STATUS REPORT ON S.I.N.

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ABSTRACT

The isochronous cyclotron of S.I.N., consisting of a sector focussed Injector Cyclotron for 70 MeV protons, followed by a Ring Cyclotron with eight separated sector magnets and four high voltage RF cavities, is designed for meson production with external proton beams of 590 MeV (fixed energy) and average currents up to 100 µA at a constant pulse rate of 50×10^6 sec^{-1}. In a different mode of operation the Injector Cyclotron can be used by itself for production of various particle beams of variable energy. Both machines were put into commission early in 1974. Main results of the beginning operation of this cyclotron facility are presented and the status as reached till August 1975 is described.

1. General

The first cyclotron stage, built by the Philips Company Holland, is a sector focussed cyclotron with variable energy which can be utilized independently in nuclear research by producing a variety of beams from protons to heavy ions. In the injector mode of operation it delivers a 70 MeV proton beam of more than 100 µA at a pulse frequency of 50 MHz (third harmonic of the cyclotron revolution frequency) and high quality.1)2)

The second stage, developped and built by SIN,2)3) is a fixed energy ring cyclotron with eight separated small gap sector magnets, and four re-entrant 50 RF resonators (cavities) providing a large energy gain per revolution. Thus beam loss is minimized

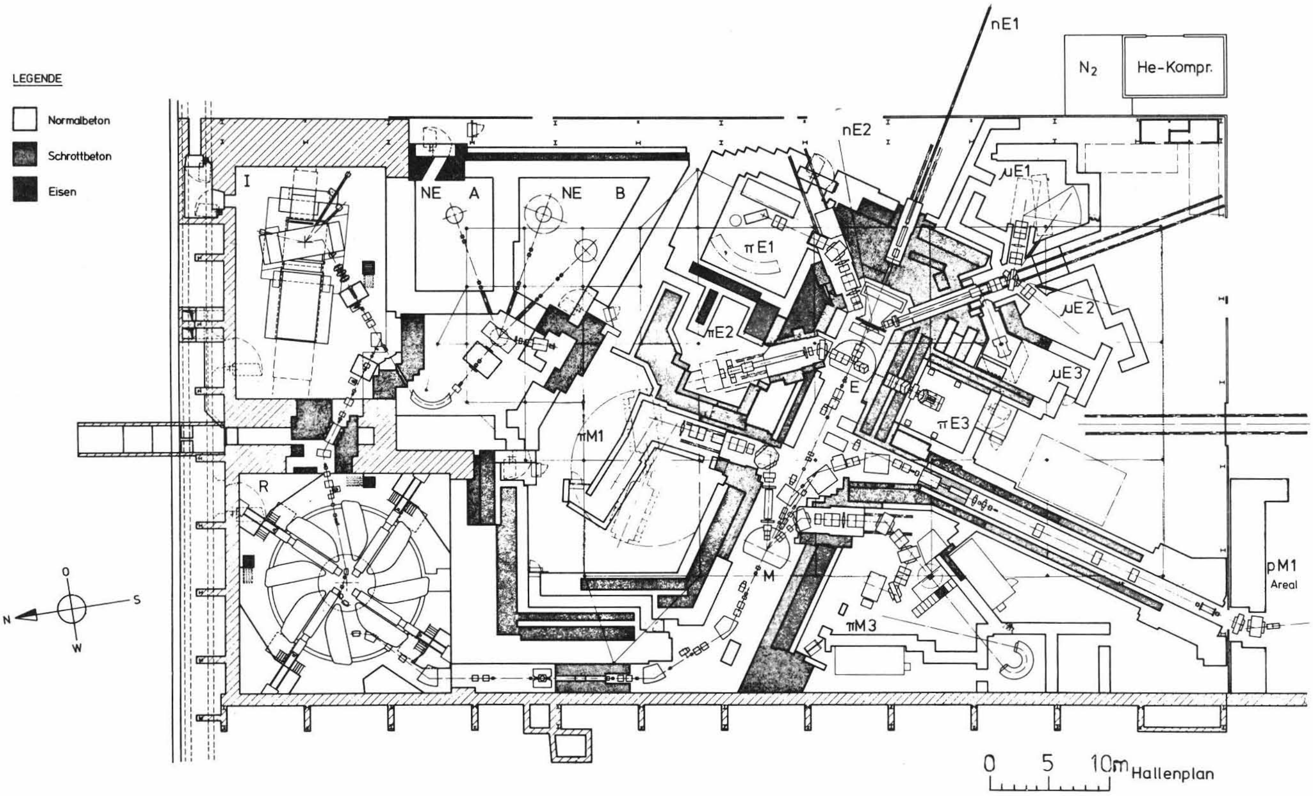

Fig. 1 The Experimental Hall of SIN, Summer 1975.

I Injector Cyclotron, R Ring Cyclotron, NE A and B experimental areas using the variable energy beam of the injector cyclotron after a 110° analyzing magnet. M, E meson production targets, πM1-3 and πE1-3 secondary beam lines for π mesons, µE1-3 µ meson beams provided by the 8 m superconducting solenoid, NE1, 2 neutron beams, pM1 low intensity proton beam line.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 33-40

and extraction improved. The mesons are produced at two external production targets.

After successful commissioning of the two stage cyclotron early 1974 the whole research facility was gradually completed. In two major 10 week shutdowns (Fall 1974 and Spring 1975) the main beam and target areas were installed. Fig. 1 shows the status of the experimental hall as reached this Summer. The 2 meson production targets M and E in the 590 MEV proton beam line are providing secondary beams simultaneously into 8 experimental areas.

