# Status report on SIN

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ABSTRACT

A two stage isochronous accelerator for proton beams of about 100 $\mu$A at more than 500 MeV is under construction at the Swiss Institute for Nuclear Research, Zurich. As previously described it consists of a sector focused isochronous cyclotron for 70 MeV, acting as injector, and an isochronous ring cyclotron.

The *injector cyclotron* will also accelerate d, $\alpha$, $^3$He, heavy ions as well as polarised d and p to variable energies. Those beams will be used separately. It will be constructed by Philips, Holland. The design goal for the *ring cyclotron* has been changed from 520 to about 580 MeV.

The status of development of the main machine components is described briefly. Prototypes of a sector magnet, an rf cavity and a vacuum chamber section are under test. Building construction work has started at the site near *Villigen.* It is expected to begin with the installation of the machines in 1971.

## 1. INTRODUCTION

The aim of the project and the design principles of the proposed accelerator have been described at the Cyclotron Conference of 1966.[1,2]

SIN is the abbreviation of Swiss Institute for Nuclear Research. This institute obtained the status of an 'Annex Institution' to the Swiss Federal Institute of Technology (ETH) in 1968. With the planned accelerator laboratory near Villigen, SIN will provide a modern research facility to Swiss Universities and other users groups.

In view of the broad spectrum of interest, in 1967 the specifications of the first cyclotron stage were changed from a pure injector machine to a multi-particle variable energy cyclotron.

Final authorisation of the project was obtained in fall 1968. Philips Eindhoven (Holland) with their experienced group got the contract for building the injector cyclotron.

With the first stage being changed to variable energy there were some plausible arguments brought forward to also provide energy variability in the ring cyclotron. Considering the rather small demand and the additional effort, it was decided to keep the design of a fixed energy ring. However, the goal was set to possibly increase the final energy without drastic alterations of the design, after it had been shown by W. Hirt *et al* at CERN[3] that the yield of pions would be greater in this particular energy range than originally expected.

In the spring of 1969 the change in the final energy from 520 to 580 MeV was set as a design goal after more knowledge had been obtained on the design and fabrication limitations of the main magnets and the consequences on beam stability.

The decision to design the ring for 580 MeV instead of 520 MeV will be final after a few more technical details have been clarified.

Immediately after placing the contract with Philips the layout of the experimental hall with the arrangement of the machines (Fig. 1) could be frozen.

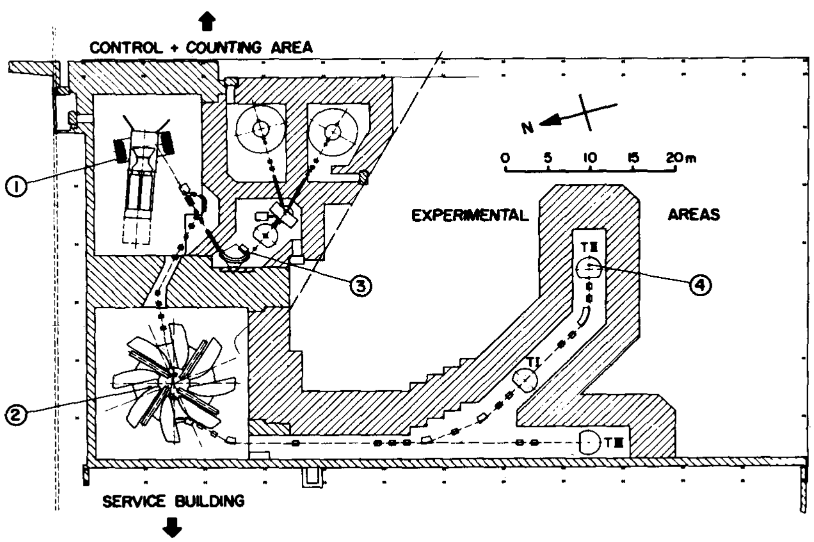



*Fig. 1. Layout of the SIN experimental hall. 1. Injector cyclotron with variable energy. 2. Ring cyclotron for 580 MeV protons. 3. Transport system for beams with variable energy, including 110° analysing magnet. 4. Production targets T I, II, III, for secondary beams (π, μ-mesons, neutrons, polarised protons); movable concrete blocks for shielding between machines and experimental hall, beam transport and target systems*

## 2. THE INJECTOR CYCLOTRON

Since the function as an injector for the high energy stage will have high priority in operation (about 75% of the scheduled beam time) the machine will be developed mainly in view of the specific requirements of this mode of operation. Most important aspects are:

(1) External beams of high quality with the highest possible intensities at well determined pulse frequency (50·8 MHz) and determined energy (72 ± 1 MeV).

(2) Stable and reliable operation.

