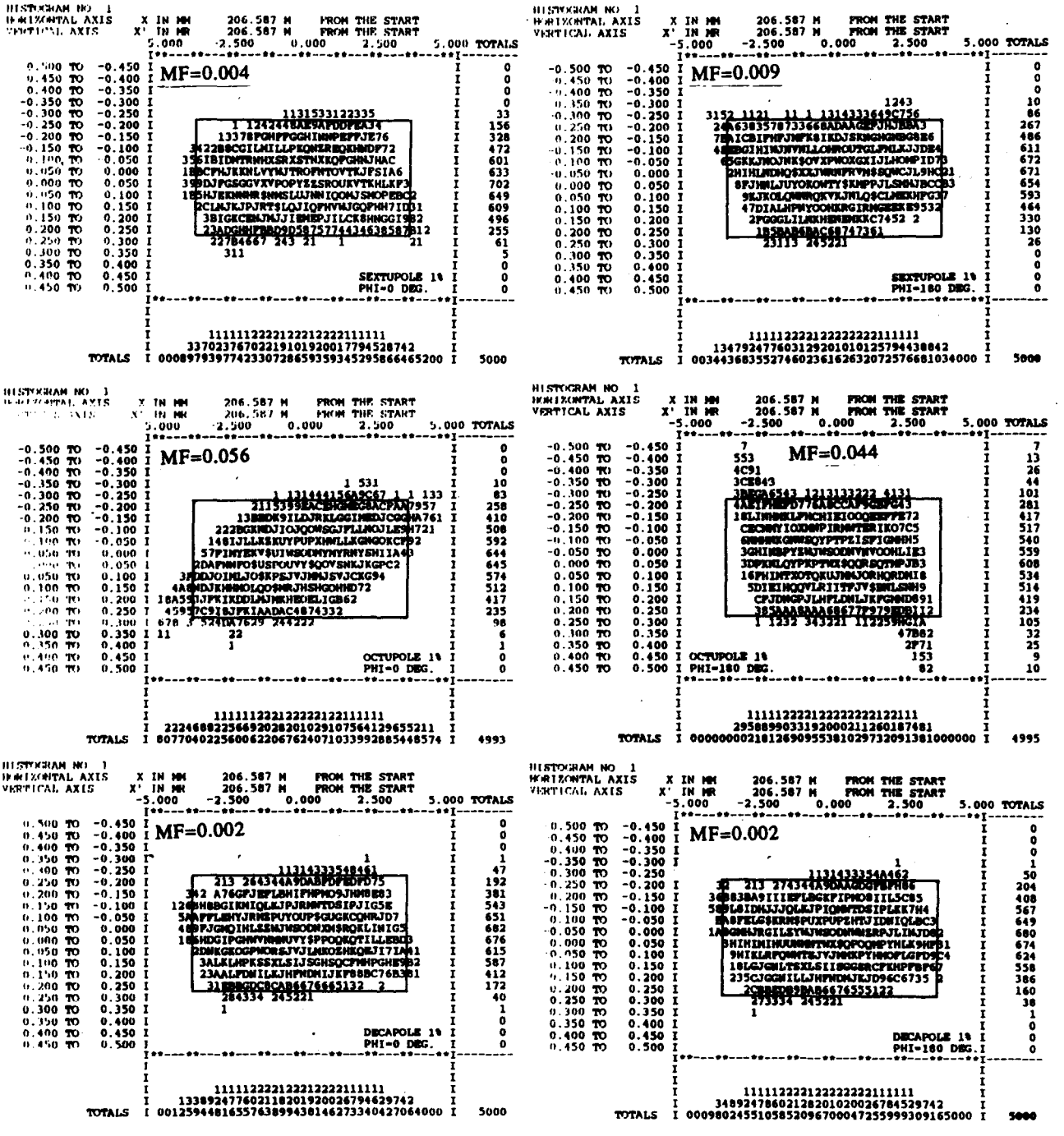

Figure 17. Effect of 1% multipole contents in all the quadrupoles as seen at the stripper in the (x, x') phase space.

quadrupoles of the transfer line. While the deformation of the phase space for even 2% decapole component is not serious, the results indicate that the sextupole component should be limited to about 1%. These conclusions are based on the number of rays falling inside the standard rectangle described above. The effect of a 1% octupole component is much more severe than the other multipoles. Figure 18 shows the effect of reducing the octupole to 0.5% and 0.2%. We judge that approximately 0.2% is a safe upper limit for the octupole component, keeping in view the presence of other errors.

5.3 Quadrupole Magnet Length and Other Errors

Figure 19 shows the histograms at the stripper when effective length of all the quadrupole magnets in the transfer line is 0.1% and 0.2% larger than the nominal values. It is evident that this error should be also controlled. Additional calculations show that slightly higher error may be tolerable for the FODO quadrupoles than for the other quadrupoles. Calculations have also been done to study the effect of misalignment of the slit by up to 0.3 mm (for a total width of 2.4 mm). There is no appreciable change in the histograms at the stripper. Further, an error of up to 0.3° on the edge rotation angles for the dipole magnets on the transfer line also has negligible effect on the phase space quality.

6. CONCLUSIONS

The proposed Linac-LEB transfer line has a flexible optical design. Although designed for a normalized rms emittance of 0.2π mm-mrad in each plane, it can transport and match a beam with almost twice the emittance. Space charge effects of up to 50 mA average beam current have been determined to be tolerable. Longitudinal space charge effects are very significant and strongly influence the position and excitation of the energy compressor RF tank. Transverse and longitudinal phase space matching to the LEB requirements at the stripper position are easy to achieve at any current level studied. Second order effects for perfect magnets are negligible. However, ray tracing calculations for 95% of the beam

