Survey of external injection systems for cyclotrons*

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ABSTRACT

Internal cyclotron ion sources produce large currents of light ions such as protons, deuterons, and α-particles. But for many other ions an internal ion source is either impossible or of low intensity. Sources of polarised ions are much too large to put in the centre of a cyclotron. To make heavy ions with the high charge states necessary for high cyclotron energy, the ion source needs high arc power input, which is supplied more easily in an external source. For negative ion acceleration, high gas flow and low pressure are needed, indicating the advantage of an external source. For these ions a number of groups have built or are planning injection from external sources. For polarised beams a few installations have used neutral beam injection. However, most polarised beam systems and all heavy-ion and negative-ion systems use ion injection because of better beam control during transport, and no loss of beam in charge exchange. The ion beams are brought in either axially through the magnet pole, or radially along the median plane. The larger cyclotrons being planned for 200-500 MeV provide adequate space in the usually crowded centre region, for transport and inflection of beams from external injection systems. This paper compares and summarises the various external injection systems operating or under construction for cyclotrons up to 500 MeV.

1. INTRODUCTION

The first external injection systems were designed to bring polarised beams to the centre of the cyclotron from external sources, since these sources were much too large for the cyclotron centre region. At CERN a source was built by Keller's group[1,2] to inject polarised hydrogen atoms into the CERN 600 MeV synchro-cyclotron. This method was tested on a model cyclotron but never used on the large machine. The first injection of ions into a cyclotron was reported at the UCLA Cyclotron Conference by Powell's group at the University of Birmingham[3]

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in 1962. They obtained excellent results with an rf source, getting a transmission of 3% from source to accelerated beam, without bunching. This work demonstrated the possibility of obtaining high intensity polarised beams by injection of polarised ions from one of the recently developed sources described at the Basle Conference in 1960.[4] At the CERN Conference in 1963 Thirion reported[5] the first successful acceleration of polarised particles in a cyclotron injecting a polarised atomic deuteron beam in the median plane, and ionising at the cyclotron centre. There was fortunately no depolarisation observed during acceleration, in agreement with calculations for other AVF Cyclotrons by Khoe and Teng,[6] Kim,[7] and Baumgartner and Kim.[8]

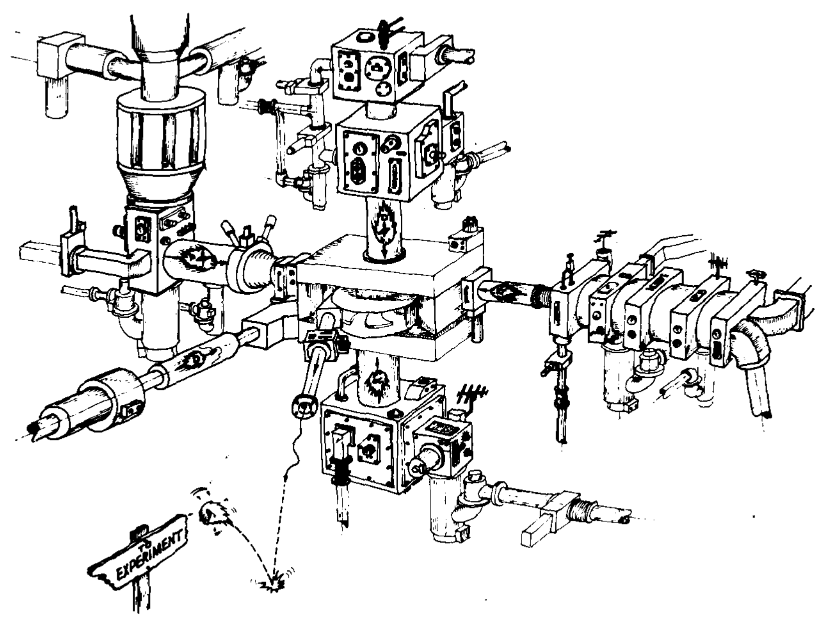


Fig. 1. View of the cyclotron as seen by various external injection systems

After these initial successful injection tests, other methods of injection, and improved sources were proposed and tested, as illustrated in Fig. 1. Some of these have been reviewed previously by Powell[9] at the Karlsruhe Conference in 1965 and again by Powell[10] at the Gatlinburg Conference in 1966. A review of polarised sources was given by Craddock[11] in 1966. Heavy-ion injection systems will be reviewed by other papers at this conference. In the following sections the various types of external injection systems for cyclotrons up to 500 MeV will be briefly discussed, to point out the principles of each. The Separated Orbit Cyclotron will be omitted, since it has special injection requirements. Finally, the relative success of each type of system will be summarised in the last section of the paper.

2. NEUTRAL BEAM INJECTION

2.1. *Thermal velocity beams*

The earliest systems of polarised beam injection injected neutral beam from a polarised source in the cyclotron median plane. This provided a simple transport method through the strong cyclotron magnetic field to the centre region, where the atoms were ionised by electron bombardment. The atoms were of thermal velocity, formed in an rf dissociator.

The first proposal was by Keller's group at CERN[1,2] for injecting polarised hydrogen atoms into the 600 MeV synchrocyclotron. The principle was tested in a 4·5 MeV model cyclotron, but not installed on the 600 MeV machine. The problem of reducing the hydrogen background below the atomic beam pressure at the cyclotron centre was difficult in this method.

This principle was successfully used by Thirion's group at Saclay to inject and accelerate polarised deuterons in the 22 MeV classical cyclotron. This system is shown in Fig. 2. The source was placed in the cyclotron vault at median plane level.[12] The atomic beam was ionised in the centre of the cyclotron by a magnetron type of ioniser. For deuterons the background problem is much less serious than for protons, and a good polarisation of 55% was obtained, with a current of 0·03 nA of deuterons on target. Although the transport was easy in this system, the ionisation efficiency was low, compared to an external ioniser.

Recently an arc type ioniser was installed by Maillard and Papineau in the centre of the deuteron cyclotron at Saclay. They report[13] a factor of 100 increase

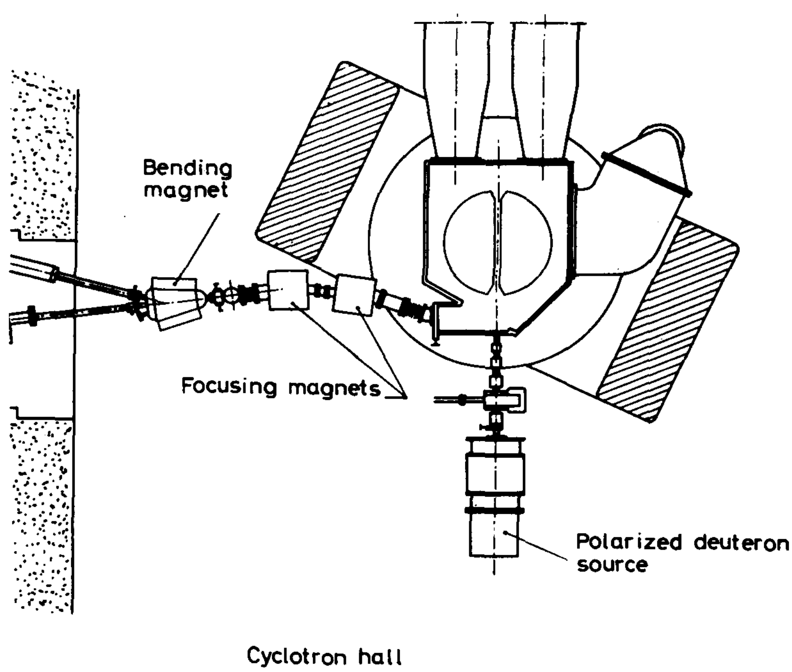


Fig. 2. Plan view of Saclay classical cyclotron showing polarised deuteron source used to inject atomic beam in median plane

in beam intensity to 5nA, with about the same polarisation, 0·5. Despite this great improvement, the intensity is a factor of ten lower than can be obtained with injection from an external ioniser on the same source. The deuteron source was removed from this cyclotron in early 1969.

