

# ISTITUTO NAZIONALE DI FISICA NUCLEARE

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MILAN BIOMEDICAL CYCLOTRON**

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**PRELIMINARY DESIGN OF THE BEAM TRANSPORT SYSTEM FOR THE MILAN  
BIOMEDICAL CYCLOTRON**

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**ABSTRACT**

This report illustrates the preliminary design of the beam transport system for the Scanditronix MC40 cyclotron to be installed in Milan. The cyclotron will be dedicated to biomedical research and the different experimental conditions that could occur will require a beam transport system flexible enough so as to deliver beams with the specified characteristics. The report describes the computer codes used, the calculations performed and the results obtained. The complete configuration of the beam lines serving the first two target rooms is given, together with typical beam profiles and the emittance ellipse variation along the transfer channels.

## 1. - INTRODUCTION

A project has been undertaken by C.N.R. (Consiglio Nazionale delle Ricerche, National Research Council) for the realization of a cyclotron - based biomedical laboratory in the Milan area. A Scanditronix MC40 cyclotron has been purchased and is due to be installed either in a hospital site or in a biomedical research institute, to be built in the near future as a joint venture between C.N.R., University of Milan and I.N.F.N. (Istituto Nazionale di Fisica Nucleare, National Institute for Nuclear Physics). The MC40 is a variable energy, multi-particle accelerator, capable of accelerating protons, deuterons,  $^3\text{He}$  and  $^4\text{He}$  ions; the range of energies and values of internal and extracted beam currents are given in Table 1, according to Scanditronix specifications.

The detailed research programme has not been completely finalized, since it is also dependent on the site where the cyclotron will be installed. Nevertheless, it is planned that the accelerator will be employed for radionuclide production (including the short-lived  $^{11}\text{C}$ ,  $^{13}\text{N}$ ,  $^{15}\text{O}$  and  $^{18}\text{F}$  for PET studies): this would include both the production and processing in massive quantities of radioisotopes currently used in medical diagnosis, and the research and development of different radionuclides and production methods. However, the capabilities of the MC40 in terms of accelerated particles, range of energies and extracted beam currents, make possible its use over a wide spectrum of applications, such as proton and neutron activation analysis (*in vitro* the former, both *in vitro* and *in vivo* the latter), radiobiology and PIXE, only to mention some of the biomedical ones.

TABLE 1. Performances of the MC40.

| Particle  | External beam energy (MeV) |            | Internal beam current ( $\mu\text{A}$ ) |            | External beam current ( $\mu\text{A}$ ) |            |
|-----------|----------------------------|------------|---|------------|---|------------|
|           | Rated                      | Guaranteed | Rated                                   | Guaranteed | Rated                                   | Guaranteed |
| Protons   | 10-40                      | 11-38      | 250                                     | 150        | 150                                     | 100        |
| Deuterons | 5-20                       | 5.5-19.5   | 250                                     | 150        | 150                                     | 100        |
| Helium-3  | 13.3-53                    | 14-52      | 200                                     | 150        | 100                                     | 70         |
| Helium-4  | 10-40                      | 11-39      | 200                                     | 150        | 90                                      | 65         |

The versatility of the project justifies the design of a facility provided with different target rooms, in order to fully exploit the potentialities of the accelerator. The original design also contemplated a radiation area large enough to allow the installation of a

rotating gantry for fast neutron radiation therapy. Yet, since the real advantages of this technique are still debated, and it is not certain that the proton energy from the MC40 is sufficiently high to produce a neutron beam suitable for therapy, no final decision has been taken about this facility.

To accomplish the variety of irradiation conditions which will be required by the multiplicity of the possible experimental situations, it is necessary to design a versatile beam transport system. This report illustrates the preliminary design of such a transport system, in terms of choice and positioning of its components, tracing of beam profiles and determination of the emittance characteristics of the beam along the line. A description is given of the input data and computer programmes used, the calculations performed and the results obtained, on the basis of the specifications and the constraints imposed on the beam.

## 2. - LAYOUT OF THE INSTALLATION AND BEAM TRANSPORT

The design of the cyclotron laboratory is based on a two level building. The ground floor consists of the cyclotron vault and the target rooms, the control room and power supply room, the electronic and mechanical workshops, together with the radiochemistry laboratories. The upper floor accommodates the offices for the staff and other laboratories.

Figure 1 shows the main structures of the ground floor, the position of the cyclotron and the central axis of the beam lines, along with the indicative positions of the components for bending and focussing the particle beam. A first switching magnet ( $-45^\circ$ ,  $0^\circ$ ,  $+45^\circ$  bending angles), positioned at SM1, deflects the beam into target rooms 1 and 2; a second, identical switching magnet at point SM4 deflects the particles into target rooms 3 and 4, or let them go straight into target room 5 (which is not completely shown in Figure 1). Target rooms 1 to 4 have about the same dimensions: two of them will be used for routine production of radioisotopes, by irradiation of either solid, liquid or gas targets. A remote controlled system will provide automatic loading and unloading of solid targets at the irradiation stations, and their transport to the hot cells. Liquid and gaseous materials will be sent to and recovered from the target body by pipes, also ensuring remote controlled operations.

The other two target rooms will be used for experimental set-ups. Target room 5 is large enough to allow the installation of several beam lines, if it will not be dedicated to neutron therapy. In particular, a line could be designed to include an analyzing magnet, so as to deliver beams with a reduced energy spread.

The main effort has been put into the design of the beam lines serving target rooms 1 and 2, since it is likely these will be the first ones to start operation. The positioning of the main components of the beam lines going into target rooms 3 and 4 has also been

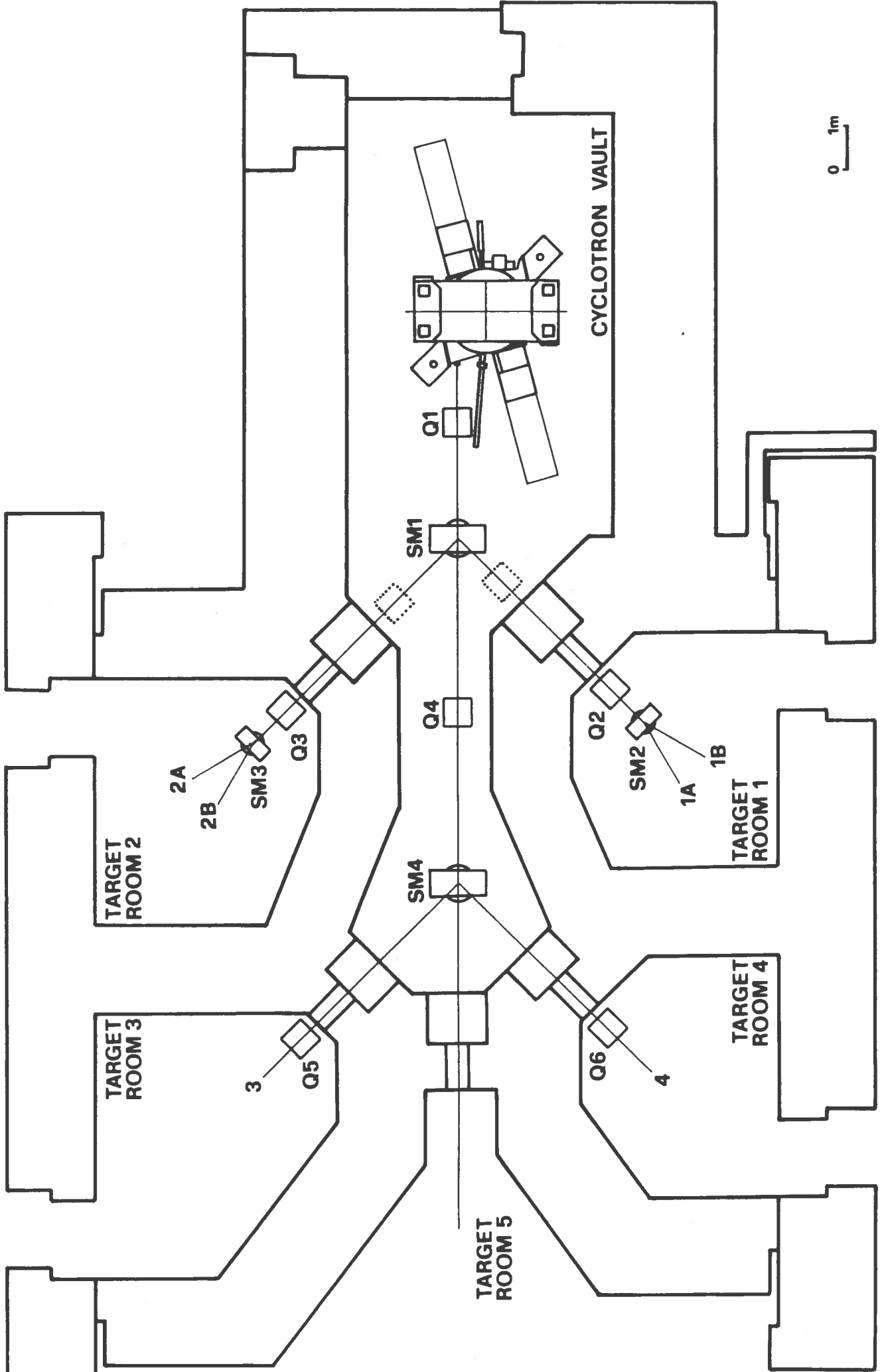


Figure 1: Main structures of the ground floor of the facility.

investigated, whilst target room 5 has not been taken into account, since its use has not been yet finalized.

In order to take into consideration the different experimental situations which could occur, the beam optics calculations performed aimed at typical values of the beam radius in the two transverse planes, at the target position, of 10x10, 5x20 and 3.5x3.5 mm<sup>2</sup>. A small beam like the third one could be required for the irradiation of high pressure gas targets, using a spinning magnet ("spinner") to obtain an uniform distribution of the beam power in the target itself, thus avoiding the production of hot spots even if the energy distribution in the beam is not uniform. The other two beam dimensions could be representative of the bombardment of solid targets: in this case it would be possible to avoid hot spots by sweeping the beam through the target by a magnet appropriately designed ("sweeping magnet").

The beam line data necessary for the beam optics calculations are the parameters of the quadrupole magnets (effective length and field gradient) and of the dipole magnets (effective length and angle of bend), and the physical distance between them. The positioning of other components, such as steering magnets, collimators, vacuum isolation valves, Faraday cups and diagnostic equipment, does not influence the beam profile and can be disregarded. They only have to be taken into account in the final design of the line, together with the special components such as spinners and sweeping magnets. The effectiveness of spinners and sweeping magnets is determined by their position in the beam line and needs to be confirmed by beam optics calculations.

### 3. - COMPUTER CODES

A set of three programmes was used for the calculations. The primary one, called BEAMS, was developed by M. Simpson of the M.R.C. Cyclotron Unit, Hammersmith Hospital, London, from an earlier programme pioneered by G. Burton and adapted for use at the Hammersmith facility.<sup>(1,2)</sup> The two others, BMPLT and ELLIP, are graphics programmes, developed by the author, giving the beam envelope and the first-order emittance ellipses at the exit of each component, in both transverse planes.

The input data required by BEAMS are the emittance parameters of a beam of particles at the entrance of the beam line, the magnetic rigidity and the momentum deviation of the particle beam, along with the parameters of the components constituting the beam transfer channel. The programme calculates, for the horizontal and vertical planes, the emittance data, the beam radius and the momentum dispersion at the exit of each component. An optimization routine gives the possibility of adjusting the quadrupole gradients to match the constraints imposed on the beam (in terms of beam radius or emittance parameters) at

specified points of the beam line. A further option calculates the transfer matrices between specified elements of the beam line.

The other two computer codes use, as input data, the output file from BEAMS. BMPLT traces the beam profiles dividing each component of the beam line into N subcomponents, and performing the calculations for each of them. N can be assigned an arbitrary value, so that the beam profile inside each element can be traced with the requested accuracy. The beam envelope is calculated with and without the contribution due to the momentum dispersion. ELLIP is a straightforward programme giving the theoretical first-order emittance ellipses at the exit of each component of the beam line.

