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THE BEAM HANDLING AND AXIAL INJECTION SYSTEM FOR THE PROJECT ISIS AT JULIC

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Abstract.- For the project ISIS (Injektion schwerer Ionen nach EZR-Stripping: Injection of heavy ions after ECR-Stripping) an external injection system has been designed to transport the beams delivered by an ECR-source over a distance of about 25 meters and inject them axially into the isochronous cyclotron JULIC using a hyperboloid inflector. Various subsystems, being double telescopic, are of separated function type and modular character. The bends are doubly achromatic. Magnetic elements are used in order to utilize the space charge neutralization. The number of parameters has been minimized. Design considerations for various subsystems are presented. Estimation and optimization of the space charge effects are discussed. Special properties of the combined system of 'hole lens' and hyperboloid inflector are described.

1. Introduction.- The project ISIS at JULIC envisages to accelerate heavy ions with Q/A ratios between 0.33 to 0.5 within an energy range of 22.5 to 45 MeV/nucleon. An ECR source[1] will be used to generate the ions. It is expected to deliver the beams with an emittance upto 160·π mm-mrad in each plane and a momentum spread of < 0.5%. The ion source will be located in the radiation-free south hall of the cyclotron building (see fig. 1) for easy access and maintenance. The beam with a rigidity of 20-25 kG-cm will be transported over a distance of about 25 meters upto the center of the cyclotron and will be inflected using a hyperboloid inflector[2]. The necessary central region modification calculations are reported at this conference[3]. The beam handling and axial injection systems consist of various subsystems to do the Q/A selection, beam transport, phase space matching, achromatic bending etc. such that a) the beam envelopes are small for a minimum number of elements and parameters for simplicity during operation b) the subsystems, as far as possible, have waist to waist and point to point transfer properties in both planes for simple visible diagnostics as well as for keeping a modular character in the system c) the higher order aberrations are small and d) magnetic elements are used in order to take advantage of the space charge neutralization. A design

