Journal of the Korean Nuclear Society
Volume 23, Number 4, December 1991

Ion Optical Study on the He^{++} Beam Transport System of the SNU 1.5-MV Tandem Van de Graaff Accelerator

Hyen-Cheol JO, Young-Dug BAE and Hae-iLL BAK
Department of Nuclear Engineering, Seoul National University
(Received April 30, 1991)

SNU 1.5-MV 직렬형 반데그라프 가속기의 He^{++} 빔 수송계에 대한 이온광학적 고찰

조현철 · 배영덕 · 박혜일
서울대학교 원자핵공학과
(1991. 4. 30 접수)

Abstract

The He^{++} beam transport system of the SNU 1.5-MV Tandem Van de Graaff accelerator is analysed by ion optical approach. The program OPTRANS is developed to determine the optimum operating conditions of each ion optical component and to simulate ion beam transport. First order matrix formalism is used and the space charge effect is neglected. Optimum operating conditions for the transport of 0.5~3.0 MeV He^{++} beam are determined by the use of the program OPTRANS. Initial ion beam emittance is assumed to be 0.5×80.0 mm·mrad from the structure of the extraction electrode and the experiment of ion beam extraction. Ion beam transport characteristics of each ion optical component according to the variation of the operating conditions are investigated, and operating conditions to minimize the beam size at each slit, stripping foil, and target are calculated. Optimum operating conditions obtained from the experiment of ion beam transport show a discrepancy of less than 15 % compared with the calculated ones. From the simulation and experiment of ion beam transport, the validity of the calculated optimum operating conditions and the usefulness of the program OPTRANS are verified.

요 약

SNU 1.5-MV 직렬형 반데그라프 가속기의 He^{++} 빔 수송계를 이온광학적으로 분석하였다. 각 이온광학요소의 최적운전조건을 결정하고, 이온빔 수송을 모사하기 위하여 프로그램 OPTRANS를 개발하였다. 일차행렬법을 사용하였으며, 공간전하효과는 무시하였다. 프로그램 OPTRANS를 사용하여 0.5~3.0 MeV He^{++} 빔 수송을 위한 최적운전조건을 결정하였다. 초기 이온빔의 방사면량은 인출전극의 구조와 이온빔 인출실험에 의해 0.5×80.0 mm · mrad으로 가정하였다. 운전조건의 변화에 따른 각 이온광학요소의 이온빔 수송 특성을 검토하였으며, 각 Slit과 Stripping Foil, 그리고 표적에서 빔 크기가 최소로 되도록 하는 운전조건을 계산하였다. 이온빔 수송 실험으로부터

얻어진 최적운전조건은 계산된 값과 오차 범위 15 % 내에서 일치하였다 이온빔 수송 모사와 실험을 통해, 계산된 최적운전조건의 타당성 및 프로그램 OPTRANS의 유용성을 입증하였다.

I. Introduction

To improve the quality of ion beam in the process of ion beam transport, optimum operating condition must be determined through the investigation of the characteristics of each ion optical component that constitutes the ion beam transport system. Since electric and magnetic field distribution in each component are obtained by finite element method or finite difference method, the behavior of ion beam passing through the ion beam transport system can be exactly described by solving each particle's equation of motion by either of these numerical methods. However, since this approach needs a lot of calculation time and memory, the motions of particles forming ion beam are analysed by the approximation method with the assumptions as the follow:

1. Most particles move near the beam axis which is set up as the reference trajectory.—Paraxial Ray Approximation
2. The force perpendicular to the direction of ion beam passage is linearly proportional to the distance from the reference trajectory.—Linear or Gaussian Optics

The approximate solution by these assumptions is represented as a vector in the phase space, and the equation of motion for the particles can be described as matrix formalism. The ion optical properties of each component of ion beam transport system are represented as matrix, which is called transport matrix, and the overall information on the ion beam transport process, especially optimum operating condition, is obtained through the manipulation of transport matrix.

In the present work, the ion beam transport system of the SNU 1.5-MV Tandem Van de Graaff accelerator was analysed by ion optical approach. The program OPTRANS was developed to determine the optimum operation conditions of each component and to simulate ion beam transport. First order matrix formalism through the paraxial ray approximation was used because the ion beam transport system was designed so that the beam size might be sufficiently smaller than that of ion optical component. The space charge effect which perturbs the electric and magnetic field configuration of ion optical component was neglected because the ion beam current in this accelerator is less than several tens of μA(1). By the use of the program OPTRANS, optimum operating conditions for the transport of 0.5~3.0 MeV He^{++} beam were calculated, and the validity of the calculated values was verified from the simulation and experiment of ion beam transport.