Both BEAMS and BMPLT perform the calculations using the matrix formalism given in ref. 3. If s is the longitudinal coordinate (i.e., the coordinate of the direction of motion) and we indicate by y either of the two transverse coordinates (x, the horizontal and z, the vertical), and by y' and  $\Delta p/p$  the corresponding angular divergence and momentum deviation, the vector transformation through a given component is:

$$\begin{pmatrix} y \\ y' \\ \Delta p/p \end{pmatrix} = M \begin{pmatrix} y_0 \\ y'_0 \\ (\Delta p/p)_0 \end{pmatrix} \quad (1)$$

where M is a rank 3 matrix representing the element of the beam line. For a drift space of length L, matrix M is given by:

$$M_L = \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

For a focussing or defocussing quadrupole, we have:

$$M_F = \begin{pmatrix} \cos KL & (\sin KL)/K & 0 \\ -K \sin KL & \cos KL & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad M_D = \begin{pmatrix} \cosh KL & (\sinh KL)/K & 0 \\ K \sinh KL & \cosh KL & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3)$$

where L is the effective length and  $K=(G/B\rho)^{1/2}$ , in which G is the field gradient and B\rho the magnetic rigidity of the beam. For a dipole magnet with an omogeneous field, the matrices for the bending plane (H) and the plane perpendicular to it (V) are respectively:

$$M_H = \begin{bmatrix} \frac{\cos(\alpha - \beta_1)}{\cos\beta_1} & \rho \sin\alpha & \rho(1 - \cos\alpha) \\ -(1 - \text{tg}\beta_1 \text{tg}\beta_2)\sin(\alpha - \beta_1 - \beta_2) & \cos(\alpha - \beta_2) & \sin\alpha + (1 - \cos\alpha)\text{tg}\beta_2 \\ \rho \cos(\beta_1 + \beta_2) & \cos\beta_2 & \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

and

$$M_V = \begin{bmatrix} 1 - \alpha \text{tg}\beta_1 & \alpha\rho & 0 \\ -(\text{tg}\beta_1 + \text{tg}\beta_2)/\rho & 1 - \alpha \text{tg}\beta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

in which  $\alpha$  and  $\rho$  are the bending angle and radius respectively, whilst  $\beta_1$  and  $\beta_2$  are the entrance and exit pole edge rotation angles. If  $\beta_1 = \beta_2 = 0$ , the matrix (4) reduces to:

$$M_H = \begin{bmatrix} \cos\alpha & \rho \sin\alpha & \rho(1 - \cos\alpha) \\ -(\sin\alpha)/\rho & \cos\alpha & \sin\alpha \\ 0 & 0 & 1 \end{bmatrix} \quad (4')$$

while (5) reduces to the matrix form (2) representing a drift space, with  $L = \alpha\rho$ . In the case of a dipole magnet with rotated pole edges, BMPLT calculates the beam profile inside the magnet by assuming that the first of the  $N$  subcomponents in which the magnet is divided has  $\beta_2 = 0$  and the entrance pole edge rotated by  $\beta_1$ , the central  $N-2$  subsections have  $\beta_1 = \beta_2 = 0$ , and the last subcomponent has  $\beta_1 = 0$  and the exit pole edge rotated by  $\beta_2$ . This is done since the focussing (or defocussing) effect due to the pole edge rotation is a fringe field effect. It is a second order effect neglected for short beam lines. If  $\beta_1 = \beta_2 = 0$ , the only focussing contribution of the dipole is in the bending plane, due to the element  $m_{21}$  of the matrix (4').

In the case of a quadrupole magnet, if  $K \ll 1$  BEAMS and BMPLT approximate the element  $m_{12}$  in the matrices (3) with the expressions:

$$(\sin KL)/K = L \quad \text{and} \quad (\sinh KL)/K = L \quad (6)$$

The programmes calculate the emittance ellipse parameters, as defined by Hereward<sup>(4)</sup>



and illustrated in Figure 2. For each component along the beam line, a transformation of the complex number  $Z$  is obtained using the relationship:<sup>(4)</sup>

$$Z_1 = \frac{m_{11}Z_0 + jm_{12}}{m_{22} - jm_{21}Z_0} \quad (7)$$

where  $Z_0$  and  $Z_1$  refer to the entrance and the exit of the component,  $m_{i,h}$  are the elements of the transfer matrix and  $j^2 = -1$ . In the trivial case of a drift space of length  $L$ , (7) reduces to:

$$Z_1 = Z_0 + jL \quad (7')$$

The beam radius  $y^*$  at the exit of the component is then calculated by the formula:

$$y^* = (E/\pi R)^{1/2} \cdot (R^2 + X^2)^{1/2} = (E/\pi R)^{1/2} \cdot |Z| \quad (8)$$

The momentum dispersion vector is calculated by the expression:

$$\begin{pmatrix} D_1 \\ D_2 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} D_1(0) \\ D_2(0) \end{pmatrix} + \begin{pmatrix} m_{13} & m_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (9)$$

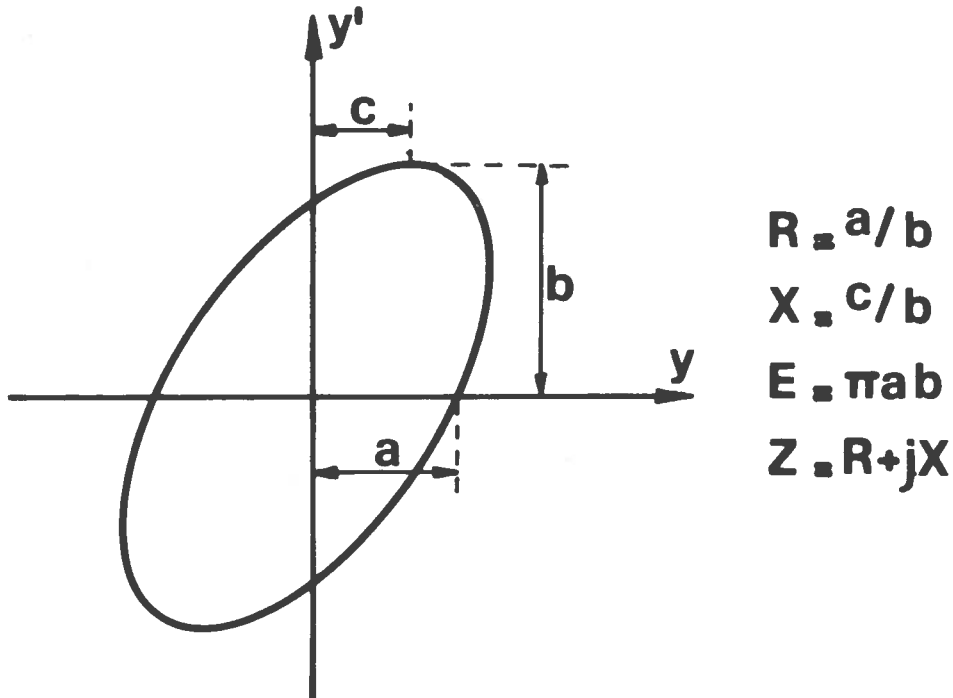


Figure 2: Representation of the emittance ellipse in phase-space.

in which  $m_{i,h}$  are the elements of any of the matrices appearing in expression (1). In the case of zero initial dispersion, as has been assumed for the present calculations, a contribution is introduced by bending the beam (which in our case only occurs in the horizontal plane). When the beam is dispersed, BMPLT traces the beam profile correcting the beam radius, as given by (8), by the expression:

$$y^*_{\text{corr}} = [y^{*2} + (D_1 \cdot \Delta p/p)^2]^{1/2} \quad (10)$$

According to experimental values obtained from measurements made by Scanditronix on MC35, an average value of  $1.5 \times 10^{-3}$  for  $\Delta p/p$  is representative, for the present purpose, for all particles and energies obtainable from the MC40.

#### 4. - INPUT DATA

All the calculations were performed for 38 MeV protons, which is the (guaranteed) beam with the highest magnetic rigidity obtainable from the MC40 (38 MeV alphas having approximately the same rigidity). The magnetic rigidity is calculated by the expression:

$$B\rho = 10^6 (2E_0 T + T^2)^{1/2} / cq \quad (11)$$

where  $c$  is the velocity of light (in m/s),  $q$  is the state of charge of the ions (1 for protons),  $E_0$  the rest energy (in MeV) and  $T$  the kinetic energy (in MeV) of the particles, and  $B\rho$  is in Tesla·metre (T·m). For 38 MeV protons,  $B\rho = 0.8997$  T·m.

Three different sets of experimental values were used as input data for the emittance parameters: the values from the Oslo MC35, the data from the measurements made in Uppsala, during the factory tests, on the MC40 Mark II cyclotron for the M.R.C. Cyclotron Unit at Hammersmith Hospital and, as soon as they became available, the data obtained at Hammersmith during the acceptance tests of the cyclotron. These data are reported in Table 2. All the measured values refer to a point 0.9 metres downbeam from the face of the cyclotron magnet yoke. It is apparent from the table that the three sets of data are fairly different from each other.

As stated earlier, the beam line parameters required for the calculations are: 1) the effective length and bending angle of the dipole magnets; if the dipole presents pole edge rotation, the angles  $\beta_1$  and  $\beta_2$  are also requested, but this is not the present case; 2) the effective length and field gradient of the quadrupoles; when use is made of the optimization routine, starting values for the gradients have also to be fed in; 3) the drift lengths between the previous components. In our case, the beam is only bent in the horizontal plane

and the deflection angle is taken positive when the beam is bent to the left (i.e., when the deflection occurs in the same direction of the circulation of the beam inside the ciclotron).

Table 2. Emittance data.

|         | Horizontal plane |           |            | Vertical plane |           |            |
|---------|------------------|-----------|------------|----------------|-----------|------------|
|         | R                | X         | E          | R              | X         | E          |
|         | (mm/mrad)        | (mm/mrad) | (mm·mrad)  | (mm/mrad)      | (mm/mrad) | (mm·mrad)  |
| MC35    | 0.1129           | 0.7097    | 15.9 $\pi$ | 0.2321         | 1.1151    | 15.9 $\pi$ |
| MC40 *  | 0.5560           | 1.270     | 22.1 $\pi$ | 1.710          | 2.190     | 16.4 $\pi$ |
| MC40 ** | 0.644            | 0.970     | 10.3 $\pi$ | 1.57           | 1.10      | 23.1 $\pi$ |

\* measured in Uppsala

\*\* measured in Hammersmith

Several sets of calculations were performed, with progressive refinements of the beam line parameters relevant to the calculations. The magnetic data of dipoles and quadrupoles and the physical dimensions of all the various components of the beam transport system were supplied by Scanditronix. Even if we have to allow for some uncertainties in the data, they are accurate enough for the present purpose. The final dipole and quadrupole parameters used in the computer codes are listed in Table 3.

Table 3. Dipole and quadrupole data.

|                    | Bending angle                | Effective length                  | Bending radius         |
|--------------------|------------------------------|-----------------------------------|------------------------|
| Dipoles SM1, SM4   | 0°, $\pm 45^\circ$           | 568.6 mm                          | 724 mm                 |
| Dipoles SM2, SM3   | $\pm 15^\circ$               | 331.0 mm                          | 1264 mm                |
|                    | Effective length of singlets | Physical spacing between singlets | Maximum field gradient |
| Quadrupole doublet | 260 mm                       | 200 mm                            | 10 T/m                 |
| Quadrupole triplet | 240 mm                       | 160 mm                            | 10 T/m                 |

## 5. - CALCULATIONS AND RESULTS

The calculations were performed with an HP1000 computer, using a 2648 graphics terminal and a 7580 multi-colour plotter. First, the configuration of beam 1B (see Figure 1) was investigated.