2.2. *Fast neutral beams*

Another system of neutral beam injection is being installed on a U-120 Cyclotron at the Nuclear Research Institute in Rez, Czechoslovakia.[14] This system is shown schematically in Fig. 3. A beam of polarised protons or deuterons is formed in a weak field ioniser, accelerated to 40 kV, focused, bunched, and neutralised in a hydrogen chamber placed in a 2·5 kG magnetic field. At the centre of the cyclotron, a stripping foil between the dees produces ions again, for acceleration.

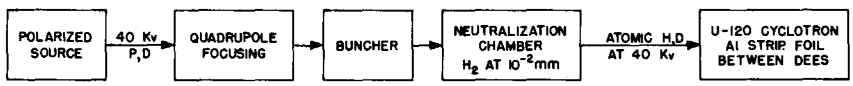


Fig. 3. Block diagram of Czechoslovakian system to inject 40 kV polarised hydrogen or deuterium atoms in median plane

As in the Saclay system, this method has the advantage of requiring negligible space and modifications in the cyclotron. This system has an advantage in beam focusing over the thermal velocity method. Also protons can be used as easily as deuterons, since there is no ioniser at the cyclotron centre to ionise backgroun gas.

3. AXIAL ION INJECTION

The first external ion injection system was installed on the Birmingham cyclotron by Powell in 1962.[3] The system was developed with an rf source.[15] Later a polarised deuteron source was installed[9] as shown in Fig. 4. The system contains six einzel lenses guiding beam down the axial hole in the upper pole. The beam is bent into the median plane by a 45° gridded electrostatic mirror as shown in Fig. 5. Special centre-region electrodes provide narrow gaps to accelerate the beam around the mirror at the rather low dee voltage of 25 kV. These are shown also in Fig. 6. Vertical grids increase the accelerating fields and adjust vertical focusing. The 45° mirror is shown in more detail in Fig. 7. The molybdenum wires are wound in a square mesh, giving 65% transparency after two traversals. The system performed well with the rf source,[15] giving 21 μA accelerated to full radius, and a transmission of 3·5% from source to full radius without bunching.

For the polarised source, the transmission is now 10% to full radius, and 2% to extracted beam, with a buncher.[16] A careful analysis of the injection optics was given at the Gatlinburg Conference.[10]

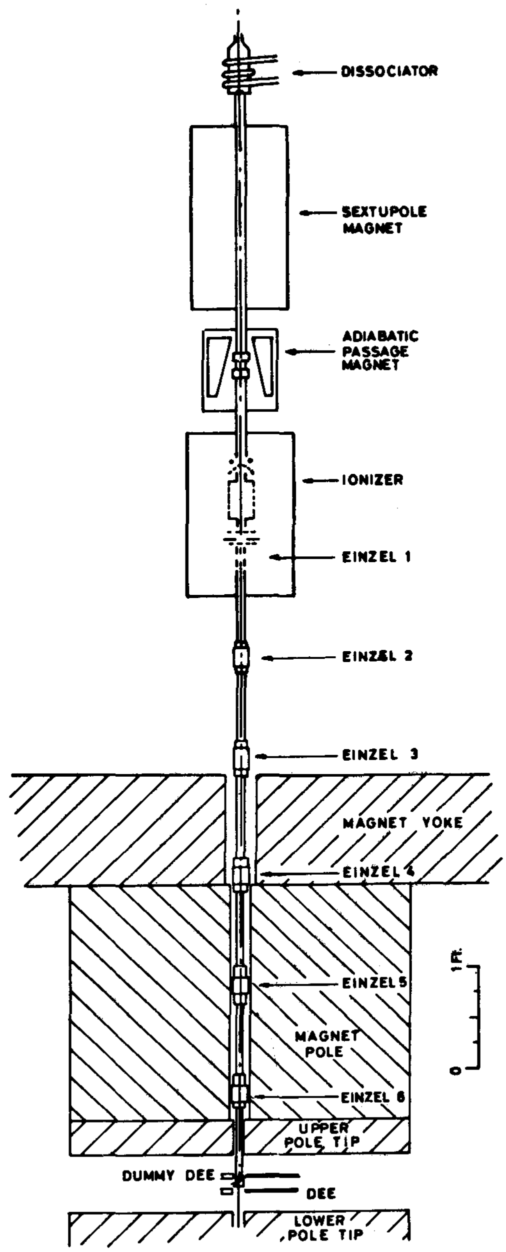


Fig. 4. Birmingham axial injection system for polarised deuterons

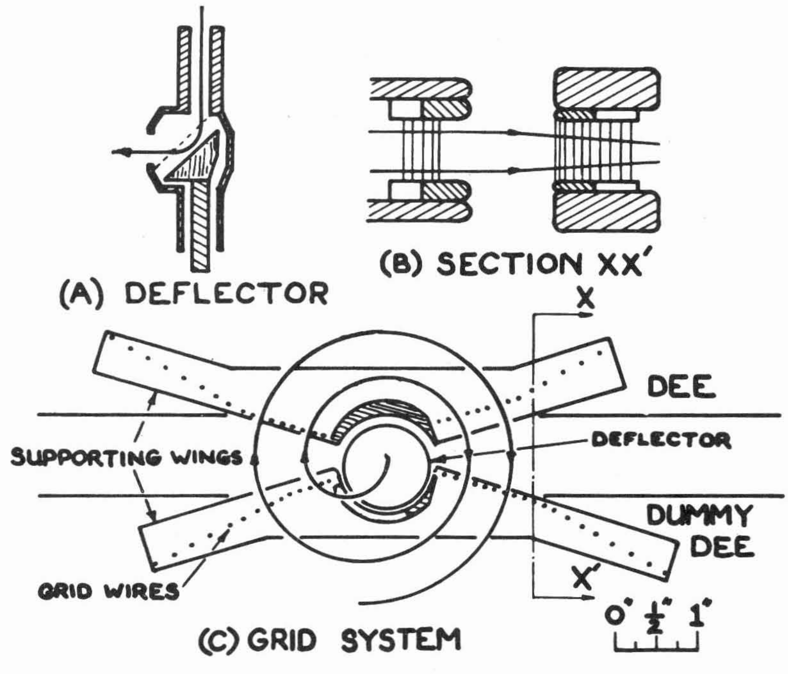


Fig. 5. Birmingham centre region showing mirror and focusing grids in dee and dummy dee

