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ION INJECTION FROM EXTERNAL SOURCES

Invited Paper

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Abstract

Discussion is restricted to low and medium energy cyclotrons. Some reasons for using external injection are given. At the present time injection is either in the median plane or axial. Among the possibilities for injection in the median plane are cycloidal motion along a sector edge, linear motion by electrostatic compensation, and high energy injection with trapping into cyclotron orbits by change of charge. In the axial direction all methods have much in common--focussing down a hole in the magnet pole and inflection into a cyclotron orbit. As an example of the problems and possibilities with external injection the axial method is discussed in more detail. Topics include basic principles, beam quality, variable energy arrangements, bunching and the choice of injection energy.

Introduction

The number of machines in which external injection is planned now exceeds the total number of AVF cyclotrons projected or under construction in 1959; without doubt the reason for this activity is the need to inject beams of polarized, heavy and negative ions into cyclotrons. When external injection is used it is possible to have high duty cycles, to increase the intensity of weak beams with bunchers and, most important from the operational point of view, to have exceptionally clean conditions inside the cyclotron.

Injection Methods

This discussion will be restricted to low and medium energy cyclotrons and Table 1 shows some of the machines in which external injection is planned or in use. It will be seen that three arrangements are being developed for injection in the median plane. At Orsay, Cabrespine[1] is using the method proposed by Tobias[2] in which heavy ions are pre-accelerated in a linac and, in a relatively low charge state, are injected and stripped into stable orbits about the cyclotron center. A later proposal by Almquist[3] in which the linac is replaced by a tandem accelerating negative heavy ions has attractive possibilities for reaching high energies. These heavy ion proposals involve relatively high injection energies and avoid the cyclotron center altogether. Two important median plane schemes involving injection energies of a few tens of keV are those of Gladishev et al.[4] at the Lebedev Institute and of Beurtey and Thirion[5] at Saclay. Very encouraging results are being obtained with these methods each of which is to be described in a separate paper.

Axial injection schemes so far reported all involve similar principles. Before entering the main cyclotron magnetic field the ions pass down a hole which can be almost free of magnetic field and in which it is possible to introduce a variety of focussing and other devices. As they enter the cyclotron they are subject to the relatively strong focussing action of the magnetic lens at this point and shortly afterwards they must be turned into the median plane. To make the turn in the space available the injection energy must be reasonably low. Perhaps the most important part of the work in the design of an axial system centers around the choice and detailed positioning of this inflector. It will be seen from the Table that two different devices are being tried, the 45° mirror and the deflector (to avoid confusion the word deflector is used here to describe devices in which the electric field is always normal to the direction of motion.) In the remainder of this paper I would like to discuss the axial injection technique in more detail, referring particularly to our experiences on the 40 inch cyclotron at the University of Birmingham.[6]

Axial Injection

Principles

To begin with it may be useful to make some simplifying assumptions and to consider to first order only the principles upon which axial injection is based.

In Fig. 1 a paraxial, symmetrical and parallel tube of beam, radius r, is shown entering the magnetic field of the cyclotron. Sections through the beam at various points and the corresponding x and y phase space components are given. Lengths in the momentum coordinates are drawn equal to $p_x/m\omega$ where ω is the cyclotron frequency (by this method, as will be seen, the size and shape of the phase space becomes the same as the distribution of orbit centers during acceleration in the cyclotron). The initial x and y phase space distributions are two lines of length 2r and zero area.

When the beam enters the magnetic field the magnetic lens (assumed--with reasonable accuracy in most cases--to have an impulse action) imparts a rotation to the particles. In x and y phase space the particles are now distributed around the edge of two ellipses with major axes of 2r and minor axes of r; the area of each is $\pi r^2/2$ and the total phase space area (if one now imagines the tube to be full of beam) is πr^2. The particles now rotate until they all come to a focus at B where the beam is purely divergent and the phase space area is zero. At an intermediate position such as C, where the beam has radius r' and is partly rotating

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and partly convergent, the phase space areas are inclined ellipses of intermediate total area $\pi r'^2$. Thus we see that with axial injection the phase space area is changing. This is due to the varying electromagnetic momentum term (see for example Sturrock[7]) which in a constant magnetic field is proportional to Br^2, where r is the radius of cross-section of beam and B is the component of magnetic field normal to it. It is convenient to consider the phase space as split into two components, one purely divergent and the other purely rotational; it can then be shown that the area of the divergent component is conserved, while the area of the rotational component is equal to the "rotational area", derived from the electromagnetic term. The rotational area is then given by $A\, B'/B \cos \gamma$ where A is the area of cross-section of the beam, B is the cyclotron field, B' is the field at the cross-section and γ is the angle between B' and the normal to the cross-section. Thus, outside the cyclotron the rotational area will usually be zero and inside it will be $A \cos \gamma$. In the present case before inflection it will be A and afterwards (if we only consider sections of beam at right angles to the median plane) it will be zero. The values of the rotational areas are given at the right hand side of Fig. 1 and in this case are simply equal to the cross-sectional area of the beam.

It is now necessary to consider the effect of turning particles into the median plane at various points down the axis. To simplify the situation we use an "impulse mirror"--an infinitely strong electrostatic mirror inclined at 45°--and place it in the first instance at A, a point of maximum cross-section, see Fig. 2. A central ray would enter the mirror down the z axis and leave along the y axis. Sections through the tube of beam immediately before and after inflection together with the velocity components are shown. To overcome the difficulty that different parts of the beam are inflected at different times, the sections are extrapolated to the origin and the inflected beam is shown in the y = 0 plane. The phase space areas before and after inflection are given; at first sight it appears that the conservation laws have not held because although the rotational area has gone to zero, the phase space areas appear to be the same. It is necessary, however, to define the direction of rotation and when this is done it will be seen that after inflection the x and z rotations are equal and opposite making their algebraic sum zero. The particles now begin to circulate in the cyclotron and the orbit centers, shown in the figure, occupy an area of $\pi r^2/2$ numerically equal to the p_x, x phase space immediately after inflection. Thus we see that even a perfect external beam with zero phase space area can have a large center spread after being axially injected into the cyclotron.

