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Author GM Stinson		*Page* 1 *of* 22
Subject A preliminary study of beam transport to the ISAC-II experimental area		

1. Introduction

An expansion of the present ISAC-I has been approved. This expansion is called ISAC-II and will accelerate ions to energies up to 6.5 MeV/u. Preliminary sketches of possible beam-transport configurations to the experimental hall have been made. Based on these sketches, more concrete preliminary designs have been made. These latter are the subject of this report.

2. Background

Before discussing these preliminary designs it is thought best to lay the groundwork upon which the designs are based. This is done in this section.

2.1 Basic relations

From the equation of motion of an ion of mass m_i, charge Q_i and momentum p_i in a constant magnetic field B we have the relation

$$p_i = Q_i\,(B\,\rho)_i$$

where ρ is the radius of curvature of the ion's trajectory. Writing Q_i in terms of the (absolute value of the) electron charge

$$Q_i = q_i \times 1.602 \times 10^{-19} \text{ Coulombs},$$

allows the previous relation to be written as

$$\begin{aligned} p_i\,c &= q_i \times 1.602 \times 10^{-19} \times (B\rho)_i \times 2.998 \times 10^{8} \text{ J} \\ &= 0.2998 \times q_i \times (B\rho)_i \text{ GeV} \end{aligned}$$

or

$$\boxed{p_i = 0.2998\,q_i\,(B\rho)_i \text{ GeV/c}}$$

with B measured in Tesla and ρ in m. For use here it is more useful to rewrite this as

$$\boxed{(B\rho)_i[\text{T-m}] = \frac{3.3356}{q_i}\,p_i[\text{GeV/c}]}$$

We now consider an ion of mass A_i amu accelerated to an energy of ϵ GeV/amu; its final energy is

$$T_i = (A_i \text{ amu})(\epsilon \text{ GeV/amu}) = \epsilon A_i \text{ GeV}\ .$$

Then, taking its rest mass to be

$$E_{i_0} = (A_i \text{ amu})(0.9315 \text{ GeV/amu}) = 0.9315 A_i \text{ GeV}\ ,$$

the momentum of the accelerated ion is

$$p_i = T_i\sqrt{1 + \frac{2\,E_{i_0}}{T_i}} = \epsilon A_i\sqrt{1 + \frac{2(0.9315A_i)}{\epsilon A_i}} = A_i\sqrt{\epsilon(\epsilon + 1.863)} \text{ GeV/c}\ ,$$

and the momentum of an equivalent proton is then

$$p_p = \frac{p_i}{q_i} = \frac{A_i}{q_i}\sqrt{\epsilon(\epsilon + 1.863)} \text{ GeV/c}\ .$$

2.2 Design data

R. Laxdal[1)] gives the following data for two of the ions to be extracted beam from the ISAC-II accelerators.

A_i (amu)	8	150
q_i	3	21
A_i/q_i	3	7
ϵ (GeV/amu)	0.022	0.009
Normalized emittance (mm-mr)	$0.2\,\pi$	$0.2\,\pi$

Using the relationships from §2.1 we calculate the following quantities.

A_i (amu)	8	150
E_{i_0} (GeV)	7.452	139.725
T_i (GeV)	0.176	1.350
p_i (GeV/c)	1.62914	19.46998
p_p (GeV/c)	0.54305	0.92714
$(B\,\rho)_i$ (T-m)	1.81138	3.09257
γ	1.02362	1.00966
β	0.21357	0.13801
Emittance (π mm-mr)	0.93645	1.44916

In order to accommodate the most rigid beam and the largest emittance, the following parameters have been used in the design of the beam lines that are discussed below.

$(B\,\rho)_{max}$	3.10 T-m
p_p	0.929368 GeV/c
T_p	382.367 MeV
Emittance	1.45π mm-mr

2.3 Design philosophy

The following sections discuss possible beam lines to the experimental target that have been design ed according to the following philosophy.

It has been assumed that accelerated beam is transported to the experimental areas in an east-west series of unit sections. Each of the proposed four areas is reached by an achromatic *D-Q-D* section in which each dipole *D* deflects the beam through 45°. The proposal is to insert the first dipole of an achromatic section such that its crossover point—the point of intersection of an incoming and an outgoing trajectory—coincides with the midpoint of an east-west unit section. As presently envisaged, the unit sections are each of the order of 8 m or 9 m in length. This requires that dipoles be designed such that they can be inserted into each unit section.

The following subsection discusses the selection of an appropriate design for a dipole for the achromatic sections.

2.4 Dipole selection

Each of the proposed beam lines to experimental locations requires two 45° dipoles and each beam line is required to be achromatic. Because space in the experimental hall is limited, it is required that the achromatic sections of beam line be short. To this end an estimate of some of the parameters required of the magnets is necessary.

The choice of the air gap of each of the dipoles will depend primarily on the emittance that is expected to be transmitted. For field calculations we assume an air gap of the dipoles of 0.07620 m and a maximum current of approximately 500 A. With these assumptions a quick, crude estimate of the parameters of the dipoles as a function of field was made. The results are tabulated below; the parameters that are tabulated are defined as follows.

$$\begin{aligned}
\rho\ (\mathrm{m}) &= 33.356\, p(\mathrm{GeV/c})/B(\mathrm{kG}) = \text{radius of curvature of the central trajectory,}\\
s\ (\mathrm{m}) &= \rho\,\theta = \text{arc length of the central trajectory,}\\
L_{eff}\ (\mathrm{m}) &= 2\,\rho \sin(\theta/2) = \text{straight-line effective length of the dipole,}\\
x\ (\mathrm{m}) &= \rho \tan(\theta/2) = \text{distance from the crossover point to the effective edge of the dipole,}\\
\Delta\ (\mathrm{m}) &= \rho[1-\cos(\theta/2)] = \text{maximum deflection from a line joining the entry and exit points}\\
&\quad \text{of the trajectory,}\\
NI/\text{pole (A-t)} &= 1.1[B(T)g(\mathrm{m})]/2\mu_0 = \text{Ampere-turns per pole,}\\
\text{Turns/pole} &= \text{number of turns/pole required for } I = 500 \text{ A.}
\end{aligned}$$

Field (kG)	ρ (m)	Arc (m)	L_{eff} (m)	x (m)	Δ (m)	NI/pole (A-t)	Turns /pole
10.0	3.10000	2.43473	2.37264	1.28406	0.23597	33,351	67
11.0	2.81818	2.21340	2.15694	1.16733	0.21452	36,687	74
12.0	2.58333	2.02895	1.97720	1.07005	0.19665	40,022	81
13.0	2.38462	1.87287	1.82511	0.98774	0.18152	43,357	87
14.0	2.21429	1.73910	1.69474	0.91719	0.16855	46,692	94
15.0	2.06667	1.62316	1.58176	0.85604	0.15732	50,027	101

The proposal is to insert the first dipole of an achromatic section such that its crossover point coincides with the midpoint of an east-west unit section. This means that the distance between the effective edge of the upstream quadrupole of a unit section and that of the first dipole of an achromatic section must be such that there is sufficient space for vacuum vessels and any necessary diagnostics to be installed. Each of the unit sections discussed below has a drift length of 2×1.575 m between the downstream edge of an upstream quadrupole doublet and the upstream edge of its downstream doublet in order that the overall length of the system be 8 m. In order to allow sufficient space for vacuum and diagnostics components, at least 0.6 m of free space must be available. From the above table we see that this requires a dipole field of at least 13 kG.

We prefer not to run a (conventional) dipole at more than 14 kG. If it is considered unlikely that the highest energy particles will not be used too often, the dipole design could be for a higher field. However, for the designs discussed below, a dipole field of 14 kG was used.

Although a detailed conceptual design for these dipoles has not been completed, an estimate of their weights has been made. As noted above, the dipole gap used in the calculations was 3 inches (7.62 cm). A rough estimate of the weight of a dipole with this gap running at an air-gap field of 14 kG is 40,000 lbs. If the gap can be reduced to 2.2 inches (5.6 cm), an estimated weight of a dipole is 20,000 lbs. We give these figures so that provision may be made for appropriate lifting apparatus may be made during the planning of the building. See, however, §5.2.

We continue with a description of the beam-line configurations that have been made to date.