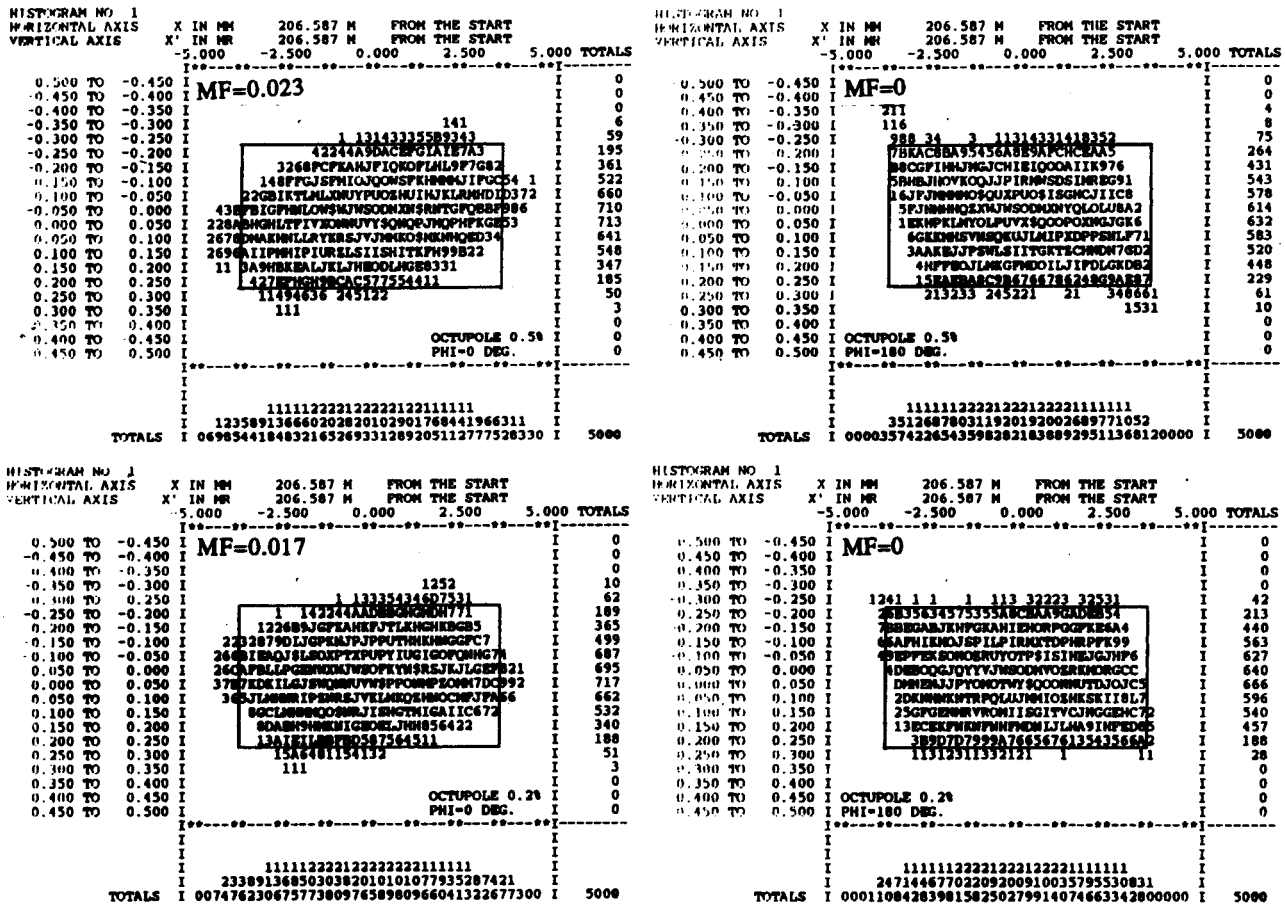

Figure 18. Effect of 0.5% and 0.2% octupole component on all the quadrupoles as seen at the stripper in the (x, x') phase space.

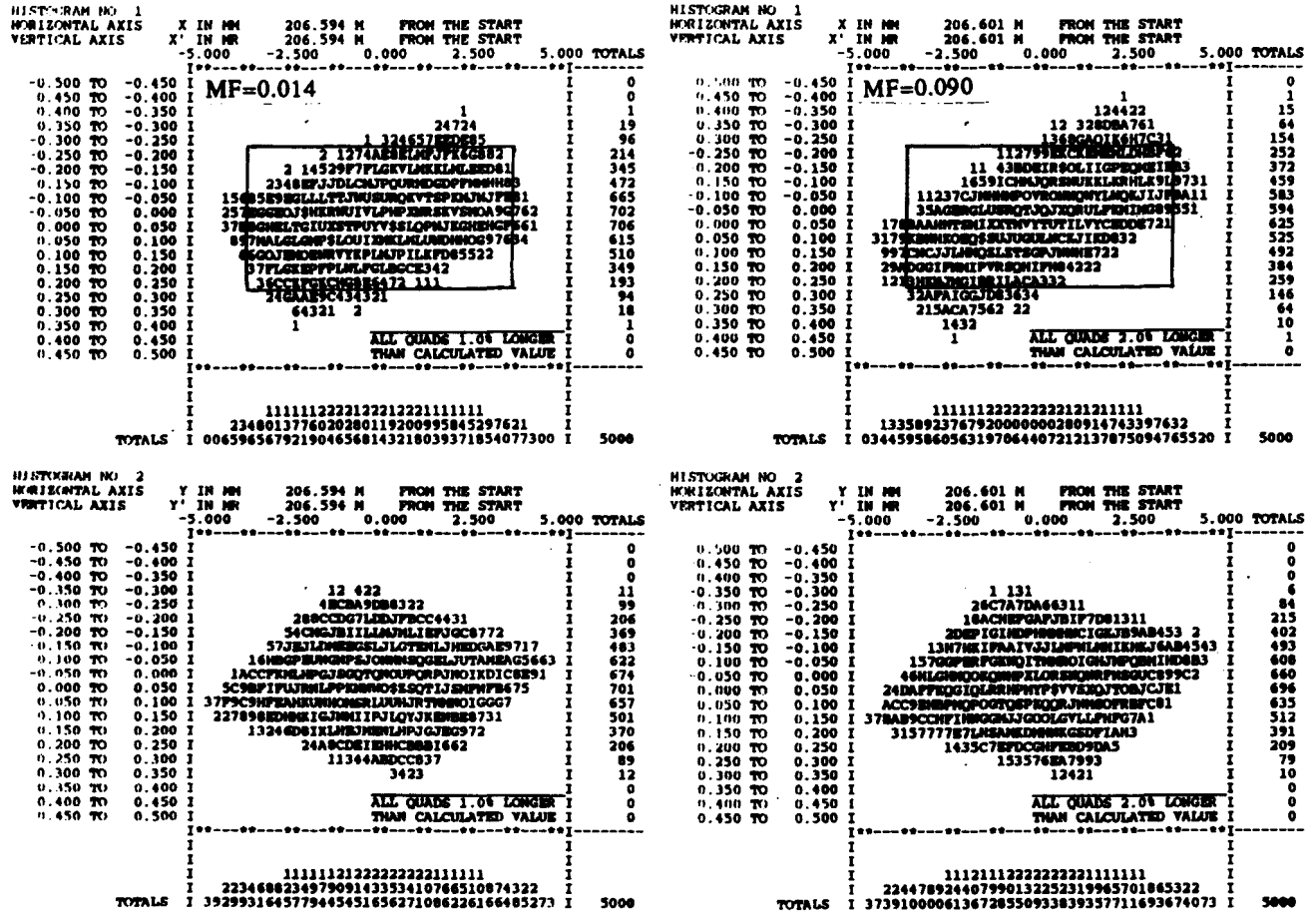

Figure 19. x, x' and y, y' histograms at the stripper when quadrupole effective length for all the magnets differs from the calculated values by: Left: 0.1% and Right: 0.2%.

show that second order field inhomogeneity in the dipole magnets of the order of 1 part in 10^3 per cm over the beam region can be easily corrected using sextupole magnets. The quadrupole magnets also require good field quality control While the sextupole component in the quadrupole field up to about 1% is tolerable, the octupole component should not exceed 0.2%. Stricter tolerances are required for higher emittance beams.

ACKNOWLEDGEMENTS

The authors greatly appreciate very deep interest and many useful suggestions from Jerry Watson during the course of this work. Our sincere thanks are also due to Dave Carey for supplying the TRANSPORT and TURTLE codes and many helpful discussions on the same. Valuable help from Deepak Raparia in running the TRACE 3-D code is thankfully acknowledged.