Since the inner diameter of the beam pipe is 70 mm, the beam radius in both the horizontal and vertical planes should not exceed about 20 mm at any point along the transfer channel, so as to allow the transport of the particle beam even if it is not perfectly centered on the axis of the channel, thus avoiding unnecessary activation of the components of the beam transport system. Moreover, the vertical gap of the switching magnets is 40 mm, so that the beam radius in the vertical plane must necessarily be less than 20 mm at these positions, and preferably not more than 10 mm. The radiation shields inserted in the walls between the cyclotron vault and each target room, and used to reintegrate the shielding thickness when that particular beam line is not in use, will also probably have a vertical gap of 40 mm, so that the same constraint applies here.

The first series of calculations was carried out using the emittance data from the Oslo MC35. The first investigations aimed at the definition of the first focussing element (component Q1 in Figure 1), i.e. whether it should be a quadrupole doublet or triplet, and its position. The focussing component Q2 was assumed to be a doublet placed inside the cyclotron vault, after the switching magnet SM1. Taking first Q1 as a doublet, its distance from the cyclotron extraction channel and the separation of the two quadrupoles were both investigated. The best solution appears that of positioning the doublet as close as possible to the cyclotron, in order to better control the divergence of the beam emerging from the accelerator. However, a minimum space has to be provided between the cyclotron and the first quadrupole in order to allocate other equipment, such as a collimator, a steering magnet and/or a beam profile monitor. Calculations were also made using an increased separation of the quadrupoles, but with no improvement in the results, so that it is better to stick to the value given by Scanditronix and reported in Table 3. Calculations were performed applying the optimization procedure to the beam line as a whole and trying to adjust all the quadrupole gradients at the same time, but also considering the line as splitted in two parts (from the cyclotron to the switching magnet SM1 and from SM1 to the target) and carrying out separate optimizations for the two sections, using the output values obtained from the first part as input values for the second one.

No attempt has been made to obtain any specified beam size at the target, since this configuration did not even allow the confinement of the beam radius below the values pointed out earlier. In particular, the largest radius always occurred at the second quadrupole of the first doublet, either in the horizontal or vertical plane depending on

whether the first quadrupole is focussing in the other plane. It is then obvious that a doublet as component Q1 is not sufficient.

In the next series of calculations, the doublet Q1 was substituted by a triplet. By testing different values of its distance from the cyclotron, it was possible to achieve a better control of the beam in the first part of the transfer channel; the final results showed a beam radius not exceeding about 21-22 mm in both planes, with the best set of gradients for the triplet being FDF in the horizontal plane.

Next, calculations were performed using the emittance data from the MC40 Mark II measured in Uppsala. This data is quite different from the previous (see Table 2), and is more applicable to the present case. On the basis of these new values, beam profiles not exceeding the required dimensions in both transverse planes were easily achieved both with a doublet and a triplet as component Q1. The possibility of obtaining specified beam cross sections on target was then investigated. As stated earlier, typical values for the radii in the two planes of  $10 \times 10 \text{ mm}^2$ ,  $5 \times 20 \text{ mm}^2$  and  $3.5 \times 3.5 \text{ mm}^2$  were studied. Calculations were carried out using: 1) Q1=triplet, emittance data from MC35; 2) Q1=doublet, emittance data from MC40; 3) Q1=triplet, emittance data from MC40. The  $10 \times 10$  beam was achieved in the three cases, but the  $5 \times 20$  beam appeared as the lower limit: it was not possible to further squeeze the beam at the target position without unacceptably increasing its size elsewhere.

Since the same type of results were obtained using either a doublet or a triplet as component Q1, it is apparent that the bad control of the beam in the second part of the transfer line is caused by the position of the doublet Q2, too far from the target. Therefore, it was moved into the target room (Figure 1). This causes the beam line to be slightly longer than before, thus having the target station closer to the wall (the same happens for the beam lines 1A, 2A and 2B). Again, both a doublet and a triplet were tested as component Q1, using the Uppsala emittance parameters (the Oslo MC35 data was abandoned, after suggestion by Scanditronix). The results indicated that all the constraints imposed on the beam radius and the test sizes on target are satisfied if Q1 is a triplet (if it is a doublet, it turned out that it was not possible to bring the beam radius at the target below  $5 \times 4 \text{ mm}^2$ ). By slightly shortening the last drift length (after the dipole SM2), it is also possible to save enough space between the target and the wall for insertion of experimental equipment.

Having defined the basic configuration of beam 1B, the arrangement of beam 2B was then investigated. This line is almost identical, except that it is 0.65 metres longer: this difference cannot be completely neglected since it increases the distance between the focussing elements Q1 and Q3, which is already large (the ideal position of the doublets Q2 and Q3 lies somewhere inside the shielding walls separating the cyclotron vault respectively from the target rooms 1 and 2). Calculations were performed with the triplet Q1 positioned as defined by the previous results and the doublet Q3 placed inside target room 2

(as shown in Figure 1). Different values of the final drift length were tested; by a suitable choice of this parameter, beam profiles similar to those ones obtained for beam 1B were achieved. Thus, the configuration of beams 1A, 1B, 2A and 2B is very much the same, as expected.

It should be pointed out that, since we have four almost identical beam lines, it would be possible to choose the best combination of right and left deflections in order to get more or less dispersed beams. A few calculations were carried out to monitor the influence of the sign of the two bending angles on the momentum dispersion of the beam.

Next, the best position for a spinning magnet was investigated. In order to allow the use of the spinner for irradiations carried out at any of the targets in rooms 1 and 2, one spinner is needed before each of the switching magnets SM2 and SM3. Although it could be placed either before or after the quadrupole doublet (Q2 or Q3), the latter solution looks better, otherwise the set up of the current in the coils of the spinner would also be dependent on the field gradient of the quadrupoles. As mentioned in section 2, the spinner will be used to spin small beams around the central axis of the line. The angular divergence the spinner has to provide in both transverse planes is easily calculated from the transfer matrix:

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix} \quad (12)$$

where the matrix transforms the beam coordinates from the spinner to the target. Since  $y'_0=0$ , the angular divergence at the spinner is given by:

$$y'_0 = y/m_{12} \quad (13)$$

where  $y$  is the required displacement of the beam centre from the axis at the target. This applies to both the  $x$  and  $z$  directions.

Figure 3 shows the final design of the beam lines serving target rooms 1 and 2, with the positions of all components. Only the vacuum isolation valves have not been indicated, since they would have been too small on a scaled drawing. The spinner dimensions were assumed from the design of this component as developed at Hammersmith (flange to flange distance 300 mm).

It should be noticed that the space available from the edge of the cyclotron magnet yoke to the first quadrupole of the triplet is limited, so that it will be possible to fit a collimator in plus a steering magnet or a beam profile monitor, but not both of them. It is advisable that the first two steering magnets (before and after the triplet Q1) can steer the beam in both the  $x$  and  $z$  directions: this is to provide the possibility of adjusting the position of the beam in

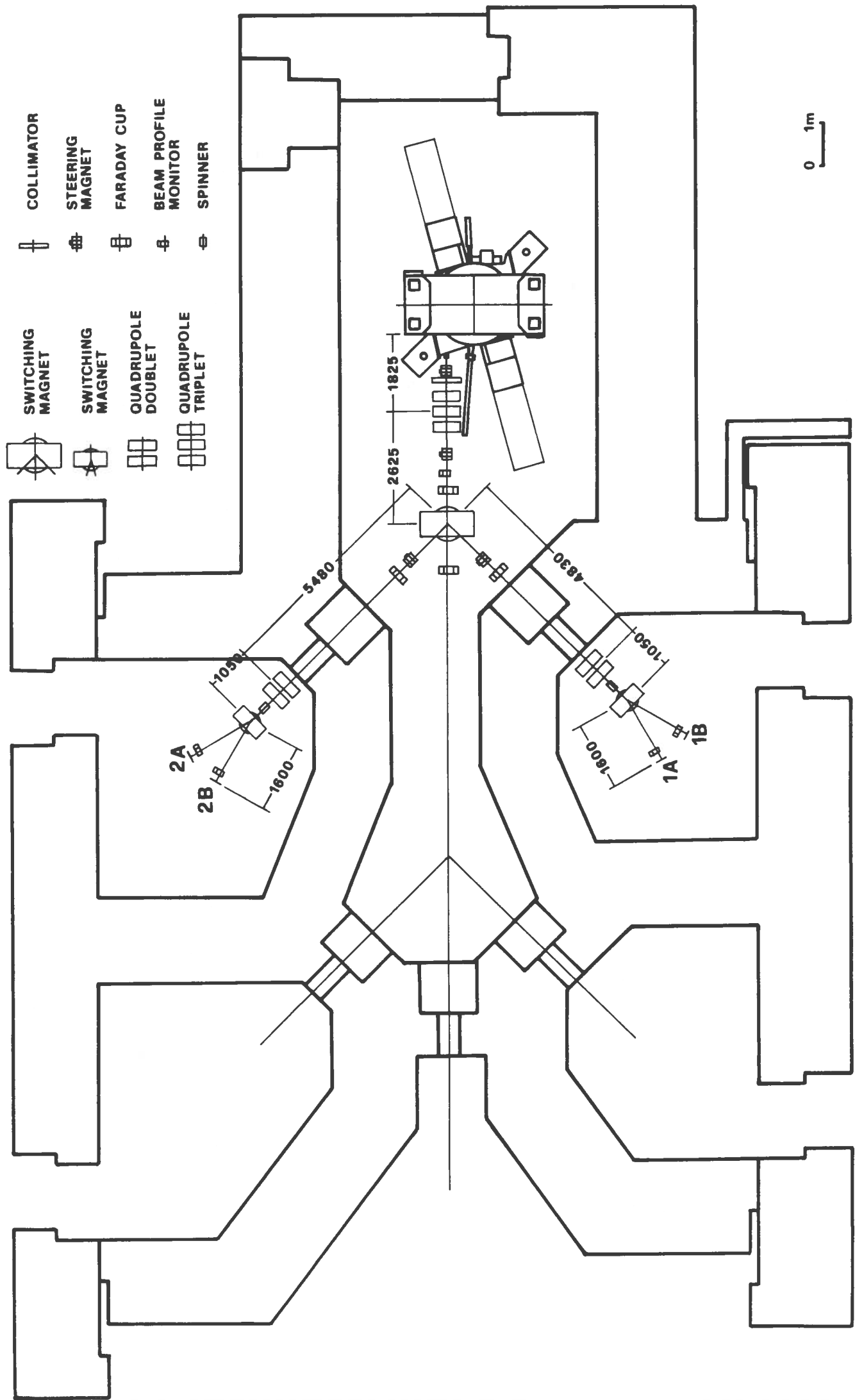


Figure 3 : Configuration of beam transport for target rooms 1 and 2.

the case it is off-axis as it emerges from the extraction channel of the cyclotron.

Figures 4 to 15 show typical beam profiles for the beam lines 1A, 1B, 2A and 2B, in both transverse planes; for the horizontal plane, the beam envelopes with and without the correction due to the momentum dispersion are both given (the largest profile being that one with the dispersion contribution). Figure 16 gives, as an example, the emittance ellipses at the exit of each component of beam line 1B for the same beam profile reported in Figure 4.

Calculations were also performed for beams 3 and 4, in order to define the position of the focussing components. The required beam cross sections on target can be achieved if Q1 is a triplet (positioned as before), Q4 is also a triplet, placed halfway between the two switching magnets SM1 and SM4, and Q5 and Q6 are doublets placed inside target rooms 3 and 4.

Finally, some more calculations were carried out for beams 1B and 2B, using the emittance data from the MC40 Mark II measured in Hammersmith during the acceptance tests. On the basis of these values, which are quite different from those obtained in Uppsala from the same cyclotron, the specified beam profiles were achieved even with a doublet as component Q1. However, because of these uncertainties on the emittance parameters, it is safer to think of component Q1 as being a triplet.

To conclude, it should be pointed out that the values of the effective length for the doublet and the triplet reported in Table 3 are slightly different. In fact, the value for the doublet was taken from a Scanditronix report, whilst for the triplet we used the data supplied to Hammersmith by Scanditronix. Most of the calculations were carried out using the value given in Table 3, except for the last series (based on the emittance data measured at Hammersmith), where use was made, for all the quadrupoles, of a value calculated by the expression:<sup>(5)</sup>

$$l_e = l + kr \tag{14}$$

where  $l$  is the length of the pole and  $r$  the aperture radius. In the present case, with  $l=200$  mm,  $r=39$  mm and assuming  $k=0.85$ , we obtain an effective length of 233 mm, not significantly different from the previous values.