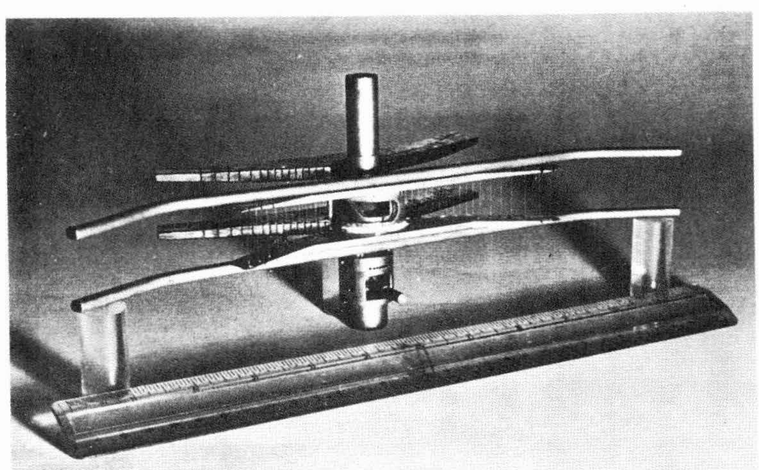


Fig. 6. Photo of Birmingham centre region

After the success of the Birmingham injection system, many other groups began planning axial injection systems. Only a few features of the other systems will be mentioned here.

The transport systems are generally composed of einzel lenses, electric or magnetic quadrupoles. The inflectors are usually gridded mirrors, as at Birmingham. However, at Grenoble, a helical channel is used,[17] as shown in Fig. 8. This channel has the possibility of 100% transmission. Another channel is described by Muller.[18]

Various beam optics calculations have been done for these systems. A region which is peculiar to the axial system is the half-solenoid lens formed at the bottom of the entrance hole, where the magnetic field rises from nearly zero to its median plane value of up to 17 kG in some cyclotrons. At the Berkeley