REFERENCES

1. J.R. Sanford and D.M. Matthews, eds., *Site-Specific Conceptual Design of the Superconducting Super Collider*, Superconducting Super Collider Publication No. SSCL-SR-1056, 163 (July 1990).

2. T.S. Bhatia, Los Alamos National Laboratory, private communication. Also Reference 1, page 81.

3. D.C. Carey, *Third Order TRANSPORT with MAD Input*, Fermi National Accelerator Laboratory Report No. 1546, (September 1988).

4. K.R. Crandall, *TRACE3-D Documentation*, Los Alamos National Laboratory Report No. LA-11054-MS, (August 1987).

5. D.C. Carey, K.L. Brown and Ch. Iselin, *Decay TURTLE—A Computer Program for Simulating Charged Particle Beam Transport Systems, Including Decay Calculations*, Report No. SLAC-246, (March 1982). The code obtained from D.C. Carey and used at SSC was a recent version of TURTLE (without decay calculations) and corresponds to TRANSPORT with MAD input (Reference 3 above).

6. J. Reich and M. Rogge, *The Ion Optical Reference Design of the Beam Transfer Line between JULIC and COSY*, IKP, KFA, Annual Report 1988.

APPENDIX

```
"Linac - LEB transfer line  April 1990                                                  "

     0
15. 1. 'MM' ;                                                                          (   1          )
15. 5. 'MM' ;                                                                          (   2          )
15. 9. 'T' 10. ;                                                                       (   3 ELEMENTS)
16. 3. 1836. 'MASS' ;                                                                  (   4          )
13. 12. ;                                                                              (   5          )
1.  .678 .2170  1.2635  .126824  .682  .02093  1.219 'BEAM' ;                          (   6          )
( Beam energy= 600.0 MeV)                                                              (   6          )
( 0.682 mm = 1.3271 deg of RF phase at 1284.0 MHz and beta =0.79244 )                  (   6 ELEMENTS)
( 0.02093 % of 1.219 GeV/c = 0.20215 MeV)                                              (   6          )
( Longitudinal emittance= 268.1 keV Deg= 0.1854 mm-mrad)                               (   6          )
( Transverse emit. in x-plane= 0.1470 mm-mrad= 0.191 mm-mrad normalized)               (   6          )
( Transverse emit. in y-plane= 0.1600 mm-mrad= 0.208 mm=mrad normalized)               (   6          )
( All emittances values are at the end of tank 59 at energy 604.84 MeV)                (   6 ELEMENTS)
( All emittances are RMS so the sizes are sigmas)                                      (   6          )
( Starting point is the center of an "D" quad at the linac exit)                       (   6          )
( Length of the FODO line is initially taken to be 98 meters)                          (   6          )
( 98 meters required for future upgrade of the linac to 1 GeV)                         (   6          )
9. 11. ;                                                                               (   7 ELEMENTS)
5.0 0.035 -0.50781 15. 'QD/2' ;                                                        (   8          )
3. 2.38 ;                                                                              (   9          )
13. 1. ;                                                                               (  10          )
5.0 0.07 0.50781 15. 'QF' ;                                                            (  11          )
3. 2.38 ;                                                                              (  12 ELEMENTS)
5.0 0.035 -0.50781 15. 'QD/2' ;                                                        (  13          )
13. 1. ;                                                                               (  14          )
9. 0. ;                                                                                (  15          )
13. 4. ;                                                                               (  16          )
5.0 0.035 -0.50781 15. 'QD/2' ;                                                        (  17 ELEMENTS)
3. 2.38 ;                                                                              (  18          )
5.0 0.07  0.50781 15. 'QF' ;                                                           (  19          )
3. 0.2649303 ;                                                                         (  20          )
13. 1. ;                                                                               (  21          )
11. 1.850139 .00062 89.9 233.47 'RF' ;                                                 (  22 ELEMENTS)
13. 1. ;                                                                               (  23          )
3. 0.2649303 ;                                                                         (  24          )
5.0 0.035 -0.50781 15. 'QD/2' ;                                                        (  25          )
13. 1. ;                                                                               (  26          )
9. 8. ;                                                                                (  27 ELEMENTS)
5.0 0.035 -0.50781 15. 'QD/2' ;                                                        (  28          )
3. 2.38 ;                                                                              (  29          )
5.0 0.07  0.50781 15. 'QF' ;                                                           (  30          )
3. 2.38                                                                                (  31          )
5.0 0.035 -0.50781 15. 'QD/2' ;                                                        (  32 ELEMENTS)
9.  0. ;                                                                               (  33          )
13. 1. ;                                                                               (  34          )
5.0 0.035 -0.50781 15. 'QD/2' ;13. 1. ;                                                (  36          )
(Emittance scraper section )                                                           (  36          )
(First aperture hehe, at the exit of an F quad )                                       (  36 ELEMENTS)
3. 9.85 ; 13. 1.; 5.0 .3  .31081 37.5 'Q1' ; 3. .3 ; 5.0 .3  -.30022 37.5 'Q2' ;      (  41          )
13. 1. ; 3. 12. ; -10. -1. 1. 0. 0.001 'R' ; -10. -3. 3. 0. 0.001 'R' ;                (  45          )
13. 1. ; 13. 4. ;                                                                      (  47          )
(Second aperture location )                                                            (  47          )
3. 16. ; 13. 1. ;                                                                      (  49 ELEMENTS)
6. 0. 2. ;                                                                             (  50          )
(Auxiliary transform used to get dispersion )                                          (  50          )
(Achromatic spectrometer)                                                              (  50          )
5.0 .3  -.25513 37.5 'Q3' ; 3. .3 ; 13. 1.; 5.0 .3  .25757 37.5 'Q4' ; 13. 1. ;        (  55          )
3. .5 ;                                                                                (  56 ELEMENTS)
(Introduce sextupole magnets SX1 and SX2)                                              (  56          )
(to correct for the second order field inhomogeneity in D1 and D1')                    (  56          )
18.0  .15  0. 37.5 'SX1' ;                                                             (  57          )
```

```
3. .35 ;                                                                    (  58          )
-10. 3. 3. 1.4 .1 ;                                                         (  59 ELEMENTS)
13. 1.; 13. 48.; 24. 1. 'SPEC';16. 5. 12.5 'GPD1' ;                         (  63          )
2. 3. ;4. 2.0009 6.'D1' ; 2. 3. ;                                           (  66          )
13. 1. ; 3. 9. ; 13. 1. ; 5.0 .3 -.12129 37.5 'Q5' ; 3. 1. ;                (  71          )
5.0 .3 .12129 37.5 'Q6' ; 13. 1. ;3. .5 ; 24. 2. 'SPEC' ;                   (  75          )
-10. -2. 6. 0. .001 'R26' ;                                                 (  76 ELEMENTS)
-10. 1. 1. 0.35  0.02;                                                      (  77          )
-10. 2. 1. 0. .001 'F' ;-10. 4. 3. 0. .001 'F' ;                            (  79          )
13. 1. ;13. 4. ;13. 24. ;                                                   (  82          )
(Maximum dispersion region)                                                 (  82          )
24. 4. 'SPEC' ; 13. 1. ;                                                    (  84 ELEMENTS)
3. .5 ;                                                                     (  85          )
18.0  .15  0. 37.5 'SX2' ;                                                  (  86          )
3. .35 ;                                                                    (  87          )
13. 1. ; 13. 4. ;                                                           (  89          )
(Begin emittance range)                                                     (  89 ELEMENTS)
5.0 .3 .25040 37.5 'Q7' ;3. .3 ;13. 1. ; 5.0 .3 -.22370 37.5 'Q8' ;         (  93          )
13. 1. ;3. 1. ;13. 1. ;3. 10. ;13. 1. ;13. 4. ;                             (  99          )
(Waist location)                                                            (  99          )
-10. 2. 1. 0. .01 'WX' ; -10. 4. 3. 0. .01 'WY' ;                           ( 101          )
3. 10. ;13. 1. ;3. 1. ;                                                     ( 104 ELEMENTS)
(Begin matching section)                                                    ( 104          )
13. 1. ;5.0 .3 .33301 37.5 'Q9' ;3. .3 ; 13. 1. ; 5.0 .3 -.34557 37.5 'Q10' ;  ( 109        )
13. 1. ; 3. 4. ;13. 1. ;                                                    ( 112          )
(Location of beam dump magnet)                                              ( 112          )
3. 2. ;13. 1. ;3. 5. ;13. 1. ;                                              ( 116 ELEMENTS)
5.0 .3 -.39885 37.5 'Q11' ;3. .3 ; 5.0 .3 .39585  37.5 'Q12' ;13. 1. ;      ( 120          )
3. 2.79317 ;13. 1. ;                                                        ( 122          )
20. 180 ;                                                                   ( 123          )
16. 5. 8. 'GPSE' ;2. 8.1159 ; 4. 1.40656 5.6608 'SEPT' ;2. -2.4551 ;        ( 127          )
3. .10009 ;13. 1. ;                                                         ( 129 ELEMENTS)
16. 5. 22. 'GPBU' ;2. 2.4551 ; 4. .60018 2.4551 'BUMP' ; 2. 0. ;            ( 133          )
20. -180. ;                                                                 ( 134          )
3. .1 ; 13. 1. ;                                                            ( 136          )
-10. 2. 1. 0. .0001 'JX' ; -10. 4. 3. 0. .0001 'JY' ;                       ( 138          )
-10. 1. 1. 1.52 .0001 'SX' ;-10. 3. 3. 1.52 .0001 'SY' ; 13. 4. ;           ( 141 ELEMENTS)
(stripper location - match for .3 mm-mrad normalized)                       ( 141          )
(assuming LEB beta function is 10 meters)                                   ( 141          )
SENTINEL

141 ELEMENTS USED OUT OF A MAXIMUM ALLOWABLE 1301
396 NUMBERS USED OUT OF A MAXIMUM ALLOWABLE  5001
```