4 experimental target stations are using the direct beam from the injector cyclotron. It operates a quarter of the beam time in the variable energy mode.

With a 10 μA proton beam at target rather high pion fluxes have been measured. They are typically:
1×10^7 250 MeV π^+ per sec. in 10 msr and a momentum band of 6 %, from a 8 mm thin Be-target at M.
3×10^8 100 MeV π^+ per sec. in 50 msr and a momentum band of 5 % taken off in the forward direction from a 12 cm Be-target at station E.
The π^- fluxes are smaller by a factor of 7-10.
In the Bio-Medical area πE3 the typical fluxes are 2×10^7 70 MeV π^- per sec. in 50 msr and 10 % momentum band.
Elastically scattered protons are taken off the thin target under 8° (pM1), and high energy neutrons are guided 65 m off the "thick target" through a collimator in the main shielding.
A 8 meter superconducting solenoid4) of 12 cm aperture with a field of 50 KG provides muon fluxes of 1×10^7 μ^+ or 2×10^6 μ^- per sec. on target areas of 25 cm^2, giving stop rates of 4×10^5 per sec and gram.

The pion production targets are conical rotating wheels candelabered into the beam. In each target station 4 different types of targets can be inserted automatically. Drives, controls and exchange mechanisms are fully automated. A special target assembly with a pin-wheel allows centering and focusing of the beam.5)

Heavy local steel shieldings help considerably in deminishing the radiation background at the experiments. The background is as low as about 20-50 times the cosmic rate with a 10 μA p-beam on target.

Fast multiwire proportional chambers, being further developped from a CERN design to suit the 50 Mc microstructure of the beam, are especially helpful as secondary beam profile monitors.

For typical 10 μA beams on target the routinely achievable proton beam transmission rates are

70-75 % extracted from the injector
90-95 % transmitted to the ring cyclotron
85-95 % transmission through the ring cyclotron
95-98 % transmitted from the ring cyclotron to target E.

2. Accelerator Operation

At present 32 experiments are sharing the high energy beam time in a wide spectrum of use in elementary particle physics, solid state physics, chemistry and radiobiology. Another 8 experiments make use of the direct beam of the injector cyclotron, operating in the variable energy mode. The demand on beam time for isotope production with low energy beam is increasing. For the moment, once a week we produce ^{123}I with 70 MeV p.

The operation schedule, is correspondingly tight. With a scheduled beam time of up to 108 hours per week, the machine and beam development is cut back to a minimum of about 16 h per week.

