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THE SIN ACCELERATORS, OPERATIONAL EXPERIENCE AND IMPROVEMENT PROGRAMS

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Summary

The SIN meson facility, in operation since 1974, consists of a 590 MeV ring cyclotron for protons and a 72 MeV injector cyclotron. The average beam current on target is presently about 50 µA, the peak being 112 µA. Extraction efficiency, once considered a severe handicap for cyclotrons, is now 99.6 to 99.9 % for the ring cyclotron and about 90 % for the injector. Many improvements in both accelerators allow single turn extraction in the ring cyclotron. The present current limit is given by the injector, while the ring itself could accept now a 600 µA beam, with 2-4 mA as an ultimate limit. Some muon experiments require a pulsed beam with on-off times in the order of the lifetime of the muon. First trials with beampulse frequencies of 200 and 400 KHz and a 50 % duty cycle have been successful.

Improvement of beam performance in the past two years

The historical development of the SIN meson facility and its performance in the first year of operation have been described in earlier conferences.[1,2,3]

In the past two years, beam intensities, beam time for experiments and reliability of operation were increased. In 1976 a total of 80'000 µAh of 590 MeV protons were used for pion production. Availability of the beam - defined as the ratio between achieved and scheduled beam time - was typically 85 %. All relevant beam parameters were improved, (see fig. 1), with the almost 100 % extraction from the ring cyclotron as the outstanding feature (see fig. 2). On Dec. 21, 1976, the initial design goal of 100 µA on target was achieved (see fig. 3). These results were obtained thanks to many improvements on both accelerators and an intensive beam development program.

The following improvements were carried out on the 72 MeV injector:

- replacement of the passive magnetic extraction channel with a more rigid version.
- replacement of the motor driven frequency tuning system by a fast hydraulic system (developed by P. Sigg). This change improved reliability and gives now an RF-stability of $2\text{-}3 \cdot 10^{-4}$.
- quartz glass tubes mounted over the support insulators of the electrostatic septum (which had caused a large fraction of down time in 1975) to protect them from coating.
- the cryopumping system was put into operation improving the voltage holding on the septum.
- a new ion source head now allows reproduceable filament positions after replacements.
- installation of vertical collimators and vertical deflection plates in the center of the cyclotron. This proved to be the most important change because it reduced not only the vertical beamsize, but also - through the phase dependent vertical electric focusing - the phase width and the energy spread. This in turn lead to higher extraction rates and extracted currents for a given activation level.
- fixing most parameters in the injector.

All these improvements gave more reproduceable beam conditions and better matching between injector and ring.

		Dec. 1974	Dec. 1975	Dec. 1976
horiz. emittance 72 MeV for 80 % of beam	mm mrad	$\pi \cdot 6$	$\pi \cdot 6$	$\pi \cdot 2$
horiz. emittance 590 MeV for 95 % of beam	mm mrad	$\pi \cdot 5$	$\pi \cdot 4$	$\pi \cdot 1$
energy spread (FWHM) at 590 MeV	%	∿0.3	∿0.15	∿0.07
extraction from injector	%	55-65	65-75	85
extraction from ring	%	80-95	90-95	99-99.9
intensity during routine operation	µA	1- 2	10-20	40-60
peak intensity	µA	12	62	112
availability of beam	%	55-60	80-90	85-90
beam production per week	µAh	20-30	1500	5000

Fig. 1 Evolution of some important beam parameters over the last two years.

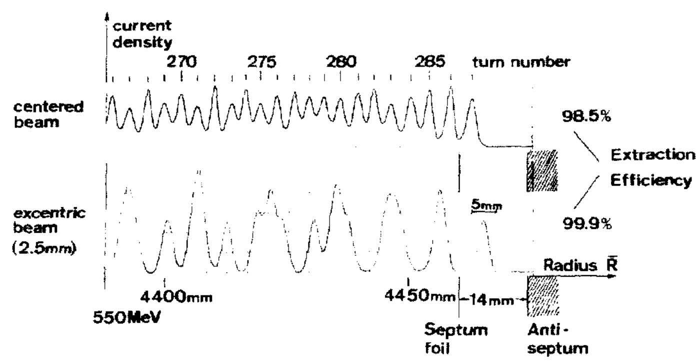


Fig. 2 The last 22 turns in the ring cyclotron. A .2 mm thick secondary emission probe measures the beam current in front of the extraction septum. The top trace shows a well centered beam with a beam quality of $\pi \cdot 1$ mm mrad. For the bottom trace the beam was injected excentrically into the ring with a coherent amplitude of 2.5 mm. The ν_r-value of 1.5 at extraction (see fig. 4) helps to double the original distance between the last two turns to 9 mm. Extraction losses given by the beam hitting the septum foil is thus reduced to .1%.

