A PROPOSED NEW INJECTOR FOR THE S.I.N. RING CYCLOTRON

S. Adam, B. Berkes, D. Collins, W. Joho, P. Lanz, M. Olivo, U. Schryber
S.I.N. - Swiss Institute for Nuclear Research, 5234 Villigen, Switzerland

Summary

A new injector for the S.I.N. isochronous 590 MeV ring cyclotron is under serious study. It is expected to produce a maximum proton current of 1 mA at a fixed energy of 72 MeV. In order to keep beam losses in the 590 MeV ring cyclotron at a tolerable level, excellent beam quality is required.

The protons are first accelerated by a DC machine to 0.8 MeV, then to the final energy of 72 MeV by a four sector isochronous ring cyclotron. Acceleration is accomplished by three different RF systems. A large turn separation of 2 cm at the extraction radius will allow a 100 % extraction efficiency.

Introduction

The S.I.N. 590 MeV ring cyclotron for protons has been described in previous conferences[1] and thus only a short summary of its basic features are given. A conventional four sector isochronous cyclotron, constructed by the Philips Company Eindhoven[2], pre-accelerates protons to 72 MeV, which are afterwards transported over 40 m toward the ring cyclotron. The ring cyclotron consists of eight separate sector magnets and four high Q-cavities which accelerate the protons to their final energy of 590 MeV, high enough to produce intense beams of pions from two external targets.

The experience gained during the first year of operation and the performance of the accelerators was discussed by W. Joho[3]. The beam transmission through the ring cyclotron is of prime importance and has been steadily improved to values of around 95 %. The highest beam current observed on target was 30 μA. The ring cyclotron has proved to be very reliable. The injector cyclotron is designed as a multi-particle cyclotron with variable energy. Its mechanical system is very complex. Maintenance and repair work will be extremely difficult in the future because of the activation level due to the extraction losses.

The injector cyclotron operates for one week out of the month in the low energy mode, providing beam for nuclear physics and for isotope production. During that time, about 85 % of the financial investment, namely the ring cyclotron plus all the high energy experimental equipment cannot be used.

The proposed new injector could, therefore, considerably improve the exploitation of the medium energy facilities. In the future, the Philips injector could serve as a stand-by injector and for the injection of polarized protons into the ring cyclotron.

The development of a new injector with a current capability of 1 mA is certainly justified by the growing European interest in meson physics. It might also be mentioned that the neutrino physics, radiomedical applications, and to a lesser extent the biological experiments, call for proton currents considerably higher than 100 μA.

The limitation in current of the ring cyclotron is found from theoretical consideration to be in the order of 1 mA. One limit is given by the beam loading of the accelerating cavities. To accelerate currents of 1 mA, the total RF power has to be increased by about a factor of two.

The extraction efficiency has to be better than 99 %, which means that the turn separation at extraction has to be perfect. To achieve this goal, it is necessary that the principle of flat-top acceleration be applied in the ring cyclotron and that the quality of the injected beam be much better than that presently produced by the Philips cyclotron.

The New Injector

Starting from the 590 MeV ring requirements, the following design goal for the new 72 MeV injector was established:

1. Average beam current $\sim$ 1 mA
2. Energy spread $<$ 150 keV FWHM
3. Pulse repetition rate 50.7 MHz
4. Pulse width $\sim 20^{\circ}$ RF
5. Axial and radial beam quality $\pi \cdot$ 2 mm mrad

Different types and combinations of accelerators able to fulfill the above specifications were discussed by a study group[4]. The concept for the new injector as recommended by the study group is described in [5] and illustrated in Fig. 1.

The protons are accelerated in two stages. The first stage is a DC accelerator of the Cockroft-Walton type with an energy of about 0.8 MeV. The second stage is a ring accelerator with four sector magnets and three different RF systems. Its unique property is the big ratio of extraction energy to injection energy of about 100. Injection is accomplished by means of an axial injection system (see Table 1).

The transition energy of 0.8 MeV between the DC pre-accelerator and the ring cyclotron is a compromise between difficulties in the central region of the ring cyclotron and the limitations of an open air Cockroft Walton. It is foreseen that the 0.8 MeV power supply is purchased as a commercial unit. The accelerating column and the duoplasmatron ion source would be of similar design as the LAMPF injector.