These requirements influence the approach in the early machine development. The precise magnet diameter for instance can only be chosen after extensive model studies, which lead to the final radius for protons with the exact energy at the determined frequency. Special attention will be given to the optimisation

**Table 1.** MAIN PARAMETERS OF THE SIN ACCELERATOR

*(1) Injector Cyclotron* (Philips Design)

*External Beams*

| *Particle* | *Energy range* MeV | *Intensity* $\mu$A | *Emittances x, z* mm mrad *norm. at* 50 MeV | *Energy spread FWHM* | *Micro-duty cycle* |
|---|---|---|---|---|---|
| *Injector mode* *p* *at* 50·8 Mc/s | 72 ± 1 | $\geqslant$ 100 | $\leqslant$ 30 | $<$0·3% | 3–5% |
| Variable energy mode p | 10–75 | 25 | $\leqslant$30 | $\leqslant$0·3% $\geqslant$100 keV | 1·5–14% |
| d | 10–65 | 25 | id. | id. | id. |
| $\alpha$ | 20–130 | 15 | id. | id. | id. |
| $^{3}$He | 15–160 | 15 | id. | id. | id. |
| Heavy Ions | ~0·6–10 MeV per Nucleon | 2 | $\leqslant$40 | $\leqslant$0·5% $\geqslant$100 keV | id. |

After 110° analysing magnet an energy resolution of $\Delta E/E < 2 \times 10^{-4}$ can be expected

*Technical Parameters:*

| | |
|---|---|
| Pole diam. | ~2·5 m |
| Max. beam radius | ~1·1 m |
| Spiral sectors | 4 |
| Isochronous field | 0·4–1·6 Wb/m$^2$ |
| Cyclotron frequencies | 1·6–17·1 MHz |
| Frequencies of dee voltage | 4·7–17·1 MHz, 50·8 MHz (third harmonic for injector mode) |
| Dee voltage (single dee) | 70 kV |
| Beam extraction | precessional |
| Extraction efficiency | 70% |
| Ion sources | internal; internal with preacceleration; external, axial injection. Polarised particles possible. |

**Table 1.** MAIN PARAMETERS OF THE SIN ACCELERATOR *(continued)*

*(2) Ring Cyclotron* (SIN Design)

*External Beam*

| *Particle* | *Energy range* MeV | *Intensity* $\mu$A | *Emittances x, z* mm mrad | *Energy spread FWHM* | *Micro-duty cycle* |
|---|---|---|---|---|---|
| *p* at 50·8 MHz | ~580 | ~100 | 10 | 0·3% | 3–5% |

*Technical Parameters:*

| | | | |
|---|---|---|---|
| Pole radii | 1·9–4·6 m | Ring vacuum chamber: | |
| Beam radii | 2·1–4·5 m | inner diam. | 3·5 m |
| Spiral sectors | 8 (separated magnets) | outer diam. | 9·2 m |
| Isochronous field | 0·6–0·9 Wb/m$^2$ } fixed | Outer diam. magnet yokes | 15 m |
| Hill field | 1·46–2·06 Wb/m$^2$ } fixed | Magnet height | 4·9 m |
| Field flutter | 1·05 | Weight (total) | ≈2000 t |
| Max. spiral angle | 33° | Power consumption | |
| Betatron frequency axial | 0·95–0·75 | magnets | ~650 kW |
| Betatron frequency radial | 1·1–1·7 | cavities | ~600 kW |
| Cyclotron frequency | 8·47 MHz | Power consumption total | ~1·5 MW |
| Rf frequency of cavities | 50·8 MHz (6. harm.) | | |
| Energy gain | ~1·7 MeV/rev | | |
| Beam extraction | at $\nu_r \approx 1{\cdot}1$ | | |
| Extraction efficiency | >90% (theoretical) | | |
| Beam injection | in midplane at 72 MeV | | |

of the centre region and the symmetry of the magnetic field (four sectors), the extraction system and its elements to guarantee a reliable beam of the required high quality. As an injector the cyclotron operates in the 3 $\omega$-mode at 50·8 MHz. In this case the single 180° dee is shorted close to the pole edge by a bar which can also be withdrawn under vacuum. An individual rf power stage, similar to the power stages used for excitation of the ring cavities, will excite the system in this mode. The whole rf power system, including the four cavities of the ring is driven by one master oscillator.

As a variable energy machine the frequency of the resonance system can be tuned between 4·7 and 17·1 MHz by shorting bars moving along the coaxial lines outside the vacuum vessel. In this case a self excited rf power system will be used.

The development of the main components of the cyclotron has started. Small scale magnets and rf models lead to encouraging results.

## 3. THE RING CYCLOTRON

A layout of the assembly of the ring cyclotron is presented in Figs 2 and 3. For reasons of clarity smaller components as for instance beam probes, etc., are not shown. It is expected that only minor changes in details of the main components (magnets, rf cavities, vacuum chamber, etc.) will take place from now on.

## 4. STATUS OF DEVELOPMENT

The reference design of the ring, as in principle established in 1963/64, was kept as a basis for the development of the main components. Instead of giving a comprehensive status report on the whole project it is intended to describe briefly the status of those subjects which deviate strongly from the normal cyclotron design.