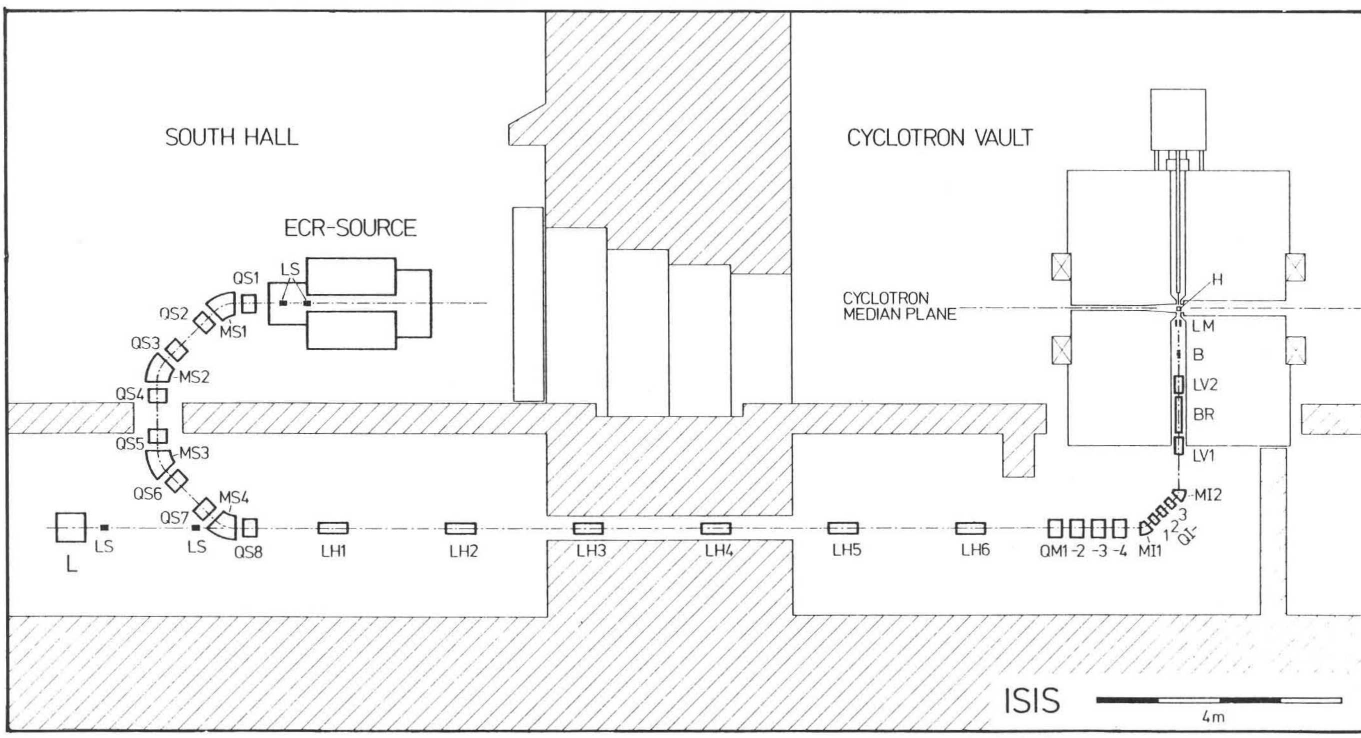

Fig. 1: Layout of the external injection system at JULIC:L-source for light ions upto Helium; LS-spherical lenses; QS, QM, QI-quadrupole magnets; MS, MI-dipole magnets; LH, LV-solenoid lenses, LM-magnetic lens, B-buncher and H-hyperboloid inflector.

of the external injection system has been evolved using the TRANSPORT code[4]. Another code MIRKO[5] was used for calculations of the space charge effects.

2. Design Aspects and Layout of the System.- The layout of the project ISIS along with this system is shown in fig. 1. Details and design considerations for the various subsystems are described below.

2.1 Source-Beam Line Matching System: For smaller beam envelopes in the injection system the beam at the entry of the 180^0 bending + charge state analysis system should have a waist of about 2 cm size in each plane for an emittance of 160·π mm-mrad. In order to magnify the assumed waists of 1·5 cm size at the extraction aperture, a double telescopic system of two spherical lenses LS is required. In the thin lens approximation its first order transfer matrix, from the focus of the first lens to that of the second, has the form

$$\begin{vmatrix} M & 0 \\ 0 & 1/M \end{vmatrix} \qquad (1)$$

in each plane with the magnification $M= -f_2/f_1$; f_1 and f_2 are the focal lengths of first and second lens, respectively. The lens separation is $(f1 + f_2)$. Since, the region over which this system has to be incorporated is strongly influenced by fringing field of the mirror coil of the ECR source, its design may be modified according of the realistic situation.

2.2 180^0 Bending + Charge State Analysis System: This system has been designed using the 'second order achromat' concept of K.L. Brown[6]. It has the properties of point to point and waist to waist imaging, vanishing second order aberrations and double achromaticity. The system consists of four identical unit cells each with the configuration drift-quadrupole-drift-dipole-drift-quadrupole-drift. The dipole is necessarily present for bending as well as for dispersion while the quadrupoles are to satisfy the following conditions for a second order achromat as well as for the vertical focussing:

$$\begin{aligned} R_{ij} &= 1 \text{ for } i = j \\ &= 0 \text{ for } i \neq j \end{aligned} \qquad (2)$$

R_{ij} are the elements of the first order transfer matrix in the TRANSPORT notation. This matrix thus is +I (unity) and, hence, the betatron phase shift[7] is 2π over the total system. For such a system the second order geometric aberrations in the transverse planes vanish automatically[6]. Additionally, proper curvatures to the faces of the dipole magnets make the second order chromatic aberrations also vanish.

The advantages of having quadrupole magnets instead of dipole edge rotations in the unit cell are:

a) tuning of the system is flexible with actively adjustable parameters available. This aspect will be useful in (i) optimizing for the space charge effects, which are different in first and second half of this system (ii) adjusting for the deviations in the realistic fringing fields from the ones taken into the calculations.

b) β_1 and β_2, which would otherwise have large values ($\sim 54^0$), are zero. Construction and alignment of such dipole magnets is relatively simpler.