We must now consider the new components of rotation introduced by the action of the mirror. Whilst algebraically these sum to zero, in terms of cyclotron beam quality they are just as harmful as any other source of center spread. However, the possibility of cancelling the components in a suitable mirror design exists and it will be seen that in the case of an impulse mirror the design should be unchanged along the x axis and in the x = 0 plane, but the lines formed by the intersection of the mirror with the various z y planes should be rotated by an angle $x/4\rho$ where ρ is the radius of curvature of particles in the cyclotron before acceleration. This is indicated in Fig. 3 where it will be seen that in the twisted mirror the rotating components are removed and the total phase space area is zero, consisting of two lines of length 2r. The center spread is therefore also a line of the same length. It should be noted that although the area is zero a center spread of this type may be bad for beam quality and energy resolution in the cyclotron; for bunching, however, it is excellent.

Next, consider an impulse mirror at B, the focus of the tube of particles. The new features of the situation are shown in Fig. 4; since all particles pass through the center of the mirror there is no rotation, the phase space before and after inflection is purely divergent and is conserved. In terms of center spread a shorter line of length r is produced and cyclotron quality and energy resolution should be better (it will be noted that the direction of the line is unfavorable for the production of short bunches).

Finally, consider an intermediate position such as C where the beam cross-section is of radius r' and both divergent and rotating components are present. Now an impulse mirror produces an inclined ellipse of center spread area $\pi r'^2/2$, see Fig. 5, and in terms of beam quality the situation is intermediate between Figures 2 and 4. By twisting the mirror the rotation can be removed, but there is the further possibility of removing the divergence also by curving the mirror into the shape of a cylindrical lens. This is indicated in Fig. 6 where it will be seen that the center spread can be reduced to a line of length 2r'.

The purpose of examining these idealized situations has been to try and discover some of the basic principles and limitations of an axial injection arrangement. For this reason the possibility of introducing additional lenses and other devices before or after the inflector has not been discussed. With these various restrictions in mind it seems that, in principle, the best way of achieving good beam quality with a mirror inflector is to inject a nearly parallel beam of small radius into the magnetic lens of the cyclotron and to inflect this in a "curved and twisted" mirror placed just before or after the focus (at the focus the curvature would have to be infinite to remove the divergence). The center spread would then be no larger than the beam cross-section at the entrance to the inflector.

Actual Situation

Unfortunately inflectors are by no means impulse devices and there are many other factors entering into the real situation. We now go on to consider some of these taking as an example the arrangements on the Birmingham 40 inch cyclotron.

Although the original axial injection scheme[8] was tested with an R.F. ion source, for the past year a polarized deuteron source has been in use.[9] At the present time this gives about 1 $\text{m}\mu$ A of 12 MeV polarized deuterons in the experimental area (in the scattering chamber after passing two 3mm slits a meter apart 10^9 p.p.s. are measured). The effective source of particles is the ionizer and, compared with an ordinary ion source, the emittance is poor. A measurement at the present injection energy of 12 keV shows the total beam from the ionizer to have an emittance of 2,100 mm. mrad. $\text{kV}^{1/2}$, which is equivalent to a center spread in the cyclotron of 9 mm^2 (this is a particularly convenient concept because the center spread in mm^2 is approximately the same as the beam quality at 50 MeV in mm. mrads).

Beam Transport. The beam is transported down the hole in the cyclotron, a distance of 180 cms, by means of six einzel lenses with an aperture of 2.2 cms. The acceptance of this system (equivalent to a center spread of 18 mm^2) is twice the emittance of the ionizer, and as will be seen from the sketch in Fig. 7 it is a beam transport system with the focal length of each lens equal to the distance between lenses, rather than a series of object and image points. After passing the last einzel lens the beam is focussed into a defining (and R.F. shielding) tube of 1 cm. bore which runs from the magnetic lens to the mirror. The acceptance of this part of the system is also 18 mm^2.

The einzel lenses behave very differently with positive and negative voltages. Negative voltages higher than the 12 keV injection energy are required to produce the necessary focussing action and with the small clearances we have these voltages are difficult to hold and in any case might be bad when phase bunching is required. With positive voltages, however, about 1 kV is sufficient. This characteristic is shown in a plot of transmitted beam current against the voltage on one of the lenses (Fig. 8). The positive voltage behavior is almost certainly due to trapped electrons derived from ionization of the residual gas and stored by the action of the electric and magnetic field (of a few hundred gauss). To begin with as the voltage is increased and the ionization potential is passed the focussing power of the lens rises--at this time the dominant electron motion is probably axial. Then at about 300V positive the cycloidal electron motion begins to provide sufficient energy for ionization and thereafter this process probably dominates, since all the trapped electrons can contribute to further ionization before eventually being lost to the walls. The process is a powerful one and to a first order independent of pressure; it can therefore be expected that the potential distribution is greatly modified. A guess at the redistributed potentials is given in the figure. Clearly such lenses must be expected to be of poor optical quality (similar effects have been noticed by Grunder at Basle University and it would be interesting to know if any more information is available on the subject), consequently it must be assumed that on the 40 inch cyclotron the beam emittance on entering the magnetic lens is equal to the 18 mm^2 acceptance of the transport system. At first sight it would appear that a similar situation would arise with the positive voltage on an electrostatic quadrupole; but because the cycloidal electron motion now moves to the back of the lens, it may be that electrons can be collected (on an insulator, for example) before the space charge has built up sufficiently to distort the lens action. If this is correct, then it may be that the electrostatic quadrupoles being used by some groups will prove much better than einzel lenses.

Central Region. We now consider the probable beam distribution in the 40 inch cyclotron between the magnetic lens and the first acceleration gap, see Fig. 9. Only the x component of phase space is shown since the y component is identical to it before inflection and similar afterwards. Before entering the magnetic lens the beam is assumed to be free from rotation with a total phase space area of about 10 x 2 mms; two diagonal tubes of particles, labelled A and B, are selected as representing extreme conditions. On entering the magnetic field they each acquire a rotation of area 39 mm^2 and the two tubes are now represented in phase space by the inclined ellipses shown; because there is considerable overlap between them, the total phase area of the beam is about 50 mm^2. Tube B is brought to a focus before the mirror and tube A afterwards, with the remainder of the beam lying between these two points. The phase areas of the tubes at the mirror are now reduced as shown.