On the ring cyclotron a number of new gadgets were installed:

- ionization chambers in the injection and extraction regions. Calibration of these spill monitors showed that the extraction losses can be determined very accurately (see fig.5).
- vertical and radial collimators at extraction
- secondary emission probes which operate up to 100 µA levels and non-intercepting phase probes[4] (see fig. 6).
- an extraction septum with 129 spring loaded molebdynum strips of 7 mm width and 50 mm thickness, eliminating thermal deformations[5].

Of big help for routine operation and beam development are an increasing number of control computer programs like:

- centering of the beam at the ring injection.
- closed loop centering of the extracted beam up to the targets. Positioning accuracy with non-intercepting probes is about .2 mm.
- program BONUS which displays a weighted sum of all beam losses from injector to target (higher BONUS means less induced overall activation).
With BONUS the effect of turning an arbitrary knob for any of the accelerators or beam lines can be seen immediately.

The 590 MeV ring cyclotron as a curled-up linear accelerator

The substantial improvement of the quality of the 72 MeV beam from the injector had a dramatic effect on the performance of the ring. The beam inside the machine shrunk to a circular cross section of 4 mm diameter (almost constant throughout acceleration). The initial phase width of 7^{o} (FWHM) in the injected beam was compressed to about 5^{o} (or .3ns in time) at extraction. This phase compression effect is due to the radial variation of the cavity voltage[6] and could be clearly demonstrated (see fig. 7). This narrow phase width means

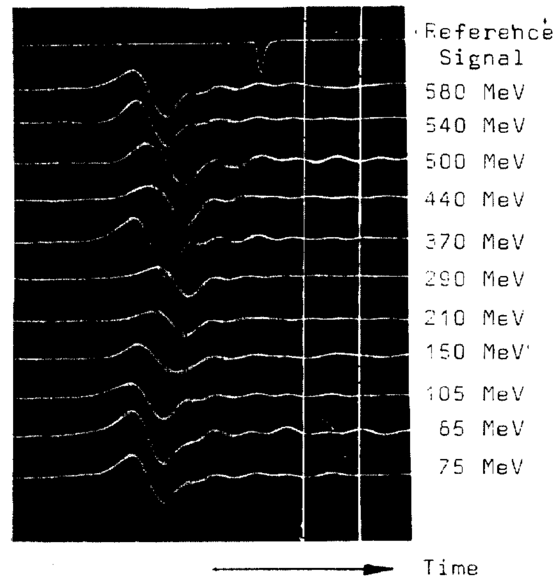


Fig. 6 Phase history of accelerated beam in ring cyclotron. Displayed are the signals from 11 internal capacitive phase probes. The two vertical lines are separated by 1 ns (or 20^{o} in phase) and show that the magnetic field is isochronous within $\pm 5^{o}$.

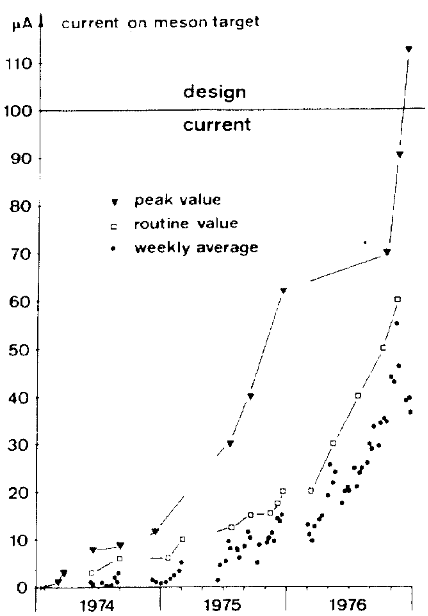


Fig. 3 Increase of the current on target over the last 3 years. The initial design goal of 100 µA was reached on December 21, 1976.

