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ISOCHRONIZATION STUDIES OF THE IUCF 200 MeV CYCLOTRON

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ABSTRACT

A non-intercepting movable beam phase probe recently installed in the south valley of the IUCF 200 MeV isochronous cyclotron has been used to study the relative beam phase variation during acceleration for the various beams accelerated by the facility. Small differences between the measured phase histories and the predictions of the field map data were observed and explained. Phase compression during acceleration has been measured, and a method for making rapid small energy changes (± 500 keV) while operating on a single RF frequency using trim coil adjustments at large radius has been developed. These and other consequences of the isochronization studies are discussed.

INTRODUCTION

Operation of a movable non-intercepting, charge sensitive beam phase probe in the Indiana 200 MeV main stage cyclotron was improved to allow a comprehensive study of isochronism over its entire operating range. The cyclotrons, which have accelerated protons to energies of from 27 to 200 MeV and other ions up to ^{6}Li to energies of 160 q^2/A MeV, is operated with routine energy and/or particle changes occurring at an average rate of 4 per week. Acceleration over this large mass energy product requires the cyclotron magnetic field to vary from a uniform radial profile to one which increases with the relativistic particle mass by up to 25% for the limiting case of 200 MeV protons. The trim coil assemblies and field mapping data upon which initial cyclotron operation depended have been previously described.[1,2,3] Cyclotron operating experience has indicated that a discrepancy exists between the predicted isochronous trim coil settings based on the field maps, and those required for isochronous operation. Initial operation of the south valley phase probe has measured the discrepancies, which are now understood.[4] Continued operation of the phase probe has provided a systematic study of main stage isochronism and provided a set of accurate trim coil settings which are used for cyclotron setup during energy changes. These data have improved the efficiency of the changes as well as the quality of the extracted beam, as described below.

PHASE PROBE PERFORMANCE

The main stage phase probe, shown in figure 1, is a non-intercepting, charge sensitive sampling device having a sampling frequency of 2.77 KHz. The probe sensor, a single aluminum pickup plate measuring 31 mm azimuthally by 6 mm radially, is mounted in a grounded aluminum RF shield, which also houses the Schottky Barrier sampling diode. The phase probe assembly is mounted on a multipurpose radial probe in the south valley of the cyclotron, permitting measurement of the beam phase from inflection to extraction radius. The radial probe may also be adjusted vertically through the cyclotron midplane to measure either beam phase, intensity or turn separation. The design and initial operating characteristics of this probe have been previously described.[4] A picture of the probe assembly in place in the south valley is shown in figure 2.

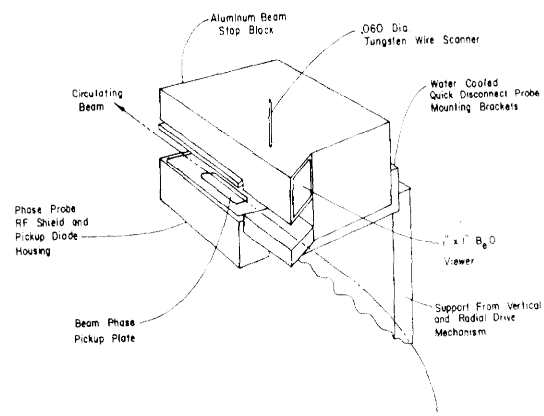

Figure 1.

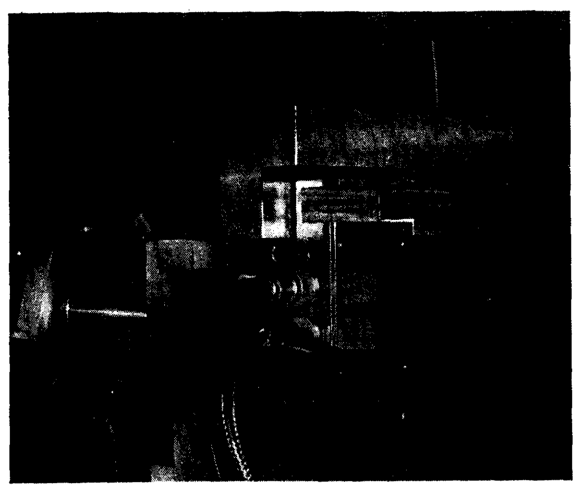

Figure 2.

Improvements in the RF shielding of the phase probe and signal cable connections, and the use of a wave form eductor to reduce incoherent noise effects, have improved the performance of the phase probe so that accurate phase histories can be obtained with as little as 30 nA of circulating beam. Figure 3 is a scope display of a phase probe signal from a 75 nA, 120 MeV proton beam near extraction radius. The scope calibration is 20° of RF phase per cm using a 50 μ sec/cm time base. The vertical scale is 20 mV per cm. Coherent noise effects are reduced by algebraic summing of the raw phase probe output and the output of the waveform eductor. The primary source of the noise is pickup from the main RF accelerating structures, which is frequency and radius dependent.