With an impulse mirror a similar phase shape would be obtained after inflection; but the actual mirror is at present operating with an electric field strength of about 28 kV/cm. and while passing through it particles rotate through an angle of 25°. Particle motion in the electrostatic mirror has been considered by Chen,[10] Oh and Talaseff[11] (the latter report is particularly detailed including dispersive effects) and to first order the transformations which concern us are

$$x = x_o + p_{x_o}/m\omega \tan \phi$$

$$p_x/m\omega = y_o - p_{x_o}/m\omega$$

$$z = -y_o + p_{y_o}/m\omega \tan \phi$$

$$p_z/m\omega = -p_{y_o}/m\omega + p_{x_o}/m\omega \tan \phi$$

in which the x and z co-ordinates after inflection are referred back to the origin at the y = 0 plane, and the x_o and y_o co-ordinates before inflection are referred to the origin at the z = 0 plane; ϕ is the angle through which particles rotate in the mirror. It will be seen that the effect of the extended mirror action in p_x,x phase space is to introduce a term in the x component equal to the product of the initial x component of momentum and tan ϕ; there is no change in the x component of momentum itself.

The A and B ellipses after inflection are shown in Fig. 9. Comparing them with the ellipses just before inflection it will be seen that the p_x components are unaltered but the A ellipse is compressed in the x direction (because the particles are convergent at the mirror) while the B ellipse is expanded (because its particles are divergent at the mirror). It can be seen that the total beam will lie roughly in the parallelogram formed by joining the corners of the two ellipses and that by suitable choice of mirror parameters it has been made reasonably compact in shape. The total phase space area occupied by the beam is now about 22 m^2, only slightly larger than the original beam entering the magnetic lens, and if these were the only factors to be considered the center spread in the cyclotron would also be 22 m^2. However, the wire mesh forming the transparent upper plate of the mirror gives rise to many small electrostatic lenses 1 mm. square and inclined at 45°; each particle passes twice through such a lens, and at each crossing can acquire up to ± 1/2 mm of $p_x/m\omega$; thus the phase space is broken up and can extend by up to ± 1 mm. in the p_x direction. The p_y component is smaller because of the inclination of the lens in this direction. A similar effect occurs when particles cross the randomly disposed wire grids in the dee and dummy dee (these are used to define the R.F. field as explained in earlier papers[6,8]). The first crossing, while the energy is low, is likely to be the most important one and again the maximum effect is estimated to be about ± 1 min. in the p_x direction. These two effects taken together can be expected almost to double the region occupied by beam, and the final area, shown dashed in the figure, is about 40 mm^2 (10 mm. in p_x by 4 mm. in x). The situation looks better when the distribution of beam is considered, for over half of it lies within a region 4 x 4 mms.

It seems that the present arrangement could usefully be improved by doubling the number of mirror wires lying in the x direction and also doubling or trebling the number of grid wires in the dee and dummy dee on the first gap crossing; but at the moment there is no point in twisting or curving the mirror. It should be noted that the deflectors of R. W. Müller[12] and J. L. Belmont[13] do not require a wire mesh, and are certainly better than the mirror in this respect.

Variable Energy, Multiparticle Arrangements

We have seen that there is probably an optimum arrangement for particle trajectories before and within the inflector; there is also an optimum ratio between injection energy and dee voltage so that particles can be accelerated on center. It would seem that the only simple way of achieving this optimum for different energies and particles is to use the same components and have constant trajectories and orbits. As with constant orbit cyclotrons this requires that injection, inflection and accelerating voltages be kept proportional to ω^2.

Fig. 10 shows possible center geometry arrangements for one and two dee cyclotrons. Both would be suitable for orbit scaling, although the two dee arrangement seems more awkward and probably requires an off-axis mirror. In both cases it might be best to provide grids in the dees to define the R. F. field and focus the beam.

Phase Bunching

Bunchers may be divided into two types; those used to improve the intensity by concentrating particles into the phase range accepted by the cyclotron (down to about 10 nanoseconds), and those used to produce very short pulses (to 1 nanosecond and less) for single turn extraction and time of flight work. A buncher of the first type has recently been applied[10] to the 40 inch cyclotron.

The buncher, which is placed between the first two einzel lenses, is itself like an einzel lens with a few hundred volts of r. f. (obtained from the cyclotron) applied to the center electrode. Its aperture is 2. 2 cms. and the distance between the accelerating gaps is 3 cms. The electrode arrangement is shown in Fig. 11 together with a graph showing the buncher characteristic; in this graph the phase of particles at the buncher is plotted against their phase when they reach the cyclotron center. With the buncher off, particles lie on a straight line of 45° slope since all particles have the same phase difference between buncher and cyclotron; the position of the line is determined by the value of this difference. When an R. F. voltage is applied to the buncher the line becomes curved by the addition of a sinusoidal component. The effect is to introduce a flat or relatively flat region in the curve; this is the desired operating condition over which a wide range of phases at the buncher are concentrated into a narrower range at the cyclotron center. For a particular value of r. f. voltage the curve has a plateau at the center of the operating region and this is the condition shown by the full curves in the graph. At higher r. f. voltages the characteristic is steeper as shown in the dashed curve; this offers a further improvement in intensity providing the phase acceptance of the cyclotron is large enough to accept it. Since the phase acceptance of the 40 inch cyclotron is known to be about 90° it might be expected that quite a high bunching voltage could be used; but this ignores several debunching effects of which the most serious occurs in the half turn from the mirror to the dee gap and is due to the spread in p_x values, giving a phase spread of $2/p\ p_x/m\omega$ radians. In the 40 inch cyclotron this is about 60°. Other factors are energy spread at the ionizer (perhaps 50 eV), different flight times in the einzel lenses and in the magnetic lens, and supply fluctuations. Altogether a spread of about 90° can be expected. Thus particles lie on a series of curves spread over 90°; this is illustrated in the graph by the three solid curves which show the range of operating condition on the cyclotron. The measured intensity improvement with the buncher is x2. 2 and the intensity reduction when tuned to the debunching condition is X0. 42; this seems to indicate a reasonable agreement with the assumptions of about 90° phase acceptance and 90° of debunching.

