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INDIANA UNIVERSITY CYCLOTRON FACILITY - THE FIRST YEAR OF OPERATION†

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Summary

A progress report on the Indiana University Cyclotron Facility in its first year of operation is presented. Research productivity in the period was substantial, with approximately 225 shifts of beam delivered to some 30 experiments. Nearly half the use was by user groups from outside Indiana University.

The versatility of the I.U.C.F. accelerator system was evident from the delivery of 20 proton energies in the range 35 to 164 MeV, 6 energies of ^{6}Li between 55 and 100 MeV, and also deuteron, alpha and ^{7}Li beams. Beam quality was good and scattering spectra with overall energy resolution of 0.05% fwhm at 135 MeV were obtained. Intensities on target began at a few nano-amperes and had risen to some hundreds of nano-amperes by the end of the year. Reliability was satisfactory with unscheduled downtime beginning at about 30% of scheduled operation and falling to below 20% by year end.

Accelerator Configuration

The three-accelerator configuration at IUCF, based on a design concept by M.E. Rickey and co-workers,[1-3] was funded in mid-1968 and began operation in the latter part of 1975. The main stage of acceleration is a 6.95 meter isochronous cyclotron with four separated 36° radial sector magnets. The beam energy is variable up to the magnet rigidity limit of 210-225 Q^2/A MeV for all ions, the higher value applying to the more relativistic light particles. The hollow center imposes a maximum radius gain factor of 3.2, or an energy gain of 10.4 to 13.4. A set of 21 radial profile coils, totalling over 25% of the ampere-turns of the main coil excitation, provides isochronous field shaping for the unusually wide range of operating energies. Two radio-frequency cavities, with two accelerating gaps each, provide up to 1 MeV/turn/charge at the extraction radius, but give 3 to 4 times less voltage at inflection, for a nominal maximum of 350 turns. The 25-35 MHz frequency range spans orbit frequencies from 1.47 to 8.75 MHz by using harmonic numbers $3 \leq h \leq 17$, where h = (rf frequency/orbit frequency), which implies a lower energy limit of 4.3 MeV/amu, and a minimum $Q/A \geq 1/7$. The values h = 9 and 10 and h = 18-20 give very small energy gain/turn and are not used. The low average magnetic field and large energy gain per turn result in turn separations of 7 mm or more at extraction.

The two accelerator stages which feed the main cyclotron presently consist of a 500 kV DC platform for the ion source, followed by a 2.1 meter injector cyclotron. The injector has a nominal maximum energy of 15 Q^2/A MeV and maximum energy gain of 23 and may be thought of as an approximately 1/3 scale working model of the main cyclotron. Although the first two stages are much smaller than the main cyclotron, they largely determine the overall performance of the system. Much of the current development and improvement program is concentrated on these smaller machines and their associated beam transfer components.

The beam line connecting the ion source terminal to the injector cyclotron contains components for pulse preparation and charge state selection which are described in later sections of this report. The transfer beam line between the two cyclotrons contains a foil stripper magazine used to remove the last electron from Li^{++} beams. Dispersive elements and slits in this line are used to constrain the transfer energy. The narrow-gap electrostatic inflection and deflection components in both cyclotrons introduce significant constraints on horizontal (radial) emittance, while the magnetic components of these inflection/extraction systems are significant vertical (axial) constraints. Finally the beam line connecting the main cyclotron to the experimental areas has provision for definition of beam size, divergence and energy resolution, with adjustments for dispersion matching, or for quasi-isochronous transfer, to maximize spectrograph resolution, or flight-timing resolution, respectively.

Most aspects of the accelerator configuration and its control system have been previously described.[4-9]

Research Equipment

The first target station in use, and the major instrument for high resolution particle detection, is a 135 cm QDDM spectrograph with 3 msr solid angle and a 3% momentum bite covering a 60 cm focal plane. The standard detector is one position-sensing proportional chamber and two scintillators.