Linac - LEB transfer line April 1990

```
(   4)  *PMASS *          "MASS"      0.18360E+04
(   6)  *BEAM*            "BEAM"      1.21900 GEV
            0.000 M                   0.0000     0.0000     0.0000 M        0.000     0.000     0.000 DEG
                                                                            0.000   0.678 MM
                                                                            0.000   0.217 MR      0.000
                                                                            0.000   1.263 MM      0.000  0.000
                                                                            0.000   0.127 MR      0.000  0.000  0.000
                                                                            0.000   0.682 MM      0.000  0.000  0.000  0.000
                                                                            0.000   0.021 PC      0.000  0.000  0.000  0.000  0.000
(   8)  *QUAD*            "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
            0.035 M                   0.0000     0.0000     0.0350 M        0.000     0.000     0.000 DEG
(   9)  *DRIFT*                       2.38000 M
            2.415 M                   0.0000     0.0000     2.4150 M        0.000     0.000     0.000 DEG
                                                                            0.000   1.267 MM
                                                                            0.000   0.295 MR      0.919
                                                                            0.000   0.489 MM      0.000  0.000
                                                                            0.000   0.389 MR      0.000  0.000 -0.537
                                                                            0.000   0.707 MM      0.000  0.000  0.000  0.000
                                                                            0.000   0.021 PC      0.000  0.000  0.000  0.000  0.266
(  11)  *QUAD*            "QF  "      0.07000 M         0.50781 T        15.00000 MM   (   -1.72756 M   )
            2.485 M                   0.0000     0.0000     2.4850 M        0.000     0.000     0.000 DEG
(  12)  *DRIFT*                       2.38000 M
            4.865 M                   0.0000     0.0000     4.8650 M        0.000     0.000     0.000 DEG
(  13)  *QUAD*            "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
            4.900 M                   0.0000     0.0000     4.9000 M        0.000     0.000     0.000 DEG
                                                                            0.000   0.312 MM
                                                                            0.000   0.471 MR      0.000
                                                                            0.000   1.057 MM      0.000  0.000
                                                                            0.000   0.152 MR      0.000  0.000  0.000
                                                                            0.000   0.781 MM      0.000  0.000  0.000  0.000
                                                                            0.000   0.021 PC      0.000  0.000  0.000  0.000  0.488
(   8)  *QUAD*            "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
            4.935 M                   0.0000     0.0000     4.9350 M        0.000     0.000     0.000 DEG
(   9)  *DRIFT*                       2.38000 M
            7.315 M                   0.0000     0.0000     7.3150 M        0.000     0.000     0.000 DEG
                                                                            0.000   1.260 MM
                                                                            0.000   0.482 MR      0.970
                                                                            0.000   0.485 MM      0.000  0.000
                                                                            0.000   0.343 MR      0.000  0.000 -0.262
                                                                            0.000   0.889 MM      0.000  0.000  0.000  0.000
                                                                            0.000   0.021 PC      0.000  0.000  0.000  0.000  0.641
(  11)  *QUAD*            "QF  "      0.07000 M         0.50781 T        15.00000 MM   (   -1.72756 M   )
            7.385 M                   0.0000     0.0000     7.3850 M        0.000     0.000     0.000 DEG
(  12)  *DRIFT*                       2.38000 M
            9.765 M                   0.0000     0.0000     9.7650 M        0.000     0.000     0.000 DEG
(  13)  *QUAD*            "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
            9.800 M                   0.0000     0.0000     9.8000 M        0.000     0.000     0.000 DEG
                                                                            0.000   0.678 MM
                                                                            0.000   0.217 MR      0.000
                                                                            0.000   1.264 MM      0.000  0.000
                                                                            0.000   0.127 MR      0.000  0.000  0.000
                                                                            0.000   1.023 MM      0.000  0.000  0.000  0.000
                                                                            0.000   0.021 PC      0.000  0.000  0.000  0.000  0.746
```

@@@@TRANSVERSE BEAM REPEATS ITSELF AFTER EVERY TWO UNIT CELLS.

@@@@LISTING OF THE UNIT CELLS #3 TO #11 HAS BEEN OMITTED HERE BECAUSE THEY ARE REPETITIVE.

