BEAM DIAGNOSTIC EQUIPMENT FOR CYCLOTRONS

M. Olivo
SIN, Swiss Institute for Nuclear Research, 5234 Villigen, Switzerland

Abstract

Some requirements for the diagnostic equipment used in accelerators are given. Aspects of diagnostic elements presently in use in medium energy cyclotrons are discussed and specific examples of different types of probes suitable for large beam intensities are shown.

I. Introduction

The aim of the diagnostic equipment in an accelerator is not only to help to bring the beam to extraction but also to optimize accelerator performance.

It might be interesting to point out certain facts related to the diagnostic equipment which are relevant to most accelerators. Figure 1 shows what the author believes are the general requirements for the diagnostic equipment to achieve a certain accelerator performance. The achievement variable is defined here as the product of the several parameters which characterize the beam, normalized to the goals set by the designers of the accelerator. The parameters to be considered might be, for instance, the extracted beam energy, intensity, energy spread, emittance and transmission (after phase selection) through the machine. The last parameter is mainly relevant to those machines capable of producing high energy beams of large intensities (those which have activation problems). The projected cost of the accelerator is purposely not included in these considerations. The ion source is turned on at $t = 0$; t_1 is the time usually needed to solve "trivial" problems (like the "walking" SIN trimming coil[1]). An ε % in the achievement scale is reached, usually in a short time after t_1, with just 4 diagnostic elements. The correlation switch plays an important role here. Usually, in these situations, we see something! ... however, a spot on the quartz can also be the product of dirty fingers. Therefore, we switch the ion source off hoping that the spot goes away. A period t_2 of 1 to 3 years (holidays and sabbatical leaves must be included) is normally needed to reach the 90 % value. To achieve the 100 % level, a degree of sophistication III in the diagnostic equipment is required. The time t_3 needed to reach the goal depends strongly on three main factors: design quality of the accelerator; beam users' pressure, and of course, funds available for good and sufficient diagnostic equipment. If the 100 % level is already achieved with a degree of sophistication II, the goals were set to a modest value!

The subject of accuracy requires a comment. Usually one plans a very good probe having a high accuracy. Unfortunately in many cases, one ends up in the cyclotron with a probe much inferior to what was supposed to be. This is mainly due to either pressure to put the machine into operation quickly or a shortage of funds. This could lead to an unpleasant situation in the future: you may have to redesign and rebuild your probes to reach your goals or you may have to survey your probes again and make either adjustment (they may already be radio-active) or write a long list of the systematic errors. The latter can lead to a tiresome operation procedure or to the false feeling that the probe is actually accurate!

II. Diagnostic equipment for beam development

Methods of cyclotron beam development and diagnostics were described in 1966 in a review paper by D. Clark[2]. Since that time, cyclotrons capable of delivering high intensity beams in the intermediate energy range are coming into operation. Notable are the TRIUMF and SIN isochronous cyclotrons, the recently modified CERN and NEVIS synchrocyclotrons and the DUBNA phasotron. Emphasis is given in this paper to diagnostic equipment which is relevant to this type of beam. Interesting examples of typical diagnostic elements may be found in figures 2 and 3, which show the lay-outs of the TRIUMF and SIN accelerators.

At the energies under consideration, the measurement of the radial and vertical distribution of the internal beam is usually done in two stages. In the first stage, the beam is fully stopped in the measuring head. In the second stage, the beam traverses the measuring device, the diagnostic signal arising from secondary emission effects or stripping, as in the case of H^- accelerators. Two main problems are encountered with probes which fully stop the beam. One is the power handling capability and the other is the activation. To get around both problems, one can either set up the machine using low intensity beams or pulse the incoming beam. For example, at the present time, the TRIUMF

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 331-340

beam is pulsed in the 300 keV transport line, while the SIN beam is kept at low intensities during set-up procedures. Note that space charge effects may be of importance and the full intensity may be required to study properly the behaviour of the beam[17]. It should be emphasized that good engineering in the design of the diagnostic elements is needed, especially because of the activation problems. Probes have to last or be easy to replace!

Let us look at examples of probes used in the first stage. Figures 4, 5 and 6 show the radial differential probe[3] used at the SIN ring cyclotron. Figures 7 and 8 show radial plots obtained with these probes. Figure 9 shows the head of the internal beam stopper used at the SIN ring cyclotron. Intensity measurements obtained with the probe were used to calculate the beam phase history[4]. Figure 10 shows the beam intensity distribution in the extraction region of the SIN injector cyclotron. The probe used here fully stops the beam. It has a maximum cooling capacity of about 3 kW. The extraction efficiency measurements at higher intensities are presently made indirectly by observing the losses with ionization chambers[5].

Examples of probes belonging to the second stage are shown in figures 11, 12, 15 and 16. These are small in order to be able to measure radial and vertical beam distributions and minimize the power dissipation in them. Because of this small size, several different probes can be mounted on the same driving shaft (Fig. 11). Large efficiency for the production of secondary electrons may be obtained if the beam is made to interact along the surface of the thin finger, as is done at SIN. Diagnostic signals obtained with the multifinger probe of figure 11 are shown in figures 13 and 14. Figures 15 and 16 show the secondary emission probe (ΔR1) used to study the extraction region of the SIN ring cyclotron. Figure 17 shows the beam intensity distribution obtained with the ΔR1 probe. Internal beam current was 5 μA. The secondary emission efficiency of this probe is ∿ 50 %. A minimum estimate for the extraction efficiency from the ring can be obtained by measuring the total transmission through the ring with the current transformers 1 and 2 and subtracting the losses (normally zero) measured at the injection region with the ΣΔR1 probe. A novel probe using secondary emission processes to study the extraction system of the improved CERN SC is presented elsewhere in these proceedings[6].