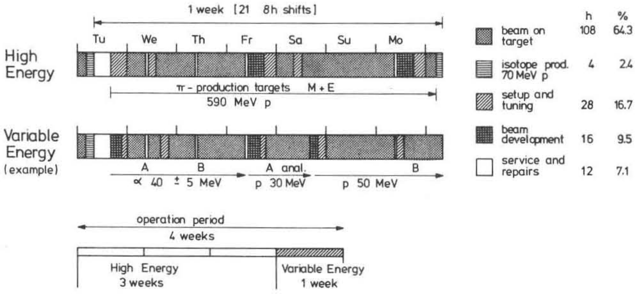

Fig. 2 SIN OPERATION SCHEDULE
(Summer 1975)

Upon 3 consecutive high energy weeks 1 low energy week follows. Results of beam time achieved during the last year and during a ten weeks operation period of this summer are graphically demostrated in Fig. 3. A summary of the operational time distribution of the last 10 weeks is given in Table I. Two facts are demostrated:

a) a rather large operational load on the injector cyclotron,

b) a significant difference in the achieved injector beam time and the achieved time of 590 MeV beam on target. The high energy beam still needs a rather large amount of setup time.

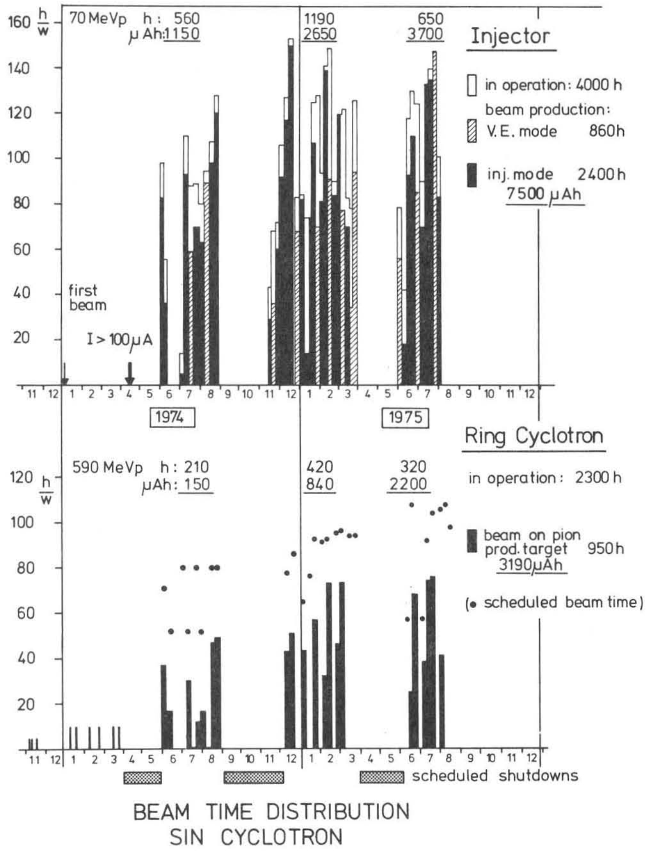

Fig. 3 Achieved beam time during first year of operation.

The operation time of the injector and the real beam time of both machines in hours per week is plotted. The amount of beam time and beam production (μAh) for each of the three operating periods and their grand total till August 1975 are noted.

Table I

Operational Time Distribution Summer 1975 (30.5. - 5.8.75)

	Injector		Ring and Beam Transport System	
	h	%	h	%
1) Beam for external use				
a) variable energy	285	20.1	-	-
b) high energy (injector mode)	650	45.8	(on targets) 320	37.6
Total beam production	935	65.9	320	37.6
2) Beam development	75	5.3	~ 80	9.4
3) Setup and tuning	100	7.0	~ 200	23.5
Total time of operation with beam 1) + 2) + 3)	1100	78.2	~ 600	70.5
4) Scheduled maintenance	155	10.9	70	8.2
5) Unscheduled down-time	98	6.9	130	15.3
6) Standby + miscellaneous	57	4.0	50	6.0
Total time of operation	1420	100.0	850	100.0

3. Performance of the two-stage cyclotron

For efficient production of pions in our case the achieved beam intensity and the beam transmission through the system are main figures of merit.

