MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

PRELIMINARY DESIGN OF THE BEAM TRANSFER LINE BETWEEN THE K-500 AND K-800 CYCLOTRONS AT M.S.U.

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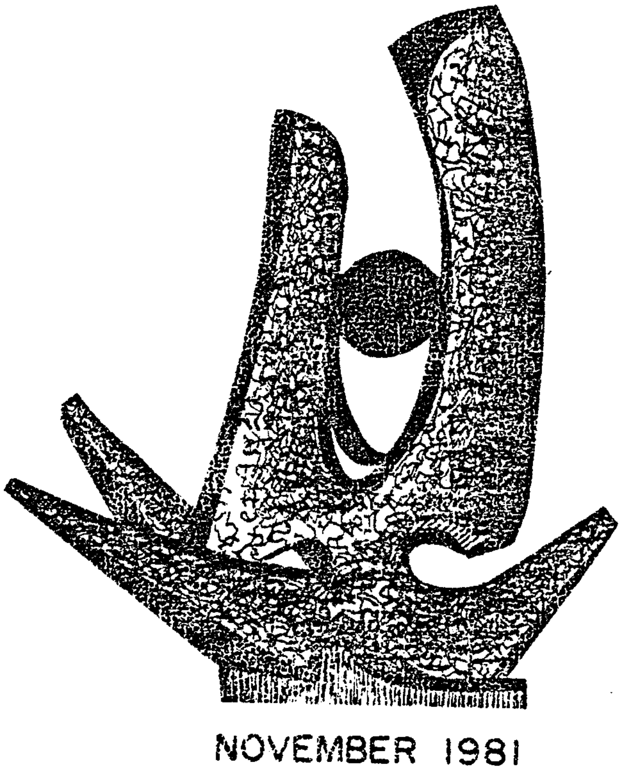

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INDEX

Preliminary Design of the Beam Transfer Line Between the K-500 and K-800 Cyclotrons at M.S.U.

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Introduction

A preliminary design study of the beam transfer line between the K-500 and K-800 cyclotrons under construction at Michigan State University was carried out in the summer of 1979. At the time, the main goal of such undertaking was to define the position of the K-800 cyclotron in the planned building expansion, which is now partially completed. A number of options were considered before the scheme discussed in the following was selected. Successively, the beam line parameters (number, type and position of optical elements) were investigated according to the matching requirements involved in the coupling of the two cyclotrons.

Mostly because of the fact that a relatively short time (three months in all) was available, this study lacks the completeness and the rigorous approach which is necessary for a final design. Also, some characteristics of the beams extracted from the K-500 have changed since these calculations were carried out (see Sect. 2.1) and the same can be expected for the beams to be injected into the K–800 cyclotron. In this sense the authors wish to stress that the preliminary character of this study should be taken literally.

These considerations notwithstanding, the conclusions reached by us seem solid enough to constitute a viable starting point for a more careful analysis. Therefore a detailed presentation of the design criteria, and of the general trend of the solutions obtained, may be of help for a final design. It is with this objective that this report has been written.

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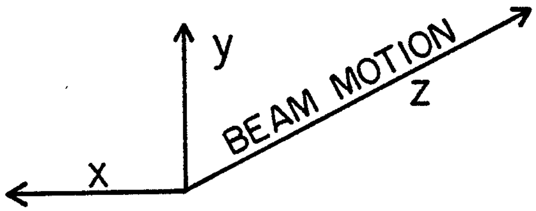
1. Definitions and Notations

All the calculations have been carried out using the program TRANSPORT.(1) Since that notation is used throughout this report, it may be worthwhile to recall some of the basic definitions.

The beam spatial behavior is described according to a righthanded coordinate system, as indicated below, where the z-axis is directed along the beam trajectory. Conventionally the (x,x') coordinates describe the horizontal motion and (y,y') the axial one. Units of spatial beam extent are cm, divergencies are expressed in mrad, lengths (whether drift or optical elements) in meters. Magnetic fields are expressed in kgauss.



TRANSPORT COORDINATE SYSTEM

In general the beam is represented with the six dimensional vector space (x,x',y,y',s,δ), these quantities being a measure of the displacements from the paraxial trajectory. The quantities s and δ refer to the longitudinal phase space, namely bunch length and momentum spread $\frac{dp}{p}$, expressed respectively in cm and percent. To first order the matrix formalism employed by TRANSPORT yields:

$$\begin{aligned}
x &= R_{11}x_0+R_{12}x_0'+R_{13}y_0+R_{14}y_0'+R_{15}s_0+R_{16}\delta_0\\
x' &= R_{21}x_0+R_{22}x_0'+R_{23}y_0+R_{24}y_0'+R_{25}s_0+R_{26}\delta_0\\
y &= R_{31}x_0+R_{32}x_0'+R_{33}y_0+R_{34}y_0'+R_{35}s_0+R_{36}\delta_0\\
y' &= R_{41}x_0+R_{42}x_0'+R_{43}y_0+R_{44}y_0'+R_{45}s_0+R_{46}\delta_0\\
s &= R_{51}x_0+R_{52}x_0'+R_{53}y_0+R_{54}y_0'+R_{55}s_0+R_{56}\delta_0\\
\delta &= \delta_0
\end{aligned}$$

where $x_0, x_0', y_0, y_0', s_0$ and δ_0 are the initial small deviations and the coefficients R_{ij} are functions of all the parameters pertaining to the beam line.

We shall deal, however, with the simpler case in which the general 6x6 matrix is decoupled into a horizontal bend matrix and a vertical non bend matrix.

The decomposition is:

$$\begin{vmatrix} x \\ x' \\ s \\ \delta \end{vmatrix} \begin{vmatrix} = \\ = \\ = \\ = \end{vmatrix} \begin{vmatrix} R_{11} & R_{12} & 0 & R_{16} \\ R_{21} & R_{22} & 0 & R_{26} \\ R_{51} & R_{52} & 1 & R_{56} \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad \begin{vmatrix} x_0 \\ x_0' \\ s_0 \\ \delta_0 \end{vmatrix}$$

in the horizontal plane and

$$\begin{vmatrix} y \\ y' \end{vmatrix} \begin{vmatrix} = \\ = \end{vmatrix} \begin{vmatrix} R_{33} & R_{34} \\ R_{43} & R_{44} \end{vmatrix} \quad \begin{vmatrix} y_0 \\ y_0' \end{vmatrix}$$

in the vertical plane. The dispersive terms are therefore R_{16} and R_{26}, respectively for the position and divergence. Of the three matrix elements influencing the bunch length, and therefore the isochronism of the line, R_{51} and R_{52} express the dependence upon the beam horizontal emittance, or, in other words, the fact that particles with different positions and divergence do have slightly different path lengths. This effect is canceled out in a non-dispersive system for which the symplectic condition holds, i.e.

$$R_{51} = R_{21}\,R_{16} - R_{11}\,R_{26}$$

$$R_{52} = R_{22}\,R_{16} - R_{12}\,R_{26}$$

since in this case $R_{16}=R_{26}=0$. This is indeed, as we shall see, our case. The bunch length is therefore mostly influenced by the R_{56} term. We note here, that for a drift length L it is

$$R_{56} = \frac{1}{\gamma^2}\,L \quad \left(L \text{ in meters, } \frac{dp}{p} \text{ in percent, s in cm}\right)$$

where

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c}}} \quad (v = \text{particle velocity}).$$

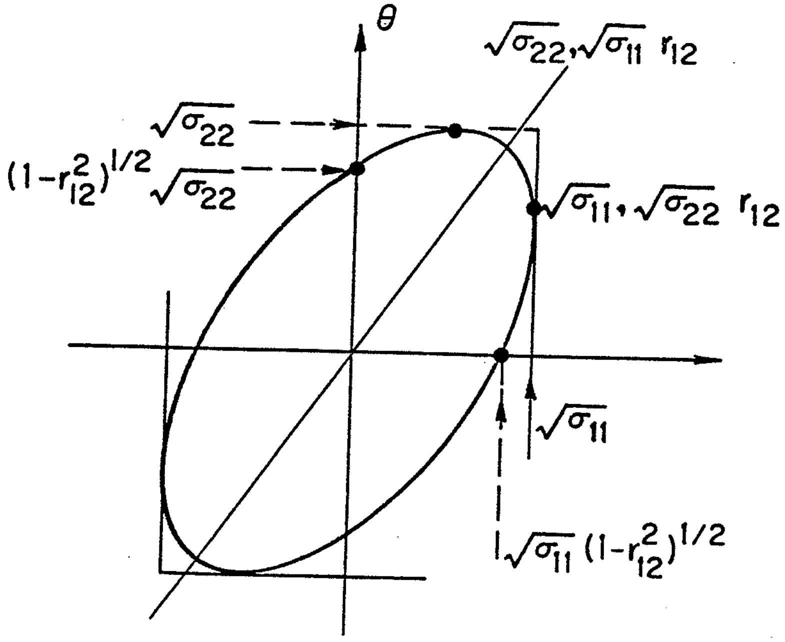
For a bending magnet of length L_o, curvature radius ρ and deflecting angle α the R_{56} term is instead:

$$R_{56} = \frac{L_o}{\gamma^2} - \rho(\alpha - \sin\alpha)$$

Horizontal and axial phase space ellipses are given according to the TRANSPORT notation, summarized in the picture below for the horizontal case.

The correlation coefficient R_{12} (or R_{34} for the axial case) is zero at a waist, i.e. where the ellipse is upright. The ellipse area, and hence the emittance, is given by:

$$\varepsilon = \pi\sqrt{\sigma_{22}}\,\sqrt{\sigma_{11}}\,\sqrt{(1-R_{12}^2)}$$



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The distance D of the waist point from where the beam is specified is, according to the above notation;

$$D = \frac{\sqrt{\sigma_{11}}\ R_{12}}{\sqrt{\sigma_{22}}}$$

In the following, since we use fixed emittance beams

(ε = 6 mm·mrad)

we shall usually specify the beams with

$\sqrt{\sigma_{11}}$ ($\sqrt{\sigma_{33}}$) and R_{12} (R_{34}) .

2. Beam matching requirements

In this section we discuss first the main characteristics of the beams extracted from the K-500 cyclotron in terms of horizontal and axial phase spaces and dispersion. We then turn to the beam parameters needed for injection into the K-800 cyclotron.

The transfer line must provide the matching between the two cyclotrons, and at the same time eliminate the bunch length increase coming from the beam energy spread. As we shall see later, this can be accomplished in two ways, either by rebunching the beam somewhere along the line or by making the transfer line isochronous.

2.1 K-500 extracted beams

A complete study of beam extraction from the K-500 cyclotron has been published elsewhere(2) and we refer to it for further details. Four beams covering the K-500 injector-mode operation were investigated. They are the Z/A (charge to mass ratio) 0.1 ion at center field values B_o of 49 and 31 kgauss and the Z/A = 0.2 ion at B_o = 49 and 35 kgauss.

The beam data listed in Table I are assumed as basis for the matching. They are given in the reference system of the K-500 cylcotron, at an azimuth $\theta = 330^o$ and a radius R = 60", i.e. at the yoke exit, for an emittance in either the horizontal or axial phase space of 6 mm mrad.

Even though largely consistent with the final results for the same beams, reported in (2), these data do not coincide since at the time of this study the extraction from the K-500 had not been finalized yet. The difference lies mostly in the R_{16} and R_{26} values of the .02/49 and .1/49 ion and is due to a different design of the magnetic channel M9 in the K-500 yoke. Less significant are the discrepancies on the phase space ellipse postures (r_{12} and r_{34}). Given the large matching range allowed by the transfer line, these differences should not have any consequence. However, the data as given in (2) should be used in a final calculation.