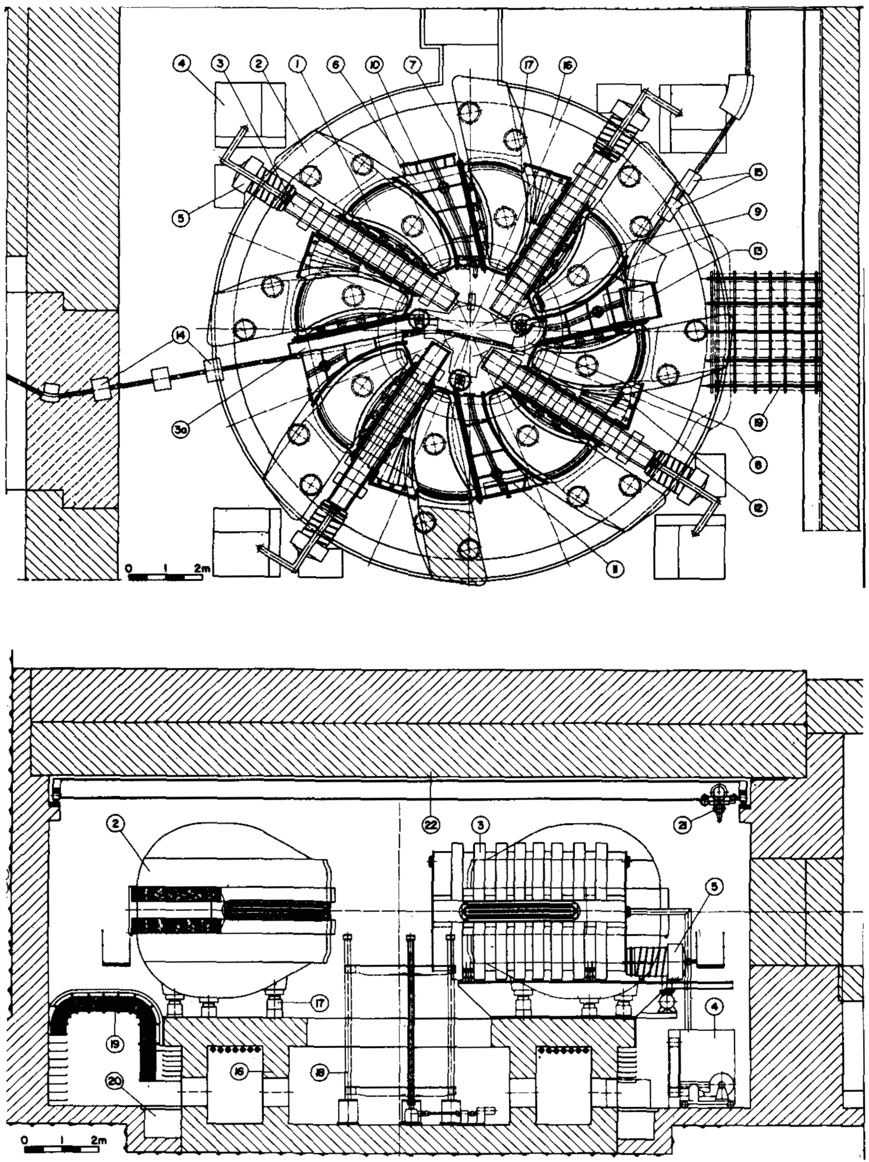
### 4.1. *Beam dynamic studies*

After establishing the tolerances for the magnetic fields[4] detailed computation based on 1:5 scale model field data have been carried out on beam extraction[5] and injection[6] as well as on the beam stability during passage of the non-linear coupling resonance $\nu_r = 2\,\nu_z$.[7]

The main results are: beam extraction efficiencies of more than 90% should be achievable in our design under normal operating conditions. The extraction system looks technically feasible. It consists of an electrostatic channel providing an electric field of 40 to 50 kV/cm over 120 cm length, a magnetic focusing element 45 azimuthal degrees downstream, and a 16 kG, 12° extraction magnet with a 2 cm septum coil, 90 azimuthal degrees after the deflector. (A prototype of such a magnet for testing a septum coil with aluminium oxide insulation was built and the coil successfully tested.) The magnetic focusing element, a 3 × 3 Panofsky quadrupole with a gradient of 300 Gauss/cm over a length of 50 cm is important to control radial beam amplitudes at the passage of the fringe field within the following sector magnet. Using a small superimposed dipole field, this element can also steer the deflected beam in radial direction.[8]

To inject a 72 MeV beam correctly, in principle two methods can be chosen:

(a) Injection on an 'accelerated centred equilibrium orbit'.



