ORBIT CENTERING STUDIES OF THE IUCF INJECTOR AND MAIN STAGE CYCLOTRONS*

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Introduction

The IUCF cyclotrons accelerate a variety of light ion beams over a wide energy range (20 to 200 MeV protons for example) for research purposes. The beams are accelerated in three stages by a DC ion source pre-injector terminal, a small (K = 15) separated sector cyclotron, and a larger (K = 200) cyclotron of similar design. Because the research program requires a flexible machine operating schedule with between two and three energy or particle changes per week, the efficiency of these machine changes can have a significant impact on the amount of useable beam time delivered in a year of operation. For a variable energy coupled cyclotron system, two of the limiting factors in reducing the time needed to make a change are attainment high efficiency single turn extraction and matching the extracted beam from the first cyclotron to the acceptance of the second. These problems are minimized if the orbit structure of the beam in both cyclotrons is centered, because the inflection and extraction orbits should then be nearly the same for all ions and energies. The resulting reproducibility of the inflection and extraction parameters will not only reduce the time needed to make an energy change, but will insure efficient single turn extraction as well. In addition, operation with centered turns was necessary for studying the behavior of a horizontally polarized beam during acceleration for several users at IUCF.[1] For this purpose, a small spin precession solenoid located in the transfer beam line to the injector cyclotron was used to rotate the spin of the protons from the vertical to the horizontal plane. During acceleration, the vertical component of the cyclotron magnetic field causes the horizontal component of the spin to precess. The spin precession rate for a 200 MeV proton beam is about 17 degrees per turn. Therefore, single turn extraction from both cyclotrons is necessary to avoid depolarization by the spin mixing of adjacent turns. A centered turn structure is needed in the main stage so that the spin direction in the horizontal plane may be selected by adjusting the DEE voltage to change from one extracted turn to the next.

If the above reasons were not sufficient, then a final (and perhaps more compelling) reason for wanting to obtain a centered turn structure is that separated sector isochronous cyclotrons are designed to operate with centered orbits. The design and operation of a simple beam profile monitor to observe the outer 8 cm of the radial turn structure in both the injector and main stage cyclotrons is described below. Some results of the orbit centering studies performed with the scanners are also presented.

Radial Turn Pattern Monitor Design and Operation

Several National Electrostatics Corporation model BPM-6 beam profile monitors[2] have been in continous service in the transfer beam lines at IUCF for many years. Because of the simplicity and reliability of the NEC system, it was used as the basis for the design of the radial turn pattern monitor, which is illustrated in Figure 1. A 7.5 cm long grounded 0.9 mm diameter stainless steel wire, which replaces the normal helical wire provided by NEC, is rotated at 15 Hz in a plane normal to the accelerated beam path by a modified NEC scanner head assembly. The secondary electrons emitted from the wire as it passes through the beam are collected by an array of three copper pickup plates located above and below the beam. The total area of the pickup plates is 125 cm^2, which is a third of the area of the beam line collector housing. However, the plates of the turn pattern monitor are placed as close as possible to the rotating wire and the median plane of the accelerated beam, so that they subtend a solid angle of 1.6 π sr, which is nearly equal to that of the beam line scanners. The collector and rotating wire are shielded from the cyclotron RF by metal jackets, and the grounded rotating scanner wire is electrically insulated from the drive motor to

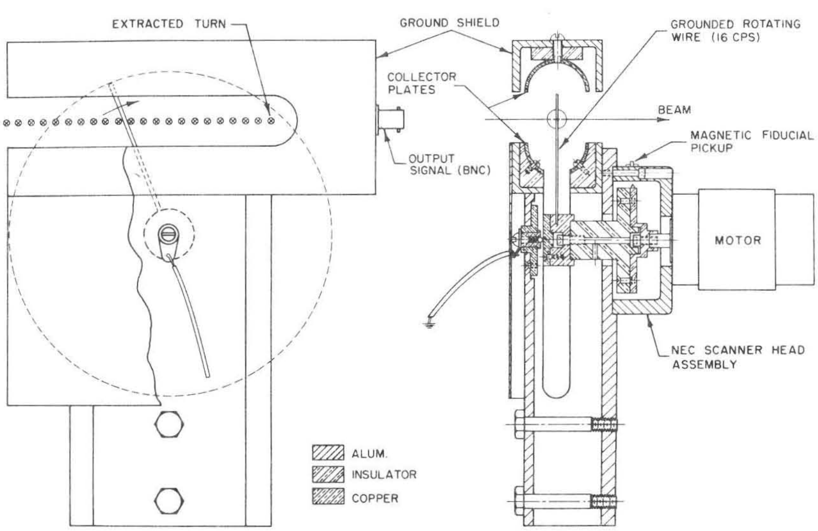

FIG. 1. Schematic view of radial turn pattern wire scanner. The scanner motor and drive assembly is a stock NEC scanner head assembly with a modified scanner wire. A new collector assembly was constructed to collect the secondary electrons emitted.