3. The unit sections

The proposed east-west section of the beam line comprises a series of unit sections. Two such sections have been investigated, although in principle they are equivalent.

The first consists of a d-Q-d-d-Q-d section in which Q represents a quadrupole doublet and d represents a drift space. Each quadrupole of the doublet is of the CRNL L1 type with an effective length of 0.266 m and a bore of 52 mm. The separation between the effective edges of two adjacent quadrupoles has been taken as 0.318 m and the distances d have been chosen to be 1.575 m so that the overall length of a unit section is 8.0 m.

It is assumed that this line will operate in waist-to-waist transport and that the initial beam size is ± 1 mm in each of the horizontal and vertical planes. The TRANSPORT input for such a section is given in table 1a and figure 1a shows the computed beam envelope for an emittance of 1.45π mm-mr. Note that in principle all quadrupoles could be powered by a single power supply. In practice, the horizontally and vertically focussing quadrupoles normally would be decoupled.

The second unit section is identical to the first except that each quadrupole doublet is replaced by a triplet. Because of the addition of two quadrupoles and two inter-quadrupole drift spaces, the overall length of this system becomes 9.168 m if we require that the drift distance d remain at 1.575 m. TRANSPORT input for this section is given in table 1b and figure 1b shows the computed beam envelope for an emittance of 1.45π mm-mr. Note that the outer quadrupoles of each triplet are equally powered.

4. Beam transport to an experimental target

The beam transport discussed here can be thought of as consisting of two independent sections—the first bringing the beam to an achromatic double focus and the second transporting that beam to an experimental location. The achromatic section has been designed to produce an achromatic double focus with (an absolute value of) magnification of unity in each of the horizontal and vertical planes. The section transporting beam to a target has been designed similarly with a double focus and (an absolute value of) magnification of unity in each of the horizontal and vertical planes at the target. This latter section may be configured with two quadrupole doublets or with a single triplet. We consider each configuration separately below.

4.1 The achromatic section

The achromatic section used in the designs presented here is a simple D-Q-D system. The dipoles D are conventional rectangular H-frame magnets that are operated at fields of 14 kG. Their parameters are listed in the table in §2.4 above. The achromatic quadrupole Q is a CRNL L1 quadrupole that is centered between the two dipoles. This configuration is used throughout this report.

4.2 A beam transport line using quadrupole doublets

To produce the doubly-achromatic double-focus at the location $F1$ the above achromatic section is placed between two doublets that are operated in mirror symmetry. The outer, horizontally-focussing quadrupoles operate at the same fields and could be powered by a single power supply. Similarly, the inner, vertically-focussing quadrupoles are operated at identical fields and could be powered by a second power supply.

Following the achromatic focus, a two doublet, mirror-symmetric section provides a double focus with a magnification of (an absolute value of) unity at the experimental target $F2$. The distance from the last quadrupole to the experimental target has been taken to be approximately 1.5 m in order to allow the installation of experimental equipment.

TRANSPORT input for this configuration is given in table 2; table 3 lists the overall transfer matrices from the upstream waist of the east-west line to the achromatic and target foci. Figure 2 shows the beam envelopes for this particular design. Because of the unit magnification of the two sections, the beam size at the each of the foci is ± 1 mm in each of the horizontal and vertical planes.

From preliminary sketches of the experimental area it is estimated that the perpendicular distance from the east-west beam line to a target location is shown to be approximately 11 m. With this particular design that distance is found to be 11.9 m. Thus, relative to the present sketches, the three eastmost targets are shifted north by approximately 1 m.

If this distance of 11.9 m is too long, it may be shortened by changing the distance between the last two doublets from the 1 m indicated in table 2 to a standard quadrupole separation of 0.318 m. No changes to the quadrupole settings are required to maintain the desired beam size at the target. With this minor change, the perpendicular distance is shortened to 11.2 m, roughly the same as in the preliminary sketches. A plot of the expected beam envelopes along a shortened line is shown in figure 3.

4.3 A modification of the above beam line

A criticism of the lines discussed above may be that the beam undergoes large excursions in the horizontal plane. This certainly is true but it may be corrected by undoing the symmetry of the achromatic portion of the beam line by replacing the doublet downstream of the last dipole with a triplet. The following unit-magnification section is unmodified.

Table 4 lists TRANSPORT input for this modification. Beam profiles along this modified line are shown in figure 4.

The addition of another quadrupole and inter-quadrupole space will increase the perpendicular distance from the east-west beam line to the target location. In this case, that distance is increased to approximately 12.5 m or 1.5 m further north than is shown in the preliminary sketches. Again, the spacing between the last two quadrupole doublets could be shortened as indicated above. This would reduce the perpendicular distance to a more manageable value of approximately 11.8 m.

4.4 A beam line using quadrupole triplets only

If the unit sections of the east-west beam line are composed of quadrupole triplets, similar triplets can be used in the achromatic section of the beam line. Listed in table 5 is the TRANSPORT input for such a beam line. Figure 5 shows the beam envelopes along the beam line.

From figure 5 it is seen that the extremes of the beam envelopes are approximately identical in each of the horizontal and vertical planes. Thus the use of a triplet unit section not only provides a 'nicer' beam envelope in the beam line to a target location but also in the east-west line as well (refer to figure 1b). However, this configuration—as with the configuration of §4.3 above—also places the target at a perpendicular distance of 12.5 m from the east-west line. However, by reducing the spacing of the two doublets upstream of the second focus, this distance can be reduced to approximately 11.8 m.

4.5 A beam line using quadrupole doublets and a final quadrupole triplet

All of the above variations on a theme have used two quadrupole doublets to transport beam from the first focus to the second. Rather than using doublets, a quadrupole triplet could be used.

Table 6 lists TRANSPORT input for a beam line that uses quadrupole doublets in the east-west line and the achromatic section of the transport line to the targets and a quadrupole triplet to transport beam from the first to the second focus of the experimental line. Figure 6 shows the beam envelopes along such a beam line.

This particular line suffers from the same problem as that discussed in §4.2—that is, the horizontal beam envelope is large in places. However, as listed in table 5, the target is located a perpendicular distance of 10.9 m from the east-west transfer line. Further, with the use of the triplet between the two foci it is possible to increase the distance from the target to the upstream quadrupole to 1.65 m.

4.6 A beam line using quadrupole triplets throughout

The horizontal beam problem discussed above can be alleviated if quadrupole triplets are used throughout the beam line. TRANSPORT input for such a system in given in table 7 and beam envelopes along the line are shown in figure 7.

It is noted again in figure 7 that the use of quadrupole triplets produces beam envelopes that have approximately the same extrema in each of the horizontal and vertical planes. In addition, this beam line puts the target at a perpendicular distance of 11.0 m from the east-west transfer line.

5. Selection of the air gap of a dipole

If it is assumed that a beam line to an experimental target will be similar to those discussed above, a reasonable estimate of the air gap of a dipole may now be made. We begin by considering the vertical beam size predicted from the optics.

5.1 Gap size as required by the optics of the beam line

The vertical half-width of the beam that is predicted by the above studies is approximately ± 6 mm for an emittance of 1.45π mm-mr. To be slightly conservative we will use a figure of ± 7.5 mm. The gap of a vacuum chamber should be at least twice the total beam height. Thus we take an optical requirement of the beam height to be 30 mm which we round up to 1.25 inches.

To this we must add the twice the thickness of the vacuum vessel. This thickness is determined by how much deflection can be tolerated in the upper and lower plates of the vessel.

5.2 Deflection of the vacuum vessel

The length of the vacuum vessel will be of the order of the effective length of the dipole, in this case approximately 1.8 m or 72 inches. The width of the pole of a dipole is nominally calculated from

$$\text{Pole width} \;=\; \text{Maximum beam width} + 2(\text{Gap}) + \Delta$$

where Δ has been defined in §2.4. From the figures shown here, the maximum width of the beam in the dipoles is of the order of ± 13 mm leading to a total width of approximately 30 mm. For our purposes we shall take the (horizontal) beam width to be 30 mm nominally and, as above, round this up to 1.25 inches. Thus we take the flat width of a pole to be

$$\text{Flat width of pole} \;=\; 1.25\text{ in.} + 2(1.25\text{ in.}) + 6.64\text{ in.} \;=\; 10.39\text{ in.}$$

We take

$$\text{Flat width of pole} \;=\; 10.5\text{ inches.}$$

[To find the physical width of the pole we must add (what has become) a canonical shim to each pole side. This adds a step 0.25 inch long, a 0.625 inch flat, a 0.625 inch chamfer, and a 0.5 inch taper to the pole root to each side of the pole. Thus the physical pole width is nominally 4 inches wider than the pole flat.]

