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INFLECTION AND EXTRACTION SYSTEMS AT THE INDIANA UNIVERSITY CYCLOTRON FACILITY†

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Summary

Properties of the magnetic and electrostatic elements which inflect beams into and extract from the injector and main stage cyclotrons at IUCF are described. Orbit separation is such that the assistance of orbit dynamical resonances is not employed. The beam stays in the median plane in all four systems. Inflection occurs after the beam has entered the cyclotron through one of the nearly field-free valleys; the beam crosses the central region and then experiences a bend of nearly 90° to enter the proper accelerated orbit. Extraction is accomplished by placing a substantial (~45°) bending magnet in one of the valleys just outside the region of circulating beam. Smaller elements upstream are then used to deflect the last turn so that it enters this magnet.

Injector Cyclotron Inflection

The inflection system must accept many different beams from a 500KV (later 800KV) DC ion source terminal which is the first stage of acceleration at IUCF. Spatial constraints in the cyclotron central region, as well as the proximity of the cyclotron magnets and circulating beam, preclude use of magnetic elements. A two-element electrostatic inflector has been designed with variable geometry to accommodate a fairly wide range of incident rigidities. One worst case is a 625KeV proton beam, inflected at minimum radius to give the maximum cyclotron energy gain of 25. The other extreme is a beam such as 2.2MeV $^{16}O^{3+}$, which must be inflected at a much larger radius consistent with its magnetic rigidity. By choosing to allow for a 10 inch range of radial adjustment, energy gains between 5 and 25 may be obtained.

In crossing a valley upon entering the cyclotron, the beam encounters a field which rises to a saddle point of about 7% of the hill field, then falls to about 4.5% near the machine center. The trajectory passes near the saddle point to avoid strong, position-dependent focussing effects. The total magnetic deflection angle for the least rigid beam up to the machine center is on the order of 20°. This deflection is compensated by a 5° bend in a beam line magnet just prior to entering the cyclotron chamber, and by a 15° "mid-course correction" in the first electrostatic inflector element. Four-jaw slits in front of the first element allow the correct adjustment of beam line quads and steering elements, while similar slits on the second element allow the correct voltage and position to be set for the first element. Transverse position adjustment and rotation of the first element allow for the range of incident rigidities and consequent trajectory variations.

The requirements of radial acceptance $\geq$ 30 mm-mrad and maximum voltage $\leq$ 60KV lead to a second element designed with 10.5cm radius and 0.4cm gap. By providing a rotational adjustment in addition to the radial adjustment described above, this element may be set for the correct value in (r,p_r) space to give a centered beam. A transverse adjustment is also required to match the incident angle to the trajectory from the first element over a range of exit angles i.e. equivalent to changing the length of the electrodes. Since there are no height constraints in the valley, the axial acceptance exceeds 100 mm-mrad for the inflector and the real limit is set by beam line optic elements upstream.

Voltage is fed to the two elements through coil springs from bushings in a vacuum plate above the central region. So little beam strikes the aluminum electrodes in normal use that water cooling has not been required with inflected beam power of 5 to 15 watts. Safety interlocks remove the electrode voltages to stop acceleration if the vault radiation integrity is lost.