The parameters of a unit cell are shown in the fig. 2a. The system has the geometric part of the first order transfer matrix as -I at the end of the 2^{nd} unit cell and a dispersed image of the entrance slit is formed at this point. The charge state selection can, hence, be done here. The charge state resolution of the system for an analysing slit width (w_i) equal to the size of the image for one charge state is given by

$$\frac{dQ}{Q} = 2 \times \frac{\text{size of the image } (=w_i)}{\text{Dispersion coefficient } (D=R_{16})} \quad . \qquad (3)$$

The intrinsic charge state resolution for w_i = 2 cm is about 1 in 30 because D = 117.8 cm. If one assumes a total momentum spread of 0.5% in the incoming beam, then, w_i should be equal to 2.08 cm. The resolution in this case is about 1 in 28. The second order aberrations at this point are negligible. The second order chromatic aberrations of the system vanish if the entry and exit faces of the dipole magnets are given the curvatures of + 58·837 cm (convex) and - 72·579 cm (concave), respectively. However, we have decided to keep them flat because even in this case these aberrations are negligibly small.

2.3 Beam Transport System of Solenoids: Since the beam has low rigidity, it has been planned to use solenoids to transport it from the exit of the analysing system to the cyclotron over a distance of 12.48 meters. The system is made of 6 identical unit cells each with the configuration drift-solenoid-drift. The first order transfer matrix for 3 such unit cells in succession is +I which corresponds to 2π phase shift. The number of solenoids being even, net beam rotation at the exit of the system can be made zero by exciting the alternate solenoids with opposite polarity. This system operates with only one parameter. Fig. 2b shows the configuration of its unit cell.

It is also possible to operate this system in a different mode wherein two unit cells in succession have a -I first order transformation matrix, i.e. π phase shift. In this case the solenoids have a lower field strength by a factor of about 1.21. However, the mode of 2π phase shift over 3 unit cells is preferable because we found that such a system is easier to tune for a transformation which is close to unity and telescopic when the space charge effects are present.

2.4 Phase Space Matching System: This system transforms the phase space in the transverse planes in such a way that the beam, after passing through the subsequent 90^0 vertical bending and axial injection systems, is matched to the focussing conditions existing at the center of the cyclotron i.e. at the exit of the hyperboloid inflector. These conditions are characterized by ν_r and ν_z, the latter of which changes slightly with the accelerating conditions. The system consists of four quadrupoles whose strengths can be independently varied. It has been empirically designed using TRANSPORT. The beam is traced back from the exit of the inflector upto the exit of the matching system. TRANSPORT is then used to calculate the quadrupole strengths to match the phase space ellipses at the entry and exit of this system. The spacings between the quadrupoles were obtained by a repeated optimization procedure such that the beam envelopes remain well below the available aperture for different ν_z values. Configuration of the resulting system is shown in the fig. 2c. The system can not be tuned in a way which is orthogonal in the transverse planes. A completely orthogonal system would need more elements and space.

2.5 Doubly Achromatic 90^0 Bending System: This system bends the beam up into the axial hole of the cyclotron. It is based upon a system after K.L. Brown[8] and is symmetric about the mid point. Its configuration is shown in the fig. 2d. The quadrupole QI2 is focussing in the bending plane while QI1 and QI3 are focussing in the non-bending plane. The system operates in the parallel to point to parallel mode and therefore QI2 has, ideally, no effect on the central momentum particles. This mode of operation makes it compact as compared to the point to point to point mode and was chosen due to the space limitation. The beam envelopes are smaller