II. Theory

A. First order matrix formalism

If the relativistic effect is neglected (in the case of $v/c<0.1$)(2), the motion of charged particle in electric or magnetic field is expressed by the Newton's equation of motion,

$$\frac{d\mathbf{p}}{dt}=q(\mathbf{E}+\mathbf{v}\times\mathbf{B}). \tag{1}$$

Where, **p** is the linear momentum of the particle, q is its charge, and **v** is its velocity. If the axis of beam line is set up as reference trajectory, the coordinates of particles can be expressed in terms of moving coordinate system whose origin is always on the reference trajectory. Moving coordinate system is shown at Fig. 1. Then Eq. (1) becomes

$$\frac{d^2\mathbf{T}}{dT^2}=\frac{q}{pv}(\mathbf{E}+v\frac{d\mathbf{T}}{dT}\times\mathbf{B}). \tag{2}$$

Where, vector **T** denotes the position of the particle along the reference trajectory.

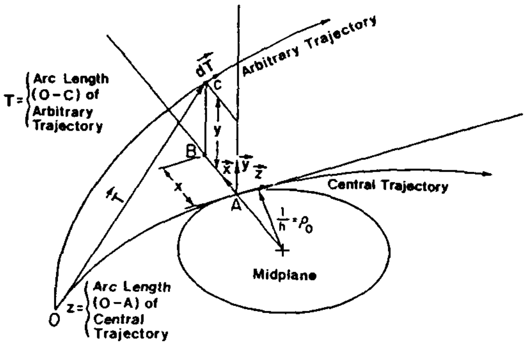

Fig. 1. Moving coordinate system.

The vector and scalar differential elements of T are

$$d\mathbf{T}=\mathbf{x}\ dx+\mathbf{y}\ dy+(1+hx)\ \mathbf{z}dz, \qquad (3)$$

$$dT\cong(1+hx)\ dz. \qquad (4)$$

Where, **x**, **y** and **z** are the orthonormal unit vectors of moving coordinate system and h is the curvature of reference trajectory. Using Eq. (3) and (4), Eq. (2) becomes

$$\frac{d^2\mathbf{T}}{dz^2}=(1+hx)^2\ \frac{q}{pv}(\mathbf{E}+\frac{v}{(1+hx)}\ \frac{d\mathbf{T}}{dz}\times\mathbf{B}), \qquad (5)$$

and, $d^2\mathbf{T}/dz^2$ in Eq. (5) is expressed as

$$\frac{d^2\mathbf{T}}{dz^2}=\mathbf{x}\left(\frac{d^2x}{dz^2}-h(1+hx)\right)+\mathbf{y}\frac{d^2y}{dz^2}+\mathbf{z}\left(2h\frac{dx}{dz}+\frac{dh}{dz}x\right) \qquad (6)$$

Generally, ion optical components used in ion beam transport system have midplane symmetry about x–z plane, then scalar potential ϕ is an odd function of y. The only terms which contribute to the first order expansion are at most linear in x or y. Therefore only the quadratic terms in ϕ are considered.

$$\phi\ (x,y)=Ay+Bxy \qquad (7)$$

Using Eq. (6) and (7), Eq. (5) can be first order approximated as

$$\frac{d^2x}{dz^2}+K(z)x=0. \qquad (8)$$

Where, z is a coordinate that represents the axial motion of particle on the reference trajectory, x is a coordinate perpendicular to z axis (in Eq.(8), x denotes both x and y coordinates) , and K is a function of z. This equation is a second order differential equation, therefore its solution is

$$\begin{pmatrix} x \\ x' \end{pmatrix}=\begin{pmatrix} C(z) & S(z) \\ C'(z) & S'(z) \end{pmatrix}\begin{pmatrix} x_o \\ x_o' \end{pmatrix}. \qquad (9)$$

Where, the prime denotes differentiation by z, x_o and x_o' are initial conditions of x and x′, and C(z) and S(z) are functions of z. The characteristics of ion optical component are calculated from the matrix of Eq.(9) and this matrix is called transport matrix.

B. Ion beam envelope

To analyse the ion beam transport in the accelerator, not the trajectory for a single particle but the motion of an ensemble of particles shall be investigated. For the effective description of the collective behaviors of ion beam particles, the concept of emittance is introduced(3). Emittance is defined as area in the phase space, and is invariant for ion optical system in which no acceleration occurs. Generally ion beam envelope in the phase space is expressed as ellipse, and emittance is the area of this phase ellipse. If vector **X** and beam matrix σ are defined as follow

$$\mathbf{X}=\begin{pmatrix} x \\ x' \end{pmatrix} \qquad (10)$$

$$\sigma=\begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix}=\epsilon\begin{pmatrix} \beta & -\alpha \\ -\alpha & -\gamma \end{pmatrix}, \qquad (11)$$

then the phase ellipse shown at Fig.2 is expressed as Eq. (12).

$$\mathbf{X}^T\ \sigma^{-1}\ \mathbf{X}=\mathbf{1}. \qquad (12)$$

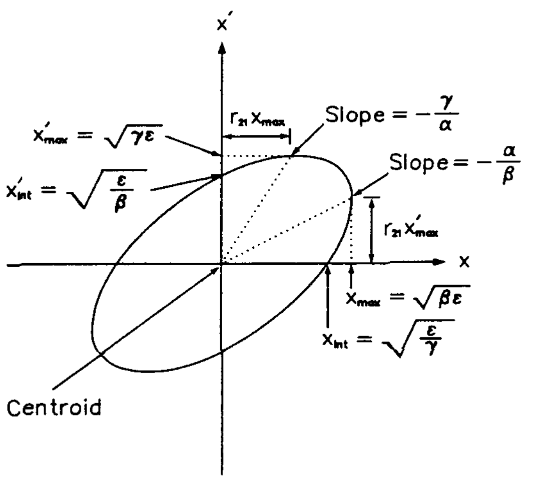

Fig. 2. Beam phase ellipse and twiss parameters.