As apparent from Table I, there is a fair spread in the waist position for these beams, especially for the horizontal phase space. This is due to the fact that the passive channel M9 scales its gradient with the magnetic field in the yoke and therefore does not allow to properly control parameters like r_{12} and r_{34}.

2.2 K-800 injection optics

Injection into the K-800 was studied earlier and is reported in (3). We briefly recall the main geometrical features of the proposed injection scheme. All injected beams originate from a common point outside the cyclotron, namely the center of a steering magnet. Steering with a range of $\pm 1.5^\circ$ at this point is sufficient to match all injection trajectories at the K-800 yoke. The center of

Table I. Beams parameters for the K-500 cyclotron.

$Z/A/B_o$	T/A MeV/n	$\sqrt{\sigma_{11}}$ cm	$\sqrt{\sigma_{22}}$ mrad	R_{12}	$\sqrt{\sigma_{33}}$ cm	$\sqrt{\sigma_{44}}$ mrad	R_{34}	R_{16} cm/%$\frac{dp}{p}$	R_{26} mrad/%$\frac{dp}{p}$
.1/49	5.16	.24	.8	0	.505	2.5	.988	-10.	2.
.1/31	2.08	.427	1.2	.927	.551	.5	.997	+1.	+20.
.02/49	.206	.4	.8	-.746	.25	3.6	.971	-14.8	+2.
.02/35	.106	.403	.9	.848	.422	4.	.994	+2.	+20.

the steering magnet lies at a distance of 3.30 m (130") from the center of the cyclotron and at $\theta = 65^{o}$ in the K–800 reference frame. The angle between the line connecting the centers of the two magnets, and the injection path outside the yoke is $15^{o} \pm 1.5^{o}$. The steering magnet center is therefore at 1.15 m from the K-800 yoke edge. These distances and angles could vary a little once magnetic field data, including fringing field measurements, are available. However no significant discrepancies are expected.

In order to provide detailed matching requirements a further study of the injection of eight representative beam was carried out.(4) Their parameters are listed in Table II, subscript 1 referring to the first machine (K–500) and subscript 2 to the K-800. As noted from the table, these ions are representative of all possible coupling modes for reaching 200 MeV/n.(13) Also a lower energy (149 MeV/n) oxygen beam was selected, together with the highest energy (49 MeV/n) uranium beam. The study of other ions (not listed in the table) confirmed that the cases chosen are indeed representative of the injection and matching conditions.(4)

For these eight ions a careful analysis was carried out, trying to optimize the matching conditions at the K–800 entry. We simply state here the conclusions reached:

- in order to keep the beam size within limits of less than 15-20 mm in either the horizontal or axial direction, a radially focusing element had to be inserted in the K-800 yoke, along the injection path, or else quadrupoles must be provided between the yoke and the steering magnet.

Table II. Parameters of beams studied for injection into the K-800.

Ion Z_1	Z_1/A	Z_2	Z_2/A	ν_{RF} (MHz)	h_1/h_2	T_1/A (MeV/n)	T_2/A (MeV/n)	B_{oI} (kgauss)	B_{o2} (kgauss)	Stripping radius (inches)	Stripping azimuth (deg)	Bunch length (cm) for $\pm 2.5^o$ R.F.width
$O2^+$	.125	8+	.5	26.566	3/1	7.2	200	46.133	34.6	8.88	131	1.97
$Ne3^+$	.15	10+	.5	26.566	3/1	7.2	200	38.444	34.6	8.98	146	1.97
$B1^+$	.1	5+	.5	26.566	4/1	4.0	200	43.250	34.6	6.68	136	1.48
$Si3^+$	.107	14+	.5	26.566	4/1	4.0	200	40.367	34.6	6.68	141	1.48
C1+	.0833	6+	.5	26.566	5/1	2.5	200	41.520	34.6	5.27	139	1.17
N1+	.0714	7+	.5	26.566	5/1	2.5	200	48.440	34.6	5.27	126	1.17
O2+	.125	7+	.4375	23.783	3/1	5.79	149	41.3	35.4	8.98	140	1.97
U13+	.0546	46+	.1933	28.078	7/2	1.470	44	47.820	47.3	7.64	151	.847

- this second option looks cumbersome since the quadrupoles should move according to the beam steering of ±1.5°.
- for the yoke both a passive and a combined passive plus active channel were examined. While a passive channel would in principle suffice, a passive plus active channel, with a reasonable gradient control, is by far the best solution.
- in particular, the latter option yields a fixed horizontal waist at a distance of 1 m upstream the steering magnet center, and an almost fixed axial waist positioned between 1.7 and 1.9 meters downstream the steering magnet center. This looked as a rather favourable situation from the point of view of experimentally checking the matching conditions, for any given beam, before injection.

According to this choice the matching requirements for all eight ions are listed in Table III, with the usual notation, assuming that the matching point is the steering magnet center. Also listed are the focusing channel gradients. The channel itself is positioned along the injection path, in the K-800 yoke, between R = 65" and R = 80". A fixed emittance of 6 mm mrad is assumed for all beams.

Table III. Matching requirements at the steering magnet center, for injection into the K-800 cyclotron, with an emittance of 6 mm mrad.

ION Z_1	Channel gradient (kgauss/inch)	$\sqrt{\sigma_{11}}$ (cm)	$\sqrt{\sigma_{22}}$ mrad	r_{12}	$\sqrt{\sigma_{33}}$ (cm)	$\sqrt{\sigma_{44}}$ (mrad)	r_{34}	R_{16} $(cm/\%\frac{dp}{p})$	R_{26} $(mrad/\%\frac{dp}{p})$
O2+ (8:2)	2.18	.6138	6.13	.9987	.917	4.65	-.999	-2.77	-21.4
Ne3+	1.80	.606	6.12	.9987	1.064	5.69	-.9995	-3.94	-34.95
B1+	2.03	.592	5.85	.9985	.936	5.03	-.9992	-2.94	-23.3
Si3+	1.86	.693	6.92	.9992	.805	4.25	-.9984	-3.51	-29.5
C1+	1.93	.646	6.45	.9989	.907	4.87	-.9991	-3.1	-25.8
N1+	2.25	.467	4.65	.9961	.873	4.93	-.9990	-2.31	-16.4
O2+ (7:2)	1.92	.746	7.31	.9994	.452	2.43	-.9843	-3.52	-29.2
U13+	2.19	.577	5.65	.9983	.917	4.95	-.9991	-4.	-35.5

3. Transfer line conceptual design

Early plans called for a coupling line between the two cyclotrons of minimal length, involving a rotation of the K-500 cyclotron of about 120° with respect to its planned Phase-I position. However, it became quickly obvious that the complex matching requirements between the two cyclotron ask for a large number of optical elements, i.e. a rather long transfer line. After a few trials it was therefore decided to study a line which would leave the K-500 in its present position, thus having a length of at least 30 m. This choice allows the building and testing of the coupling line independently of the K-500 Phase-I operation, thus minimizing scheduling conflicts, etc.

In principle, the transfer line should:

a) - provide the necessary horizontal and axial phase space matching between the K-500 cyclotron and the center of the steering magnet in front of the K-800.

b) - provide the dispersion matching, namely the required R_{16} and R_{26} values at the K-800 entry.

c) - keep the beam bunch length constant.

d) - keep the beam dimensions within some reasonable value. A maximum half width of 3 cm for an emittance of 6 mm mrad has been tentatively assumed.

e) - allow the beam diagnostics to be performed in a reasonably simple way.

In order to satisfy these requirements, and to keep the transfer line as simple as possible, we have adopted the scheme of principle shown in Fig. 1.

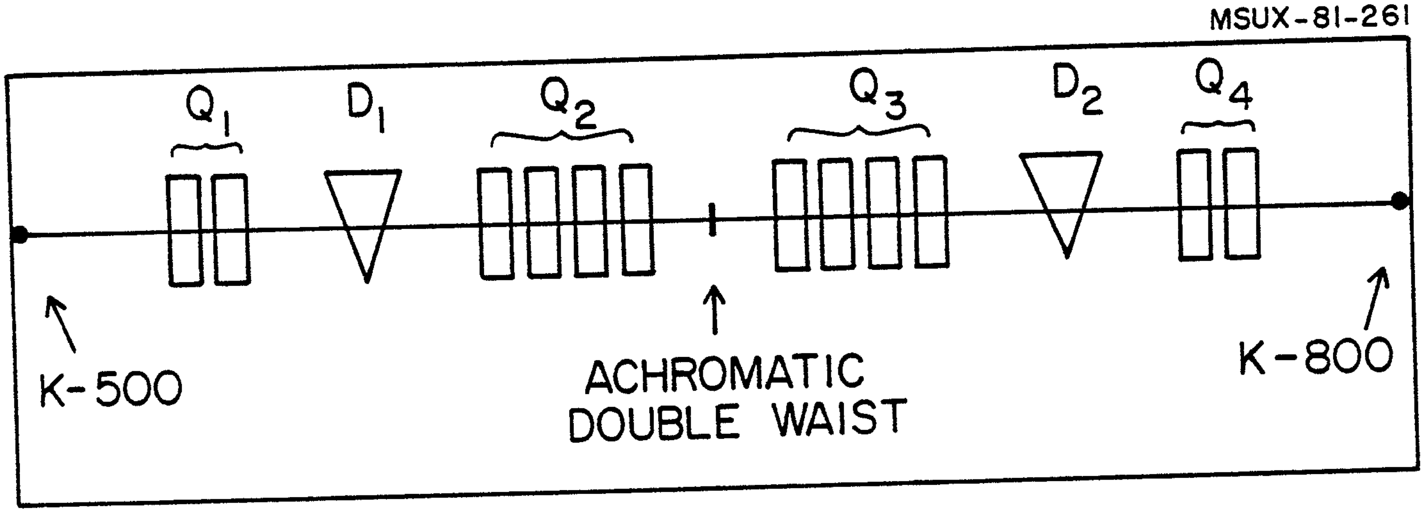

FIG. 1.

This scheme is based upon these concepts:

i. all beams from the K-500 are brought to a double achromatic waist (horizontal and axial), with the same width, at the same location (D.W. point).

ii. from that point the second part of the line, which is obviously independent from the first, provides the matching for injection into the K-800.

According to this scheme and following the notations of Fig. 1 the different sections of the line perform these functions:

- The set of quadrupoles Q_1 (two at minimum) and the dipole D_1 make the beam achromatic ($R_{16}=R_{26}=0$) at the exit of D_1. The beam will remain achromatic downstream D_1 up to D_2.
- The set of quadrupoles Q_2 provides the double waist with the required dimension at DW.
- The four quadrupoles Q_3 allow the matching of the horizontal and axial phase spaces at the center of the steering magnet. (Their setting depends upon D_2 and Q_4, but does not influence the dispersion matching since the beam is achromatic.)
- The dipole D_2 and the quadrupoles Q_4 control the R_{16} and R_{26} dispersion matching into the K-800 (center of the steering magnet).

The number of elements sketched in Fig. 1 is the minimum necessary to perform these functions. In reality, as we shall see, a larger number of elements is necessary for the Q_1 and Q_4 sections especially for keeping the beam dimensions within 25-30 mm.

Concerning the conservation of the bunch length, as outlined in section 1, in practice one only needs to compensate for the line total length. Two options exist, namely:

- rebunch the beam, with an R.F. buncher, at some point along the line. In the present design that would clearly be close to the DW point.
- making the whole line isochronous, that is using magnets to compensate for the drift length.