The knowledge of the time distribution of the internal and extracted beam is important. The use of the information may, however, be applied differently depending on the accelerator in question. Figure 18 shows the phase probe at the IUCF. Here the probe is used to isochronize the field for the different particles to be accelerated. Figure 19 shows one head of the phase probe used at the SIN ring cyclotron[7]. Since the machine is of a fixed energy, the non-interacting probe signal is more useful as a stability check than as a phase measurement. This is particularly important when the ring operates at a 100 μA level. Figure 20 shows the diagnostic signals obtained with the phase probes and the 50 Ω strip lines which are installed at injection and extraction. Excellent work on phase measurements has been carried out at different laboratories[8], especially at the Eindhoven University of Technology[9]. Figure 21 shows the time structure of the extracted 72 MeV beam from the SIN injector cyclotron using elastically scattered protons. This technique gives better time resolution than the one employing γ-rays[5].

III. Diagnostic equipment for routine operation

During the commissioning and initial operation of the accelerator, all the probes initially thought to be needed are normally used. However, after having some running experience, the normal machine set-up is done with a lesser number of probes. Collimators and fast diagnostic elements are normally employed. Figures 22 and 24 show the radial and vertical scanners used at the SIN ring cyclotron. Figures 23 and 25 show the diagnostic signals obtained with these devices. Visual aids and thermal beam sensors (Figures 26 and 27) are also utilized as diagnostic elements. In high energy and high intensity cyclotrons, special glass[10] for the viewing windows is required. Television monitors, if placed close to strong sources of radiation, must utilize special lenses and not include solid state components. Thermal sensors (thermocouples attached to metal fingers) are usually slow but noise free. They are employed mainly to study slowly varying beam drifts.

Finally, in this type of accelerator (large beam power and activation potential), certain types of diagnostic elements are required for the interlock system. Under normal running conditions, static current sensors and non-interacting devices are very useful. Ionization chambers[11] placed throughout the accelerator vault are specially useful to monitor beam losses. Other diagnostic equipment which can be utilized in the interlock system are capacitive or inductive beam current and position monitors, as well as phase probes.

IV. Conclusion

A sufficient number of precise and reliable diagnostic equipment is required throughout all the stages of the cyclotron's life, be it during commissioning, normal set-ups, beam production and, last but not least, trouble-shooting. Experience at many laboratories indicates that excellent diagnostic elements are a must to extract the best performance from the accelerator.

Acknowledgements

I wish to gratefully acknowledge interesting and helpful discussions with my colleagues S. Adam, J. Collins, W. Joho, L. Rezzonico, U. Schryber, Th. Stammbach and H. Willax. I would like to thank J. Collins for the careful reading of the manuscript. Special thanks go to Mrs. E. Pedroni for her patience and careful typing of this paper.

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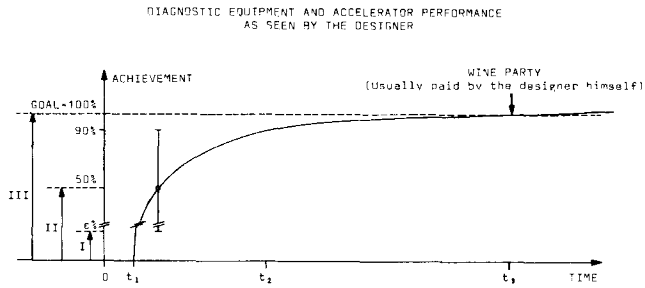


Degrees of Sophistication	Diagnostic Equipment	
I	Number	4: One probe that moves in ... and out! One quartz (at extraction) One correlation switch One good "eye"
	Accuracy	Enough to get going with the champagne party (usually paid by the director)
II	Number	Sufficient minus one
	Accuracy	Enough to appease the beam users' thirst
III	Number	Sufficient plus one
	Accuracy	Enough to fulfill the dreams of the accelerator physicist

Fig. 1
Requirements for diagnostic equipment in achieving a certain accelerator performance.

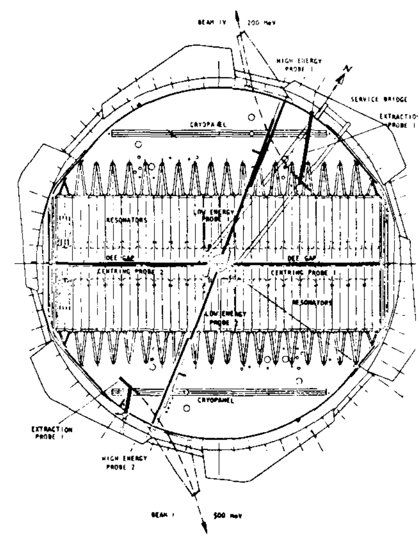


Fig. 2
Plan view of the TRIUMF 520 MeV H^- cyclotron, showing the location of the diagnostic elements. The beam is fully stopped in the head of the low energy probes (first turn to 70 MeV), while the H^- beam is stripped in the five fingers of the high energy probes[18]. Other diagnostic elements are the centering probes, located along the dee gap, and slits, located at the entrance and exit of the inflector-deflector devices. The central region contains, in addition, phase and vertical defining slits. Because of the large size of the cyclotron, the design of the diagnostic elements is particularly difficult.