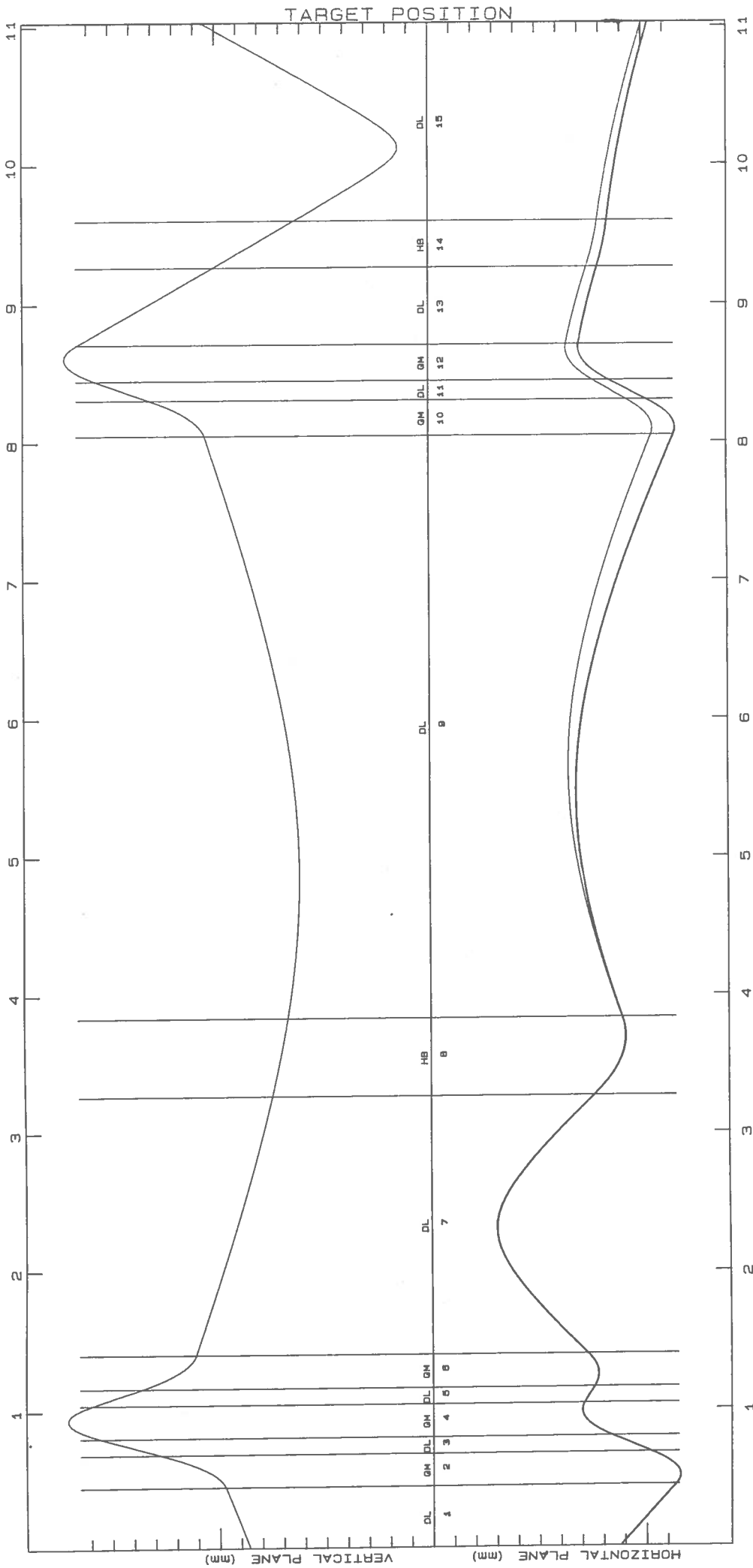
## 6. - CONCLUSIONS

The sketch shown in Figure 3 reports the exact position of the dipoles and quadrupoles in the beam lines serving the first two target rooms; the positions of the other components are only indicative, since they are not particularly critical. Additional collimators may be placed at different locations, and in particular before the target stations, to cut undesired tails that may be presented by the beam.



MILAN CYCLOTRON PROJECT - BEAM 1B - 38 MeV PROTONS - MC40 Mk II EMITTANCE

BEAM DIRECTION →

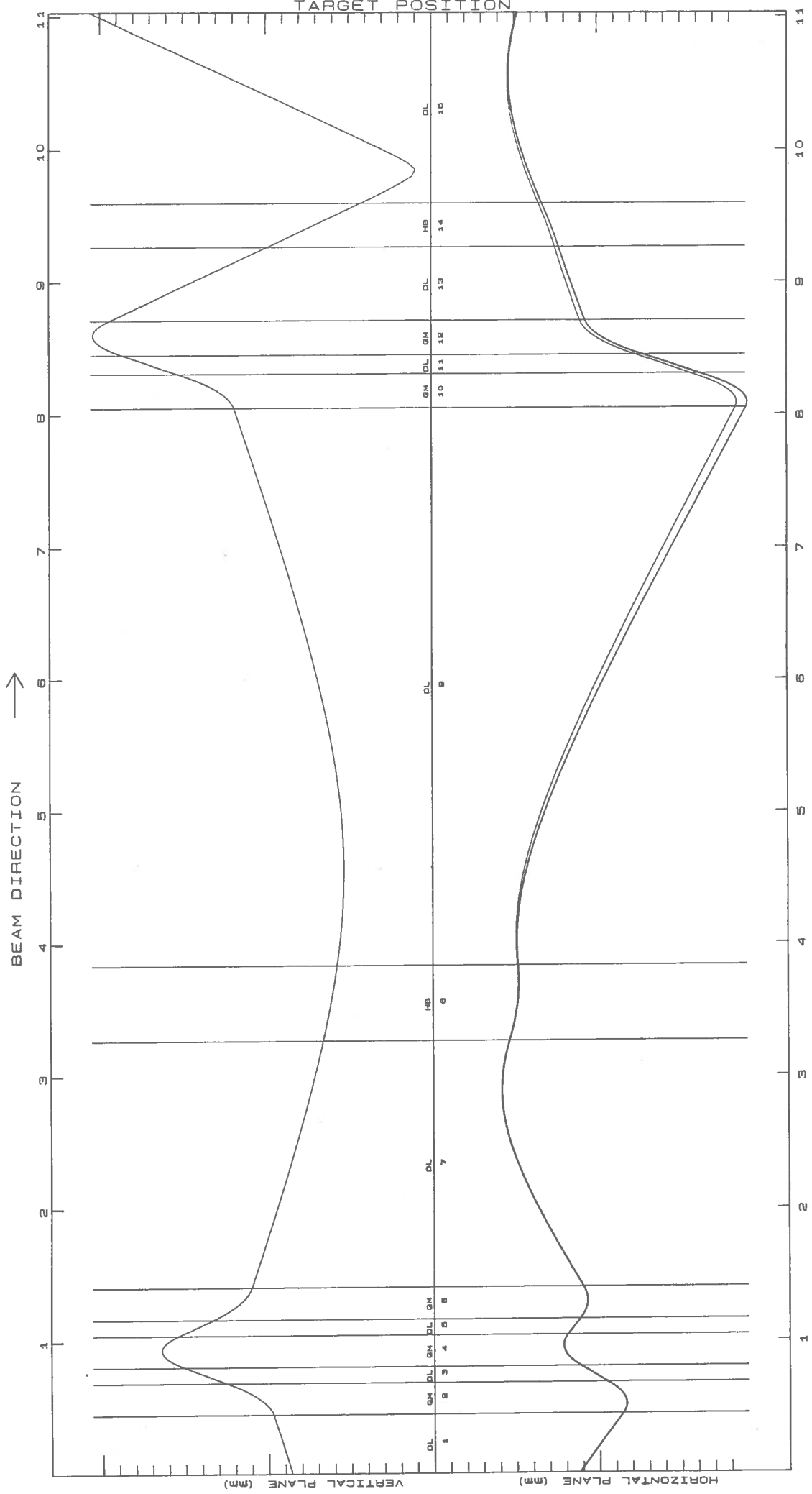


HORIZONTAL SCALE IN METRES

| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB  | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.1 | 8.3 | 8.5 | 8.7 | 9.3 | 9.6 | 11.0 |

DL=DRIFT LENGTH GM=QUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

MILAN CYCLOTRON PROJECT - BEAM 1B - 38 MeV PROTONS - MC40 MK II EMIITANCE



| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB  | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.1 | 8.3 | 8.5 | 8.7 | 8.3 | 8.6 | 11.0 |

DL=DRIFT LENGTH GM=QUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 5 : Beam profile in beam line 1B: beam radius on target: 5x20 mm<sup>2</sup>.