With 90° of debunching in the present arrangement, the shortest beam pulse that can be produced is of about 20 nanoseconds duration. With better quality beams and the aid of slits and defining apertures this could undoubtedly be reduced to a few nanoseconds (at the expense of beam intensity); but it does seem that it may be quite difficult to produce nanosecond and subnanosecond pulses by these methods.

Negative and Heavy Ion Injection

External injection is attractive for these particles because the special sources required can be placed away from the cyclotron. Most of the problems involved concern the sources themselves and are outside the scope of this paper. Reasonably low pressures are required to avoid electron stripping or attachment, but this should be relatively easy to achieve. In the case of a cyclotron injecting both negative and positive ions if electron trapping is important in the lenses careful attention must be paid to the effect of changing polarity.

Injection Energy and Related Matters

For some work high intensity beams may be required and since the intensity of a space charge limited beam is proportional to $V^{1/2}$ a higher injection voltage appears to be called for. However, one may not always achieve an increased intensity by raising the injection energy; in the mirror arrangement, for example, an earlier limit may be set by heating and distortion of the wire mesh and it might even be that higher intensities would be achieved by reducing the injection energy, and consequently the overall power into the mesh. Obviously the most profitable way of increasing intensity is by bunching since no power increase is involved; but even without special arrangements quite high beams can be transported--Bennett at the Rutherford laboratory has had 5 mA of 25 keV protons in a 1/2 inch diameter spot over a distance of 70 cms. with one einzel lens and on the 40 inch cyclotron 25 μA circulating beams have been obtained. It seems fairly certain that currents in excess of 100 μA could be obtained from the mirror arrangement at quite modest injection energies, but again it should be noted that deflectors do not require a mesh and may be the best way of realizing the very highest intensities.

The center spread (and hence final beam quality) is not improved by increasing the injection energy, for although the quality at injection is better, when a beam injected at lower energy has been accelerated by the corresponding amount its quality is the same.

It will be clear from the previous discussion on bunching that the possibilities are improved in proportion to $V^{1/2}$ when the injection energy is raised.

One last factor should be mentioned. In the first few acceleration turns the phase spread on the beam causes different particles to have different orbit centers[14] and this gives rise to a further center spread. In Figure 12 this center spread is plotted against R.F. phase spread for different injection energies at a constant dee voltage of 25 kV. The 40 inch cyclotron is seen to be operating with an additional center spread in the x direction of nearly 2 mm (with a conventional source the spread would be 2-1/2 mm.). The curves show that the effect is smallest at high injection energies; but that the main improvement comes at the more modest energies.

For most purposes there do not seem to be good grounds for going to high injection energies. As discussed in connection with variable energy arrangements, it seems that the main consideration is to choose an energy which gives the best geometry in the magnetic lens and the inflector, a reasonable clearance on the first turn, and good beam centering. For most cases this energy probably lies somewhere between 10 and 40 keV.

Conclusion

External injection is beginning to prove useful for the acceleration of polarized ions, and when present plans are realized negative and heavy ions will be injected by these methods. Many groups are now active in these fields and a period of rapid advance can be expected.

Whilst one may look forward to the time when all sources are external it seems probable that further work is needed to improve the quality, intensity and bunching possibilities before this can be realized.

Acknowledgements

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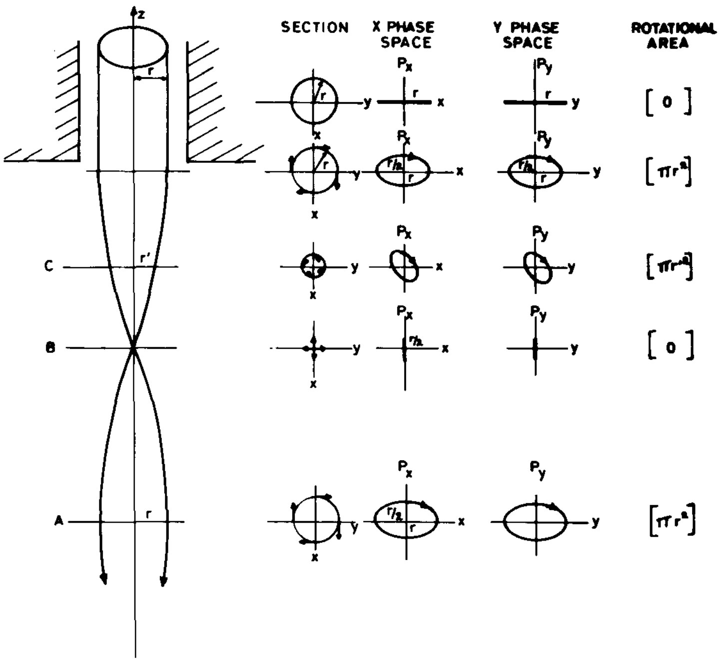
Table 1. External Injection into Cyclotrons, Specifications.

