PRESENT STATUS OF THE 590 MeV RING CYCLOTRON OF SIN

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Summary

A 590 MeV ring cyclotron, using a 72 MeV cyclotron injector (Philips design), for a cw proton beam of 100 μA at 50 MHz is under construction at the Swiss Institute for Nuclear Research (SIN), near Villigen, Switzerland.

While the mechanical assembly approaches completion, tests of sub-sections of the machine are being carried out. A 1/4 ring section, containing internal elements, was investigated under operating conditions. Results are presented and discussed.

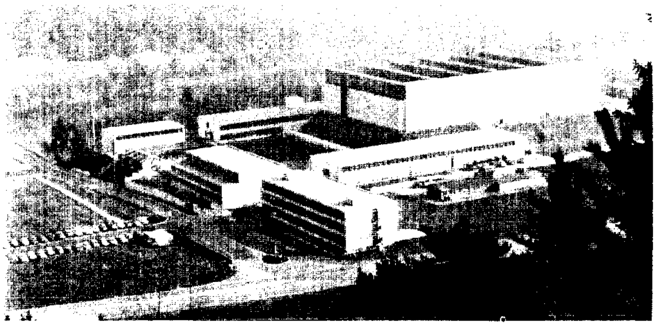


Fig. 1 SIN site, November 1972

Introduction

The institute is financed and operated by the Swiss Confederation. It is an annex institution of the Swiss Federal Institute of Technology (ETH). The 27 acre site of the SIN laboratory near Villigen is in close neighbourhood to the Swiss Federal Institute for Reactor Research (EIR) of Würenlingen, about 40 km west of the Zurich airport. The main goal[1] is to provide intense meson beams to experimental groups from Swiss universities and from other research laboratories. Protons, as primary particles, are accelerated in two stages to an energy of about 590 MeV. The first stage is a conventional AVF-cyclotron designed for the acceleration of protons at fixed energy and high beam intensities, as well as d, α particles and heavy ions at variable energy. This feature also enables the research on nuclear structure-physics, which is a field of activity of several Swiss universities.

The secondary beams will be produced by the 590 MeV protons (fixed energy), essentially on external targets[2]. A layout of the experimental areas as planned for the early operational phase is shown in Fig. 2.

In Table I the main parameters for pion beams, computed under the assumption of 100 μA protons of 590 MeV are summarized.

A 50 kG superconducting solenoid of 12 cm inner diameter and 8 m length is under development to be used as muon channel[3]. The muon beams expected are typically 10^8 μ/s (50 MeV) at an experimental target area of 20 cm^2.

The contract for building the 72 MeV Injector Cyclotron was given to Philips Holland in fall 1968. (Description and status report[4].)

