CYCLOTRON INJECTION SYSTEMS*

D. J. Clark
Lawrence Berkeley Laboratory, University of California,
Berkeley, Calif. 94720

ABSTRACT

A review is given of the various methods which have been used for injecting beam into cyclotrons from external ion sources. The methods of injection include neutral beam, radial ion, and axial ion systems. The performance of presently operating systems is tabulated. Larger separated sector machines now under construction or proposed will use radial ion systems.

INTRODUCTION

The early work on developing injection systems for cyclotrons was directed toward injecting polarized beams from the polarized ion sources which were first developed about 1960. These sources were much larger than the space available in the cyclotron center region. Development work was started by Keller at CERN. The first injection of unpolarized beam into a full size cyclotron was the axial system reported by Powell at Birmingham in 1962. In 1963 Thirion at Saclay injected a polarized neutral deuteron beam, which was ionized at the center of the cyclotron and accelerated without loss of polarization. Many other groups developed radial and axial injection systems in the following years. The progress in this field has been reviewed previously by Powell in 1965 at the Karlsruhe Conference,[1] again by Powell in 1966 at the Gatlinburg Conference,[2] and by Clark in 1969 at the Oxford Conference.[3] In the following sections, the various systems will be briefly described and illustrated, with emphasis on the developments during the past 3 years. A summary of the performance of presently operating systems is given in Table I.

RADIAL NEUTRAL INJECTION

The earliest development work by Keller at CERN used neutral beams of thermal velocity, such as would be obtained directly from a polarized source.[3] This principle was successfully used at Saclay in 1963 to inject polarized deuterium atoms to the center of a classical cyclotron, where they were ionized.[3] The current on target was about .03 nA, which was adequate to do experiments.

A thermal neutral beam injection system is being used at the Lyon 28 MeV synchrocyclotron.[4] A polarized deuteron atomic beam is injected radially to the cyclotron center. Here it is ionized by an

*Work performed under the auspices of the U. S. Atomic Energy Commission.

electron beam or an arc. It is interesting that the arc gives 50 times the intensity of the electron beam method.

Another method of neutral beam injection was proposed by Plis *et al.* at Dubna in 1965.[5] Here an unpolarized beam of 30 keV protons was neutralized in a gas canal and measured about 2 m downstream. This simulated injection of a polarized beam into the center of the Dubna synchrocyclotron, where a stripping foil could be placed to produce ions again.

The above injection principle was used at a classical U-120 cyclotron at Rez, Czechoslovakia to inject a polarized deuteron beam.[6] The system is shown in Fig. 1. Here an rf source produces a beam of

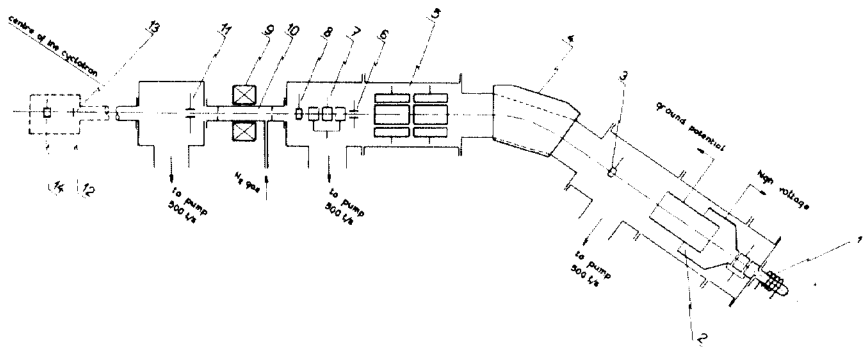


Diagram of the injector: 1 – rf ion source; 2 – acceleration tube; 3 – 8 – 14 – Faraday cup; 4 – mass analysing magnet; 5 – electrostatic quadrupole doublet; 6 – vertical deflection plates; 7 – buncher; 9 – solenoid (1500 G); 10 – neutralization chamber; 11 – horizontal deflection plates; 12 – auxiliary measuring chamber; 13 – ionization foil.