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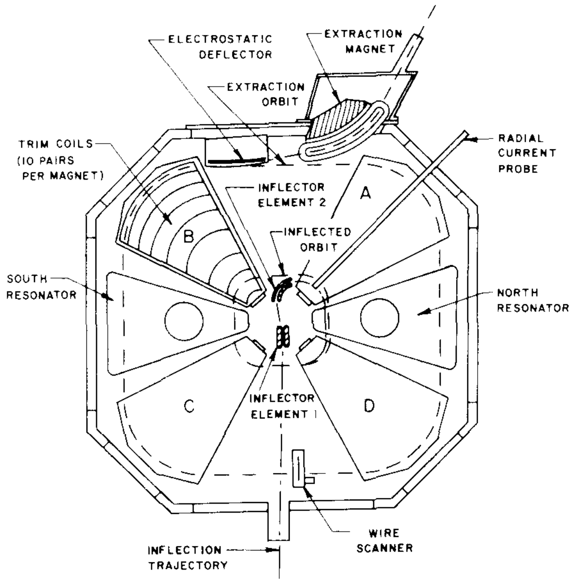

Figure 2. Injector Cyclotron

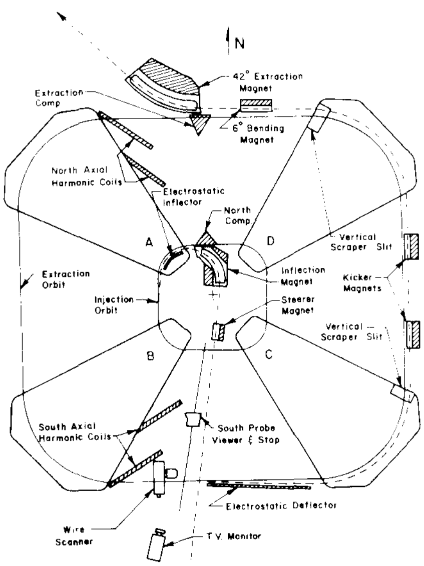

Figure 3. Main Stage Cyclotron

reduce noise pickup. Nevertheless, the signal to noise ratio of this collector configuration is about half of that observed for the standard scanner located in the extraction beam line of the main cyclotron, which observes beams of equal intensity and energy simultaneously with the turn pattern monitor. The minimum beam intensity required to produce useable signals varies as expected with energy from about 10 nanoamps for 2.2 MeV ^{3}He to about 100 nanoamps for 200 MeV protons. The signals from the collector plates of this modified scanner are displayed using the standard NEC amplifier and control units. The normally air-cooled drive motor, which was fitted with a water cooled copper jacket to prevent overheating in vacuum, has performed reliably.

The locations of the wire scanners in the injector and main stage cyclotrons are shown in Figures 2 and 3 respectively, along with components used for beam centering. The wire scanner in the main cyclotron is located in the south valley immediately upstream of the radial beam current probe and the electrostatic deflector. This placement is convenient because it allows observation of the last turn just before entering the extraction channel. The location of the

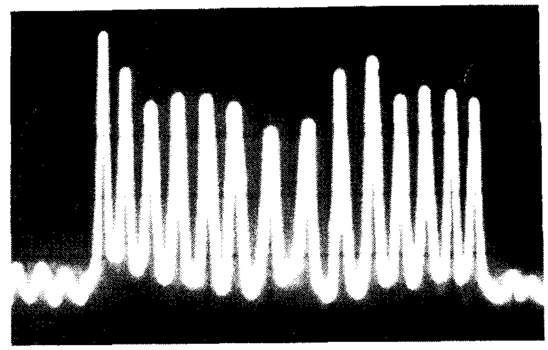

Figure 4. Photograph of wire scanner display for an 80 MeV deuteron beam in the main cyclotron.

wire scanner in the injector cyclotron was determined soley by space limitations.