Machine or Installation	Focussing	Inject. Energy keV	Inflection	Comments	Results
			AXIAL		
88" Berkeley	Electro Quads	25	Mirror		Construction. Quads tested
Grenoble		45	Deflector	Variable Energy	Electron Model.
					Ion model designed.
A.E.G.	Electro Lens	10	Deflector		Ion Model
C.S.F.			Mirror		Electron Model
					5 mA thro Einzel lens
V.E.C. Harwell	Elec and Mag.	20 - 30	Mirror		30 KV/mm on Mirror
				Polarized Ions	In operation,
40" Birmingham	Einzel lens	12	Mirror	Buncher	2 x 10^9 polarized p.p.s.
55 MeV Princeton		10		Inject off Axis	
50 MeV Karlsruhe					
50 MeV UCLA				H^- injection	
15 MeV Duke	Einzel lens	10	Mirror	H^- injection	
N.R.L.				As Berkeley	
Davis				As Berkeley	
ORIC	Electro Quads	30			
100 MeV Maryland					
50 MeV Manitoba					
M.S.U.				H^- Injection	
100 MeV Swiss U.				Polarized Ions	
		MEDIAN PLANE - Charge Exchange			
C.E.V.I.L. Orsay		1 MeV/Nucl	Stripper	Linac Inj.	Construction
		MEDIAN PLANE - Cycloid down Sector Edge			
Lebedev Institute	Stable region	low energy	Electro		Tested in cyclotron
		MEDIAN PLANE - E cancelling H			
Saclay	Stable region	low energy		Polarizations	Ion Model tested

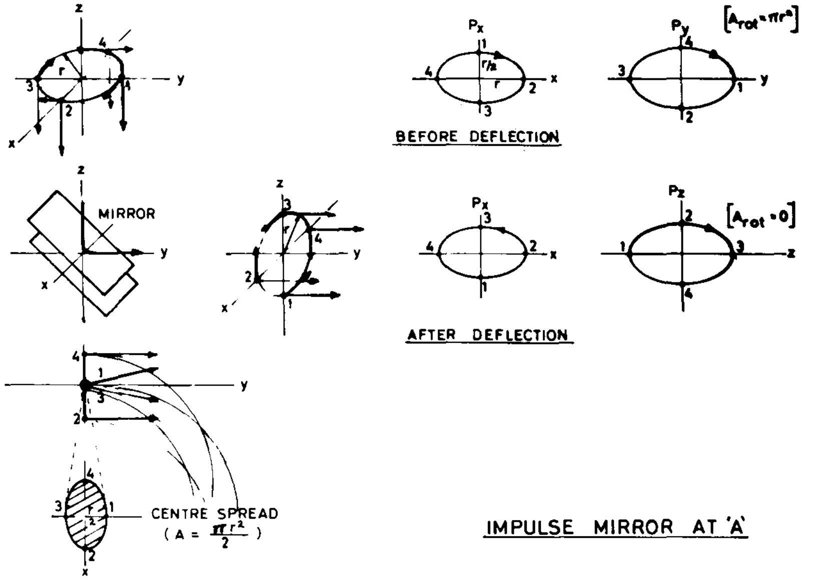
EXTERNAL INJECTION, SPECIFICATIONS



PHASE SPACE OF AXIAL BEAM TUBE

Fig. 1

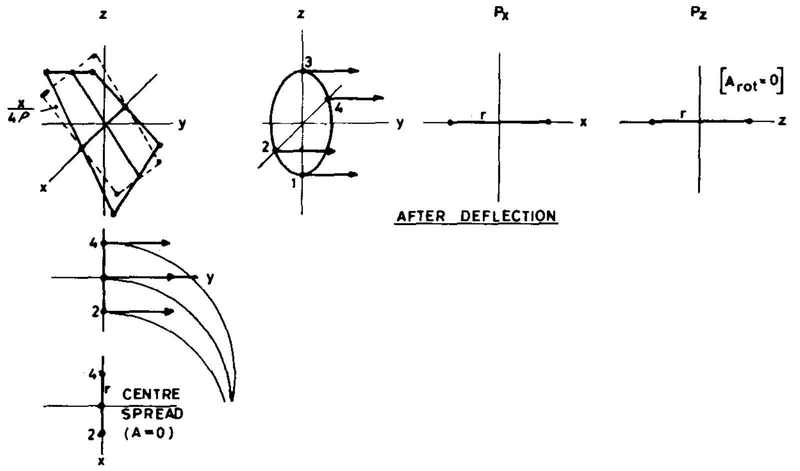
A parallel tube of beam is shown entering the cyclotron field down the axis. Sections through the beam, together with x and y components of phase space and the corresponding rotational areas are given. Distances in the p_x direction are drawn equal to $p_x/m\omega$ to give them the same dimensions as x.



IMPULSE MIRROR AT 'A'

Fig. 2

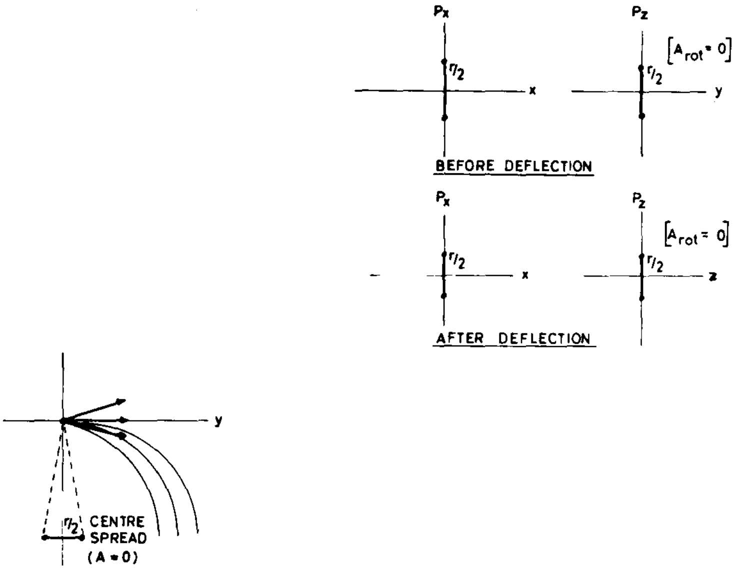
An impulse mirror is placed at A (see Fig. 1). Sections through the beam and phase space components before and after inflection are shown, together with the positions of orbit centers on the first half turn in the cyclotron.



