RECENT AND FUTURE DEVELOPMENTS AT S.I.N.

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Summary

The 590 MeV ring cyclotron produces 60-80 µA of protons which are mainly used for meson production. A special pulsed mode gives an average intensity of 30-40 µA at a repetition frequency of 400 kHz and a duty cycle of 40 %. Recent developments are: computer aided set-up for single turn extraction, periodic centering of beam on target, and closed loop computer control of the magnetic fields of injector and ring cyclotron. A third harmonic flattop cavity is ready for installation. A new injector which will deliver beams of more than 1 mA has been funded and the main efforts are concentrated on buildings, magnets, RF-system, ion source development and computer control. Preparations for the start up of the medical pion applicator are underway. Further goals are: I^{123} isotope production around the clock and an improved polarised ion source for low energy research. Serious studies for a medium flux slow neutron facility using an intense 590 MeV beam have started.

1. Introduction

The SIN accelerator facilities have been described in previous reports[1,2,3] and only a very short description is given here. An injector cyclotron produces 72 MeV protons which are further accelerated to 590 MeV in an eight sector ring cyclotron with four 50 MHz RF cavities. The injector can produce as well protons, deuterons and α-beams of variable energy. About a quarter of the available beam time is reserved for this low energy mode of operation.

2. Recent developments

Since the last international cyclotron conference in 1975 the 590 MeV beam intensity on target has increased steadily and the original design value of 100 µA was surpassed in December 1976 (see fig. 1). At the same time the beam time available for experiments has reached 4600 hours in 1977. A distribution of the accelerator time over the past few years is shown in fig. 4. Among the notable achievements during this period are:

- 99.9 % extraction rate from the ring cyclotron with the help of eccentric injection and single turn extraction[3] (see fig. 2). This remarkable and unexpected result (i.e. without flattopping) helped to reduce the anticipated activation problem dramatically.
- More than 10'000 µAh of 590 MeV beam on target within one week (August 1978).
- 91 % extraction rate from the injector cyclotron.
  This result is obtained with the implementation of vertical collimators[4] in the center of the cyclotron to prepare the beam prior to acceleration. Without this relatively high extraction rate severe activation problems would hinder regular high intensity production.
- Construction of a 590 MeV beam pulser[5] operating at 400 kHz. The pulsed beam has a duty cycle of 40 % and is used for studies of the possible neutrinoless decay of a muon into an electron[6]. Average intensities of 40 µA have been obtained in this mode. The suppression rate was better than 10^{-7} during beam-off time.
- Automatic (computer) set up of the beam between injector and target[7].
- Closed loop computer stabilization[8] of the magnetic field of the injector and of the ring magnets. Phase probes in the external beam lines (see fig. 3) measure the relative phase of the beam with an accuracy of .2° and keep the magnetic fields constant to 1 part in 10^6.
- Production of the radioactive isotope I^{123} on a regular 4 hours per week basis in collaboration with the Swiss Institute for Reactor Research (EIR). The total activity of 2 Curies per week represents the largest single supply of this isotope in Europe.

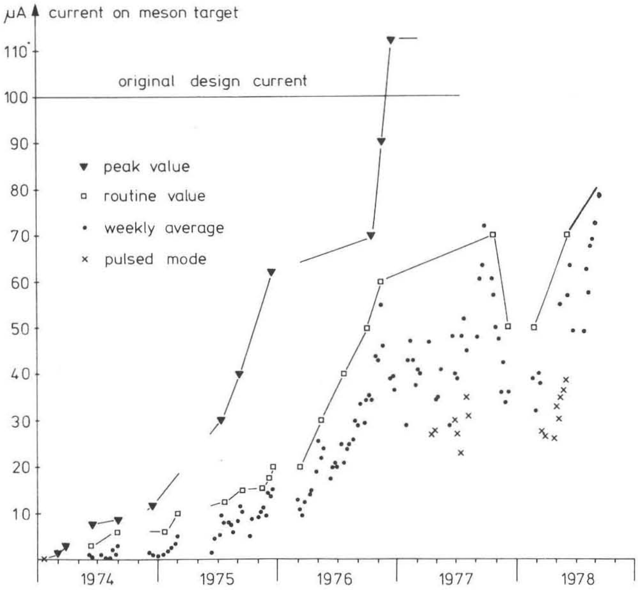

Figure 1 *Trend of 590 MeV beam intensity since start-up of the ring cyclotron in January 1974. The original design current was reached in December 1976. During 1977 and 1978 a substantial fraction of beam time was devoted to a 400 kHz pulsed mode with 40% macroscopic duty cycle and a correspondingly lower average beam intensity.*

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- Production of 90 MeV α beams by the injector in the variable energy mode. The energy is expected to reach the maximum value of 130 MeV soon.
- Sustained 3 cavity operation of the ring. During a drop out of one of the four cavities for a period of one day the ring had to operate with the remaining three cavities only. Despite this handicap 40 μA of beam could be brought to target with a 97 % transmission through the ring cyclotron.
- Visual display of weighted beam losses. A "BONUS"-value, which depends on the beam losses weighted according to the beam energy, is periodically displayed for various beam sections between injector and target. This gives the operators an overview of the accelerator performance.