*Figs. 2 and 3. Assembly drawings of ring cyclotron, simplified. 1. Poles of sector magnets. 2. Yokes of sector magnets. 3. Rf cavities, 50 MHz. 3a. Space for 150 MHz rf cavity (for future flat-top acceleration). 4. Rf generators 250 kW. 5. High vacuum pumps (titanium sublimators and ion getter pumps). 6. 'Free section' of vacuum chamber. 7. Pneumatic inserts for vacuum sealing. 8. Injection magnet, 94°. 9. Magnetic injection channel, 3 kG. 10. Electrostatic inflector. 11. Electrostatic deflector. 12. Magnetic focusing and steering element for deflected beam (Panofsky quadrupole). 13. Extraction magnet with 2 cm septum coil. 14. Focusing elements for 72 MeV beam. 15. Focusing elements for 580 MeV beam. 16. Concrete ring foundation. 17. Adjustable magnet supports. 18. Supporting structure for elements in the machine centre. 19. Cable conduits. 20. Trench for cooling water pipes. 21. Small auxiliary crane, 2·5 t. 22. Demountable concrete beams (roof shielding)*

(b) Precessional injection with the aid of a radially controlled first harmonic field bump.

*Method (a)* requires three injection elements: a 94 degree injection magnet; a magnetic inflector element which increases the field in the pole gap of one sector magnet locally by about 3 kG; and an electrostatic inflector channel with a field strength of 80 kV/cm. This element could also be replaced by a magnetic channel with a current carrying sheet. The technical feasibility of these components has been investigated.

*Method (b)* does not require the last inflector channel, however, the radial dependence of the first harmonic amplitude is critical and linked to the energy gain per revolution. This method, therefore, seems to be more tricky.

The horizontal acceptance $A_x$ of the ring cyclotron, mainly determined by the acceptance of the injection elements and the energy gain per revolution $E_g$, can be made larger than 50 mm mrad for an initial $E_g$ of 1 MeV/rev, as achievable with cavity peak voltages of 350 kV. The vertical acceptance $A_z$ is larger than $A_x$. It is important to keep the energy spread of the injected beam small compared to $E_g$.

Ideal matching can theoretically be achieved in our case for an energy spread of $\Delta E/E \leqq \pm 2 \times 10^{-3}$ with the proposed injection beam transport system.[9] This system is designed to be used as an adjustable energy filter if it should prove necessary to select a small energy band of the injector beam. The transmittance of this system has been computed to be 100% for the energy band width of 200 keV.

The passage of the *x-z* coupling resonance $\nu_r = 2\,\nu_z$ has been computed for different initial amplitudes without and with acceleration, using quadratic and cubic terms in the field expansion. In our case the increase of the vertical beam amplitudes would remain within 10% of the initial amplitude passing the resonance near 490 MeV in a 585 MeV field configuration.[7]

### 4.2. *Main magnets*

A prototype of the sector magnet (Fig. 4) has been built according to earlier description of the design.[10] Extremely close tolerances had to be requested on the magnetic properties of the steel and on the machining of the individual elements in view of accurate field reproducibility in the magnets of the series. The results achieved with the prototype were encouraging. The steel castings and forgings, as manufactured by 'Gusstahlwerke Bochumer-Verein', Germany, showed magnetisation characteristics within 60% of the specified tolerance band width which was ±150 G for the forgings and ±250 G for the castings along a specified magnetisation curve. The machining of the poles (executed by Brown, Boveri Company (BBC) Switzerland), was most carefully prepared in view of repeating the operation for the following magnets. On a large vertical turning lathe of high precision the pole side contours can be reproduced with accuracies of 0·1 mm with the aid of master templates. The same lathe is used for the most critical machining operation, the milling of the inner pole surfaces to yield the isochronous field configuration. This contour is copied from carefully prepared templates which are contoured with an accuracy of ±0·02 mm according to a computer tabulation. By these means the individual pole surfaces can be milled

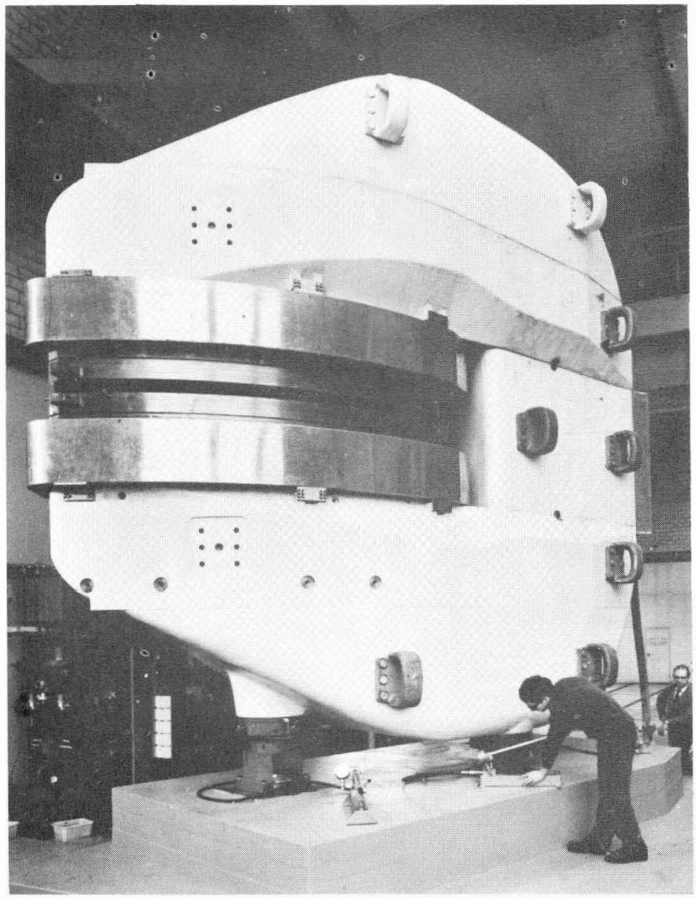


*Fig. 4. Prototype of a sector magnet. Dimensions: 5·2 m length, 4·9 m height, 245 metric tons. (Fabrication by Oerlikon Engineering Company (MFO), Switzerland; Brown, Boveri Company (BBC), Switzerland. Steel from 'Gusstahlwerke Bochumer Verein', Germany.)*

