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ISOCHRONISM STUDIES AT IUCF

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ABSTRACT

A non-intercepting, charge sensitive, sampling beam phase probe, similar to the design developed for the 15 MeV injector cyclotron[1], was recently installed on the moveable south valley probe of the Indiana 200 MeV main stage cyclotron. The probe permits continuous measurement of beam phase from inflection to extraction radius at beam intensities as low as 200 nanoamperes. The measured phase histories obtained show that small deviations from the predictions of our field mapping data are required for isochronous acceleration. The characteristics of the phase probe and the results of the beam phase measurements are discussed.

INTRODUCTION

The Indiana University 200 MeV isochronous cyclotron has accelerated protons over an energy range of from 35 to 200 MeV and other light ions up to ^{6}Li to energies of 160 q^2/A MeV[2]. Acceleration over this large range of particle mass and energy requires that the radial profile of the magnetic fields of both the injector and main stage cyclotrons be adjustable to match the relativistic mass increase of the accelerated particle. The trim coil assembly and phase history studies for the injector cyclotron were previously reported[1]. The radial field adjustments in the main cyclotron are provided by an assembly of 21 trim coil pairs placed in the gap of each magnet. Trim coil current settings for isochronous acceleration of the various beams were determined from the field mapping data taken on one of the four magnets, the results of which were also previously reported [3,4].

During initial operation of the facility, accelerated beam phase acceptances in the main cyclotron, as measured via the Smith-Garron technique, were observed to be smaller than predicted. Furthermore, because of the tendency of the experimental running schedule to make full use of the variable particle and/or energy capability of the cyclotrons, trim coil settings for a given energy were not always precisely reproducible despite a consistent main magnet computer controlled cycling procedure. These effects cause delays which hamper rapid machine energy changes and reduce the stability and efficiency of the extracted beam.

The recent installation of the sampling beam phase probe on the south valley radial probe assembly of the main cyclotron has permitted a precise study of the isochronism during acceleration. These studies have observed the differences between the predicted and measured radial field profiles, and provide the data necessary for correcting the earlier predictions.

Phase Probe Design

The main cyclotron phase probe is similar in design and operation to the injector phase probe in that it is a non-intercepting, charge sensitive sampling device utilizing a sampling frequency of 2.77 kHz. The probe assembly is mounted on the south valley multi-purpose radial beam probe, shown in figure 1, and has been simplified in several ways.

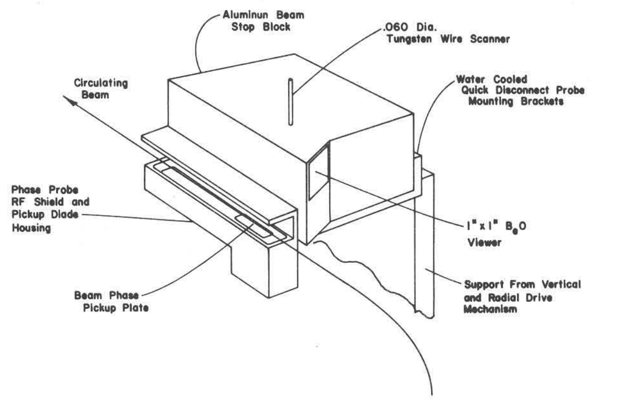

Fig. 1.

The probe sensor now consists of a single aluminum pickup plate, measuring 31 mm azimuthally by 6 mm radially, mounted in a grounded aluminum RF shield which allows beam to pass over, but not onto, the plate. The RF shield, which also houses the Schottky Barrier sampling diode, is the primary method of RF induced pickup cancellation. The probe may be adjusted vertically through the cyclotron midplane to measure either beam phase, beam intensity or turn separation. Beam passing through the phase probe is stopped in the beam current probe on which it is mounted. Radiation damage to the sampling diode due to its close proximity to this intense radiation source has not been observed.

A block diagram of the simplfied phase probe electronics is shown in figure 2. The sensor plate is tied to the sampling diode which closes each time a negative 2 volt pulse is applied, allowing the beam induced charge to build. This charge is slowly bled off through a 5.6 KΩ resistor, thereby charging the signal cable capacity. Together they serve as a

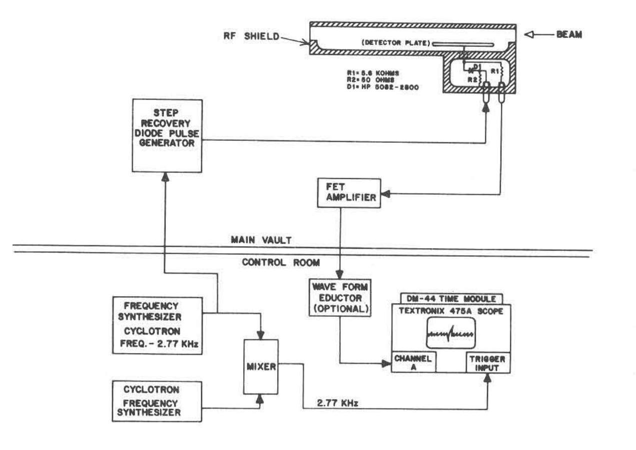

Fig. 2.