In Fig. 4 the development of the technical performance during the first year of operation is demostrated.

The beam transmission through the ring cyclotron was brought up from typically 30 - 40 % in the beginning to 85 - 95 % at present in two mayor steps:

a) after learning about proper injection of the beam onto fairly well centered orbits, without loosing it at injection elements,

b) after adjustment of the cyclotron frequency of both machines by 6×10^{-4} to fit the main magnetic field profile of the ring cyclotron to better isochronism^{6}) and after compensation of small horizontal magnetic field components near injection and extraction radii of the ring, using a weak asymmetric excitation of trimcoils.

The beam transmission, as measured through the toal beam transport system (including the ring) from the exit of the injector cyclotron to the production targets, has increased accordingly.

Since the 70 MeV transfer line^{7}) is designed as a emittance and energy "filter"^{8}) a beam loss at the slit system of up to 10 % of the low energy beam available from the injector was normally taken into account. A pronounced improvement of the transmission through this system could be noted, after decreasing the vertical aperture of our beam defining slit near the injector cyclotron center from 2 cm to 1 cm. This also lead to an improvement of the extraction rate routinely achievable in the injector cylotron (at present 70 - 75 %). The intensity of the 590 MeV p-beam available at the production targets has been brought up to 10 - 15 μA at present. In short experimental tests maxima of about twice the routine intensities were produced. Basic technical limitations have not appeared during those tests. The practical limitations at present are given by the accumulated beam loss at the septum of the injector cyclotron, leading to high levels of induced activity. The operational limitation we have choosen for the present beam period is an accumulated loss of 60 μAh at the 70 MeV-extraction within a 8 hour beam shift.

With our still limited experience in these matters, we want to be cautious for the following 2 reasons:

a) In case of failure, a fast repair of a component of the extractor system should still be possible. As long as the second complete extractor system which we have is not yet readily available for exchange, too much experimental beam time is on risk otherwise.

b) For the next shutdown it is foreseen to install modified elements in the injector machine, aiming for better reproducibility of beam properties. The assembly work of those components should not be hampered by a high common activation level of the machine. An analysis of this general problem of our injector, based on operational experience, is being carried out.

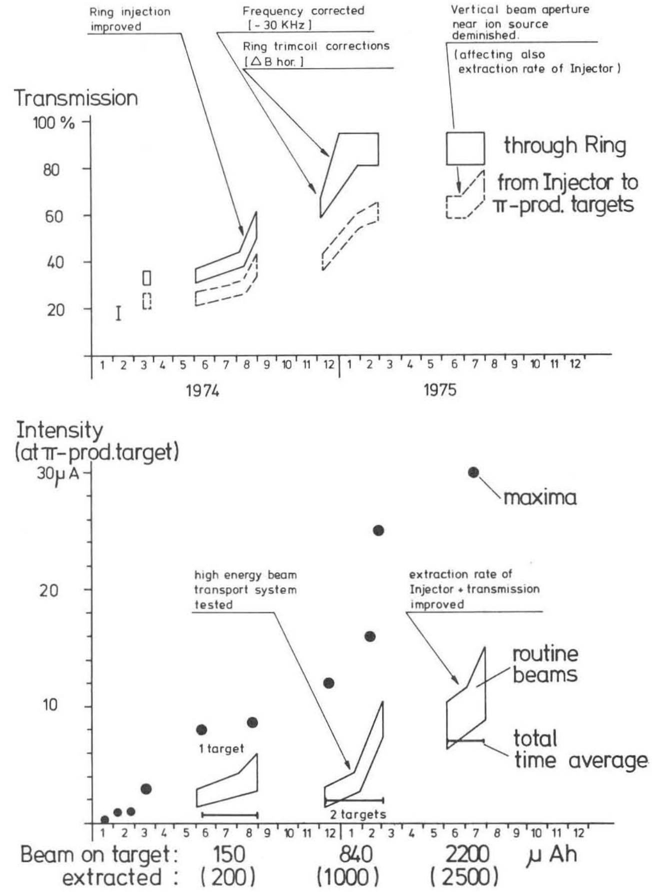

Fig. 4 Improvement of beam transmission and intensity in graphical demonstration.

