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PERFORMANCE AND CHARACTERISTICS OF THE IUCF INJECTOR CYCLOTRON*

R.E. Pollock, P. Schwandt, and J.W. Hicks
Indiana University Cyclotron Facility
Bloomington, Indiana

Introduction

The Indiana University Cyclotron Facility (IUCF) will produce variable-energy light ion beams of energy up to 220 Q^2/A MeV. The three stage accelerator consists of a 600KV DC ion source terminal, an injector cyclotron of nominal 16 Q^2/A MeV and a main stage cyclotron. The two cyclotrons are of isochronous separated-radial-sector design and similar except for overall scale. The project was funded in 1968 and will begin operation during 1975. The first two stages were assembled in a temporary location and operated for a few months in 1972. Following relocation and reconstruction in the accelerator laboratory, the first two stages have been in use with internal beam since November 1973 and with extracted beam since October 1974. Many of the design characteristics of IUCF have been previously reported[1]. The present paper is intended to record the current status of the injector cyclotron design and some of its performance characteristics as predicted and as observed in beam development studies. We feel that our experience may be of interest in the future evolution of isochronous cyclotron design.

Magnetic Characteristics and Isochronization

The magnet ring consists of four narrow-gap uniform field 36° sectors, assembled such that the eight straight effective-field-boundaries intersect at the machine center. The focussing characteristics of this configuration have been described[2]. The sectors are truncated to open the central region for access; beam from a preceding accelerator being inflected into an appropriate trajectory relative to the inflection-energy equilibrium orbit to begin acceleration. Radial gradient trim coils consisting of pole face windings on the individual sectors maintain isochronism over the range of particles and final energies.

In the IUCF injector, there are two field shape effects which cause departures from isochronism which are larger in their effect upon trim coil design than the relativistic mass change of the light particles. The most important of these is a reduction of orbit frequency at the smaller radii, caused in part by proximity to the fringing of the weak field in the central region, in part by the rounding and circumference lengthening of the equilibrium orbit due to appreciable ($\geq$ 5% of hill field) field in the nominally field-free valleys, and in part by modification of the definition of the effective-field-boundary owing to the presence of an adjacent sector (the integral extends only to the valley centerline so that a straight magnet edge gives a curved efb). This effect scales with the main field and has been compensated by shaped magnetic shims which reduce the gap and raise the average field at the smaller radii. The second field shape effect is a parabolic rounding of the uniform field caused by pole tip saturation. This was first encountered[3] in field studies of a main stage sector and later found to be important in the injector as well. In the injector cyclotron, the central shims give a relatively strong perturbation to the field and also show saturation effects. The shims in fact are made deliberately too strong so that the inner trim coils must reduce the central field for operation at low energies, then change sign and add to the central field at the highest energies. The outer coils give primarily the relativistic correction at low fields, then add additional radial gradient in the operation above 10 Kg to correct for the parabolic effect.

The number of trim coils (10) is selected such that, in a 100 turn pattern, the departures of the phase history from perfect isochronism which arise from discontinuities in current density at the boundaries of adjacent coils are held to below ±1 particle phase degree, to permit operation on rf harmonic numbers as high as 16 or 17 ($q/m < 1/4$) with good beam quality. The radial width of coils is adjusted for convenience and economy in power supply design (eg. equal maximum currents in the inner coils) subject to the width constraint mentioned above. The inner four coils carry a total of ± 12% of the main coil ampere turns, while the outer six carry between 0 and 3% of the main excitation.

The shim was designed by iterative mapping. Trim coil currents to isochronize various ions and energies are predicted from measured half-sector maps at a few excitations and from individual coil perturbation maps, using superposition by a least-squares adjustment to the desired phase history. Predicted coil currents have been checked over a range of magnetic field settings by direct beam phase measurements with a device reported elsewhere in these proceedings[4]. A small and smoothly-varying correction is applied during operation which is based on these checks. The correction is most likely due to the departures of the average profile from that measured for half of one sector and amounts to about 0.2%.