@@@@FOLLOWING IS THE FIRST ORDER TRANSFER MATRIX FOR 11 SUCCESSIVE UNIT CELLS.

```
        *TRANSFORM 1*
            -0.00020  -1.44003   0.00000   0.00000   0.00000   0.00000
             0.69443  -0.00020   0.00000   0.00000   0.00000   0.00000
             0.00000   0.00000  -0.00019  -8.33654   0.00000   0.00000
             0.00000   0.00000   0.11995  -0.00020   0.00000   0.00000
             0.00000   0.00000   0.00000   0.00000   1.00000 200.50902
             0.00000   0.00000   0.00000   0.00000   0.00000   1.00000
(  17)  *QUAD*          "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
            53.935 M                 0.0000     0.0000    53.9350 M        0.000     0.000     0.000 DEG
(  18)  *DRIFT*                      2.38000 M
            56.315 M                 0.0000     0.0000    56.3150 M        0.000     0.000     0.000 DEG
(  19)  *QUAD*          "QF  "      0.07000 M         0.50781 T        15.00000 MM   (   -1.72756 M   )
            56.385 M                 0.0000     0.0000    56.3850 M        0.000     0.000     0.000 DEG
(  20)  *DRIFT*                      0.26493 M
            56.650 M                 0.0000     0.0000    56.6499 M        0.000     0.000     0.000 DEG
                                                                         0.000   1.196 MM
                                                                         0.000   0.294 MR     -0.909
                                                                         0.000   0.551 MM      0.000  0.000
                                                                         0.000   0.389 MR      0.000  0.000  0.663
                                                                         0.000   4.463 MM      0.000  0.000  0.000  0.000
                                                                         0.000   0.021 PC      0.000  0.000  0.000  0.000  0.988
(  22)  *ACCEL*         "RF  "      1.85014 M         0.00062     (    1.21900) GEV      89.90000          233.47000
            58.500 M                 0.0000     0.0000    58.5001 M        0.000     0.000     0.000 DEG
                                                                         0.000   0.741 MM
                                                                         0.000   0.291 MR     -0.731
                                                                         0.000   1.163 MM      0.000  0.000
                                                                         0.000   0.392 MR      0.000  0.000  0.936
                                                                         0.000   4.572 MM      0.000  0.000  0.000  0.000
                                                                         0.000   0.011 PC      0.000  0.000  0.000  0.000  0.961
(  24)  *DRIFT*                      0.26493 M
            58.765 M                 0.0000     0.0000    58.7650 M        0.000     0.000     0.000 DEG
(  25)  *QUAD*          "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
            58.800 M                 0.0000     0.0000    58.8000 M        0.000     0.000     0.000 DEG
                                                                         0.000   0.683 MM
                                                                         0.000   0.216 MR      0.022
                                                                         0.000   1.267 MM      0.000  0.000
                                                                         0.000   0.126 MR      0.000  0.000  0.017
                                                                         0.000   4.584 MM      0.000  0.000  0.000  0.000
                                                                         0.000   0.011 PC      0.000  0.000  0.000  0.000  0.961
```

@@@@LISTING OF THE UNIT CELLS #13 TO #20 HAS BEEN OMITTED HERE BECAUSE THEY ARE REPETITIVE.

@@@@FOLLOWING IS THE BEAM MATRIX AT THE END OF THE FODO ARRAY SEGMENT.

```
            98.000 M                 0.0000     0.0000    98.0000 M        0.000     0.000     0.000 DEG
                                                                         0.000   0.683 MM
                                                                         0.000   0.216 MR      0.022
                                                                         0.000   1.267 MM      0.000  0.000
                                                                         0.000   0.126 MR      0.000  0.000  0.017
                                                                         0.000   6.182 MM      0.000  0.000  0.000  0.000
```