Here ϵ is emittance and α, β and γ are twiss parameters(4). The maximum values of x and x′ are given by emittance and twiss parameters,

$$x_{max} = \sqrt{\beta\epsilon}, \tag{13}$$

$$x'_{max} = \sqrt{\gamma\epsilon}. \tag{14}$$

If ion beam passes through the optical component whose transport matrix is R, twiss parameters and emittance are transformed into

$$\begin{pmatrix} \beta_2 \\ \alpha_2 \\ \gamma_2 \end{pmatrix} = \frac{1}{N} \mathbf{M} \begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix} \tag{15}$$

$$\mathbf{M} = \begin{pmatrix} R_{11}^2 & -2\, R_{11}R_{12} & R_{12}^2 \\ -R_{11}R_{21} & R_{11}R_{22} + R_{12}R_{21} & -R_{12}R_{22} \\ R_{21}^2 & -2\, R_{21}R_{22} & R_{22}^2 \end{pmatrix} \tag{16}$$

$$\epsilon_2 = N\, \epsilon_1, \tag{17}$$

where, N is the determinant of R and subscript 1 and 2 denote initial and final state, respectively.

Any phase space distribution of ion beams which can be described in terms of an ellipse is specified by twiss parameters and emittance. These parameters are calculated by the matrix transform Eq. (15), (16) and (17) only if the initial values of those and transport matrix of corresponding component are given. So the overall information on the characteristics of ion beam at specific point of ion beam transport system can be obtained from twiss parameters and emittance.

III. Analysis of Ion Beam Transport System

A. The ion beam transport system of the SNU 1.5-MV Tandem Van de Graaff accelerator

Fig. 3 shows the ion beam transport system of the SNU 1.5-MV Tandem Van de Graaff accelerator. In the case of He ion beam transport, He^{+} beam is extracted from the duoplasmatron ion source and is passed through the Rb charge exchange cell that produces the He^{-} beam. He^{-} beam is accelerated in the lower energy accelerating tube and becomes the He^{++} beam by stripping process at carbon stripping foil. He^{++} beam is re-accelerated in higher energy accelerating tube. The He^{++} beam of specific energy is transported to target chamber by the action of 90 analysing magnet and used for RBS(Rutherford Backscattering Spectrometry) or PIXE(Particle Induced X-ray Emission) experiment.

For the efficient ion beam transport, two einzel lenses, two EQT(Electrostatic Quadrupole Triplet) lenses, and a MQD(Magnetic Quadrupole Doublet) lens are installed as adjustable ion optical components in the ion beam transport system of this accelerator. Einzel lenses are used for ion optical matching between ion source and 90° deflection magnet. The first and third electrode of einzel lens are grounded. The diameter of einzel lens is 40 mm, the gap between electrodes is 4 mm, and the length of lens action region is 40 mm. EQT lenses are used for ion optical matching between 90° deflection magnet and lower energy accelerating tube and between higher energy accelerating tube and 90° analysing magnet. For the first EQT lens,