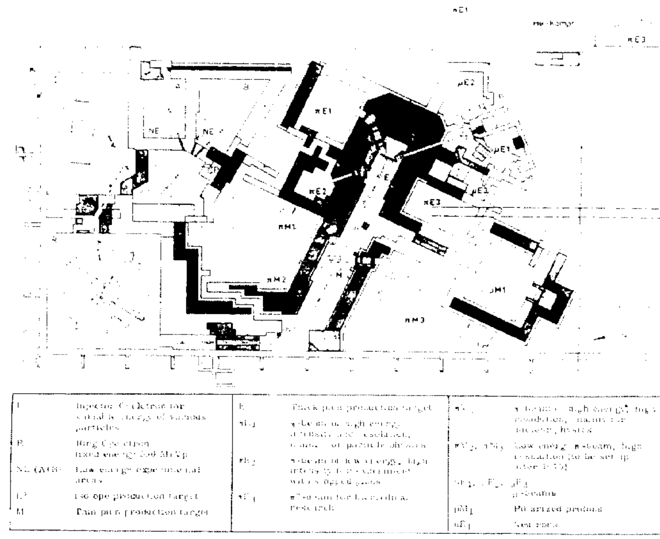


Fig. 2 Layout of the SIN experimental hall

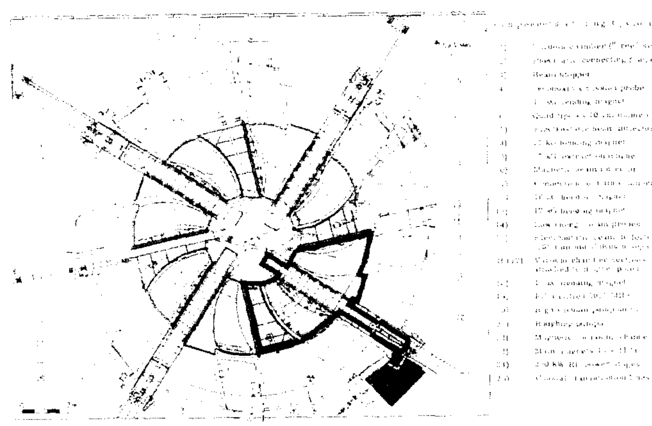
Table I
Expected π-beams at SIN

Target	Beam	θprod	Range of Energy (MeV)	Δp/p	Intensity (sec^{-1})	Conditions
C 12 cm	πE_1	0°	50 - 330	± .2 %	π^+ 1 x 10^{10} π^- 7 x 10^8	at 250 MeV Δp/p = ± 2.5 % Ω= 40 msr; l = 17 m
Mo 3 cm	πE_2	90°	50 - 100	± 1.5 %	π^+ 1 x 10^9 π^- 3 x 10^8	at 60 MeV Δp/p = ± 4 % Ω= 60 msr; l = 9.3 m
	πE_3	90°	50 - 100	± 1.1 %	π^- 5 x 10^8	at 60 MeV Δp/p = ± 6 % Ω= 50 msr; l = 10.5 m
C .5 cm	πM_1	22.5°	50 - 400	± .03 %	π^+ 5 x 10^7 π^- 6 x 10^6	at 300 MeV Δp/p = ± 2 % Ω= 13 msr; l = 20 m
	πM_2	67.5°	50 - 150	± .4 %	π^+ 2 x 10^8 π^- 2 x 10^7	at 100 MeV Δp/p = ± 5 % Ω= 50 msr; l = 11 m
	πM_3	22.5°	50 - 400	± .1 %	π^+ 1 x 10^8 π^- 6 x 10^6	at 250 MeV Δp/p = ± 3 % Ω= 11 msr; l = 15 m

The Ring Cyclotron

The ring cyclotron[5] has eight separated 250 t C-magnets, providing an isochronous field over a radial range from 200 to 460 cm. The magnet sectors are slightly spiralled (33°) since pure flutter-focussing would not be sufficient for the energies under consideration. The pole gap varies from 9 to 5 cm with increasing radius, providing a hill field from 15 to 20.8 kG with a main excitation of 148,000 At for each magnet. The isochronous field (γ x 5.55 kG, corresponding to a cyclotron frequency of 8.45 Mc/s) is not variable. Eighteen sets of 400 At pole face windings in each second magnet, as indicated in Fig.3 are designed for small field corrections. In the other magnets, only injection and extraction radii are controlled by gradient correction coils[6].

Four large matchbox-shaped RF cavities, resonating on a TE_{101}-mode, produce high accelerating voltages at 50.7 MHz, which is the 6th harmonic of the particle revolution frequency. They are excited by individual 250 kV RF power amplifiers, jointly driven by a highly stabilized master oscillator. Voltage and phase control are provided in the circuits[7].



The shaded area indicates the first operational 1/4 ring section. It was under system test from September 30 to December 15, 1972. Seven sector magnets were installed and operational at this time, as well as one complete set of correction coils. For the system test, several probes were installed:

△ vacuum gauges	beam phase probes	Gauss-meter
▲ thermo-couples	RF probes	γ-dosimeter

Fig. 3 Plan view of the SIN ring cyclotron

The stainless steel vacuum chamber sections are directly joined to the magnet poles by flexible welded joints. The remaining sections of the vacuum chamber, built of aluminum ("free sections")contain probes, collimators, injection and extraction devices. The individual sections can be joined either with metal gaskets or inflatable bellows, carrying radiation resistant elastomers as gaskets. In view of the activation of machine components, a main design goal was a relatively simple assembly, and quick mounting - demounting procedure for all main parts.

