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THE S. I. N. RING CYCLOTRON AFTER ONE YEAR OF OPERATION

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Summary

The 590 MeV isochronous ring cyclotron produced its first extracted proton beam in January 1974. One year later the situation is as follows:

Two external targets with a total of six secondary pion beam lines and one neutron line are operational and a number of experiments with medium energy pions have been performed. The superconducting muon channel is operating successfully and produces the highest muon fluxes ever recorded. Transmission through the ring cyclotron is more than 95 %. Typical currents on the targets are 5 µA, the maximum being 25 µA.

Introduction

The S. I. N. 590 MeV ring cyclotron for protons has been described in previous conferences[1] and thus only a short summary of its basic features are given. A conventional 4-sector isochronous cyclotron, constructed by the Philips Company Eindhoven,[2] pre-accelerates protons to 72 MeV, which are afterwards transported over 40 m towards the ring cyclotron (Fig. 1). The ring cyclotron consists of eight separate sector magnets and four high Q-cavities which accelerate the protons to their final energy of 590 MeV, high enough to produce intense beams of pions from two external targets.

The project of the S. I. N. cyclotron facilities was officially approved by the Swiss Government in 1966/1968 and the ring cyclotron was essentially completed in autumn 1973. Director of the institute is Prof. J. P. Blaser.

The virtue of the ring cyclotron concept (devised in 1962 by H. A. Willax)[3] compared with conventional cyclotrons is the existence of field free regions between sector magnets. This leads to a number of benefits:

1. The accelerating cavities can be made very efficient because they do not have to be squeezed into the magnetic gap. Voltages up to 700 kV have been obtained across the accelerating gap with a power consumption of only 250 kW.[4]
2. Due to this high energy gain per turn, the radial spacing between two turns at injection and extraction is relatively large. This leads to small extraction losses allowing the acceleration of intense beams.[5]
3. The resultant low number of turns gives relaxed conditions on magnetic field tolerances for isochronism and single turn extraction is possible.
4. The sector magnets are very economic. The power consumption for all eight sector magnets together is only 650 kW due to the small magnet gap of 5 to 10 cm. The small gap gives strong vertical focusing at the sharp magnet edges. As a consequence, the vertical beam diameter is small and tolerances on the magnetic field are relaxed.[6]
5. The free sectors give excellent access to the beam for diagnostic elements, injection- and extraction-elements and local collimators to shield against the particles lost at the extraction septum. As a further curiosity, the 1 m long S. I. N. extraction septum is completely straight, which allows it to be very precisely constructed.