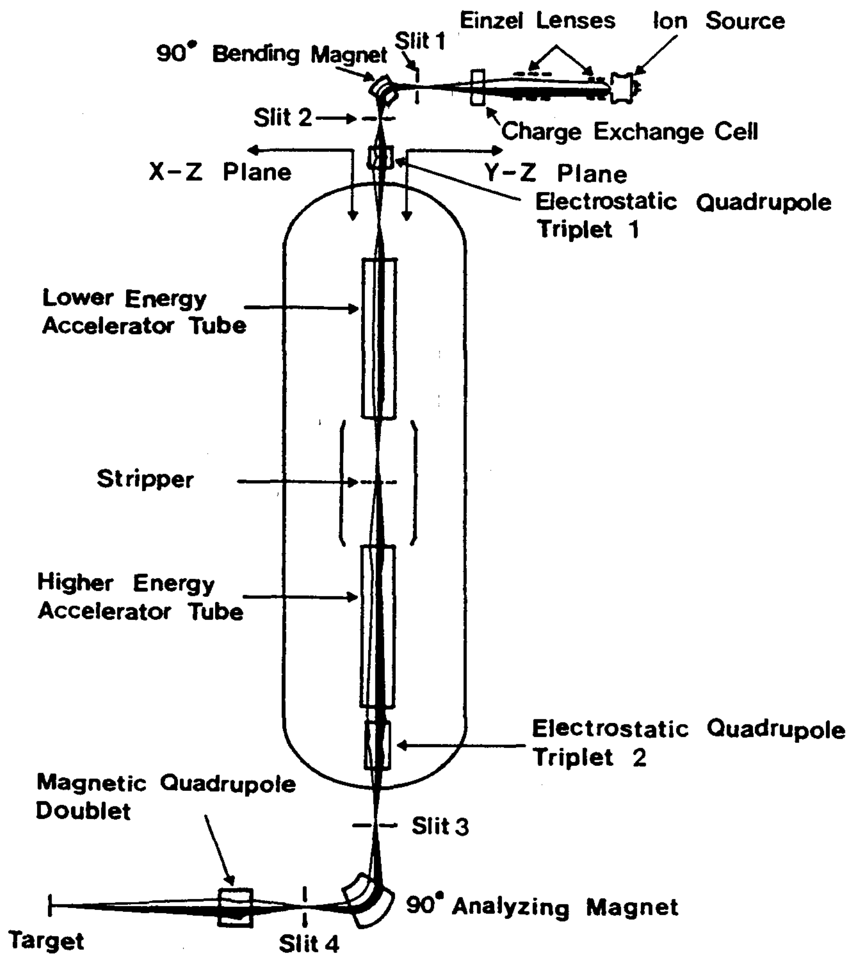

Fig. 3. Beam transport system of the SNU 1.5–MV Tandem Van de Graaff accelerator.

its diameter is 40 mm, the length of each component is 40 mm, 80 mm and 40 mm respectively, and the gap between each component is 20 mm. For the second EQT lens, its diameter is 30 mm, the length of each component is 130 mm, 180 mm and 130 mm respectively, and the gap between each component is 50 mm. MQD lens is used for ion optical matching between 90° analysing magnet and target. Its diameter is 25 mm, the length of each component is 180 mm, and the gap between each component is 180 mm.

B. Program OPTRANS

The program OPTRANS, on the basis of first order matrix formalism, was developed to analyse the ion beam transport system of the SNU 1.5–MV Tandem Van de Graaff accelerator. The input parameters of this program are design constants of each component, plane coupling mode, ion beam element to be transported, extraction and terminal voltage, and initial emittance of ion beam. In order for ion beam to be transported efficiently, beam size should be as small as it could be at each slit, stripping foil and target. Thus beam size was to be minimized at slit 1 by einzel lenses, at stripping foil by the first EQT lens, at slit 3 by the second EQT lens and at target by MQD lens. These constraints must be satisfied for optimum transport of ion beam. The program OPTRANS calculates the operating conditions that satisfy those constraints for adjustable ion optical components. This program also calculates the ion beam envelope at each slit, stripping foil and target according to the variation of operating conditions. From the calculated ion beam envelope, ion beam transport characteristics of each component were investigated. The simulation of ion beam transport was performed under the calculated operating condition. The validity of calculation was verified by the result of the simulation. The program OPTRANS was written by the PASCAL language and its flow chart is shown at Fig. 4.

Table 1 shows the optimum operating conditions for the transport of 2.0 MeV He^{++} beam calculated by the program OPTRANS. Fig.5 shows the result of the simulation of He^{++} beam transport under the condition of Table 1. Initial emittance of ion beam was assumed to be 0.5×80.0 mm·mrad from the structure of extraction electrode and the experiment of He^{+} beam extrac-