The deflection δ of a rectangular plate with all four sides fixed and with a uniformly distributed load is given in ref[2)]

$$\delta_2 \;=\; k_1 \frac{w\,\ell^4}{E\,t^2}$$

where w is the load in lb/in^2, ℓ is the short dimension of the plate, E is Young's modulus for the material, t in the plate thickness in inches, and k_1 is a constant that depends on the ratio of the long side of the plate L to the shorter side ℓ. In our case with $L = 72$ inches and $\ell = 10.5$ inches, $L/\ell = 6.85$ and the tabulated value of k_1 is 0.028 for a ratio 4, the highest ratio for which a value is tabulated. In ref[3] an alternate expression,

$$\delta_3 \;=\; \frac{0.0284\, w\, \ell\, L}{E\, t^3 \left[\dfrac{L}{\ell^3} + \dfrac{1.056\, \ell^2}{L^4}\right]}$$

is given and it is easily seen that the above two expressions produce the same value of δ for $L/\ell = \alpha \gg 1$.

Figure 8 is a plot of the predicted maximum deflection of the top and bottom plates of the vacuum vessel according to the expression for δ_2. Two curves are shown. The solid curve is for the case of a pole that has a flat width of 10.5 inches and a base width of 14.5 inches. This is the case developed above and assumes that the vacuum vessel lies between the side shims of the pole.

The dotted curve is for a pole with a flat portion 15 inches wide. We show this to emphasize that if it is necessary to increase the pole width either for magnetic (field uniformity) and/or optical (increased emittance) reasons, the required thickness of the top and bottom plates of the vacuum vessel is dramatically affected. Thus, for example, if a deflection of 0.01 inch (0.25 mm) is acceptable then a plate thickness of approximately 0.25 inch would appear to be satisfactory for a pole flat of 10.5 inches. If the flat portion of the pole is required to be 15 inches, the thickness of the vacuum vessel is required to roughly double.

If a dipole air gap of 5.0 cm (1.47 inches for optics + 0.50 inches for vacuum vessel thickness = 1.97 inches) is chosen and the coil is taken as an 8×8 array of 0.516 inch conductor carrying 500 A, a recalculation of dipole parameters as in §2.4 predicts a magnet weight of approximately 25,000 lbs. This weight might be reduced if the pole were curved so as to follow the trajectory of the beam. Further investigation is required to ascertain that this would be the case. In any case, it appears that provision for dipoles weighing in the order of 20,000 lbs should be made.

6. Discussion

This report has presented preliminary calculations for an east-west transport line and for beam delivery to the ISAC-II targets. For each of the above lines several variations on a theme have been proffered.

Arising from this study are several questions that need to be answered. Among these are the following.

1. Is the emittance of 1.45π mm-mr that was used in these calculations adequate? Should larger or smaller emittances be considered? The vertical emittance is an important parameter in defining the size of the magnet gap. Are we sure that the vertical emittance is adequate?
2. The size and weight of the dipoles will depend critically on the gap and pole widths required. The latter strongly depends on the field uniformity required. What is considered to be a reasonable field uniformity to demand and over what volume of field?
3. Has consideration been given to the use of superconducting dipoles? Should they be considered?

References

1. R. E. Laxdal, *Private communication*, TRIUMF, August, 2001.
2. E. A. Avallone and T. Baumeister, Eds., *Marks' Standard Handbook for Mechanical Engineers*, Ninth edition, p. 5-53, McGraw-Hill Book Co.
3. *Machinery's Handbook, 20th edition*, p. 444, Industrial Press Inc. NY, (1976).

Table 1a

TRANSPORT input for a unit section using doublets

```
'ISAC II 8-M UNIT SECTION - D-QH-QV-D-D-QH-QV-D - 0.266 M QUADS - 01/08/28'
 0
13.                 12.00000;
 1.0    'BEAM'       0.10000     1.45000    0.10000    1.45000    0.0    0.10000    0.93000;
 3.0    'D1 '        1.57500;
 5.00   'Q1 '        0.26600     3.26217    2.54000;
 3.0                 0.31800;
 5.00   'Q2 '        0.26600    −3.26217    2.54000;
 3.0    'D3 '        1.57500;
 3.0    'MID '       0.00001;
 3.0    'D4 '        1.57500;
 5.00   'Q3 '        0.26600     3.26217    2.54000;
 3.0                 0.31800;
 5.00   'Q4 '        0.26600    −3.26217    2.54000;
 3.0    'D6 '        1.57500;
SENTINEL
SENTINEL
```

Table 1b

TRANSPORT input for a unit section using triplets

```
'ISAC II 9-M UNIT SECTION - TRIPLETS - 0.266 M QUADS - 01/08/28'
 0
13.                 12.00000;
 1.0    'BEAM'       0.10000     1.45000    0.10000    1.45000    0.0    0.10000    0.93000;
 3.0    'D1 '        1.57500;
 5.00   'Q1 '        0.26600     2.27109    2.54000;
 3.0                 0.31800;
 5.00   'Q2 '        0.26600    −4.11151    2.54000;
 3.0                 0.31800;
 5.00   'Q3 '        0.26600     2.27109    2.54000;
 3.0    'D3 '        1.57500;
 3.0    'MID '       0.00001;
 3.0    'D4 '        1.57500;
 5.00   'Q4 '        0.26600     2.27109    2.54000;
 3.0                 0.31800;
 5.00   'Q5 '        0.26600    −4.11151    2.54000;
 3.0                 0.31800;
 5.00   'Q6 '        0.26600     2.27109    2.54000;
 3.0    'D6 '        1.57500;
SENTINEL
SENTINEL
```

Table 2

TRANSPORT input for a beam line that uses quadrupole doublets only.

```
'ISAC II ACHROMATIC SECTION - QHQV-DQHD-QVQH - QHQVDQVQH - 01/08/29'
 0
13.                    12.00000;
 1.0     'BEAM'         0.10000     1.45000    0.10000    1.45000    0.0    0.10000    0.93000;
 3.0     'D1 '          1.57500;
 5.00    'Q1 '          0.26600     4.28395    2.54000;
 3.0                    0.31800;
 5.00    'Q2 '          0.26600    −3.03617    2.54000;
 3.0     'B1IN'         0.65719;
20.0                  180.00000;
 2.0                   22.50000;
 4.000   'B1 '          1.74028    14.00000    0.00000;
 2.0                   22.50000;
20.0                 −180.00000;
 3.0     'B1EX'         0.00001;
 3.0                    0.49743;
 5.00    'QACA'         0.13300     4.46964    2.54000;
 3.0     'MID '         0.00001;
 5.00    'QACB'         0.13300     4.46964    2.54000;
 3.0     'B2IN'         0.49743;
20.0                  180.00000;
 2.0                   22.50000;
 4.000   'B2 '          1.74028    14.00000    0.00000;
 2.0                   22.50000;
20.0                 −180.00000;
 3.0     'B2EX'         0.00001;
 3.0                    0.65719;
 5.00    'Q3 '          0.26600    −3.03617    2.54000;
 3.0                    0.31800;
 5.00    'Q4 '          0.26600     4.28395    2.54000;
 3.0     'F1 '          1.57500;
 3.0     'D7 '          1.00000;
 3.0                    0.50000;
 5.00    'Q5 '          0.26600     3.91428    2.54000;
 3.0                    0.31800;
 5.00    'Q6 '          0.26600    −2.86485    2.54000;
 3.0     'D8 '          0.50000;
 3.0     'MID2'         0.00001;
 3.0     'D9 '          0.50000;
 5.00    'Q8 '          0.26600    −2.86485     .54000;
 3.0                    0.31800;
 5.00    'Q7 '          0.26600     3.91428    2.54000;
 3.0                    0.50000;
 3.0     'F2 '          1.00000;
SENTINEL
SENTINEL
```