The output of the wire scanner system exhibits two instrumental effects that are illustrated in Figure 4, which is a photograph of the wire scanner display for a centered 80 MeV deuteron beam in the main stage cyclotron. The turn number is increasing from left to right from a valley radius of 2.64 to 2.73 m. The last turn on the right is the one extracted from the cyclotron. The apparent decrease in the turn spacing from center to edge is caused by the variation in the linear velocity of the scanner wire as it cuts through the plane of the beam at a constant angular velocity. This variation amounts to about 17% from center to edge and is not operationally significant, since the precise location of each turn is determined from the position readout on the radial beam current probe as it intercepts each turn while being moved toward smaller radius. Beam orbit position measurements are made in this way to a precision of about 0.25 mm. The second and less pronounced instrumental effect is a similar apparent decrease in the radial width of the turns from center to edge, which is also caused by the variation of the linear velocity of the scanner wire.

Injector Cyclotron Centering Studies

Centered orbit patterns were obtained over the entire operating range of the injector cyclotron, representing a span of inflection radius from 17.3 to 26.7 cm. Examples of the turn structure for several beams that were centered to an accuracy of about 3 mm are shown in Figure 5. The data obtained from the centering studies were used to generate a table of the five position parameters for the two inflector elements as a function of inflection radius. Only one of these five parameters, the position of the second inflector normal to the inflected beam trajectory, differed from the original predictions calculated from the magnetic field data. Using these new predictions, the procedure for obtaining centered orbits in the injector cyclotron is simple and reproducible, and is usually accomplished in a few minutes. With beam accelerated to extraction radius, small adjustments to the chopper and klystron buncher phases relative to the accelerating RF are required to maximize the peak to valley ratio of the observed turn pattern, which is then usually ordered correctly. Small adjustments of the second inflector radius (<0.2 cm) and both inflector voltages (<0.5 kv) then complete the centering process. Beam transmission losses that occur for the resulting centered beam are then removed by adjusting the steering magnets upstream of the inflectors.

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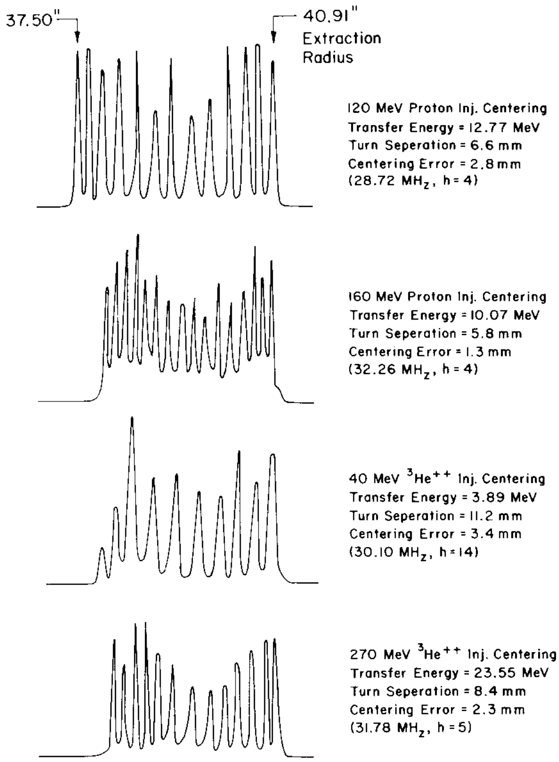

Figure 5. Injector Wire Scanner Display

Several properties of the inflection process specific to the injector were discovered which make this procedure possible. A crucial parameter for obtaining reproducible centering is the RF DEE voltage, since the energy gain of the beam on the first turn is about 20% of the incident energy. A large variation in DEE voltage for a given particle energy will result in a family of inflector positions for centered orbits. Also, a minimum DEE voltage (or threshold) for obtaining centered turns is determined by the necessity to acquire a large enough radius gain on the first turn to pass by the backside of the second inflector element. For the highest energy proton beams, this DEE voltage threshold is about 32 kV, which corresponds to an energy gain of nearly 130 keV. Finally, the relative magnitude of the two RF DEE voltages can have a significant effect on beam centering. For imbalances greater than 3 kV (10%), the attainment of a centered beam is difficult. Therefore, the proper setting of the DEE voltages is also an important part of the centering procedure.