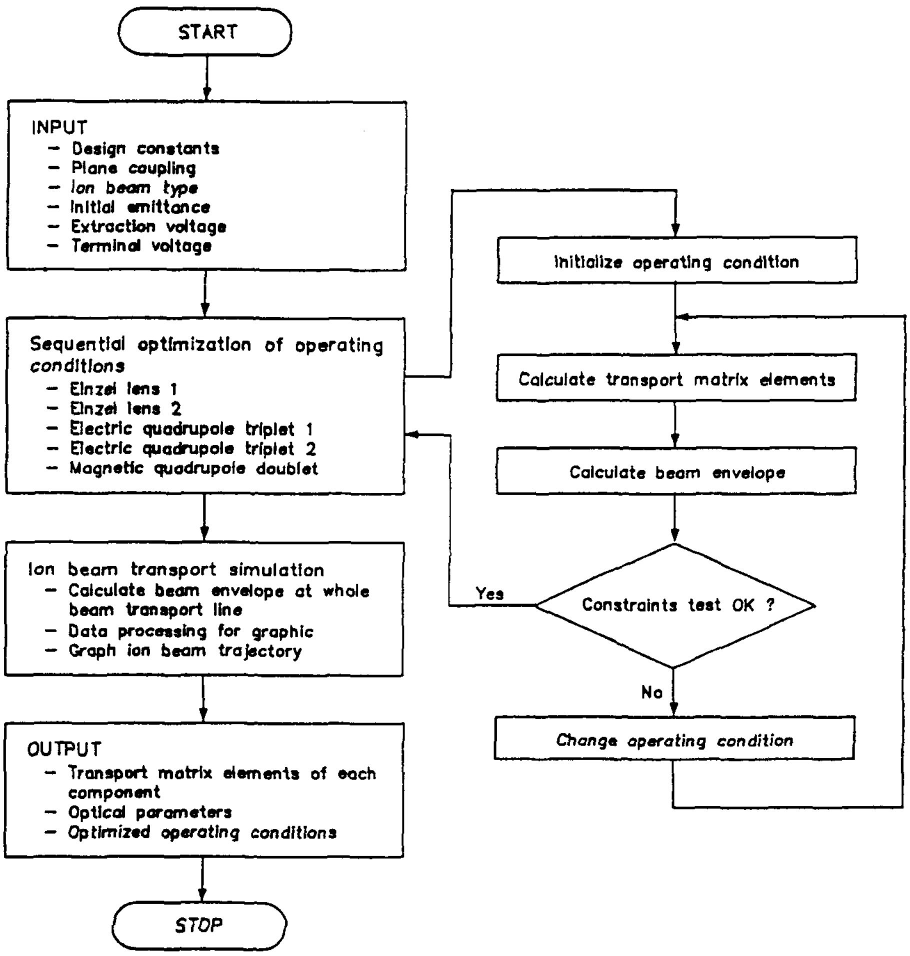

Fig. 4. Flow chart of the program OPTRANS.

tion. The shape of the He^{++} beam transported to target was upright ellipse of 4.2 mm×0.5 mm.

Table 1. Optimized operating conditions for 2.0 MeV He^{++} beam transport calculated by the program OPTRANS.

Optical Components	Figures
Extraction Electrode	5.72 kV
Terminal	664.76 kV
Einzel Lens 1	4.37 kV
Einzel Lens 2	2.93 kV
EQT1 Pole 1	0.695 kV
Pole 2	0.634 kV
Pole 3	0.695 kV
EQT2 Pole 1	3.30 kV
Pole 2	4.68 kV
Pole 3	3.30 kV
MQD Pole 1	2.05 A
Pole 2	1.84 A

Ⅳ. Results and Discussion

By the use of the program OPTRANS, optimum operating conditions for the transport of 0.5~3.0 MeV He^{++} beam from the SNU 1.5-MV Tandem Van de Graaff accelerator were calculated at an interval of 0.25 MeV. Calculated optimum operating conditions were fitted by the least square method as functions of extraction and terminal voltage, and used as guides in the experiments. Experimental optimum operating conditions were determined through fine adjustment near the calculated conditions.

Fig. 6, 7, 8 and 9 show the optimum operating conditions determined by calculation and experiment. Extraction voltage was set to 5.72 kV by considering the efficiency of charge exchange cell and the bending ability of 90 deflection magnet. Terminal voltage was set to 164.76~998.09 kV for the production of 0.5~3.0 MeV He^{++} beam. Figures show the discrepancy of less than 15 % and good agreement of the trend of variation between calculated and experimental optimum operating conditions. The discrepancy is thought to be caused by the errors from the paraxial ray approximation and incorrect data for ion optical component, especially the effective length of quadrupole. For the case of the first EQT lens and MQD lens, the consistent discrepancy is thought to be mainly due to the incorrect data for effective length of each component.

Ⅴ. Conclusion

For the ion optical analysis of ion beam transport of the SNU 1.5-MV Tandem Van de Graaff accelerator, the program OPTRANS was developed. First order matrix formalism through the paraxial ray approximation was used, and the space charge effect was neglected.

By the use of the program OPTRANS, optimum operating conditions for the transport of 0.5~3.0 MeV He^{++} beam were calculated, and the simulation of He^{++} beam transport was carried out to verify the validity of the calculated conditions. Calculated optimum operating conditions were used as guides in the experiments. Optimum operating conditions obtained by experiments agree well with the calculated conditions within 15%. The trend of variation of operating conditions was nearly the same for calculation and experiment. From the result, the usefulness of the program OPTRANS for the analysis of the ion beam transport system was certified.