The values achieved in routine production runs over several hours of beam time are lying within the marked fields. The intensity maxima shown were reached in short beam experiments. The integrated amount of beam (μAh) on target and extracted from the ring for each period of operation is noted.

4. Status of the Cyclotron

4.1 The Injector Cyclotron

The most unique feature of this single Dee machine is the combination of 2 basically different rf-systems.

For the variable energy mode of operation ($1/4$ of the time) a self exited system is used with two power triodes acting parallel on a $\lambda/2$ resonant line which consists of two parallel Dee stems in separate liner tanks. The shorting plates, movable in air, provide resonance frequencies between 4.7 and 17.1 MHz.

Initial problems of parasitic frequencies in the oscillators were successively removed. Beams of intermediate energies were produced even with only one oscillator operating. The feedback systems for frequency and amplitude control provide adequate stability for standard operation (beam directly used on target). The frequency stability needs to be further improved for injection of 1 ω p-beam of 70 MeV at 16.9 MHz into the ring cyclotron. This is an interesting alternative for time of flight experiments with the high energy beam.

As an injector the machine produces the 70 MeV p-beam in the third harmonic mode. The 50.6 MHz resonance structure is provided by inserting a pair of shorting bars across the Dee near the pole edge under vacuum. The change from one to the other mode of operation can thus be made in less than 1 hour.
A separate 50 MHz power amplifier, of the same type as being used supplying a ring cyclotron cavity^{9}), excites the Dee via capacitive coupling near the front Dee edge. The frequency is determined by a stable master oscillator common to injector and ring cyclotron. The relative phase of both machines is adjustable. The resonance frequency of the Dee structure is tuned by a servo-system including drive mechanisms for trimming capacitors. This system, in connection with the feedback loops for amplitude and phase control has lead to operational difficulties in the beginning. The fact, that in this operation mode a complex pulse electronic for the start up is neccessary to overcome multipaction, (a Dee bias being ruled out) added to the complexity. In several steps the 50 MHz rf-system was brought under operational control during the last year. The amplitude stability at typically 70 kV Dee voltage is now approximately $5 - 7 \times 10^{-4}$.

The injector cyclotron is equipped with 3 ion sources (Fig. 5). At present, most of the operational beams are produced by the internal source which can be inserted radially. An Ortec Duoplasmatron, feeding into the axial injection system^{10}) can deliver a few mA (d.c.) of protons and deuterons. The rf buncher, so far working for injection in the 1 ω mode, provides a bunching factor between 2 and 3, depending on the particle energy. A source for polarized protons and deuterons, built by the University of Basle, is installed in a separate vault underneath the injector main vault. Presently it delivers polarized p and d beams up to 0.5 µA (d.c.) within the X-Y acceptance of ~500 mm mrad of the cyclotron injection system. No attempt has been made on optimization of the polarized beam production.