The ring cyclotron employs many ideas of the 590 MeV ring and is even very similar in size. It

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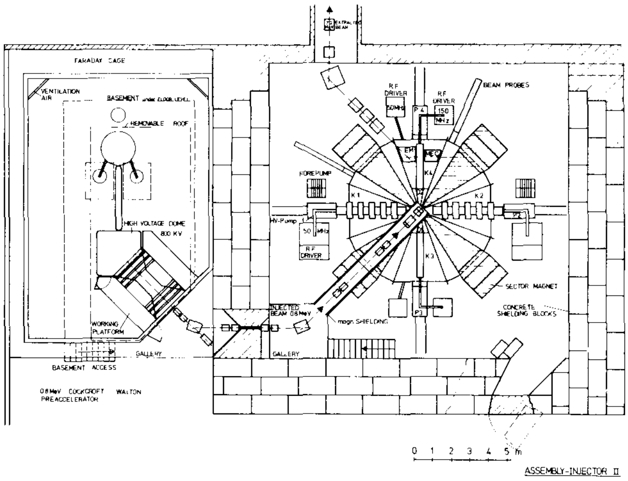

Fig. 1
Plan view of the two stage injection accelerator. The HV generator of the pre-accelerator will be of the air insulated Cockroft Walton type. The 0.8 MeV beam line crosses the first sector magnet 3.0 m above the mid-plane of the 72 MeV ring cyclotron. Between the sector magnets the four RF sections containing the three different RF systems can be seen. K1 and K2 are the main RF cavities, D1 and D2 the Delta resonators and K3 and K4 the flat-top cavities. The new injector will be installed in a separate building to be erected north of the present experimental hall.

consists of four magnets with a magnetic field of 10 kG and an azimuthal width of 26°. The weight of each magnet is approx. 120 t. The accelerating frequency is 50.7 MHz, the same as for the 590 MeV ring cyclotron. The harmonic number for the new injector cyclotron will be 10.

The 0.8 MeV DC beam of protons from the pre-accelerator is guided through an axial beam transport system toward the center of the ring cyclotron. It is injected on a quasi equilibrium orbit by means of a vertical 90° bending magnet and a magnetic cone in the gap of one sector magnet.

The RF system consists of three different systems with a total of six resonators. There are two Dee's and two main cavities operating at 50.7 MHz. The two Dee's with an azimuthal width of 18° are built as $\lambda/4$ resonators with a maximum voltage of 80 kV at the injection radius. Taking transit time effects into account, the resulting energy gain is 300 keV per turn. The turn separation between the first orbits will be 5.5 cm. These resonators which have a Delta shape drive the beam into the useful range of the high Q-cavities which have zero voltage at their ends.

Apart from the size and the mechanical design the main cavities operating in a H_{101} mode will be copies of the successful resonator boxes from the 590 MeV ring cyclotron. They will have a peak voltage of 500 kV and produce an energy gain at the extraction radius of 900 keV. The resulting turn separation will be about 20 mm, a comfortable value to achieve an extraction efficiency of 100 %.

The flat-top cavities will be operating at 152 MHz. They superimpose a third harmonic oscillation on the fundamental accelerating voltage. The flat-top cavities will be located together with the Delta resonators, 90° apart from the main cavities.

The extraction of the beam will be straight forward, making use of the turn separation due to the energy gain. Instead of using an electrostatic extractor channel we plan to have a septum magnet with a magnetic field strength of 2.8 kG, producing a deflection angle of 70 mrad. The beam will then be extracted by a 12.6 kG septum magnet.

A special feature of the new injector cyclotron is the radial dependence of the energy gain per revolution as shown in Fig. 2. The energy gain first decreases with increasing radius because of the voltage characteristics of the Delta system.