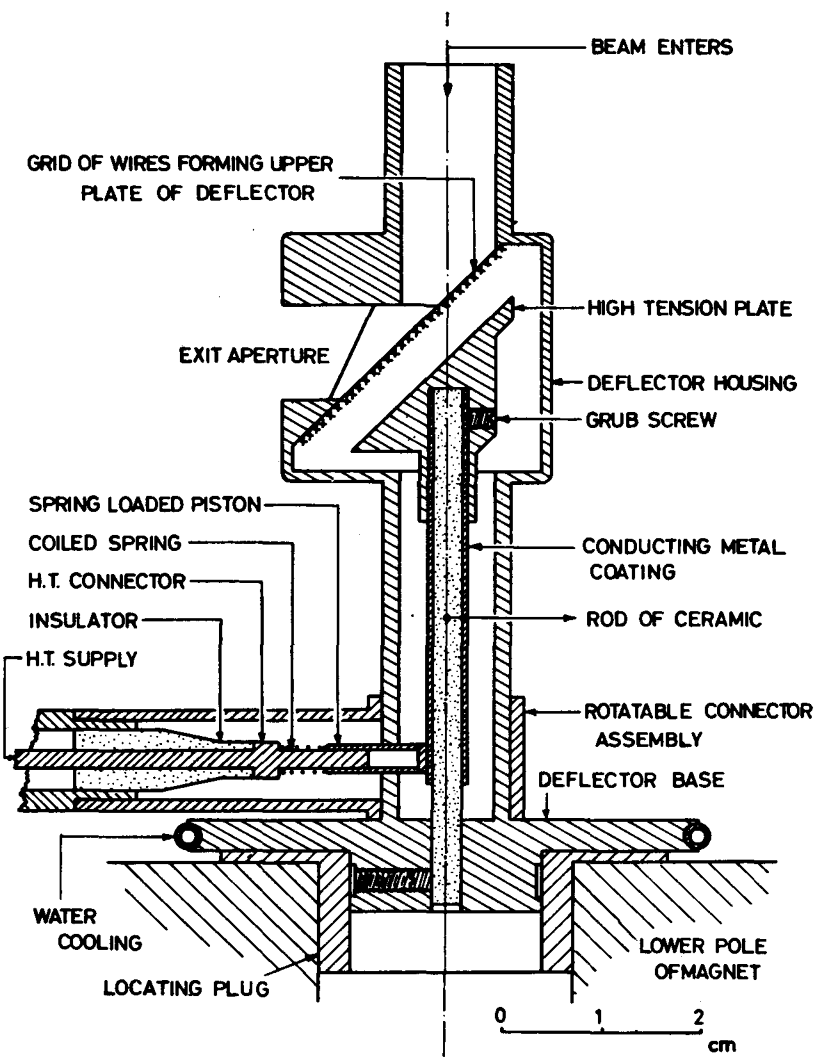


Fig. 7. Cross-section of Birmingham mirror inflector

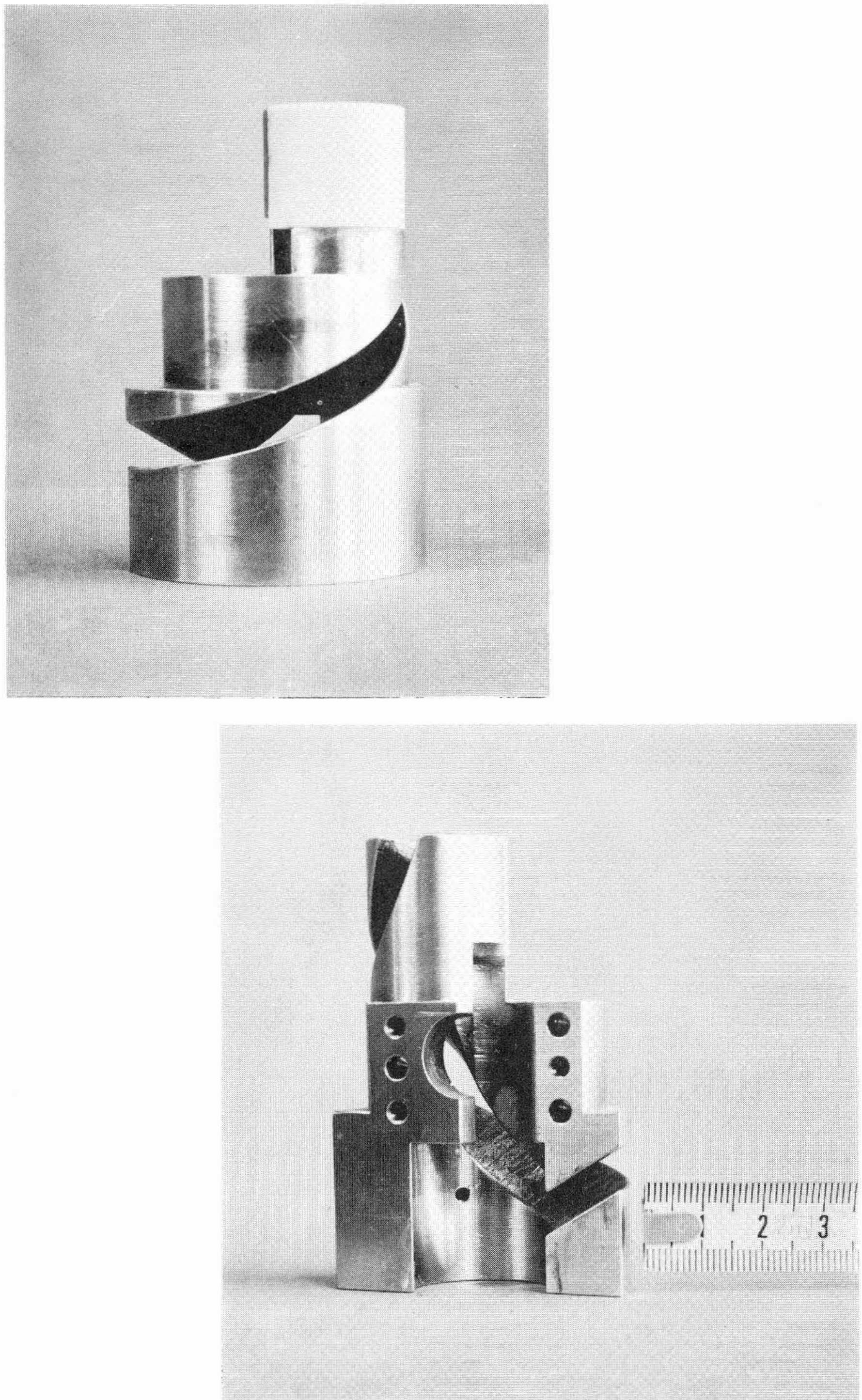


Fig. 8. Photo of Grenoble channel type electrostatic inflector for axial injection

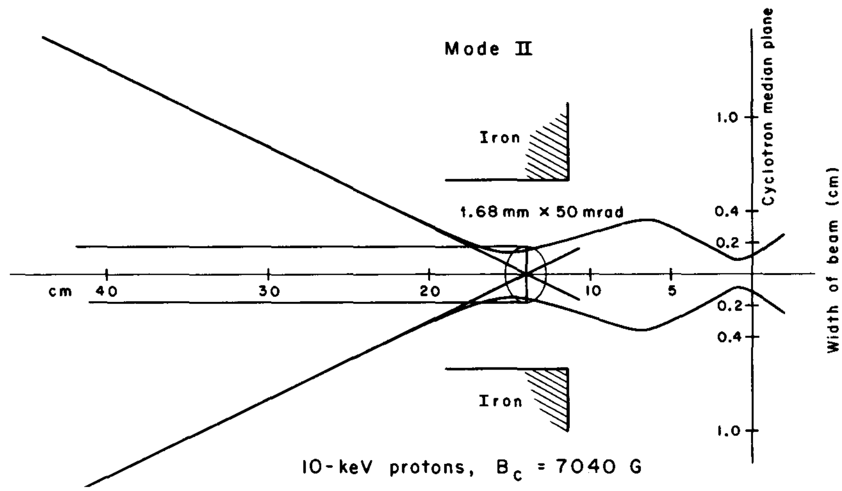


Fig. 9. Beam envelope calculation in 'λ-mode' through 'hole-lens' in Berkeley axial injection system

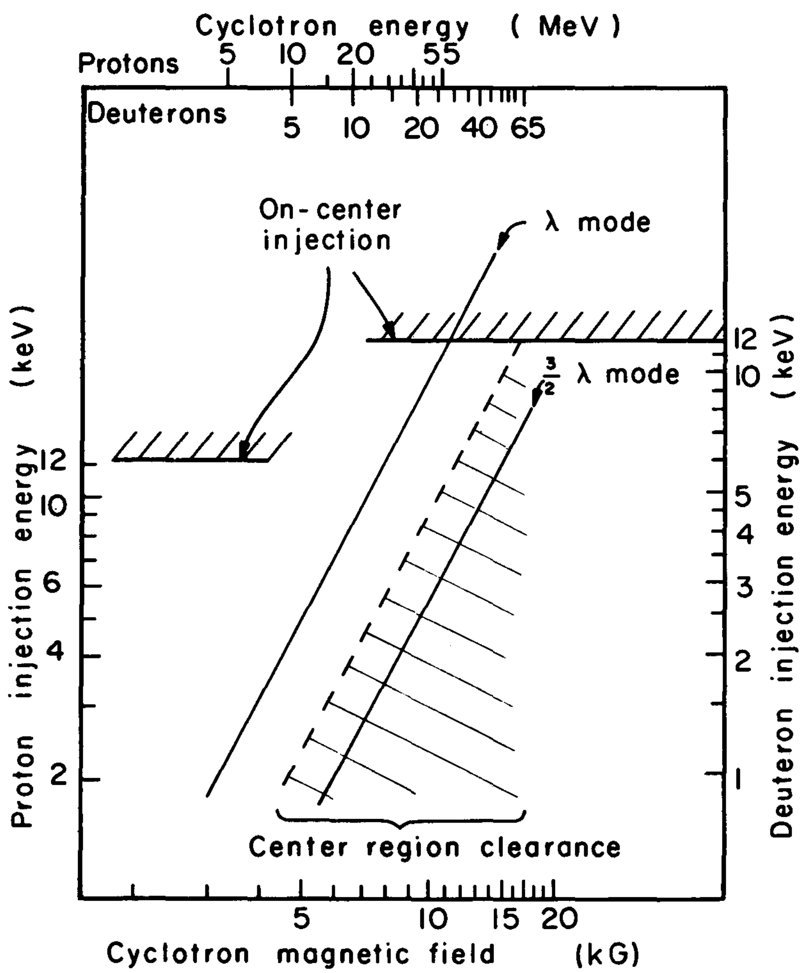


Fig. 10. Regions of allowed (unshaded) operation, and mode lines for Berkeley system

88-in Cyclotron some calculations of beam trajectories through this 'hole lens' were done by Luccio.[19] A typical beam envelope given by these calculations is shown in Fig. 9. In this 'λ mode' the beam is transformed from a waist outside the lens to a similar waist in the median plane. By scaling the injection energy proportional to cyclotron energy (magnetic field squared) one can stay on this mode, as shown in Fig. 10 for the Berkeley case.[20] In practice several modes are used, because of various limitations such as inflector clearance, maximum dee voltage, and minimum injection energy from ion sources.