Beam developments on both accelerators, made possible by the excellent diagnostic equipment[9], played a major role in improving the performance over the past years. As an example the phase probes (see fig. 3) are used in the following procedures:

- Rapid on-line determination of the phase history in the ring cyclotron.
- Measurement of the radial variation of the cavity voltage[10] to an accuracy of 1 %.
- Closed looped stabilisation of the magnetic fields, as mentioned above.
- Calibration of injector energy with a time of flight measurement (see fig. 5).

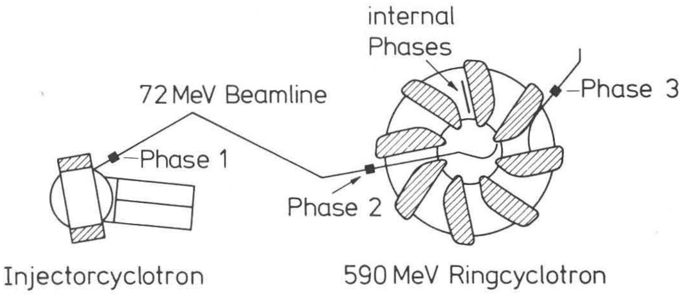

Figure 3 Layout of phase measurements at injector and ring cyclotrons. Phase probe 1 measures the extracted 72 MeV beam phase and gives a signal for the closed loop correction of the magnetic field of the injector. Phase probe 2 in combination with phase 1 provides a time of flight measurement and thus determines the energy of the injector. Flight path between phases 1 and 2 is 21.2 m, between phase 1 and first internal probe 33.2 m. The phase 2 signal is further used to set the correct phase shift between injector and ring RF system. The internal phase signals allow a quick check on isochronism of the ring. Phase probe 3 measures the extracted 590 MeV beam phase and provides a signal for the closed loop correction of the magnetic field of the ring cyclotron. Phase signals are thus the key factor in obtaining a stable beam on target.

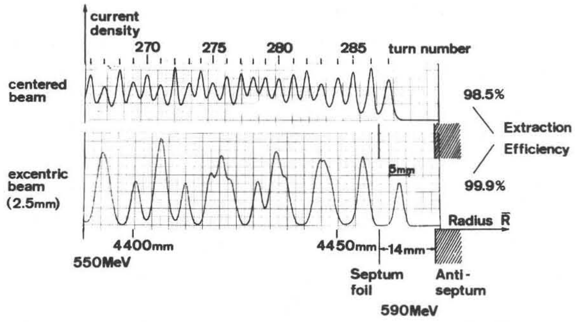

Figure 2 The last 22 turns in the ring cyclotron. A .2 mm thick secondary emission probe measures the beam current in front of the extraction septum. The top trace shows a well centered beam with a beam quality of π·1 mm mrad. For the bottom trace, the beam was injected off-center into the ring with a coherent amplitude of 2.5 mm. The ν_r-value of 1.5 at extraction helps to double the original distance between the last two turns to 9 mm. Extraction losses given by the beam hitting the septum foil are thus reduced to .1%.

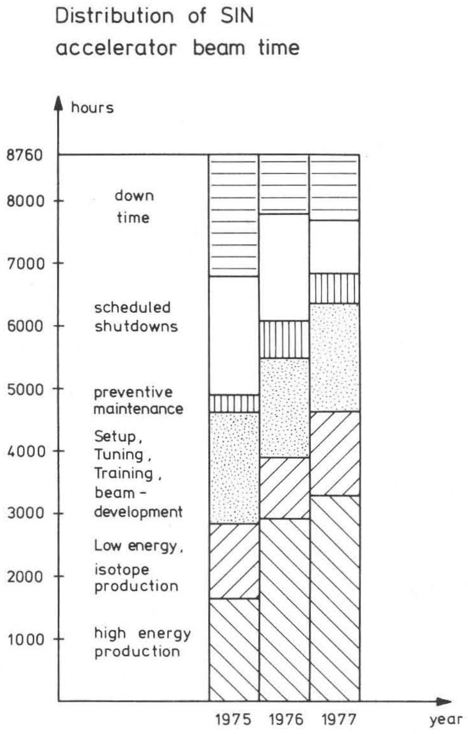

Figure 4 Distribution of accelerator beam time in the first three years of regular operation. Roughly 25% of scheduled beam time for experiments is devoted to research with low energy beams from the Phillips injector. The accelerator facilities were in operation for about 73% of the time in 1977. Down time was about 15% of scheduled beam time.