Both these approaches have advantages and disadvantages, and they have both been tried. While in the first case the conceptual design of the line remains as given in Fig. 1, in the second approach it is necessary to modify the line set-up from the K-500 to the D.W. point. Schematically this is shown in Fig. 2.

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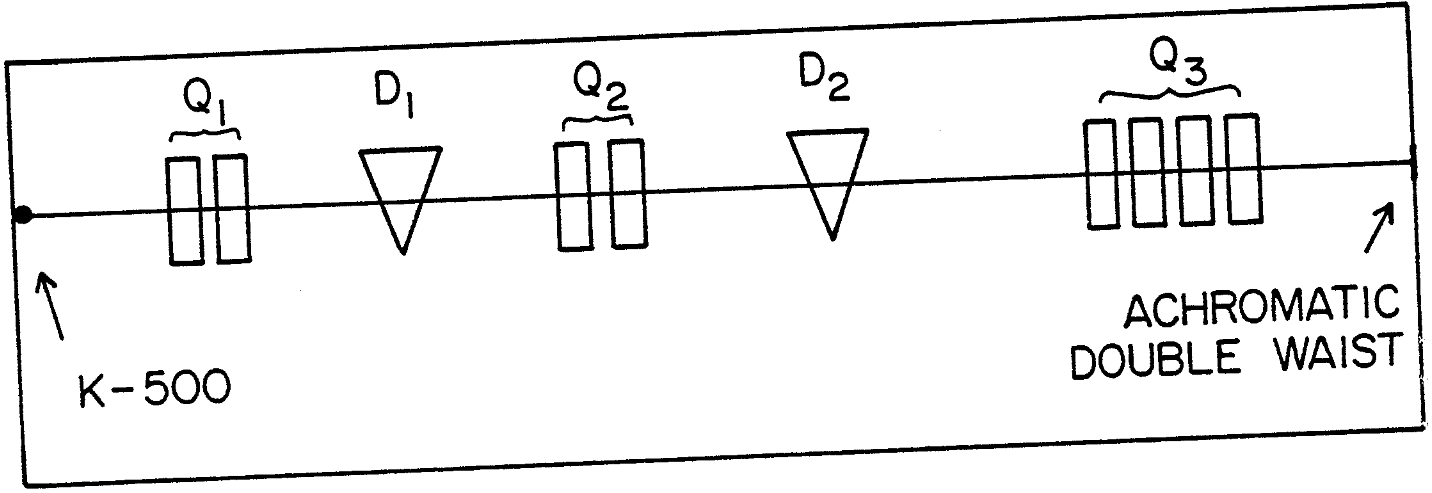

FIG. 2.

In principle this design works as follows:

- the set of quadrupoles Q_1 operates in such a way that the R_{56} term at the exit of the dipole D_1 is equal to $-\frac{L}{\gamma 2}$ where L is the total length of the line. The dipole D_1 thus makes the line isochronous.
- the quadrupoles Q_2, together with the dipole D_2, make the beam achromatic ($R_{16}=R_{26}=0$) at the exit of D_2.

- the four quadrupoles Q_3 provide the double waist at D.W. as in the previous scheme.

Again, as will be seen shortly, the number of elements necessary in practice is larger than outlined here. The second part of the line, from D.W. to the K-800, remains unaltered.

We now turn to an analysis of the actual line design following the conceptual approach of Fig. 1, i.e. on the hypothesis that isochronism will be taken care of with an R.F. buncher. Section 5 will describe the preliminary design of a fully isochronous line, according to the scheme of Fig. 2.

4. Transfer line design without isochronism requirement

Taking into account the overall geometry, the scheme we are proposing is shown in Fig. 3. The first part of the line, from the K-500 cyclotron to the D.W. point, consists of two dipoles D_1 and D_2, with 25° and 140° bending angle respectively, plus seven quadrupoles. Three of these are positioned between the K-500 and D_1, and together with the dipoles make the beam achromatic ($R_{16}=R_{26}=0$) at the exit of D_2, while keeping the beam dimensions reasonable. The other four provide the matching to a double waist at the D.W. point, with variable magnification if required.

The main purpose of the first dipole, D_1, is to introduce a 25° steering so that the Phase-I beams, going directly into the experimental areas, can clear the D_2 dipole. As of now, D_1 is conceived as a superconducting high field magnet, with a max field of 40 kgauss, a pole radius of 20 cm, and a useful gap of about 5 cm.

The 140° dipole D_2 provides most of the bending angle needed to bring the beams backward toward the K-800 cyclotron, besides helping in getting an achromatic beam at its exit. It is conceived as a window frame, uniform field, magnet with a maximum field of 19 kgauss, a bending radius of 1.8 m and a useful axial gap of 4-5 cm. Taking into account the observed R_{16} and R_{26} values in the magnet, the horizontal useful width should not exceed 8-10 cm. The coils could be either room temperature or superconducting. This magnet also has a 25° wedge, both at the entry and exit, for axial focusing purposes. Its effective length is 4.42 m. No serious thought has been given to build this magnet as a really high field one, because proper control of its optical properties at high fields requires a very careful study not possible at the time.

The quadrupoles have an effective length of .4 m and a total aperture of 8 cm, which is quite sufficient for the predicted beam sizes. When arranged as doublets the quads are .2 m apart. The maximum poletip field is, for 4 cm half aperture, 12 kgauss. The quadrupoles could be either at room temperature or superconducting but with low fields.

The length of the line from the K-500 yoke exit to the D.W. point is 16.612 m. This is made up as follows:

- K-500 yoke exit to Q_1 entry = .5 m
- Q_1 length = .4 m
- Q_1 exit to Q_2 entry = 1 m
- Q_2 length = .4 m
- Distance between Q_2 and Q_3 = .2 m
- Q_3 length = .4 m
- Q_3 exit to D_1 entry = 1.1 m
- D_1 effective length = .392 m
- Exit of D_1 to entry of D_2 = .8 m
- D_2 effective length = 4.42 m
- D_2 exit to Q_4 entry = 1.5 m
- Q_4 length = .4 m
- Distance between Q_4 and Q_5 = .2 m
- Q_5 length = .4 m
- Q_5 exit to Q_6 entry = 1.5 m
- Q_6 length = .4 m
- Distance between Q_6 and Q_7 = .2 m
- Q_7 length = .4 m
- Q_7 exit to D.W. point = 2 m

The calculations with TRANSPORT were carried out for the four beams listed in Table I, with the purpose of obtaining for all of these an achromatic double waist at DW. To ensure a reasonable flexibility, both a .3 cm and .6 cm half width waists were required, for 6 mm mrad emittances. In the following, however, we report only the results for .3 cm half width waists. All calculations were made for a fixed 1 GeV/c proton beam, which is about the maximum equivalent rigidity of any beam to be injected in the K-800 cyclotron.

For the four beams of Table I, the resulting horizontal and axial beam envelopes for .3 cm waist half-width are plotted in Figs. 4 and 5, together with the corresponding R_{16} values. The axial beam envelope mostly determines the necessary apertures in the quadrupoles but is however confined to within ±2.5 cm.

The quadrupole fields needed for the four beams, again assuming 1 GeV/c protons as the maximum rigidity case, are listed in Table IV, for a half-aperature of 4 cm. The sign convention is as in TRANSPORT, namely a positive sign indicates focusing in the horizontal direction.

Table IV. Quadrupole fields for matching the K-500 beams to the double waist points according to the scheme of Fig. 3.+

ION Quad #	$Z/A/B_o$			
	.1/49	.1/31	.02/49	.02/35
Q_1	+2.425	+2.834	+2.315	+2.614
Q_2	-5.354	-3.716	-5.94	-3.653
Q_3	+6.016	+2.205	+7.37	+1.89
Q_4	-3.37	+2.724	-3.244	-3.716
Q_5	+4.488	-4.0	+4.57	+4.488
Q_6	-6.30	+5.826	-6.125	-6.85
Q_7	+3.00	-11.764	+2.567	+2.11

\+ - All fields in kgauss, assuming 4 cm half-aperature, 1 GeV/c equivalent proton rigidity

- Matching to achromatic .3 cm double waist halfwidth, 6 mm·mrad emittance
- See Table I for ion beam parameters.

The second part of the line, according to the conceptual scheme discussed in Sect. 3, consists of four quadrupoles Q_8 to Q_{11} followed by a dipole D_3 and three more quadrupoles, Q_{12} to Q_{14}, up to the center of the steering magnet. This, as will be recalled, is the assumed matching point for injection into the K-800.

The purpose of the D_3 dipole is both to allow the proper matching in the (R_{16}, R_{26}) space and to bend the beams in an acceptable position toward the K-800 cyclotron. It is this latter objective that led to a choice, as seen in Fig. 3, of a bending angle of 30^o. For the (R_{16}, R_{26}) matching, in fact, a number of other angles could have been selected. In this way another 30^o dipole on the extracted beam path can bring the K-800 beams in a direction almost parallel to the experimental areas.

At present, the 30^o D_3 dipole is conceived as a window frame uniform field magnet, with a maximum field of 18 kgauss, a curvature radius of 1.81 meters and an effective length of 1 m. As in the D_2 dipole, a 25^o wedge is envisaged, for added axial focusing. The useful axial gap is 4-5 cm, and its horizontal useful width should also be around 8–10 cm. The coils could be either room temperature or superconducting, as for the D_2 dipole.

All the quadrupole have the same characteristics discussed for those belonging to the first part of the line.

The length of the line between the D.W. point and the center of the steering magnet is 13.1 m. This is made up as follows:

- D.W. point to Q_8 entry = 3 m
- Q_8 length = .4 m
- Distance between Q_8 and Q_9 = .2 m
- Q_9 length = .4 m
- Q_9 exit to Q_{10} entry = 2 m
- Q_{10} length = .4 m
- Distance between Q_{10} and Q_{11} = .2 m
- Q_{11} length = .4 m
- Q_{11} exit to D_3 entry = .6 m
- D_3 effective length = 1. m
- D_3 exit to Q_{12} entry = 1 m
- Q_{12} length = .4 m
- Distance between Q_{12} and Q_{13} = .2 m
- Q_{13} length = .4 m
- Q_{13} exit to Q_{14} entry = 1.5 m
- Q_{14} length = .4 m
- Q_{14} exit to steering magnet center = .6 m

The calculations with TRANSPORT were carried out for the eight beams listed in Table III, starting from the achromatic double waist at D.W. As before, a fixed 1 GeV/c proton momentum was assumed for all ions. We have obtained complete matching for all beams.

The resulting envelopes are presented in Figs. 6,7,8,9 together with the plots of R_{16}.

As can be seen from the figures, in the second part of the line the requirements on quadrupole aperture are more evenly split between the horizontal and axial motion.

The maximum axial width is 3 cm, the maximum horizontal width is 2.1 cm.

The resulting quadrupole fields are listed in Table V, again assuming a half aperture of 4 cm. The same sign convention holds.

From Table V, it can be noted that quadrupoles Q_{13} and Q_{14} have the same (negative) sign, and field strengths which are, in many cases, similar. This indicates that perhaps the two quadrupoles could be substituted by just one, although with a larger length or a higher field. Our trials in this direction were not successful and in fact it is even questionable whether there would be much advantage in such a solution. We wish however to point out that this is indeed a possibility and should perhaps be investigated more carefully also by varying the positions of Q_{12} and Q_{13} with respect to the steering magnet.

The line thus designed seems to fulfill the requirements set forth in Sections. 2 and 3. None of the elements, i.e. either dipoles or quadrupoles, seem of particularly difficult construction and in fact they are, apart from the possible use of superconducting coils, of quite straight-forward design. A summary of their parameters is given in Table VI.