Table 1

Parameters of the Ring Cyclotron 0.8 MeV - 72 MeV

Beam Characteristics			
Extracted beam:			
Energy		72	MeV
Average current (design goal)		1	mA
Beam quality horiz. and vertical (including π)	<	6	mm mrad
Energy spread (FWHM)	~	150	keV
Phase width	<	20°	(RF)
Injected beam:			
Energy		0.8	MeV
Beam quality horiz. and vertical (including π)	<	40	mm mrad
Energy spread (FWHM)	~	100	eV
Phase width	<	80°	(RF)
Cyclotron Parameters			
Sector magnets:			
Number of sector magnets		4	
Angle of sector magnets		26°	
Flux density		10	kG
Gap width		35	mm
Weight per magnet	~	120	t
Injection radius (between magnets)		0.36	m
Extraction radius (between magnets)		2.96	m
Extraction radius (inside magnets)		3.75	m
Betatron frequency horizontal		$1.2 < \nu_r < 1.4$	
Betatron frequency vertical		$1.15 < \nu_z < 1.6$	
Cyclotron frequency		5.07	MHz
Harmonic number		10	
RF-Systems:			
Accelerating frequency		50.7	MHz
2 Delta Systems (18°), peak voltage		80	kV
Power consumption of one Delta System	~	30	kW
2 cavities, peak voltage		500	kV
Power consumption of one cavity	~	125	kW
2 cavities for 3rd harmonic flat top			
Acceleration, peak voltage	~	70	kV
Internal beam:			
Orbit separation at injection (for ΔE = 0.30 MeV)		5.5	cm
Orbit separation at extraction (for ΔE = 1.0 MeV)		1.9	cm
Number of revolutions		105	
Extraction efficiency		100	%
Injection:			
Axial beam transport system			
90° bending magnet (B = 10 kG) deflects beam into mid plane. Magnetic cone with field index of n = 0.5 in the gap of sector magnet 1.			
Extraction:			
Magnetic extraction channel length	~	60	cm
deflection angle		70	mrad.
Extraction magnet deflection angle		42°	
flux density		12.5	kG

The minimum energy gain is in the overlapping region of the Delta systems and the cavity resonators. The ratio of the energy gain between extraction and injection radius is 3. It is well known from the Maxwell equations that a radial variation of the RF amplitude is connected with a magnetic RF field which is parallel or antiparallel to the field in the sector magnets. This RF field slightly affects the time needed for a revolution. This effect depends on the particle phase. It can be shown theoretically that a radially increasing accelerating voltage results in a phase compression and vice versa[6]. Since in the new ring there is an overall increase in the accelerating voltage of a factor 3, a considerable phase compression can be expected which means that the phase acceptance of the ring is increased and that the conditions on the DC pre-accelerator could be relaxed.

Fig. 3 shows the axial part of the 0.8 MeV beam transport system from the pre-accelerator. The horizontal beam line crosses the sector magnet 3 m above the mid-plane. The vertical beam transport system is built in sections containing magnetic elements, slit systems and beam stoppers. The sections are contained in iron tubes which reduce the stray magnetic field from the sector magnets along the axis to a tolerable value of about 10 G. The beam is bent into the mid-plane by a 10 kG magnet. A magnetic cone produced by a pair of shims in the gap of sector magnet 1 guides the beam on a quasi equilibrium orbit (see Fig. 4). The cone is characterized by a magnetic field strength of 15 kG along the beam trajectory and a field index of 0.5.

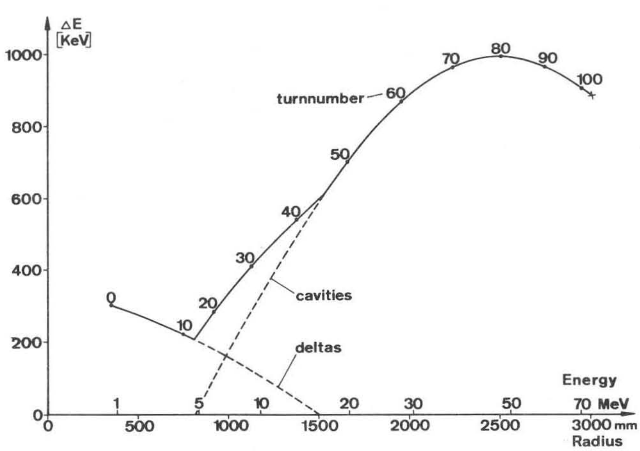

Fig. 2
The characteristic energy gain per turn versus radius in the 72 MeV ring cyclotron results from the superposition of the voltage distribution of the Delta systems and the main cavities. The radial gain per turn increases by a factor of 3 between injection and extraction radius.