A point of interest in the beam optics is the behaviour of the beam at high intensities where space charge forces are important. In systems where there is no compensation of this charge by neutralisation, the beam size increases and lens strengths must be increased to produce the same waists. This is illustrated by a calculation by Resmini at Berkeley[21] in Fig. 11. The beam profiles are shown

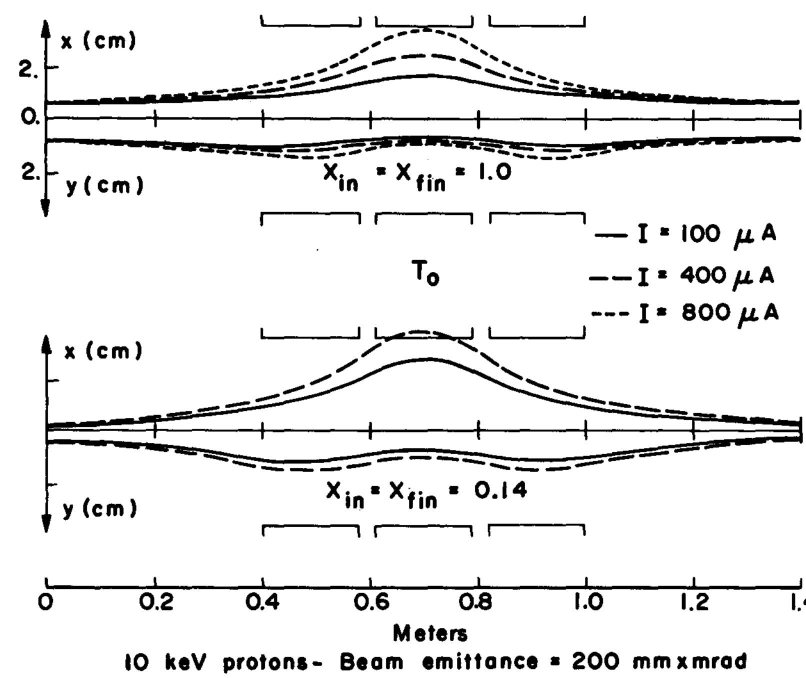


Fig. 11. Beam envelope calculation, including space charge, through Berkeley quadrupole triplet

for 100 μA, 400 μA, and 800 μA for a 10 keV proton beam. More work of this type would be useful in the hole lens and inflector regions. Groups such as the Rutherford Laboratory report[22] use of space charge compensation, which should permit high-current transmission without blow-up.

Other systems now operating or under construction include one by the Cyclotron Corporation for H^- injection into a compact cyclotron,[23] a Philips system for a compact cyclotron,[24] a system for polarised ion injection into ORIC at Oak Ridge,[25] and H^- injection into the 500 MeV TRIUMF cyclotron.[26]

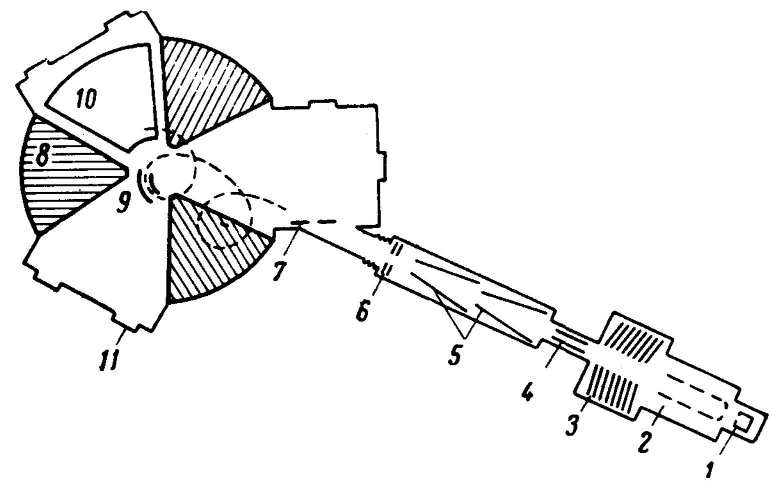


Fig. 12. Radial trochoidal injection in median plane at Lebedev Institute, Moscow

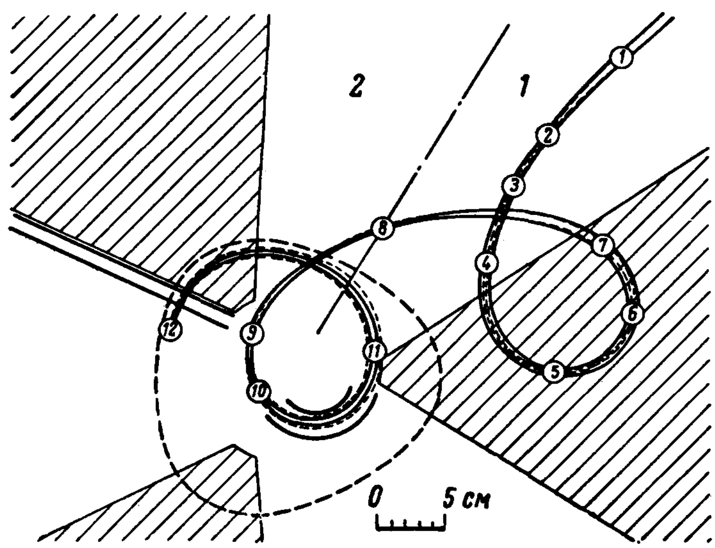


Fig. 13. Lebedev radial injection centre region, showing channel inflector

4. RADIAL ION INJECTION

4.1. *Trochoidal injection*

The earliest of the radial ion-injection systems is that of the Lebedev Institute in Moscow.[27] Here the hill-valley magnetic field difference of an AVF cyclotron is used to send the beam on a trochoidal path to the centre region as shown in Fig. 12. This is an 'anti-spill beam' system, the inverse of a commonly observed instability of AVF cyclotrons. At the centre an electrostatic channel is used to inflect the beam into a centred orbit, as shown in Fig. 13. The injection energy is 30 keV, 10% of the 300 keV cyclotron energy, so the loops are well separated, giving adequate space for the inflector. The beam focusing is good and the transmission of 20% from external source to accelerated beam at full radius is excellent.

An example of this method applied to a larger cyclotron is shown by a calculation by Blosser's group at Michigan State[28] in Fig. 14. Here injection is

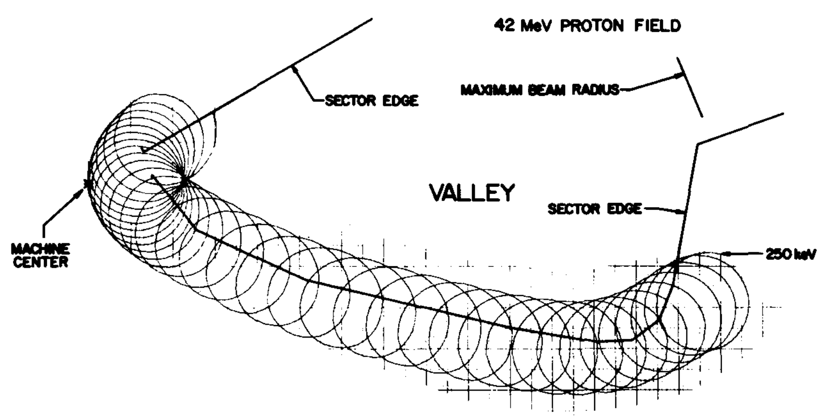


Fig. 14. Michigan State calculated trochoidal injection at 250 keV. Inflector is not designed yet

at 250 keV for a 42 MeV proton cyclotron field. The injection energy is now only 0·6% of the cyclotron energy. The loops overlap and the inflection is more difficult. The stability and optical quality are excellent.[28]