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                                                                                  0.000   0.011 PC      0.000  0.000  0.000  0.000  0.979
( 35)  *QUAD*          "QD/2"      0.03500 M        -0.50781 T        15.00000 MM   (    3.42584 M   )
          98.035 M                 0.0000     0.0000    98.0350 M        0.000     0.000     0.000 DEG
                                                                          0.000   0.687 MM
                                                                          0.000   0.298 MR      0.694
                                                                          0.000   1.261 MM      0.000  0.000
                                                                          0.000   0.387 MR      0.000  0.000 -0.945
                                                                          0.000   6.183 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.979
( 37)  *DRIFT*                     9.85000 M
          107.885 M                0.0000     0.0000   107.8850 M        0.000     0.000     0.000 DEG
                                                                          0.000   3.443 MM
                                                                          0.000   0.298 MR      0.990
                                                                          0.000   2.657 MM      0.000  0.000
                                                                          0.000   0.387 MR      0.000  0.000  0.988
                                                                          0.000   6.588 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.981
( 39)  *QUAD*          "Q1  "      0.30000 M         0.31081 T        37.50000 MM   (   -1.68640 M   )
          108.185 M                0.0000     0.0000   108.1850 M        0.000     0.000     0.000 DEG
( 40)  *DRIFT*                     0.30000 M
          108.485 M                0.0000     0.0000   108.4850 M        0.000     0.000     0.000 DEG
( 41)  *QUAD*          "Q2  "      0.30000 M        -0.30022 T        37.50000 MM   (    1.64400 M   )
          108.785 M                0.0000     0.0000   108.7850 M        0.000     0.000     0.000 DEG
                                                                          0.000   2.379 MM
                                                                          0.000   0.305 MR     -0.979
                                                                          0.000   3.943 MM      0.000  0.000
                                                                          0.000   0.187 MR      0.000  0.000 -0.976
                                                                          0.000   6.625 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.982
( 43)  *DRIFT*                    12.00000 M
          120.785 M                0.0000     0.0000   120.7850 M        0.000     0.000     0.000 DEG
                                                                          0.000   1.416 MM
                                                                          0.000   0.305 MR      0.940
                                                                          0.000   1.821 MM      0.000  0.000
                                                                          0.000   0.187 MR      0.000  0.000 -0.882
                                                                          0.000   7.120 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.984
       *TRANSFORM 1*
           -2.06970  -0.86457   0.00000   0.00000   0.00000   0.00000
           -0.39903  -0.64985   0.00000   0.00000   0.00000   0.00000
            0.00000   0.00000  -1.41187   2.89842   0.00000   0.00000
            0.00000   0.00000   0.11368  -0.94165   0.00000   0.00000
            0.00000   0.00000   0.00000   0.00000   0.48876 339.82959
            0.00000   0.00000   0.00000   0.00000  -0.00217   0.53433
( 48)  *DRIFT*                    16.00000 M
          136.785 M                0.0000     0.0000   136.7850 M        0.000     0.000     0.000 DEG
                                                                          0.000   6.231 MM
                                                                          0.000   0.305 MR      0.997
                                                                          0.000   1.627 MM      0.000  0.000
                                                                          0.000   0.187 MR      0.000  0.000  0.850
                                                                          0.000   7.782 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.987
( 50)  *UPDATE*                   R2
( 51)  *QUAD*          "Q3  "      0.30000 M        -0.25513 T        37.50000 MM   (    1.94306 M   )
          137.085 M                0.0000     0.0000   137.0850 M        0.000     0.000     0.000 DEG
( 52)  *DRIFT*                     0.30000 M
          137.385 M                0.0000     0.0000   137.3850 M        0.000     0.000     0.000 DEG
                                                                          0.000   7.860 MM
                                                                          0.000   3.534 MR      1.000
                                                                          0.000   1.358 MM      0.000  0.000
                                                                          0.000   0.656 MR      0.000  0.000 -0.984
                                                                          0.000   7.807 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.987
( 54)  *QUAD*          "Q4  "      0.30000 M         0.25757 T        37.50000 MM   (   -2.02422 M   )
          137.685 M                0.0000     0.0000   137.6850 M        0.000     0.000     0.000 DEG
                                                                          0.000   8.304 MM
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                                                                                  0.000   0.614 MR     -1.000
                                                                                  0.000   1.265 MM      0.000  0.000
                                                                                  0.000   0.128 MR      0.000  0.000  0.118
                                                                                  0.000   7.819 MM      0.000  0.000  0.000  0.000
                                                                                  0.000   0.011 PC      0.000  0.000  0.000  0.000  0.987
( 56)  *DRIFT*                      0.50000 M
          138.185 M                 0.0000     0.0000   138.1850 M        0.000     0.000     0.000 DEG
( 57)  *SEXT*          "SX1 "       0.15000 M         0.00000 T       37.50000 MM
          138.335 M                 0.0000     0.0000   138.3350 M        0.000     0.000     0.000 DEG
( 58)  *DRIFT*                      0.35000 M
          138.685 M                 0.0000     0.0000   138.6850 M        0.000     0.000     0.000 DEG
                                                                                  0.000   7.690 MM
                                                                                  0.000   0.614 MR     -1.000
                                                                                  0.000   1.286 MM      0.000  0.000
                                                                                  0.000   0.128 MR      0.000  0.000  0.215
                                                                                  0.000   7.861 MM      0.000  0.000  0.000  0.000
                                                                                  0.000   0.011 PC      0.000  0.000  0.000  0.000  0.987
( 63)  *HGAP  *        "GPD1"       0.12500E+02
( 64)  *ROTAT*                      3.00000 DEG
          138.685 M                 0.0000     0.0000   138.6850 M        0.000     0.000     0.000 DEG
( 65)  *BEND *         "D1  "       2.00090 M         0.21281 T      0.00000      (    19.107 M   ,   6.000 DEG )
          140.686 M                -0.1047     0.0000   140.6823 M       -6.000     0.000     0.000 DEG
( 66)  *ROTAT*                      3.00000 DEG
          140.686 M                -0.1047     0.0000   140.6823 M       -6.000     0.000     0.000 DEG
                                                                                  0.000   6.464 MM
                                                                                  0.000   0.614 MR     -0.999
                                                                                  0.000   1.358 MM      0.000  0.000
                                                                                  0.000   0.126 MR      0.000  0.000  0.341
                                                                                  0.000   7.978 MM     -0.091  0.112  0.000  0.000
                                                                                  0.000   0.011 PC      0.002  0.019  0.000  0.000  0.983
( 68)  *DRIFT*                      9.00000 M
          149.686 M                -1.0454     0.0000   149.6330 M       -6.000     0.000     0.000 DEG
                                                                                  0.000   0.969 MM
                                                                                  0.000   0.614 MR     -0.959
                                                                                  0.000   2.041 MM      0.000  0.000
                                                                                  0.000   0.126 MR      0.000  0.000  0.780
                                                                                  0.000   8.349 MM      0.034  0.108  0.000  0.000
                                                                                  0.000   0.011 PC      0.122  0.019  0.000  0.000  0.984
( 70)  *QUAD*          "Q5  "       0.30000 M        -0.12129 T       37.50000 MM   (     4.14094 M   )
          149.986 M                -1.0768     0.0000   149.9313 M       -6.000     0.000     0.000 DEG
( 71)  *DRIFT*                      1.00000 M
          150.986 M                -1.1813     0.0000   150.9259 M       -6.000     0.000     0.000 DEG
( 72)  *QUAD*          "Q6  "       0.30000 M         0.12129 T       37.50000 MM   (    -4.24095 M   )
          151.286 M                -1.2127     0.0000   151.2242 M       -6.000     0.000     0.000 DEG
                                                                                  0.000   0.426 MM
                                                                                  0.000   0.484 MR     -0.569
                                                                                  0.000   1.556 MM      0.000  0.000
                                                                                  0.000   0.103 MR      0.000  0.000 -0.033
                                                                                  0.000   8.416 MM      0.350  0.088  0.000  0.000