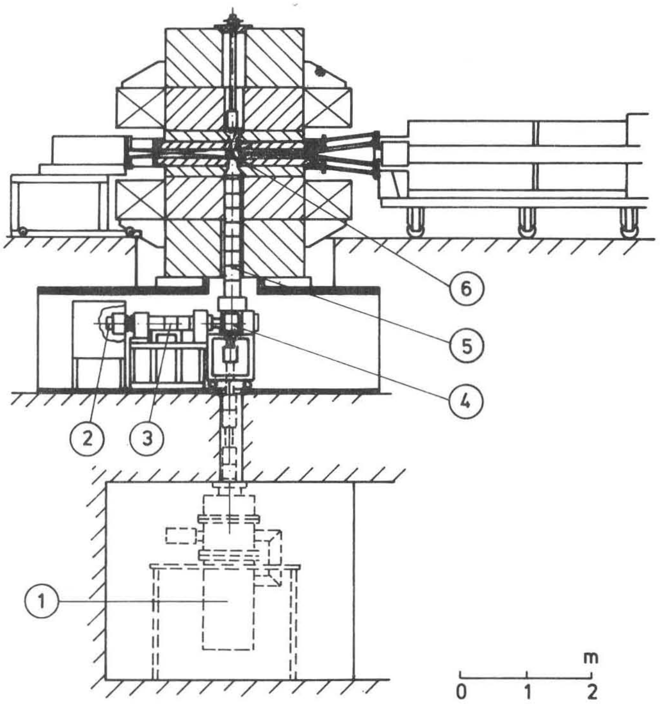

Fig. 5 Vertical section of the injector indicating positions of ion sources.

(1) Source for polarized p and d. (2) Ortec duoplasmatron source. (3) Quadrupol lenses. (4) 90° switching magnet. (5) rf buncher. (6) electrostatic inflector (mirror with grid) or, alternatively, position of the internal source as inserted radially.

The beam extraction system is optimized for 70 MeV p. It consists of a 60 cm electrostatic deflector with slotted water cooled copper septum operating at 60 KV accross a 5 mm gap. The high voltage electrode is freon cooled. An ironfree deflector-coil, providing a small field gradient in addition to the proper field depression follows. A passive magnetic field channel, giving a larger field gradient is finally passed by the beam.

The deflector elements are mounted on the main flange. For easier maintenance and repair at high induced activities two complete interchangeable systems are available.

Beam of the Injector Cyclotron

Several typical beams of light ions at various energies have been produced mainly using the internal ion source. This Spring an attempt was made to accelerate $^{16}O^{4+}$ ions to 100 MeV, also using the internal source with modifications on the filament. A beam of ~1.5 µA could be extracted for a short time. However filament lifetime as well as vacuum conditions appear to prohibit routine production of heavy ion beams at present.

From June 1974 till August 1975 the machine has produced a total of 7500 µAh of 70 MeV protons, operating in the injector mode (50 MHz) for 2400 effective beam hours. In routine runs for injection into the ring 15-20 µA are extracted with an efficiency of 70-75 %. In order to keep the induced activity, especially of extractor elements in limits, only for short beam tests the intensities of extracted beams were increased by a factor of 2-3.
Typical figures of the beam properties are:

Energy : 71 ± 0.6 MeV
Emittance Ax, Az: π × 5 mm mrad (80 % of beam)
Energy spread : 200 KeV (FWHM)
Phase width : 20° rf (50.63 MHz)
Time structure : triangular pulse shape, peaked at center

At present it appears difficult however to reproduce beam optical parameters, such as energy, dispersion, emittance and position of virtual sources of the external beam with proper accuracy. These parameters also seem to depend on beam intensity and - or - conditions of the discharge of the ion source. In our application of the machine, where the beam needs to be matched to a second stage cyclotron, a high degree of reproducibility of those beam parameters is highly desirable from the operational point of view. Efforts on improvement have been started.

4.2 The Ring Cyclotron (Fig. 6)

The machine has been described previously.[3][11] With the aid of a diversified beam diagnostic system[12], which was successively improved, we were able to check the main machine parameters. Isochronism and betatron frequencies, as well as the beam behaviour at injection, extraction or near resonances correspond to theoretical predictions.[13]

The technical performance of main machine components has reached a high niveau of reliability. From radial beam profiles, to be observed in reproduceable details, we deduce a stability of the main magnetic field of better than 1×10^{-5}. RF-phase and amplitude stabilization at 500 KV accelerating voltage in each cavity are better than the design specifications (10^{-3} and ± 2°).

The operational performance of the rf cavities at these high voltages has gradually improved due to aging in high vacuum. The mean time between "drop outs" of a cavity (discharges) has increased from originally 1/2-1 hour to 6-8 hours. The interruptions in beam production due to a cavity drop out are usually not longer than ten minutes, which time is needed for recouvery from multipactoring.