4.2. *Electric field cancelling magnetic field*

In 1965, a new method of radial ion injection was suggested by Beurtey and Thirion at Saclay.[29] This system was designed to transport polarised protons from the source through the median plane to the cyclotron centre,[30] as shown in Fig. 15. It uses a system of electrodes, shown schematically in Fig. 16, shaped to provide a horizontal electric field to cancel the force from the magnetic field on a 5 keV proton beam, and to focus it on its path to the cyclotron centre.[31,32]

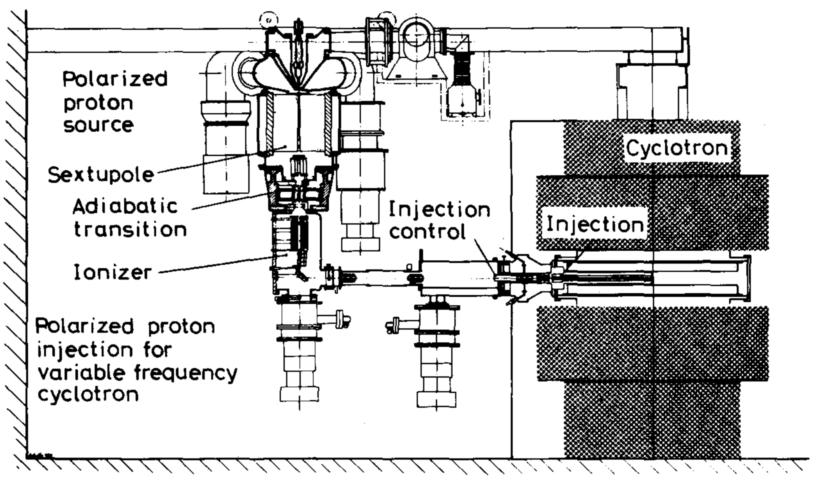


Fig. 15. New Saclay radial system for injecting polarised ions into AVF cyclotron

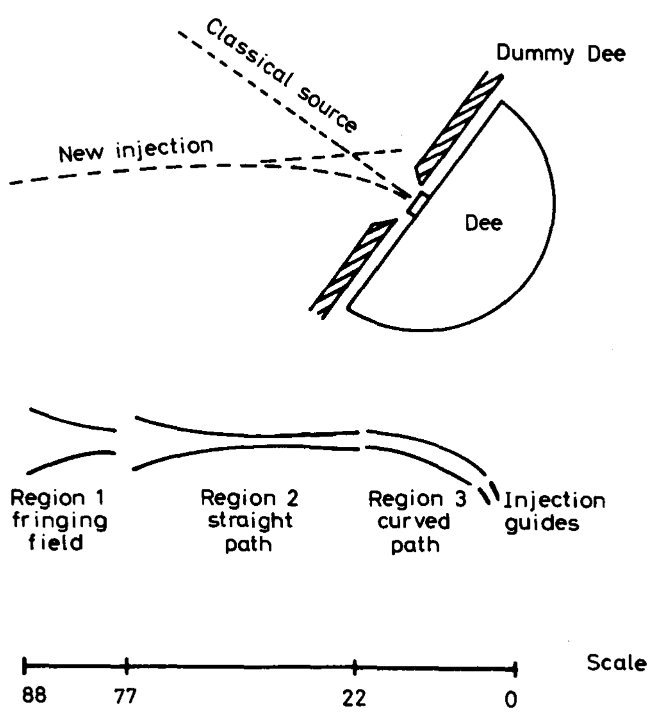


Fig. 16. Schematic layout of new radial ion injection at Saclay

The magnetic field profile to be cancelled is shown in Fig. 17. By the use of four bars, the voltages can be adjusted to give an electric field with a linear portion as shown in Fig. 18. This shape provides transverse focusing of the ion beam. The results obtained with this system[33] show transmission from polarised source to accelerated beam of 4% and to extracted beam 1·4%. The external beam intensity is 70 nA, an excellent result due to the fine source performance and good injection transmission.

4.3. *Linac heavy-ion injection*

A third method of radial ion injection was proposed by Cabrespine's group at Orsay.[34] Fig. 19 shows the system with a linac injecting heavy ions into the median plane of the cyclotron. The ions have a charge/mass ratio of 0·1 and an energy of 1 MeV/nucleon from the linac. The radius of curvature is large enough to bring this beam into the centre of the cyclotron in about a half turn, as shown in Fig. 20. Here it is stripped in a foil placed at a position to give a centred orbit at the higher charge state. This two-stage device gives final cyclotron energies of up to 370 MeV for krypton. For the heaviest ions final energy is equal to that of a single cyclotron of 2·5 times the radius of this one.

4.4. *Injection into separated sector cyclotrons*

For higher energy cyclotrons, a separated sector design is often used. The first project of this type was the 500 MeV SIN Cyclotron at Zurich. This cyclotron is now under construction and was described at the Tokyo Nuclear Structure