XBL 726-1110

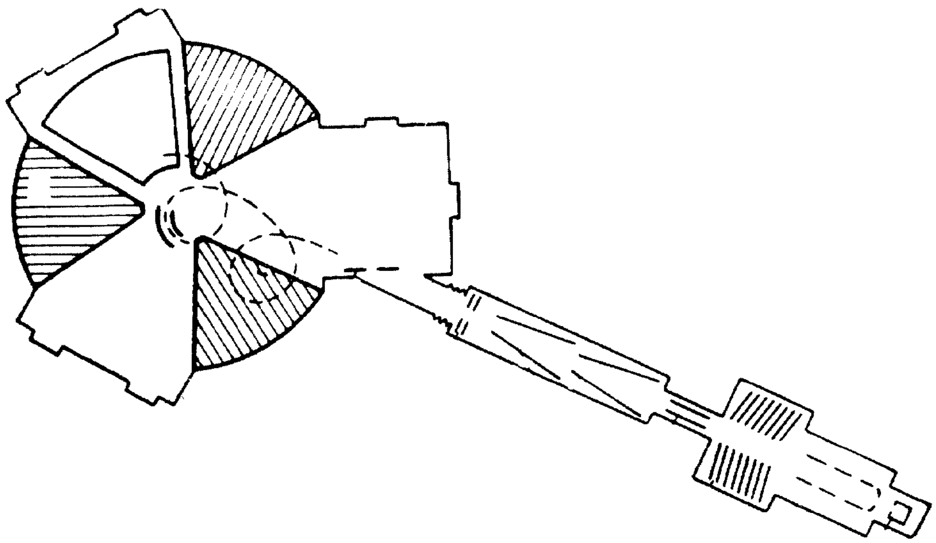
Fig. 1. Neutral beam system at Rez, Czechoslovakia, using double charge exchange.

deuterons at 40 keV. It is focused into a neutralization chamber, where it is converted to neutral beam. A magnetic field in this chamber prevents depolarization in the case of a polarized beam. The beam then drifts to the center of the cyclotron, where some of it changes charge in a foil and is accelerated by the dee system. This method gives better transmission than the thermal neutral beam injection.

RADIAL ION INJECTION

A very simple system for injecting ions radially is the trochoidal method used by the Lebedev Institute in Moscow.[7] As shown in Fig. 2, the orbit of the injected beam loops inward along the hill-valley boundary, and is inflected into the first turn by an electrostatic channel. Focusing is achieved by the hill-valley field gradient. A reported 20% of the injected beam is accelerated in this small 300 keV deuteron cyclotron. Calculations were done using this principle by Blosser for a full size cyclotron.[3]

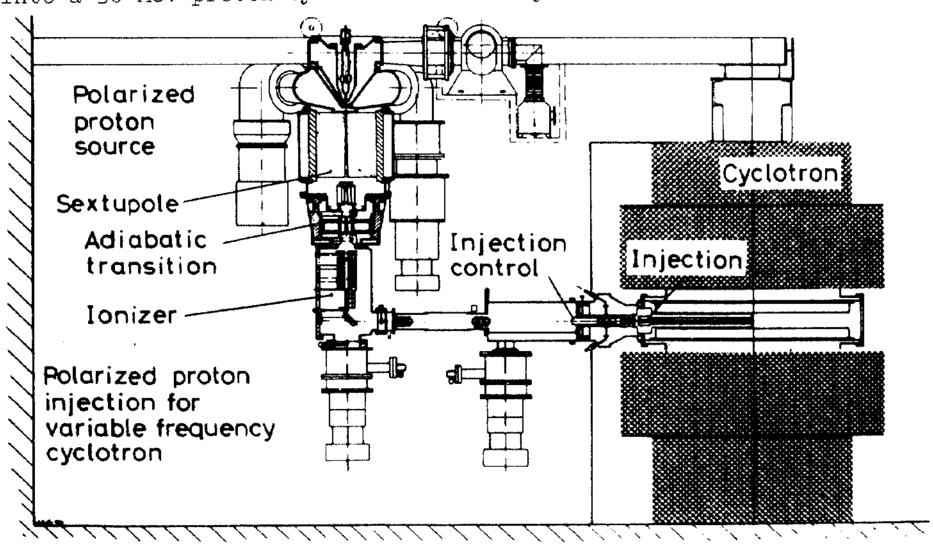
A related method is used at Saclay to inject polarized protons



XBL 698-1233

Fig. 2. Trochoidal system of Lebedev, Moscow.

into a 30 MeV proton cyclotron.[8] The system is shown in Fig. 3. The



XBL 726-1108

Fig. 3. Radial system at Saclay for polarized ions. Electric field cancels magnetic field.

polarized source is mounted vertically inside the cyclotron vault. The beam is injected radially through a system of electrostatic bars which compensate the transverse magnetic force on the 5 keV beam, to guide the beam directly to the center region. Recently, electrostatic quadrupoles have been installed to improve the transmission between source and cyclotron.