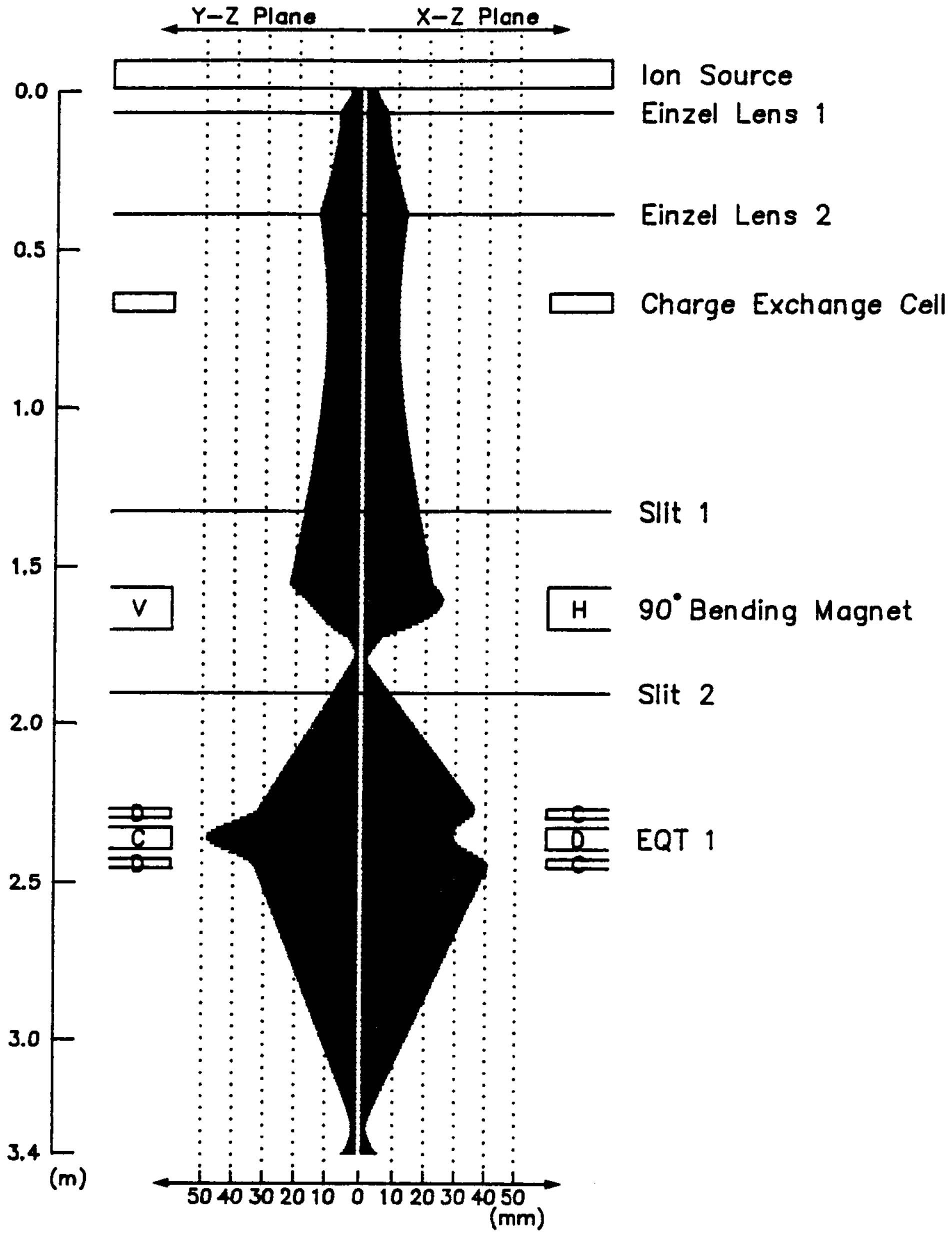

Fig. 5. He ion beam transport simulation by the program OPTRANS.

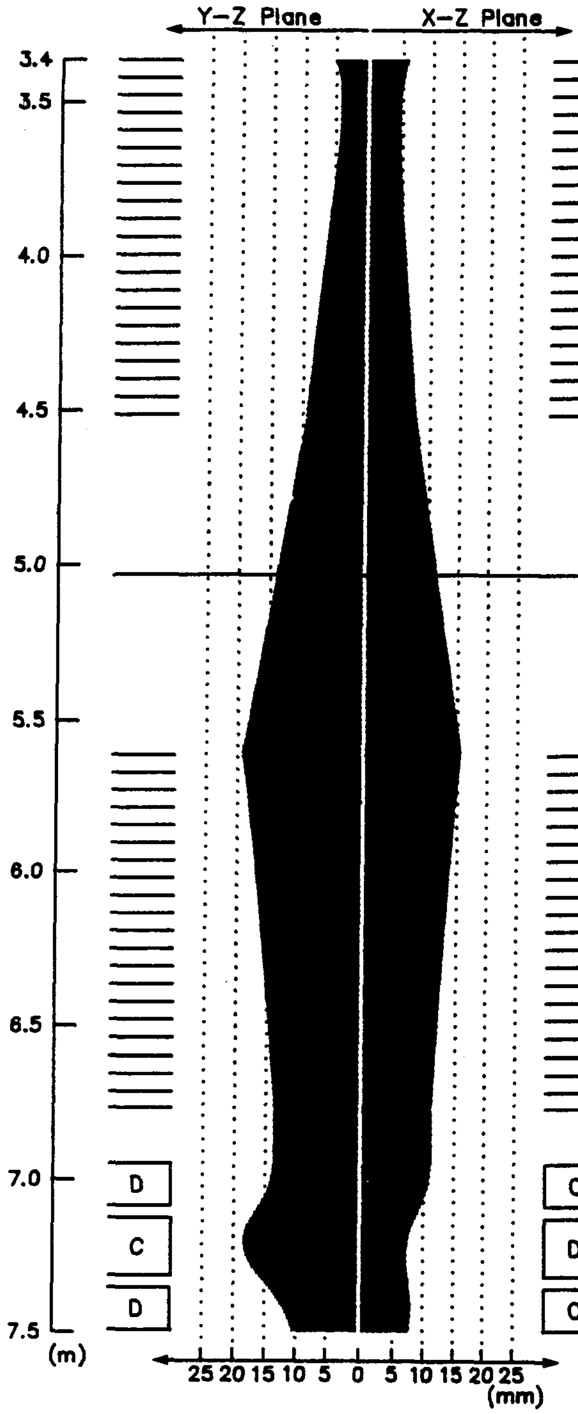

Fig. 5. (continued).