A combination of turbo-molecular pumps and titanium sublimators joined to the RF cavities, provide 14, 000 l/s each at 10^{-6} Torr operating pressure.

The beam is injected at 72 MeV in the mid-plane through a combination of bending magnets, followed by a magnetic injection channel and brought onto the equilibrium orbit by means of an electrostatic inflector channel. There is a complete separation of the orbits at injection radius, assuming cavity voltages > 400 kV. With about 1.5 MeV energy gain per revolution the radial gain is 6 mm near extraction radius, increasing to ∿8 mm at the extraction point due to the turnover of the magnetic field gradient. Incoherent radial beam amplitudes will be of the order of 3 to 4 mm in this region. The extraction system consists of a 1.2 m electrostatic channel of 50 kV/cm with a very thin septum (Mo), placed in a "free section". It is followed by a magnetic focussing element 45° downstream and an extraction septum magnet 90° downstream. For such a system extraction rates of above 90 % have been computed[8].

Several probes will be used for tune-up. Three multifinger probes, entering the ring chamber from the inner radius, are designed to stop the circulating beam up to a radius corresponding to ∿150 MeV. With secondary emission probes and a heavy internal radius, the beam can be traced out to the extraction radius. Eleven pairs of non-interfering phase probes at different radii will provide information on isochronism during operation.

Table II
Main parameters of the SIN ring cyclotron

Beam	
Protons	590 MeV
Intensity	∿ 100 μA
Emittances x, z	< 10 mm mrad
Energy spread	< 0.3 % FWHM
Duty cycle (macro)	100 %
Duty cycle (micro)	5 - 8 %
Pulse sequence	50.7×10^6 sec^{-1}
or, with injector on 1st harm. mode	16.9×10^6 sec^{-1}
Cyclotron	
Injection energy	72 MeV
Radial range of acceleration	2.1 - 4.5 m
Isochronous field (fixed)	γ x 5.55 kG
Hill field	15 - 20.8 kG
No. of magnets	8
Flutter factor	F ∿ 1.05
Spiral angle	∿ 35° max.
ν_z	0.9 - 0.75
ν_r (acceleration)	1.1 - 1.7
ν_r (extraction)	∿ 1.1
Acceleration (4 cavities)	∿ 4 x 0.5 MeV/rev
RF-frequency (fixed)	50.7 MHz (6th harm.)
Beam injection and extraction	using large radial gain/rev without forced precession

Mechanical Data	
Vacuum chamber	12 individual sections
Vacuum pumps	Turbomolecular plus Ti-sublimators
Operating pressure	$1 - 5 \times 10^{-6}$ torr
Weight of magnets	8 x 245 tons
Excitation of magnets	8 x 148, 000 At
Pole gap	8.5 - 4.5 cm
Power consumption of magnets	8 x 75 kW
Power consumption of correction coils	40 kW (max)
Dimensions of RF cavities	5.3 x 3.3 x 0.4 m
Material of RF cavities	Aluminum
Peak resonance voltage achieved	∿ 650 kV
RF power loss (at 500 kV/cavity)	4 x 130 kW
Power consumption of RF system	∿ 4 x 300 kW
Total power consumption of machine	∿ 2.5 MW
Cooling system	demineralized water. Individual circuits for copper, aluminum and radiation exposed systems.
Primary cooling installed	river water ∿ 6.5 MW

The accelerator control system[9] is designed to use a computer as an operating aid (IBM-1800 23 K 3 Disc). The signal transfer to and from the control center is digitized and a multiplexing system handles the flow of information (ROAD, Rapid Operation + Acquisition Dataway). The hardware is modular. Hardware and software can be adjusted to the increasing demand of automation. For the initial operation, manual control of the important parameters is provided by "setpoint units", allowing "knob twiddling". In the early phase the computer will mainly be used for routine settings and rapid data acquisition.