with an accuracy of $\sim \pm 0{\cdot}05$ mm to the requested contour. For the magnet prototype we had to take into account an uncertainty in the true elastic deformation of the pole gap spacers and the poles under magnetic forces. Nevertheless, the gap contour of the excited magnet remained within the tolerance of 0·26 mm of the specified value. The magnetic field of this magnet was measured point by point over the interesting azimuthal and radial range. The 40 000 mesh points of one complete field map are taken by an automatic measuring system as illustrated in Fig. 5. With this machine the time for a complete map is 2·5 hours. The resolution is 0·5 G and the positioning accuracy ±0·2 mm per sensing element. An absolute accuracy of ±3 G can be achieved.

At the nominal excitation of 126 000 ampere-turns this field came within 0·5% of the design value of the expected isochronous field for 525 MeV protons. Figs 6 and 7 demonstrate the results.

In Figs 6 and 7 also the isochronous hill-field and the corresponding $\nu_r$, $\nu_z$ curves for a final energy of 585 MeV are shown, based on an unchanged sector

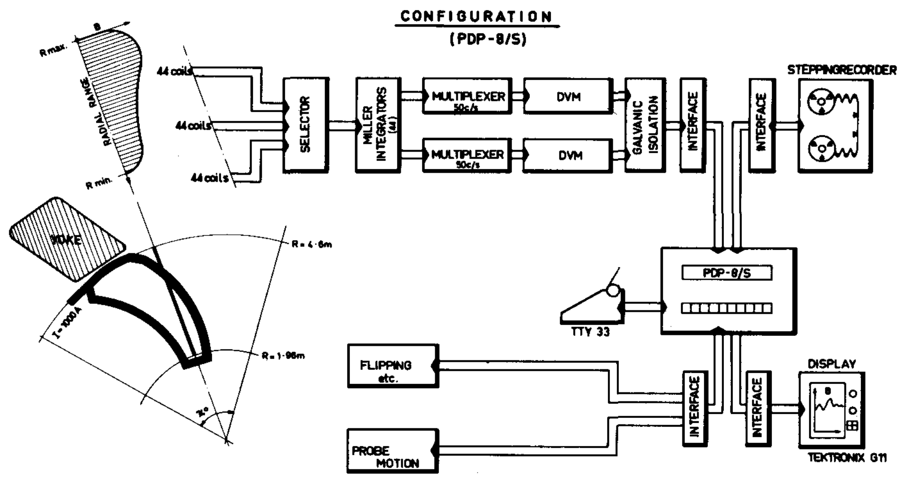



*Fig. 5. Principle of automatic field measuring system. 132 flipping coils are equidistantly mounted on a 2·64 m long radial rod. The signals of 1 radial group of 44 coils are integrated simultaneously by 44 integrators. For a complete field map the rod is flipped 180° around its radial axis three times at each azimuthal position. The three groups of coils are switched onto the 44 integrators consecutively*