                                                                                  0.000   0.011 PC      0.407  0.000  0.000  0.000  0.985
( 74)  *DRIFT*                      0.50000 M
          151.786 M                -1.2649     0.0000   151.7215 M       -6.000     0.000     0.000 DEG
                                                                                  0.000   0.350 MM
                                                                                  0.000   0.484 MR     -0.001
                                                                                  0.000   1.555 MM      0.000  0.000
                                                                                  0.000   0.103 MR      0.000  0.000  0.000
                                                                                  0.000   8.436 MM      0.487  0.088  0.000  0.000
                                                                                  0.000   0.011 PC      0.494  0.000  0.000  0.000  0.985
       *TRANSFORM 1*
            0.17875  -1.28595   0.00000   0.00000  -0.03335   8.19567
            0.65399   0.88951   0.00000   0.00000   0.00000   0.00003
            0.00000   0.00000   1.19722  -2.84868   0.00000   0.00000
            0.00000   0.00000   0.01892   0.79026   0.00000   0.00000
            1.00311   1.36436   0.00000   0.00000   0.23810 401.43079
            0.00000   0.00000   0.00000   0.00000  -0.00217   0.53433
       *TRANSFORM 2*
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          -0.62929  12.88478   0.00000   0.00000   0.00000  15.33826
          -0.07005  -0.15473   0.00000   0.00000   0.00000   0.00005
           0.00000   0.00000  -0.80353  13.40835   0.00000   0.00000
           0.00000   0.00000  -0.10765   0.55181   0.00000   0.00000
          -0.10745  -0.23740   0.00000   0.00000   1.00000  55.76700
           0.00000   0.00000   0.00000   0.00000   0.00000   1.00000
( 74)  *DRIFT*                    0.50000 M
          152.286 M              -1.3172     0.0000   152.2187 M       -6.000     0.000     0.000 DEG
                                                                      0.000   0.425 MM
                                                                      0.000   0.484 MR      0.568
                                                                      0.000   1.556 MM      0.000  0.000
                                                                      0.000   0.103 MR      0.000  0.000  0.033
                                                                      0.000   8.457 MM      0.451  0.088  0.000  0.000
                                                                      0.000   0.011 PC      0.407  0.000  0.000  0.000  0.985
( 72)  *QUAD*          "Q6  "     0.30000 M         0.12129 T      37.50000 MM   (   -4.24095 M   )
          152.586 M              -1.3486     0.0000   152.5171 M       -6.000     0.000     0.000 DEG
( 71)  *DRIFT*                    1.00000 M
          153.586 M              -1.4531     0.0000   153.5116 M       -6.000     0.000     0.000 DEG
( 70)  *QUAD*          "Q5  "     0.30000 M        -0.12129 T      37.50000 MM   (    4.14094 M   )
          153.886 M              -1.4844     0.0000   153.8100 M       -6.000     0.000     0.000 DEG
                                                                      0.000   0.968 MM
                                                                      0.000   0.614 MR      0.959
                                                                      0.000   2.041 MM      0.000  0.000
                                                                      0.000   0.126 MR      0.000  0.000 -0.780
                                                                      0.000   8.523 MM      0.205  0.068  0.000  0.000
                                                                      0.000   0.011 PC      0.122 -0.019  0.000  0.000  0.985
( 68)  *DRIFT*                    9.00000 M
          162.886 M              -2.4252     0.0000   162.7607 M       -6.000     0.000     0.000 DEG
                                                                      0.000   6.464 MM
                                                                      0.000   0.614 MR      0.999
                                                                      0.000   1.357 MM      0.000  0.000
                                                                      0.000   0.126 MR      0.000  0.000 -0.341
                                                                      0.000   8.895 MM      0.085  0.064  0.000  0.000
                                                                      0.000   0.011 PC      0.002 -0.019  0.000  0.000  0.986
( 66)  *ROTAT*                    3.00000 DEG
          162.886 M              -2.4252     0.0000   162.7607 M       -6.000     0.000     0.000 DEG
( 65)  *BEND *         "D1  "     2.00090 M         0.21281 T       0.00000      (    19.107 M   ,   6.000 DEG )
          164.887 M              -2.7381     0.0000   164.7360 M      -12.000     0.000     0.000 DEG
( 64)  *ROTAT*                    3.00000 DEG
          164.887 M              -2.7381     0.0000   164.7360 M      -12.000     0.000     0.000 DEG
( 63)  *HGAP  *        "GPD1"     0.12500E+02
                                                                      0.000   7.690 MM
                                                                      0.000   0.614 MR      1.000
                                                                      0.000   1.286 MM      0.000  0.000
                                                                      0.000   0.128 MR      0.000  0.000 -0.215
                                                                      0.000   8.947 MM      0.000  0.000  0.000  0.000
                                                                      0.000   0.011 PC      0.000  0.000  0.000  0.000  0.990
( 85)  *DRIFT*                    0.50000 M
          165.387 M              -2.8420     0.0000   165.2251 M      -12.000     0.000     0.000 DEG
( 86)  *SEXT*          "SX2 "     0.15000 M         0.00000 T      37.50000 MM
          165.537 M              -2.8732     0.0000   165.3718 M      -12.000     0.000     0.000 DEG
( 87)  *DRIFT*                    0.35000 M
          165.887 M              -2.9460     0.0000   165.7142 M      -12.000     0.000     0.000 DEG
                                                                      0.000   8.304 MM
                                                                      0.000   0.614 MR      1.000
                                                                      0.000   1.265 MM      0.000  0.000
                                                                      0.000   0.128 MR      0.000  0.000 -0.118
                                                                      0.000   8.989 MM      0.000  0.000  0.000  0.000
                                                                      0.000   0.011 PC      0.000  0.000  0.000  0.000  0.990
       *TRANSFORM 1*
          11.20511  15.44911   0.00000   0.00000   0.00000   0.00097
           0.81800   1.21707   0.00000   0.00000   0.00000   0.00007
           0.00000   0.00000   0.75870   6.50537   0.00000   0.00000
           0.00000   0.00000  -0.07443   0.67983   0.00000   0.00000
           0.00000   0.00001   0.00000   0.00000   0.12414 429.43964
           0.00000   0.00000   0.00000   0.00000  -0.00217   0.53433
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( 90)  *QUAD*          "Q7  "      0.30000 M         0.25040 T        37.50000 MM   (   -2.08070 M   )
          166.187 M                -3.0084     0.0000   166.0076 M       -12.000     0.000     0.000 DEG
( 91)  *DRIFT*                      0.30000 M
          166.487 M                -3.0707     0.0000   166.3010 M       -12.000     0.000     0.000 DEG
                                                                          0.000   6.851 MM
                                                                          0.000   3.422 MR     -1.000
                                                                          0.000   1.544 MM      0.000  0.000
                                                                          0.000   0.637 MR      0.000  0.000  0.987
                                                                          0.000   9.013 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.990
( 93)  *QUAD*          "Q8  "      0.30000 M        -0.22370 T        37.50000 MM   (    2.22286 M   )
          166.787 M                -3.1331     0.0000   166.5945 M       -12.000     0.000     0.000 DEG
                                                                          0.000   6.259 MM
                                                                          0.000   0.568 MR     -0.999
                                                                          0.000   1.627 MM      0.000  0.000
                                                                          0.000   0.124 MR      0.000  0.000 -0.607
                                                                          0.000   9.026 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.990
( 95)  *DRIFT*                      1.00000 M
          167.787 M                -3.3410     0.0000   167.5726 M       -12.000     0.000     0.000 DEG
                                                                          0.000   5.691 MM
                                                                          0.000   0.568 MR     -0.999
                                                                          0.000   1.556 MM      0.000  0.000
                                                                          0.000   0.124 MR      0.000  0.000 -0.555
                                                                          0.000   9.068 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.990
( 97)  *DRIFT*                     10.00000 M
          177.787 M                -5.4201     0.0000   177.3541 M       -12.000     0.000     0.000 DEG
                                                                          0.000   0.259 MM
                                                                          0.000   0.568 MR     -0.002
                                                                          0.000   1.347 MM      0.000  0.000
                                                                          0.000   0.124 MR      0.000  0.000  0.278
                                                                          0.000   9.483 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.991
       *TRANSFORM 1*
          -0.13976   1.10987   0.00000   0.00000   0.00000   0.00000
          -0.77965  -0.96377   0.00000   0.00000   0.00000  -0.00007
           0.00000   0.00000  -0.15316  10.51265   0.00000   0.00000
           0.00000   0.00000  -0.09708   0.13433   0.00000   0.00000
           0.00000   0.00001   0.00000   0.00000   0.02789 453.09338
           0.00000   0.00000   0.00000   0.00000  -0.00217   0.53433
( 102) *DRIFT*                     10.00000 M