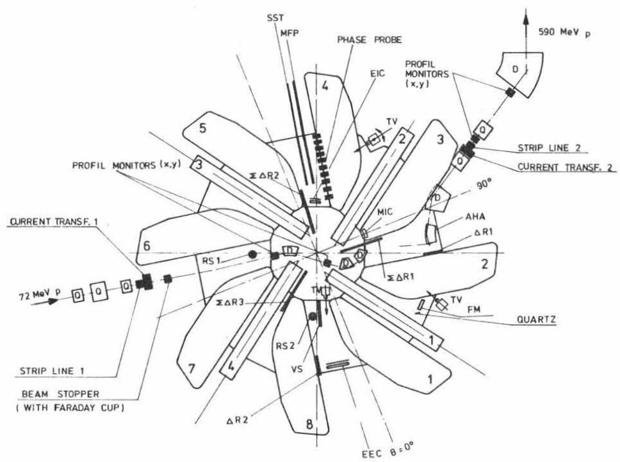


Fig. 3
Lay-out of the diagnostic elements of the SIN 590 MeV proton ring cyclotron. The energy and emittance of the incoming 72 MeV proton beam are measured upstream, in the vicinity of the SIN injector cyclotron[12]. The beam intensity is measured with the 72 MeV beam stopper which is fitted with a Faraday cup. The intensity calibration is transferred to the non-interacting (coaxial resonators[13]) current transformers 1,2. The horizontal and vertical beam amplitudes are measured at the entrance and exit of the ring with profile monitors. The ring contains 3 radial probes (ΣΔR) at injection and 2 radial probes (ΔR) at extraction. In addition, there are fast radial and vertical scanners (RS and VS), a multifinger probe (MFP) and an internal beam stopper (SST). The phase history of the beam is measured with the strip lines and phase probe. The ring contains also several current and thermal sensors as well as visual diagnostic gadgets (using SiO_2 and Al_2O_3 viewers).

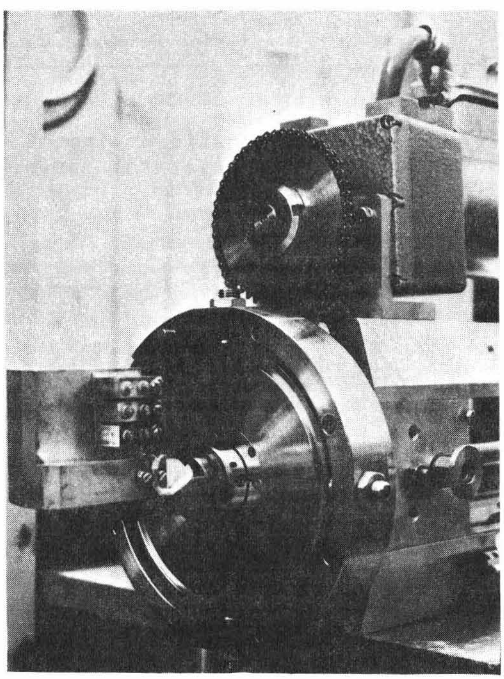


Fig.4
Differential probe (ΣΔR) used in the SIN ring cyclotron. This probe provides radial and vertical beam information. The beam is fully stopped in the water cooled copper head. The cooling capacity is 3 kW. The fingers are 10 mm high with a separation between them of 1 mm. They protrude behind the head by 1 mm. The stepping motor can position the probe in 0.1 mm steps. The overall absolute radial accuracy of the probe is ± 0.25 mm.

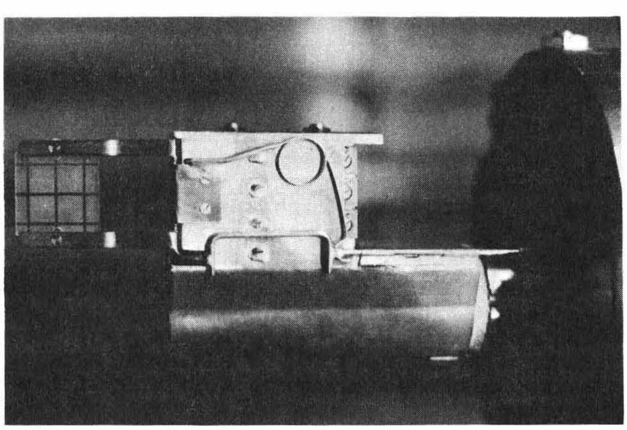


Fig. 5
Close-up of the head of the differential probe (ΣΔR2) looking upstream along the beam path. The probe has been fitted with a grounded copper shield to stop spurious (RF induced) charges from hitting the head and fingers. This head has also a quartz (1 x 1 cm grid) viewer. The beam can be visually inspected at the exit of the EIC as well as after one revolution in the ring.

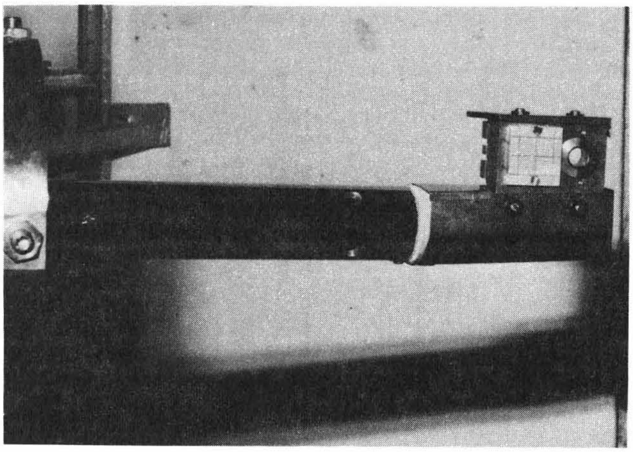


Fig. 6
View of the head of the ΣΔR1 probe as seen by the beam. This head has, in addition to the fingers and Al_2O_3 viewing plate (1 x 1 cm grid), a hole (12 mm dia.) which is used to define the beam injection radius. The beam is centered through this hole and through the entrance collimators of the EIC which is located 90° downstream. The middle finger of this probe has a vertical height of 5 mm.