TWISTED IMPULSE MIRROR AT 'A'

Fig. 3

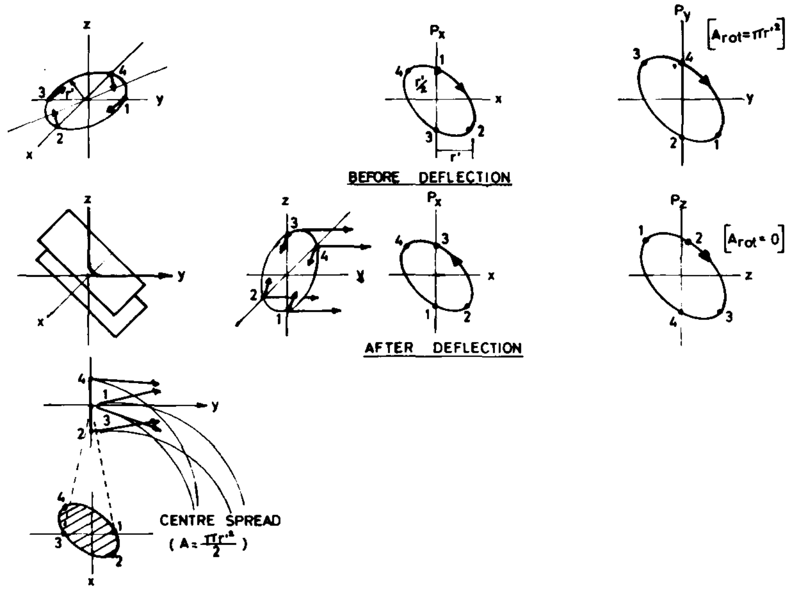
The mirror at A is now twisted to remove rotational components (Compare with Fig. 2)



IMPULSE MIRROR AT 'B'

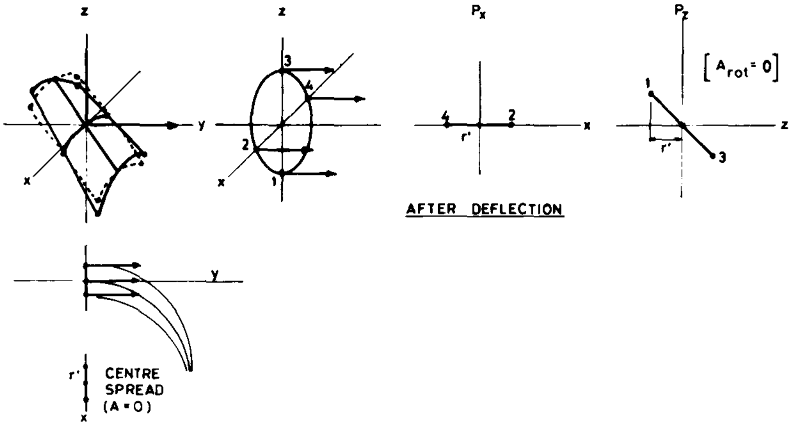
Fig. 4

An impulse mirror is placed at B (see Fig. 1). There are no rotational components and the center spread of the cyclotron orbits is reduced (compare with Figs. 2 and 3).



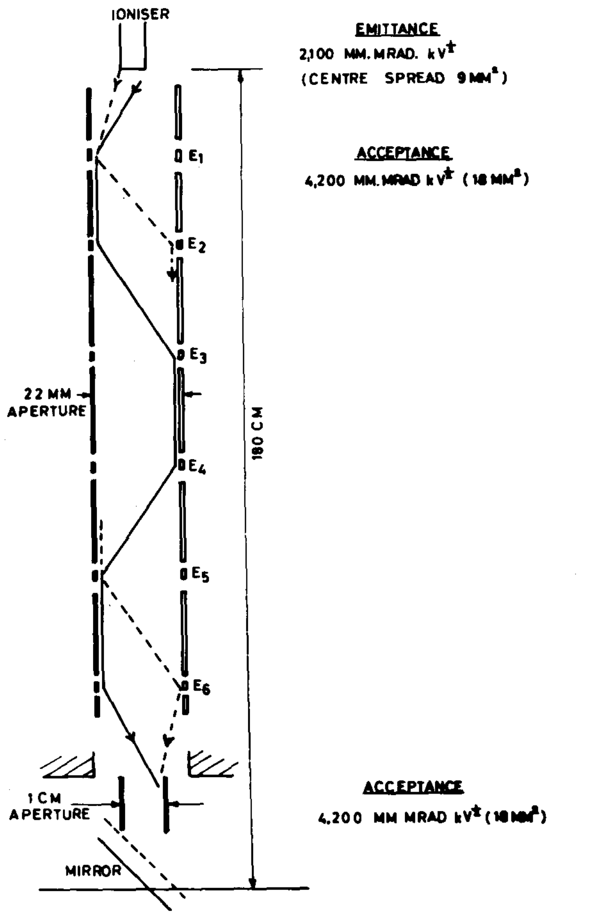
IMPULSE MIRROR AT 'C'

Fig. 5
An impulse mirror is placed at C (see Fig. 1). Particles are both divergent and rotational. The center spread is intermediate between positions A and B.



CURVED AND TWISTED IMPULSE MIRROR AT 'C'