          187.787 M                -7.4992     0.0000   187.1356 M       -12.000     0.000     0.000 DEG
                                                                          0.000   5.690 MM
                                                                          0.000   0.568 MR      0.999
                                                                          0.000   2.068 MM      0.000  0.000
                                                                          0.000   0.124 MR      0.000  0.000  0.780
                                                                          0.000   9.899 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.992
( 104) *DRIFT*                      1.00000 M
          188.787 M                -7.7072     0.0000   188.1137 M       -12.000     0.000     0.000 DEG
                                                                          0.000   6.258 MM
                                                                          0.000   0.568 MR      0.999
                                                                          0.000   2.166 MM      0.000  0.000
                                                                          0.000   0.124 MR      0.000  0.000  0.802
                                                                          0.000   9.941 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.992
( 106) *QUAD*          "Q9  "      0.30000 M         0.33301 T        37.50000 MM   (   -1.57746 M   )
          189.087 M                -7.7695     0.0000   188.4072 M       -12.000     0.000     0.000 DEG
( 107) *DRIFT*                      0.30000 M
          189.387 M                -7.8319     0.0000   188.7006 M       -12.000     0.000     0.000 DEG
                                                                          0.000   4.782 MM
                                                                          0.000   3.454 MR     -1.000
                                                                          0.000   2.886 MM      0.000  0.000
                                                                          0.000   1.578 MR      0.000  0.000  0.999
                                                                          0.000   9.966 MM      0.000  0.000  0.000  0.000
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                                                                                  0.000   0.011 PC      0.000  0.000  0.000  0.000  0.992
( 109)  *QUAD*          "Q10 "      0.30000 M        -0.34557 T        37.50000 MM   (    1.42198 M   )
           189.687 M               -7.8943     0.0000   188.9941 M       -12.000     0.000     0.000 DEG
                                                                          0.000   4.206 MM
                                                                          0.000   0.451 MR     -0.997
                                                                          0.000   3.054 MM      0.000  0.000
                                                                          0.000   0.481 MR      0.000  0.000 -0.994
                                                                          0.000   9.978 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.992
( 111)  *DRIFT*                      4.00000 M
           193.687 M               -8.7259     0.0000   192.9067 M       -12.000     0.000     0.000 DEG
                                                                          0.000   2.412 MM
                                                                          0.000   0.451 MR     -0.991
                                                                          0.000   1.163 MM      0.000  0.000
                                                                          0.000   0.481 MR      0.000  0.000 -0.958
                                                                          0.000  10.145 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.992
( 113)  *DRIFT*                      2.00000 M
           195.687 M               -9.1418     0.0000   194.8630 M       -12.000     0.000     0.000 DEG
                                                                          0.000   1.523 MM
                                                                          0.000   0.451 MR     -0.977
                                                                          0.000   0.367 MM      0.000  0.000
                                                                          0.000   0.481 MR      0.000  0.000 -0.416
                                                                          0.000  10.228 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.992
( 115)  *DRIFT*                      5.00000 M
           200.687 M              -10.1813     0.0000   199.7537 M       -12.000     0.000     0.000 DEG
                                                                          0.000   0.833 MM
                                                                          0.000   0.451 MR      0.920
                                                                          0.000   2.274 MM      0.000  0.000
                                                                          0.000   0.481 MR      0.000  0.000  0.989
                                                                          0.000  10.436 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.993
( 117)  *QUAD*          "Q11 "      0.30000 M        -0.39885 T        37.50000 MM   (    1.22568 M   )
           200.987 M              -10.2437     0.0000   200.0471 M       -12.000     0.000     0.000 DEG
( 118)  *DRIFT*                      0.30000 M
           201.287 M              -10.3061     0.0000   200.3406 M       -12.000     0.000     0.000 DEG
( 119)  *QUAD*          "Q12 "      0.30000 M         0.39585 T        37.50000 MM   (   -1.33539 M   )
           201.587 M              -10.3684     0.0000   200.6340 M       -12.000     0.000     0.000 DEG
                                                                          0.000   1.583 MM
                                                                          0.000   0.098 MR     -0.310
                                                                          0.000   1.568 MM      0.000  0.000
                                                                          0.000   0.104 MR      0.000  0.000 -0.194
                                                                          0.000  10.474 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.993
( 121)  *DRIFT*                      2.79317 M
           204.380 M              -10.9492     0.0000   203.3661 M       -12.000     0.000     0.000 DEG
                                                                          0.000   1.520 MM
                                                                          0.000   0.098 MR     -0.143
                                                                          0.000   1.538 MM      0.000  0.000
                                                                          0.000   0.104 MR      0.000  0.000 -0.008
                                                                          0.000  10.590 MM      0.000  0.000  0.000  0.000
                                                                          0.000   0.011 PC      0.000  0.000  0.000  0.000  0.993
( 123)  *SROT*                     180.00000 DEG
           204.380 M              -10.9492     0.0000   203.3661 M       -12.000     0.000   180.000 DEG
( 124)  *HGAP  *        "GPSE"      0.80000E+01
( 125)  *ROTAT*                      8.11590 DEG
           204.380 M              -10.9492     0.0000   203.3661 M       -12.000     0.000   180.000 DEG
( 126)  *BEND *         "SEPT"      1.40656 M         0.28561 T         0.00000     (    14.236 M   ,   5.661 DEG )
           205.787 M              -11.1732     0.0000   204.7542 M        -6.339     0.000   180.000 DEG
( 127)  *ROTAT*                     -2.45510 DEG
           205.787 M              -11.1732     0.0000   204.7542 M        -6.339     0.000   180.000 DEG
( 128)  *DRIFT*                      0.10009 M
           205.887 M              -11.1843     0.0000   204.8536 M        -6.339     0.000   180.000 DEG
                                                                          0.000   1.520 MM
                                                                          0.000   0.098 MR     -0.047
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                                                                                  0.000   1.522 MM      0.000  0.000
                                                                                  0.000   0.105 MR      0.000  0.000 -0.007      '
                                                                                  0.000  10.654 MM     -0.008  0.114  0.000  0.000
                                                                                  0.000   0.011 PC      0.006  0.114  0.000  0.000  0.993
( 130)  *HGAP  *          "GPBU"      0.22000E+02
( 131)  *ROTAT*                       2.45510 DEG
           205.887 M                 -11.1842     0.0000   204.8537 M        -6.339     0.000   180.000 DEG
( 132)  *BEND *           "BUMP"      0.60018 M          0.29030 T        0.00000      (    14.007 M   ,   2.455 DEG )
           206.487 M                 -11.2377     0.0000   205.4514 M        -3.884     0.000   180.000 DEG
( 133)  *ROTAT*                       0.00000 DEG
           206.487 M                 -11.2377     0.0000   205.4514 M        -3.884     0.000   180.000 DEG
( 134)  *SROT*                       -180.00000 DEG
           206.487 M                 -11.2377     0.0000   205.4514 M        -3.884     0.000     0.000 DEG
( 135)  *DRIFT*                       0.10000 M
           206.587 M                 -11.2445     0.0000   205.5512 M        -3.884     0.000     0.000 DEG
                                                                                  0.000   1.520 MM
                                                                                  0.000   0.098 MR     -0.001
                                                                                  0.000   1.520 MM      0.000  0.000
                                                                                  0.000   0.105 MR      0.000  0.000  0.001
                                                                                  0.000  10.684 MM      0.008 -0.163  0.000  0.000
                                                                                  0.000   0.011 PC     -0.012 -0.162  0.000  0.000  0.993
        *TRANSFORM 1*
             2.15913   1.88551   0.00000   0.00000   0.00359  -0.88352
            -0.03891   0.42918   0.00000   0.00000   0.00307  -0.75434
             0.00000   0.00000   0.96922  -7.10265   0.00000   0.00000
             0.00000   0.00000   0.04947   0.66923   0.00000   0.00000
             0.31125   0.19522   0.00000   0.00000  -0.20489 510.30127
             0.00000   0.00000   0.00000   0.00000  -0.00217   0.53433

        *LENGTH*        206.58687 M
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