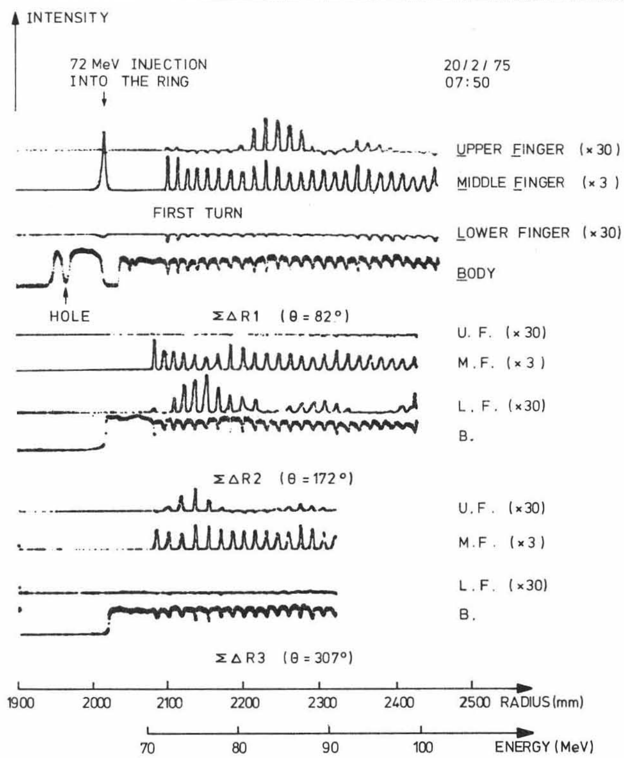


Fig. 7
Radial plots obtained with the three ΣΔR probes. Each head provides 4 signals which are simultaneously displayed on the storage oscilloscope. The signals from the three fingers can be added to the signal from the body to give the total intensity of the incoming and accelerated beam. The vertical distribution of the accelerated beam can also be studied with these probes. The radial range of ΣΔR3 is shorter than the other two due to space limitations.

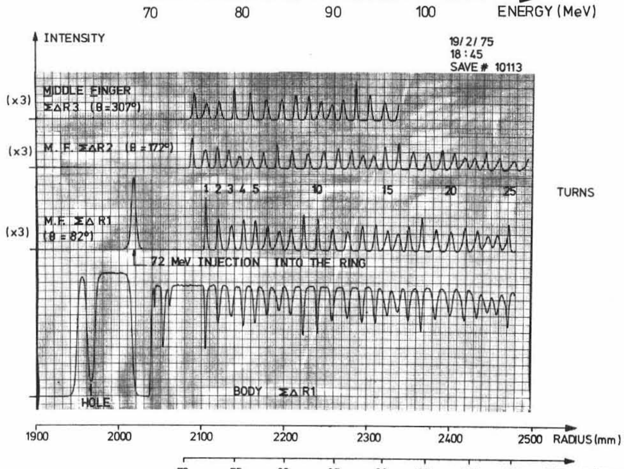


Fig. 8
For centering purpose the signals from the middle finger of the three radial probes are plotted on millimeter paper. The radial positions of 5 consecutive peaks from each probe are fed into a computer program which then provides optimum settings for the injection parameters. In the future, the computer will drive and read the probes, and center the beam in the ring automatically[14].

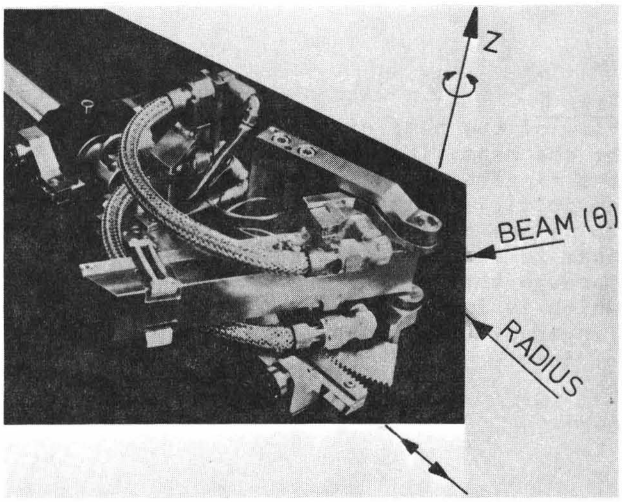


Fig. 9
The internal beam stopper (SST) used at the SIN ring cyclotron. The electrically insulated, water-cooled, tungsten alloy head can be oriented parallel to the internal beam at any given radius. It is designed to fully stop a 590 MeV, 5 µA proton beam. The SST covers an energy range from 110 to 590 MeV. It is mainly used to stop the beam while diagnostics are done with the other probes at smaller radii, thus avoiding unnecessary activation of machine components. This probe is also used to tune the main magnetic field.

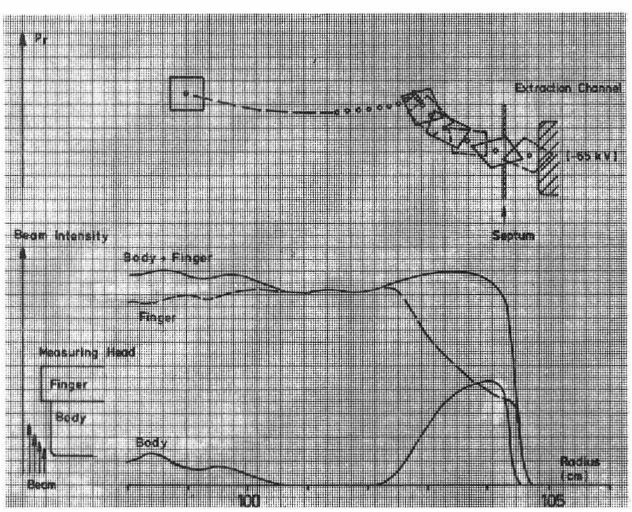


Fig. 10
Precessional extraction pattern obtained with a radial probe at the SIN 72 MeV proton injector cyclotron. The probe's head fully stops the beam.

