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AXIAL INJECTION SYSTEMS FOR CYCLOTRONS

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Abstract.- Existing and planned axial injection systems are reviewed. Centre region design, types of inflectors, beam guiding and bunching systems are discussed. Specific problems of beam transport and matching between the external source and the cyclotron centre are exposed. Axial injection for superconducting cyclotrons is considered. The axial injection system for CYCLONE is briefly described.

1. Introduction.- Some twenty years ago Powell and co-workers [1)] reported the first successful axial injection of ions into an isochronous cyclotron. At the University of Birmingham Radial Ridge Cyclotron they accelerated 3 % of the injected current up to extraction radius, without bunching. This method of external injection looked very promising and a few years later axial injection was being studied or tested for some fifteen other machines [2)]. Since then, although the number of operating cyclotrons increased constantly, the number of axial injection systems being designed or coming into operation remained fairly constant - or even decreased (see review papers by D.J. Clark [3,4)].

Recently axial injection has regained interest : existing systems have been improved and operate now very reliably, several new systems are being designed or constructed and design studies for superconducting cyclotrons are under way. How comes this evolution ?

The first systems were intended for the acceleration of polarized ions which can only be produced by a source far too big to be placed in the centre of a cyclotron. Alternative ways of injection of polarized ions as radial neutral beam injection and ionisation in the centre, trochoidal injection along a hill-valley boundary or straight radial injection through an electrostatic compensating channel have also been developed [4)] but not applied extensively due to the relatively small transmission obtained.

Axial injection was subsequently used successfully for the injection of negative ions [5-8)]. Negative ions are fairly unstable and require a good vacuum during acceleration. On the other hand, negative ion sources require high gas flow for optimum production [9)]. Operated in the centre of a cyclotron, even equipped with large vacuum pumps, such a source will deteriorate the vacuum leading to beam losses and as a consequence heating and activation of the tank walls. With axial injection, the ion production can be separated from the cyclotron by differential pumping.

There are a number of arguments in favour of external heavy ion sources vs. internal source operation so at several places [10-13)] the axial injection of heavy ions was also experimented. Some or other version of a P.I.G. source was used. Positive arguments are :

- improved vacuum in the acceleration region
- all ions with wrong charge to mass ratio are removed before acceleration resulting in less RF-loading and reduced sputtering of centre region components
- deposit of source material on machine components is is avoided
- external P.I.G. sources can be more robust, can be equipped with an oven for metallic or alkali ions
- multiple source operation becomes possible, an external source is more accessible for maintenance.

In spite of these favourable arguments axial injection of heavy ions was in most cases not competitive with internal source operation and the system was more or less abandoned. Problems encountered were : excessive beam loss due to charge exchange with the residual gas in the injection line [12)], the large emittance of P.I.G.-sources and related difficulties with the multiple matching requirements between source-injection line-cyclotron centre.

Other ways were developed then to obtain either higher charge states or improved beam quality : preaccelerated ions of a lower charge state are injected radially and stripped (e.g. ALICE [14)], VICKSI [15)]...). However, axial injection of heavy ions has been improved and e.g. at Grenoble or Karlsruhe satisfactory results are obtained. It has further become very attractive again since new types of highly stripped heavy ion sources [16-19)] yielding higher charge states and/or improved luminosity have become available.

Design considerations.- Usually an axial injection system has to be fitted into an existing cyclotron and the designer has to live with its characteristics and constraints such as : accelerating structure, harmonic mode, centre region geometry (eventually compatible with internal source operation), magnet gap, dimensions of the axial hole and fringing field inside etc... This led to a wide variety of system layouts. In the following paragraphs design considerations and characteristics of the main elements of various systems will be reviewed.

2. Central region.- The injection voltage is essentially derived from beam dynamics considerations in the centre region. The beam has to be guided on (or close to) the machine axis, bent into the median plane and placed on an orbit so that the orbit centre converges to the machine centre after a certain number of revolutions. Vertical focusing, radial centre spread and resulting RF-phase acceptance have to be taken into account. The first turn must further clear eventual dee and dummy-dee posts and the inflector housing (RF-shield). Multiple (2 or 3) dee-dummy-dee systems designed for internal source operation will often set an upper limit on the injection radius (and thus the injection voltage) to keep the trajectory before acceleration inside the grounded RF-shield. This inflector housing must be kept at some distance from the dee tips to avoid sparking. If after all some degree of freedom is left in the choice of the injection voltage it may be advantageous to take the maximum allowed value. The effects of space charge, the sensitivity to electric and magnetic stray fields and the energy dispersion due to the axial fringing field - see fig. 10 - decrease with increasing energy of the low velocity ions. On the other hand, increased injection voltage calls for higher inflector voltages. Most of the axial injection systems work with an injection voltage around 10 kV and magnetic radius of 10 to 20 mm. The TRIUMF-design [20)] is an exception requiring a large injection radius (∿ 30 cm ; 300 keV H^- ions) to get around a structural post in the centre.