As for the isochronism requirement, this line, as stated earlier, calls for an R.F. beam "buncher" placed perhaps at D.W.

No design work has been carried out on a possible R.F. buncher. Even though it looks as a challenging piece of

Table V. Quadrupole fields for matching the beams from the double waist point to the steering magnet center, according to the scheme of Fig. 3^{+}.

ION Quad #	O 2+ (8:2)	Ne 3+	B 1+	Si 3+	C 1+	N 1+	O 2+ (7:2)	U 13+
Q_9	+3.48	-4.976	-3.953	-4.62	-4.52	-3.89	-4.33	-4.69
Q_9	-4.346	+4.756	+4.047	+5.102	+4.38	+7.12	+5.42	+4.71
Q_{10}	+8.771	-	+4.157	+4.16	+2.88	+6.65	+4.362	-1.18
Q_{11}	-3.055	+1.181	-1.827	-1.95	-1.34	-3.54	-2.46	_2.14
Q_{12}	+5.464	+4.913	+5.291	+4.95	+5.13	+6.25	+4.84	+4.88
Q_{13}	-7.291	-5.921	-6.803	-5.97	-6.205	-10.4	-5.73	-6.08
Q_{14}	-5.055	-7.575	-5.43	-6.44	-6.283	-3.94	-6.205	-7.04

+ - All fields in kgauss, assuming 4 cm half aperture, 1 GeV/c equivalent proton rigidity

- Matching from achromatic .3 cm double waist, 6 mm mrad emittance, to required kgauss phase space

- See Table III for K-800 injection requirements on all beams.

Table VI. Summary of optical elements parameters.

Dipoles	type	Max field (kgauss)	Bending angle (degrees)	Curvature radius(m)	pole radius(m)	wedge focusing	Effective length(m)
D_1	conventional	38	25°	.9	.2	-	.392
D_2	window frame	18	140°	1.81	-	25°	4.42
D_3	window frame	18	30°	1.81	-	25°	1

Quadrupoles	type	Half aperture (cm)	Max pole tip field (kgauss)	length (m)
Q_1 to Q_{14}	conventional or superconducting	4	12	.4

equipment, it might just be feasible. As an order of magnitude estimate let us assume that:

- the energy spread of the beams out of the K-500 is $\frac{\Delta E}{E} = \pm .1\%$
- the pulse width of the beams is about $\pm 4^{\circ}_{rf}$.
- the buncher is located in the middle of the line, where the beam is fully achromatic.

We should then have, in first approximation, a buncher which provides a $\frac{\Delta E}{E}$ $\pm .2\%$, that is, for e.g. 7 MeV/n Z/A = .125 ions, a $\Delta E = \pm 14$ KeV/n, or else a ± 100 KV voltage. By selecting a suitable harmonics of the R.F. frequency, like h=20, it would then be possible to rebunch the beam with a peak voltage of ≈ 100 kV, operating at = 500 MHz. This, or any other choice in the few hundreds MHz range, would probably be feasible.

It is obvious that a serious feasibility study must be carried out before such an option is selected. It is also for this reason that we have studied a scheme of a fully isochronous transfer line, as discussed in the following section.

5. Matching with isochronism requirement

If an R.F. buncher is not used, magnet compensation of the path length must be introduced. That this is necessary can be seen from the following order of magnitude estimate. If $\Delta E/E = \pm .1\%$ and the line is approximately

30 m long, then the bunch length increase due just to the line length will be

$$\Delta s = R_{56} \cdot \Delta p/p = \frac{L'}{2} \frac{\Delta p}{p} = 30 \text{ x } .1 = 3 \text{ cm.}$$

If we compare this number with the bunch lengths listed in Table I we see that in most cases they will more than double.

Following the design criteria discussed in Sect. 3, we have tried to compensate for the energy spread in the first part of the line, i.e. from the K-500 exit to the double waist point. This is in fact the only practical option, since only the first part of the line anticipates a magnet with a large enough bending angle. Consequently, and according to the above order of magnitude estimate, we sought a scheme where R_{56} = -30. at the exit of the large magnet. This compensates for the total line length and makes the line substantially isochronous. In fact the variations of R_{56} due to the other magnets, considering the R_{16} and R_{26} dispersions at their entry points are in first approximation negligible.

The presently envisaged scheme is shown in Fig. 10. It should be taken as a scheme of principle since no real optimization was carried out, mainly because of lack of time.

The first part of the line consists of 12 quadrupoles and three dipoles, D_1, D_2, D_3 and operates as follows:

- The first three quadrupoles, between the K-500 and D_1, bring the beam to the D_1 entry with the following characteristics:
  - R_{16}: between 5 and 10
  - $R_{26} = 0$
  - $r_{34} = 0$, i.e. a waist in the (y,y') subspace.
- The D_1 dipole, as in the previous scheme, provides a 25° bending so that the K-500 stand-alone beams can clear the D_2 dipole.
- The quadrupoles Q_4 and Q_5 (actually, as we shall see, one only may be necessary), are used together with D_2 in order to have $R_{56} = -30$ at the exit of D_2.
- The quadrupoles Q_6 and Q_7 (again, only one may be necessary) provide together with D_3 an achromatic beam ($R_{16}=R_{26}=0$) at the exit of D_3.
- The remaining quadrupoles, Q_8 to Q_{12} give the required double waist of .3 cm half-width at D.W. point.

The quadrupoles have the same design characteristics as described in sect. 4. The same is true for the dipole D_1.

The dipole D_2 has a bending angle of 120° (instead of 140°), but is otherwise similar (for maximum field, bending radius and wedge focusing (25°)) to the one discussed in Sect. 4. The dipole D_3 has a 35° bending angle and otherwise the same characteristics. No wedge focusing has been considered for this magnet. The splitting of the large dipole into D_2 and D_3 (with respect to the line of Sect. 4) is made necessary by the isochronism (R_{56}=-30) requirement, and by the fact that an achromatic beam is still wanted at D.W. point. The functions had therefore to be separated. As stated above, no real optimization has been carried out, so that a lesser bending for D_3 could also be possible. Unquestionably, this line needs more space south of the K-500 cyclotron, as can be seen from a comparison between Fig. 3 and 10. This is due mostly to the need of inserting the extra quadrupoles Q_4 to Q_7. The resulting line length from the K-500 yoke exit to the D.W. point is 21.4 m, as compared to 16.6 m before. This is made up as follows:

- K-500 yoke exit to Q_1 entry a = .5 m
- Q_1 length = .4 m
- Q_1 exit to Q_2 entry = 1 m
- Q_2 length = .4 m
- Distance between Q_2 and Q_3 = .2 m
- Q_3 length = .4 m
- Q_3 exit to D_1 entry = 1.1 m
- D_1 effective length = .392 m
- Exit of D_1 to Q_4 entry = .4 m
- Q_4 length = .4 m
- Distance between Q_4 and Q_5 = 1 m
- Q_5 length = .4 m
- Q_5 exit to D_2 entry = .4 m
- D_2 effective length = 4.18 m
- Exit of D_2 to Q_6 = 1 m
- Q_6 length = .4 m

- Distance between Q_6 and Q_7 = 1 m
- Q_7 length = .4 m
- Q_7 exit to D_3 entry = .4 m
- D_3 effective length = 1.22 m
- Exit of D_3 to Q_8 entry = .4 m
- Q_8 length = .4 m
- Distance between Q_8 and Q_9 = .2 m
- Q_9 length = .4 m
- Distance between Q_9 and Q_{10} = .2 m
- Q_{10} length = .4 m
- Distance between Q_{10} and Q_{11} = 1.4 m
- Q_{11} length = .4 m
- Distance between Q_{11} and Q_{12} = .2 m
- Q_{12} length = .4 m
- Exit of Q_{12} to D.W. point = 1.4 m

The calculations with TRANSPORT were carried out for all four beams listed in Table I, adding to the double waist achromatic requirement at D.W. the R_{56}=-30 condition. The resulting beam envelopes, and the R_{16} and R_{56} plots are presented in Figs. 11 and 12, for the case of a .3 cm waist half-width. Beam dimensions are still within the limits discussed previously.

The quadrupole field strengths, again assuming 4 cm half apertures, are listed for all beams in Table VII. Just a few comments are in order:

Table VII. Quadrupole fields for matching the K-500 beams to the double waist point, including isochronism, according to the scheme of Fig. 10.[+]

Ion Quad #	$Z/A/B_o$			
	.1/49	.1/31	.02/49	.02/35
Q_1	+3.07	-3.51	+2.73	-3.40
Q_2	-5.33	+4.61	-5.59	+4.72
Q_3	+4.71	-4.06	+5.30	-4.53
Q_4	-2.53	-3.83	-2.06	-3.32
Q_5	- .70	- .66	-1.62	- .79
Q_6	-5.73	-1.39	-1.47	-1.56
Q_7	- .97	-7.20	-6.23	-6.67
Q_8	+3.57	+3.83	-4.28	_3.25
Q_9	-6.91	-6.85	+6.72	-6.06
Q_{10}	+3.56	+3.83	-4.28	+3.25
Q_{11}	-6.87	-9.55	+8.52	+ .96
Q_{12}	+5.75	+7.67	-	-7.07

[+] - All fields in kgauss, assuming 4 cm half aperture, 1 GeV/c equivalent proton rigidity.

- Matching to achromatic .3 cm double waist halfwidth, 6 mm mrad emittance
- See Table I for ion beam parameters.

- the sign sequence in the first three quadrupoles is (+, -, +) or (-, +, -) for either high field or low field ions. As a glance to Table I will show, this corresponds to a sign change in R_{16}, and a definite increase in R_{26}.
- the fields of the four quadrupoles Q_4 to Q_7 are all negative. This is correct from the point of view of fulfilling the R_{56}=-30 condition at the exit of D_2, having therefore an achromatic beam at the exit of D_3. However, as anticipated before, it may be feasible to accomplish the same results with only two quadrupoles, i.e. one in front of D_2 and one more in front of D_3. This has not been explored, and should certainly be done in a final study.
- we found it necessary to use all five quadrupoles, Q_8 to Q_{12}, after D_3, in order to keep the beam dimensions within ± 2.5 cm - In other words, an acceptable solution with just four quadrupoles, as per the scheme of Fig. 3, was not found. Not much effort was put in that direction, however.

No calculations were carried out for the second part of the line, as it is sketched in Fig. 10. This part should work as its analogous of Fig. 3, the only difference being the 51° bending magnet, instead of the 30° one of Fig. 3. The bending angle difference is not expected to play any sensible role on the line design, even though calculations should be carried out if such a scheme is adopted. The

K-800 center position is the same in the two schemes (Fig. 3 and Fig. 10) but in the latter it is rotated counter-clockwise by about 10°. Also the north movable wall of the K-800 vault is displaced by about 1 m, to allow the space for the second part of the transfer line. This geometry, of course, hinges critically on the bending angle of the D_3 magnet. If that can be reduced, then D_4 could have a lesser bending angle, and the K-800 itself could be in the same position as depicted in the scheme of Fig. 3.

6. Conclusions

This study shows that at least two comparable design schemes exist for the coupling between the K-500 and K-800 cyclotron, the relative geometry of the two machines being almost exactly similar.

The two schemes, of Fig. 3 and Fig. 10 respectively, differ critically in whether the beam bunch length is preserved:

i) by using an R.F. buncher between the two machines (Fig. 3)

ii) by making the line fully isochronous via magnet compensation of the flight times of the particles (Fig. 10).