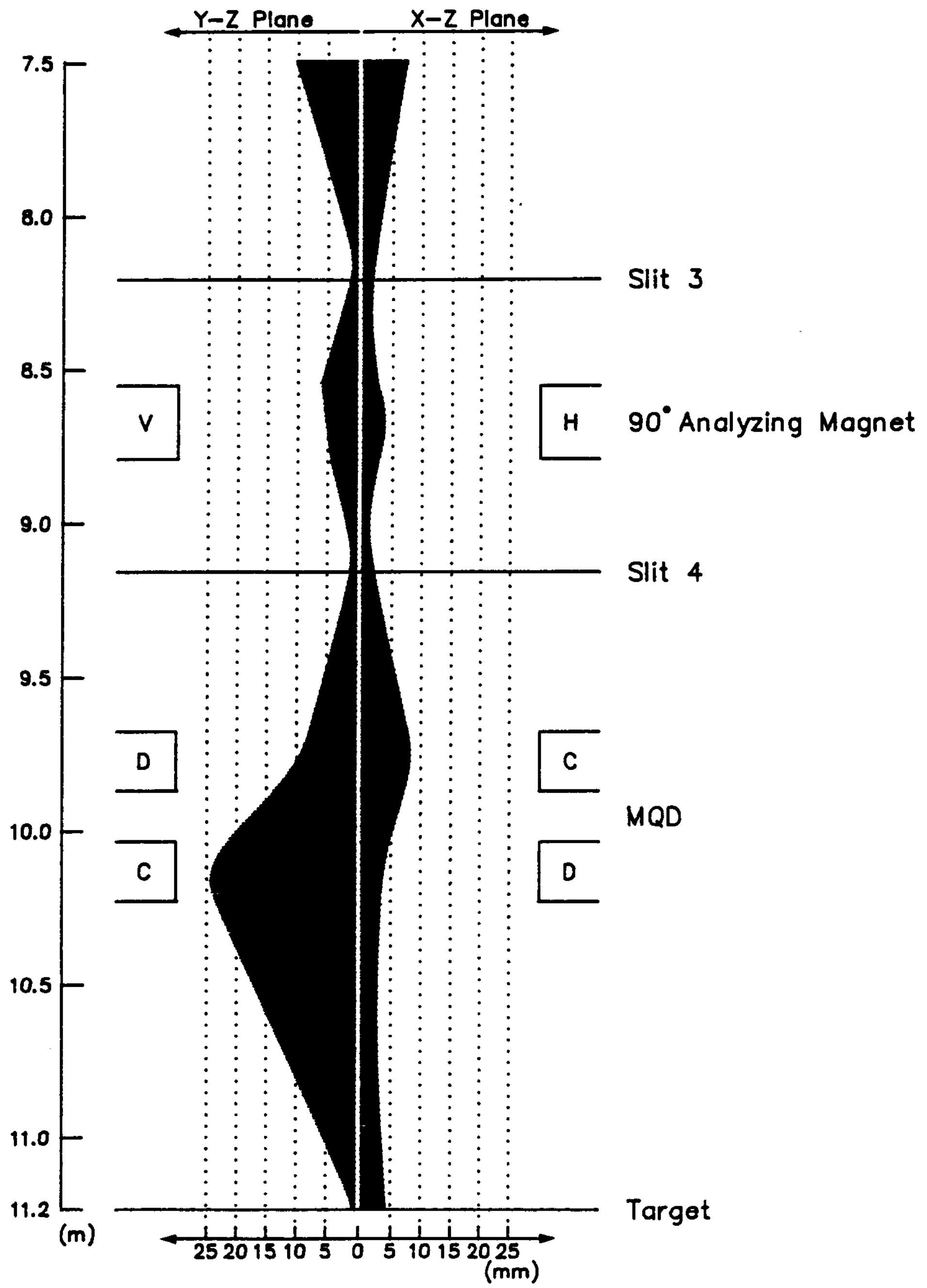

Fig. 5. (continued).

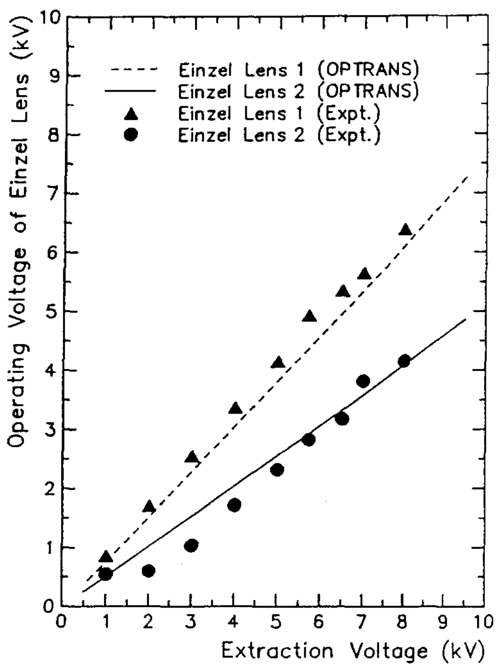

Fig. 6. Optimized operating voltages of einzel lenses calculated by the program OPTRANS.