MILAN CYCLOTRON PROJECT - BEAM 1B - 38 MeV PROTONS - MC40 MK II EMIITANCE

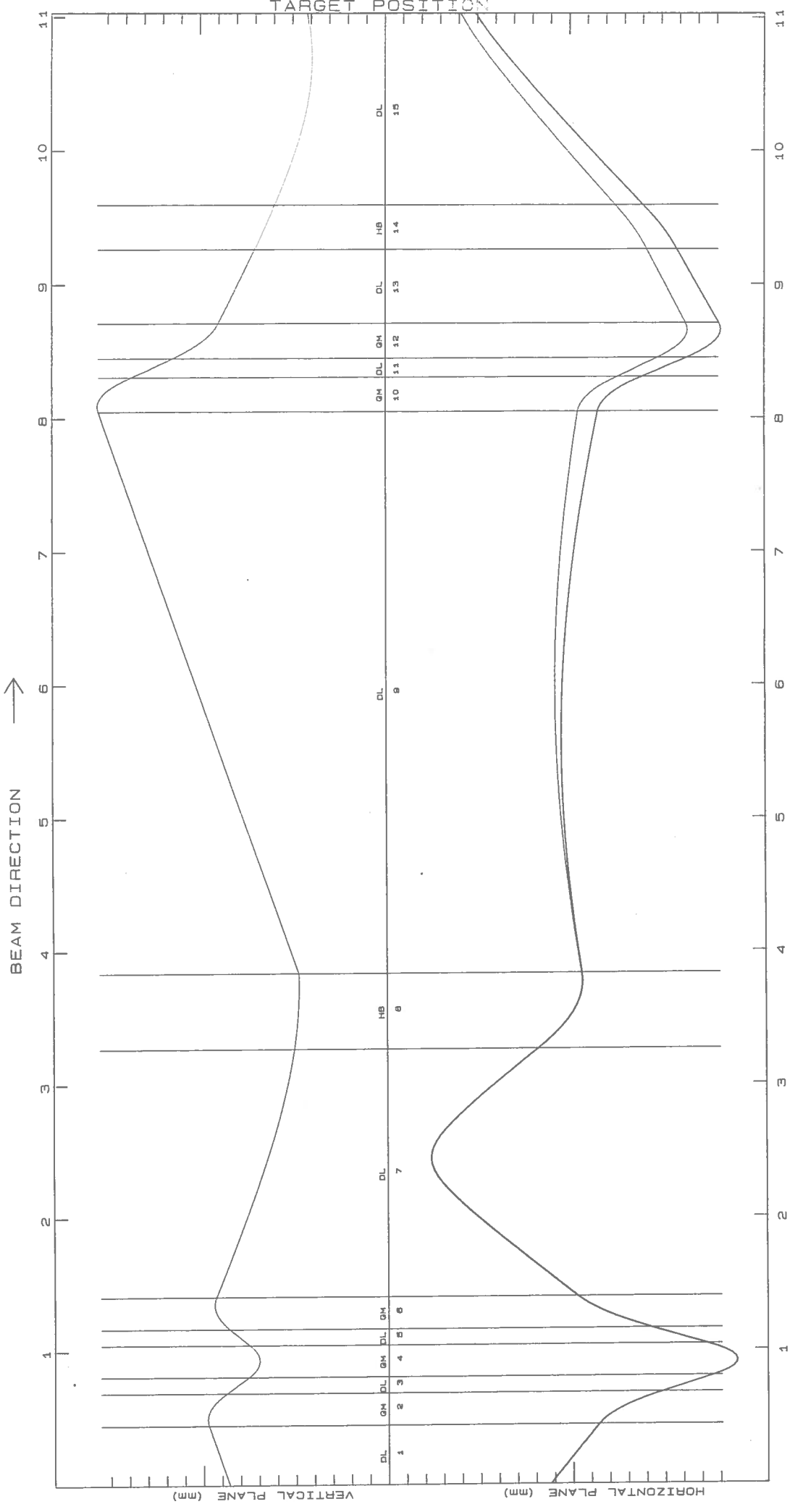
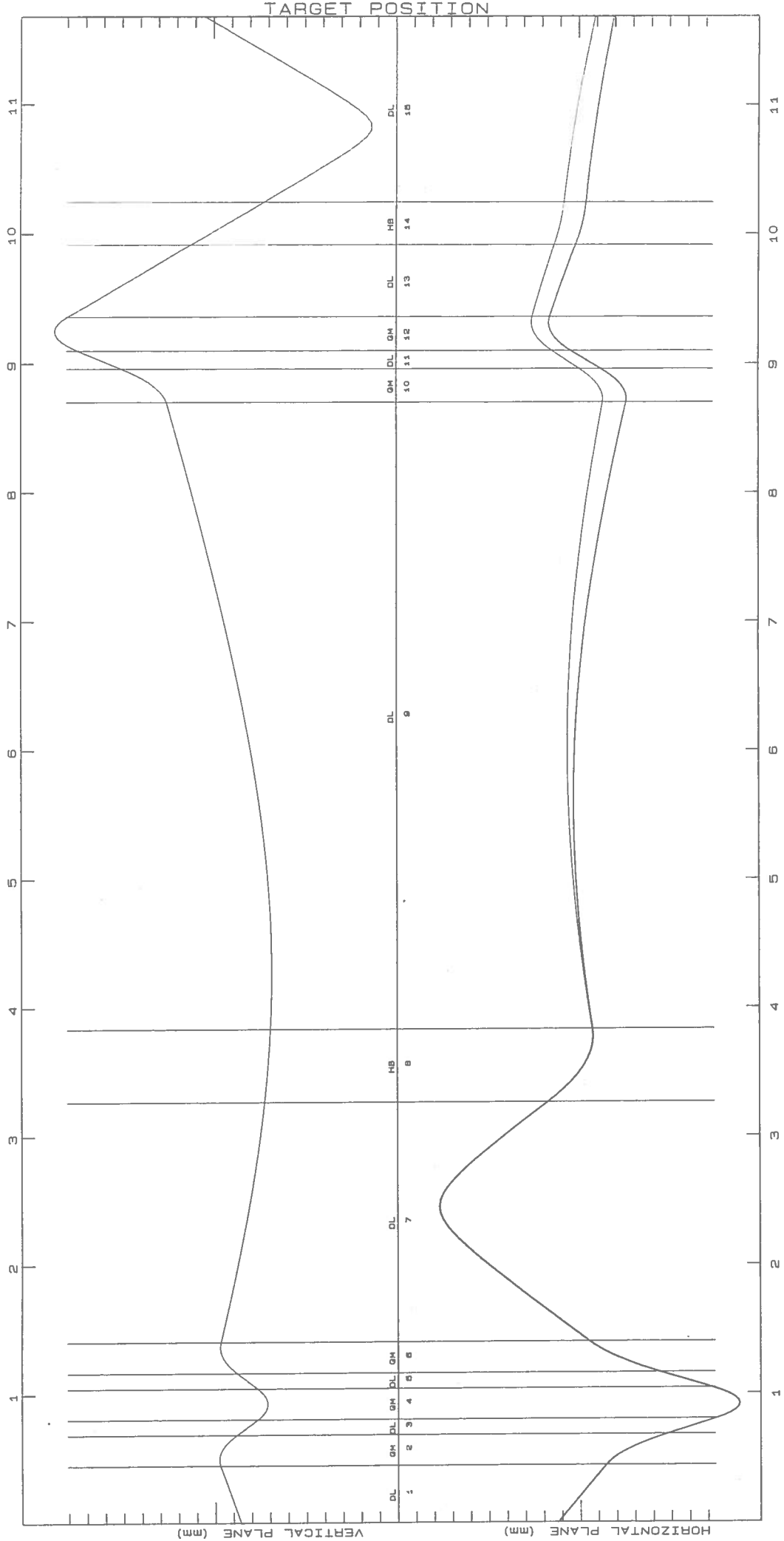


Figure 2: Beam profile in beam line 1D, beam radius on target. 0 5.0 E mm=2

MILAN CYCLOTRON PROJECT - BEAM 2B - 38 MeV PROTONS - MC40 MK II EMISSION

BEAM DIRECTION →



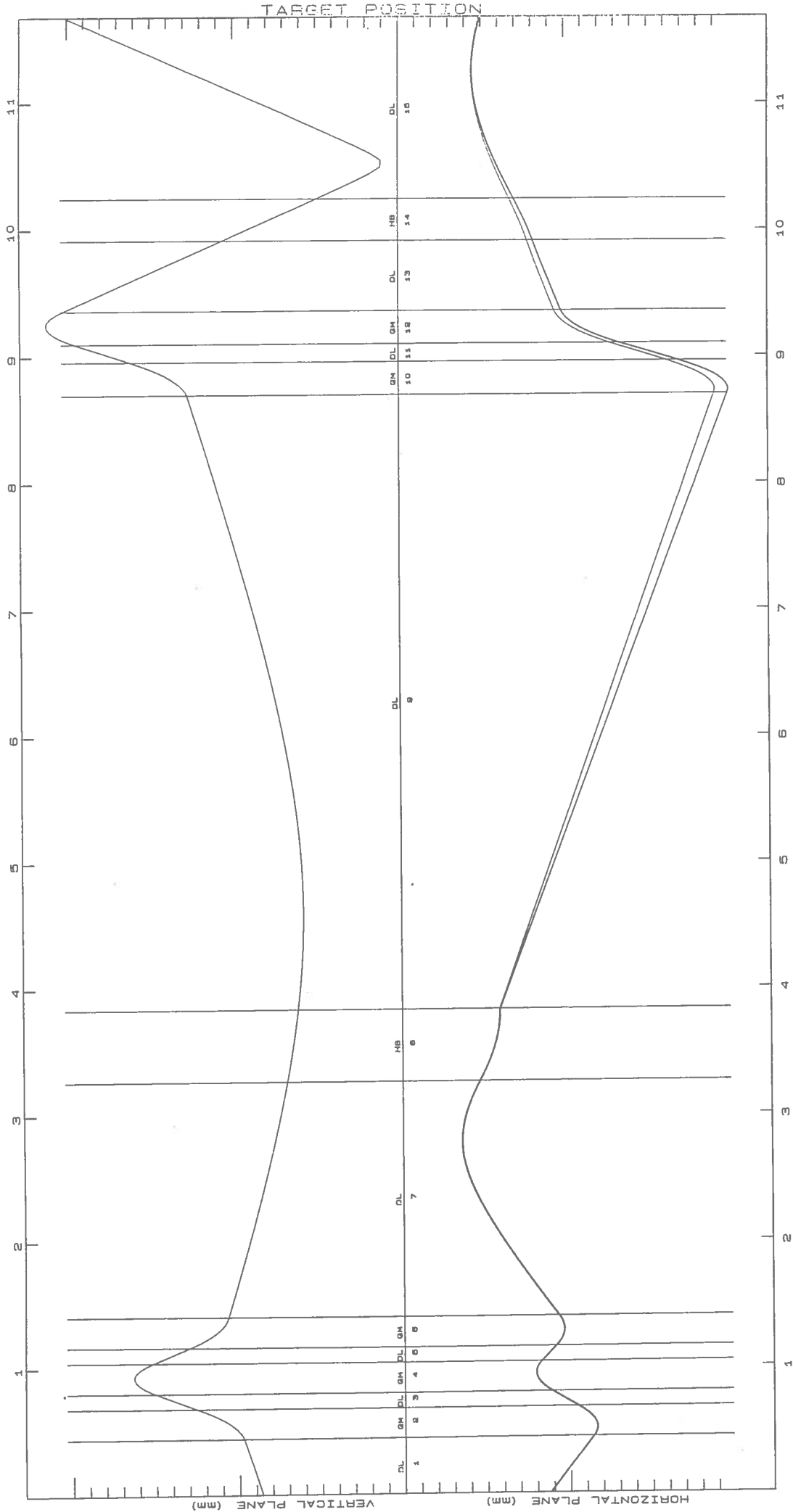
| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15   |      |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB  | DL   |      |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.7 | 8.7 | 9.0 | 9.1 | 9.4 | 9.9 | 10.2 | 11.7 |

DL=DRIFT LENGTH GM=GUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 7. Beam profile in beam line 2B. beam radius on target: 10x10 mm<sup>2</sup>

MILAN CYCLOTRON PROJECT - BEAM 2B - 38 MeV PROTONS - MC40 MK II EMISSION

BEAM DIRECTION →

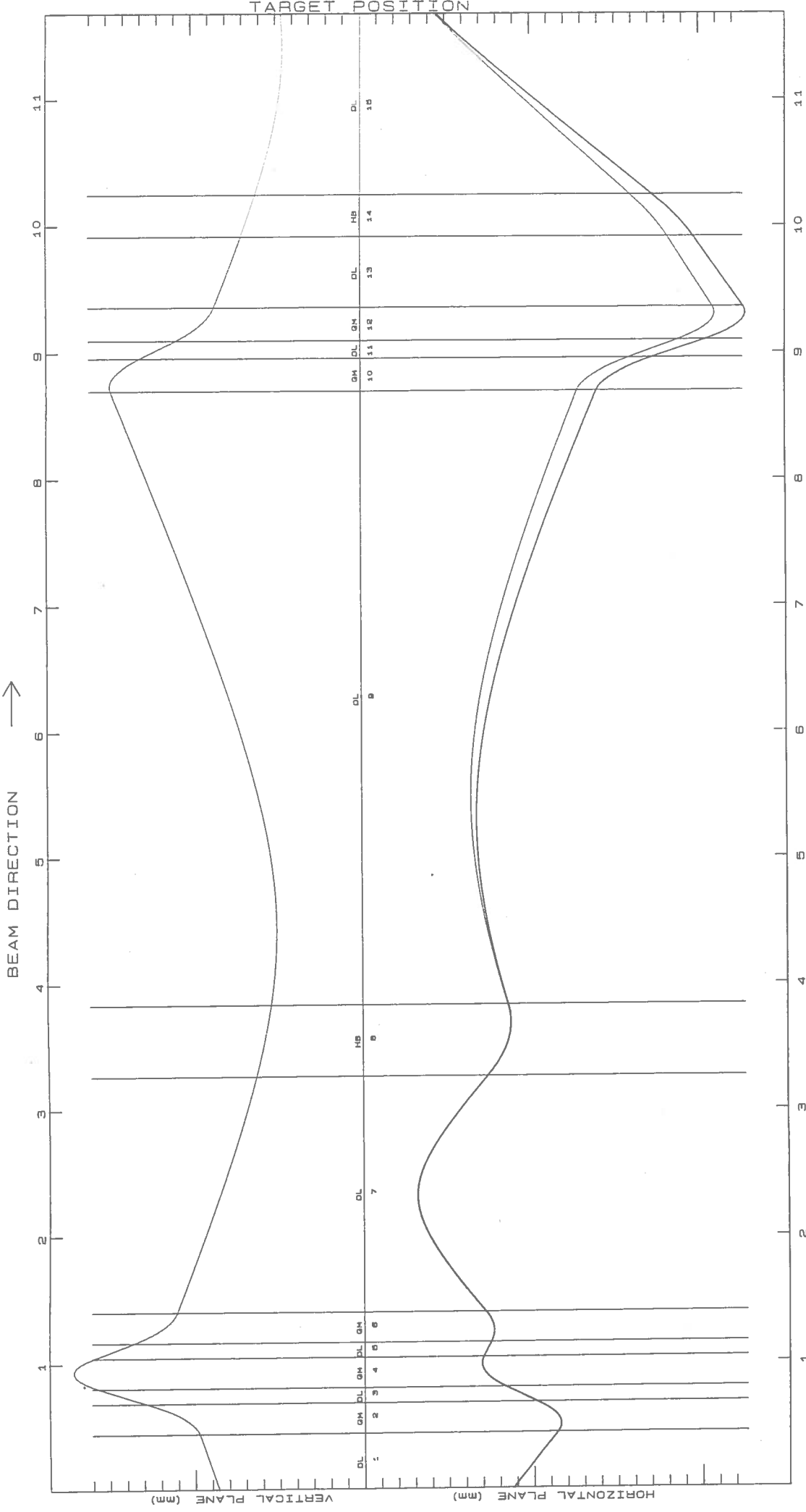


| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14   | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB   | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.7 | 9.0 | 9.1 | 9.4 | 9.9 | 10.2 | 11.7 |

DL=DRIFT LENGTH GM=QUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 8 : Beam profile in beam line 2B; beam radius on target: 5x20 mm<sup>2</sup>.