Central region designs for the various accelerating systems have been described extensively in the literature [20-23)]. Special features applied in recent designs are the use of the first acceleration gap (housing-puller) as an additional buncher (the central phase particle crosses this gap at an RF-phase = -100°) [24)] and the introduction of a strong excentric field bump to recentre the initially off-centered beam (and by the same occasion improve the acceptance and decrease the effect of DEE-voltage variations) [25)].

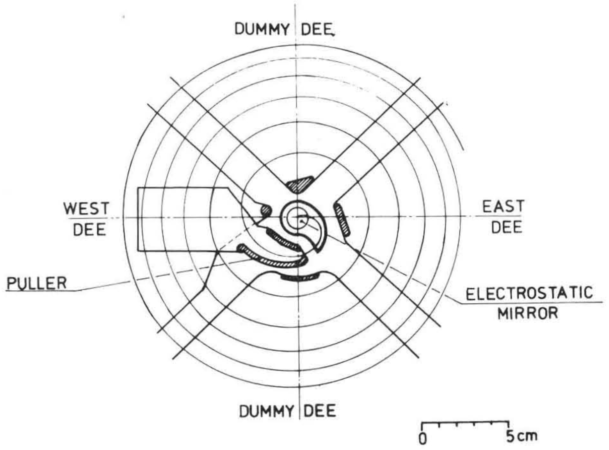


Fig. 1. First harmonic mode centre region geometry for CYCLONE. $E_{FINAL} = 27.5$ MeV/A ; $Q/A = 1/2$; $V_{DEE} = 42$ kV ; $V_{INJ} = 6.2$ kV ($Rm = 10$ mm)

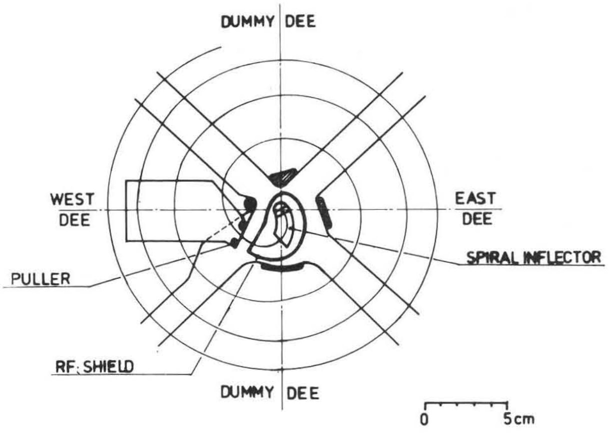


Fig. 2. Second harmonic mode centre region geometry for CYCLONE. $E_{FINAL} = 20$ MeV/A ; $Q/A = 7/16$; $V_{DEE} = 44$ kV ; $V_{INJ} = 14$ kV ($Rm = 16$ mm)

3. Inflector types

3.1. Principles of operation

Near the median plane the axial beam is bent 90 degrees by means of some electrostatic field configuration (no magnetic bending system was used up to now). Figure 3 shows three types of inflectors commonly used. About two out of three injection systems (see table 1) are equipped with an electrostatic mirror. It consists of an electrode inclined at about 45° with respect to the median plane and a grid placed parallel to the electrode a few mm apart.

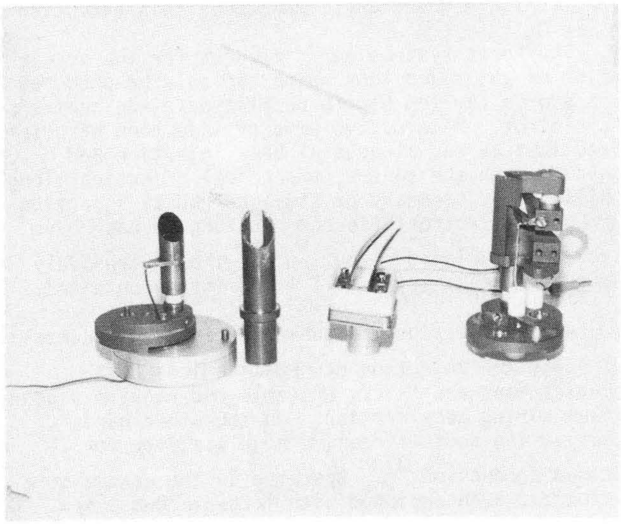


Fig. 3. Electrostatic inflector types :
Left : 45° mirror with high voltage electrode and grid.
Centre : hyperboloid inflector used at Karlsruhe (beam enters below).
Right : spiral inflector for CYCLONE, second harmonic mode (beam enters on top)