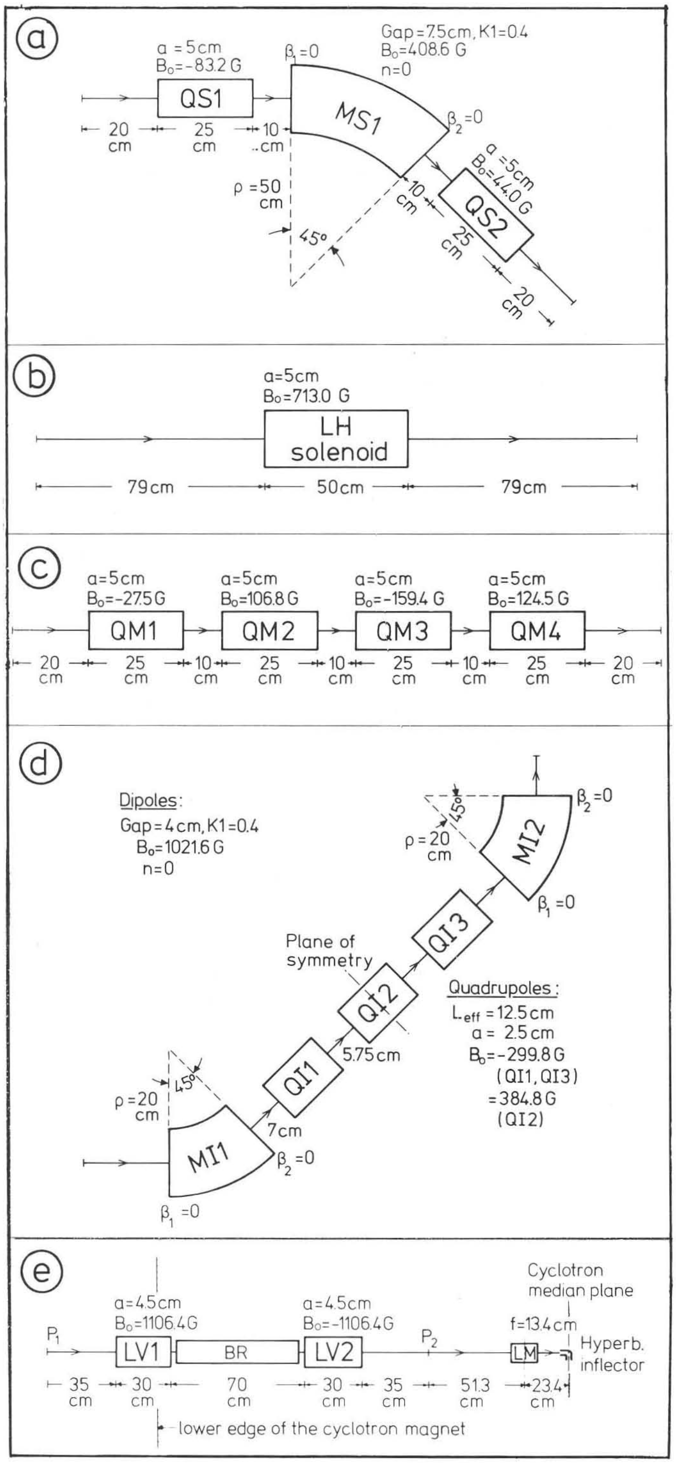

Fig. 2: Configuration and design parameters of a) a unit cell of the 180° bending + charge state analysis system b) a unit cell of the beam transport system of solenoids c) the phase space matching system d) the doubly achromatic 90° bending system and e) the axial injection system. Magnetic field values shown are for a beam of 20.432 kG-cm rigidity (i.e. 5 keV/nucleon and Q/A=1/2).

making the magnets compact. Quadrupole magnets have been used for the axial focussing instead of dipole edge rotation due to the reasons given earlier. The first order transfer matrices of the system in the bending and the nonbending planes have the following form:

$$\begin{aligned} R_b &= [-I] \times [\text{Matrix of a drift space of } 16.58 \text{ cm}] \\ R_{nb} &= [-I] \times [\text{Matrix of a drift space of } -0.82 \text{ cm}] \end{aligned} \qquad (4)$$

The effective emittance increase due to second order aberrations is only 5.4% and 4.0% in the bending and non-bending planes, respectively, as calculated with TRANSPORT.