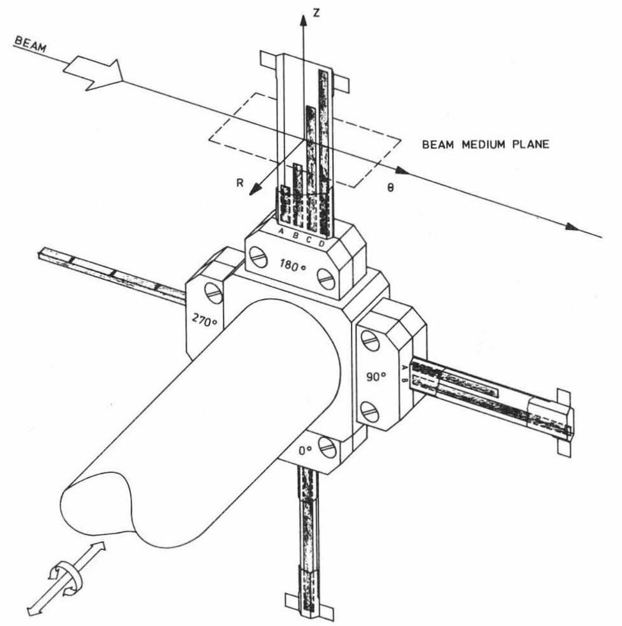


Fig. 11
Schematic view of the head of the multi-finger probe (MFP) used at the SIN ring cyclotrons[15]. This probe covers an energy range from 110 to 590 MeV. The head contains 4 different probes. The diagnostic signals from the 0°, 90° and 180° probes arise from secondary emission processes. The fourth probe (270°) is a quartz finger. The driving mechanism (similar to that of ΣΔR probe) allows for a stepping movement of 0.3 mm with an absolute overall radial accuracy of ± 0.5 mm.

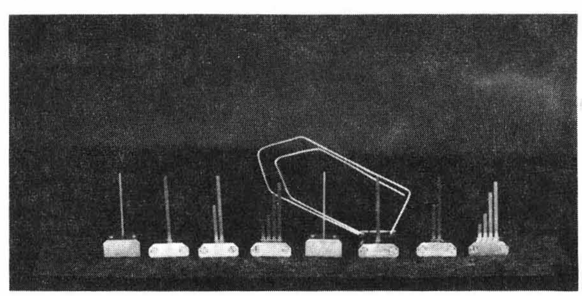


Fig. 12
Shown here are a duplicate set of fingers for the multifinger probe (MFP). The quartz finger (far left) is 2 mm (radially) x 1 mm (longitudinally) x 35 mm (vertically). The other fingers measure 0.1 mm x 2 mm x 35 mm and are shown here without the 0.02 mm thick electron collector. A potential of + 200 V is normally applied to the collector, which also acts as a shielding against RF induced charges. Both, collectors and fingers are made out of molybdenum. The overall radial dimension of the probes is 2 mm.

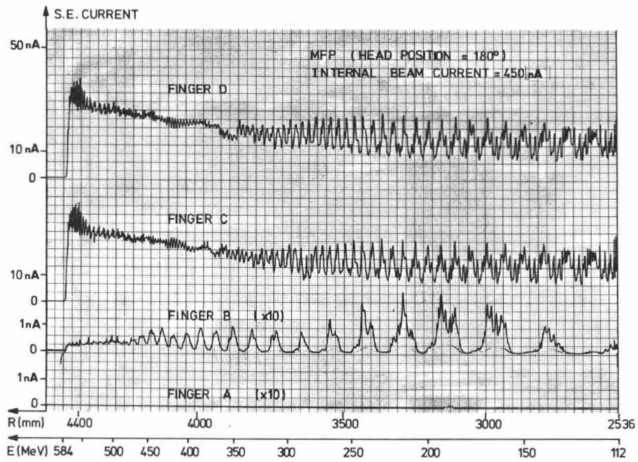


Fig. 13
Radial beam distribution obtained with the four-finger probe (180^{o}). The ends of fingers A, B, C, D are separated from the medium plane by -12 mm, -6 mm, +6 mm, +12 mm, respectively. Vertical information about the beam can be obtained by processing and displaying the signals from the fingers, e.g. A, B-A, C-B and D-C. A similar processing can be made with the double probe (90^{o}), which is more sensitive to vertical coherent oscillation of the beam. The signals from the fingers to be displayed might be A, B-A and (B-A)-A.

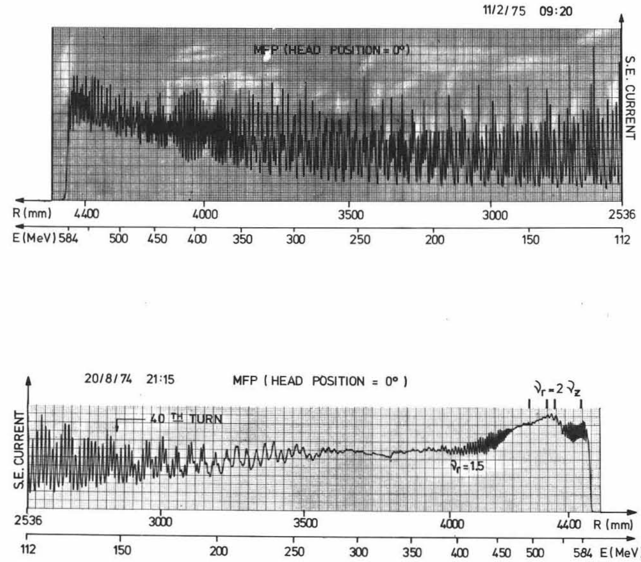


Fig. 14
Plots taken with the single-finger probe (0^{o}). The upper plot shows a well centered beam while the lower plot shows clearly beam loss, close to the extraction region, due to the $\nu_r = 2\ \nu_z$ resonance.