This ring cyclotron, being an unconventional version of a sector focussed cyclotron in the technical sense, has gone through several phases of study and development before the design was frozen and fabrication of the components started. In the beginning, the development progressed slowly since direct experience in accelerator engineering scarcely existed at ETH. Early model work, linked with theoretical studies, was carried out from 1963 - 1966. The main concerns were beam dynamics, the development of sector magnets, RF cavities and vacuum system as well as some principal design studies. In 1967 it was decided to change the design goal of the injector from fixed energy to an additional, multi particle variable energy capability. More serious project studies[10] and the construction and testing of full scale prototypes of the main components followed in the years from 1967 - 1970. Encouraged by the good results achieved with the prototypes of a sector magnet, an RF cavity and a vacuum chamber system, in spring 1969 the final design energy of the ring was changed from 520 to 590 MeV without basic alteration of the mechanical design. The design limitations of the magnets had to be approached (excitation raised by 15 %, flux density in the yoke exceeding 16 kG) and a refined system of correction coils had to be developed (number of radial sections increased from 11 to 18). After re-machining of the prototype poles, an adequate field profile for 590 MeV was achieved in the prototype magnet. At that time (1970), the prototype of a 250 kW RF power stage had performed well and RF voltages in the prototype cavity exceeding 500 kV were achieved, the original design goal being 350 - 400 kV. The fabrication of the main components could be started.

First System Tests

During prototype development the conditions under which a combined system had to function could not be simulated. Figs. 4 and 5 indicate the geometrical arrangement of the main components in relation to the main field.

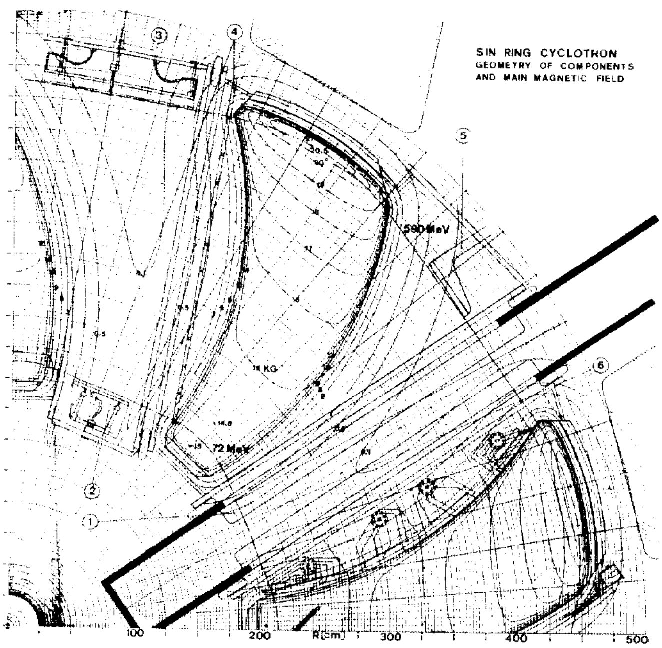


Figure 4

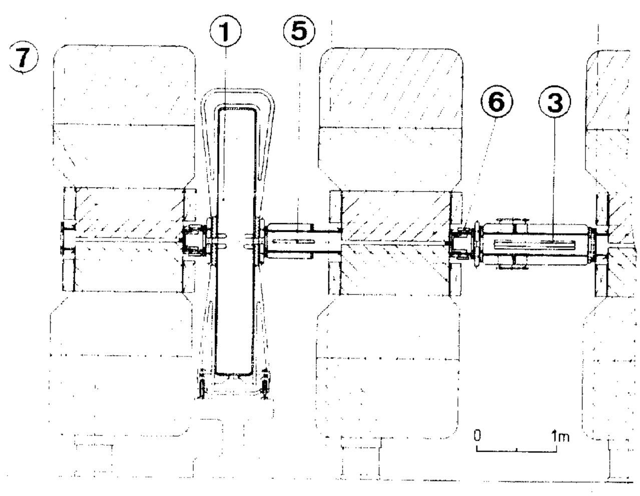


Fig. 5 Cylindrical section through ring cyclotron at an outer radius

Components in Figs. 4 and 5:

1) RF-cavity
2) Electrostatic inflector
3) Electrostatic extractor
4) Phase probes
5) Magnetic focussing channel
6) Feeds of the TC
7) Magnet poles

Tests under such conditions were planned as early as the fabrication and mounting schedule would permit in order to ensure the basic technical performance of the machine and to initiate possible design changes. The tests were concentrated on the following:

1) The effects of stray fields of neighbouring magnets upon each other.
2) The achievement of accelerating voltages exceeding 350 kV in the given magnetic field geometry (a basic condition for inflection and extraction of high intensity beams).
3) The achievement of proper voltages on inflection and extraction channels within the existing magnetic field and under RF influence.
4) Learning about the problems of RF "noise" in the system.

Besides getting acquainted with the problems of the accelerator components working together, the system test was valued as an early opportunity to start debugging the primary installations and to start functional testing of the control system.

One year after the assembly of the accelerator had started (July 1971) we were able to measure the influence of neighbouring magnets upon each other. The total effect of seven excited magnets on the individual sector field was found to be a homogeneous depression of ~ 1 %, almost exactly following the contour of the hill field. With an increase of the main excitation by ~ 3 % (which is within the capacity of the main power supply), this effect could be almost completely compensated. The remaining fractions of the field changes were well within the 10^{-3} region and within the correction capacity of the edge shims[6].

In September 1972 a complete set of correction coils (TC) was mounted in one magnet of the 1/4 ring test section. Trouble with faulty fabrication of the ceramic insulated high vacuum feed-throughs for the TC-leads caused some delay. Since RF leakage from the cavity into the vacuum chamber on the order of a few kW could be expected, all TC-leads within the chamber had to be protected by RF shielding-covers. On Sept. 30, 1972, the 1/4 ring test section, consisting of three neighbouring magnets, one RF cavity, two vacuum chamber sections joined to the magnet poles and one "free section" of the vacuum chamber were mounted (Fig. 3). As expected, a large amount of water vapour, mainly from the large anodized aluminum surfaces of the TC-assemblies had to be pumped initially. Baking those elements at temperatures between 100° and 150° C for several hours (by exciting the coils without cooling) helped. Within three days an operational pressure of 1×10^{-6} Torr was achieved.

The bake-in of the cavity, which had been previously tested as a prototype, took more effort than for the initial prototype assembly. Even though the cleaning of the surfaces by multipactor discharges could be enhanced in exciting the magnets to about 10 % of full excitation, ~ 10 hours (compared to 5 - 7 hours in the prototype) were necessary to achieve the "brake-through" for resonance conditions. Also, the surface outgassing at higher voltages took more effort than in the prototype test.

The reason for the unexpected misbehaviour of this cavity was attributed to the presence of flying dust, carried in from the work area of the experimental hall during the assembly time. This assumption was verified recently, when the second 1/4 ring was mounted, taking special care of the dust problem. In this case, the bake-in process was similar to the prototype.

Exciting the cavity of the first 1/4 ring to 520 kV for a total of ∿ 20 hours, it was possible to achieve resonance voltages of more than 620 kV at the proper frequency. The voltage holding seemed to be better with the magnets excited. In the beginning of the test period, however, the RF resonance would brake down once the magnet excitation was altered by 10 %. Later on, even drastic changes in the magnetic field did not affect the RF voltage.

The tests of the electric inflector and extractor channels, temporarely mounted in the "free section" were successful. After a few hours of bake-in,on both electrodes 105 kV (E = 87 kV/cm) could be held, the spark rates being about .6/hour without magnetic fields and .2/hour with the magnets excited. The RF did not show any significant influence on the voltage holding capability.

The capacitive phase probes were picking up too much RF-"noise" originally. By adding the signals of upper and lower plates, this "noise" was reduced by a factor of 20. The RF shielding is being improved.