2.6 Axial Injection System: In the cyclotron axial hole the beam is transported using two solenoids and one magnetic lens. Identical solenoids LV1 and LV2 are the focussing elements of a 2 meters long system which has a -I first order transfer matrix. Both the solenoids are excited to the same field level. The fig. 2e shows, from P_1 to P_2, the configuration of this part of the system. A 'beam rotator' solenoid BR is placed symmetrically between LV1 and LV2 for adjustable coordinate rotation. The unwanted optics of BR in this arrangement is minimum. The transfer matrix R_{ax} from P_1 to P_2 instead of being -I in each plane, is then given by

$$R_{ax} = [-I] \times [\text{Matrix of a drift space of } f^2/f_r] \;. \quad (5)$$

in the thin lens approximation. f is the focal length of LV1 and LV2 and f_r is that of BR. In order to make this apparent drift space smaller, BR should be made longest possible for a given desired rotation.

The magnetic lens LM focusses the beam in both the planes into the narrow opening of the inflector through the 'hole lens'. Its focal length is 13.42 cm. A quadrupole triplet, which will give more or less aberration free optics, could not be used because the beam traced back from the inflector exit appears strongly divergent in both planes at this lens. Very large aperture quadrupoles will be required to accomodate such a beam while the space is restricted.

2.7 Hyperboloid Inflector and 'Hole Lens': The hyperboloid inflector has unique optical properties. Its transfer matrix is analogous to that of the exit edge of an ideal solenoid[9]. The 'hole lens'[10], which is the focussing action of the axial magnetic field form as seen by the ions approaching the cyclotron median plane, followed by this inflector acts like a 'solenoid' whose transfer matrix $R_S = R_\alpha \cdot R_f$; R_α is a matrix representing coordinate rotation about the optic axis and Rf representing the quadrupole focussing in the transverse planes, simultaneously, is given by

$$R_f = \begin{bmatrix} \cos\alpha & 2\sin\alpha & 0 & 0 \\ -\frac{1}{2}\sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & \frac{\sqrt{6}}{2}\sin\alpha & -\sqrt{6}\cos\alpha \\ 0 & 0 & \frac{\sqrt{6}}{6}\cos\alpha & \frac{\sqrt{6}}{3}\sin\alpha \end{bmatrix} \qquad (6)$$

α is equal to $\omega L/2v_0$, where ω is the ion revolution frequency in the cyclotron, L is the length of the region of constant magnetic field traversed by the beam before entering into the inflector and v_0 is the ion velocity. It is obvious that a coordinate system rotation by α in the proper direction before entry into the 'hole lens' will lead to a decoupling of the transverse motions at the exit of the inflector.

Fig. 3 shows a plot of the axial magnetic field in the axial hole of JULIC. For the analytical calculations it was assumed that the field rise is concentrated at the location D where the field is 0.5 times the median plane field[11]. Over the next ∿ 2.7 cm the field is assumed to remain constant. The entry into the inflector, ∿ 3.7 cm below the median plane, is assumed to be at this field level. For this case $\alpha=51.1^{0}$. The matrix R_f was evaluated and the beam traced back assuming double waists corresponding to $\nu_r=1$ and $\nu_z=1/6$, 1/4, 1/3, 1/2, 2/3 at the exit of the inflector for $r_{mag}\sim 1.5$ cm and $\varepsilon_x=\varepsilon_y=160\cdot\pi$ mm-mrad. Only for $\nu_r=1$ and $\nu_z=1/6$ the beam upstream the 'hole lens' is circular and has a double waist, practically of the size of the waist corresponding to $\nu_r=1$ at the exit of the inflector, 2.0 cm upstream the location D. For higher ν_z the corresponding waist moves closer to D and eventually for $\nu_z=2/3$ it is formed downstream. The waist size increases from 1.55 mm for $\nu_z=1/6$ to 2.20 mm for $\nu_z=1/2$.