For heavy ion injection a method of charge change at a stripping foil in the cyclotron center is used by Orsay and Dubna. The Orsay system[9] is illustrated in Fig. 4. A linac accelerates ions

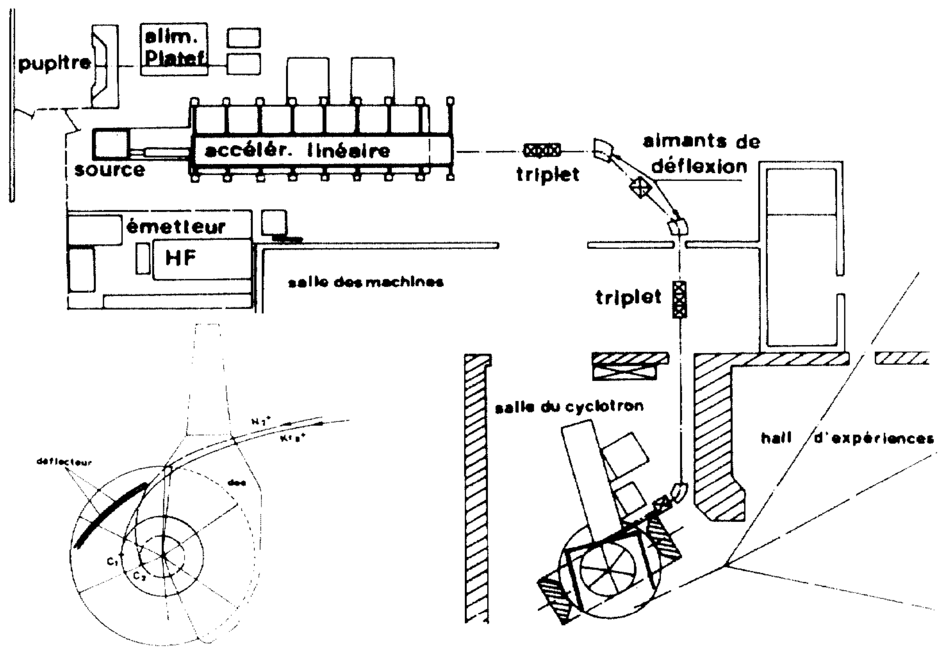
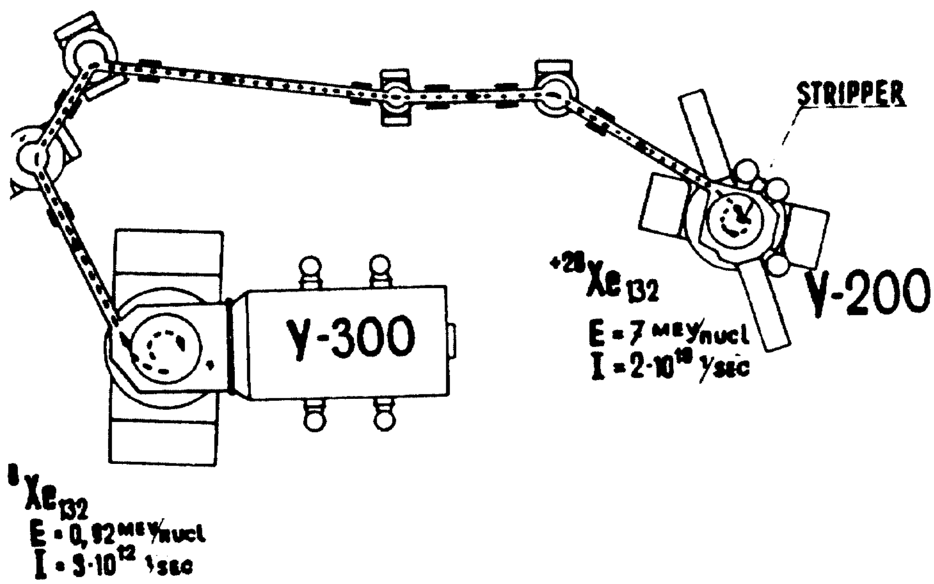


Fig. 4. Linac injecting heavy ions at Orsay. Inset shows inflection by stripping.

such as Kr^{8+} to 1 MeV/nucleon. The krypton beam is transported to the center of the sector cyclotron where it is stripped to Kr^{23+} in a thin carbon foil. It is then on a centered orbit for the new charge state, as shown in the inset of Fig. 4. This beam at 5 MeV/nucleon energy is not available from any other accelerator, except for the Dubna two-cyclotron system of the following section. Intensities of argon, also at 5 MeV/nucleon, are about 20 times larger than for krypton.

A second heavy ion system has recently come into operation at Dubna.[10] It is shown in Fig. 5. A beam of Xe^{8+} is accelerated to .9 MeV/nucleon in the big U-300 classical cyclotron. It is then transported to the U-200 sector cyclotron, where it is stripped in the center region, as at Orsay. It accelerates in the U-200 to about 7 MeV/nucleon. This is an impressive achievement, utilizing two



XBL 726-1111

Fig. 5. U-300 classical cyclotron injecting U-200 sector cyclotron with heavy ions at Dubna.

accelerators, built independently in the same laboratory, with a 70 meter transport line between them. The xenon beam is unique, until the Berkeley Superhilac comes into full operation.