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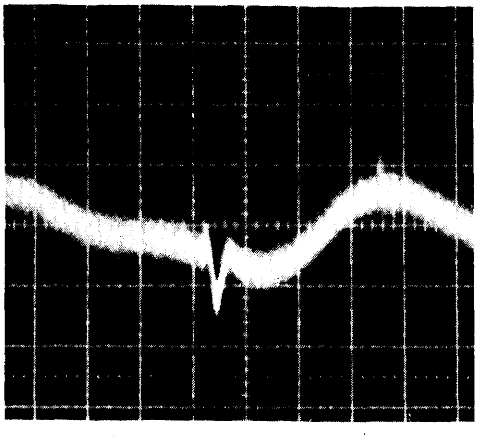

Figure 3.

PHASE HISTORY MEASUREMENTS

Examples of the measurements obtained using the phase probe are shown in figure 4 for proton energies from 27 to 200 MeV, which required acceleration on 3rd, 4th, 5th and 7th harmonics. The radial field profile variation over this energy range spans the design limits of the cyclotron. These isochronous phase histories were obtained by an iterative manual process in which trim coil corrections were calculated from observed phase histories until phase errors were reduced to approximately ± 5° of RF. This was usually accomplished in three to five iterations. Reduction of phase errors to less than 5° of RF are possible, but pointless because the field reproducibility errors are larger than this, and are dependent on magnet excitation history, in spite of a computer controlled magnet cycling procedure.

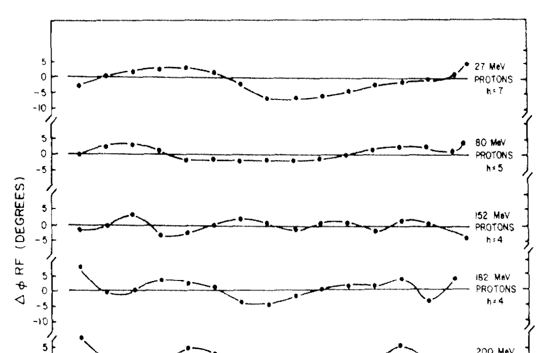

Figure 4.

The phase history shown for the 200 MeV proton beam is particularly noteworthy because it represents the first attempt to accelerate protons in the main cyclotron on the 3rd harmonic. With the average dee voltage during this run at less than 50% of the design value, and 3rd harmonic operation giving approximately 80% of the maximum energy gain per turn available on 4th harmonic, acceleration to extraction radius required nearly 900 turns, three times the number called for under ideal conditions. Furthermore, the larger than average phase slip at small radius for the 200 MeV case is the result of a fault in the trim coil shunt network which prevented operation of the first three trim coil pairs in their design configuration. The fact that both of these electrical faults could be overcome demonstrates the overall flexibility of the trim coil assemblies to shape the radial profile of the cyclotron magnets.

A reason for the tolerance of the Indiana University cyclotrons to relatively large errors in trim coil currents is the effect of phase compression during acceleration. This effect, which minimized the problems of acceleration in the main cyclotron prior to the installation of the phase probe, was originally discussed by Müller et al.[5] Phase compression (or dilatation) results from two sources: an oblique dee gap crossing at phases off maximum, and an inhomogeneous voltage distribution along the dee gap. The first effect produces an average radial electric field dependent on the phase error, while the second effect induces an axial magnetic field component, also dependent on the phase error. The amount of phase compression produced by the non-normal dee gap crossing goes as the energy gain raised to the harmonic number, while the amount of compression resulting from an inhomogeneous dee gap voltage depends on the ratio of the dee voltage at inflection and extraction radius. Phase compression effects during acceleration in the main cyclotron were measured at proton energies of 35, 60, 115 and 150 MeV. Figure 5 illustrates the data from the 60 MeV measurement, which was accomplished by adjusting the main RF dee phase relative to the injector RF.

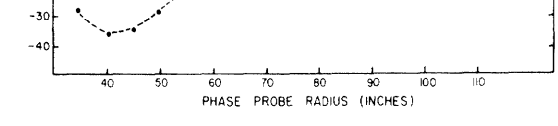

Figure 5.

This is equivalent to changing the starting phase of the inflected beam relative to the main RF. The difference in the sine of the beam phase errors observed for the two extremes of phase adjustment varies roughly as the inverse of the dee gap voltage increase with radius, as shown in figure 6a. The dee gap voltage change with radius, whose reciprocal is indicated in figure 6 by the solid curve, thus appears to be the dominant effect.