The present version of the extraction septum[14], consisting of molybdenum strips of 0.05 mm thicknes which are mounted vertically one after another over the total length of 1 m, has not shown any beam deteriorating effects at intensities up to 30 µA. The beam extraction rate is routinely above 90 %, in many cases above 95 %. Except for a failure of the high current density coil of the extraction magnet due to accidental thermomechanical "cycling" last Spring, we did not have any problem with the beam extraction system yet. A complete set of spare units is being prepared however, for replacements, not to be forced to repair highly activated components in case of failure.

During the two shutdowns of Fall 1974 and Spring 1975 the design principle of the machine proved its validity. The mechanical separation of main components, being joined by quickly removable vacuum seals, allowes access to all essential machine parts without exposing personnel to high radiation doses. In these periods also the alignement of the main magnets as mounted on reinforced concrete ring floating in the subsoil (gravel) was checked. The relative position of the magnets with respect to each other had only changed by a few tenths of mm since October 1973.

The change of the ring position with respect to the vault became several mm, probably due to the increased shielding load in the enviroment. Bending magnets near the pivot points of the beam transport systems help compensating relative changes of positions of the main system units.

Beam of the Ring Cyclotron

Providing beam transmission rates up to 75 %, the ring is not fastidious on the beam it receives at the injection, as long as the geometrical acceptance (typically ~60 mm mrad in X and Z) is met. The main beam loss in these cases occures between 500 and 590 MeV, where the free vertical aperture is limited to 20 mm by two sets of graphite collimators placed 90° apart in azimuth. For better performance however, precise matching of the geometrical phase areas and the dispersion become important.[8] Well matched beams can be accelerated to full radius without any significant loss. In such cases, even separated orbits have been observed at extraction radius.[13] Measured beam intensities, as achievable at present with some reliability are:

Injector internal	: 22	µA
extracted	: 16	µA (71.3 MeV)
Ring injection	: 14	µA (71.3 MeV)
at 3rd revolution	: 13.5	µA
extracted	: 12.5	µA (587 ± 1 MeV)
at Target	: 12	µA
Emittances (for 90 % of the beam)		
A_X	: 4	π mm mrad
A_Z	: 3	π mm mrad
Energy resolution	: ~2	MeV (FWHM)

Beams of those properties can be produced steadily during several hours. The highest intensity at target measured in a short beam experiment last July was 30 µA with a ring transmission of 90 %.

In experimental beam shifts were produced recently:

- A beam with a 17 MHz pulse structure as achieved from the injector operating in 1 ω mode. 1-3 µA were brought to the production target with a ring transmission of 70 %.

- A beam of polarized protons created by scattering of the 587 MeV main beam at a thin carbon target and taken off under 8° into pM1 (see Fig. 1). (With a 3 µA incident primary beam a well defined beam of 2×10^8 p/sec. and a polarization of 41 % was measured in this case.[15])

- A beam of polarized protons, as created in the source for polarized particles of the injector, was accelarated to 587 MeV and brought, to target M. The beam intensity was 1.5 nA and the polarization 53 %, (the source and the injection into the first cyclotron stage not being optimized). The beam setup in this case, using the axial injection system while the injector was operating in the 50 MHz mode, was achieved with a pilot beam from the duoplasmatron source (Fig. 5).

Acknowledgments

A number of enthusiastic and dedicated Engineers and Physicists of S.I.N. have contributed in operating the machine around the clock. Especially acknowledged needs to be the effort of several members of our technical staff who - in many cases - did not avoid any hardship to keep the systems functionable.