For operation with a large radius gain per turn, the accelerated orbit circumference in the central region begins to depart from that of the appropriate equlibrium orbit. This is a dee-voltage dependent departure from isochronism which can slip phase by 20° or more unless the inner coils are adjusted to compensate.

Operation has been tested for rf harmonics h = 4,5,6,7, 13 and 14. The effective dee angle has been adjusted to disallow h = 9, 10 and 18-20, with the rf tuning range to be extended to span 25.5 to 35.0 MHz to avoid an energy gap in changing from h = 11 to h = 8.

In future accelerators of this type, a slightly bulbous nose on the magnet would eliminate the central shim and its attendent saturation problems, while a pole tip edge profile which placed the field boundary closer to the position of the pole base would reduce the parabolic rounding phenomenon. Field data on a magnet with these characteristics, operated to very high field, would be of great value in establishing a true upper limit on field strengths usable in separated-sector cyclotrons; the IUCF limit of approximately 16 Kg is presumably considerably below

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the practical limit in an optimum design.

Phase Selection and Intensity

With an internal ion source, central region obstacles or slits tend to be phase selective because of the strong correlation between first-turn radius and rf phase at the instant the ion emerges from the source. By inflecting a beam of appreciable energy (compared to the dee voltage) from a previous accelerator stage, it is in contrast quite feasible to accelerate any ion which gains enough radius to clear the inflector after one turn. Operating the IUCF injector with a DC beam inflected, we have observed phase groups reaching full radius with widths greater than 80°fwhm. In this mode, widths $\sim 60^{\circ}$ and intensities which are 1/6 of the DC inflected intensity are commonly obtained.

A computer study of the phase-radius history of a bundle of rays entering the cyclotron on a common trajectory and differing only in starting phase correctly predicts the wide phase bundle reaching extraction radius, and the turn-back of the rays with the wrong phase after some acceleration is consistent with the observed profile of radius versus intensity for DC inflection. This machine characteristic is perhaps of some interest in considering high intensity compact designs for isotope production, where the large low-field valley would permit the use of complex internal target mechanisms.

To obtain extracted beam of high quality with single turn extraction it is necessary to restrict the phase width prior to or during acceleration. Internal slits have given convenient phase selection with phase widths of a few degrees at MSU in a cyclotron with a fixed orbit geometry.[5] As our injector cyclotron is required to operate with overall energy gain between 5 and 25 and with variable energy gain per turn, it is somewhat less convenient for us to adopt this mechanism. We have been working instead with rf selective devices in the beam line which connects the DC source terminal to the injector stage. A low-power two-gap linac with gap spacing matched to the dee width on the first internal orbit (to give the same stop band in rf harmonics as the dee) has been used for klystron phase compression. With an 8 meter flight path between the velocity modulator and the point of inflection, an energy modulation less than 3 KeV is required, which is negligible in comparison with the 10 to 20 KeV resolution desired upon extraction. One difficulty with this device is that it introduces an extreme sensitivity to ripple in the ion source terminal voltage, the internal phase probe showing a starting phase ripple $\sim 20^{\circ}$. Another problem is that the internal beam measurements cannot easily be used to set the optimum phase and amplitude of the buncher voltage, because of the great tolerance to starting phase mentioned above. Typically this device increases the internal beam by a factor of two or three, probably with some over bunching. It will be most useful later in conjunction with the phase selector described below.

A recently-installed transverse rf modulator ("chopper") which sweeps the beam vertically across slits on the next waist downstream can be used to select a phase group of 20° or less. The beam line and inflection settings are optimized with this device turned off. The inflected beam is observed, after one-half revolution and one dee crossing, on a quartz viewer. With the dee off, a beam spot is observed, giving a useful centering check. With the dee on, a band of illumination is obtained which can be used to check the dee voltage. When the chopper is turned on, the band is resolved into two spots which can be made to coincide by adjusting the starting phase by 90°, or to have maximum separation by choosing the optimum starting phase. The chopper amplitude can be increased to reduce the phase width. The 20° width is obtained with 100 watts of excitation, the drive system being capable of supplying 1200 watts.