Table 3

Beam sizes at the achromatic focus $F1$ and the target focus $F2$

Parameter	Location	
	$F1$	$F2$
$\pm x$ (cm)	0.100	0.100
$\pm\theta$ (mr)	7.213	7.864
$\pm y$ (cm)	0.100	0.100
$\pm\phi$ (mr)	1.456	1.793
R_{11} (cm/cm)	1.0022	0.6887
R_{12} (cm/mr)	−0.0001	−0.0684
R_{16} (cm/%)	0.0000	−9.9999
R_{21} (mr/cm)	−70.6473	2.5008
R_{22} (mr/mr)	1.0022	1.2036
R_{26} (cm/%)	0.0001	−9.9999
R_{33} (cm/cm)	−1.0000	1.0100
R_{34} (cm/mr)	0.0000	−0.0001
R_{43} (mr/cm)	−1.3079	1.4074
R_{44} (mr/mr)	−1.0000	1.0332

Table 4

TRANSPORT input for a modified beam line that uses quadrupole doublets.

```
'ISAC II ACHROMATIC SECTION - QHQV-DQHD-QHQVQH - QHQVDQVQH - 01/08/29'
 0
13.                     12.00000;
 1.0    'BEAM'           0.10000    1.45000   0.10000   1.45000   0.0   0.10000   0.93000;
 3.0    'D1 '            1.57500;
 5.00   'Q1 '            0.26600    4.15167   2.54000;
 3.0                     0.31800;
 5.00   'Q2 '            0.26600   -3.11882   2.54000;
 3.0    'B1IN'           0.65719;
20.0                   180.00000;
 2.0                    22.50000;
 4.000  'B1 '            1.74028   14.00000   0.00000;
 2.0                    22.50000;
20.0                  -180.00000;
 3.0    'B1EX'           0.00001;
 3.0                     0.49743;
 5.00   'QACA'           0.13300    4.46964   2.54000;
 3.0    'MID '           0.00001;
 5.00   'QACB'           0.13300    4.46964   2.54000;
 3.0    'B2IN'           0.49743;
20.0                   180.00000;
 2.0                    22.50000;
 4.000  'B2 '            1.74028   14.00000   0.00000;
 2.0                    22.50000;
20.0                  -180.00000;
 3.0    'B2EX'           0.00001;
 3.0                     0.65719;
 5.00   'Q3 '            0.26600    3.38238   2.54000;
 3.0                     0.31800;
 5.00   'Q4 '            0.26600   -5.00317   2.54000;
 3.0                     0.31800;
 5.00   'Q5 '            0.26600    3.38238   2.54000;
 3.0    'F1 '            1.57500;
 3.0    'D7 '            1.00000;
 3.0                     0.50000;
 5.00   'Q5 '            0.26600    3.91428   2.54000;
 3.0                     0.31800;
 5.00   'Q6 '            0.26600   -2.86485   2.54000;
 3.0    'D8 '            0.50000;
 3.0    'MID2'           0.00001;
 3.0    'D9 '            0.50000;
 5.00   'Q8 '            0.26600   -2.86485    .54000;
 3.0                     0.31800;
 5.00   'Q7 '            0.26600    3.91428   2.54000;
 3.0                     0.50000;
 3.0    'F2 '            1.00000;
SENTINEL
SENTINEL
```

Table 5

TRANSPORT input for a beam line that uses quadrupole triplets.

```
'ISAC II - 9.168 M UNIT SECTION - VHV TRIPLETS - 01/08/29'
 0
13.                       12.00000;
 1.0      'BEAM'           0.10000     1.45000     0.10000     1.45000     0.0     0.10000     0.93000;
 3.0      'D1 '            1.57500;
 5.00     'Q1 '            0.26600    −2.51802     2.54000;
 3.0                       0.31800;
 5.00     'Q2 '            0.26600     3.77468     2.54000;
 3.0                       0.31800;
 5.00     'Q3 '            0.26600    −2.51802     2.54000;
 3.0      'B1IN'           0.65719;
20.0                     180.00000;
 2.0                      22.50000;
 4.000    'B1 '            1.74028    14.00000     0.00000;
 2.0                      22.50000;
20.0                    −180.00000;
 3.0      'B1EX'           0.00001;
 3.0                       0.49743;
 5.00     'QACA'           0.13300     4.46964     2.54000;
 3.0      'MID '           0.00001;
 5.00     'QACB'           0.13300     4.46964     2.54000;
 3.0      'B2IN'           0.49743;
20.0                     180.00000;
 2.0                      22.50000;
 4.000    'B2 '            1.74028    14.00000     0.00000;
 2.0                      22.50000;
20.0                    −180.00000;
 3.0      'B2EX'           0.00001;
 3.0                       0.65719;
 5.00     'Q4 '            0.26600    −2.51802     2.54000;
 3.0                       0.31800;
 5.00     'Q5 '            0.26600     3.77468     2.54000;
 3.0                       0.31800;
 5.00     'Q6 '            0.26600    −2.51802     2.54000;
 3.0      'F1 '            1.57500;
 3.0      'D7 '            1.00000;
 3.0                       0.50000;
 5.00     'Q7 '            0.26600     3.91428     2.54000;
 3.0                       0.31800;
 5.00     'Q8 '            0.26600    −2.86485     2.54000;
 3.0      'D8 '            0.50000;
 3.0      'MID2'           0.00001;
 3.0      'D9 '            0.50000;
 5.00     'Q9 '            0.26600    −2.86485      .54000;
 3.0                       0.31800;
 5.00     'Q10 '           0.26600     3.91428     2.54000;
 3.0                       0.50000;
 3.0      'F2 '            1.00000;
SENTINEL
SENTINEL
```

Table 6

TRANSPORT input for a beam line that uses quadrupole doublets and a triplet.

```
'ISAC II - ACHROMATIC SECTION QHQV-DQHD-QVQH-QHQVQH - 01/08/29'
  0
13.                       12.00000;
 1.0      'BEAM'           0.10000    1.45000    0.10000    1.45000    0.0    0.10000    0.93000;
 3.0      'D1 '            1.57500;
 5.00     'Q1 '            0.26600    4.28395    2.54000;
 3.0                       0.31800;
 5.00     'Q2 '            0.26600   −3.03617    2.54000;
 3.0      'B1IN'           0.65719;
20.0                     180.00000;
 2.0                      22.50000;
 4.000    'B1 '            1.74028   14.00000    0.00000;
 2.0                      22.50000;
20.0                    −180.00000;
 3.0      'B1EX'           0.00001;
 3.0                       0.49743;
 5.00     'QACA'           0.13300    4.46964    2.54000;
 3.0      'MID '           0.00001;
 5.00     'QACB'           0.13300    4.46964    2.54000;
 3.0      'B2IN'           0.49743;
20.0                     180.00000;
 2.0                      22.50000;
 4.000    'B2 '            1.74028   14.00000    0.00000;
 2.0                      22.50000;
20.0                    −180.00000;
 3.0      'B2EX'           0.00001;
 3.0                       0.65719;
 5.00     'Q3 '            0.26600   −3.03617    2.54000;
 3.0                       0.31800;
 5.00     'Q4 '            0.26600    4.28395    2.54000;
 3.0      'F1 '            1.57500;
 3.0      'D7 '            1.00000;
 3.0                       0.65000;
 5.00     'Q5 '            0.26600    3.83901    2.54000;
 3.0                       0.31800;
 5.00     'Q6A '           0.13300   −5.87068    2.54000;
 3.0      'MID2'           0.00001;
 5.00     'Q6A '           0.13300   −5.87068    2.54000;
 3.0                       0.31800;
 5.00     'Q7 '            0.26600    3.91428    2.54000;
 3.0                       0.65000;
 3.0      'F2 '            1.00000;
SENTINEL
SENTINEL
```