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3. Short term projects

At the moment there are several projects in progress at SIN which should be finished during 1979:

- a flattop cavity[11] operating at 150 MHz is ready for installation in the next shutdown.
- the medical annex and the mechanical components of the medical pion applicator[12] (see fig. 6) are essentially finished. The superconducting coils will be mounted next year and test runs with beam start next year.
- a high voltage splitter septum[13] for the 590 MeV beam has been constructed and is ready for tests. This splitter can shave off any fraction of the primary proton beam and direct it towards the medical pion target. The grounded septum foil, which is made out of Mo, is 39 cm long and has a thickness of 50 µm. Movement of the foil, which is effected hydraulically, requires 25 ms for a .1 mm displacement. The septum foil will intercept about .2 % of the beam.
- a new superionizer for the polarized ion source of the injector cyclotron has been ordered. 1 µA of protons and deuterons are expected on target with a polarization of 70-80 %.
- an ion source test stand for the internal source of the Philips injector has been constructed and is used to investigate source efficiency, brightness, lifetime of filaments etc. of the present source design. Further studies will concentrate on a biased ion source and heavy ion sources.
- the computer control system will be extended (see fig. 7) in order to cope with the increased complexity of operation. The new system will handle the equipment of the new injector II as well.

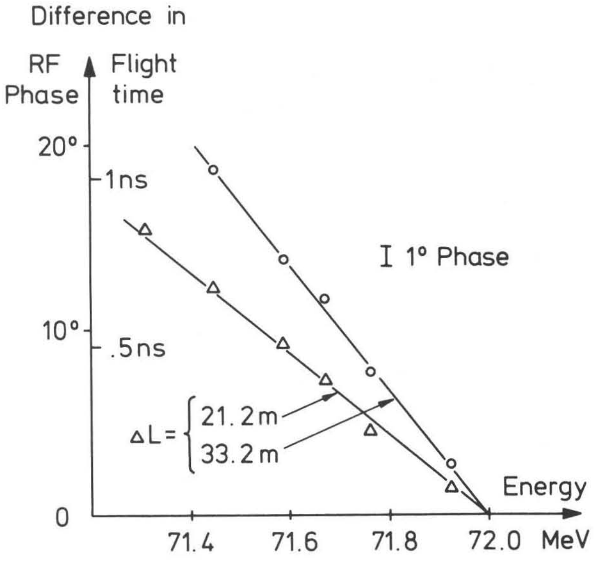

Figure 5 *Time of flight measurement giving calibration of injector energies. Phase probes along the injection path between injector and ring cyclotron measure the arrival time of particle bunches with an accuracy of about 20 ps. Injector energy changes of 20 keV can thus be detected. Flight time differences over a length of 21.2 m and one of 33.2 m were measured with 72 MeV as reference energy.*

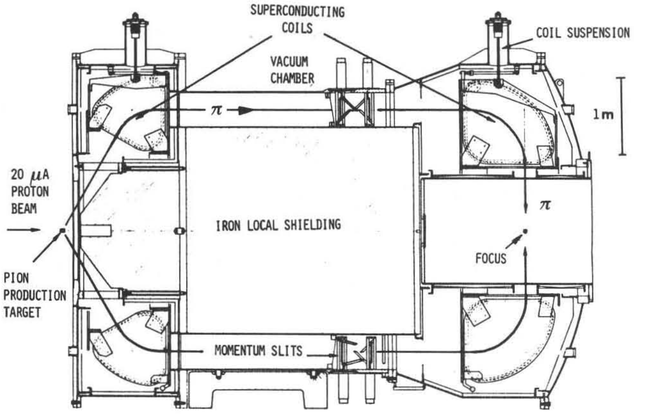

Figure 6 *Pion applicator for medical therapy project. A 20 µA proton beam hits a Mo or Be target. The negative pions are taken off the target at a 60° angle and are guided towards the focus with two superconducting torus coils. The patient lies horizontally at the focal point and can be moved in any direction during the tumor irradiation. As a shield against fast neutrons, 140 t of iron are placed between target and patient. Each torus consists of 60 pancake coils defining 60 separate pion beams which can be controlled individually with 60 momentum slits. The coils produce a maximum field of 25 kGauss. They are cooled by the forced circulation of supercritical helium at 4.5 K. Installed power for the cooling system is 450 kW, giving a cooling power of 550 W at 4.5 K. Due to the high solid acceptance angle of 1 sterad, the achievable dose rate can be as high as 50 rad/min for a 1 liter tumor volume. Start-up of the facility is expected during summer of 1979.*