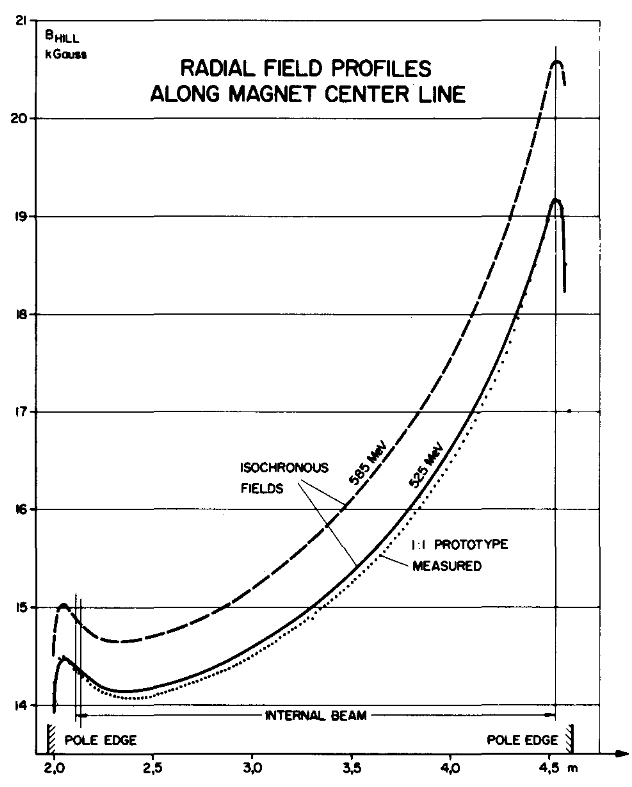



*Fig. 6. Measured and required hill fields in the sector magnets*

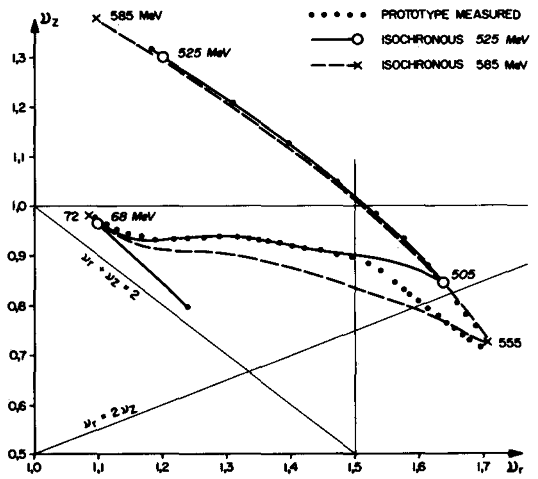



*Fig. 7. $\nu_r$-$\nu_z$ working diagram for sector field geometry of the ring cyclotron. The behaviour of the values taken from prototype field measurements at $\nu_r > 1{\cdot}5$ is due to the larger radial gradient at the outer radius (see Fig. 6)*

geometry. In this case the passage of the $\nu_r$, $\nu_z$ coupling resonance becomes unavoidable.

It is technically possible with the present design of the sector magnet to reach the required peak hill field of 20·6 kG using a pole gap of 5 cm at the outer edge. The excitation has to be increased from $126 \times 10^3$ ampere-turns to $\approx 150 \times 10^3$ ampere-turns increasing the magnet power to $\approx 75$ kW per sector. However, 1:5 scale measurements have shown already the increased difficulties in shaping the hill field correctly for isochronism and beam extraction. It is very likely that a more complex set of pole face windings than originally planned has to be considered. Meanwhile, the poles of the prototype magnet have been re-machined to a first order of accuracy for this final energy of 585 MeV.

### 4.3. *Accelerating cavities and rf power system*

A prototype rf cavity as an integrated system of vacuum chamber and resonator has been built (Fig. 8) and, at the moment is still operated with our home made 50 MHz power stage, delivering not more than $\approx 80$ kW. This cavity is a welded construction of 20 mm pure aluminium sheet with cast supporting ribs for mechanical rigidity. The inner surfaces of totally 40 $m^2$ are treated by rolling with polished steel rolls. By this method it was possible to reduce the rf power loss to about 70% of the originally expected value. The $Q$ value of this cavity turned out to be 32 000.

With a combination of a 2000 $m^3/h$ turbo molecular pump (Pfeiffer), a titanium sublimator (Ultek) and a ion getter pump (Varian) of total 14 000 l/s effective pumping speed we can reach vacua of $1 \times 10^{-6}$ torr after 2 h of pumpdown. After 200 h pumping the final pressure is $5 \times 10^{-8}$ torr. The cavity has been baked in and was operating at about 400 kV. With the new pumping system the multipactor barrier is no problem any more, since contamination of the surfaces seems to be largely reduced compared to operation with oil diffusion

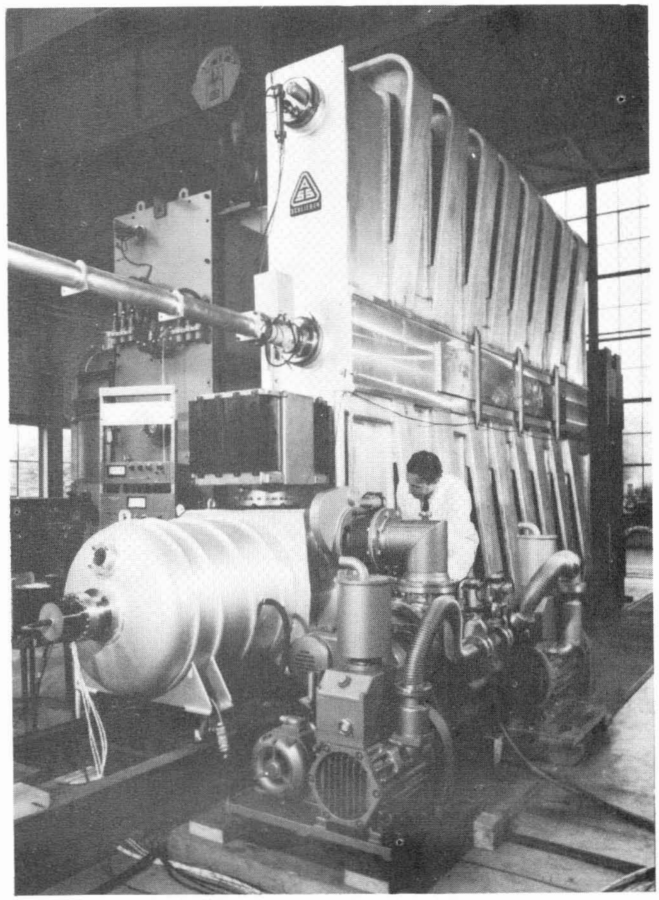


*Fig. 8. Prototype rf cavity with vacuum pumps. Dimensions: length 5·3 m (inner), height 3·3 m (inner), width 0·4 m (inner), weight ~8 metric tons. [Fabrication by 'Aluminium Schweisswerk Schlieren', Switzerland. The titanium sublimator with the connected ion getter pump is joined directly to the cavity.]*