References

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

2) J.P. Blaser, H.A. Willax
IX International Conference on High Energy Accelerators, Stanford 1974, p. 643

3) H.A. Willax
IEEE Trans. Nucl. Sci. NS 20, 3, 202

4) G. Vecsey
"Supercritically cooled superconducting muon channel", IPEC 5, Kyoto 1974

5) M. Daum
Profile Monitors for the SIN external Proton Beams*)

6) S. Adam
The Isochronism in the SIN Ring Cyclotron*)

7) J. Zichy et al.
The Design, Assembly and Performance of the SIN Beam Transfer Line*)

8) W. Joho
Beam Transfer between Accelerators*)

9) P. Lanz
Cyclotrons 1972, AIP Conf. Proc. No. 9, p. 467

10) N. Hazewindus et al.
"The axial injection system of the S.I.N. Injector Cyclotron, Philips Research Report M.S. 8996

11) H.A. Willax
CERN 63-19, 386 (1963)

12) M. Olivo
Beam Diagnostic Equipment for Cyclotrons*)

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

14) M. Olivo
The Electrostatic Extractor Channel for the SIN Ring Cyclotron*)

15) R. Hess, D. Werren
private communication

*) Proceedings of this Conference

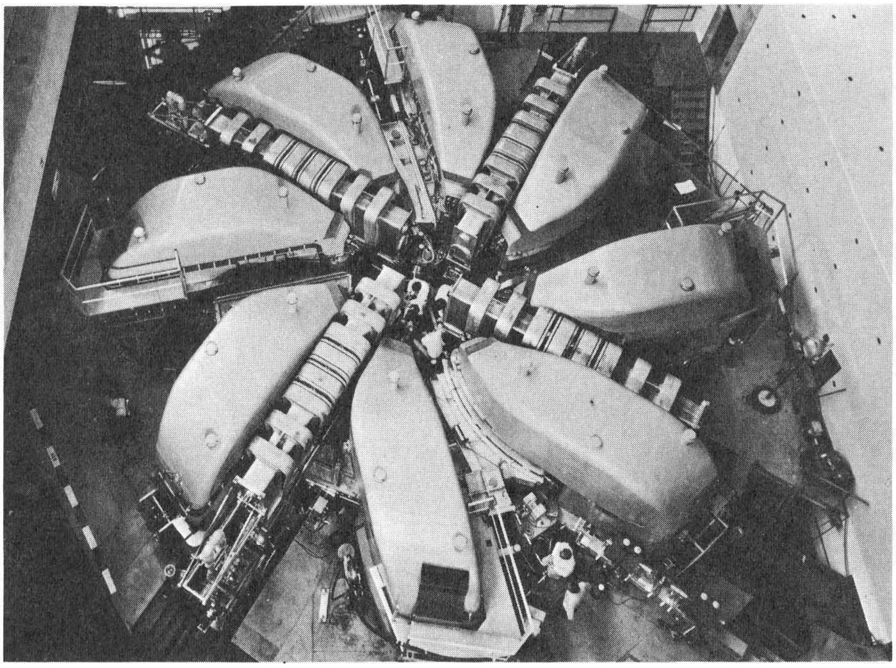

Fig. 6

The Ring Cyclotron before closing the vault in October 1973.

DISCUSSION

E.G. MICHAELIS: What was the proton-beam intensity to which the pion fluxes referred which you quoted?

H.A. WILLAX: 10 µA.

H.G. BLOSSER: I am interested in how easily the 100 µA run in the first machine, how much you have run it and so on.

H.A. WILLAX: By the SIN staff the 90 µA has been repeated in a special beam development shift. We have not really made a serious attempt to look at the 100 µA again since our operational load is so high.

H.G. BLOSSER: So you have not done it very often yet?

H.A. WILLAX: No, we have done it once.

Y. BECHTOLD: How do you measure the polarization of the polarized protons?

H.A. WILLAX: The polarization is measured by looking at the counting rate of the scattered polarized protons in this 8° channel, with polarization of the source, cyclotron source on and off. How the polarimeter for the scattered polarized protons worked? I am not competent to say: M. Daum will give an explanation.

M. DAUM: The beam from the polarized source was measured in the high-energy area in the following way. We scattered the polarized beam on a carbon target and measured the intensity of the scattered protons under 8°. We selected the momentum and set slits on the elastic peak and measured then the intensity difference between spin-up, spin-zero, and spin-down.