4. Green light for the new injector II

In February of 1978 the Swiss government approved 15 MSfr. for the construction of a new injector[14]. This 72 MeV cyclotron is to be built with four magnet sectors and two different RF systems, one[15] operating at 50 MHz and the other one at 150 MHz to flattop the RF voltage. The 10th harmonic is used for acceleration and the extraction radius is correspondingly large (3.5 m). This in turn allows the injection of a low energy beam of 860 keV from a conventional Cockcroft-Walton preinjector (see fig. 8 and 9) and leads to a 100 % extraction efficiency.

Although the original design goal for the current is 1 mA, preparations are being made to push the beam intensity to its theoretical limit of 2-4 mA in the near future (see fig. 10).

Progress on the injector II project has been made in the following areas:

- the layout of the building has been fixed and construction will begin towards the end of 1978.
- all four sector magnets have been ordered.
- the 50 MHz RF system is designed and work on a 1:1 prototype is in progress.
- the vertical injection of a 860 keV DC beam into the center of the cyclotron has been designed[16]. Optical solutions have been found which match the beam size as well as the dispersion properties in both transversal directions for a continuous variation of the beam intensity from 0 to 50 mA.
- an ion source test stand for the preinjector together with a 300 keV acceleration column is under construction[13]. The concept of a source separated from the acceleration column has obvious advantages at the price of an additional beam guiding system (see fig. 8). Two 40 keV ion sources[17,18] capable of delivering initially 30 mA protons will be tested. Of special interest is the study of the high current behaviour of the source as well as space charge effects and their compensation with electrons. Further studies will investigate the behaviour of a chopper and a buncher for the 40 keV beam. The first beam out of the new injector is scheduled for the end of 1982.

5. Further medium range projects

Although the primary interest for the injector II is the increase of the proton beam for the pion targets, it was realized that a beam intensity of 1 mA or more opens up new applications. It is planned to install an isotope annex next to the injector II building (see fig. 11). Using a beam splitter, about 100-300 µA of 72 MeV protons will be taken off the main beam parasitically. This will allow the production of the isotope I^{123} on a daily basis.

On the high energy side no sizable modification in the experimental hall will be needed for currents up to about 500 µA, but above these intensities the beam lines, targets, and associated equipment will have to be modified extensively. This matter is under study — it is closely connected with considerations entailed in setting up a spallation neutron source at SIN (see fig. 12). The liquid Pb/Bi target will have a diameter of 10 cm and a length of 30-40 cm. The usable flux will be about 10^{14} n/s cm^2 for a 1 mA beam[16]. A feature of this neutron source will be the vertical beam entrance and the production of cold neutrons. The Be moderator eases the problem of power dissipation in the cold H_2/D_2 moderator and enhances slightly the neutron flux.

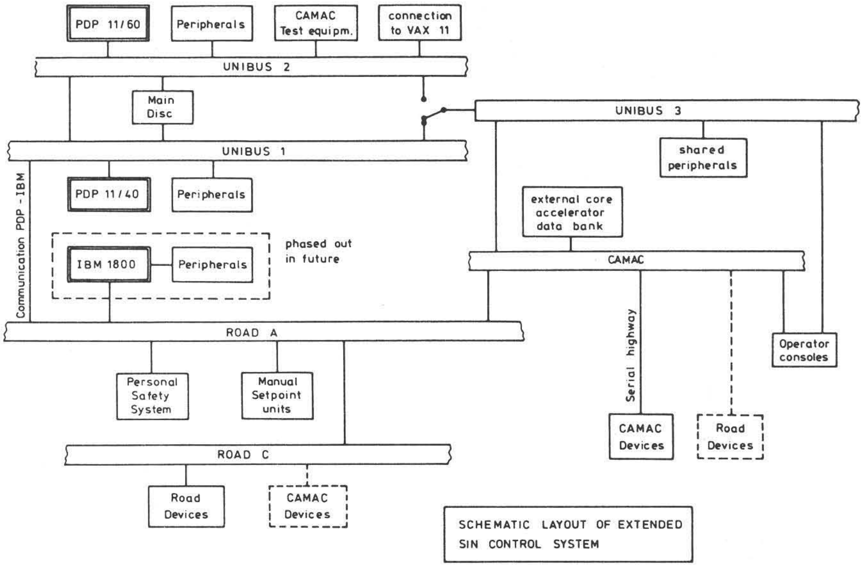

Figure 7 *Layout of the extended SIN control system. Dual computer system with PDP 11/40 and PDP 11/60 provides redundancy as well as extended computing and control capabilities. Peripherals necessary for running the accelerators are connected to UNIBUS 3, which is switchable between the two computers. Key element of the control system is the external core memory containing the accelerator data bank. Before any parameter can be varied via knobs on the operator console or via computer programs, the legality of the desired action is checked against values of upper and lower limits stored in the memory. Likewise, priority conflicts for access to certain parameters are arbitrated through the data bank. Present system is controlled by the SIN system "ROAD" for digital data transmission. The extended system will service both the present system and CAMAC devices. Presently only the left part of the diagram (without PDP 11/60) is in operation with the IBM 1800 as main computer and PDP 11/40 as satellite computer. The IBM computer is being phased out.*