The grid is grounded and a static high voltage is applied to the electrode. Incident particles cross the grid entering the electric field where they are decelerated axially, reaccelerated radially and leave the field again through the grid. Another class of inflectors, sometimes called deflectors consist of two parallel electrodes, at equal but opposite voltages, shaped so that the electric field is perpendicular to the reference particle's velocity at any time, thus leaving its energy unchanged during deflexion. In other terms, the central - or reference trajectory lies on an equipotential surface between the electrodes. The main difference between deflectors arises from the way this equipotential (and thus the electrode) surface has been defined.

The spiral inflector $^{26,27)}$ is in principle analogous to a cylindrical deflector : in the absence of a magnetic field, an electric field between the plates of a cylindrical condensor will cause a particle (at the right velocity) to describe a circular path in a plane, parallel to the electric field. An (axial) magnetic field Bz parallel to the incident beam will rotate this plane as the particles gain radial velocity and the projection of the particle trajectory on the median plane will become a curve. Its shape and length is determined by the ratio between the electric radius A and the radius Rm in the magnetic field Bz. The trajectory described in the rotating tangent plane however remains a circle of radius A. (A will also be the height of the inflector). Figure 4 shows a set of normalized median plane trajectories as a function of the parameter K = A/2Rm and the locus of corresponding orbit centres at the exit. The electric field is directed along the x-axis at the entrance and its magnitude remains constant throughout the whole inflector. To obtain still a more flexible design, the last condition can be omitted and a radial electric field component, proportional to the magnetic force along the trajectory can be introduced. This way, an adjustable shift of the orbit centre at the exit can be obtained for a given K-value. Such an electric field is obtained by gradually tilting the electrode surfaces and decreasing the gap. This generalized inflector allows the orbit centre after deflexion to be located anywhere in some region near the machine centre to answer the centering requirements that impose both the entrance into the dee and the direction of the particle velocity. Its versatility has to be paid for by an increased complication of the machining procedure because of the continuously varying gap requirement.

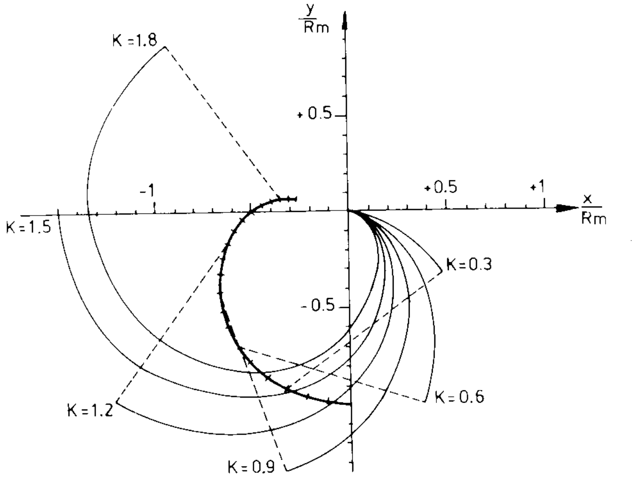


Fig. 4. Spiral inflector : normalized median plane trajectories and related orbit centres at the inflector exit as a function of parameter K = A/2Rm. (A = electric radius of curvature, Rm = magnetic radius of curvature).

The hyperboloid inflector $^{28)}$ - fig. 5 - evolved as the result of a systematic research for an electric field geometry possessing rotational symmetry, the possibility of analytical treatment of the particle motion and specific optical properties (see next paragraph). ;The electrodes are thus formed by two pieces of concentric hyperboloids and their rotation axis is parallel to the magnetic field.