The ultimate design goal for phase selection is 2.5°, or about 0.25 nanoseconds. Using a gamma ray arrival time monitor near a Faraday cup on the external line, the best time resolution observed to date is 0.6 nsec fwhm, or 0.5 nsec after unfolding the 0.3 nsec detector resolution. It now appears that the combination of chopper plus buncher, one selecting a pulse width and the other compressing it, can achieve the design goal with accelerated beam intensities of about 5% of the DC inflected beam, although external pulse width measurements after extraction to set the buncher amplitude and some sort of active feedback to eliminate the last of the ion source ripple may be required.

Another rf device now under fabrication will provide pulse selection by horizontal transverse modulation at a subharmonic of the rf frequency eg 2/3 to select 1 pulse in three. Although built to facilitate flight timing in the experimental program, this device will also give a useful direct measurement of the success of single turn extraction. For example selecting one pulse in three while operating in rf fourth harmonic mode, one may examine the intensity in the nominally empty intervals preceding and following the extracted pulse for the fraction of beam extracted one turn too early or late respectively.

Typical good intensity values for proton beams are 60-80 μA leaving the DC source terminal accelerating tube through 6 mm x 6 mm aperture, 15-25 μA arriving at a 2 mm x 6 mm tuning aperture at the inflector entrance, 2-3 μA internal, 1 to 2 μA extracted (depending on phase selection and centering, 100% extraction has been observed). The losses in transmission between ion source and injector cyclotron are still not totally understood. We are confident of our ability to deliver 1/2 to 1μA of proton beams to the main stage cyclotron as required for our first operation. Alpha particles are obtained by source operation on He^{+} and stripping in a 5 $\mu g/cm^2$ Carbon foil after the chopper slits. Intensity is lost through the equilibrium fraction and through an emittance increase so that the intensity available at inflection is 10 to 15 times lower than for the proton beam. A beam of $^7Li^{++}$ has been inflected and accelerated but our experience is still too limited to give a reliable performance estimate. So far, beams delivered for research use to a target station on the diagnostic leg of the transfer beam line have included protons up to 11 MeV, $^1H_2^{+}$ and $^4He^{++}$. A source of multiply-charged ions is an obvious improvement on which design and procurement have begun.

Betatron Amplitudes

The reproducible achievement of uniformly-spaced well-resolved radial turn structure under conditions of variable inflection geometry has proven to be the most troublesome part of machine setup. Using an acceleration code and the measured field, one may predict the correct inflector position by timereversed deceleration inward from the desired uniform spiral. Placing the inflector at the calculated position has given coherent radial amplitudes less than 1.5 mm, or within a factor of three of the condition desired for an invariant extraction geometry. The calculations show several perturbing effects in the first few turns which make it rather difficult to reverse this process and find the centered condition by trial-and-error changes in the inflected beam radius and angle. For example, there is a phase-dependent radial impulse at the dee gaps, which are not orthogonal to the beam trajectory in a separated sector cyclotron of this type. This couples with the phase shift induced by a departure from the equilibrium orbit (mentioned above) to shift the starting position by a few millimeters.

The incoherent radial amplitude is limited during inflection by the acceptance of 2 slits of 2 mm width placed 20 cm apart, allowing a value slightly less than the measured source emittance.

The excitation of axial coherent amplitude in passing through a $\nu_z = 1$ resonance in the central region has not been a problem. Attempts to induce axial excursions by unbalancing the trim coil currents at radii close to the resonance have negligible effect on the beam. The full incoherent beam height is limited to 6 mm by inflector slits while the extraction magnet aperture is 9 mm.

Conclusion

While beam development studies are continuing, the inflector stage cyclotron at IUCF is now ready for use in the first acceleration studies with the main stage cyclotron this summer. Performance in general has been developed so as to begin to approach the design goals in most of the important parameters.

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