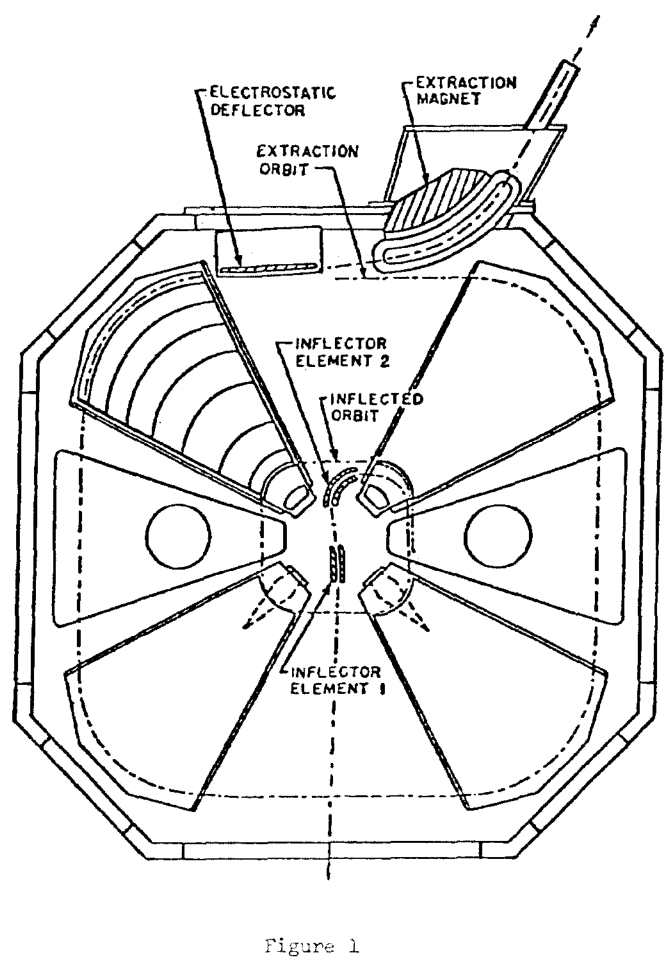

Figure 1

Injector Cyclotron Inflection and Extraction Elements

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The inflector motion is obtained by stepping motors outside the vacuum chamber, driving differential lead screws. Limit switches prevent interference with other central region elements. Absolute feedback is obtained from helical potentiometers with turn counters for calibration. The control computer drives the five motors and two high voltage supplies, displaying for the operator not only voltage and position step count, but also radial and transverse positions and angles in machine coordinates for direct comparison with the computed settings. A system of fiducials allows the absolute settings to be checked manually.

This system has been in routine use for several months, replacing a fixed geometry device used earlier.

Injector Cyclotron Extraction

A total exit bend angle of 60° is obtained by an electrostatic 6.5° deflector element encountered by the beam upon leaving one cyclotron magnet sector, followed, after a drift space sufficient to open the spacing between internal and deflected beam to 1.8 inches, by a 53.5° magnet with 0.37 inch gap and 19" radius. The magnet has a sharp enough field fall-off (assisted by field clamps designed after mapping) to avoid scrambling of the internal orbits upon excitation. Computer studies show that the sense of the uncompensated fringing perturbation is such as to slightly increase orbit separation at the septum of the deflector.

The electrostatic element has 5mm gap, 15 inch length and 60KV maximum DC excitation. The exit is fixed at a precalculated position and the entrance position is remotely adjustable over a moderate range to optimize transmission. Water cooling has not been required in operation with beam power up to 25 watts.

The extraction system has been in operation since October 1974, and has delivered beam to the transfer beam line with a demonstrated extraction efficiency > 90%.

Main Cyclotron Inflection

The system comprises two magnetic elements followed by a variable-geometry electrostatic element with three mechanical motions. The first magnetic element produces a "mid-course correction" of between 0° and 2°, much smaller than in the case of the injector cyclotron because the incident rigidity is matched to the injector stage and because the valley field at the saddle point is only 2% of the hill field. This element could be avoided altogether except that the saddle point field reduces to 1.6% as the cyclotron magnet saturates and that a range of inflection radii has been allowed for in case of future use with an electrostatic injector stage.

The main magnetic element produces a nominal bend of 83° in a magnet with 18.75 inch radius and 0.46 inch gap, operating at a field 10 to 15% lower than the cyclotron sector field. The yoke of this magnet perturbs the valley field by as much as 250 gauss, the perturbation having been measured in place near the end of isochronous mapping sequence. This perturbation must be reduced by a factor of three by compensating windings on the magnet yoke to reduce the centering perturbations to within acceptable limits. The gap fringing field is a perturbation of opposite sign, damping much more rapidly, and less significant in its effect on centering.

The electrostatic inflection element lies within the gap of one cyclotron sector magnet. The trim coils in this region have been relieved to give a total clearence of 5cm for this element which is operated at 60KV. For use in beam centering, the exit radius and angle of this element may be changed to select the proper starting point in (r, p_r) space. The radial adjustment is made large enough (4 inches) to accommodate the beams from the present injector cyclotron near one end of the travel and also to match the equilibrium rigidity of foil-stripped heavy ions from a future electrostatic injector stage. The inflector acceptance with a gap of 5mm is 16mm-mrad, about 50% larger than that of the injector cyclotron extractor. The gap at the entrance is made adjustable