Table 7

TRANSPORT input for a beam line that uses quadrupole triplets throughout.

```
'ISAC II - 9.168 M UNIT SECTION - VHV TRIPLETS THROUGHOUT - 01/08/29'
  0
13.                          12.00000;
 1.0      'BEAM'              0.10000     1.45000    0.10000    1.45000    0.0    0.10000    0.93000;
 3.0      'D1 '               1.57500;
 5.00     'Q1 '               0.26600    -2.51802    2.54000;
 3.0                          0.31800;
 5.00     'Q2 '               0.26600     3.77468    2.54000;
 3.0                          0.31800;
 5.00     'Q3 '               0.26600    -2.51802    2.54000;
 3.0      'B1IN'              0.65719;
20.0                        180.00000;
 2.0                         22.50000;
 4.000    'B1 '               1.74028    14.00000    0.00000;
 2.0                         22.50000;
20.0                       -180.00000;
 3.0      'B1EX'              0.00001;
 3.0                          0.49743;
 5.00     'QACA'              0.13300     4.46964    2.54000;
 3.0      'MID '              0.00001;
 5.00     'QACB'              0.13300     4.46964    2.54000;
 3.0      'B2IN'              0.49743;
20.0                        180.00000;
 2.0                         22.50000;
 4.000    'B2 '               1.74028    14.00000    0.00000;
 2.0                         22.50000;
20.0                       -180.00000;
 3.0      'B2EX'              0.00001;
 3.0                          0.65719;
 5.00     'Q4 '               0.26600    -2.51802    2.54000;
 3.0                          0.31800;
 5.00     'Q5 '               0.26600     3.77468    2.54000;
 3.0                          0.31800;
 5.00     'Q6 '               0.26600    -2.51802    2.54000;
 3.0      'F1 '               1.57500;
 3.0      'D7 '               1.00000;
 3.0                          0.41600;
 5.00     'Q7 '               0.26600    -4.20260    2.54000;
 3.0                          0.31800;
 5.00     'Q8A '              0.26600     6.20141    2.54000;
 3.0      'MID2'              0.00001;
 5.00     'Q8B '              0.26600     6.20141    2.54000;
 3.0                          0.31800;
 5.00     'Q9 '               0.26600    -4.20260     .54000;
 3.0                          0.41600;
 3.0      'F2 '               1.00000;
SENTINEL
SENTINEL
```

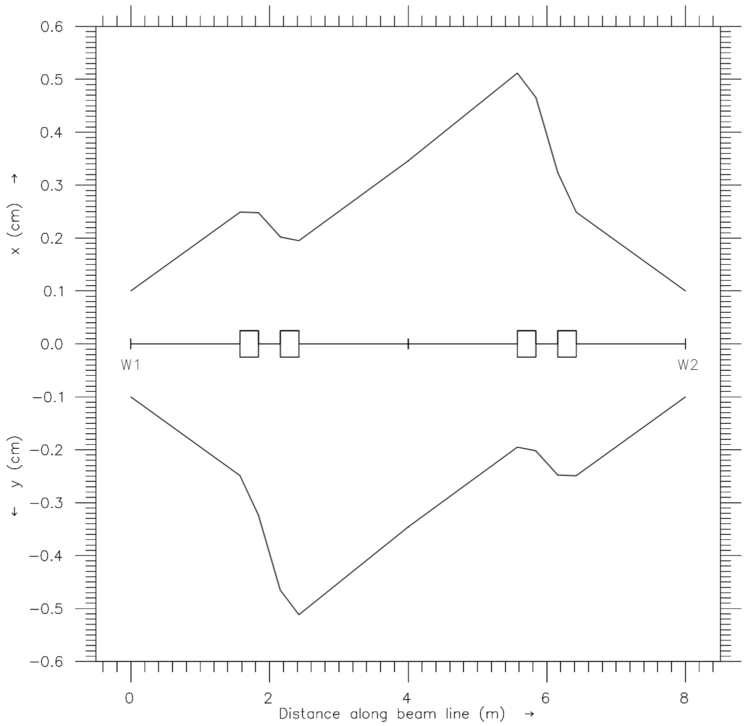

Fig. 1a. Beam envelopes for an 8 m long unit section using quadrupole doublets.

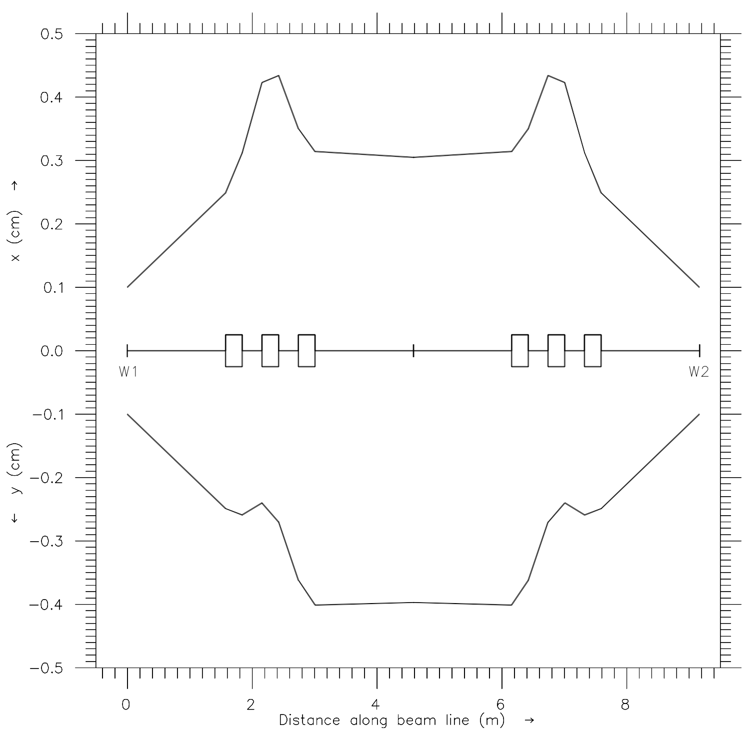

Fig. 1b. Beam envelopes for an 9.2 m long unit section using quadrupole triplets.

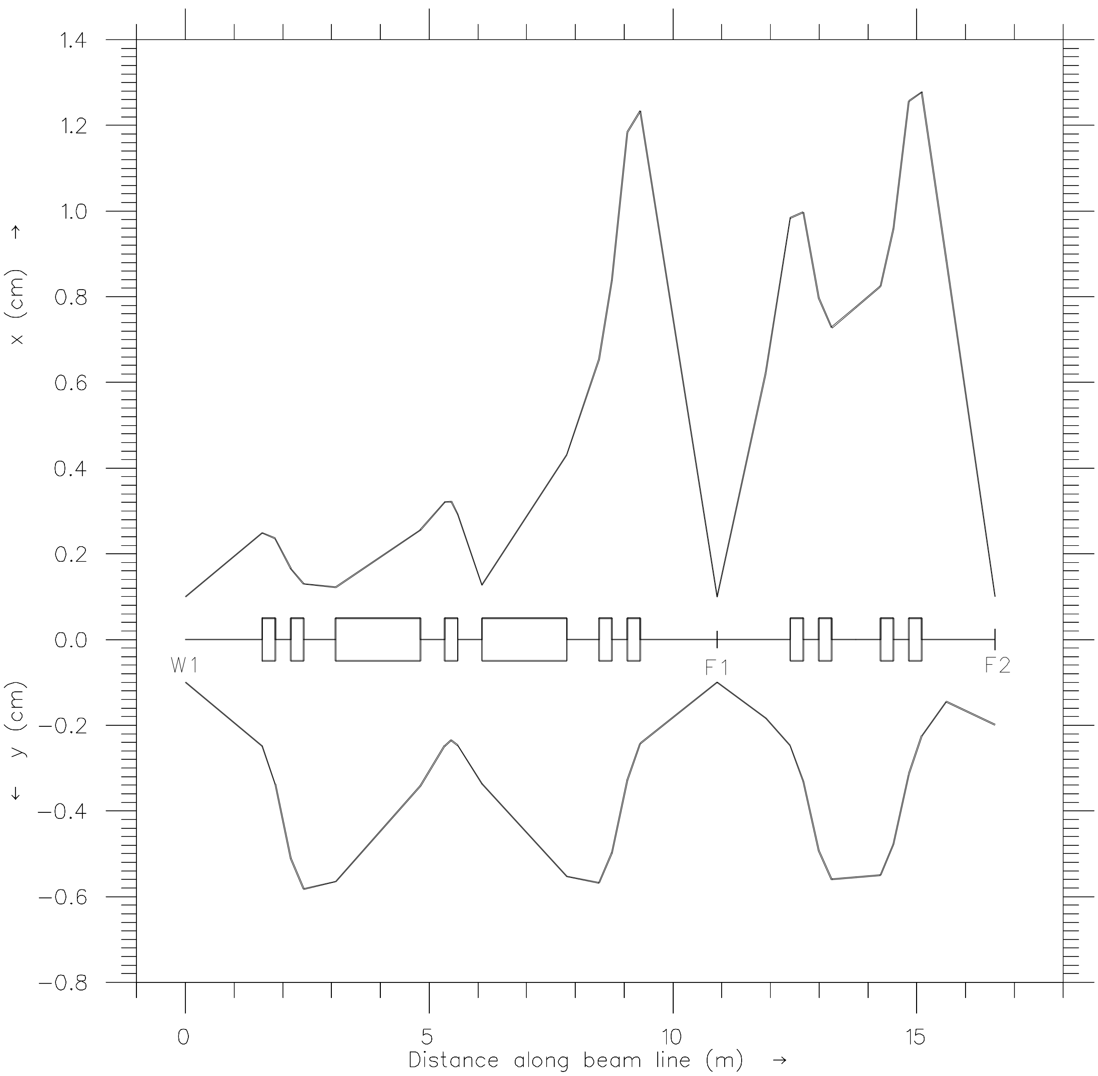

Fig. 2. Beam envelopes for a beam line that uses quadrupole doublets only.