6. Long range project studies

An accelerator can basically expand its potential (and thus its chance to survice in the long run!) along three major directions: intensity, energy or the atomic number of the accelerated particles (see fig. 13). For SIN high intensity has always had the highest priority, since this was the main argument for building this meson facility in the first place. With the injector II SIN is in a good position to exploit the basic intensity limits of present day cyclotrons. The first fundamental barrier is probably the longitudinal space charge limit (see fig. 10), which depends strongly on the energy gain per turn. This shows that a future trend might be the construction of even more powerful accelerating systems in order to reach average beams in the order of 10 mA.

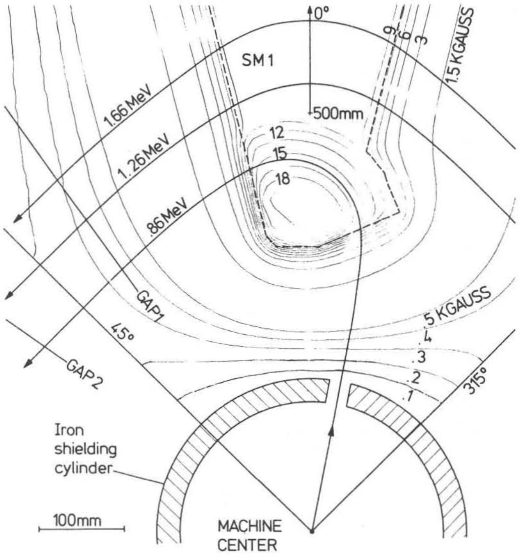

Figure 9 Plan view of center region of the new 72 MeV injector. An 860 keV DC beam is guided vertically along the axis of a shielding cylinder towards the machine center. There a magnet bends the beam by 90° into the median plane and directs it toward the nose of the first sector magnet SM1. A magnetic conus with a guiding field of 15.7 kG and a field index n = .5 injects the beam into its equilibrium orbit and provides double focusing in the horizontal and vertical directions. The beam gets its first acceleration at gap 1 and gap 2 of the delta type RF system. The following magnet sector provides energy—and thus phase selection. Particles with undesired phases are all collected on 20 kW collimators. After one turn, the remaining beam has gained an energy of 400 keV and experienced a radius increase of 7 cm, enough to clear the injection conus. The angular width of each of the four sector magnets is 29°. The field inside the 35 mm gap is 10 kG. Contour lines of constant magnetic field are indicated.

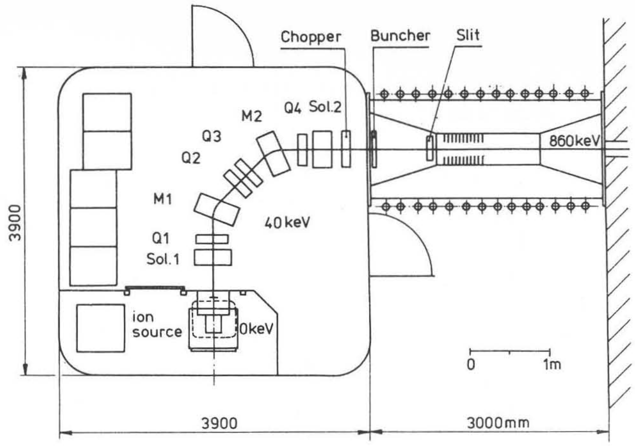

Figure 8 High voltage dome and acceleration column for the 860 keV pre-injector for injector II. A 40 keV proton beam from the ion source is guided over 4 m towards the acceleration column. The 90° bend cleans the beam from parasitic H_2^+ and H_3^+ ions which otherwise would hit the acceleration electrodes. An additional advantage is the possibility to do maintenance work on the source without breaking the acceleration tube vacuum. S1, S2 are solenoids, and Q1-Q4 are quadrupoles which provide matching parameters for beam size and dispersion. A chopper and buncher will be installed in the dome for diagnostic purposes.