pumps. It was also interesting to notice the x-ray level being down by a factor of 10, compared to the first working model at equivalent voltage.[12]

We have not found the 'break down' limit in this cavity yet. To reach a peak voltage of 500 kV, an rf power of 110 kW would be necessary.

The rf power system will be designed for 250 kW at 50 MHz. The first complete system, including the chain of pre-amplifiers with regulating network and the d.c. supplies with protection circuits is built by AEG-Telefunken Berlin at the time being and will be delivered next spring. The power amplifier is a newly developed water-cooled Telefunken tetrode type RS 1998.

Up to now only theoretical investigations have been carried out on the problem of voltage and phase stabilisation. Also the problem of beam loading was investigated theoretically in cooperation with C. Passow of the Karlsruhe Accelerator Group.[13, 14] It has been shown that there is not a stability problem as long as the beam power per cavity does not exceed about one-quarter of the rf power loss in the cavity. If a fast amplitude and phase regulating system can be applied, the beam power could be carried far beyond this limit. It is the goal to design the system to obtain amplitude stabilities within $\Delta V/V < 1 \times 10^{-3}$. To build such a fast amplitude and phase regulating system, however, imposes some difficulties,[15] since the time constants of the elements in the servo loop need to be 500 times smaller than the time constant of the cavity, which is $10^{-4}$ s.

### 4.4. *Vacuum chamber*

One of the major design problems was considered to be the vacuum tight and radiation proof joint of the stainless steel chamber to the magnet poles.[2] After successful attempts at smaller models a full scale prototype of such a section, including the poles of a magnet, was built (Fig. 9).

The welded connection of the chamber with the pole by means of a double collar of 1 mm stainless steel sheets (which can be cut and rewelded several times, in case a pole disassembly becomes necessary) presented a few problems, mainly of technological nature. The prototype chamber, however, could be welded tightly to a leak rate smaller than $5 \times 10^{-4}$ torr l/s.

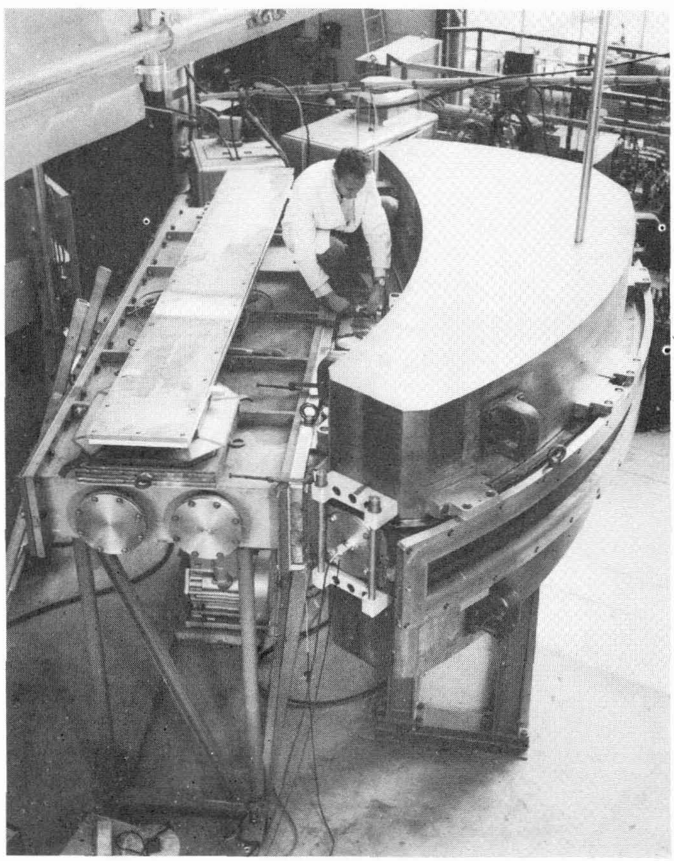


*Fig. 9. Prototype of a vacuum chamber section joining the magnet poles. This section was built to master the difficulties of the welded joints between chamber walls and poles, as well as the problems of metal gaskets for curved flanges of large dimensions. [Fabrication and welding by Oerlikon Engineering Company (MFO), Switzerland.]*

### 4.5. *Cyclotron control system*

It is planned to have a medium-size digital computer as an aid for operating the machine. In the first phase of operation it will be mainly used for automatic logging of data, in the second phase for parameter settings and limit control. In the third phase of operation it possibly could enter as an active element into a part of the control function. The development of analog-digital converters goes along the lines of the CERN developments.