Phase compression was also tested at higher harmonics using the 75 MeV $^{6}Li^{3+}$ beam accelerated on the 13th harmonic. The results of this are shown in figure 6b for comparison with the 60 MeV proton measurement. For this high harmonic case, at large radius the effect of phase compression appears to be slightly

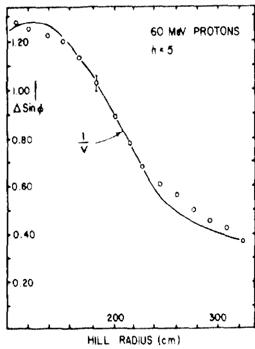

Figure 6a.

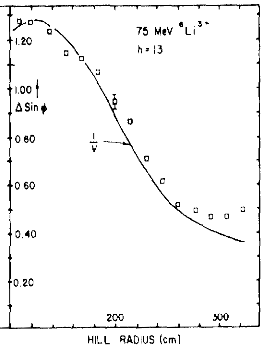

Figure 6b.

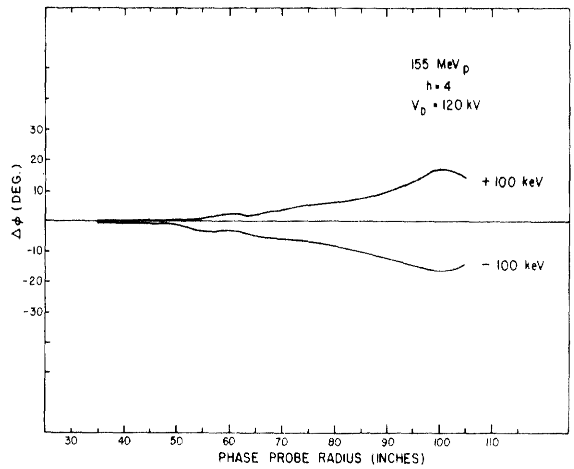

Figure 7.

reversed, as indicated by the deviation of the measured phase errors from that expected by the inhomogeneous dee gap voltage. This phase dilatation at high harmonic operation may be caused by the non-normal dee gap crossing, which is dependent on harmonic number. If this is the case, the effect is small compared to the phase compression resulting from the inhomogeneous dee gap voltage. Furthermore, the change in the inhomogeneity of the dee voltage as a function of RF frequency is not known, and this could account for some of the difference observed. However, the dee voltage is never expected to decrease with radius at any frequency on which we operate, which is the only other explanation for the phase dilatation observed at large radius for h=13. The amount of phase dilatation predicted by Muller's[5] theory for the Indiana cyclotron would be three times larger for h=13 than for h=5, but the absolute value predicted is larger than observed for either case we've measured. One reason for this is our imprecise knowledge of the dee crossing angle as a function of radius. It is known that this angle increases with radius because of fringe field effects, and this is consistent with observed results for h=13 at large radius. Work is continuing to more carefully measure these effects in an effort to understand their source.

CONCLUSIONS

This work led to the development of a simple method for carrying out small, quick energy changes ($\Delta E \leq \pm 500$ keV) while operating at a given RF frequency. Deviations from isochronism are induced by changing the current in the five outer trim coils equally. By increasing (decreasing) the field at large radius in this way, the energy of the particles arriving at the entrance to the extraction system is increased (decreased). Figure 7 shows the calculated change in phase when the energy has been changed by ±100 keV for a 155 MeV proton beam. This technique has made it practical to measure nuclear reaction excitation functions routinely. The time required for a 100 keV energy change is approximately 10 minutes. This technique also makes it possible to easily reproduce the energy for a given frequency, a request frequently made by experimenters whose data are accumulated over several runs.

The isochronous data collected on the main cyclotron was used to generate a table of trim coil currents in one MeV steps for the operators. Hermite polynomial interpolation was used to fit the trim coil currents at energies where the beam was carefully isochronized. The isochronized fields correspond to proton energies ranging from 27 to 200 MeV. Below 160 MeV, the tables give accurate predictions for the trim coil settings, and operators are able to accelerate beams to new energies with good phase acceptance. The spacing of the isochronized field settings above 160 MeV is presently too large to guarantee accurate predictions of trim coil settings. The predicted settings in this energy region are, in general, adequate for acceleration to full radius. Using the techniques described above, a satisfactory phase history can then be obtained within one or two iterations of trim coil adjustment. As more sets of isochronous trim coil currents are obtained, they will be fed back into the fitting procedure.

Finally, we would like to express our appreciation to Mr. Kent Berglund for his efforts in making the phase probe assemblies and for his help in making the measurements shown here.

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