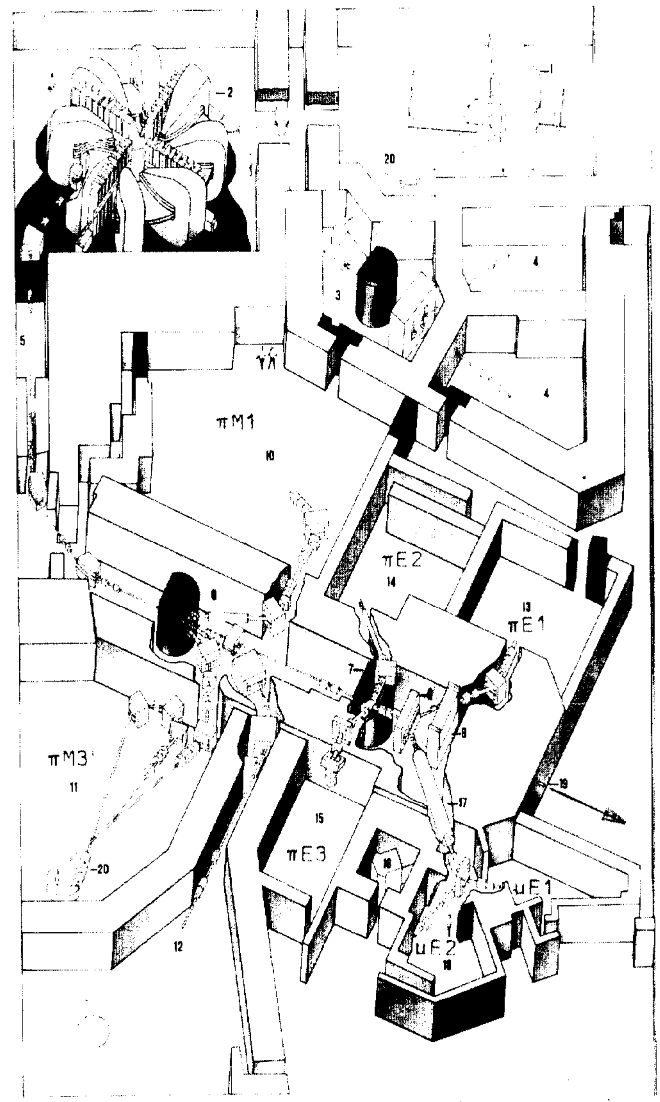

Fig. 1 S. I. N. Experimental Hall
1 Injector cyclotron (2.5 pole diam) 72 MeV p
2 Ring cyclotron (15 m outer diam) 590 MeV
3 Analyzing system for low energy beams
4 Experimental areas for low energy beams
5 590 MeV p beam line
6 Pion production target "M" (thin target)
7 Local shielding for thick target "E"
8 Secondary beam bending magnet
9 Beam dump
10 Experimental area πM1 for pion spectrometer
11 Experimental area, used for first pion detection and experiments (πM3)
12 Polarized proton beam
13, 14 Pion experimental areas πE1, πE2
15 Biomedical pion beam area πE3
16 Muon experimental area, crystal spectrometer
17 Superconducting muon channel
18 Muon experimental area µE2
19 Neutron beam
20 µ-neutrino mass experiment

Beam Development During 1974

The ring cyclotron obtained the first proton of 72 MeV from the injector in early January and on January 18, 1974 protons were successfully accelerated to 590 MeV and extracted from the cyclotron, although only three of the four cavities were operational during that day. One month later the proton beam was guided to the first target station and the first pions were detected in the experimental area πM3. During a 3 months' shutdown in autumn 1974, the second target station with its secondary beam line was installed and the production of pions and neutrons from this target started in the middle of December. The rest of the year was devoted to pion production from the thin target, beam development on the two cyclotrons and training of machine operators.

What are the main achievements on the cyclotron performance during this first year of operation? The injector cyclotron was successfully commissioned by Philips and delivered the required 100 μA beam at 72 MeV within the specified beam properties. Noteworthy is the 75 % extraction efficiency, quite high for this type of isochronous cyclotron but absolutely necessary for a high intensity operation. The commissioning of the ring cyclotron went very smoothly. The raw magnetic field of the cyclotron proved to be surprisingly isochronous if one takes into account that, for the first time, a relativistic mass increase of 63 % had to be taken into account for the isochronous revolution frequency. Since the harmonic number is 6 (6 bunches per revolution), a field change of 2×10^{-4} prohibits acceleration to maximum energy. Fig. 2 shows the measured particle phase ϕ, relative to the peak voltage of the RF cavities.