The use of radial ion injection is planned on several of the new separated sector cyclotrons now under construction. The 580 MeV Zurich meson factory[11] will be injected from a 70 MeV sector cyclotron. The injection region is shown in Fig. 6. The beam enters the ring through one of the valleys with no rf cavity. It is bent into the equilibrium orbit with two bending magnets, a high field magnetic channel, and an electrostatic channel.

The Indiana University cyclotron project[12] will use radial injection into open valleys of both the 15 MeV injector cyclotron and the 200 MeV final stage.

The separated sector design has the advantage of leaving space in the valley for injection of beams of several hundred kilovolts up to tens of MeV. It is much easier to transport high intensity beams of these energies, than at 10 keV where many existing systems operate. The use of separated sector cyclotrons is particularly valuable for proposed heavy ion projects such as the MTC at Argonne,[13] Apache[14] and its successor NHL[15] at Oak Ridge, because an injector stage is needed to produce the high charge state beam to get a high energy from the final stage acceleration.

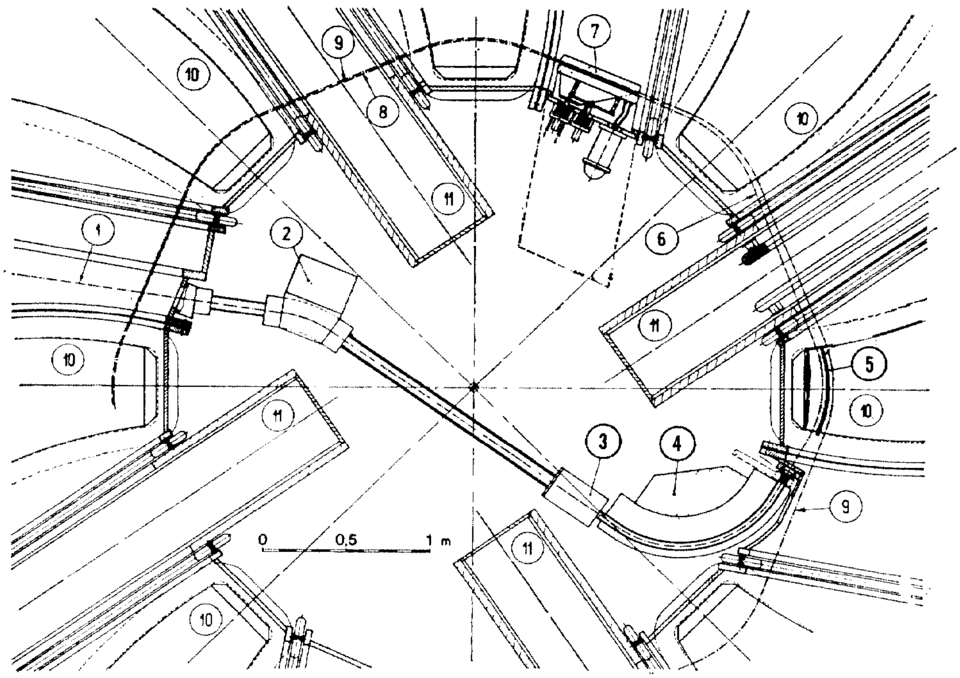
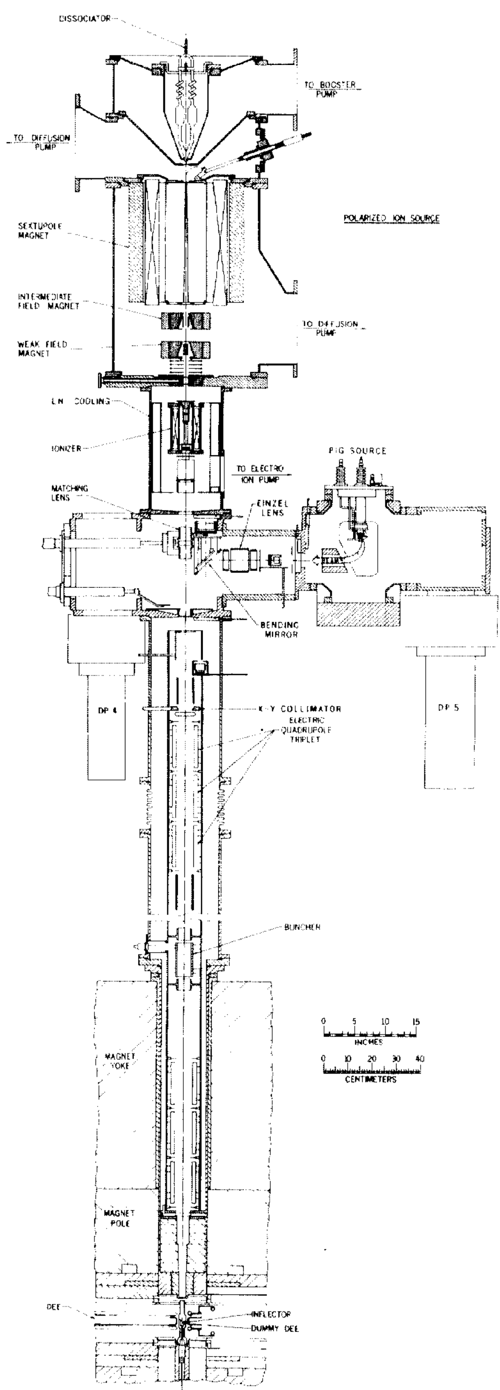