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low pass filter, allowing only the slowly varying average charge induced on the pickup plate to pass to an FET differential amplifier having a gain adjustable from 300 to 600. The sampling diode is strobed with a step recovery diode pulse generator which provides the negative 2 volt sampling pulse. This pulse is incrementally advanced along the RF by a second stable frequency synthesizer tuned to the RF frequency plus 2.77 kHz. The probe rise time and jitter are approximately 1 nsec and ± 2° respectively at 30 MHz. The phase information is displayed on a Tektronix 475A oscilloscope having a DM244 timing module. The scope trigger is provided by the 2.77 kHz output of a mixer whose inputs are the RF and sampling pulse synthesizers. With this arrangement, relative beam phase fluctuations over a range of 360 degrees can be read from the DM44 digital display with an accuracy of ± 1/2 degree without the need for the electronics associated with RF phase angle fiducial markers.

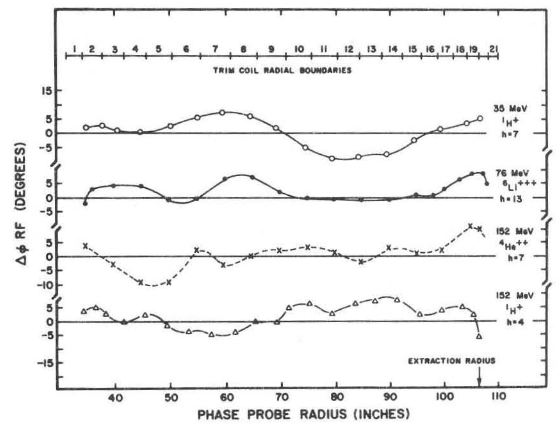

Fig. 4.

Performance and Measurements

The phase probe has recently been used to obtain data on the level of isochronism of the main cyclotron for a variety of beams at intensity levels as low as 200 nanoamperes. Figure 3 is an example of the scope display of the phase probe signal for a 500 nanoampere, 35 MeV proton beam near the extraction radius. The scope is calibrated at approximately 40° of RF phase per cm using a 0.1 msec per cm time base. The vertical scale is 0.1 volts per cm. A signal to noise ratio of about 4 to 1 is observed, where the primary source of the noise is the main RF accelerating structures. The amount of RF pickup noise is frequency and radius dependent, with amplitude fluctuations being of the order of a factor of 2.

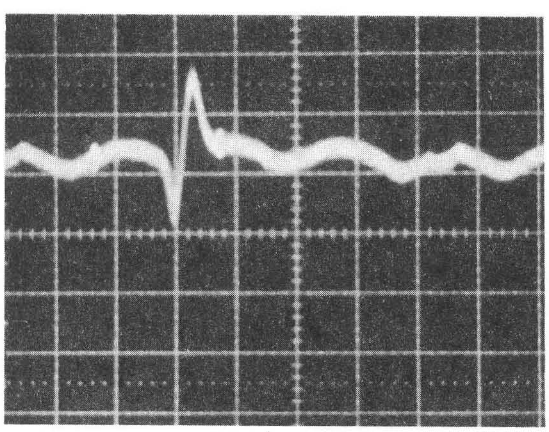

Fig. 3.

The phase probe has been used to isochronize the main cyclotron for a variety of particles and energies. Examples of these phase histories are shown in figure 4, along with the radial boundaries of the 21 trim coil pairs. An average of 300 turns are required for acceleration to full radius at a peak dee voltage of about 200 kV. Isochronization of the cyclotron is done by an iterative manual process in which trim coil current corrections are calculated from observed phase histories until phase errors are reduced to approximately ± 5° of RF phase. A phase history measurement from inflection to extraction radius takes about 5 minutes, where a significant fraction of that time is the probe travel time between points. The phase histories in figure 4 are for particle beams which require radial field profiles near the extreme limits of the cyclotron design. The radial field profile varies from a uniform field for the 152 MeV alpha particle beam to a radial field profile having a 12% increase with radius for the 152 MeV proton beam. Prior to isochronization using the phase probe, oscillations of ± 40° were observed in the phase histories for these beams.

The phase history shown in figure 5 for a 150 MeV proton beam illustrates the effect of phase compression on our accelerated beams. Phase compression in the main stage, the result of a radially increasing dee voltage caused by the standing wave on the resonators. was observed by varying the main cyclotron RF phase relative to the equilibrium RF phase of the beam inflected from the injector cyclotron. This is equivalent to adjusting the phase of the inflected beam relative to the main RF phase, and is more easily accomplished at our facility. The difference in the sine of the beam phases for the correct and adjusted starting phases was found to vary roughly as the inverse of the dee voltage, as expected. This effect doubtlessly made the initial acceleration of beam in the main ring without the use of a phase probe a manageable task.