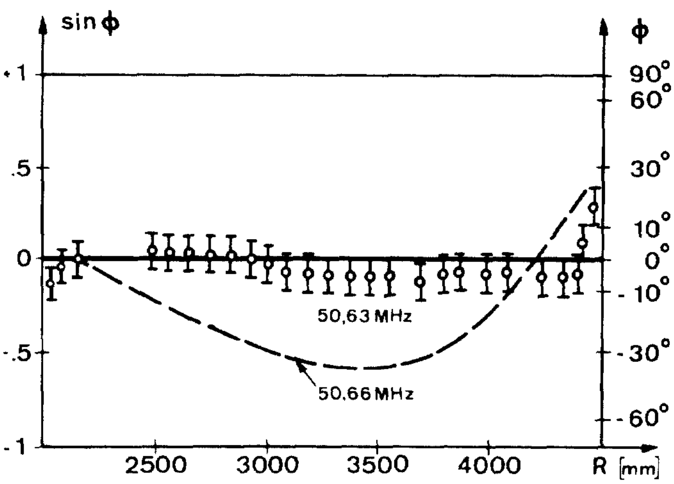

Fig. 2
RF-phase ϕ of the accelerated particles as a function of radius for the original design frequency of 50.66 MHz and the final frequency of 50.63 MHz. Both curves were obtained without exciting any trim coils and show that the magnetic field is isochronous to $\pm 5^{\circ}$ between 75 and 580 MeV. With trim coils the field is isochronous everywhere, an important prerequisit for future flattop operation and single turn extraction.

A big effort on beam development went into the 72 MeV beam line between injector and ring, since the beam has to be properly prepared to match the input requirements of the ring cyclotron. Of prime importance is the radial and vertical centering at injection plus the matching of the beam ellipses in radial and vertical phase space. Special care has to be taken for avoiding an increase in phase space due to the energy spread of 0.2 % in the proton beam. To obtain the best matching for this dispersion, different settings of the injector were tried out. Fig. 3 shows that our efforts were quite successful. The first 25 turns in the cyclotron are displayed, indicating that the beam quality from the injector is indeed satisfactory ($\pi \times 6$ mm-mrad for 80 % of beam) and that no particles are lost at injection.

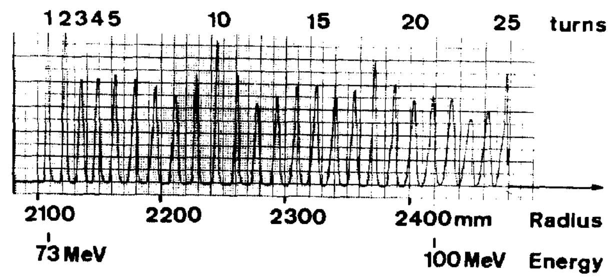

Fig. 3
The first 25 turns in the ring cyclotron, measured with a 1 mm wide differential probe. Displayed is the beam current versus radius for a 1 μA beam. The turn separation at injection is 15 mm and the average radial beam diameter is 6 mm, leading to 100 % injection efficiency.

The vertical focusing frequency ν_z is close to one at injection and the vertical beam position is sensitive to a first harmonic of a horizontal magnetic field component B_r. The vertical beam position was measured with a differential current probe consisting of three fingers and a copper block stopping the beam. A residual B_r-component of about 1 G was deduced and finally corrected with an asymmetric trim coil excitation. The result is shown in Fig. 4. After the correction, all the beam is vertically contained in a 10 mm high strip, indicating again a good beam quality and good matching in the vertical phase space.

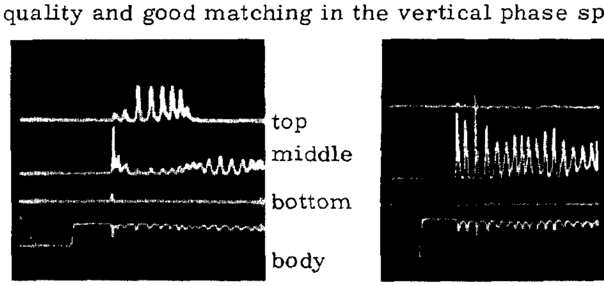

Fig. 4
The vertical distribution of the beam during the first 17 revolutions in the ring cyclotron, measured with a 3-finger differential probe. The four curves show the current on the top, middle and bottom finger as well as on the body of the copper probe. The left and right pictures show the situation before and after correction of the residual horizontal magnetic field ($\sim$ 1 G) with asymmetric trim coil excitation. After the correction all the beam is vertically contained on the 10 mm high middle finger.

While the first 25 orbits are measured with three differential probes moving out from the center of the ring, the rest of a total of 280 turns are scanned with a secondary emission probe moving in from maximum radius. The measuring foil has a thickness of 0.1 mm.