Fig. 6. Injection into ring at SIN, Switzerland. 1. 68 MeV proton beam. 2.,4. Bending magnets. 3. Beam probe assembly. 5. Magnetic channel. 6. Inflected orbit. 7. Electrostatic inflector channel. 8. Equilibrium orbit. 9. Beam after one turn. 10. Magnet sectors. 11. rf cavities.

AXIAL ION INJECTION

The development of axial injection into cyclotrons was pioneered by Powell's group at Birmingham in 1962[16] by injecting beam into the 12 MeV radial ridge cyclotron from an rf source. Later a polarized deuteron source was installed on the injection line.[1]

Many other groups have built axial injection systems. A typical installation is at the Berkeley 88-Inch cyclotron,[17] shown in Fig. 7. The system was built to inject polarized ions into the cyclotron. The source is a conventional atomic beam polarized ion source for protons and deuterons. An alternate source which is under development is a heavy ion PIG source, based on the Berkeley Hilac design. Other laboratories are operating similar polarized sources, PIG type sources for heavy ions or negative ions, and duoplasmatron sources. The injection energies are 7-15 keV to center the beam when it is injected on or near the axial center line. Beam intensities from the source are a few microamps from polarized sources, up to around a milliamp for unpolarized light positive or negative ions, or heavy ions. Polarized sources are in operation also at Grenoble[18] and Oak Ridge[19] and planned at Texas A&M, Karlsruhe, Bonn, SIN, Calcutta,



Osaka, Tokyo, and elsewhere. Negative ion injection systems were developed by the Cyclotron Corp. of Berkeley[20] for use in Cyclograaffs, and at U.C.L.A. Manitoba is also developing an H^- system. A heavy ion injection system has been tested at Harwell[21] and is now under development. Heavy ion injection is also planned at Karlsruhe. An injection system for a compact cyclotron has been built by Philips.[22]

The Berkeley transport line has three electrostatic quadrupole triplet lenses, two of which are shown in Fig. 7. There are also steering plates for both transverse planes. The beam transport has been calculated for waist-to-waist transport, at various beam intensities, assuming no space charge neutralization.[23] The beam envelopes are shown in Fig. 8. In fact, there will be some space charge neutralization, except in the electrostatic quadrupoles, so the calculation is pessimistic in that respect. However, several groups find it difficult to maintain continuous neutralization at low energies of 10 keV and beam intensities of a milliamp. Other groups use electrostatic or magnetic quadrupoles, einzel lenses, or solenoids. The magnetic type of lenses have the advantage of allowing space charge neutralization

Fig. 7. Berkeley 88-Inch Cyclotron external ion sources and axial injection system.

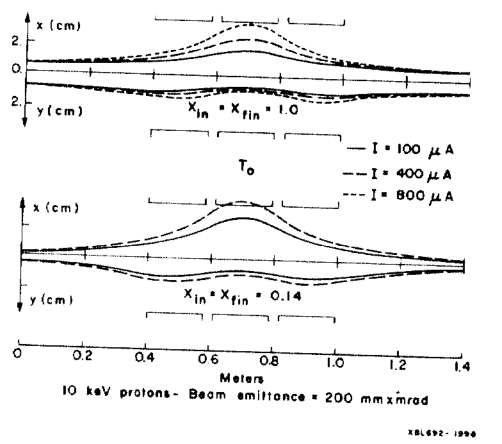


Fig. 8. Beam profile calculation for Berkeley injection system. No space charge compensation.

throughout the line. However, the largest injected and accelerated currents are reported by the Cyclotron Corp.[20] (Table I) using electrostatic doublets. Recently, Birmingham replaced their einzel lenses by electrostatic quadrupoles, and found a definite improvement in stability, by eliminating the electron storage problem in the einzel lenses.[24] A number of studies of the optics of axial injection lines have been made by various groups, such as Philips,[25] Groningen,[26] and A.E.G.[27]

A drift tube sine-wave buncher is used at Berkeley to increase the rf acceptance of the DC beam. A voltage of about 10% of the injection voltage is fed to the drift tube from the main cyclotron rf system. This increases the accelerated beam by a factor of 3, which is very helpful. Other groups find a similar factor of improvement. The amplitude and phase of the buncher rf are adjustable to optimize the external beam current.