In order to estimate the effect of a slower field rise the transfer matrix of the field distribution of fig. 3 was calculated using the SORTM code[12]. This code carries out the orbit integration prior to calculating the matrix elements. The resulting first order matrix was fed to TRANSPORT. It was not possible to decouple the two motions completely, however, the best results were obtained for a coordinate rotation of $\alpha=60.1^{0}$. In this case, for $\nu_r=1$ and $\nu_z=1/2$, the beam envelopes are 2.50 mm, 68.7 mrad (2.19 mm, 72.5 mrad-ideal case) in the vertical plane and 1.78 mm, 115.4 mrad (1.55 mm, 102.6 mrad-ideal case) in the median plane at the exit of the inflector. These values are 4.06 mm, 53.9 mrad in vertical plane and 2.37 mm, 76.8 mrad in median plane when no rotation is applied.

Proper combination of the polarities of LV1, LV2 and LM will be chosen such that the rotation to be introduced by the 'beam rotator' is minimum. The ultimate rotation to be introduced by this 'rotator' will be determined by the relative orientations of the coordinate systems of the injection line, the cyclotron and the hyperboloid inflector as shown in the fig. 4.

3. Space Charge Effects.- Space charge effects were calculated for a 100 μA beam of 10 keV deuterons (rigidity= 20·432 kG-cm) using the MIRKO code which is based upon the Vladimirskij-Kapchinskij formalism[13]. The same code was used for optimization of the system in order to control the blow up of the beam due to space charge. Space charge neutralization has, however, been ignored in these calculation. In the fig. 5a beam envelopes with and without the space charge effects are shown corresponding to $\nu_r=1$ and $\nu_z=1/2$. The optimization was carried out in 3 steps without adding new parameters. In the first step the parameters of the subsystems 1 and 2 were varied such that the beam conditions closest to the zero beam current case are obtained at the exit of the subsystem 2. The subsystem 3 was then optimized with the new beam conditions at its entry in such a way that the beam envelopes are reduced and a broad beam with smaller divergence appears at its exit. Such a beam was acceptable to the subsequent subsystems. In the last step the parameters of subsystems 4 and 6 were varied such that the beam conditions corresponding to zero beam current are obtained at the location D. In fig. 5b the beam envelopes are shown for the optimized system. Fig. 5c shows the details of the last part of Fig. 5b. Table 1 compares the parameters for the zero current and space charge optimized systems. In fig. 6 phase space ellipses for the described cases are shown.

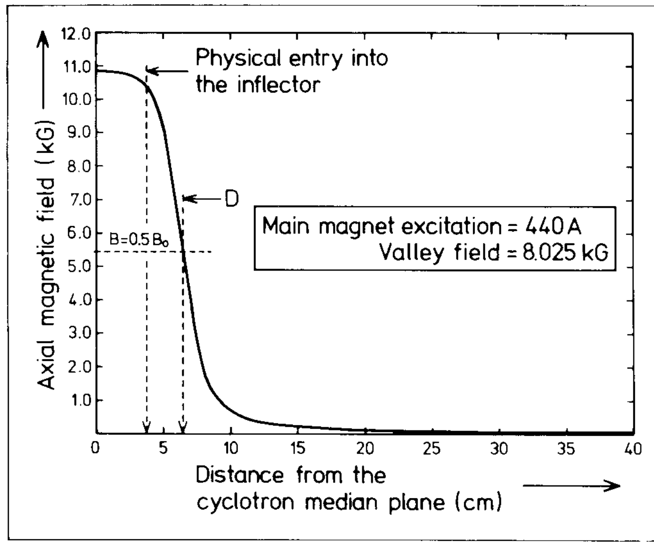

Fig. 3: Magnetic field measured in the axial hole through the cyclotron magnet yoke. Measurements carried out along the axis of the present ion source tube.