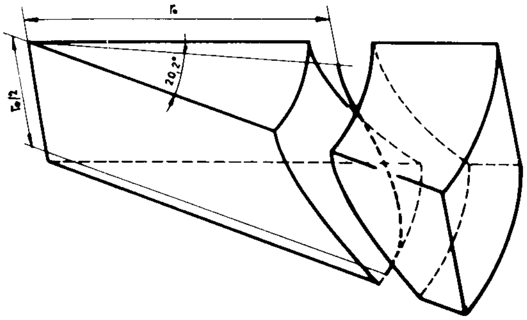


Fig. 5. Hyperboloid inflector

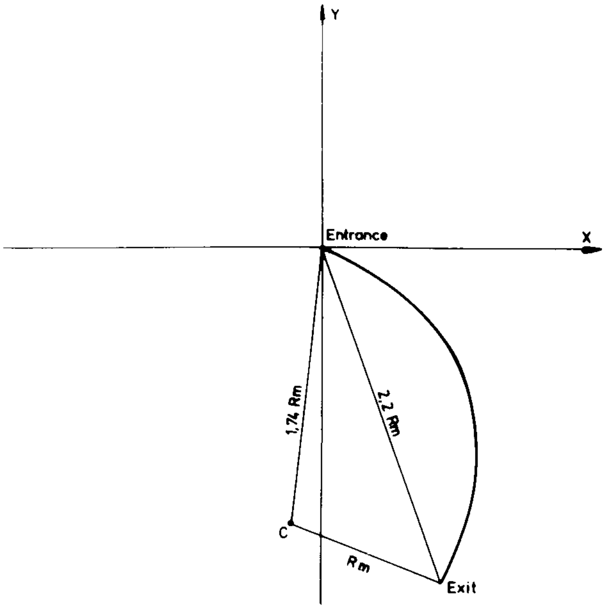


Fig. 6. Median plane trajectory for the hyperboloid inflector. C = orbit centre ; $r_0 = 2\sqrt{6} \star$ Rm

As a result of the above restrictions, the inflector geometry is completely fixed once the magnetic radius of curvature has been choosen. Figure 6 shows the projection on the median plane of the particle trajectory.

3.2. Considerations for comparison

From the constructional point of view the spiral inflector may seem by far the most elaborate. In practice, if the fixed gap inflector is considered, the time required (a few hours) for milling the electrodes (both can be obtained in the same operation) is small compared to the total manufactoring time of a complete inflector including support, insulators, housing, etc...

The electrodes of hyperboloid inflector can be machined on a lathe.

The spiral inflector leaves a maximum of freedom for the centre region design allowing almost any configuration of the triangle entrance/exit/orbit centre. The hyperboloid inflector is completely rigid and requires more space in the centre for a given Rm - compare figs. 4 and 6.

All inflectors gain a degree of freedom if a variable "drift" length inside the dummy dee or inflector housing is allowed : the orbit centre is fixed and the beam rotates in the median plane (like in a bending magnet) to join the required injection point in the DEE. This idea was first applied in the centre region designs for one DEE machines and later also with the spiral inflector to avoid the use of titled electrodes.

For variable energy, multiparticle machines, both hyperboloid and spiral inflector have to be used in a constant orbit mode.

The voltage required by a mirror is of the order of the injection voltage ; the electrode voltages for the deflector types are a factor three to five lower.

The grid of the electrostatic mirror is somewhat harmful : the beam has to cross it twice resulting in beam loss, heating and sputtering by heavy ions. The beam quality is also affected by the distorsion of the field in the vicinity of the grid wires.

Optical properties have been studied for the E.S. mirror by Talalaeff 29), Powell 2) and others. Müller 28) analysed the optics of the hyperboloid inflector and Pabot 30) and Root 31) the spiral inflector. It is most useful to consider the combined effect of both fringing field and inflector : the magnetic field acts as a half solenoid lens, imposing a rotational component on the beam which can then no longer be considered decoupled at the entrance of an inflector. This problem has been analysed by Powell 2), Hazewindus 32) and others.

On the basis of computations made for CYCLONE we will briefly comment on some optical characteristics. Due to a lack of space in the centre of CYCLONE, the use of an E.S. mirror was considered for the N=1 mode - see fig. 1.

The strong dependence of the resulting axial and radial phase spaces at the mirror exit from the shape of the beam at the entrance of the fringing field is illustrated in figs. 7 and 8. Three beam envelopes are shown for different lens settings giving all an axial symmetric waist at the mirror.