The choice between the two schemes hinges therefore on whether a suitable R.F. buncher can be designed and built. The R.F. buncher option may have these advantages:

- it separates the "geometrical" and "dispersive" phase space matching from the longitudinal one.
- it makes beam diagnostics quite a bit easier
- it saves space
- it gives more flexibility to the whole coupling system also in view of the yet unknown real characteristics of the K-500 beams.

It is therefore desirable that some design study of an R.F. buncher be carried in order to make a final decision.

In the case that the scheme of Fig. 3 is selected, from a practical point of view the only further study to be carried out at present should be addressed as to whether Q_{13} and Q_{14} can be replaced by a single quadrupole, properly positioned.

Should instead the scheme of Fig. 10 be preferred, especially in view of the cost and technical problems associated with an R.F. buncher, the following points should be investigated:

- optimizing the splitting in bending angle between D_2 and D_3, with the aim of preserving space and eventually reducing the bending angle needed for D_4.
- search for a solution where Q_4-Q_5 can be replaced by just one quadrupole, and similarly for Q_6-Q_7.
- try to reduce the five quadrupoles Q_8 to Q_{12} to just four, perhaps more properly positioned.
- try, as in the previous scheme, to replace the Q_{13}-Q_{14} quadrupoles with just one.

For both schemes an engineering study of the various elements, especially the dipoles, should be undertaken. No difficulties are however expected on this side.

As for the general philosophy behind these two schemes, we do not expect significant changes to be introduced. Given the overall complexity of the matching requirements, we believe that the schemes presented here are rather straightforward, at least in principle if not in execution.

Figure Captions

FIG. 1. Conceptual design of the first part of the transfer line.

FIG. 2. Conceptual design of the first part of the transfer line with isochronism requirement.

FIG. 3. Scheme of the coupling line between the K-500 and K-800 cyclotrons with no isochronism requirement.

FIG. 4. Beam envelopes and R_{16} values in the first part of the coupling line for the $Z/A = .1$ ion at $B_o = 49$ and 31 kgauss.

FIG. 5. Beam envelopes and R_{16} values in the first part of the coupling line for the $Z/A = .02$ ion with $B_o = 49$ and 35 kgauss.

FIG. 6. Beam envelopes and R_{16} values in the second part of the coupling line for the O_{2+} and the 3+ ions.

FIG. 7. Beam envelopes and R_{16} values in the second part of the coupling line for the B_{1+} and Si_{3+} ions.

FIG. 8. Beam envelopes and R_{16} values in the second part of the coupling line for the C_{1+} and N_{1+} ions.

FIG. 9. Beam envelopes and R_{16} values in the second part of the coupling line for the O_{2+} and N_{13+} ions.

FIG. 10. Scheme of the coupling line between the K-500 and K-800 cyclotrons with isochronism requirement.

FIG. 11. Beam envelopes and R_{16}, R_{56} values in the first part of the line, with isochronism requirement, for the Z/A = .1 ion and B_o = 49 and 31 kgauss.

FIG. 12. Beam envelopes and R_{16}, R_{56} values in the first part of the line, with isochronism requirement, for the Z/A = .02 ion and B_o = 49 and 35 kgauss.

References

1. Transport - A.C. Paul - LBL-2697 (Feb. 1975) and references therein.
2. The extraction system for the K-500 cyclotron at M.S.U. E. Fabrici, D. Johnson, F. Resmini - MSUCP-33 and Nucl. Insts. and Methods.
3. G. Bellomo, E. Fabrici, F.G. Resmini, Injection studies for the K-800 superconducting cyclotron. IEEE Trans. Nucl. Sci. NS-26 (1979) 2090.
4. A study of phase space matching at injection in the K-800 cyclotron, G. Bellomo, F. Resmini, to be published.

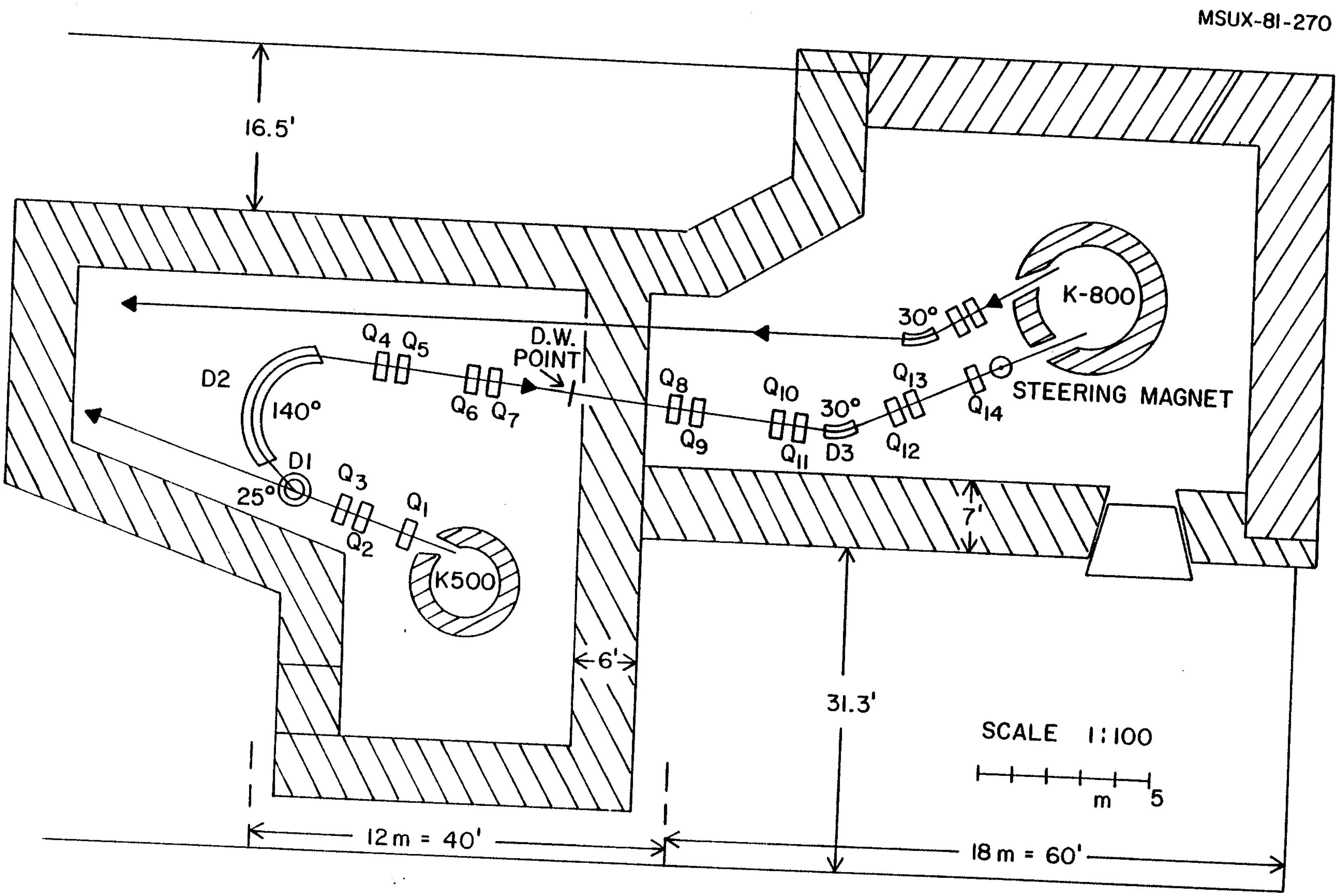
MSUX-81-270
16.5'
K-800
30°
STEERING MAGNET
Q4 Q5
D.W. POINT
D2
140°
Q6 Q7
Q8
Q9
Q10
Q11
30°
D3
Q13
Q12
Q14
D1
25°
Q3
Q2
Q1
K500
7'
6'
31.3'
SCALE 1:100
m 5
12 m = 40'
18 m = 60'

FIG. 3.

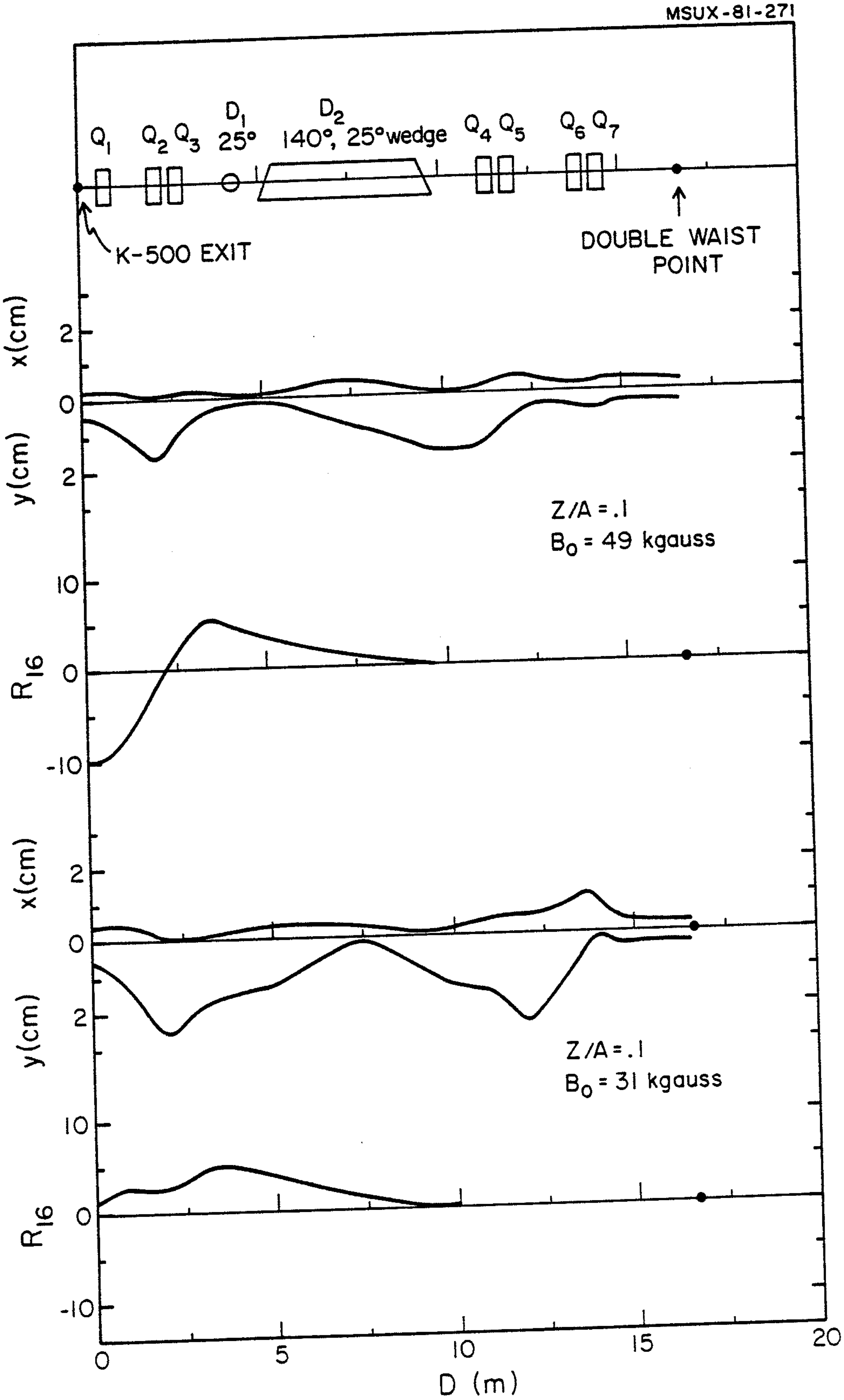
MSUX-81-271
Q1
Q2 Q3
D1 25°
D2 140°, 25° wedge
Q4 Q5
Q6 Q7
K-500 EXIT
DOUBLE WAIST POINT
x(cm)
y(cm)
2
0
2
Z/A = .1
B0 = 49 kgauss
10
R16
0
-10
x(cm)
y(cm)
2
0
2
Z/A = .1
B0 = 31 kgauss
10
R16
0
-10
0
5
10
15
20
D (m)

FIG. 4.