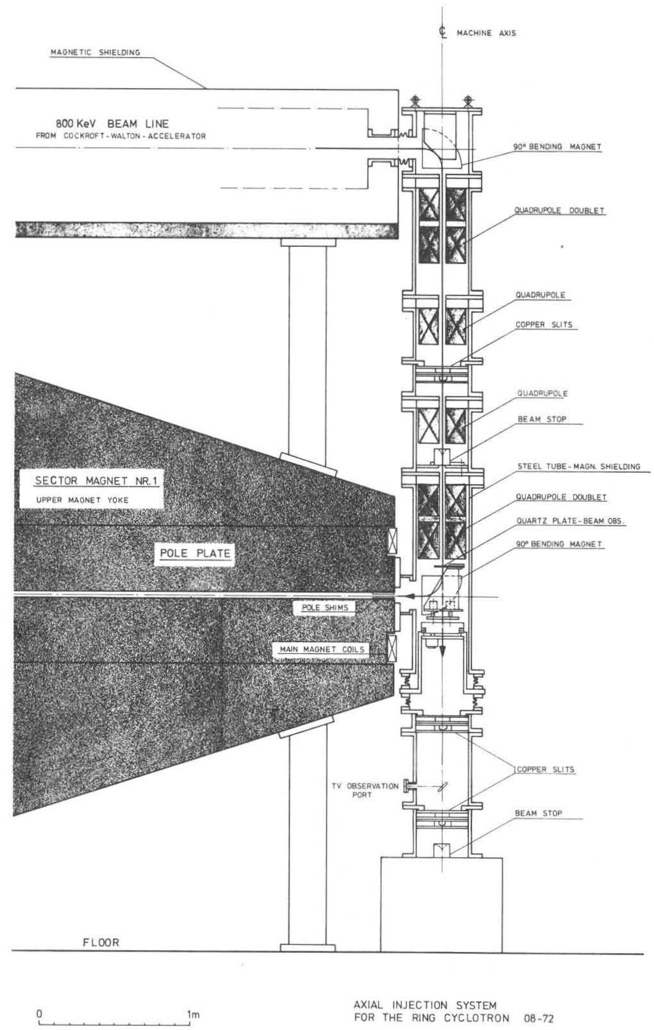

Fig. 3
The axial part of the 0.8 MeV injection beam line is built up in sections containing magnetic lenses, diagnostic systems and beam stoppers. The sections are enclosed inside iron tubes which shield the beam from the magnetic stray field of the sector magnets.

The injection parameters for the orbits shown in Fig. 4 were chosen such that the orbit center motion is minimal. Since particles with different RF phases require individual injection positions and directions, 50.7 MHz steering electrodes are planned which will compensate for the orbit center spread.

The perspective picture in Fig. 5 shows a sector magnet and two neighbouring RF sections. It also gives an idea of a possible solution to the mechanical problems. Since the sector magnets have zero spiral angle, the vacuum chambers can be built with straight flanges. (In Fig. 5 the vacuum chamber of the sector magnet is omitted for purpose of clarity.) With the arrangement planned, the sector magnets will remain fixed while the RF sections can be withdrawn radially

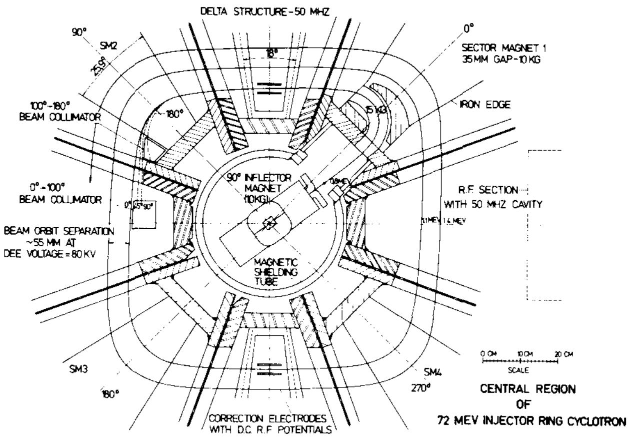

Fig. 4
Central region of the 72 MeV ring cyclotron. The beam trajectories shown are based on numerical integration through measured fields on model magnets. Selection of particles in the proper RF phase is done with a pair of high power collimators.