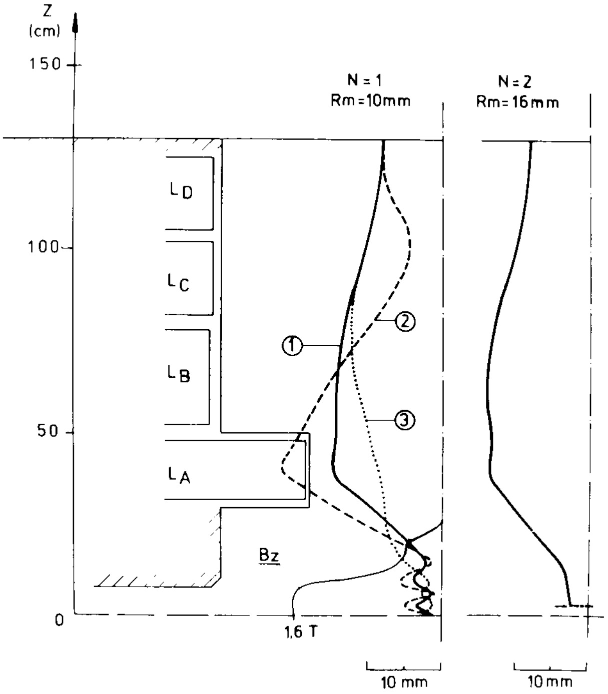


Fig. 7. Axial beam transport system layout for CYCLONE and beam envelopes for different lens settings and different injection energies. The beam is supposed cylindersymmetric. The emittance is in all cases 200 πmm mrad. The axial field Bz is plotted.

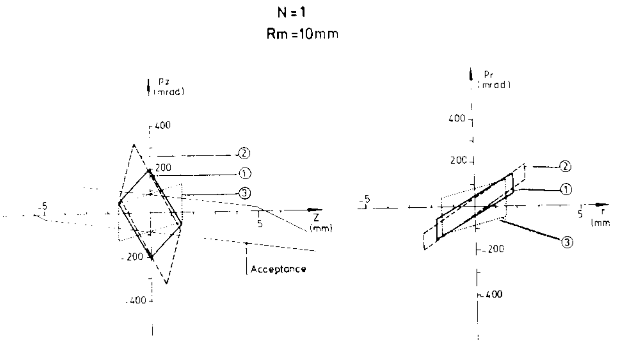


Fig. 8. Phase space plots at the mirror exit (N=1 mode). The numbers refer to corresponding transport modes shown in fig. 7.

Fig. 8 shows the corresponding axial and radial phase spaces obtained by projecting the four dimensional phase space on both planes. Setting 3 seems the most favourable although the axial matching is somewhat better for setting 1.

For the N=2 mode, a spiral inflector with a K = 0.9 and a magnetic radius of 16 mm was selected - see fig. 2. To pass the spiral inflector without losses, the incident beam has to be slightly convergent at the entrance. The exit beam is rather strongly divergent in the axial plane but radially the centre spread is uniform in all directions. The beam envelope is shown on the right of fig. 7 and the resulting phase space projections are represented on fig. 9. In figs. 8 and 9, the momentum scale used for the drawing equals the displacement scale if the momentum is expressed in units of the magnetic radius (radians x Rm).

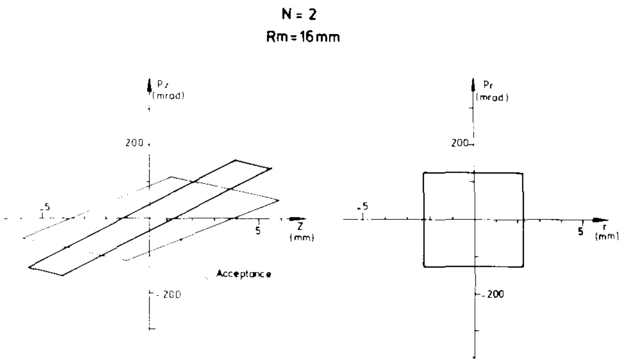


Fig. 9. Phase space plots at the spiral inflector exit (N=2 mode).

The optics of the hyperboloid inflector is unique by the fact that its action combined with the effect of the magnetic field provides complete decoupling between radial and axial planes : the hyperboloid inflector could be looked at as the exit portion of the solenoid. But the magnifications in both planes are quite different : axially a broad and relatively parallel beam is produced whereas the beam is "round" in the radial plane. (Radial centre distribution is a circle). The whole system behaves like a doublet-solenoid combination.

The "third" dimension, energy dispersion should not be neglected either. Here again the dispersive action of the magnetic lens has to be considered together with the effect of the inflector. Although dispersion is small in the mirror itself beams of slightly different energies will have somewhat different rotation angles after crossing the field. This will then result in modified phase space projections after deflexion.

Fig. 10 illustrates the effect of a 5 % energy variation in the N=1 mode for CYCLONE.