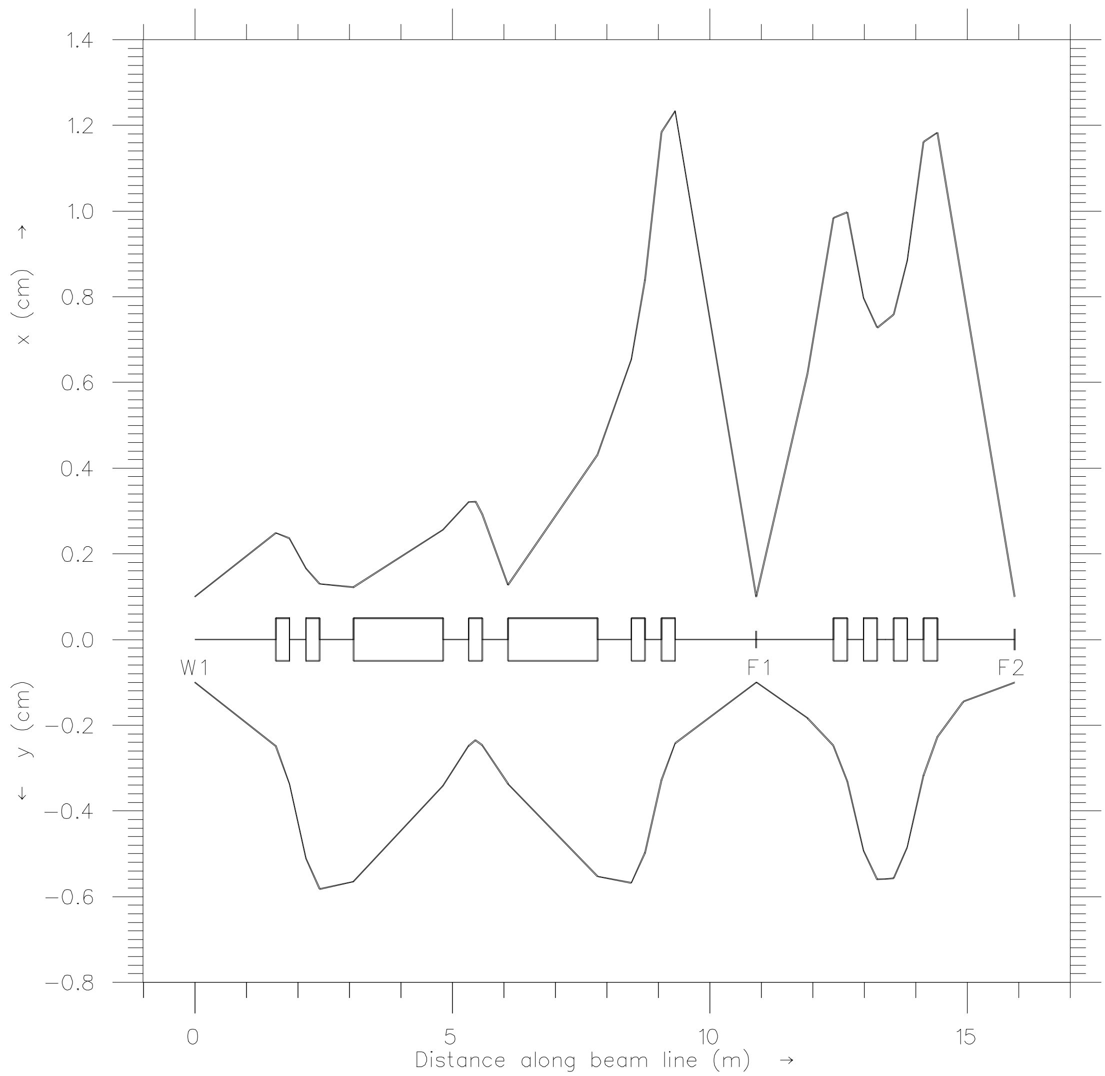

Fig. 3. Beam envelopes for a shortened beam line that uses quadrupole doublets only.

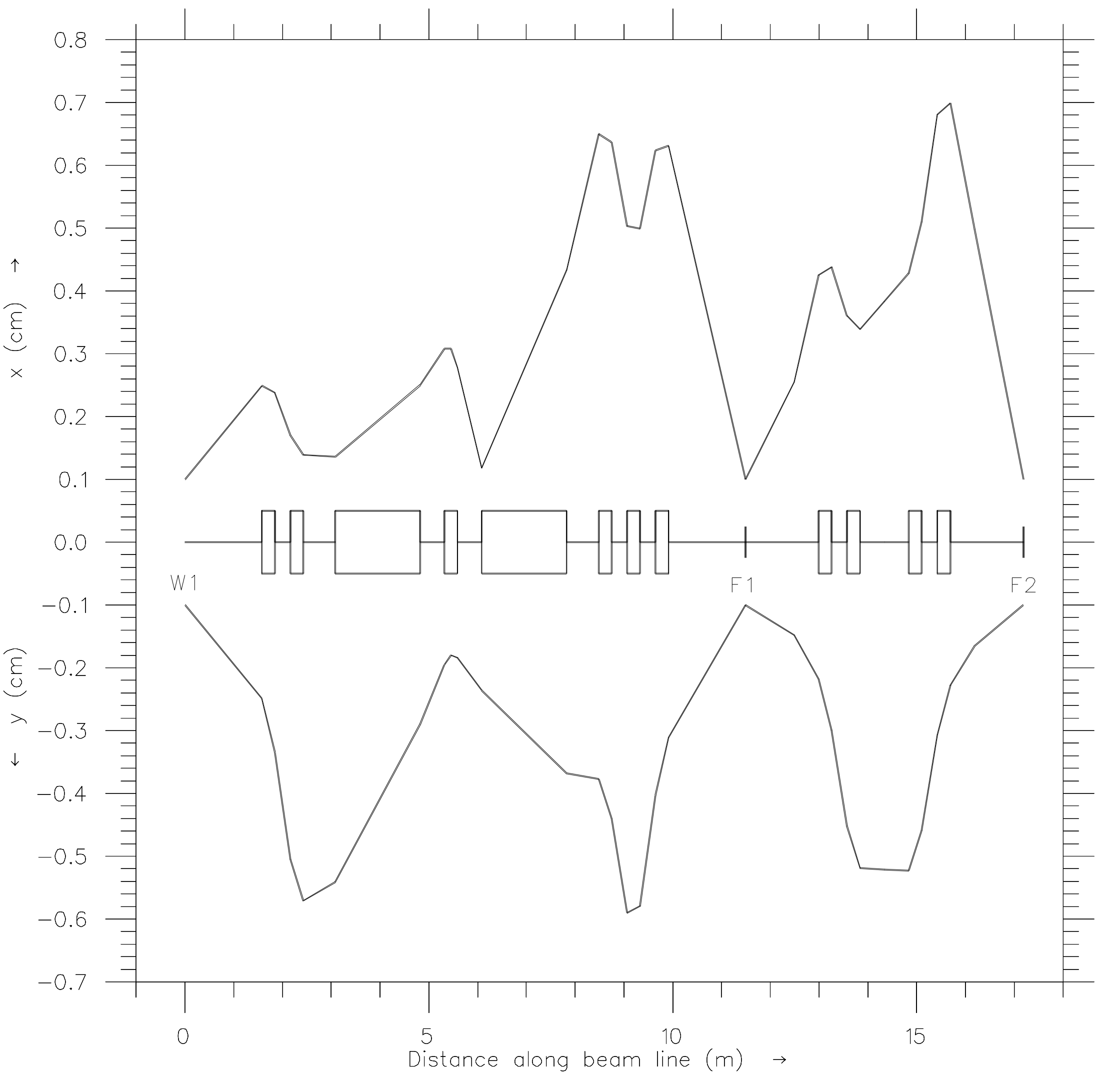

Fig. 4. Beam envelopes for a modified beam line that uses quadrupole doublets.