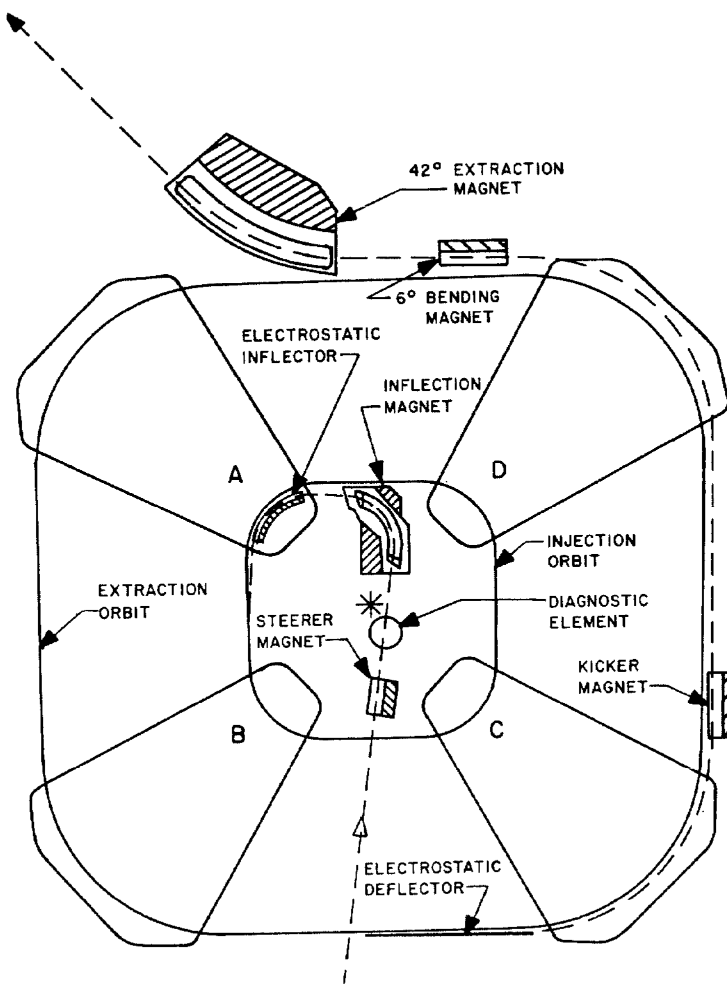

Figure 2

Main Cyclotron
Inflection and Extraction Elements

to increase the acceptance substantially for beams other than protons. Changes in position of the electrostatic element must be accompanied by small adjustments in the field of the two preceding magnetic elements to maintain an invarient incident trajectory. The pole tip width of the 83° magnet was chosen to allow for the variations in trajectory within this element.

These components are nearly complete and awaiting installation.

Main Stage Extraction

A total exit bend of 45° is obtained by a 39° magnet similar to beam line bending magnets used in the experimental area, preceded by a 6° magnet with a sharper field boundary. These magnets are placed on opposite sides of the extraction valley with sufficient drift space between them so that the nominal 2 inch separation between internal and extracted beams opens to about 6 inches at the 39° magnet entrance. There is space between these two elements for a vertical steerer which forms part of the beam line optics and for a probe on the valley centerline.

The electrostatic deflector must be located in the opposite valley to avoid operation within the rf dee. This element has a 48 inch length and operates at 60KV DC with a 6mm gap. The entrance position is fixed and the exit adjusted for best transmission. For the best turn separation with high energy protons, there is an appreciable advantage to beginning the deflection process near the valley centerline where the ratio of turn spacing to width is twice as good as within the magnet sectors.

The field shape changes associated with the differing relativistic masses in variable energy operation give substantial changes in ν_r (the ratio of radial betatron frequency to orbit frequency), the values lying between 1.15 and 1.55. This means that a given outward deflection by the electrostatic element leads to rather different displacements at the entrance of the 6° magnet. In fact for the highest values of ν_r, the extracted orbit separation would be negative rather than the +2 inches required by the magnet fringe field. To overcome this difficulty and to accommodate the large variations in ν_r, an additional magnet is used to introduce an additional outward kick of up to 2° to the beam as it passes through the intervening rf valley. The deflector can be adjusted in strength and exit angle sufficiently to give a constant separation at this 2° magnet and the bend within it in turn adjusted to give an invariant separation at the 6° magnet. The outermost trim coil, in the two cyclotron sectors which the extracted beam encounters, may be adjusted to reduce the deflector voltage by about 20% for the highest proton energies without causing a phase slip of more than 5°, but cannot remove the need for the small kicker magnet. The dee frame is designed to hold the 80 pound mass of this magnet and the current leads are brought out through the dee stem.

This system should be installed and tested in the summer of 1975.