Besides the effect of the magnetic lens, the deflectors cause additional displacements : different energies emerge at different axial positions after the hyperboloid inflector (ex. : 0.5 mm for $\Delta E/E = 5\%$ for Rm = 16 mm). The spiral inflector causes both displacement and a change of direction in the axial plane (ex. : for $\Delta E/E = + 5\%$ at Rm = 16 mm and K = 0.9, $\Delta Z \cong - 1$ mm and $\Delta p_z \approx - 30$ mrad).

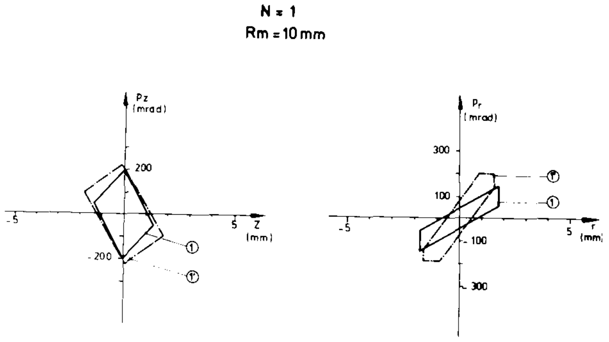


Fig. 10. Phase space plots at the mirror exit for
1) En, same as in figs. 7 and 8 and 1')
E = 0.95 En.

4. Beam guiding and matching.- From the above considerations it appears that the matching of the external beam to the acceptance of the inflector and the cyclotron centre is of great importance. A minimum number of optical elements is necessary to provide the required degrees of freedom. In the first designs Einzel lenses [2,33] have been used but spheric aberrations become important if more than say 40 % of their aperture is filled and in the presence of axial magnetic fields penning discharges develop. This type of lens is still used in the AEG machines at Karlsruhe [34] and Bonn [35] to produce the small size strongly converging beam before entering the magnetic field. In these machines the magnet gap is relatively small, the centre field is moderate and the aperture in the centre plug is small so that the fringing field vanishes quickly and no specific problems are encountered.

Most injection lines are equipped with a variable number of electrostatic quadrupoles. They require virtually no power and allow different adjustable magnifications in perpendicular planes. Careful design of the insulators and HV feedthroughs should avoid instabilities and sparking.

Magnetic focusing elements have the advantage that they can be installed completely outside the vacuum. The SIN injector cyclotron uses magnetic quadrupoles. Because of the centre region geometry the injection axis is not exactly on the machine axis. It was thus absolutely imperative to cancel the residual field along the line. This problem has been treated in ref. 36.

It is attractive to build further on the axial symmetry of the fringing field and introduce cylindrical electromagnetic lenses. This idea was first applied at Grenoble.

The injection system for CYCLONE is similar, using four of these lenses - see fig. 11. The final two matching elements between the periodic focusing structure and the inflector in the Groningen [25]

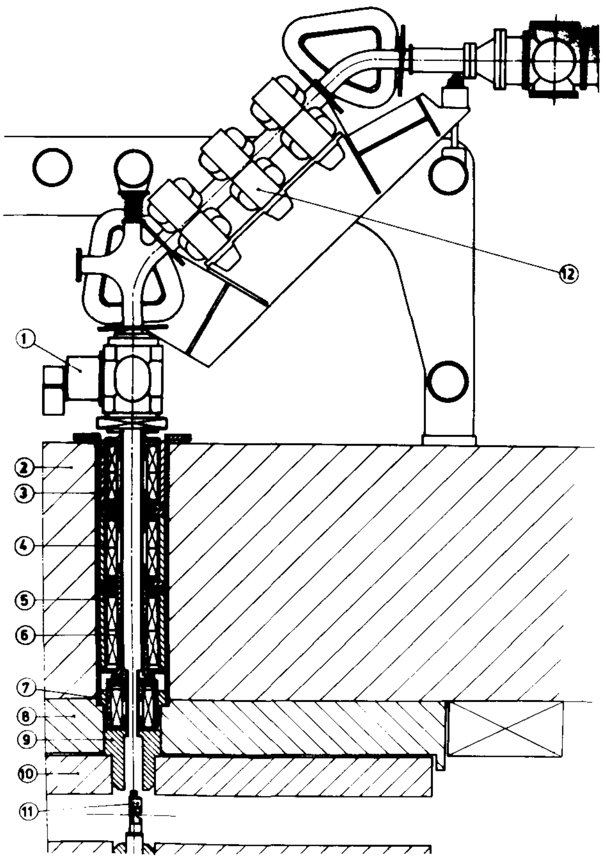
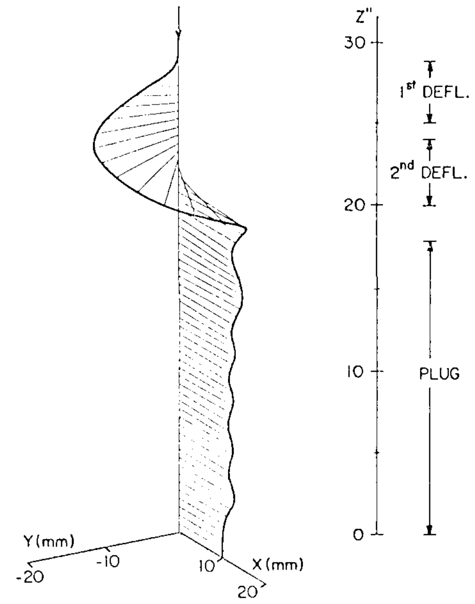