At the bottom of the hole in the yoke, the magnetic field of the cyclotron rises quickly to its median plane value. This forms a strong lens, and must be included in a complete optics calculation.

To inflect the beam into the median plane, the simplest device is a 45 degree gridded mirror, used at Birmingham, Berkeley and by several other groups. Some beam is intercepted by the grid, so some groups use a channel such as that of Grenoble,[28] Fig. 9. It is designed to put the injected beam on a centered orbit with high transmission. A hyperboloid design for the channel shape has been proposed by Müller,[29] and is used in the A.E.G. system at Karlsruhe.[27] The inflector for the TRIUMF 500 MeV H^- cyclotron[30] will also be a channel. Here, there is ample space, since the injection energy is 300 keV, and the central field is only 3 kG. A full scale center region model is now operating to study injection problems.

The center region of the cyclotron has to be properly designed to accelerate the injected beam. The geometry used at Berkeley[17] is shown in Fig. 10. The incoming beam is shielded from the cyclotron rf by the mirror housing. A baffle is placed inside the dee in the first half turn to eliminate radial, non-accelerating electric fields. Insert dee and dummy dee electrodes are used, which plug in through an air lock. A different set of inserts is used for the internal ion source. The change from one set to the other takes about an hour. A number of studies have been made of center regions for axial injection, such as at Birmingham,[2] Philips,[31] A.E.G.[27] and TRIUMF.[32]

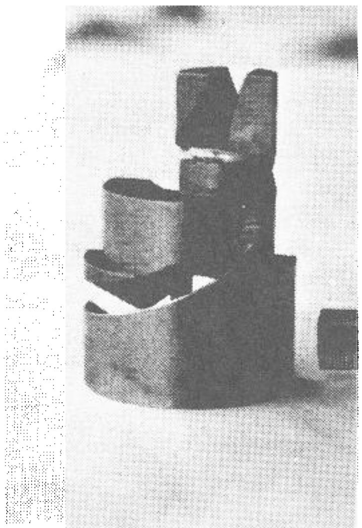


Fig. 9. Helical inflector channel for Grenoble cyclotron.

SUMMARY

The various injection systems for cyclotrons which are now in operation are shown in Table I. The neutral systems have the advantage of simplicity, but the ion systems give better transmission. Radial and axial ion systems are comparable in performance when they are carefully designed. The rebuilt injection line at Birmingham looks quite good on first tests, giving 12% transmission from source to external beam. The record for accelerated beam intensity from an external source of 120 μA is still held by the Cyclotron Corp. Someone should be able to beat that with positive ions. The construction of the new separated sector machines such as at Zurich and Indiana makes higher energy injection easy. This would be especially useful for two-stage heavy ion designs.