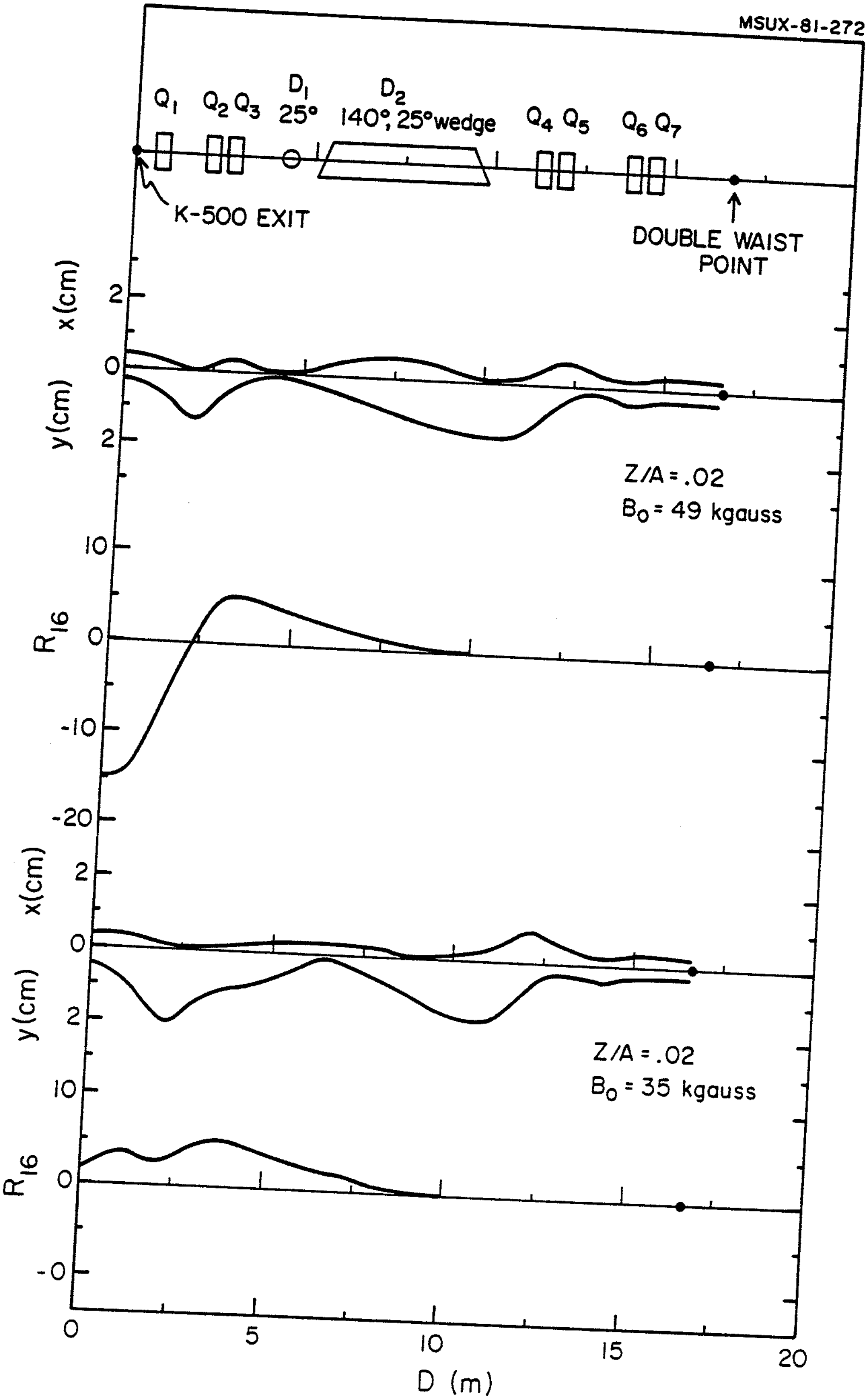
MSUX-81-272
Q_1
Q_2 Q_3
D_1
25°
D_2
140°, 25° wedge
Q_4 Q_5
Q_6 Q_7
K-500 EXIT
DOUBLE WAIST POINT
x(cm)
2
0
y(cm)
2
Z/A = .02
B_0 = 49 kgauss
10
R_{16}
0
-10
-20
x(cm)
2
0
y(cm)
2
Z/A = .02
B_0 = 35 kgauss
10
R_{16}
0
-0
0
5
10
15
20
D (m)

FIG. 5.

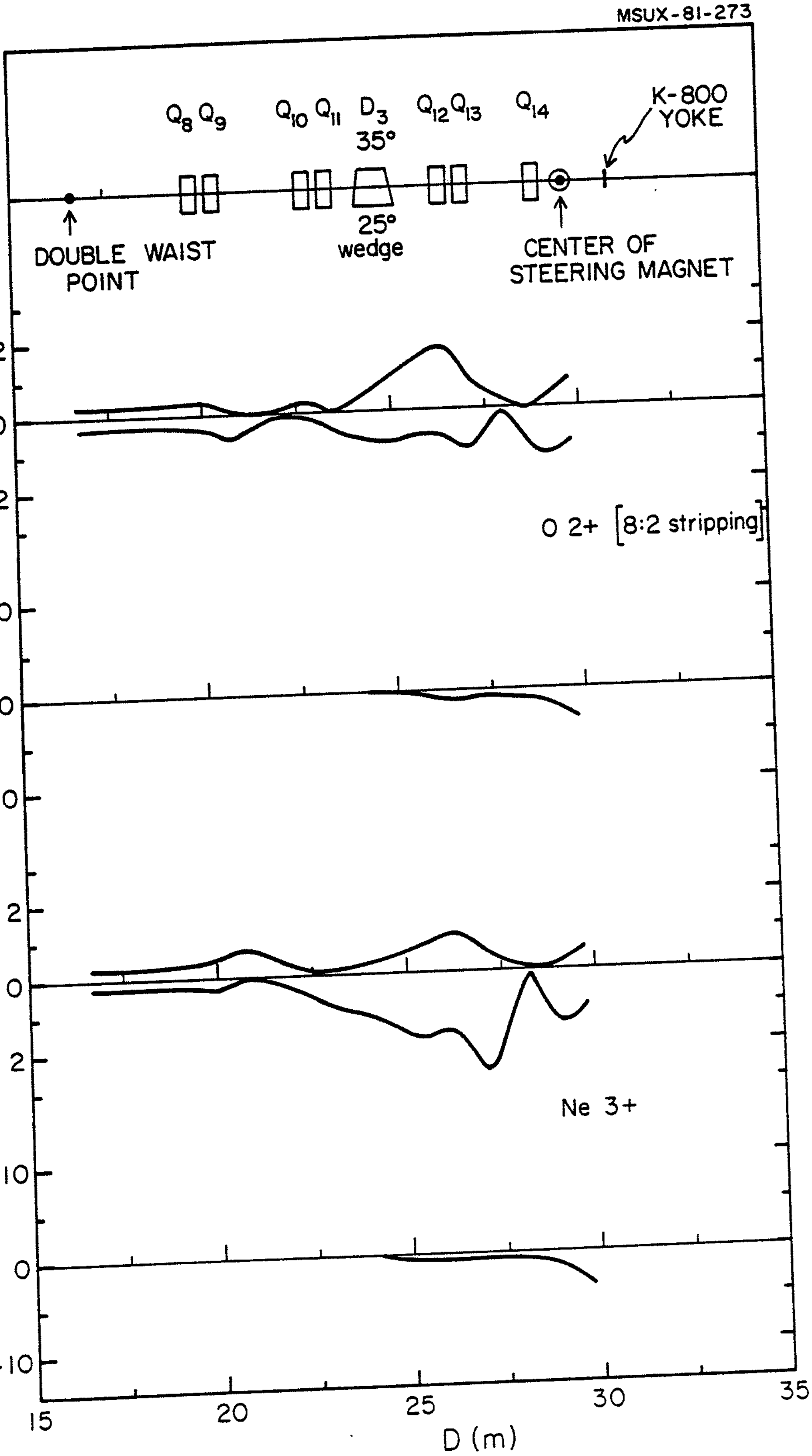
MSUX-81-273
Q8 Q9
Q10 Q11
D3 35°
Q12 Q13
Q14
K-800 YOKE
25° wedge
DOUBLE WAIST POINT
CENTER OF STEERING MAGNET
x(cm)
y(cm)
2
0
2
O 2+ [8:2 stripping]
10
R16
0
-10
x(cm)
y(cm)
2
0
2
Ne 3+
10
R16
0
-10
15
20
25
30
35
D (m)

FIG. 6.

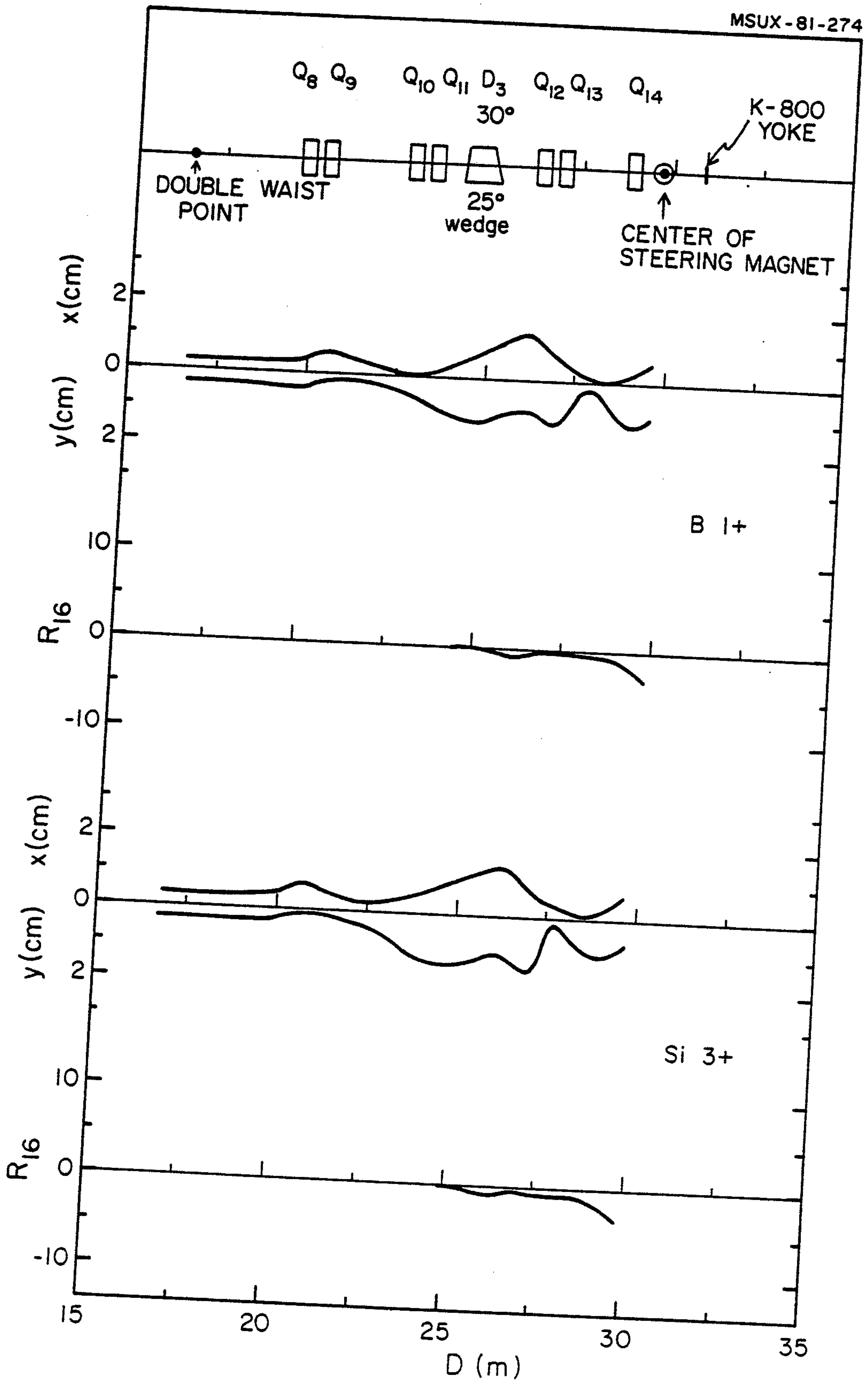
MSUX-81-274
Q8 Q9
Q10 Q11 D3
30°
Q12 Q13
Q14
K-800
YOKE
DOUBLE WAIST
POINT
25°
wedge
CENTER OF
STEERING MAGNET
x(cm)
2
0
y(cm)
2
B 1+
10
R16
0
-10
x(cm)
2
0
y(cm)
2
Si 3+
10
R16
0
-10
15
20
25
30
35
D (m)