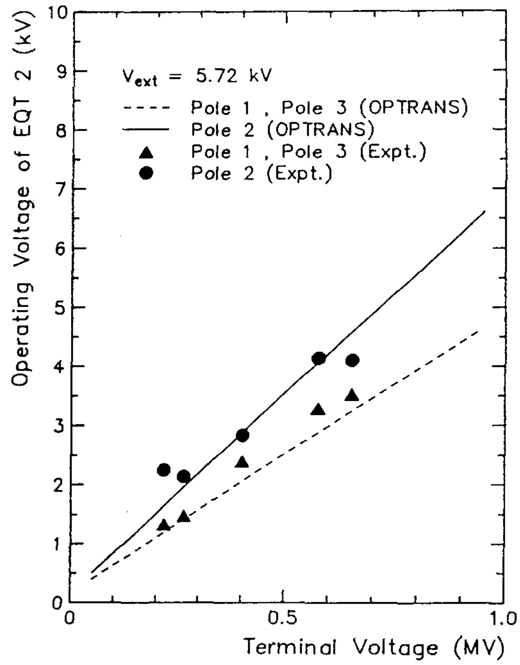

Fig. 8. Optimized operating voltages of EQT2 calculated by the program OPTRANS.

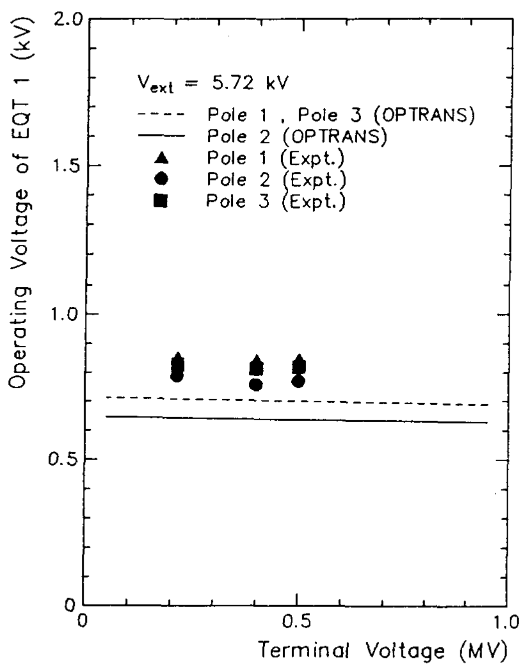

Fig. 7. Optimized operating voltages of EQT1 calculated by the program OPTRANS.

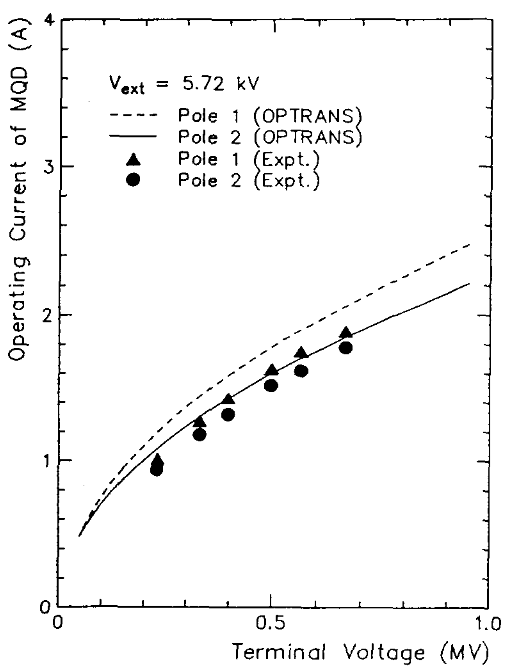

Fig. 9. Optimized operating currents of MQD calculated by the program OPTRANS.

References

1. R.G. Wilson and G.R. Brewer, "Ion Beams with Application to Ion Implantation", 132, John Wiley and Sons, New York (1973).
2. S. Humphries, Jr, "Principles of Charged Particle Acceleration", 24, John Wiley and Sons, New York (1986).
3. W.G. Mourad, "Outline of Beam Optics Program at NEC", NEC Report, No. 1/5(1979).
4. E.D. Courant and H.S. Snyder, *Ann. Phys.*, **3**, 5(1958).
5. E. Harting and F.H. Read, "Electrostatic Lenses", Elsevier, Amsterdam (1976).
6. H. Wollnik, "Optics of Charged Particles", Academic Press, London (1987).
7. D.C. Carey, "Optics of Charged Particle Beams", Harwood Academic Publishers, New York (1987).