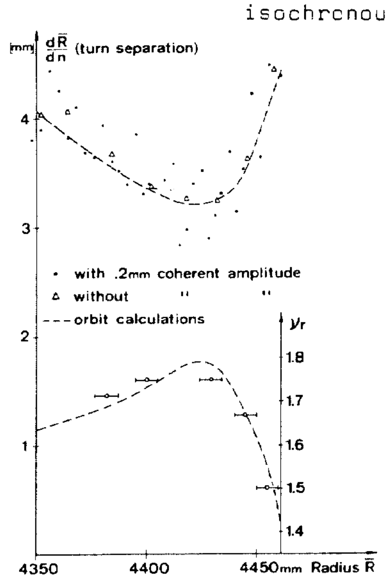


Fig. 4 The upper half shows the radial gain per turn in the extraction region of the ring, as obtained from fig. 2. The lower part shows a measurement of the focusing frequency ν_r. The onset of the magnetic fringe field decreases ν_r toward 1.5 and increases the average radial gain from 3 to 4.5 mm at extraction. With excentric injection the last radial gain can be as high as 9 mm.

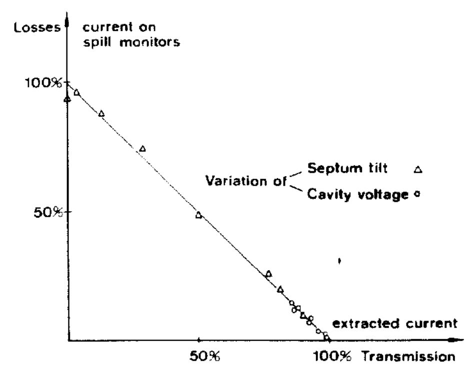


Fig. 5 Calibration of the extraction efficiency in the ring cyclotron. Variation of cavity voltage and tilting the septum changed the extraction rate from almost 100 % down to 0. Plotted vertically is the total current of all beam spill monitors (ionization chambers) and horizontally the signal from an external secondary emission current probe. The straight line through the measured points shows that the spill monitors are indeed linear with beam losses.

that practically all particles make the same number of revolutions and can be extracted in a single turn (see fig. 2). Placing the septum between the last two turns of a well centered beam gives an extraction efficiency of about 98.5 %. But one can do even better by producing a coherent amplitude at injection which persists to extraction and doubles the distance between the last two turns to 9 mm. This method has lead to extraction efficiencies of over 99.9 %, although routine values are more like 99.7 %. With the installation of a flattop cavity (1978), extraction losses can be reduced even further.

The ring cyclotron can thus be viewed as a curled-up version of a linear accelerator which fits into an area of 19x19 m^2! The problem of radioactivity, which long seemed to limit the intensity of cyclotrons, is under control up to very high currents. The existing ring accelerator could accelerate a beam of up to 600 μA and, with some modifications, the target stations could handle such a beam. Installation of more RF power would push the limit into the range of 2-4 mA, the exact value given by space charge effects. The intensity is presently limited by the injector to about 50-100 μA for routine operation. In view of this situation, it is more and more evident that we have to construct a more powerful injector, delivering beams in the order of a few mA. Details for such a machine are already worked out[7], but authorisation of the project by the Swiss Government is still pending.

Operational Experience

The distribution of beam time and down time in 1976 is summarized in Fig. 8. Pions were produced during 3000 hours. During a few shifts about 30 nA of polarized 590 MeV protons were produced and 850 hours were devoted to research with a wide spectrum of alpha, deuteron and