MILAN CYCLOTRON PROJECT - BEAM 2B - 38 MeV PROTONS - MC40 MK II EMITTANCE



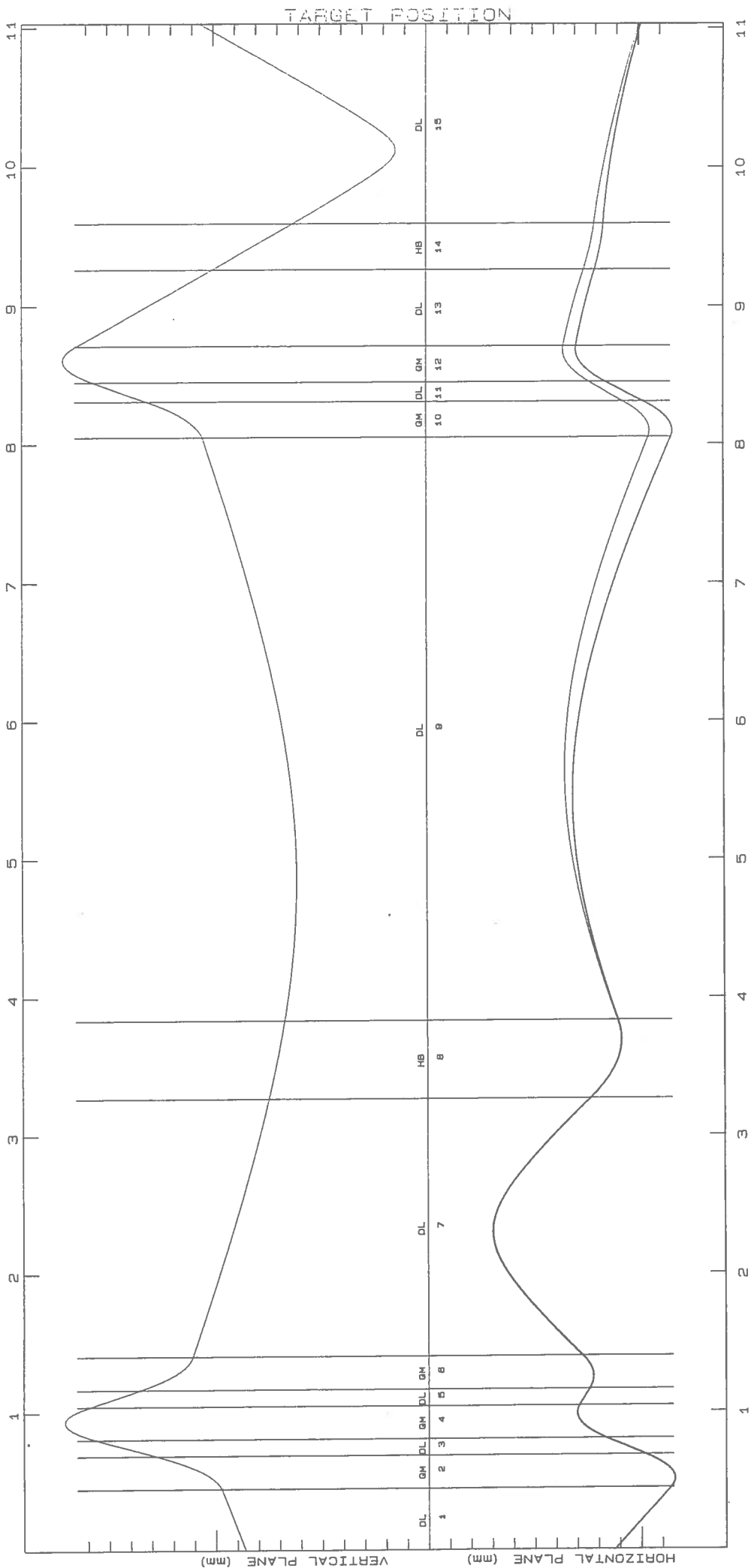
| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14   | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB   | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.7 | 9.0 | 9.1 | 9.4 | 9.9 | 10.2 | 11.7 |

DL=DRIFT LENGTH GM=QUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 0 - Beam profile in beam line 2B: beam radius on target: 3.5x3.5 mm<sup>2</sup>

MILAN CYCLOTRON PROJECT - BEAM 1A - 38 MeV PROTONS - MC40 MK II EMISSION

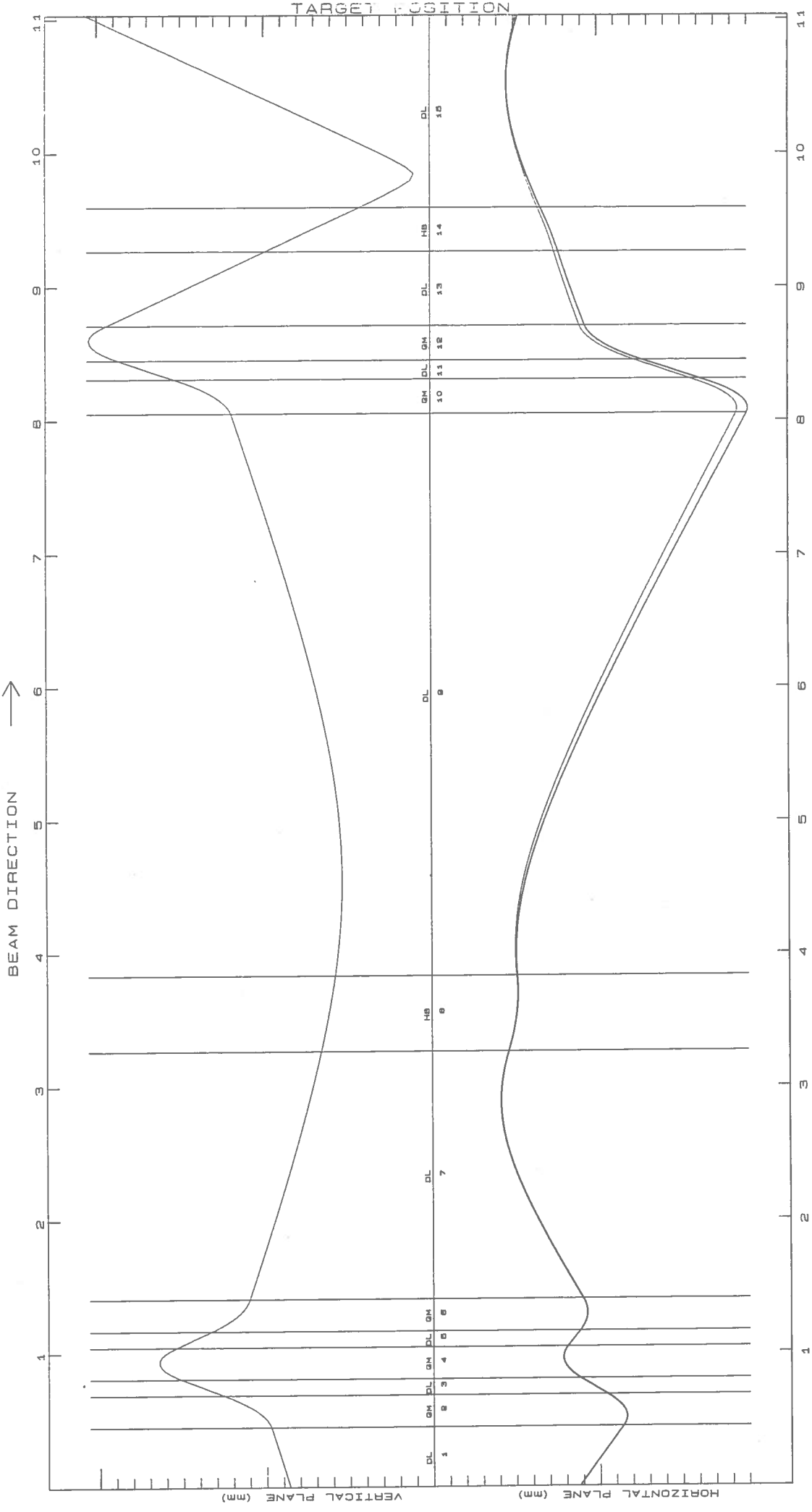
BEAM DIRECTION →



| COMPONENT NUMBER             | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15   |
|------------------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| COMPONENT TYPE               | DL | GM | DL | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL   |
| DISTANCE IN METRES           | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.1 | 8.3 | 8.5 | 8.7 | 9.3 | 9.6 | 11.0 |
| DL=DRIFT LENGTH              |    |    |    |     |     |     |     |     |     |     |     |     |     |     |      |
| GM=QUAD MAGNET               |    |    |    |     |     |     |     |     |     |     |     |     |     |     |      |
| HB=HORIZONTAL BENDING MAGNET |    |    |    |     |     |     |     |     |     |     |     |     |     |     |      |
| VB=VERTICAL BENDING MAGNET   |    |    |    |     |     |     |     |     |     |     |     |     |     |     |      |

Figure 10. Beam profile in beam line 1A. beam radius on target: 10x10 mm<sup>2</sup>.