Fig. 5 shows the last 11 turns in the cyclotron and demonstrates better than any words that the S.I.N. ring cyclotron is operating successfully. Despite a relatively large phase width of 20° (total width of triangular shape), a clear turn structure is observed. About 50 % of the beam is contained in the 5° phase interval necessary for single turn extraction. Since the diagram is reproducible, a stability of the cavity voltage of better than 10^{-3} is inferred.

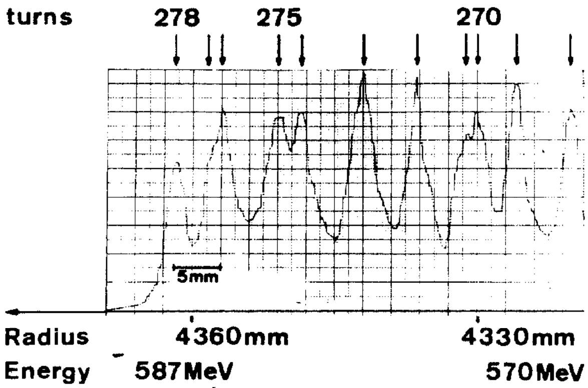

Fig. 5
The last 11 turns in the ring cyclotron measured with a 0.1 mm wide secondary emission probe. About 50 % of all particles are in a "single turn-narrow phase width" mode and give the pronounced separated turn structure. The four high voltage cavities produce an energy gain per turn of 1.7 MeV and a turn separation of 4 mm. A coherent amplitude from a slightly eccentric injection is still noticeable at extraction. Placing the septum (0.05 mm thick) between two turns leads to an extraction efficiency of more than 95 %.

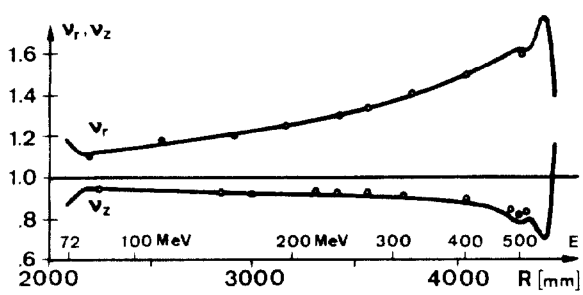

Fig. 6
A comparison between the calculated (solid line) and measured (open circles) values of the radial and vertical focusing frequencies ν_r, ν_z. Note the strong vertical focusing, typical for ring cyclotrons with their sharp sector edges. The integer resonance $\nu_z = 1$ is avoided except for one rapid crossing four revolutions before extraction.

Analysis of a complete turn pattern gives a very precise determination of the focusing frequencies, ν_r and ν_z. Rather than measuring ν_r at a given radius, the radial position of the characteristic pattern of rational ν_r values is determined. Fig. 6 shows the measured values with open circles representing ν_r-values of 11/10, 7/6, 6/5, 5/4, 10/3, 4/3, 7/5, 3/2 and 8/5. ν_z-values were obtained by observing coherent vertical oscillations on a multifinger secondary emission probe.

In 1967 it was decided to increase the maximum field of the ring cyclotron from 19 to 21 kG to obtain the present 590 MeV instead of the originally planned 520 MeV. This meant that the coupling resonance $\nu_r = 2\,\nu_z$ had to be crossed at least twice. No beam losses are observed as long as the centering of the beam is better than 5 mm, as expected from calculations.[5]

Present Performance of the Cyclotron and Future Plans

The original design goal for the proton intensity is 100 μA. As of early March 1975, the highest beam current measured on the targets is 25 μA (during a trial run of 10 minutes). This represents a beam power of 15 kW at 590 MeV and special care has to be taken in tuning up such a beam. Effects of space charge and beam loading are clearly observable. Our next effort will go into beam studies at different current levels before routine operation at high intensities is possible. The beam transmission through the ring cyclotron is of prime importance and has been steadily improved to a present maximum of well over 95 %. Typical values during routine operation are presently 85 to 95 %. The extraction septum consists of four individually stretched molybdenum strips followed by a single 0.05 mm thick and 1 m long foil. At currents above 10 μA a slight buckling of the foil is observable on a TV screen, giving a reduction in transmission by 5 %, while the strips show no deformation at all. An improved septum with strips throughout will be ready for installation during the next shutdown. The injection and extraction septa run at 70 kV across a 15 mm gap and 90 kV across a 13 mm gap, respectively, and no sparking problems have occurred. The accelerating cavities run steadily at 500 kV peak voltage with a typical availability of all four cavities of 90 %. The mean time between cavity drop-outs is about 5 hours, 20 hours not being unusual. With only three cavities running, transmission through the ring is about 60 to 70 %. The cavity voltage will be gradually increased to 600 kV in the future.