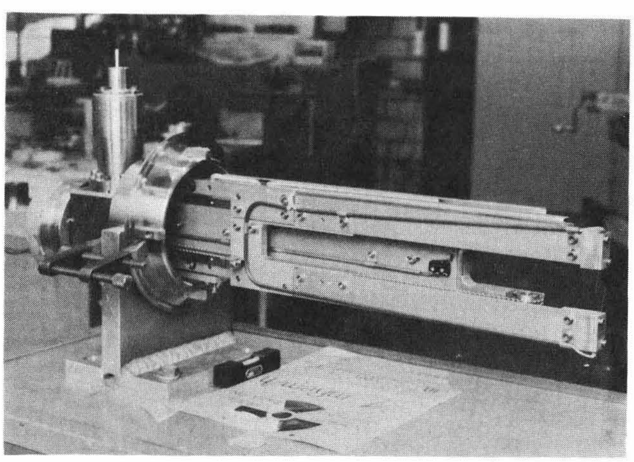


Fig. 15
The ΔR probe used to study the extraction region of the SIN ring cyclotron. This probes covers an energy range from 450 to 590 MeV.

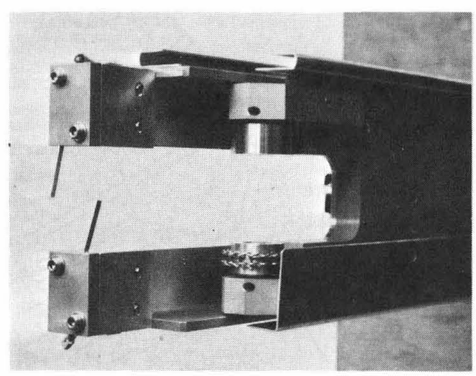


Fig. 16
Close-up view of the ΔR head. The molybdenum fingers have a radial thickness of 0.2 mm by 2 mm along the beam direction. The upper and lower fingers, both located at the same radius, and both ending at the medium plane, are tilted and longitudinally displaced so that secondary emission electrons from one finger, trapped in the ring magnetic field, can escape without hitting the other finger.

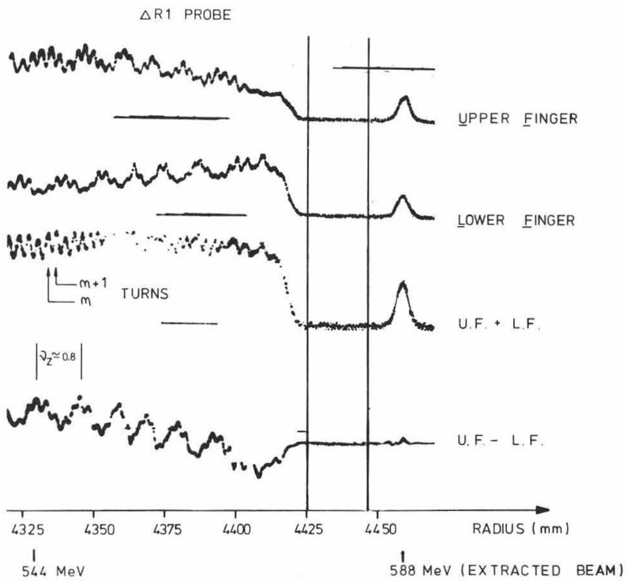


Fig. 17
Plots obtained with the ΔR1 probe. The two vertical lines simulate the thickness of the septum coil of the extraction magnet (AHA). This probe can be used with a 100 μA beam without disturbing the beam users.

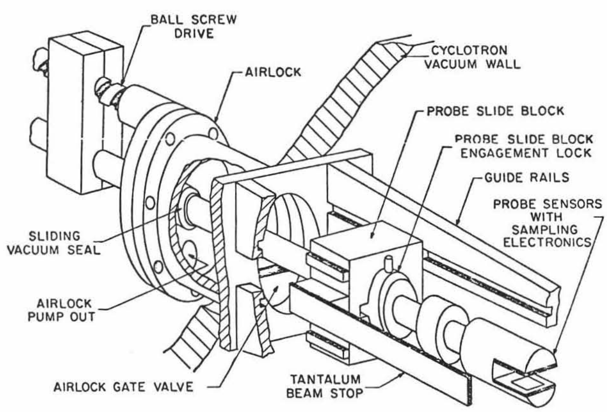


Fig. 18
Radially displaceable phase probe used at the IUCF injector cyclotron[16]. The sampling diode is contained in the head, close to the pick-up plate. Similar heads mounted at fixed radii are foreseen. This probe gives excellent results with beam intensities of less than 1 μA.

Fig. 21 (right)
Time structure of the extracted 72 MeV proton beam from the SIN injector cyclotron. A time of flight method, using elastically scattered protons from a 0.2 mg/cm^2 carbon foil, was used. The detector consisted of the fast scintillator NE 110 and the photomultiplier XP 1020. Beam intensity was 30 μA.