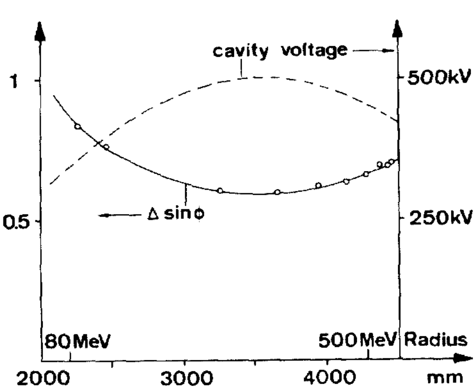


Fig. 7 First demonstration of the phase compression - phase expansion effect in a cyclotron. The cosine-like radial distribution of the cavity voltage produces an RF-magnetic field which first compresses, then slightly expands the bunch length of the circulating beam. Actually, the central phase Φ(R) of the bunch was measured for different initial phases at injection. The circles are the measured differences ΔsinΦ. The solid line gives the theoretical prediction ($E_G \cdot \Delta\sin\Phi$ = constant) for this effect, where E_G is the energy gain per turn of the particles.

proton beams (the latter two also polarized) from the injector. In addition the injector is reserved for 4 hours per week for the production of the radioisotope I^{123}. With typically 120 μAh of 72 MeV protons, an activity of 1.5 Curie is produced after chemical processing. This is, to our knowledge, the highest yield of I^{123} produced anywhere. Targeting and processing of this isotope is performed by the Swiss Institute for Reactor Research (EIR).

Due to the excellent performance of the ring cyclotron, the scheduled beam development time for 1977 has been strongly reduced. Emphasis will be mainly on the injector and on more computer control applications. Dropouts of the cavities make up half the down time of the ring cyclotron. These cavities[8] operate at the very high voltage of 520 kV with a Q of 30'000. Typical mean times between dropouts is 6 h with an average interruption of about 12 minutes. Pulsing the cavity voltage through the multipacting stage should reduce the down time to about one minute in the future.

The rotating targets (designed by C. Tschalär) continue to behave very reliably and gave no problem during the 100 μA test. The favorite targets for pion production are Be and C due to their low electron contamination in the pion beams.

Activation

In spring 1977, a typical production run with 50 μA on target produces about the following beam losses:

5 μA at 72 MeV, extraction from injector
.2 μA at 72 MeV, beam transport + injection
.05-.2 μA at 590 MeV extraction from ring
.1 μA at 590 MeV beam transport
1 μA lost in thin target

Activation doses obtained by SIN personel in 1976 were about evenly distributed between injector, ring and target installations plus beamline. 7 persons received doses between 1-2 rem/year. The induced dose from the injector came mainly from routine operation. Changing the filament gives 15 man-mrem each time, while changing the septum electrodes, for example, leads to an absorbed dose of 200 man-mrem. The activation in the ring cyclotron is produced mostly during setup, tuning and beam development. New control computer programs for optimizing the beam quickly and reliably should help to reduce this activation.

590 MeV p on targets	33.5 %	63.0 % accelerator in operation
isotope production	1.4 %	
low energy p, d, α-beams	9.7 %	
beam development	10.0 %	
setup, tuning, training	8.4 %	
regular service	6.1 %	26.1 % planned shutdowns
planned shutdown	20.0 %	
drop outs injector	4.9 %	10.9 % unscheduled shutdowns
drop outs ring	4.8 %	
drop outs varia	1.2 %	
total = 8784 hours in 1976	100.0 %	

Fig. 8 Distribution of beam time and down time for the SIN accelerators in 1976.

Typical activation levels, one day after the beam has been turned off, are:

injector vault, average	10 mr/h
ring vault, average	5 mr/h
ring vault, extraction region	30-50 mr/h
vacuum chamber above septum	2r/h
1.5 m in front of thin target	30 mr/h
quadrupoles after thin target	2 r/h
1.5 m in front of thick target	1 r/h

Radiation levels during operation with 50 μA are:

above vault roofs of accelerators	2-5 mr/h
above target roof	10 mr/h
inside experimental areas	5-50 mr/h
in experimental hall, outside shielding at beam heigth	100 mr/year