Distribution of beam time between middle of December 1974 (installation of thick target finished) and early March 1975 is as follows: 9 scheduled weeks for medium energy experiments, 14 full days lost due to unscheduled maintenance and repairs. Scheduled maintenance: 14 h/week. The remaining thousand beam hours are partitioned into:

production of pions from targets	:	40 %
set up and training	:	18 %
beam development	:	12 %
down time (less than 24 h periods)	:	30 %

During about 420 h of beam time a total of 840 μAh were produced on the targets. During day time the average beam current was reduced to below 1 μA, while during night shifts currents were in the range of 1 to 10 μA.

Activation levels: 4 hours after a shutdown of the accelerators the activation levels are typically:

injector vault	:	2 mR/h
injector extraction system/beam stop	:	10 R/h
ring cyclotron vault	:	10 mR/h
ring cyclotron extraction system	:	3 R/h

During operation a set of 24 ionisation chambers indicate immediately where beam spills are occurring.

Work on the injector is concentrated on improving the reliability of critical components (like the RF-system) and establishing stable beam conditions. The injector cyclotron operates for one week per month in the low energy mode, providing variable energy beams of protons, deuterons and α 's to nuclear physicists. A polarized proton source was successfully commissioned together with the axial injection system into the cyclotron. A polarized proton beam of 10 nA was injected and accelerated to 30 MeV. Priority on these beam tests is very low, since the 590 MeV polarized proton line will not be ready until later this year.

What are the future plans on the accelerator side?
a) In order to convert the best performances of today into the routine performances of tomorrow, more and more use has to be made of on-line computer control. Different computer programs have been written for the S. I. N. cyclotron as set-up aids for the operators (e. g., centering at injection into the ring), but so far no periodic survey of key parameters is being done. There is clearly a need for such control functions, since changes in the ion source conditions can be observed at the targets.
b) A flattop cavity operating at 152 MHz is under construction and will be installed in the ring in late 1977. Single turn extraction will then be possible for a phase width of 20°, resulting in a further reduction of extraction losses and a smaller energy spread.
c) The project of a new injector consisting of an 800 kV Cockroft-Walton stage and a four-sector ring cyclotron is still under serious study. A 72 MeV proton beam of excellent beam quality and 1 mA intensity is envisioned. The accelerating system consists of a combination of Indiana-type deltas between 0.8 and 5 MeV and S. I. N. -cavities between 5 and 72 MeV. With a 2 cm turn separation at the maximum radius of 3.7 m, the extraction efficiency will be 100 %. Such a high quality beam can be extracted from the 590 MeV ring with an extraction efficiency of 99 %.

Experimental Facilities

A sizeable amount of the building money for S. I.N. went into construction of the experimental facilities. The following systems fell into this category (see Fig. 1): Beam transport for the primary proton beam, installation of the target stations M and E with their local shieldings, secondary beam lines for pions, the superconducting muon channel, a polarized proton target at 0.5 K, a 60 m long neutron channel and a pion spectrometer.

A view of a target assembly is shown in Fig. 7. At the thick target station, up to 10 % of the total beam power is absorbed in the target wheel. The wheel rotates at a frequency of 0.5 Hz and is cooled by radiation. The beam remaining after the target is stopped in a copper beam dump which can dissipate 60 kW.