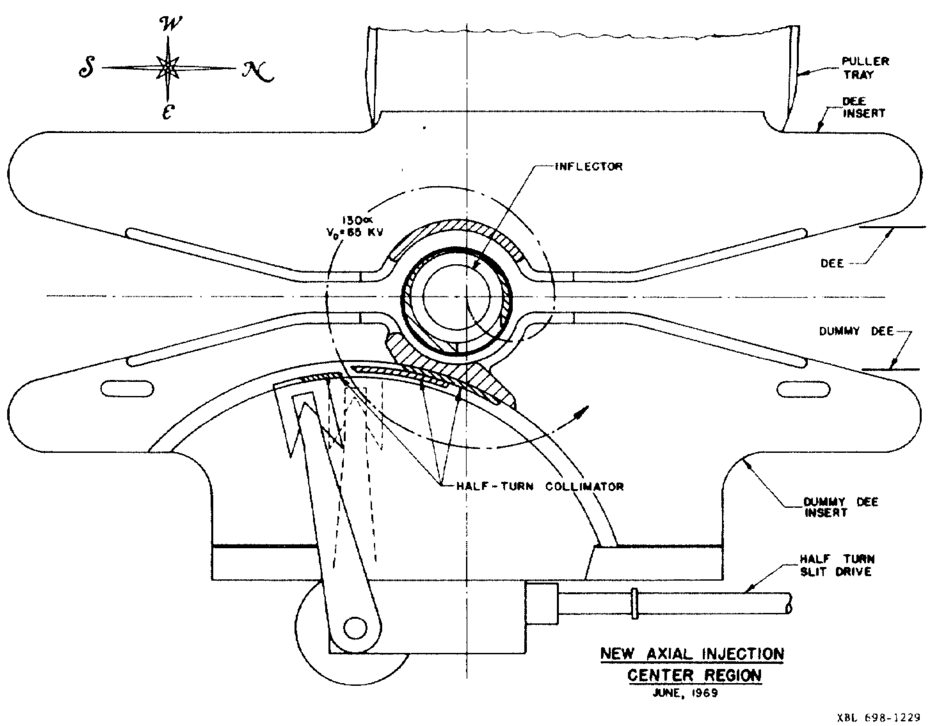


Fig. 10. Berkeley center region geometry for axial injection.

Table I. EXTERNAL INJECTION SYSTEMS IN OPERATION

	CYCLOTRON ENERGY (MEV)	SOURCE: TYPE	SOURCE: ENERGY	SOURCE: INJECTED CURRENT	TRANSPORT: FOCUSING	TRANSPORT: BUNCHER	TRANSPORT: INFLECTOR	CYCLOTRON BEAM*: ACCEL.	CYCLOTRON BEAM*: EXTERNAL	TRANSMISSION SOURCE TO: ACCEL.† (%)	TRANSMISSION SOURCE TO: EXT.† (%)	COMMENTS
RADIAL NEUTRAL BEAM												
Lyon, France	28 d	Pol.	Thermal	.1 mA	None		Ionizer		.01 nA			FM Cycl.
Rez, Czech.	13 d	rf/Pol.	40 keV	4.5/.3 μA	Elec. grad.	Yes/	Foil		6/.075 nA		.14/.03	Classical Cycl.
RADIAL ION												
Dubna	7 MeV/A Xe	Cyclotron	.9 MeV/A	1 μA Xe^{9+}	Quads	Cycl.	Foil	14 nA Xe^{28+}		3		Classical Cycl.
Indiana Inj.	15 p,..	Duo.	700 keV		Quads		Channel					Testing
Lebedev	.15 p, .3 d	Penning	15-30 keV	5 μA	Sect. grad.	No	Channel	1 μA		20		1964
Orsay	5 MeV/A Kr,..	Linac	1 MeV/A	3 μA Kr^{8+}	Mag. quads		Foil	20 nA Kr^{23+}	4 nA Kr^{23+}	.2	.05	80 nA Ar^{12+} ext.
Saclay	27 p,..	Pol.	5 keV p	5 μA	Einzel	Yes			100 nA			
AXIAL ION												
Berkeley	65 d,..	Pol.	10 keV p	2 μA	Elec. quads	Yes	Mirror	400 nA	150 nA	20	7	
Birmingham	12 d,..	Pol.	11 keV d	100 nA	Elec. quads	Yes	Mirror	35 nA	12 nA	3!	12	New ionizer, transp.
Cycl. Corp.	30 H^-	Ehlers	15 keV	2.5 mA	Elec. quads	Yes	Mirror	120 μA	40 μA	5	1.5	For A.N.U.
Duke	15 H^-	Ehlers	16 keV p	1 mA	Elec. quads	Yes	Mirror	90 μA	25 μA	9	2.5	Cyclograaff
Grenoble	60 p,..	Duo./Pol.	10 keV d	100/3 μA	Mag. quads	Yes	Channel	10/.3 μA	5/.12 μA	10	5/4	
Harwell	50 p,..	PIG	16 keV/q	240 μA C^{2+}	Mag. quads	No	Mirror	40 μA		16		1969 Test
Karlsruhe	55 d	Duo.	10 keV d	7 μA	Elec. quads + einzel	No	Channel	.7 μA		10		Plan Pol., PIG source
Livermore	15 H^-	Ehlers	15 keV	Similar to Duke								Cyclograaff
Oak Ridge	65 p,..	Pol.	12 keV p	3 μA	Elec. quad + Sol.	Yes	Mirror	50 nA	30 nA	1.7	1	
Philips	14 p	PIG	7.5 keV d	800 μA	Elec. quads	No	Mirror	30 μA	10 μA	3.7	1.2	
UCLA	50 p	Ehlers	15 keV H^-	2-.1 mA	Elec. quads		Mirror	5 μA				

*electrical current
†particle transmission

ACKNOWLEDGEMENTS

The author wishes to acknowledge the help of people from many laboratories, who supplied information for this paper.