The injector wire scanner is also useful for adjusting other injection parameters such as the buncher and chopper voltages and relative phases during the routine setup of the injector cyclotron. Improper bunching is readily observed with the scanner. Figure 6 shows two scanner displays of the same centered 200 MeV proton beam that differ only in buncher voltage and phase. The extraction efficiency from the cyclotron varies roughly as the peak-to-valley ratio. Therefore, tuning the injection beam line for better transmission of beam into the cyclotron at the expense of reducing the peak-to-valley ratio is not productive. Another observable feature of the accelerated beam in the injector is the periodic alternation of the radial (and axial) width of the turns (see Figure 5A, for example), which is caused by the rotation of the beam in phase

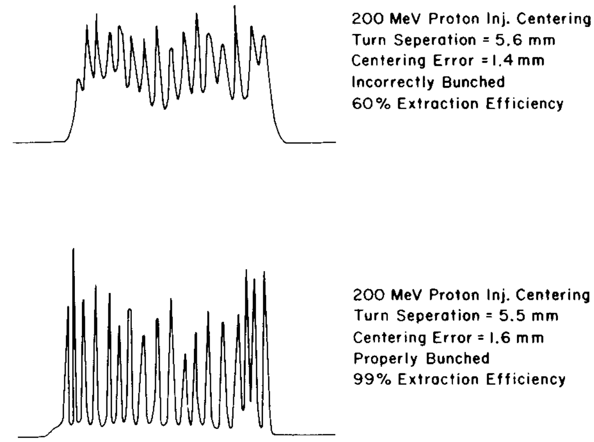

Figure 6

space during acceleration. This effect is minimized by making small adjustments to the buncher and chopper phases, as well as to the final focussing elements in the injection beam line.

Main Cyclotron Centering Results

The procedures for centering beams in the main stage are not as simple or reproducible as in the injector. Part of the reason for this may be that the inflection trajectory is not well enough defined and is dependent on the extracted beam energy of the injector. While beam centering in the injector minimizes this problem, it has not eliminated it. Proton beams between 60 and 160 MeV and an 80 MeV deuteron beam have been centered in the main stage to within 1 mm, for which examples are shown in Figure 7. Attempts to

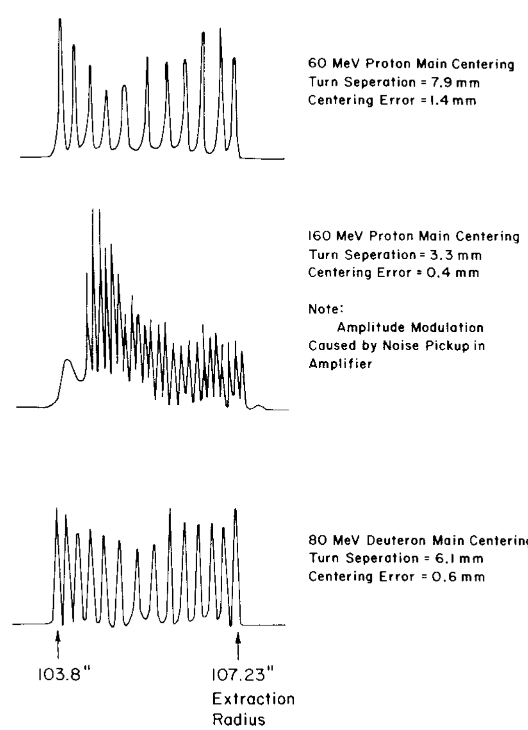

Figure 7

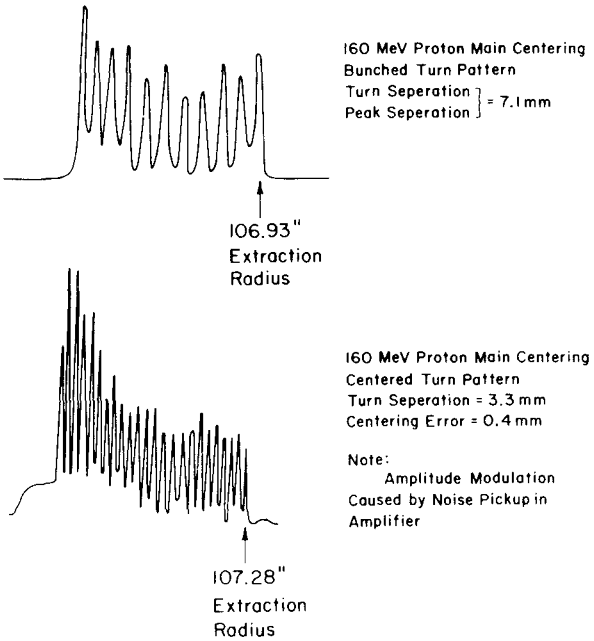

Figure 8

center proton beams of energies greater than 160 MeV have not yet been successful. Because the available RF DEE voltage is the same for all proton energies (about 120 kV) and varies with radius by a factor of three from inflection to extraction,[3] the radius gain per turn is roughly a constant during acceleration, and varies inversely with the incident beam energy. Therefore, at energies greater than 160 MeV, the radius gain on the first turn may not be enough to allow a centered orbit trajectory to clear the backside of the electrostatic inflector. This situation is aggravated by having a maximum available DEE voltage that is 60% of the design value. Except for this threshold, however, the centered turn patterns obtained were quite insensitive to the sum of or the differences in the voltage on the DEES. This is expected since the initial energy gain per turn is only about 2 to 3% of the incident energy.