The Superconducting Muon Channel [7]

Experiments with muonic atoms and stopped μ^+ in solids are of general interest at S. I. N. Rather than building a classical quadrupole muon channel (like at LAMPF), the decision was made in 1971 to design and construct a novel superconducting channel. The 8 m long solenoid is partitioned into 16 sections and produces a magnetic field of 50 kG. The inner diameter is 12 cm, the nominal current 870 A and the current density 150 A/mm^2.

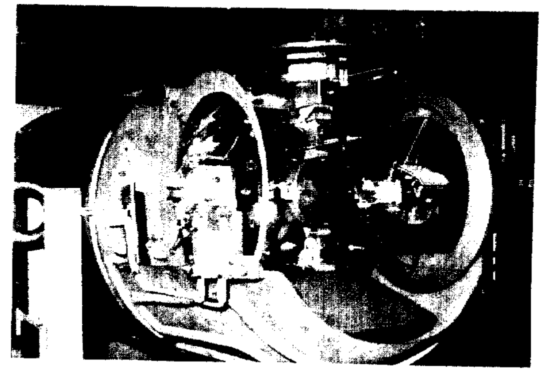

Fig. 7
The target wheel assembly with its four target wheels on a test stand. Every wheel can be brought into the beam path by a rotation of the array in steps of 90°. The wheels have a diameter of 30 cm and are made out of C, Be, Mo or Cu. This view is from a down stream beam position backwards towards the target and shows how the beam (simulated by a light source slightly to the left of the center) would hit the wheel along its rim. The beam is focused onto the 5 mm wide target with a precision of about 1 mm.

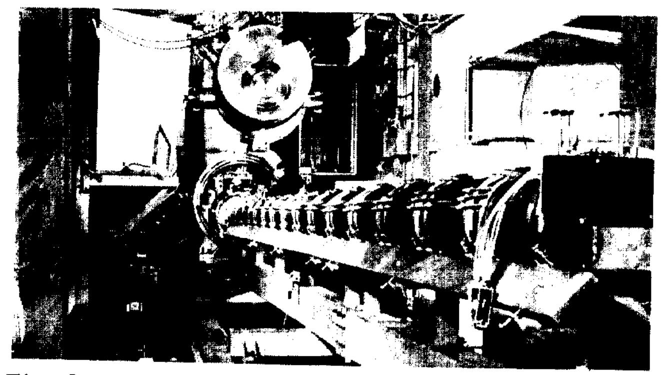

Fig. 8
A view of the S. I. N. super-conducting muon channel during final assembly. The channel is 8 m long and partitioned into 16 sections. A current of 870 A through a NbTi conductor produces a field of 50 kG. A 3 t iron cylinder (at 4.5 K) shields the surroundings against this strong field.

Advantages of such a channel are:
- close to 100 % efficiency in the collection of all muons from pion decay for the whole momentum band
- low π, e contamination,
- high muon polarization,
- no tuning of channel necessary.

The superconducting coil consists of NbTi filaments embedded in a copper matrix for intrinsic stability. Cooling of the coil and the 2.7 t iron shield to 4.5 K is done indirectly by the forced circulation of supercritical helium gas at 9 at. The advantage of this system against cooling with liquid He is:
- small He-volume (30 l for the whole magnet!),
- stable single phase circulation, small pressure and temperature drop between input and output,
- the solenoid is in vacuum and the magnetic energy of 1.4 MJ can be discharged with a peak voltage of 2 kV in 2 s,
- system losses at 4.5 K are 20 W.

The muon channel has operated successfully since January 1975 without supervision, producing the highest muon flux recorded anywhere. A comparison between the measured μ^+-fluxes at S. I. N. and LAMPF normalized to the design proton current is given below:

LAMPF	:	$1.4 \times 10^7\ \mu^+/s$ ·	$1000\ \mu A$
S. I. N.	:	$2 \times 10^7\ \mu^+/s$ ·	$100\ \mu A$

A second muon channel will be installed during 1975 for beam area πE2 (see Fig. 1).