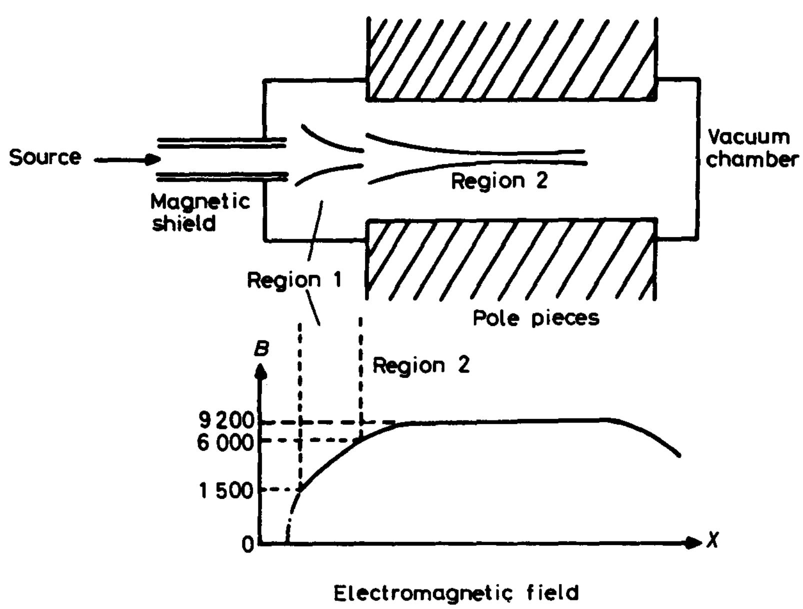


Fig. 17. New Saclay injection system, showing magnetic field behaviour

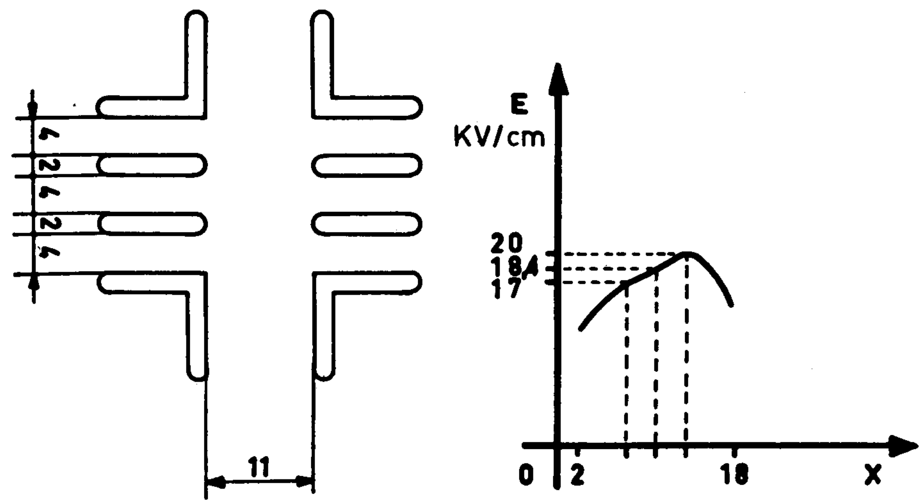


Fig. 18. Electrodes to produce an electric field which cancels magnetic field

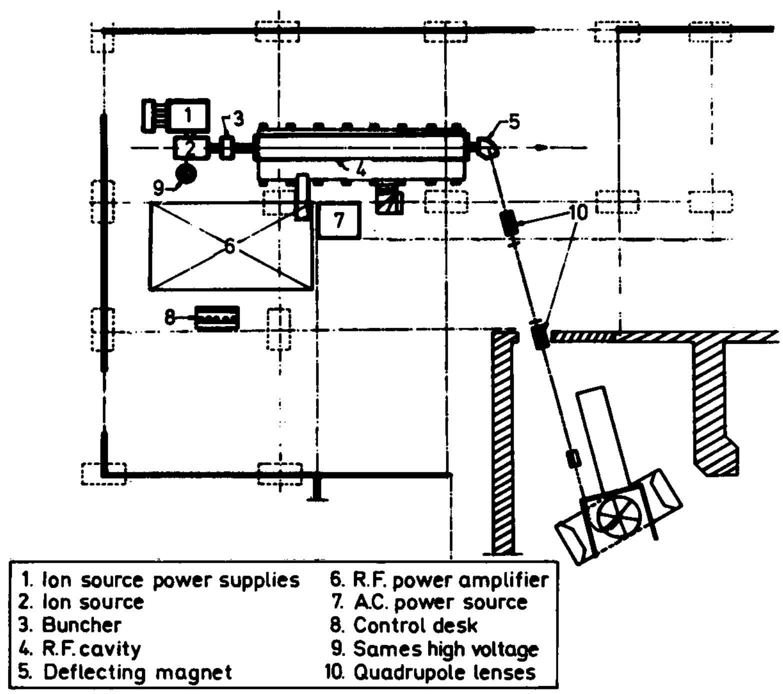


Fig. 19. Orsay heavy-ion radial injection from a linear accelerator

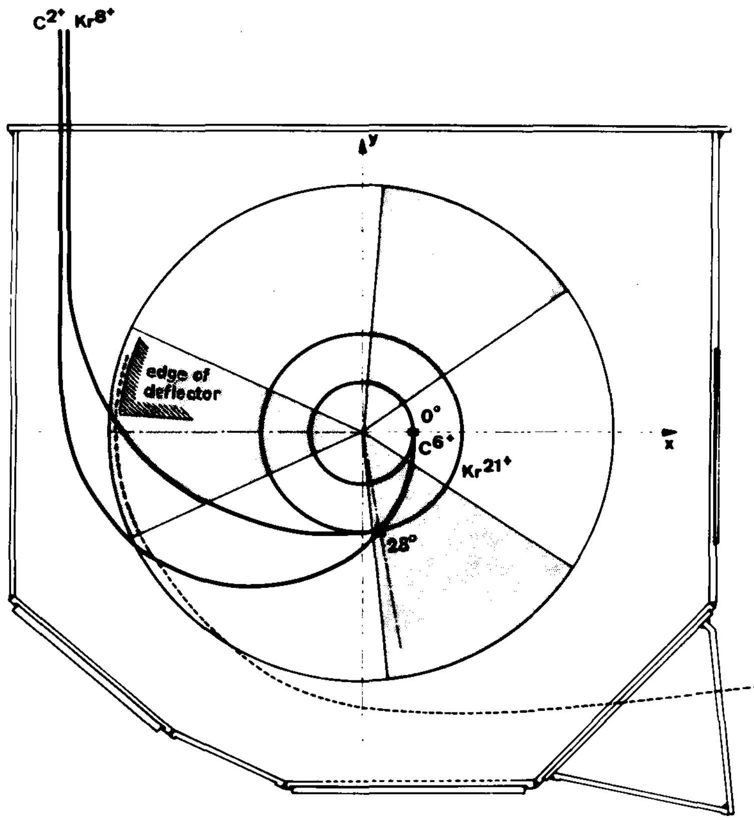


Fig. 20. Orsay centre region, showing heavy ions from linac being stripped, to bring them into a centred orbit

Conference in 1967,[35] and at this conference. Fig. 21 shows the injection beam line for binging 68 MeV protons through a bending magnet and an electrostatic channel into the initial orbit. Since the magnetic field is nearly zero between sectors and in the centre, there is adequate space for the inflection channels.

The 200 MeV final stage and 15 MeV injector stage Indiana Cyclotrons,[36] now under construction, are also of the separated sector design. The injection here is similar to that of Zurich. There are also a number of new proposals for separated sector cyclotrons, which will be described at this conference.

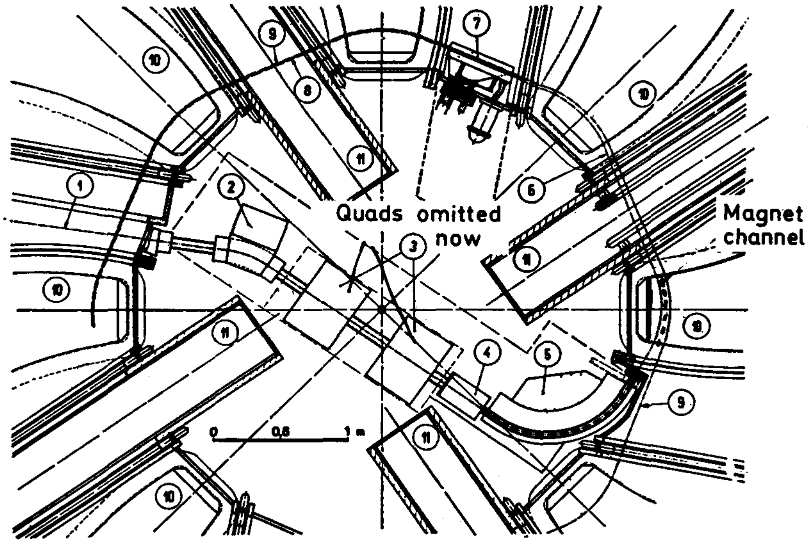
5. SUMMARY

To collect information on the various external injection systems now operating or under construction, questionnaires were sent to groups doing work in this area. The information received was sorted and is partially displayed in Table 1. Since several systems are operating now, the last columns are used to show the transmission and beam currents, measured or predicted. Both axial and radial ion injection work well, with overall transmission from source to extracted beam in the region 1-5%. In the larger machines being built, the higher injection energies and smaller phase space areas promise efficiencies of up to 30%, starting