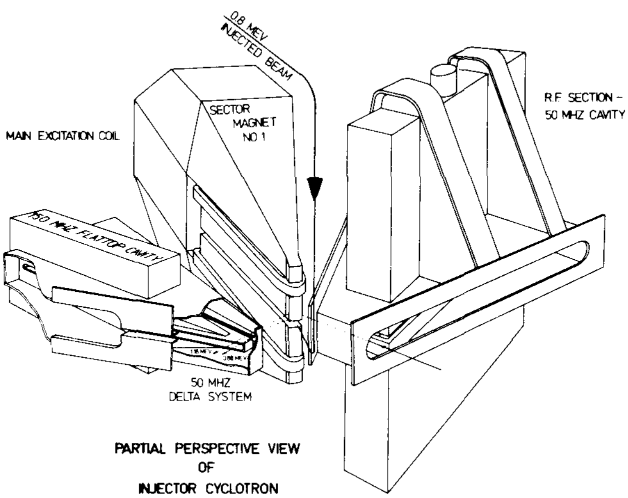

Fig. 5
Perspective view of a sector magnet and its neighbouring RF sections. The vacuum chamber of the sector magnet is omitted for reasons of clarity. The cutaway view of the RF section on the left shows some details of the Delta resonator.

for maintenance and repair. Inflatable seals will be used between the RF and the magnet sections.

Each sector magnet will be energized by a pair of pole coils providing 35 000 At. The main excitation coils of the four magnets will be connected in series. Individual correction coils for each magnet allow compensation of the machining and assembly tolerances.

Instead of using conventional pole face windings which imply complicated and expensive vacuum feed-throughs, the following possibilities have been sucessfully investigated:

1. movable shims outside the vacuum chamber on one side of each pole plate[7],
2. trim coils fixed on the side face of the pole plates outside the vacuum chamber[8) 9)].

Both solutions allow field corrections in the order of $5 \cdot 10^{-3}$ of the magnetic field.

Acknowledgments

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References

1) J.P. Blaser, H.A. Willax, Proc. 9th Int. Conf. on High Energy Accelerators, Stanford 1974, p. 643.

2) A. Baan et al., IEEE Trans. Nucl. Sc. NS 20, 3, 257 (1973).

3) W. Joho, IEEE Trans. Nucl. Sc. NS 22, 3, 1397 (1975).

4) Feasibility Study for a New S.I.N. Injector. S.I.N. report, August 1972.

5) Der neue Injektor für die S.I.N. Beschleuniger-anlage, S.I.N. report, December 1973.

6) W. Joho, Particle Accelerators 6, 41 (1974).

7) B. Berkes, M. Ianovici, Proc. 5th Int. Conf. on Magnet Technology (MT-5), Rome 1975, p. 192.

8) B. Berkes, S.I.N. report TM-53-04, 1974.

9) D. Brombach, B. Berkes, S.I.N. report TM-53-06, 1974.

DISCUSSION

F.G. TINTA: Which is the proposed schedule for installing the new SIN injector?

U. SCHRYBER: The project is not yet approved by the Government, but we will ask for the approval, say, in one year from now. According to a preliminary time schedule it requires at least four years from now on to have the cyclotron ready.

F.G. TINTA: What is the relative cost of the new injector as compared with the cost of the whole machine?

U. SCHRYBER: The price for the new injector is approximately 20 million Swiss francs compared to 130 million Swiss francs for the whole SIN facilities, as it is now. It is an approximately 15% investment including building.

F.G. TINTA: How do you intend to build it? In house or with an external contractor?

U. SCHRYBER: The new injector would be built by SIN.