An interesting property of the orbit structure capability of the main stage was observed which can lead to turn patterns that look centered but are not. Examples of this are shown in Figure 8 for a 160 MeV proton beam. In Figure 8A, the turn pattern observed by the scanner looks centered, and is in fact ordered correctly. However, the turn separation is twice that expected for the DEE voltage and the turns have a larger radial width than expected. Also, the change in DEE voltage required to change from one extracted turn to the next is four times larger than expected. Finally, when delivering this "centered" beam to the spin transfer group, the measured spin precession angle per extracted turn is also four times larger than predicted. This suggests that each peak in the observed turn pattern actually contains several turns. Yet extraction efficiencies of nearly 100% are obtained while operating in this "bunched" mode, and no depolarization of the extracted beam is observed. Therefore, only one of the turns in each peak is extracted. This turn pattern is possible at the higher proton energies because V_r is approaching 1.5. This phenomenon has not been observed at proton energies below about 100 MeV or for heavier ion beam energies, for which V_r is about 1.2. Verification of these conjectures was achieved by subsequently obtaining a truly centered orbit structure for 160 MeV protons, as shown in Figure 8B. For this beam, the measured turn separation, DEE voltage change per turn, and spin rotation angle change per turn were all within 5% of the predicted values for the DEE voltage used.

Operating the main cyclotron in the "bunched" mode has satisfactorily met the requirements of the spin transfer group. For their 200 MeV proton beam with the bunched turn pattern, the predicted and measured turn separation was 3 and 5 mm respectively. Yet a single turn extraction efficiency of 90% was obtained and no depolarization of the extracted turn was observed. This can occur because the two overlapping turns observed at the wire scanner have different trajectories, and are therefore radially separated at the entrance to the electrostatic deflector (whose septum thickness is 0.05 mm) located one meter downstream. Tuning the main cyclotron in this manner has become the preferred (if not the only) mode of operation for the spin transfer group because of the improved cleanliness of the extracted turn. For the correctly centered 160 MeV proton beam, a 0.4 kV change in DEE voltage is required to change from one extracted turn to the next. Because of the stability limits of the cyclotron magnetic field (10 parts per million) and RF systems (0.5%), small DEE voltage adjustments are continually required to keep the peak beam extracted. Because of the relatively low DEE voltage, the turn separation for high energy protons is small (<3mm) and small changes of the DEE voltage can cause a momentary extraction of adjacent turns. While operating in the bunched mode, however, the different trajectories of the turns adjacent to the extracted turn will not allow them to pass through the deflector even when incident on it. The effect of making small adjustments to the DEE voltage for this beam is to reduce the extraction efficiency of the desired turn rather than to change to the next turn. The DEE voltage to go from one extracted turn to the next in this mode is 1.6 kV.

Conclusions

The ability to observe the last 8 cm of the radial turn structure in both cyclotrons and to rapidly center the injector cyclotron beams has enhanced IUCF operations by minimizing the setup time of the accelerators while optimizing their performance. As diagnostic devices, the wire scanners detect phasing and other errors in the preparation of the beam for injection into the accelerators, both during the tune-up and routine operations. For example, the distinction between RF phase and magnetic field changes which cause the beam to be lost is easily observed using the wire scanner. The scanners were also used to verify the buncher voltage predictions, and the DEE voltage calibrations for both cyclotrons, which were all found to be accurate to within 5%. The development of centered beams in the main cyclotron, however, is not complete. While the discovery of the bunched turn structure capability of the main stage led to the successful use of the transversely polarized beams for experiment and routine single turn extraction at the higher proton energies, the inability to reproducibly obtain centered beams over the entire operating range contributes to delays and uncertainties in the tuning procedures. Further studies on the bunched operating mode and the parameters limiting the attainment of routine and reproducible centering in the main cyclotron are continuing.

References

1. E.J. Stephenson et al., Horizontally Polarized Proton Beams at IUCF, this publication.
2. National Electrostatics Corp., Middleton, Wisconsin, 53562.
3. D.L. Friesel, W.P. Jones, and J.C. Collins, IEEE. Trans. Nucl. Sci. NS-26 (1979) 3389.