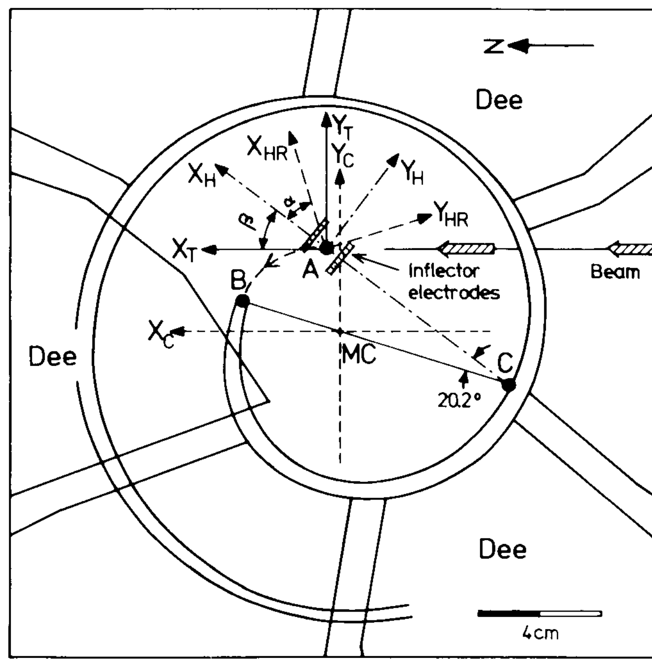

Fig. 4: Relative orientations of various coordinate systems as seen in the direction of the beam. In all the cases the z-axis goes into the plane of the paper. (X_T, Y_T) is the coordinate system of the axial injection line as used in TRANSPORT; (X_H, Y_H) is the coordinate system of the inflector at its physical entry A: X_H being in the direction of the inflector electric field; (X_{HR}, Y_{HR}) is the orientation of the (X_H, Y_H) coordinate system upstream of the hole lens entry i.e. at the location D in fig. 3; (X_C, Y_C) is the cyclotron coordinate system. (X_T, Y_T) should coincide with (X_{HR}, Y_{HR}) in order to decouple the transverse motions at the inflector exit B. The transformation of the hole lens + inflector system is such that X_{HR} corresponds to the axial motion and Y_{HR} to the radial motion in the centre of the cyclotron. MC is the machine centre and CA = r_0, the characteristic radius of the inflector.

Acknowledgements

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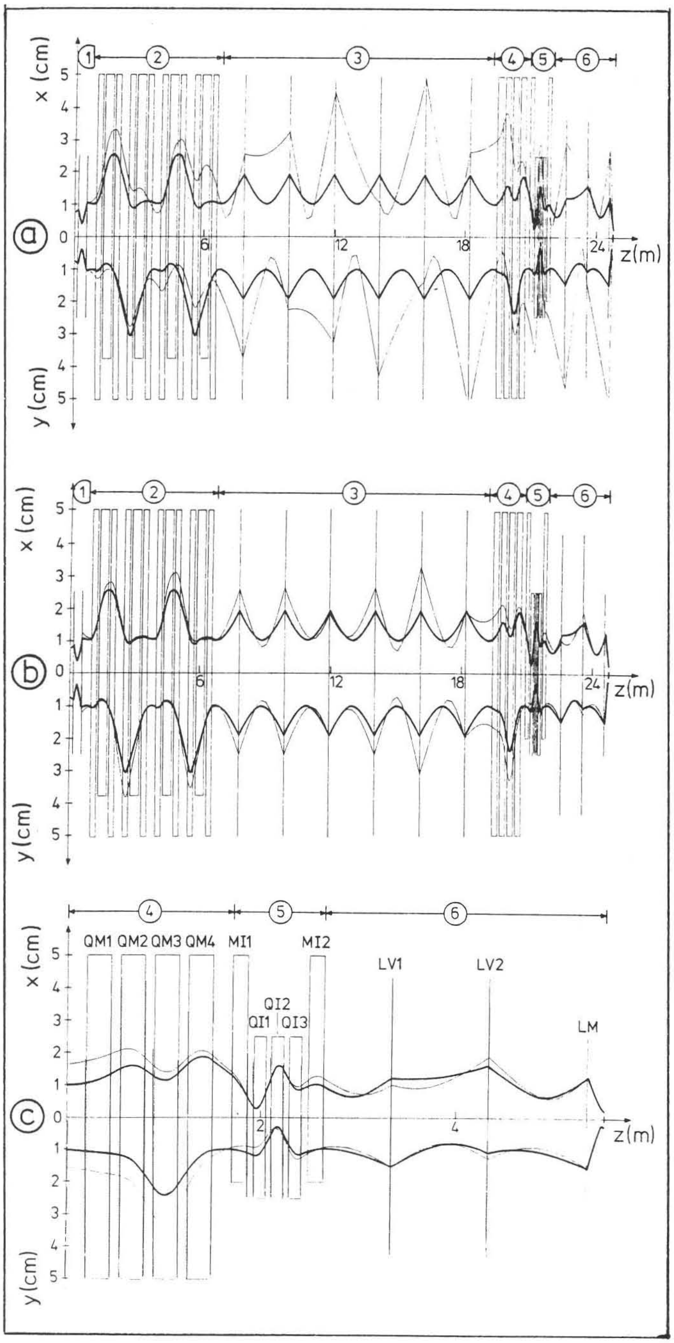