Fig. 11. Axial injection line for CYCLONE.
1. cryopump (1000 l/s) ; 2. yoke ; 3.4.5.7. cylindrical lenses ; 6. magnetic steering ; 8. pole ; 9. plug ; 10. sector ; 11. inflector ; 12. 2 x 45° achromatic bend.

design are similar but use the cyclotron field. Since these lenses are weak focusing elements, they require a high amount of power (in the case of CYCLONE this is 20 kW).

A special case of focusing appears in superconducting cyclotrons where the field extends very far along the machine axis. It acts as a very long solenoidal lens of variable strength, producing a more or less modulated beam envelope. The matching elements have to be located at the end of this field, one meter or more from the median plane. Off axis injection is very delicate to achieve but difficult to avoid in the MSU design [37]. Two sets of each two pairs of parallel E.S. deflexion plates are located at some distance from each other in the strong axial field giving the necessary degrees of freedom to bring the beam on a finally off-centered path. Fig. 12 shows an example of the beam path.

The Orsay design [38] allows on axis injection into the superconducting cyclotron, using an electrostatic mirror.



O^{8+} $B_o = 34.6$ kgauss $V_{inj} = 20$ kV

DEFL.	POS.	E_x(kV/cm)	E_y(kV/cm)
1	25"-29"	-.983	-.485
2	20"-24"	1.255	-2.285

Fig. 12. Off-centered axial injection path into a superconducting cyclotron

5. Bunching.- The phase interval during which particles will be accelerated by the cyclotron varies between 10 to 40 degrees but the external source delivers a DC current. The result is a poor transmission of maximum 2 to 10 % excluding all other losses. The amount of useful ions produced by the source is often limited so that ways have been searched to improve the acceptance. By modulating the beam intensity during the RF period, more particles can be squeezed into the RF acceptance. The intensity modulation is achieved by slowing down the earlier particles and accelerating the later ones by a small amount at some position in the beam line so that they all arrive simultaneously at the cyclotron centre. This klystron-type of bunching has been applied in most of the axial injection systems. In the real situation a number of factors will limit the efficiency of this bunching. Space charge effects tend to lengthen the bunch as it shrinks. The initial velocity spread causes particles crossing the buncher at the same time to arrive at different instants at the centre. To obtain a seizable effect, the energy modulation has to be considerably larger than the initial energy spread. The dispersive action of fringing field and inflector will in turn cause a degradation of the beam quality. Consequently, there is an optimum distance between buncher and cyclotron centre.

Imperfections in the buncher such as effective longitudinal gap and non linearity (sine - wave buncher) in the time/voltage relation will also decrease its effectiveness.

In practice, the overall transmission is improved by a factor of three by bunching, in most cases.

A new type of buncher using the radiofrequency quadrupole principle 39) has been proposed. It was also suggested that the RFQ could be used eventually as a preaccelerator 40).

New concept.- A new concept for injection of high energy beams into a very large high field cyclotron (K=3200) has been proposed by Hudson 41). The principle is shown on fig. 13.