### 4.6. *General*

There are quite a few problems left which need more effort in the development from now on. The system of magnet trimcoils for higher final energy, the probes for a fair diagnosis of the beam behaviour between 200 and 600 MeV, beam collimators and local neutron shields are to be mentioned. It is hoped to incorporate those systems into the design at the right time.

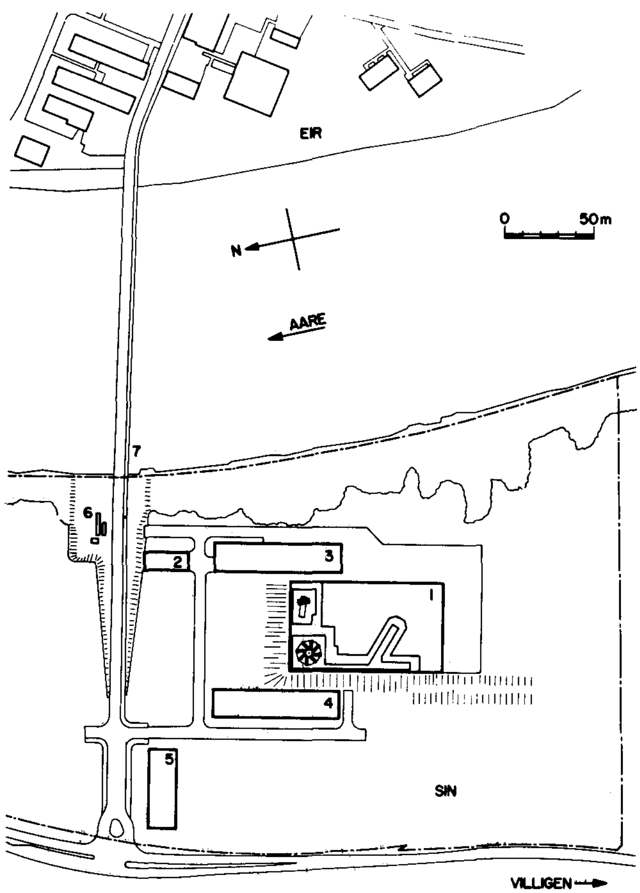



*Fig. 10. The SIN Laboratory at the site near Villigen. 1. Main experimental hall with the accelerator and shielding for two target stations indicated. 2. Transformer station. 3. Control and operations building. 4. Service building for electric and cooling water supplies. 5. Laboratory building. 6. Waste water purification plant. 7. Bridge connecting the SIN with the Swiss Federal Institute for Reactor Research (EIR)*

## 5. BUILDINGS AND MAIN INSTALLATIONS

The laboratory will be built in Villigen, 35 km northwest of Zürich, close to the Swiss Federal Institute for Reactor Research (EIR), at the river Aare. Fig. 10 shows the general layout.

The main parts will be:

(a) the experimental hall with 85 X 48 m floor space and 18 m height. A 60 ton crane spanning the whole width will service the area from 12 m height. The hall contains the two accelerators in vaults at the north end. The shielding walls of the accelerator will be partly cast concrete, partly movable blocks. The roof shielding consists of removable concrete beams. The experimental area available outside the vaults is 2700 $m^2$.

(b) the operations building adjoining the northeast part of the experimental hall. It contains control room, counting rooms, offices and workshops (a total of ~2000 $m^2$ useful area).

(c) the service building adjoining the northwest part of the experimental hall. It contains general utilities, the cooling system, the main power conversion system and a small workshop for special purposes (a total of 1500 $m^2$ useful area).

(d) the laboratory building, situated about 70 m northwest of the main hall. It contains a total useful area for offices and laboratories of about 1800 $m^2$.

Building construction work has started. In connection with the design of the building the main power distributions and the cooling water circuits have been designed. There is a total of 10 MW electric power and 6 MW cooling power available in the first phase of operation. This capacity can be expanded.

## 6. SCHEDULES

The main buildings are scheduled for summer 1971. The injector cyclotron will be installed from summer 1971 to summer 1973. Its first beam is expected towards the end of 1973. The ring accelerator will be assembled during the years 1971-73. The experimental programme is in preparation and it is hoped that not much time will be lost from the startup of the machine to the delivery of experimental beams.

## 7. FINAL REMARKS

The team working on the project could be increased during the last two years. For the machine development and project planning SIN employs at the moment 85 people of whom 24 have academic and 26 engineering degrees. Independently of this group 12 to 15 physicists are working on planning and preparation of experiments. Several groups outside SIN have been engaged in the project. Those are, besides Philips Holland; Oerlikon Engineering Company (MFO); Brown, Boveri Company (BBC); AEG-Telefunken Berlin; the Architect Engineering firm Schindler and the Swiss Federal Institute for Reactor Research (EIR). Their effort is a very significant contribution to the progress.

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