MILAN CYCLOTRON PROJECT - BEAM 1A - 38 MeV PROTONS - MC40 MK II EMITTANCE



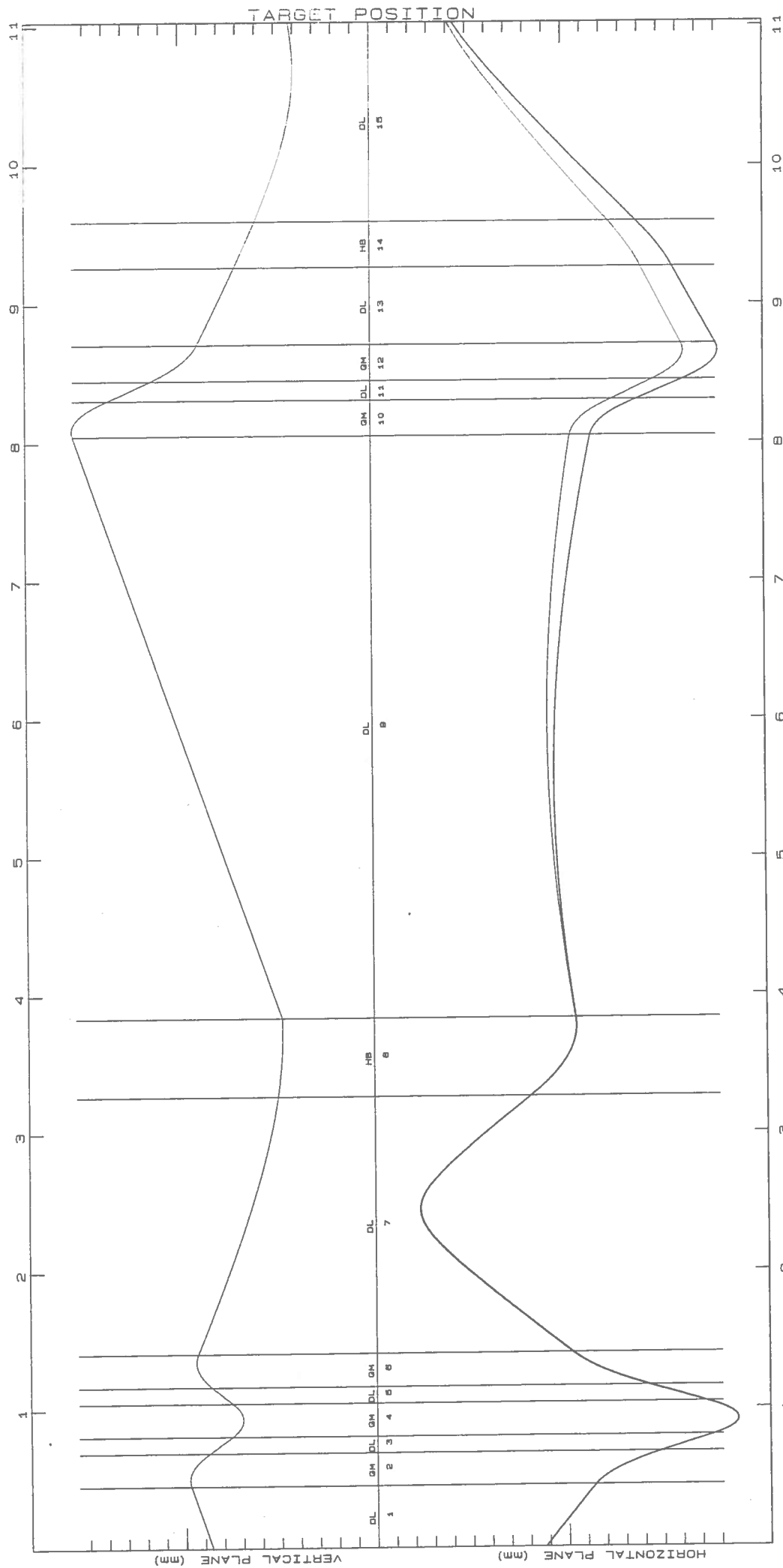
| COMPONENT NUMBER   | 1               | 2              | 3                            | 4                          | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15   |
|--------------------|-----------------|----------------|------------------------------|----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| COMPONENT TYPE     | DL              | GM             | DL                           | GM                         | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB  | DL   |
| DISTANCE IN METRES | .4              | .7             | .8                           | 1.0                        | 1.2 | 1.4 | 3.3 | 3.8 | 8.1 | 8.3 | 8.5 | 8.7 | 9.3 | 9.6 | 11.0 |
|                    | DL=DRIFT LENGTH | GM=QUAD MAGNET | HB=HORIZONTAL BENDING MAGNET | VB=VERTICAL BENDING MAGNET |     |     |     |     |     |     |     |     |     |     |      |

Figure 11 - Beam profile in beam line 1A; beam radius on target: 5x20 mm<sup>2</sup>.



MILAN CYCLOTRON PROJECT - BEAM 1A - 38 MeV PROTONS - MC40 Mk II EMITTANCE

BEAM DIRECTION →



| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | HB  | DL  | GM  | DL  | GM  | DL  | HB  | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.1 | 8.3 | 8.5 | 8.7 | 9.3 | 9.6 | 11.0 |

DL=DRIFT LENGTH GM=GUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 10 - Beam profile in beam line 1A, beam radius on target, 3.5v3 5 mm<sup>2</sup>

MILAN CYCLOTRON PROJECT - BEAM 2A - 38 MeV PROTONS - MC40 MK II EMITTANCE

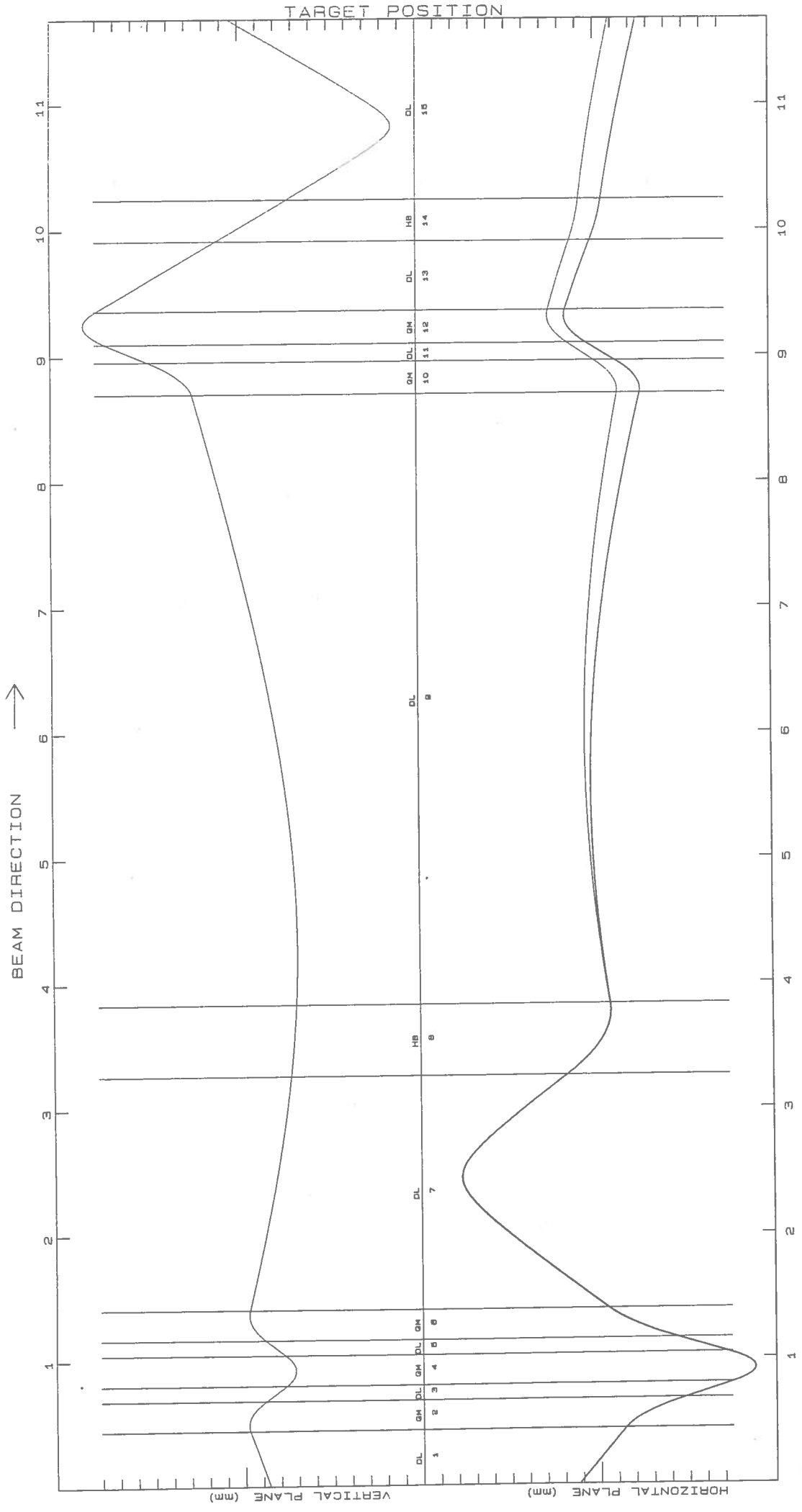
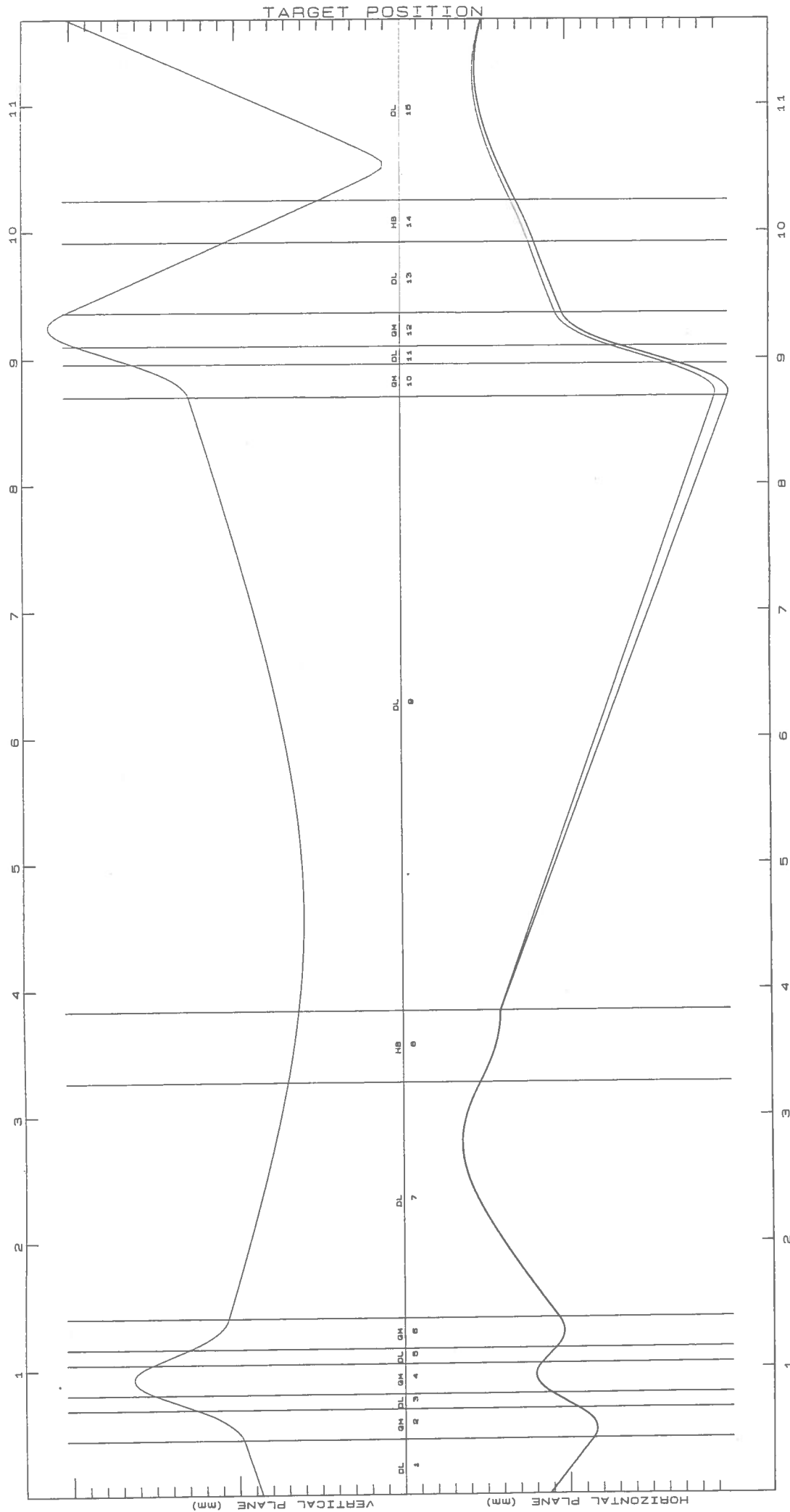


Figure 13 : Beam profile in beam line 2A: beam radius on target: 10x10 mm<sup>2</sup>.