Comparison with Field Map Data

An extensive program of magnetic field mapping and calculations was carried out in order to determine optional trim coil currents for the wide variety of cyclotron operating conditions[3,4]. Not unexpectedly, these predictions often required modification in order to accelerate beam with a wide phase acceptance. Some of the limitations of the field mapping program that caused us to anticipate the need to modify the trim coil currents from the predictions included: the fact that only one half of one sector was mapped; that in sectors other than the one being mapped only the main coils were excited; and that slight differences exist between the power supply analogue readouts used during the mapping process and the digital readouts used during present operation.

Figures 6 and 7 show the magnitude of these differences for the acceleration of 150 MeV protons. The isochronous phase history used for this comparison is illustrated in figure 5, in which phase oscillations were reduced to about ± 7°. An analytic field was generated using the original 150 MeV map data and the differences between the predicted currents and those obtained using the phase probe. Figure 6 shows the difference between the isochronous field and the field

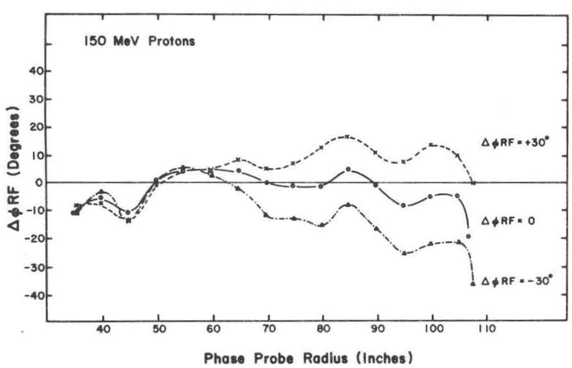

Fig. 5.

obtained with the predicted currents. Figure 7 shows the voltage threshold function F(E) where

$$\mathrm{Sin}(\phi(E)) = \mathrm{Sin}\phi_o + \frac{h}{Eg} F(E).$$

Eg is the maximum energy gain per turn and h is the ratio of the RF frequency to the orbit frequency. Beyond the nose region of the cyclotron, the field errors led to phase excursions of less than ± 30° for 4th harmonic operation at 150 kV dee voltage. The larger errors at small radii are due primarily to two sources.

1) The magnetic shims in the nose region are not identical in all sectors.
2) Current was shunted away from some of the inner trim coils in order to improve centering and inflection efficiency.

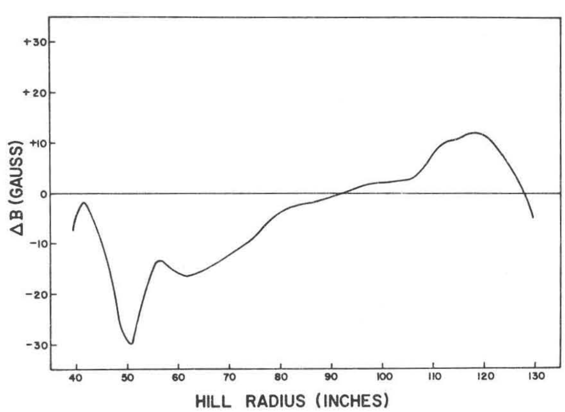

Fig. 6.

The gradual slope in the field difference from 60 inches outward shown in figure 6 is due to a radial displacement of about .025 inches between the average location of the four trim coil sets and the location of the temporary trim coil set that was used for field mapping. This displacement is well within the accuracy with which the trim coil sets could be positioned. Although the field mapping data have not enabled us to predict the exact trim coil currents needed for isochronous acceleration, they do provide reasonable starting parameters for any energy beam and also gives a good measure of the trim coil current changes needed for modest energy changes in the accelerator.

Conclusions

While the main cyclotron phase probe has already contributed to a more efficient use of cyclotron beam time, it is still inadequate for a facility such as ours which requires machine changes regularly over a large range of particle mass and energy. The major improvement being made is to interface the device with the control computer for automatic phase history measurement, trim coil correction calculation and adjustment. This system will consist of several fixed non-intercepting phase probes mounted on the centerline of one magnet. In addition, future efforts are focussing on improving the sensitivity of the probe, which requires a reduction in the RF noise now observed there. We would like to express our appreciation to Mr. Kent Berglund for his efforts in making these phase probe assemblies and for his help in making the measurments shown here.

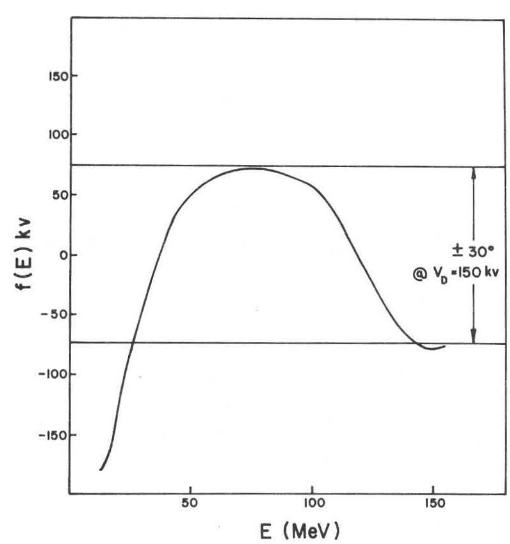

Fig. 7.

References

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