Even though the TC-leads were well shielded against the direct influence of the RF field leaking through the accelerating gap, at 500 kV in the cavity about 1 - 5 V pp were measured at the vacuum feed-throughs. Careful blocking of this RF noise is necessary.

By measuring the temperatures of the TC-assemblies and the RF shielding plates under different magnetic field conditions, we came to the conclusion that a certain amount of the RF power leakage through the acceleration gap of the cavity could be carried by accelerated electrons which are created by field emission and residual gas ionization. This effect, however, has to be investigated more carefully.

Several runs during this period were devoted to investigations of voltage and phase stabilization of the cavity. No principle deviation from the behaviour of the prototype[7] could be noticed.

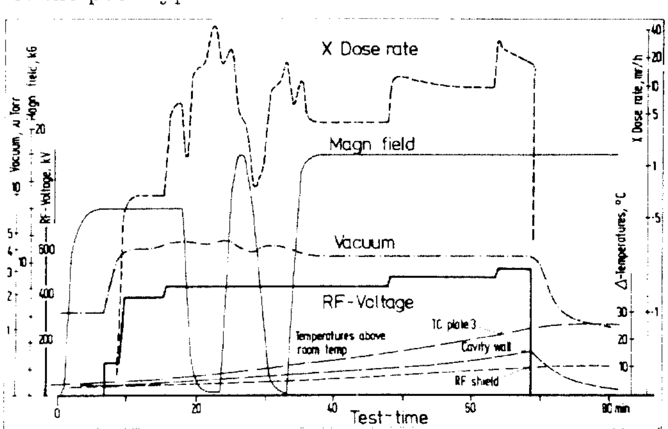


Fig. 6 Trace of different parameters taken during a typical 1/4 ring test run at probe positions as indicated in Fig. 3. In this case the main magnet excitation was changed computer-controlled.

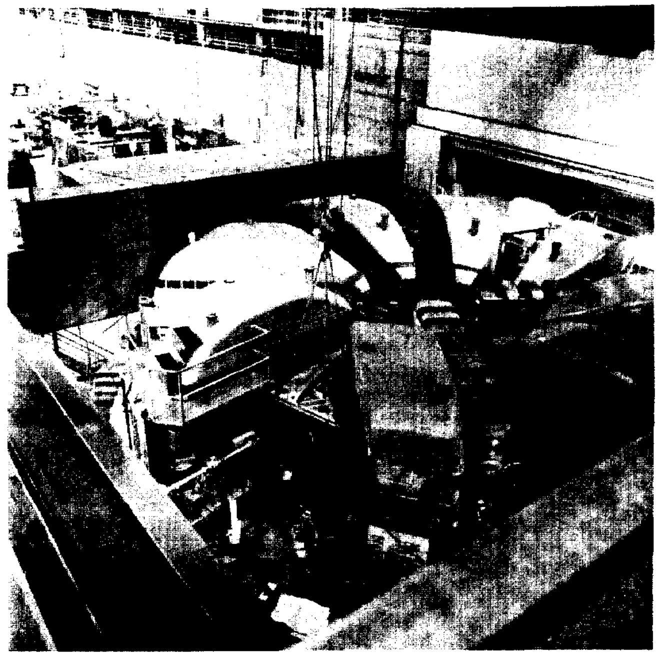


Fig. 7 Ring cyclotron during assembly. A "free section" of the vacuum chamber is being inserted. The time necessary for complete mounting (demounting) of this component is < 1 hour.