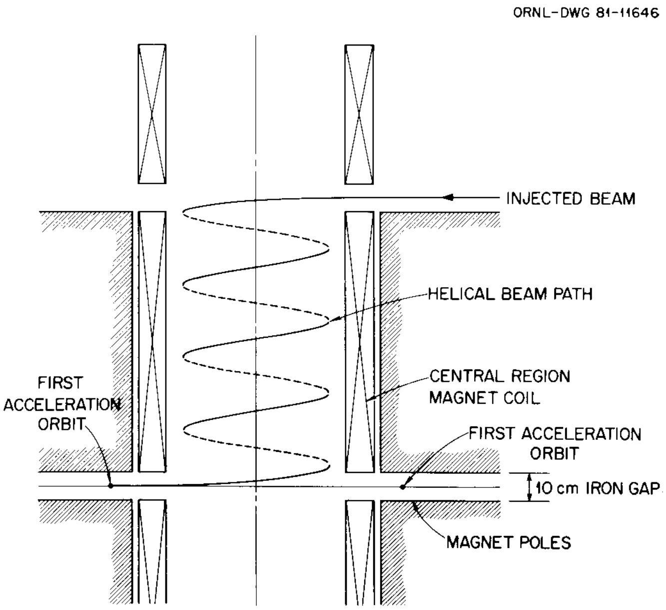


Fig. 13. Helical axial injection concept for cyclotrons

The incoming beam is in a plane parallel to, and 1 m from the median plane. It is deflected into a helical path, transported to the median plane and inflected into an accelerated orbit. The field along the axis is about twice the median plane field.

Conclusion.- The main interest for axial injection systems lies in their use with solid pole cyclotrons (conventional or superconducting) to accelerate ions which cannot be obtained by means of an internal source like polarized ions, highly stripped heavy ions, etc... Axial injection allows eventually a tight control of the injected beam by pulsing to make beam diagnostics on the cyclotron and for certain experiments requiring specific time structure of the accelerated beam. New promising ideas are the use of the Radio Frequency Quadrupole as a buncher (and eventually as a preaccelerator) and injection at much higher energy along a helical path. New types of heavy ion sources together with axial injection could become very competitive with two stage machines using intermediate stripping.

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Table 1 : Axial Injection Systems

	Particles	Inflector Type	On Axis	Axial transp. Line	Transmission* Buncher ON	%	Comments
Berkeley	$\vec{p},\vec{d}$/h.ions	Mirror	Yes	E.S.quads	Yes	17/2	
Birmingham	$\vec{d}$, $_3\overrightarrow{He}$	Mirror	Yes	E.S.quads	Yes	12	
Bonn	$\vec{p},\vec{d}$/h.ions	Hyperboloid	No	E.S.quads + Einzel l.	Yes	15-10	
CYCLONE	h.ions	Spiral	Yes	Cyl. Magn.			Constr.
Duke Univ.	H^-,d^-	Mirror	No	E.S.quads			
Grenoble	$\vec{p},\vec{d}$,h.ions	Spiral	Yes	Cyl. Magn.	Yes	5-10	
Groningen	h.ions	Hyperboloid	Yes	Cyl. Magn.			Design
Jülich	h.ions	Hyperboloid	No	Solenoid			Design
Karlsruhe	$\vec{p},\vec{d}$,h.ions q/m=1/2	Hyperboloid	No	E.S.quads + Einzel l.	Yes	8	
Livermore	H^-	Mirror	No	E.S.quads			
Manitoba	H^-,d^-	Mirror	No	E.S.quads + Einzel l.			
Osaka	$\vec{p},\vec{d}$	Mirror	Yes	E.S.quads			
SIN-injector	$\vec{p},\vec{d}$	Mirror	No	Magn. quads	Yes	10	
Texas A & M	$\vec{p},\vec{d}$, $_3\overrightarrow{He}$	Mirror	Yes	E.S.quads			
Tokyo Univ.	$\vec{p},\vec{d}$	Mirror	Yes	E.S.quads			
TRIUMF	H^-	Spiral	Yes	E.S.quads			
Superconducting Cyclotrons							
Milan	l. & h.ions	Mirror					Design
MSU	h.ions	Mirror	No	Solenoids or Einzel l.			Design
Orsay	h.ions	Mirror	Yes				Design

* ratio of extracted beam vs. injected in the axial line.

References (continued)

36. N. Hazewindus et al., Nucl. Instr. Meth. 111 (1973) p. 181
37. G. Bellomo, private communication
38. J.P. Shapira, Proceedings of this conference
39. R.W. Hamm et al., Proceedings of this conference
40. G. Hendrie, private communication (see paper by R.W. Hamm et al, this conference)
41. E.D. Hudson, Proceedings of this conference.

" DISCUSSION "

D.J. CLARK : My question is about how to increase the transmission through the axial injection system from source to accelerated beam. One of the best transmissions is at TRIUMF where injection energy is high : 300 kV. Could you comment on the importance of injection energy or other factors for getting high transmission ?

G.H. RYCKEWAERT : A high injection voltage is certainly an advantage : space charge effects, stray field effects etc... become less important.
At higher injection energy the beam emittance is lower so the beam is easier to get through.
For heavy ions the vacuum in the axial line is important for high transmission.