MILAN CYCLOTRON PROJECT - BEAM 2A - 38 MeV PROTONS - MC40 MK II EMISSION

BEAM DIRECTION →



HORIZONTAL SCALE IN METRES

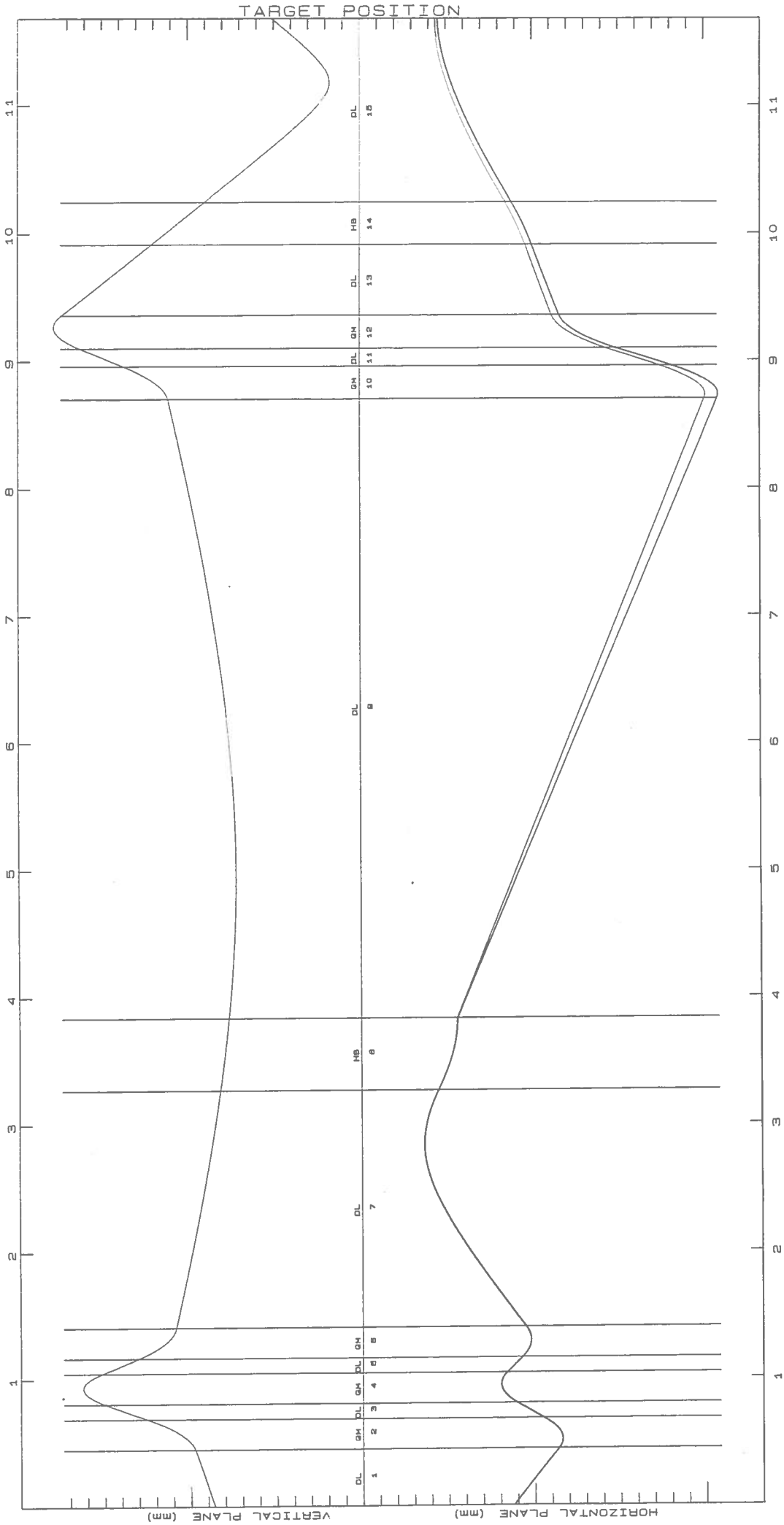
| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14   | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL  | GM   | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 8.7 | 9.0 | 9.1 | 9.4 | 9.9 | 10.2 | 11.7 |

DL=DRIFT LENGTH GM=QUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 14. Beam profile in beam line 2A: beam radius on target: 5x20 mm<sup>2</sup>.

MILAN CYCLOTRON PROJECT - BEAM 2A - 38 MeV PROTONS - MC40 MK II EMIITANCE

BEAM DIRECTION →

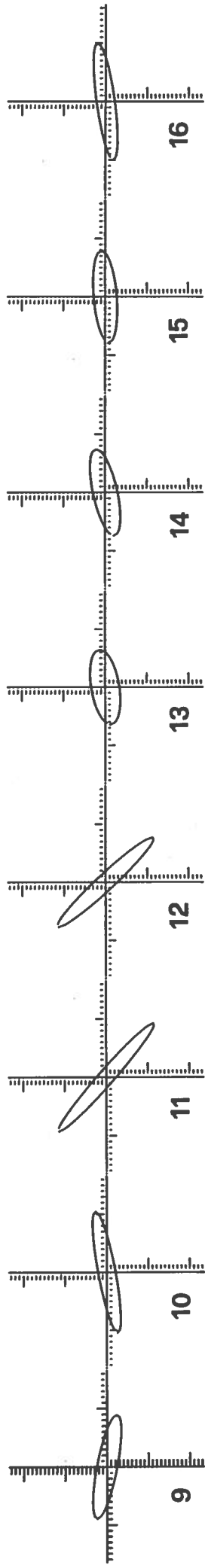
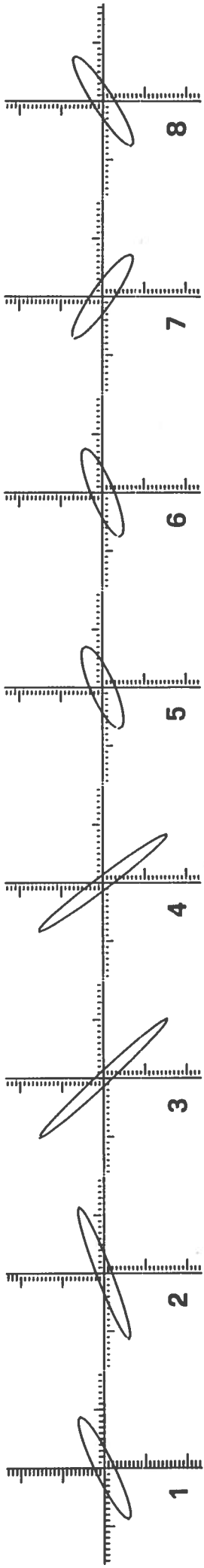


| COMPONENT NUMBER   | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14   | 15   |
|--------------------|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| COMPONENT TYPE     | DL | GM | DL | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL  | GM  | DL  | GM   | DL   |
| DISTANCE IN METRES | .4 | .7 | .8 | 1.0 | 1.2 | 1.4 | 3.3 | 3.8 | 6.7 | 8.0 | 9.1 | 9.4 | 9.9 | 10.2 | 11.7 |

DL=DRIFT LENGTH GM=QUAD MAGNET HB=HORIZONTAL BENDING MAGNET VB=VERTICAL BENDING MAGNET

Figure 15: Beam profile in beam line 2A; beam radius on target: 3.5x3.5 mm<sup>2</sup>.

HORIZONTAL PLANE



VERTICAL PLANE

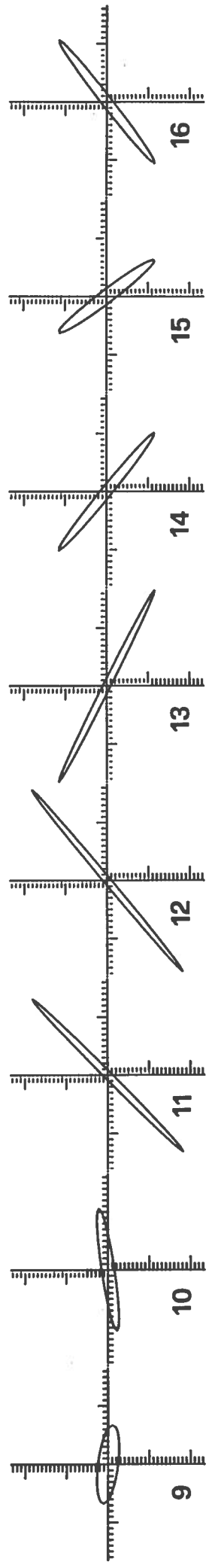
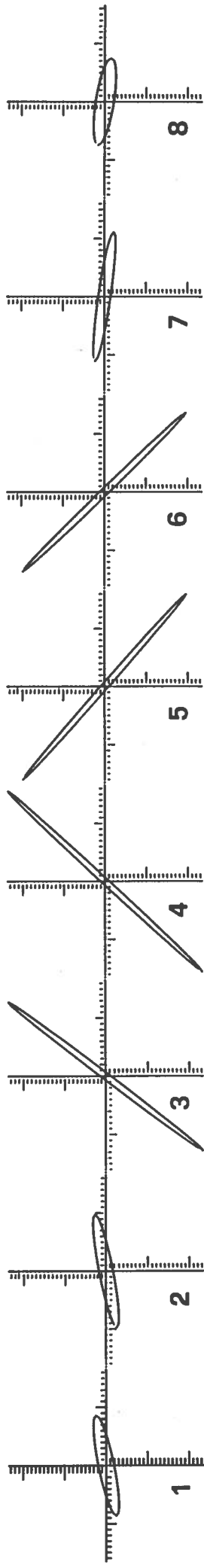


Figure 16 : Phase-space ellipses at the exit of each component for the beam profile of Fig. 4.

No final decision has yet been taken about the beam transport system for target rooms 3, 4 and 5. As an alternative to the arrangement described in this report (i.e., the use of the switching magnet SM4 to direct the beam in either of the three rooms), a preliminary investigation was made of a system for the simultaneous irradiation of different targets placed in target rooms 3 and 4 (and possibly 5). This "beam sharing" system<sup>(6)</sup> would require a "kicker" magnet placed after the switching magnet SM1, and two "septum" magnets instead of the switching magnet SM4. The  $+45^\circ$  (or  $-45^\circ$ ) deflection could be achieved, for example, by using a  $30^\circ$  septum magnet and a  $15^\circ$  normal dipole. The kicker would give the beam periodic kicks and send it through either of the septum magnets, which then direct it into target room 3 or 4. If a  $0^\circ$  channel is provided between the two septum magnets and the kicker is appropriately designed, the beam can also be directed into target room 5, to allow the simultaneous irradiation of three targets. "Simultaneous" in effect means that the beam is bombarding either target for a fraction of the overall time. By an appropriate design of the kicker, it would be possible to vary the percentage of the time the beam is hitting any particular target.

If target room 5 will be used for neutron therapy, a dedicated beam line will take the beam into an isocentric gantry. In the case neutron therapy will not be undertaken, the room is large enough to allow the set-up of different beam lines. This could be achieved by placing a switching magnet with multiple exit ports just after the wall separating target room 5 from the cyclotron vault. In this case, the possibility of providing one beam line with an analyzing magnet should be considered with interest.

## 7. - ACKNOWLEDGEMENTS

I am greatly indebted to Mr. G. Burton and Mr. M. L. Simpson of the M.R.C. Cyclotron Unit, Hammersmith Hospital, London, for introducing me to the subject of beam optics and for supplying the data obtained from their MC40 Mark II cyclotron for use in the calculations, whilst John Cheetham helped me in the development of one of the graphics programmes. I also wish to thank all the members of the Engineering Section for their support and friendship during the two years I spent in the Unit. In particular, I will always remember the smile and cheerfulness of Mr. Bill Edwards, who sadly died a few days before his retirement.

## 8. - REFERENCES

- (1) Colonias S. J., Particle accelerator design computer programs (Academic Press, 1974), pp. 1-89.
- (2) Burton G., de Raad B. and Strolin P., Methods to compute the optics of beam transfer channels, Nucl. Instr. Meth. 82, 259 (1970).
- (3) Penner S., Calculations of properties of magnetic deflection systems, Rev. Sci. Instr. 32, 150 (1961).
- (4) Hereward H. G., The properties of particle beams in optical matching systems, in terms of phase-plane ellipse-shapes, CERN PS/Int. TH 59-5 (1959).
- (5) Banford A. P., The transport of charged particle beams (E.&F.N. Spon Limited, 1966).
- (6) Burton G., Renton M. L. and Simpson M. L., The beam sharing project of the Hammersmith cyclotron, Proceedings of the Ninth International Conference on Cyclotrons and their Applications, Caen, September 1981, edited by Gendreau G. (France), pp. 715-717.