FIG. 7.

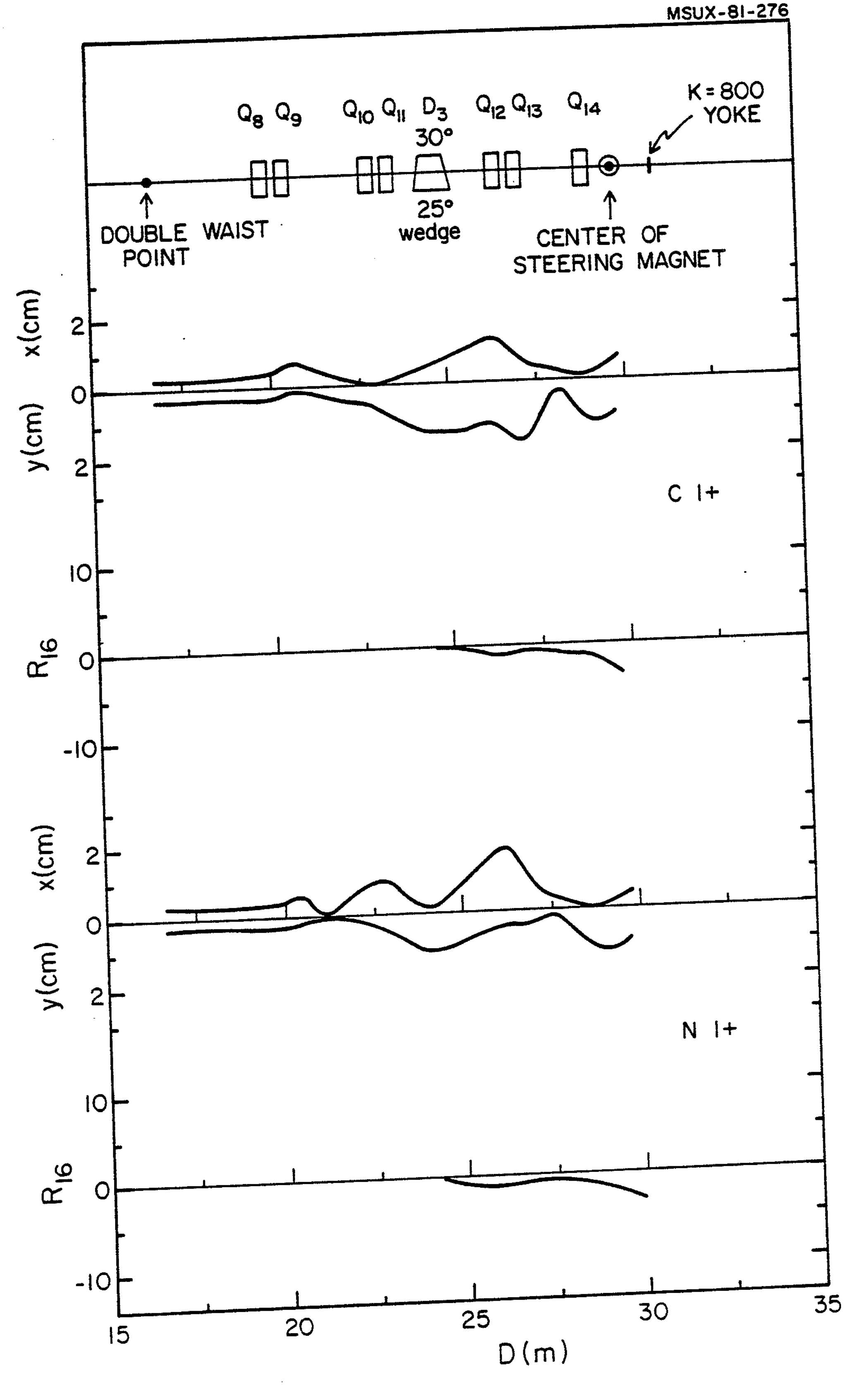
MSUX-81-276
Q8 Q9
Q10 Q11
D3
30°
25°
wedge
Q12 Q13
Q14
K=800
YOKE
DOUBLE WAIST
POINT
CENTER OF
STEERING MAGNET
x(cm)
y(cm)
2
0
2
C 1+
10
R16
0
-10
x(cm)
y(cm)
2
0
2
N 1+
10
R16
0
-10
15
20
25
30
35
D(m)

FIG. 8.

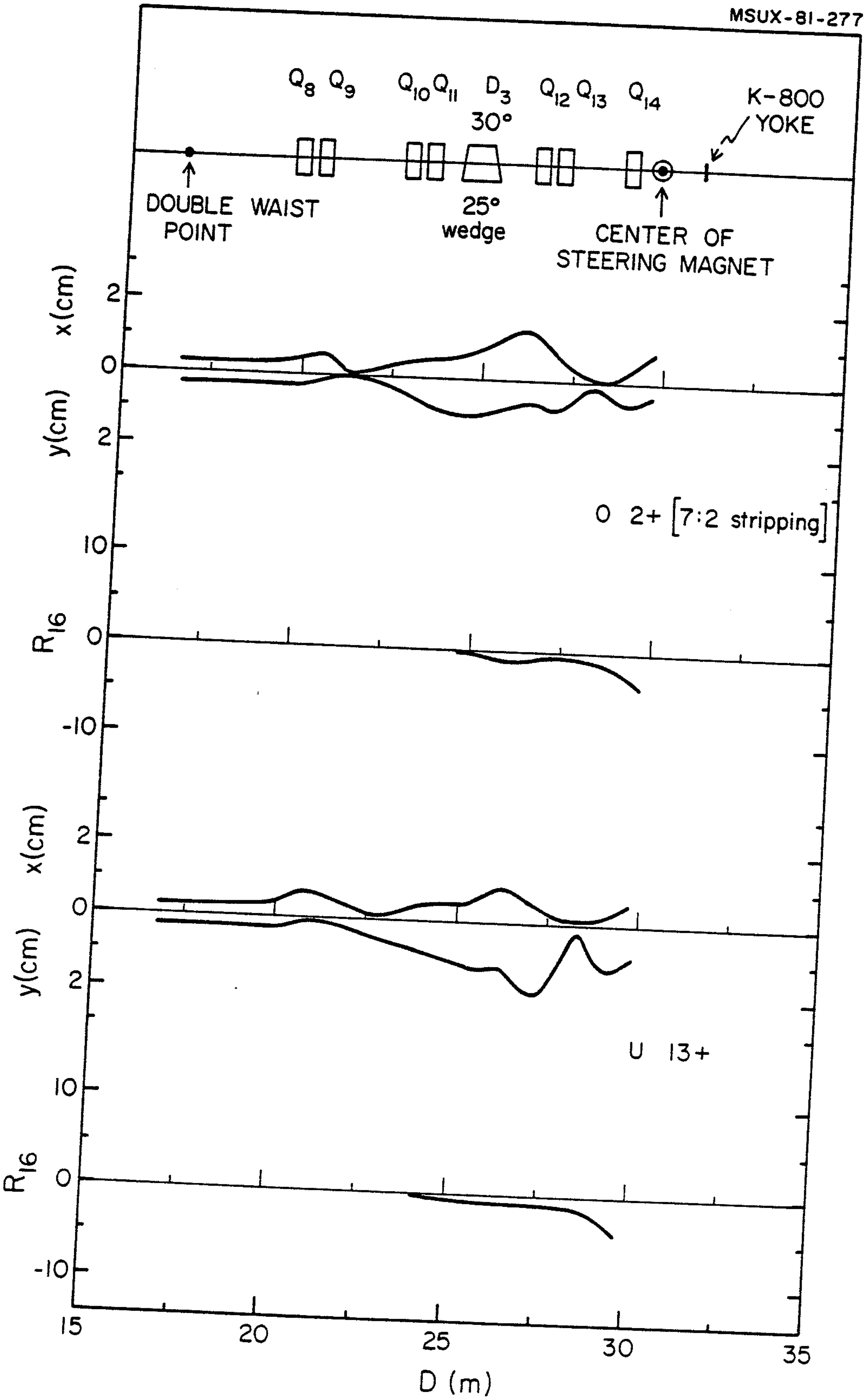
MSUX-81-277
Q8 Q9
Q10 Q11
D3
30°
Q12 Q13
Q14
K-800
YOKE
DOUBLE WAIST
POINT
25°
wedge
CENTER OF
STEERING MAGNET
x(cm)
y(cm)
2
0
2
O 2+ [7:2 stripping]
R16
10
0
-10
x(cm)
y(cm)
2
0
2
U 13+
R16
10
0
-10
15
20
25
30
35
D (m)

FIG. 9.