Experiments

Thanks to the excellent shielding, the background in the experimental areas is very low, as can be seen in Fig. 9. It shows a time of flight spectrum measured by a group from Karlsruhe in the biomedical area πE3. Special advantage is taken of the 50 MHz proton beam structure in identifying the different particles. The spectrum was taken by starting a TAC with a counter signal and by stopping it with the 50 MHz signal! The maximum pion intensity in this biomedical area was measured[8] at 170 MeV/c and dosimetry measurements showed a dose of 0.3 rad/μA · min in the 300 cm^3 Bragg peak region. Biologists have performed preliminary experiments with this π^- beam by irradiating drosophila eggs and pregnant mice.

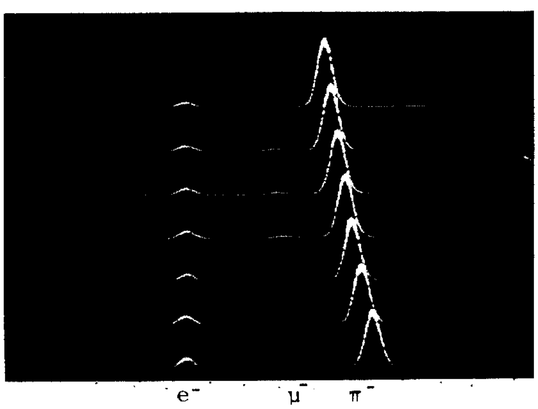

Fig. 9
Time of flight spectra in the biomedical beam from a 12 cm Be target. The different curves are obtained in momentum steps of 5 MeV/c from 150 MeV/c at bottom to 180 MeV/c at top. The spectra are taken for the same total integrated counts. Contamination of the pion beam by electrons and muons is low and decreases with higher momentum.

Although the main effort at S. I. N. is on basic research in nuclear and elementary particle physics, experiments on applications in chemistry, solid state physics, biology and medicine are in progress too. At the moment, eight experimental areas are used simultaneously.

Among the presently performed experiments are: formation of muonic helium at low gas pressure, π-N scattering from a polarized target, measurement of σ_{tot} of π^+ and π^- on deuterium, depolarization of muons in solids, investigation of muonic γ-rays with a high precision crystal spectrometer, pion induced fission, measurements of the characteristics of the unpolarized neutron time of flight facility, pion absorption in nuclei and further dosimetric and biological experiments with the biomedical π^- beam.

Fig. 10 shows the kind of experiment which can be done with intense pion beams. The spectroscopic quadrupole moment of the holmium nucleus could be determined[9] with a precision of ± 3 %.

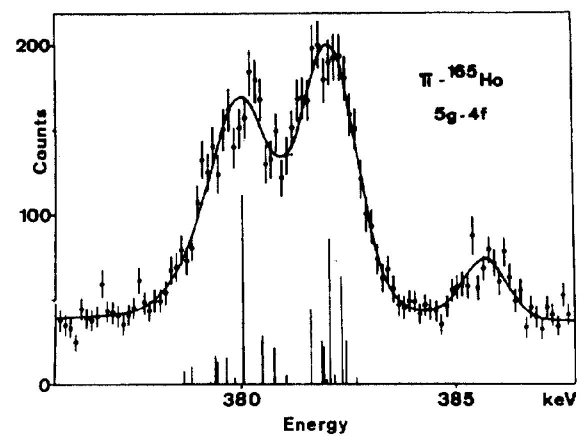

Fig. 10
Result from the first published nuclear physics experiment at S. I. N. : measurement of the spectroscopic quadrupole moment Q of holmium from pionic X-ray measurement. The quadrupole splitting of the 5g - 4f transition gives a value of 3.47 ± 0.11 b for Q. The energy resolution of the Ge (Li) detector was 1.2 keV FWHM at 412 keV.

Acknowledgments

The smooth commissioning of the S. I. N. cyclotron was only possible thanks to the enthusiastic effort of many people of the S. I. N. staff. Especially involved in the different beam development programs between ion source and target were S. Adam, J. Collins, M. Daum, W. Joho, C. Markovits, M. Olivo, L. Rezzonico, U. Schryber, P. Sigg, T. Stammbach, E. Steiner, H. Willax and J. Zichy.

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