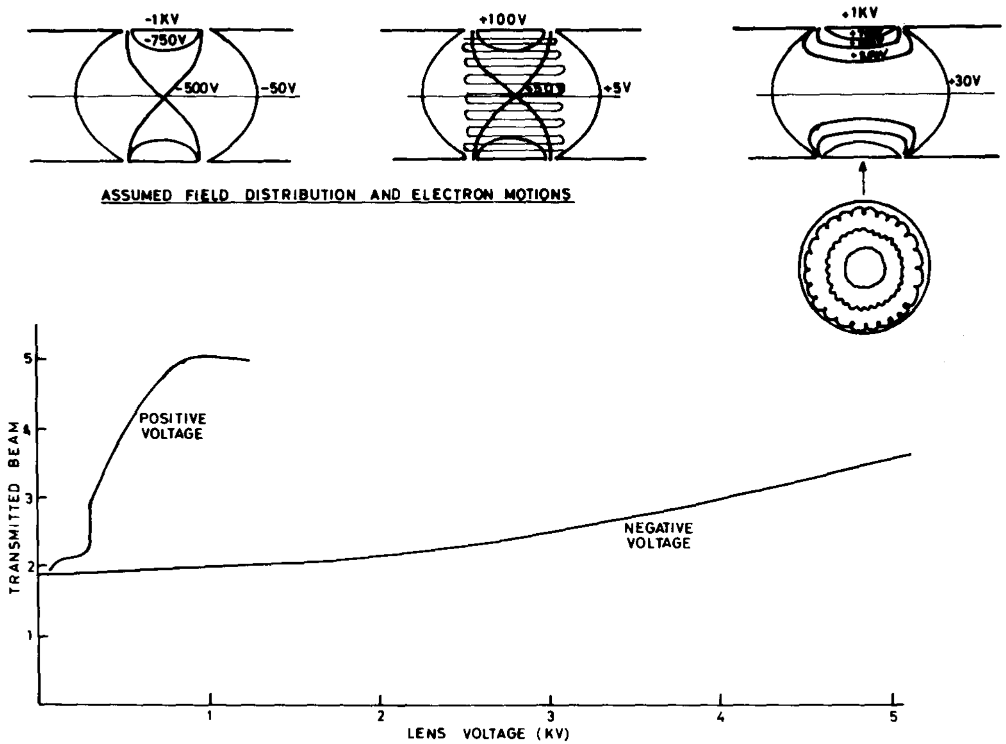
Fig. 6
The mirror at C is curved and twisted to remove both rotational and divergent components. The center spread is now smaller than in any other case.



BEAM TRANSPORT DOWN AXIAL HOLE

Fig. 7

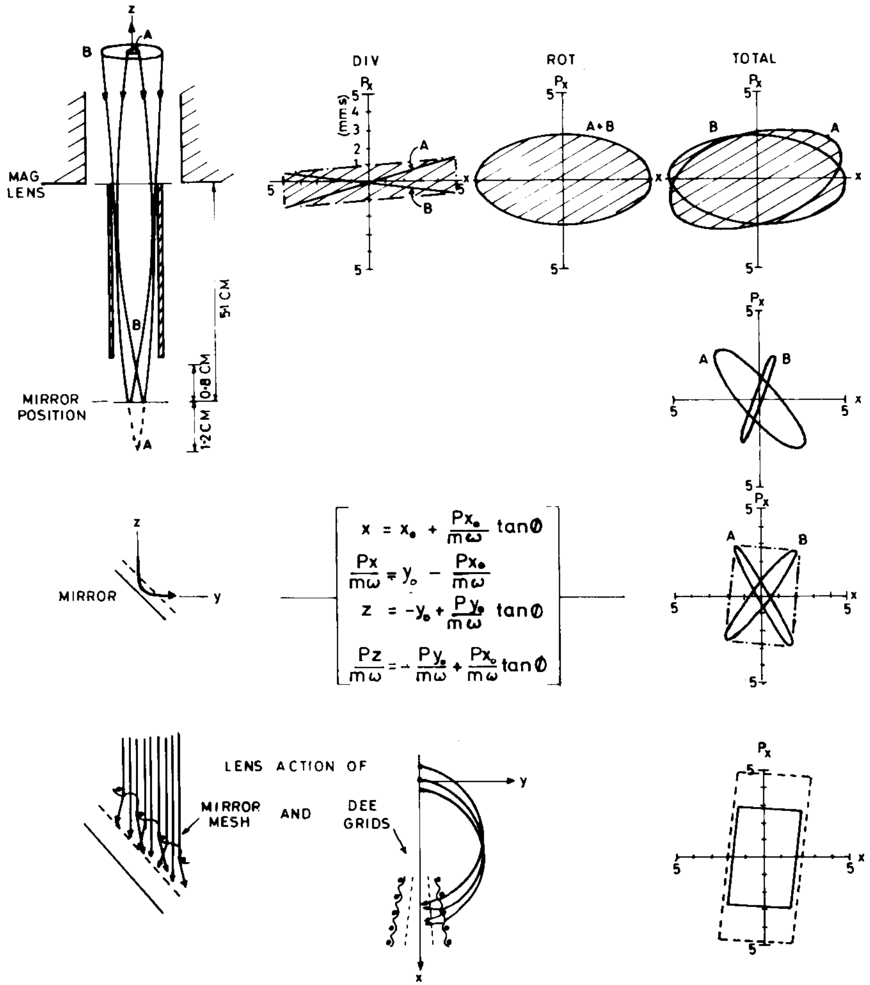
Beam transport down axial hole showing einzel lenses.



TRANSMITTED CURRENT AS A FUNCTION OF EINZEL LENS 3 VOLTAGE

Fig. 8

Graph showing how transmitted current varies with positive and negative voltages on an einzel lens. The effect of trapped electrons on the positive voltage distribution is indicated.

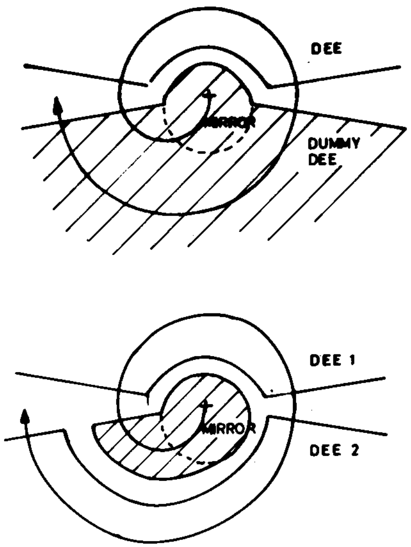


$$x = x_0 + \frac{P_{x_0}}{m\omega}\tan\Phi$$
$$\frac{P_x}{m\omega} = y_0 - \frac{P_{x_0}}{m\omega}$$
$$z = -y_0 + \frac{P_{y_0}}{m\omega}\tan\Phi$$
$$\frac{P_z}{m\omega} = -\frac{P_{y_0}}{m\omega} + \frac{P_{x_0}}{m\omega}\tan\Phi$$