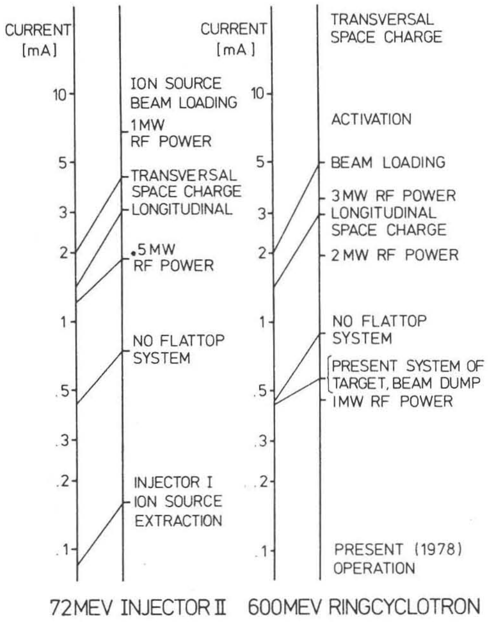

Figure 10 Current limits of injector II cyclotron and 600 MeV ring cyclotron. Limits from RF power and targets are of a technical nature and can be pushed up given enough money and time. Current limits from space charge, however, are fundamental in nature. The exact value of these limits depends on details like particle distribution within the beam and the amount of possible neutralization from electrons.

An increase of the available proton energy is also under consideration at SIN. Acceleration from 600 MeV to 3 GeV in a single stage with superconducting sector magnets looks feasible. This might be a useful project for a Kaon facility. The higher intensity of a continuous beam from a cyclotron may offset the disadvantage in energy against a pulsed beam from a rapid cycling synchrotron.

On the application side there is the possibility of using a fraction of the intense 72 MeV beam from the injector II parasitically for neutron research (see fig. 11). Candidates for the resulting high flux of fast neutrons are medical neutron therapy or material studies for fusion reactors.

The possibility of using high intensity accelerators for electrical breeding of fissionable material has been examined[19]. Although Linacs are considered to be the only economical choice a 3 GeV cyclotron with a current of several mA could provide a good pilot plant for further studies.

7. Conclusions

Some recent developments and future projects at SIN have been discussed with special emphasis on the accelerator facilities. For progress made on experimental equipment like secondary beam lines, spectrometers and detectors the reader is referred to the SIN annual reports. Experiments performed with the facilities will be mentioned in another paper[20] of this conference.

8. Acknowledgements

This paper reports the developments at SIN performed by a large number of people and credit for this work goes to the entire staff of SIN. I personally thank my colleagues S. Adam, T. Blumer, D. Dohan, S. Drack, W. Fischer, H. Keller, M. Olivo, U. Schryber, T. Stammbach and H. Willax for their contributions to this paper through stimulating discussions.