REFERENCES

1. W. B. Powell, Proc. 2nd International Symposium on Polarization Phenomena of Nucleons (Birkhäuser, Basel, 1966), p. 47.
2. W. B. Powell, IEEE Trans. Nucl. Sci., NS-13, 4, 147 (1966).
3. D. J. Clark, Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 583.
4. J. Kouloumdjian et al., Nucl. Instr. Methods 79, 192 (1970).
5. Yu. A. Plis et al., Soviet Physics-Tech. Physics 12, 3, 348 (1967). Transl.
6. V. Bejsovec et al., Nucl. Instr. Methods 87, 229 (1970).
7. V. A. Gladyshev et al., Sov. Atom. Ener. 18, 3, 268 (1965). Transl.
8. R. Beurtey et al., Nucl. Instr. Methods 57, 313 (1967).
9. C. Bieth et al., IEEE Trans. Nucl. Sci., NS-19, 2, 93 (1972).
10. G. N. Flerov, IEEE Trans. Nucl. Sci., NS-19, 2, 9 (1972).
11. H. A. Willax, Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 58.
12. M. E. Rickey et al., IEEE Trans. Nucl. Sci., NS-16, 3, 397 (1969).
13. T. K. Khoe et al., Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 30.
14. J. A. Martin et al., Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 41.
15. J. A. Martin, private communication.
16. A. J. Cox et al., Nucl. Instr. Methods 18-19, 25 (1962).
17. D. J. Clark et al., Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 610.
18. J. Fermé et al., Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 134.
19. R. Lord, private communication.
20. A. A. Fleischer et al., Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 658.
21. J. R. J. Bennett, Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 602.
22. N. Hazewindus et al., IEEE Trans. Nucl. Sci., NS-16, 3, 459 (1969).
23. F. G. Resmini et al., IEEE Trans. Nucl. Sci., NS-16, 3, 465 (1969).
24. W. B. Powell, private communication.
25. N. Hazewindus, Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 625. Nucl. Instr. Methods 76, 273 (1969). Nucl. Instr. Methods 96, 227 (1971).
26. O. C. Dermois, Fifth International Cyclotron Conference (Butterworths, London, 1971), p. 620.
27. W. P. Lutter et al., IEEE Trans. Nucl. Sci., NS-18, 3, 321 (1971).

28. J. L. Belmont *et al.*, IEEE Trans. Nucl. Sci., NS-13, 4, 191 (1966).
29. R. W. Müller, Nucl. Instr. Methods 54, 29 (1967).
30. J. B. Warren, IEEE Trans. Nucl. Sci., NS-18, 3 (1971).
31. J. M. van Nieuwland *et al.*, IEEE Trans. Nucl. Sci., NS-16, 3, 454 (1969).
32. R. J. Louis *et al.*, IEEE Trans. Nucl. Sci., NS-18, 3, 282 (1971).

DISCUSSION

HENDRY: Two questions. The first is, is it impossible to arrange your central region so that you can use a little higher injection voltage? I notice that 10 kV seemed fairly low. We are able to adjust our central region to work at that injection voltage, but we suffer a great deal of beam loss if we do that. I just wondered if you have considered working at a bit higher voltage?

CLARK: Yes, that is a good point, particularly for the heavier ions. In our case, the injection energy should be about a fifth of the dee voltage so that is what fixed the 10 kV compared with about 50 kV dee voltage. But we could inject a little bit off centre, for example, and get up to a higher injection voltage by reshaping the iron a little bit in the hole so that it is off the machine centre-line. I think we could go up to about 30 kV that way. But we haven't done that--it's an interesting idea.

HENDRY: I just wanted to mention our experience on that. The way we designed our machines we aren't fortunate enough to have a lot of adjustments, and we guessed a little bit wrong on this last machine we built, which meant that the orbits indeed weren't centred properly. We found out that a set of coils at 5 in. really took care of those discrepancies quite nicely. So I would think there is probably a very good opportunity to maybe do the same thing in your machine.

CLARK: Yes, that's another possibility.

HENDRY: The second question: we use doublets but I notice you used triplets.

CLARK: We thought about this and it seems as though you use probably the same number of elements. If you count the number of singlets altogether, you probably have about the same number in either case. We were thinking at one time of a saw-tooth buncher which we never built. It sounded pretty good, so we wanted to leave a lot of space for that in case we needed it. So with triplets you can have more open space than you can with doublets, but if you don't need that open space, I don't think there is a great deal of difference.

REGENSTREIF: I think I have a question to Resmini, but maybe you can answer this. When you consider the influence of space charge on the emittance, do you mean the modification of the absolute value of the emittance, or have you also considered the distortion of the emittance configuration, filamentation and so on?

CLARK: I believe it is just the blow-up which can then be focused again if you have enough aperture. But perhaps Resmini would like to comment?

RESMINI: Yes, it is just the absolute value.