MSUX-81-269

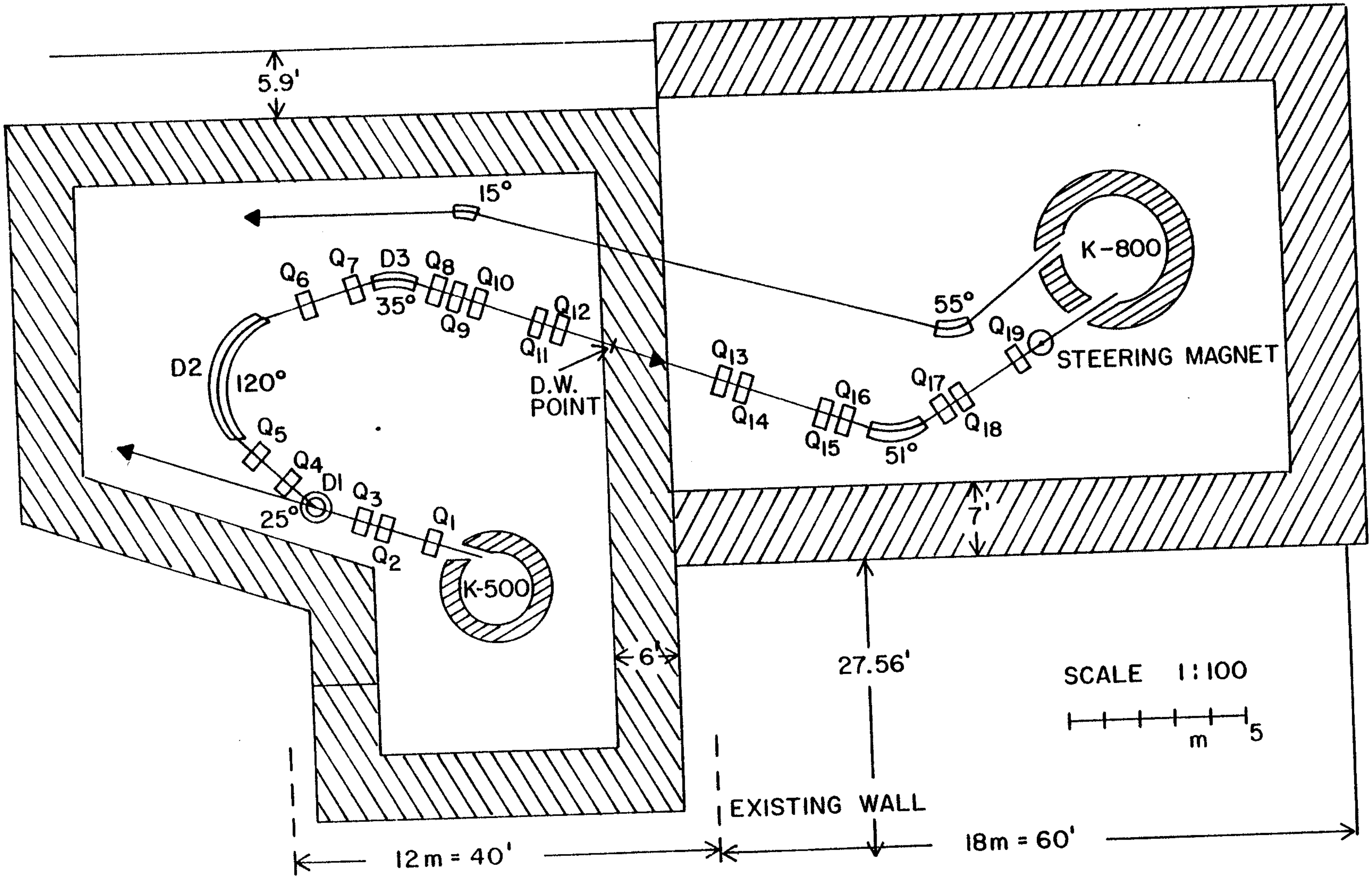

FIG. 10.

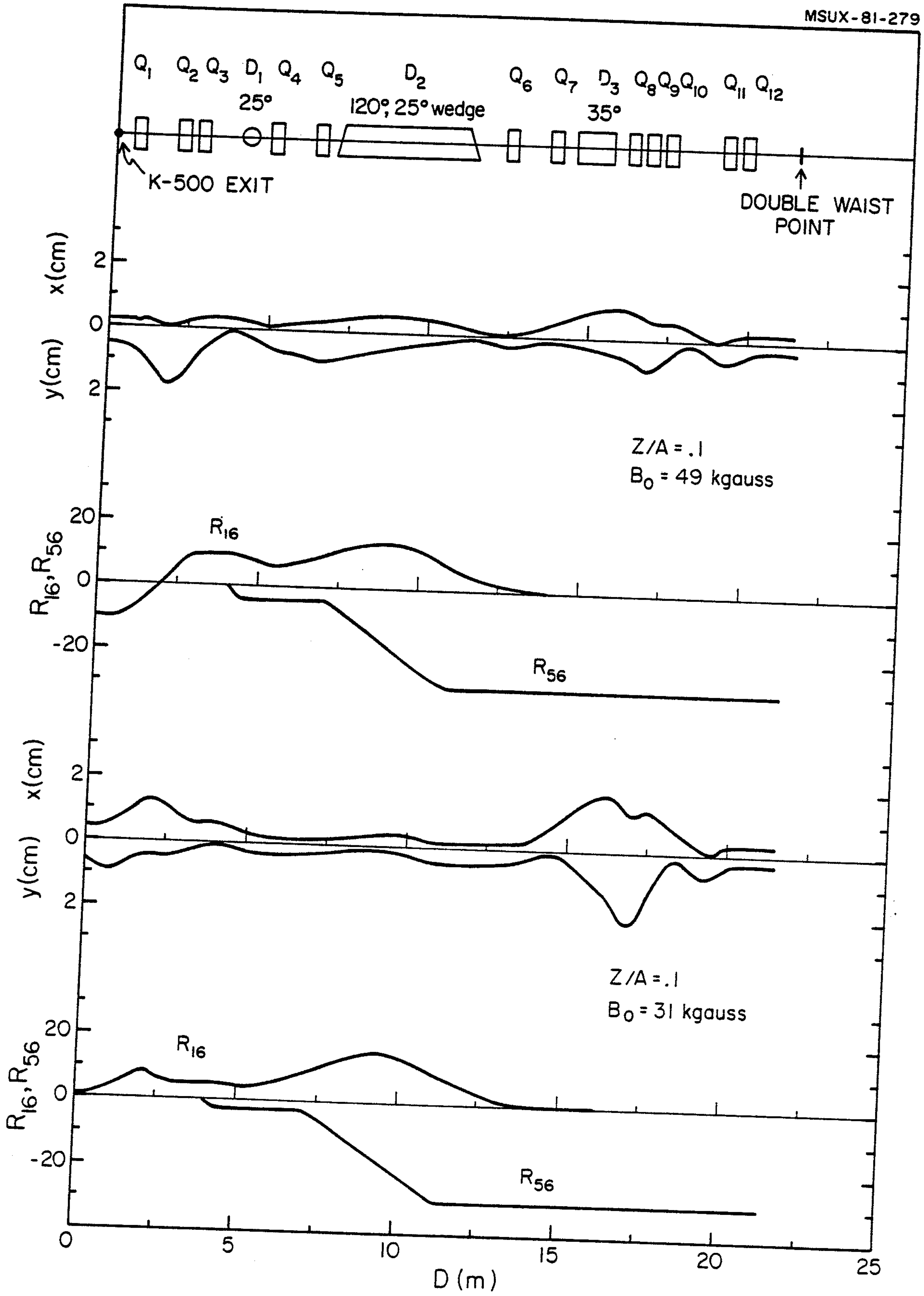
MSUX-81-279
Q1 Q2 Q3 D1 Q4 Q5 D2 Q6 Q7 D3 Q8 Q9 Q10 Q11 Q12
25°
120°, 25° wedge
35°
K-500 EXIT
DOUBLE WAIST POINT
x(cm)
y(cm)
2
0
2
Z/A = .1
B0 = 49 kgauss
R16, R56
20
0
-20
R16
R56
x(cm)
y(cm)
2
0
2
Z/A = .1
B0 = 31 kgauss
R16, R56
20
0
-20
R16
R56
0
5
10
15
20
25
D (m)

FIG. 11.

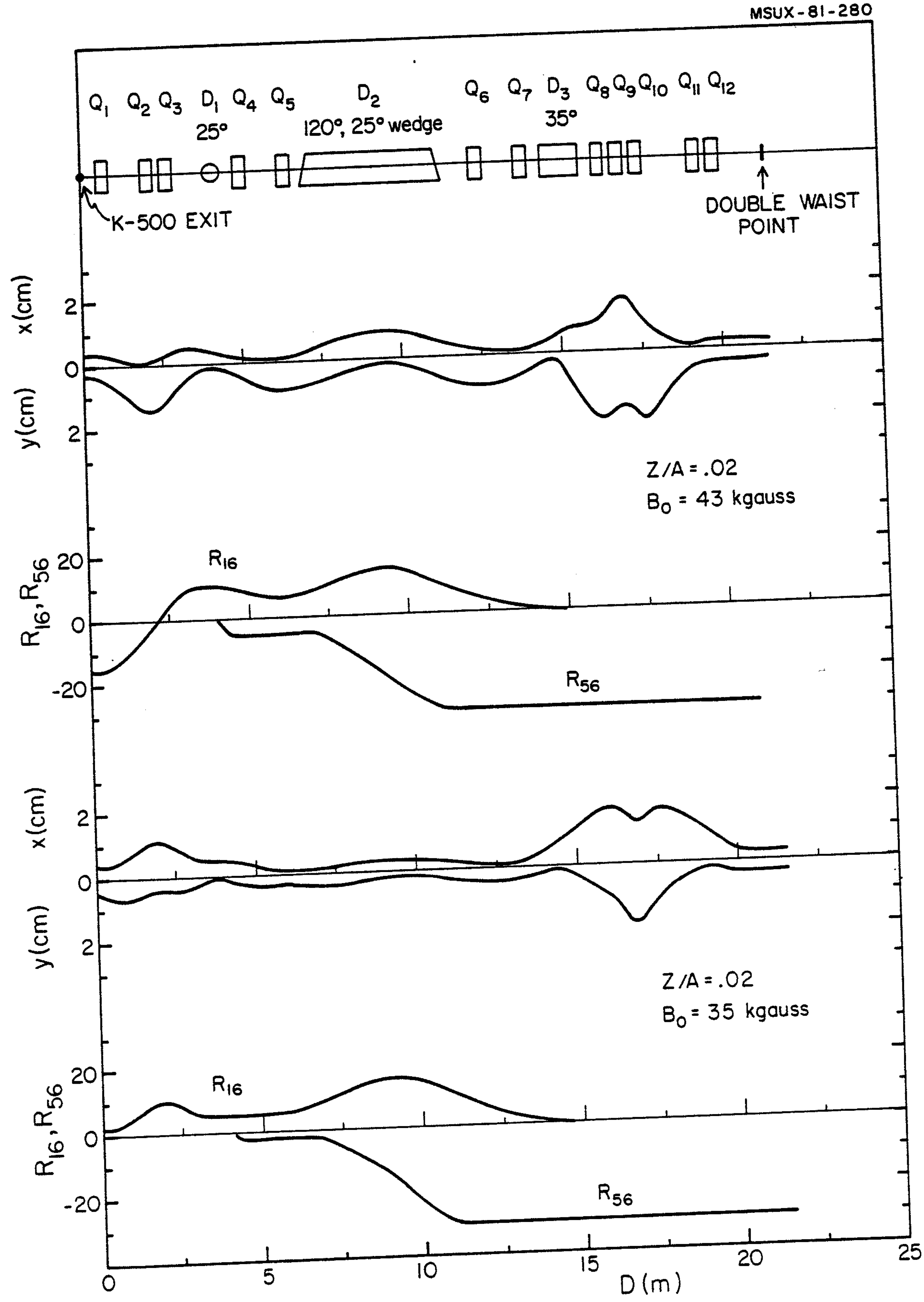
MSUX-81-280
Q1 Q2 Q3 D1 Q4 Q5 D2 Q6 Q7 D3 Q8 Q9 Q10 Q11 Q12
25°
120°, 25° wedge
35°
K-500 EXIT
DOUBLE WAIST POINT
x(cm)
y(cm)
2
0
2
Z/A = .02
B0 = 43 kgauss
R16, R56
20
0
-20
R16
R56
Z/A = .02
B0 = 35 kgauss
0
5
10
15
20
25
D(m)

FIG. 12.