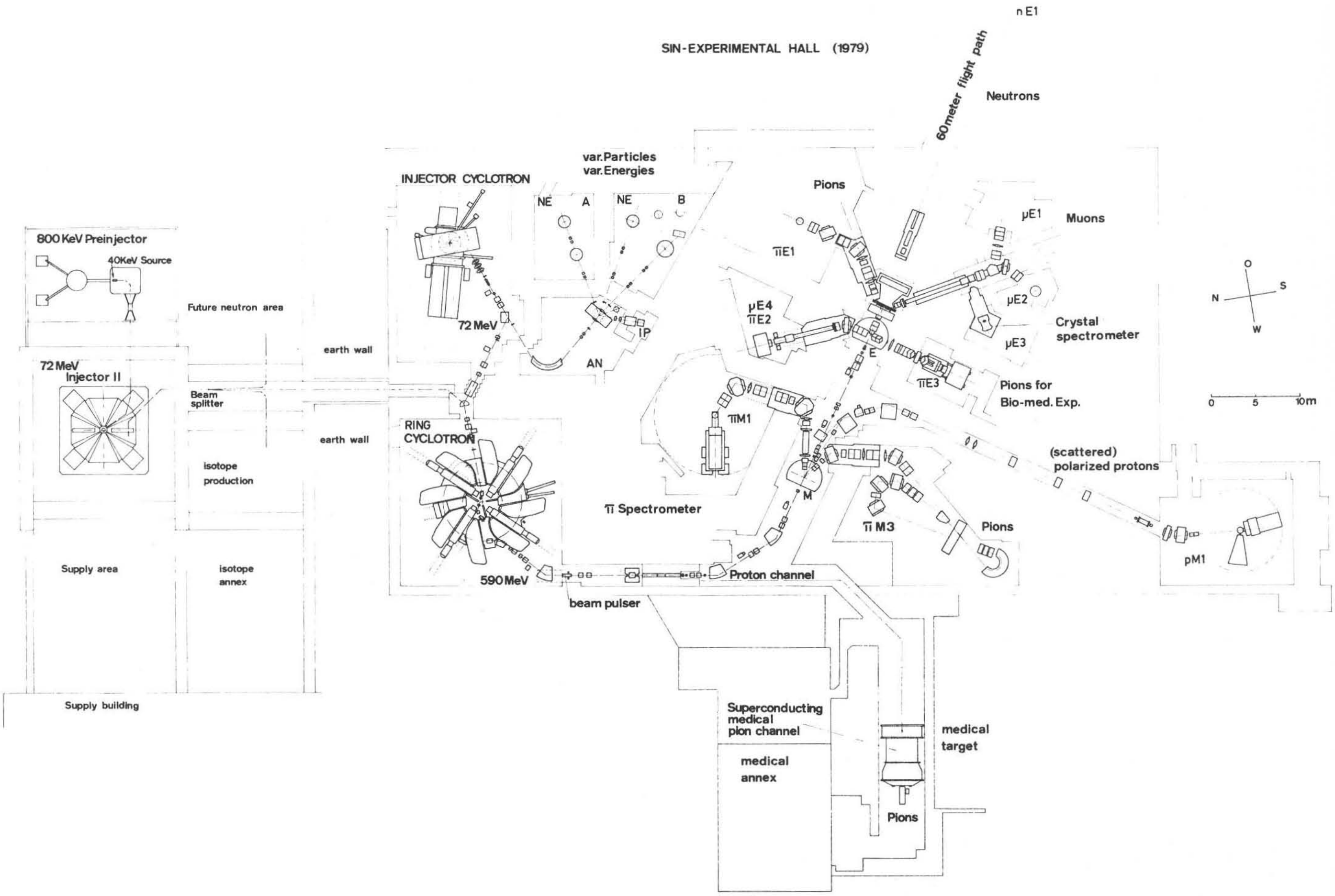

Figure 11 *Layout of SIN accelerators and experimental installations. The 590 MeV proton beam hits first a thin target M and then a thick target E. Both targets are radiation-cooled wheels of Be, graphite, or aluminum oxide. Two superconducting muon channels feed the four muon areas* $\mu1$-$\mu4$. *In addition to four pion areas, there exists a beam of fast neutrons and a parasitic beam of elastically scattered protons which are 40% polarized. The present injector cyclotron produces 72 MeV protons as well as low energy particles of variable energy. The new injector located in the left part of the diagram will be operational towards the end of 1982. It will also provide a parasitic beam of the order of 100-300 μA for continuous production of the isotope* I^{123}. *The medical pion applicator at the bottom of the diagram will start first tests in 1979.*

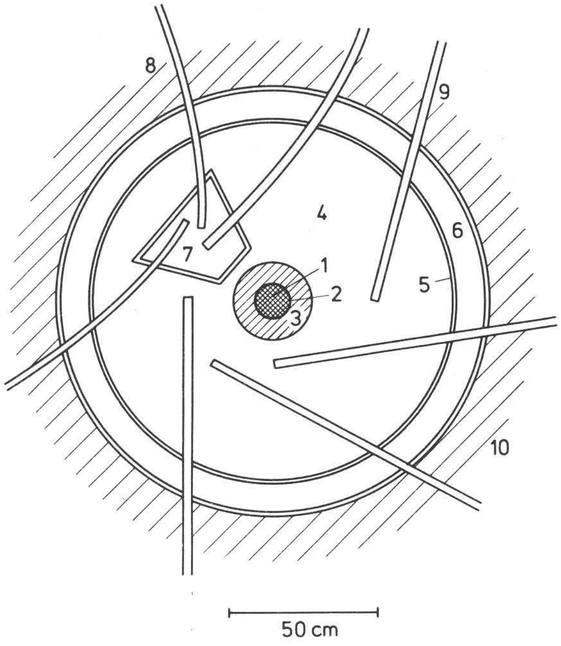

Figure 12 Conceptual arrangement of planned spallation neutron source (plan view). The beam will enter the target from above and the neutron guides are all in the horizontal plane. Since a fairly high beam power of around 1 MW will be dumped in this target a solid depleted uranium target would lead to considerable technological difficulties. The concept of a liquid heavy metal target has been chosen. This Pb/Bi euthecticum represents also the primary cooling circuit.