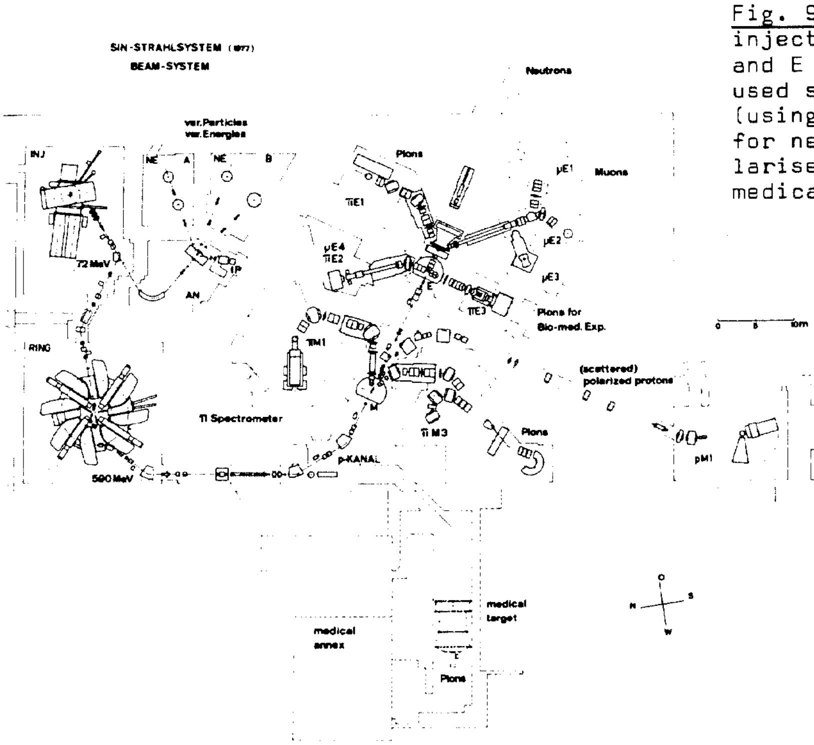
This last figure corresponds to the difference in the natural background between Zürich and St. Moritz in the Alps!

Pulsed beam

To reduce the background for some muon experiments, an external 590 MeV beam pulser was designed by U. Schryber, P. Lanz and M. Märki[9] and made operational in spring, 1977. First trials with beam pulse frequencies of 200 and 400 KHz and a 50 % duty cycle have been successful. Together with a prepulser right after the ion source, a suppression of particles to better than 10^{-6} during the beam-off time has been achieded.

New experimental facilities

In the past two years, the following new facilities have been put into operation:
- the pion spectrometer SUSI in area πM1 (see fig 9)
- a second superconducting solenoid for high fluxes of muons, feeding area μE4.
- a beam splitter after the first muon channel producing muons for areas μE1 and μE2 simultaneously. As a consequence SIN has now the three most intense muon beams in existence.



- an appendix to the beam line πE3, producing a large flux of slow pions. Muons from the pion decay are subsequently trapped in a magnetic bottle for muonium formation.

A major extension of the facilities will come with the construction of a medical annex[9] for pion therapy, starting this year. The new annex can be seen at the bottom of fig. 9. A beam splitter consisting of a 50 μm thick septum will divide the extracted 590 MeV beam in an arbitrary ratio between the present targets and a new medical target. A superconducting pion collector à la Stanford[10] with an acceptance of 1 sterad will focus pion beams from 60 different directions onto the tumour. After remeasuring the pion cross section at 60° and 90° take off angles, it was decided to modify the Stanford geometry and adopt the 60° version. With a 20 μA beam and a 1 l tumour region, the produced dose will be 50 rad/min, which will allow relatively short irradiation periods.

Experiments

For a description of all ongoing experiments at SIN we refer to the SIN Physics Report Nr. 1 of December 1976, available from the SIN secretariat. Further results will be published in the proceedings of the upcoming "7th International Conference on High Energy Physics and Nuclear Structure" to be held at the end of August 1977, in Zürich.

Acknowledgements:

Successful operation of the SIN accelerators was only possible with the dedicated effort of the operating crew (headed by T. Blumer), maintenance crew and technicians, who developed many new gadgets. Special thanks go to S. Adam J. Collins, S. Drack, W. Fischer, H. Keller, C. Markovits, L. Rezzonico, U. Rohrer, U. Schryber and E. Steiner, who contributed to the improvement of our accelerators with their regular beam development work.

Fig. 9 Layout of the experimental hall with injector, ring and the two targets M (thin) and E (thick). 10 experimental stations can be used simultaneously: 4 for pions, 4 for muons (using 2 superconducting solenoids) and one for neutrons and scattered protons (40 % polarised). The broken lines indicate the future medical annex for pion therapy.

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