PHASE SPACE DISTRIBUTION IN 40" CYCLOTRON

Fig. 9

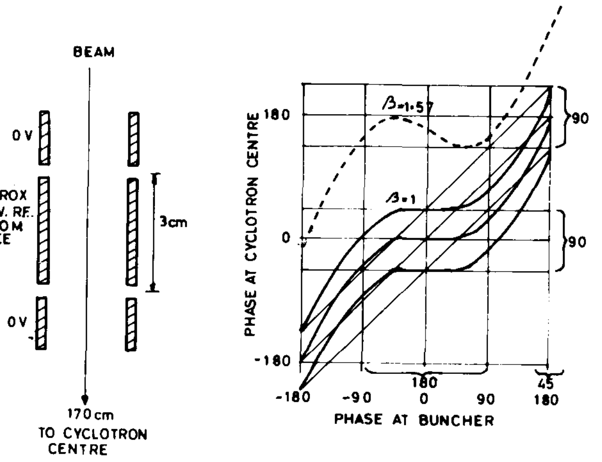
Shows the estimated phase space distribution in the 40 inch cyclotron. Representative tubes A and B are taken; most of the beam lies between them (compare with Figs. 1 to 6).



POSSIBLE CENTRE GEOMETRY FOR ONE AND TWO DEE CYCLOTRONS

Fig. 10

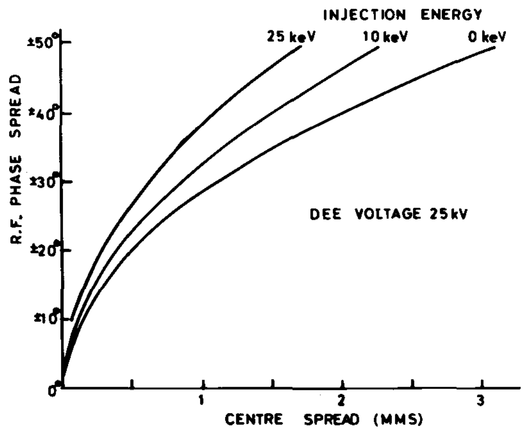
Possible center geometry for one and two dee cyclotrons.



BUNCHER

Fig. 11

Shows the buncher electrode, also the phase at the cyclotron center as a function of the phase at the buncher. The continuous curves represent the probable operating conditions on the 40 inch cyclotron and the dashed curve shows the effect of increasing the buncher voltage.



SPREAD OF CENTRES DUE TO PHASE SPREAD OF DEE VOLTAGE ON 40" CYCLOTRON (SMALL GAP ASSUMPTION)

Fig. 12

Shows the spread of orbit centers on the first turns as a function of the phase spread of the dee voltage for various injection energies.

DISCUSSION

LIVINGSTON: You gave a good deal of information rather rapidly, and there is one point that I want to be sure I have the right conclusion on. I think Dr. Hagedoorn mentioned yesterday that there is some possibility of getting, with regular ion sources, 10 mm-millirad beams. I have always believed that the key to getting high quality beams was an external injector system. Should I be disillusioned by what you are saying? Perhaps it is more difficult than I thought to get low emittance beams by the route that you are describing?

POWELL: I think we shouldn't be too disillusioned, but I was trying to correct some remarks I have heard (kindly directed at us sometimes) in which people have implied that with axial injection you would get pinpoint beams, just like that! I think we have to work for it.

It may be that the deflectors (as opposed to mirrors) that are coming along now (which I have rejected myself on the grounds of size), which do not require wire mesh, will be better. Dee grids may need to be removed, and everything will have to be very nicely lined up. But, there are still some problems to lick! That is really how I would like to put it.

VAN KRANENBURG: Did I understand you to say that for a system in which we require beams to be bunched in time, it will be difficult to use axial injection because of debunching.

POWELL: Yes. If we were asked to produce a nanosecond pulse on the Birmingham cyclotron, I would be much happier to have the work devolve on somebody else! It seems to me it would be very difficult; but in principle it could be done with a really good quality source and a carefully designed transport system.

WEGNER: In the opposite direction, what do you feel is the maximum duty cycle you can achieve with an axial source, and how does this compare with the maximum that you can achieve with an internal source?

POWELL: I think it is right to talk in practical terms of 90° for an axial source. You can certainly get more by allowing more beam to sweep around the center, but as you approach 180° width the quality would be ruinously bad; so I would think 90° or 100° is the right sort of number to be thinking of. With ordinary ion sources I think experience differs a little. You can perhaps get up to 60 degrees full width--and of course you can always make it less.

RICHARDSON: What is the maximum overall efficiency you have had; a certain current of ions is injected into your axial transport system, what fraction do you get out at a reasonable radius, well past the grids?

POWELL: It's better than it used to be. We had a measured figure of 2% from the source to full radius when we first worked, as reported at the UCLA Conference. We have been working with polarized beams only recently. One of the problems of polarized beams is that the intensity is low, and it is quite awkward to have suitable measuring devices all the way down to see what is happening. We haven't done this and so our figures are estimates. Approximately, we now have an efficiency of 6-7% from source to full radius.

REISER: For the injection of normal ions such as protons, is it possible to use the techniques that the Van de Graaff people are using? Moak at Oak Ridge uses a very high density duoplasmatron ion source, chopper, and buncher; I think they are down to 1 nanosecond pulse width, very high quality spot-size beams. Of course, this would only be useful for the formation of the beam itself; the transport system down into the cyclotron and the inflection into the median plane would be separate problems. Would you comment on this?

POWELL: I think if you have 1 nanosecond, and, as I said before, you have very good quality, in principle you would be all right; but with only 10 keV injection energy, I wonder if the space charge repulsion would lead you into trouble. I believe these things work at 200 kV, or something like that, don't they?

REISER: The voltages are much higher than the 10 kV.

POWELL: This could be the trouble then, but at lower intensities presumably you would be o. k.

CLAUSNITZER: Concerning the application to polarized particles, have you measured or calculated any spin precessions in the transition region, from low to high magnetic fields?

POWELL: We decided there would be no trouble with this and our experience seems to bear this out. We have a fairly genuine 60% polarization in the experimental area. The theoretical maximum is only 66%, and we know there is background which must contribute 3 or 4%. So, if there are any other effects they must be very small indeed.