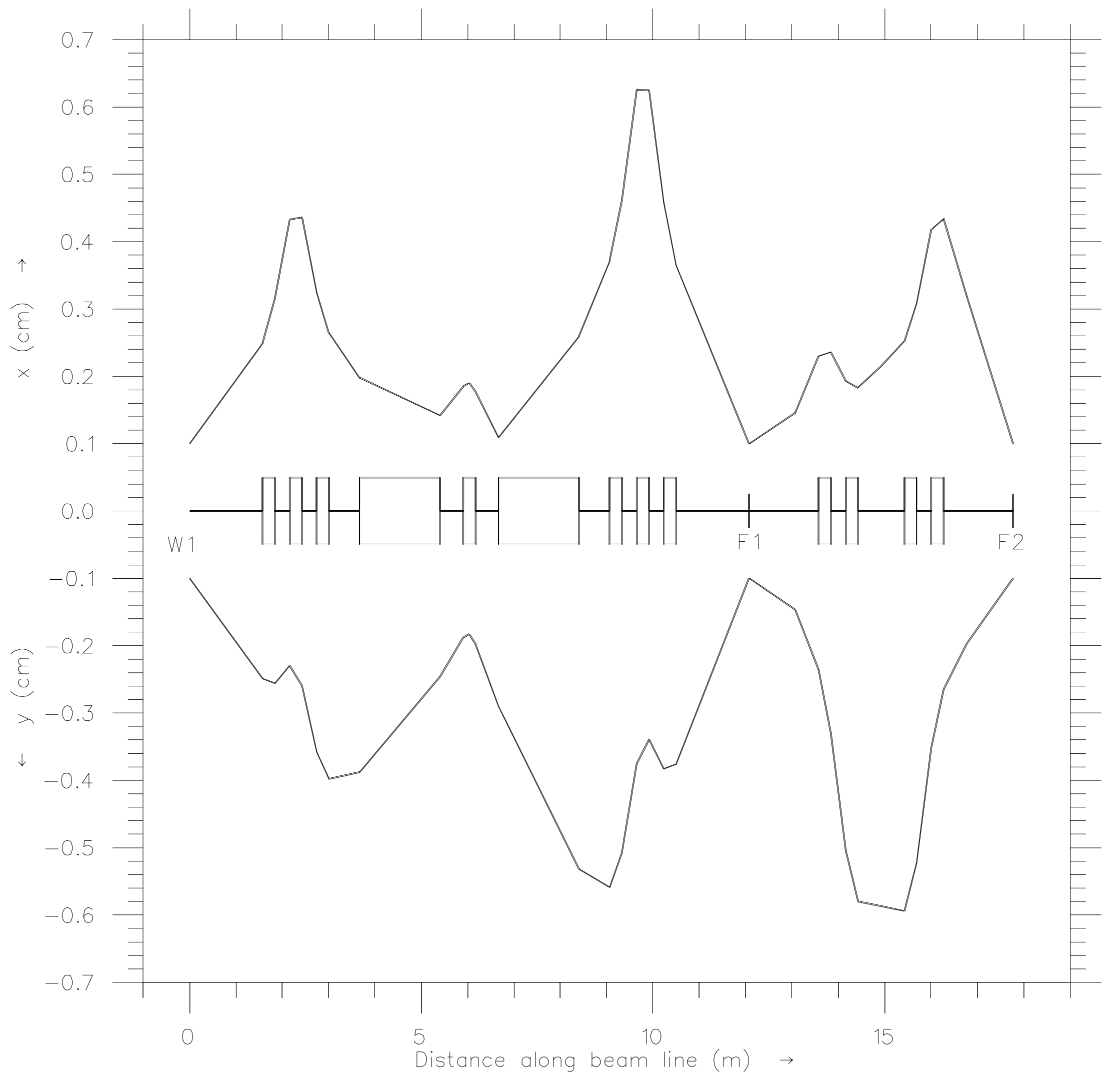

Fig. 5. Beam envelopes for a beam line that uses quadrupole triplets.

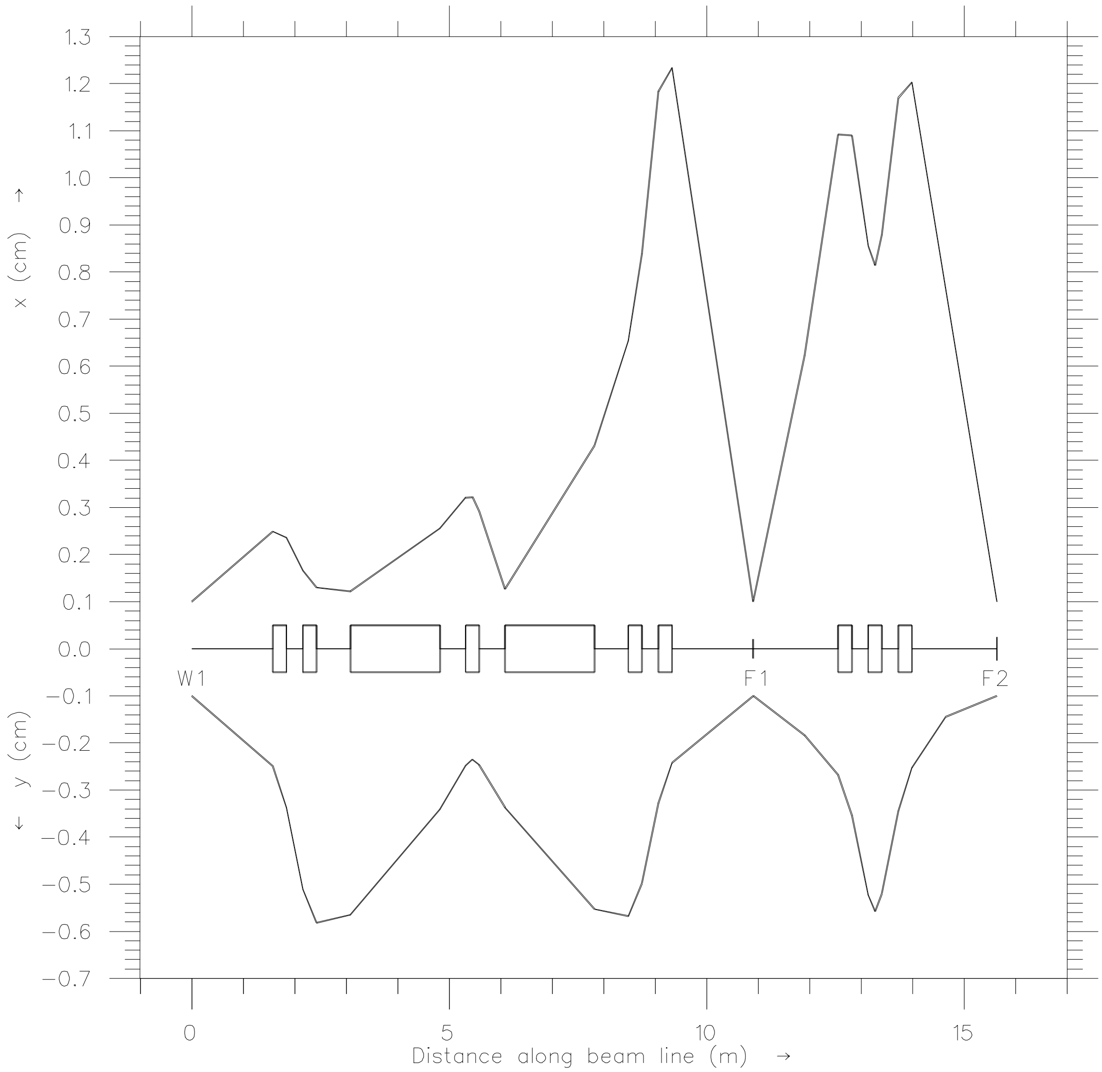

Fig. 6. Beam envelopes for a beam line that uses quadrupole doublets and a quadrupole triplet.