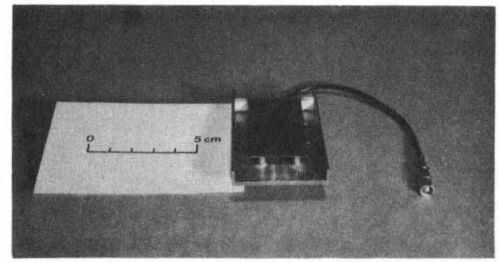


Fig. 19
One of the phase probe heads used at the SIN ring cyclotron. There are 22 of these charge sensitive, 50 Ω terminated heads mounted in pairs above and below the medium plane at different radii. The signals from each pair are summed, partially eliminating the 50 MHz pick-up noise. Because of the high radiation level encountered in the vicinity of the phase probe during machine operation, solid state electronics close to the head are not feasible.

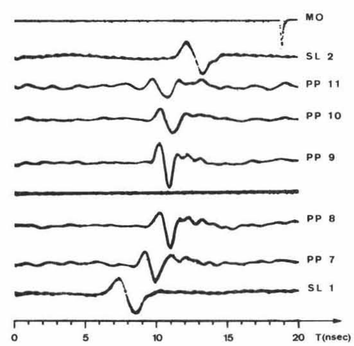
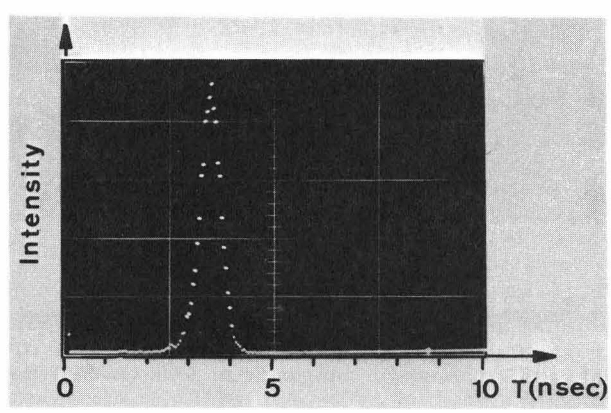


Fig. 20
Signals from the phase probe (PP7 ≡ 470 MeV, PP11 ≡ 585 MeV) and 50 Ω strip lines (SL1, 2) at the SIN ring cyclotron. The upper most trace is a reference signal from the master oscillator (MO). The lower most trace shows the 1 nsec structure of the incoming 72 MeV proton beam from the SIN injector cyclotron. The beam intensity is 10 μA. The phase stability and sensitivity of this probe is 70 psec and 1 μA, respectively.



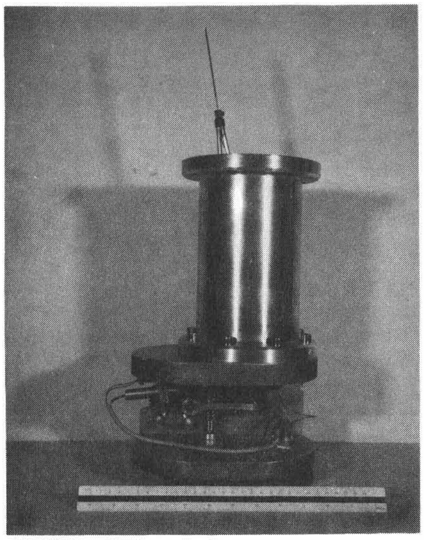


Fig. 22
Radial scanner (RS) used at the SIN ring cyclotron. The indirectly water-cooled molybdenum finger sweeps across the accelerated beam giving the pattern shown in the following figure. The radial thickness of the finger is 0.5 mm. The diagnostic signal is derived from fully stopped protons plus secondary emission electrons. This scanner is an adaption of the profile monitors used in the SIN beam transport lines[12].

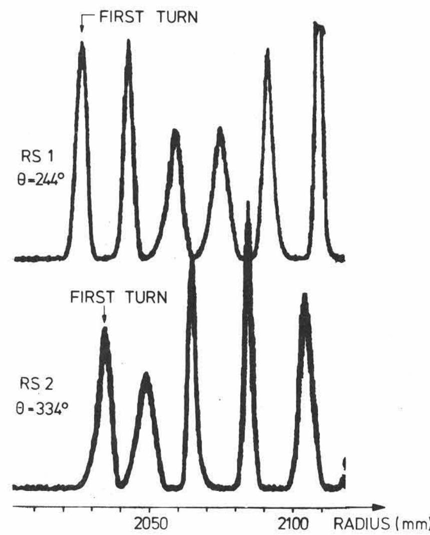


Fig. 23
Diagnostic signals from RS1 and RS2 displayed on a storage oscilloscope. The scanners cover an energy range from injection to ∿ 80 MeV. With these devices a fast check of the injection region can be made. The full pattern is obtained in ∿ 2 sec.

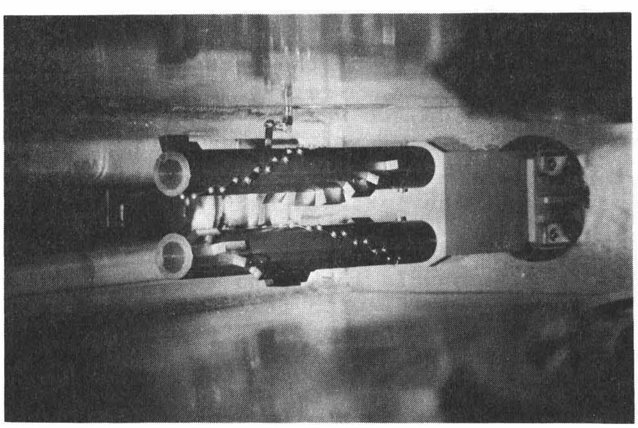


Fig. 24
Vertical scanner (VS) used at the SIN ring cyclotron to monitor beam behaviour from injection to 100 MeV. Electrically insulated, radiation cooled, copper fingers are attached to the upper and lower cyclinders. By rotating the cylinders, the different fingers intercept the beam at different radii. The closest approach of the fingers to the medium plane is 6 mm. The driving mechanism and read-back electronics are similar to those used for the profile monitors.