Fig. 5: Beam envelopes through the total system except the hole lens to inflector part (∿ 8 cm). a) For zero beam current (thick lines) and 100 µA beam current (thin lines) b) For 100 µA beam current in the optimized system (thin lines). Envelopes for the zero beam current system (thick lines) for comparison. c) Detailed view of the last part of fig. 5b i.e. in the subsystems 4, 5 and 6.

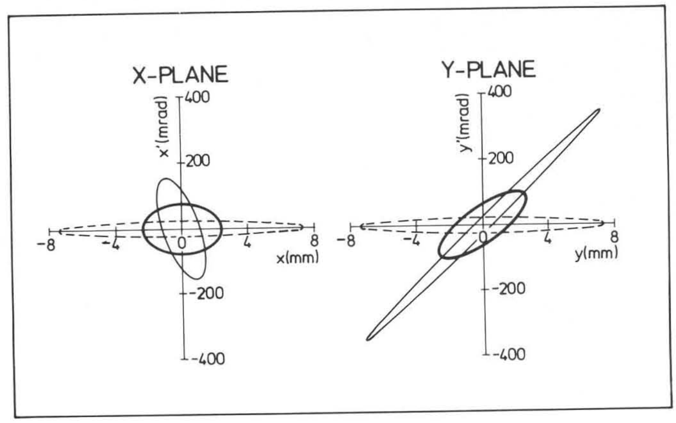

Fig. 6: Phase space ellipses. Dotted lines: at the beginning of the system; thick lines: at the end of the system for zero beam current as well as for the system optimized for 100 µA; thin lines: at the end of the non-optimized system for 100 µA beam current.

Table 1: Comparison between the parameters of the systems with zero beam current and 100 µA beam current after optimization, for 10 keV deuterons. f: focal length in cm, B_0: pole tip field in gauss.

Varied Element	Parameter	Value of the parameter: zero beam current system	Optimized system for 100 µA beam current
LS1	f	17.14 cm	15.55 cm
LS2	f	22.86 cm	20.34 cm
QS1,QS3 QS5,QS7	B_0	-83.25 G	-92.37 G
QS2,QS4 QS6,QS8	B_0	44.05 G	54.62 G
LH1 to LH6	f	70.96 cm	57.47 cm
QM1	B_0	-27.54 G	-6.75 G
QM2	B_0	106.82 G	87.10 G
QM3	B_0	-159.41 G	-153.76 G
QM4	B_0	124.54 G	118.67 G
LV1,LV2	f	50.00 cm	38.46 cm
LM	f	13.42 cm	12.70 cm

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" DISCUSSION "

H.W. SCHREUDER : What are the vacuum requirements for the injection beam line ?

R.K. BHANDARI : ∿ 10^{-7} torr for a transmission of ∿ 95 % for Ne^{10+} ion beam.