TABLE I. EXTERNAL INJECTION SYSTEMS, SPECIFICATIONS

	CYCLOTRON ENERGY (MeV)	INJECTOR STATUS	SOURCE TYPE	SOURCE ENERGY(kV)	SOURCE POL.	SOURCE CURRENT	TRANSPORT MODE	TRANSPORT FOCUSING	TRANSPORT INFLECTOR	TRANSPORT BUNCHER	CYCLOTRON BEAM ACCEL.	CYCLOTRON BEAM EXTERNAL	TRANSMISSION SOURCE TO: ACCEL. (%)	TRANSMISSION SOURCE TO: EXT. (%)	COMMENTS
ATOMIC BEAM															
Saclay	22d	Shutdown 1969	Pol.	Thermal	.5 d		Radial	None	Ionizer	No		.03 nA			
Czech.	12d	Inst. 1969	Pol.	40 p,d	.3 d	.3 μA	Radial	None	Stripping	rf					.1 nA external beam pred.
AXIAL ION															
Birmingham	12d	Oper.	Pol.	12 d	.55 d	.2 μA	Axial	Ein. Lens	Grid-mirror	rf	20 nA*	4 nA*	10*	2*	Grids in center region
		Shutdown	rf	12 d	0	600 μA	"	" "	" "		21 μA		3		1962 tests only
Cycl. Corp.	15 H^-	Oper.	Ehlers	10-14 H^-	0	2.5 mA	Axial	Elec. Quads	Grid-mirror	rf	120 μA*	40 μA*	5*	1.5*	Sold to LRL Livermore
Duke	15 H^-,8 H_2^-	Oper.	Ehlers	17 H^-,10 H_2^-	0	2.5 mA	Axial	Elec. Quads	Grid-mirror	rf	80 μA*	30 μA*	3*	1.5*	Built by Cycl. Corp.
Grenoble	60 p,..	Oper.	Pol.	13 p	.78 p	1.9 μA	Axial	Mag. Q.+ Ein.L.	Channel	rf(study)	23 nA	7 nA	1.2	.4	22 Mag. Quads + 8 Ein. L.
		Oper.	Duoplas.	13 p	0	3 mA	"	" "	"	"	20 μA	4.2 μA			Space Charge comp.
Philips	14 p,7.5 d	Testing	Penning	7.5 d	0	5 mA	Axial	Elec. Quads	Grid-mirror	rf(const.)	30 μA		2		Prelim. results
Berkeley	55 p,65 d	Oper.	Pol.	12 p	.7 p	1.4 μA	Axial	Elec. Quads	Grid-mirror	rf(const.)	50 nA	20 nA	3.5	1.5	Old line tested 1966
		Oper.	Duoplas.	10 p	0	40 μA-p	"	" "	" "	"	3.6 μA	1.8 μA	9	4.5	New duoplas. since 1966
Harwell-VEC	53 p,40 d	Inst. 9-69	P.I.G.	30 p,He	0	200 mA	Axial	Mag. Quads	Mirror	No					Space Charge comp.
Groningen	70 p,..	Inst. 1969					Axial	Mag. Lens	Mirror						90% transm. in inj. line
ORNL-ORIC	65 p,40 d	Inst. 11-69	Pol.	15 p,d	.9 p	5 μA	Axial	Elec. Quads	Grid-mirror	Sawtooth					Heavy-ion Source planned
TRIUMF	500 H^-	Inst. 1972	Ehlers	300 H^-	0	5 mA	Axial	Elec. Quads	Channel	rf	1.5 mA*†	1.5 mA*†	30*†	30*†	Polarized source planned
UCLA	48 p	Const.	Ehlers	15 H^-	0	2 mA	Axial	Elec. Quads	Mirror						
Manitoba	48 p,24 d	Const.	Duoplas.	H^-,D^-	0		Axial	Elec. Quads	Grid-Mirror						
C.S.F.	Model	Study			0		Axial		Mirror						Electron Model Tests
A.E.G.	Model	Study		10	0		Axial	Quads	Channel						Ion model tests.
RADIAL ION															
Lebedev	.15 p,.3 d	Oper.	Penning	15 p,30 d	0	5 μA	Troch.	Sector gradient	Channel	No	1.0μA		20		Operating 1964
M.S.U.	56 p,..	Study		250 p			Troch.	Sector gradient							Good optical quality
Saclay	27 p,..	Oper.	Pol.	5 p	.9 p	5 μA	E ⊥ B	Ein. Lens		rf	200 nA*	70 nA*	4*	1.4*	Heavy ion source-constr.
Orsay	140 N^{+5},..	Const.	Linac	1 MeV/A	0		Radial		Strip.						
Zurich	585 p	Inst. 1973/74	AVF Cycl.	70 MeV p	0	100 μA	Radial	Mag. Quads	Channel	No	100 μA†	100 μA†			Proj. complete 1974
Indiana Inj.	15 p,..	Inst. 3-70	Duoplas.	500 p	0	50 μA	Radial	Elec.,Mag. Q.	Channel	rf	10 μA*†	10 μA*†			Building pol. He^3 source
Indiana Fin.	200 p,..	Inst. 3-70	AVF Cycl.	15 MeV p	0	10 μA	Radial	Mag. Quads	Channel	No	10 μA†	10 μA†	90†	90†	Cyclotron complete 1-72

*Buncher used. †Design goal.



Injection system of the ring accelerator.

1. **68 MeV proton beam crossing vacuum chamber**
2. **Bending magnet**
3. **Quadrupole-pair**
4. **Beam-probe assembly**
5. **Bending magnet with high density current coil**
6. **68 MeV orbit through the first two magnets**
7. **Electrostatic injection electrode for orbit correction**
8. **68 MeV equilibrium orbit**
9. **Proton beam after first orbit**
10. **Magnet sectors**
11. **Cavities**

Fig. 21. Centre region of Zurich separated sector cyclotron, showing magnetic and electrostatic inflection channels

with a d.c. beam. This is very encouraging since the increase in beam current can come from an increase in acceptance, as well as the greater output of the external source, compared to an internal source.

6. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the help of W. B. Powell, and all those who furnished questionnaire data and separate reports. Also the craftsmanship of T. Chan is appreciated for Fig. 1.

DISCUSSION

Speaker addressed: D. J. Clark (L.R.L.)

Question by E. Regenstreif (Rennes, France): You have shown a 10 keV proton beam going through a triplet under the influence of space charge.

(1) What assumptions did you make about the initial space charge distribution?

(2) Did you assume strictly laminar flow?

Answer: The calculation was done for waist-to-waist transfer using the programme 'Beamcal' from Los Alamos (D. W. Allison), which integrates the Vladimirsky-Kapchinsky equations. Reference UCRL-18596, L.R.L., Berkeley, California.

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