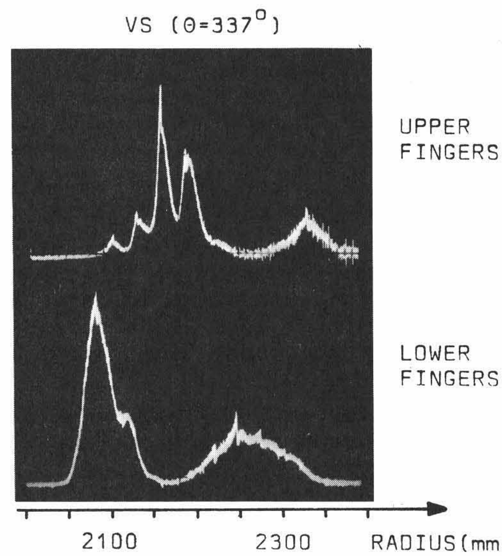


Fig. 25
Diagnostic signals obtained with the VS and displayed on a storage scope. For this picture, the 72 MeV beam was injected into the ring slightly below the medium plane, thus inducing a coherent vertical oscillation.

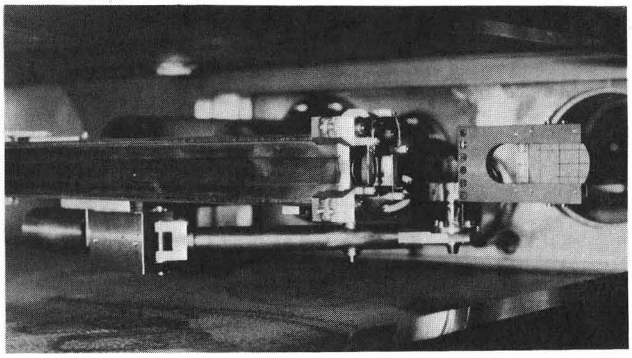


Fig. 26
View of the focusing magnet (FM) built into the SIN ring cyclotron. Four thermal sensors (thermocouples attached to molybdenum fingers) are mounted at the entrance of the 20 mm diameter channel. A quartz with a 1 cm x 1.4 cm ruled grid can be flipped from the position shown here into the path of the extracted beam from the control room.

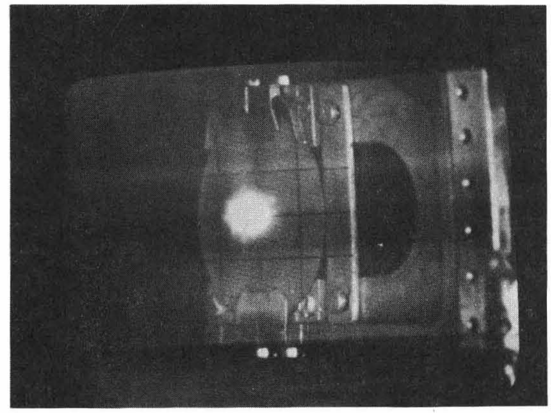


Fig. 27
Picture taken from a TV monitor showing a 590 MeV, 1 μA beam at the entrance of the FM. The beam diameter is approx. 1 cm.

DISCUSSION

H.G. BLOSSER: The probe patterns you showed seemed to all have clear coherent oscillations. Is it a routine matter to tune and get rid of these?

M. OLIVO: Dispersion mismatching is probably the main cause of the coherent oscillations you see in most of the plots. To get rid of these oscillations, the injector and beam transport system have to be precisely tuned. Since the ring cyclotron is rather "generous" (transmission in the ring is very good in spite of these oscillations), a perfect tuning is not routinely done.

T. KUO: How far is the separation of the two fingers of your differential probe?

M. OLIVO: Both fingers end at the medium plane of the machine and are located at the same radius. The separation is only longitudinal and this is to prevent secondary electrons emitted by one finger from hitting the other.

J. REICH: Could you briefly comment on what you did to prevent all your different probes from RF-pick-up?

M. OLIVO: We were faced with two different types of RF disturbances: One which affected the current monitors (coaxial resonators) and phase probes (which have a band width of 1.4 GHz) and the other which affected the D.C. probes (radial probes). We got rid of the troubles by tuning the coaxial resonators at the second harmonic (100 MHz) of the accelerating cavities and by installing high pass filters in the phase probes. To get rid of the spurious signals in the D.C. probes, we installed simple shieldings. The RF induced charges arise probably from the bremsstrahlung originating in the cavities. This radiation goes through the gap of the main sector magnets of the ring cyclotron and produces secondary charged particles in the vicinity of the probe heads. We have made tests which seem to confirm these processes.

J.R. RICHARDSON: Have you made any studies on the efficiency of the secondardy emission as a function of energy and any variation from day to day or week to week?

M. OLIVO: We have not, mainly because we are interested in the radial and vertical behaviour of the internal beam rather than in the relative intensity throughout the machine. What you mention is a very interesting problem and we should look into it. (Note added on proof: TRIUMF, with its variable energy beam, is in a very good position to study this problem if the extracted beam intensity can be well determined by other means).

G. DUTTO: How accurate is your measurement of the absolute beam current at high energies?

M. OLIVO: We have identical non-interacting beam current monitors in the low energy (72 MeV) and high energy (590 MeV) beam lines. In the low energy beam line, we also have beam stoppers, fitted with a Faraday cup, which can give a reading with an accuracy of better than 1 %. This absolute calibration is transferred to the low and high energy non-interacting current monitors. The relative calibration of all the non-interacting resonator-type current monitors at SIN is done using a reference signal from a master oscillator.