1	Pb/Bi liquid target
2	target vessel (stainless steel or zirkalloy
3	Be (D_2O cooled)
4	D_2O-moderator
5	moderator tank (Al)
6	H_2O-reflector
7	cryogenic moderator H_2/D_2 at 20 K
8	neutron guides for cold neutrons
9	neutron beams tubes
10	iron and concrete shielding (∿ 5 m)

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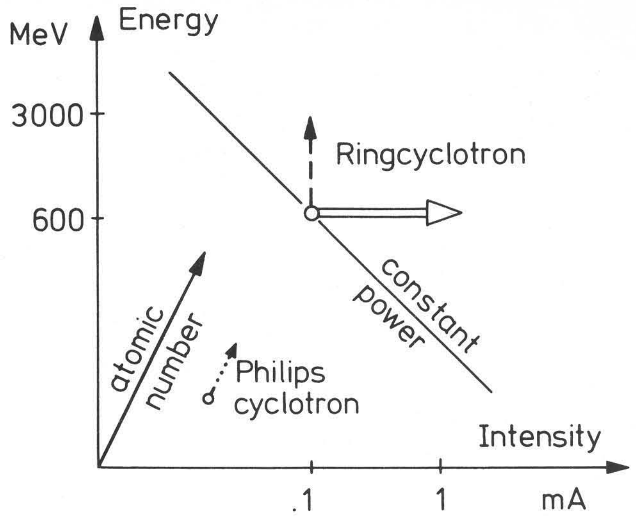

Figure 13 Expansion possibilities of SIN cyclotron facilities. An accelerator can be characterized by three main parameters: energy per nucleon, average intensity and atomic number. In the near future expansion at SIN will go in the direction of higher intensity, with a possible conversion later on into a Kaon facility. With the construction of the new injector the present Philips cyclotron will become free for expansion towards light and medium light ion beams.

** DISCUSSION **

G. DUTTO: What type of source are you planning to use?

W. JOHO: We will test two different sources: the single aperture reflex arc source by John Osher at Livermore and the bucket ion source from Thompson at Culham. Both should be able to deliver 100 mA DC beam with very good beam quality, but we will operate them initially at about 30 mA DC.

Y. JONGEN: What is the time schedule foreseen for the second injector?

W. JOHO: We expect the first beam out of the machine not before summer 1982, since we have only a limited number of people to work on this particular project.

E. BLACKMORE: You mention that you have axial injection in this new injector. How do you do the 90° bend into the median plane?

W. JOHO: We use a 90° dipole bending magnet with a field of 11 K Gauss. For the axial injection you have to match four different conditions, two for beam size and two for dispersion. Thus, we need for a symmetric solution two times four quadrupoles. The quadrupole excitations depend strongly on the beam current.

J. NEED: At what current was the 90% extraction efficiency measured for the Phillips injector?

W. JOHO: At currents up to 90 μA. The precessional extraction method is used to increase the turn separation.

R. VADER: For your old injector, do you notice any broadening of the beam bursts because of space charge effects which will affect single-turn extraction?

W. JOHO: In the old injector we do not have separated turns. There is some evidence for slight changes in the beam behavior at higher currents, which are generally attributed to space charge effects. But up to 100 μA no drastic effects are observed. We do restrict the beam very nicely in phase with vertical collimators in the center. As a result, we have quite a narrow phase width, which gives good extraction and also a small energy spread. This gives the basis for single-turn extraction in the ring.

M. CHAUDHRI: Have you already started this pion treatment? And, secondly, with your new superconducting magnets what dose rate are you expecting, and what proton energy are you using to produce the pions?

W. JOHO: The medical applicator will be ready next year. Everything is mounted, with the exception of the coils, which will come later this year. We then expect that with 20 μA on the medical target we will get about 50 rad per minute in a 1 liter volume. So with, say, 300 rad per fraction, you expect a treatment time of six minutes or so.

The proton energy is 590 MeV, and the pion energy is in the neighborhood of 70 MeV; the range can be between 10 and 20 cm.

F. HINTERBERGER: I have a question concerning the minimizing of intensity loss with the magnetic field and the dee voltage. How did you measure these contour plots, and do you use them routinely for optimization?

W. JOHO: The isolated strip in front of the septum is used on-line by the operators to minimize losses. They vary the cavity voltage by 10^{-4} or so, to see where the minimum really is. Then they change the magnetic field a bit to trace out that minimum. Once you hit the local minimum, the operator is able to keep the beam there. So we can really do this optimization at the level of 80-90 μA, on-target, on-line. Contour plots are made during beam development studies and take about half an hour to perform.

V. DMITRIEVSKY: What is the limiting intensity in strong-focusing ring cyclotrons?

W. JOHO: I think that the current limit is given by space charge effects, mainly in the longitudinal direction. One remedy against this problem is to blow up the beam vertically a bit. Another remedy, more for the future, is to increase the energy gain per turn. At the moment we have 500 kV per cavity. If we go to 1 MV we can probably increase the space charge limit into the 5-10 mA region.

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