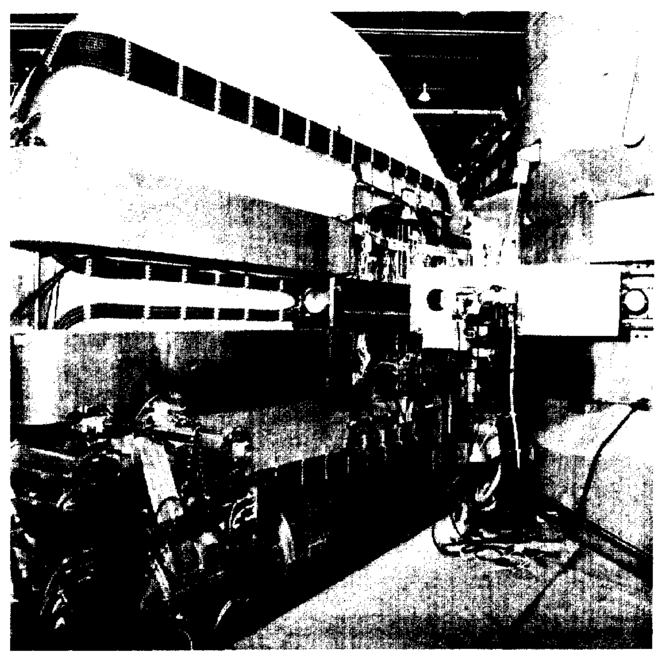


Fig. 8 Space between two magnet sectors, ready for insertion of an RF cavity. Along the magnet yoke TC-leads visible. Flanged onto the vacuum chamber are the feeds and adjusting mechanism of the magnetic focusing channel for beam extraction (center). Left foreground: A combined set of turbo-molecular pumps and Ti-sublimator, to be flanged onto the cavity.

A series of tests was carried out to obtain information on the x-ray dose rates at different locations, emitted from the cavities. A significant depression of the dose rate by a factor of 3 - 5 (depending on the location of measurement) could be noticed once the magnetic field was turned on. In Fig. 6 a typical measurement of the x-radiation, varying with the RF voltage and the magnetic field, is shown.

The system tests of the first 1/4 ring section were ended on Dec. 15, 1972, when the program for precision alignment of the magnets had to be started.

Conclusion

The system of main cyclotron components assembled in the ring seems to be technically functionable. Accelerating voltages of > 500 kV per cavity can safely be expected. Special care has to be taken with the cleanliness of inner surfaces during mounting, in order to achieve high accelerating voltages within reasonable time after assembly or after opening the vacuum chamber. For components being mounted closely to the accelerating gap of the cavities, special care is to be taken in RF shielding and eliminating the RF "noise".

Further Procedure

After the second 1/4 ring section had been assembled on Jan. 24, 1973, operational tests were carried out last month. The special care in cleanliness was rewarded. A 1/2 ring section is assembled by March 7, 1973.

While thorough tests with two cavities will be carried out, the magnetic field measurements are concentrated on the influence of the magnetic injection and extraction elements, placed closely to the radial range of acceleration. To apply the proper corrections for these field disturbances, we allow three months. It is the goal to have the ring cyclotron ready for beam acceptance by fall of this year.

Acknowledgement

To get the ring cyclotron project to this point, where completion within the cost estimate and the general time schedule can be visualized, has been the result of good team work of the SIN group. The number of people directly involved in the construction of the accelerator is ∿200. We are grateful for the support we have received from our authorities and the help obtained from industries, fabricating the components. A special address of thank ought to be given to the Swiss public who is patiently waiting for a result of the financial investment in this project.

References

1 J.P. Blaser, ETH Bulletin, Feb. 1971, p. 8

2 H.J. Gerber et al., SIN Users Handbook, Nov. 1972

3 C. Petitjean, G. Vécsey, IEEE Trans. Nucl. Sci. NS-18/3, 723 (1971)

4 A. Baan et al., paper "The SIN Injector Cyclotron", this conference

5 H.A. Willax, Cyclotrons 1972, p. 114 *)

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

7 P. Lanz, Cyclotrons 1972, p. 467 *)

8 G. Tripard, W. Joho, Nucl. Instr. and Methods 79, 293 (1970)

9 L.J. Besse, Cyclotrons 1972, p. 510 *)

10 W.M. Brobeck, 171-1R1, "A Survey of the Ring Cyclotron Project", July 1968

*) Sixth Intl. Cyc. Conf. Vancouver, AIP Conference Proceedings No. 9 (American Institute of Physics, New York, 1972)