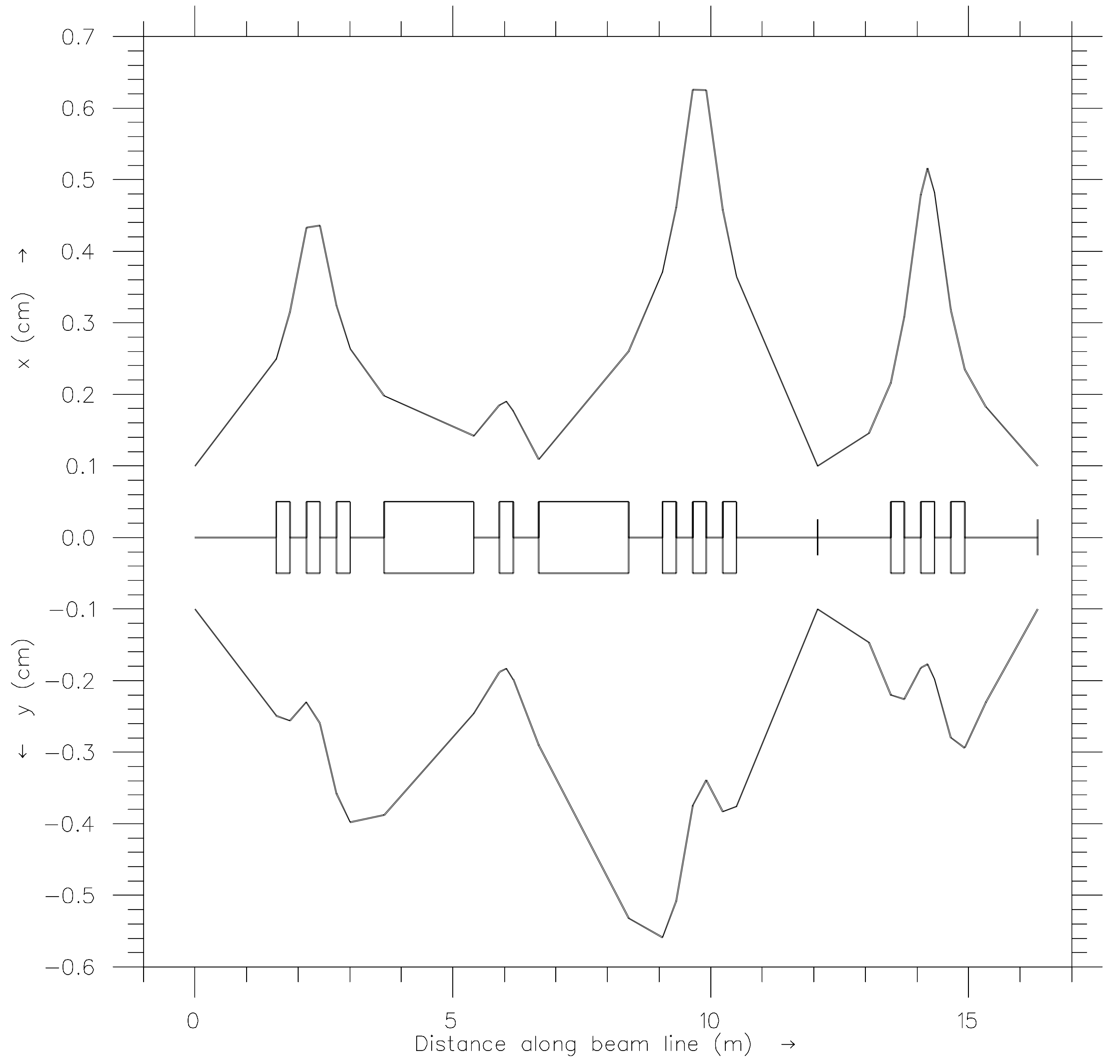

Fig. 7. Beam envelopes for a beam line that uses quadrupole triplets throughout.

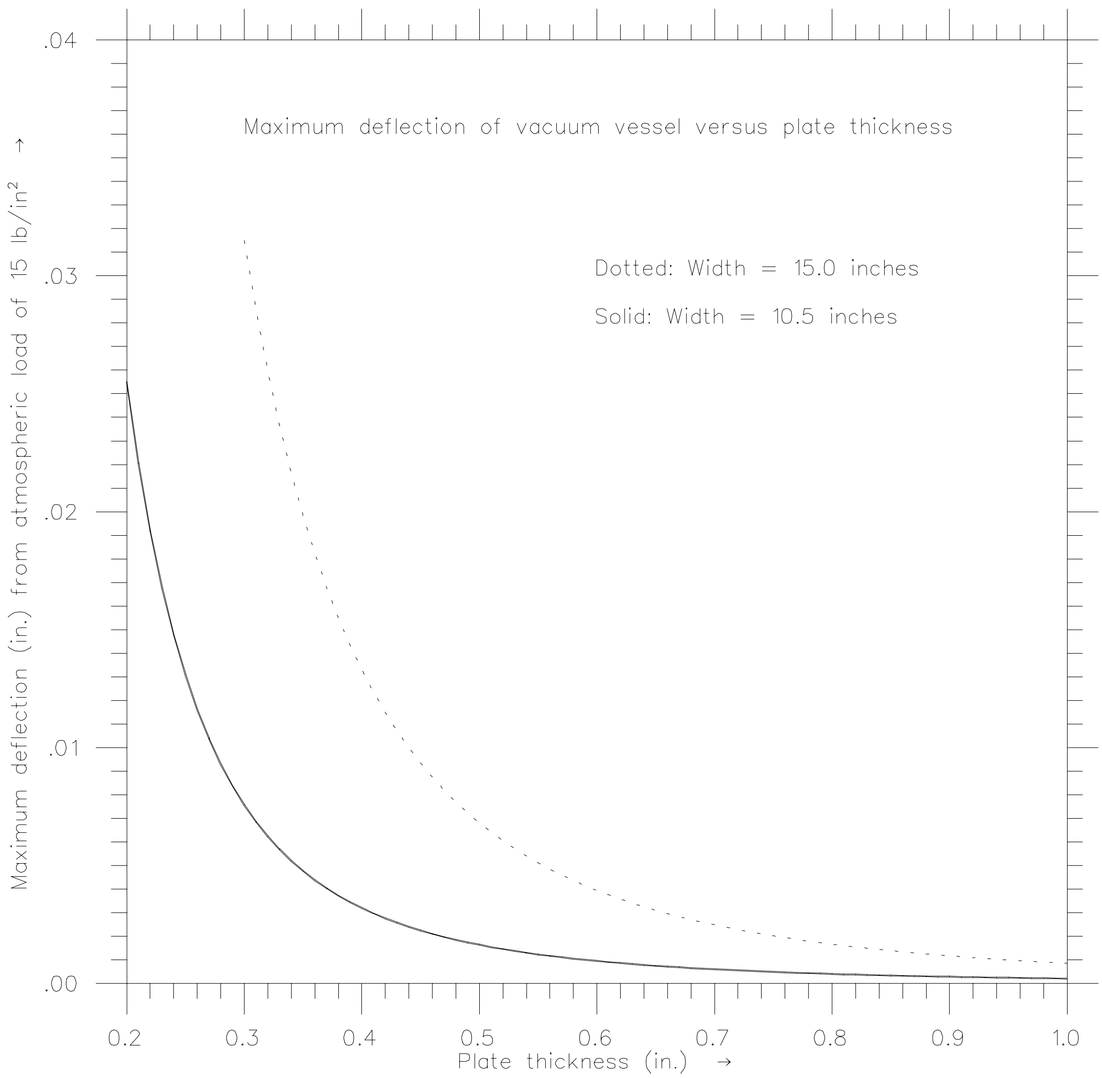

Fig. 8. Maximum calculated deflection of a vacuum vessel as a function of pole width.