A target station for in-beam gamma spectroscopy is in frequent use. With careful beam preparation and an optimized beam dump geometry, the counting rate, with proton beams of 135 MeV, for an empty ½ inch target frame can be as low as 5% of the rate from a 2 mg/cm^2 A ∿ 60 target. This is of course largely a measure of freedom from beam halo.

A general purpose scattering chamber of 162 cm diameter has been used with multiple arrays of solid state detectors for scattering and reactions with $Z > 1$.

A neutron time-of-flight station provides 30 meter paths for $0° \leq \theta \leq 20°$ with a dump magnet for the forward beam. Time resolutions $\leq$ 0.6 nanosec. overall have been obtained. Shadow bar measurements show $\geq$ 95% of the flux is from the target directly.

An isotope production area has produced ^{123}I in batches of several millicuries and provides for neutron and particle bombardments in a variety of configurations, with rapid transfer to a fast chemistry and off-line counting annex.

A small spectrometer optimized for threshold pion detection (very large solid angle, short path, moderate resolution) is in development.

Accelerator Availability

The IUCF main cyclotron produced first acceleration on August 9, 1975, first extracted beam on September 24, and first beam on target on October 4, 1975. Following a six-week shutdown, research use began in the last weeks of 1975.

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During 1976 the facility was typically scheduled for 15 shifts of eight-hour duration during running weeks. At intervals of a few weeks, operation was halted for one or two weeks of scheduled maintenance, improvements, or new construction, for a total of 40 weeks of scheduled operation during 1976. During the year the unscheduled downtime for breakdowns and repairs fell from about 30% of the scheduled time to a value between 15 and 20%. No single subsystem was responsible for a dominant portion of the downtime. Radio-frequency elements, high voltage elements, and mechanical drives accounted for about half the lost time. The reliability in fact was unexpectedly high for initial operation of an accelerator configuration of this complexity.

Of the 450 shifts scheduled and available, half was charged to research use for approved experiments, and a further 15% to development activities, both for accelerators and for commissioning of new research equipment, for a total of nearly 300 shifts of useful operation. The balance of the time, in which the machine was operable but not "useful" consisted of weekly startups, changes of particle type or energy to satisfy the requirements of the many short duration early experiments, operator training, retuning as required, and experiment setups with beam. The goal for 1977 is to deliver 500 useful shifts in 45 weeks of operation, with the principal improvement to come not from better reliability, but from improvements in operating efficiency. The trend toward somewhat longer production runs will help this ratio, as will a bookkeeping change which charges experiments for setup time with beam and for energy or particle changes within runs to encourage experimental optimization. Nevertheless the flexibility of beam choice, and the single use mode with runs typically a few shifts in duration, will always make IUCF beam delivery statistics rather different from those of other intermediate energy machines.

Accelerator Performance

The operation during 1976 can be divided into three phases. Through April, the emphasis was on production of three proton energies 135, 80 and later 100 MeV, and on preliminary runs for many experiments, for the purpose of background assessment and evolution of techniques. Intensities on target were typically 1 - 10 nA with occasional excursions to 50 nA or more. Operators who began the year with little or no experience were learning the rudiments of startup and beam tuning. Beam line installation continued, and the number of target stations in use increased from 1 to 3. Most of the technical staff were preoccupied either with new construction, emergency repairs or reliability improvements.

The next three months was a period of exploration in which the energy range for protons was extended to many energies from 35 to 150 MeV. The first excitation function runs were attempted just above the pion threshold, energy changes of two hour duration being interspersed with 4 to 6 hours of data-taking. First beams of $^{2}H^{+}$ and $^{6}Li^{3+}$ were made available, the latter at subnanoamp levels at first, suitable for in-beam gamma ray experiments. Studies of transmission factors for the Li beams helped the intensity of other ion beams as well, and for protons 50 nA on target became more common.

During the summer the number of target stations available increased to five. Scheduling efficiency was also improved when a second data acquisition system came on-line, permitting the over-lapping of electronic setup with operation.

The last four months of 1976 were more characteristic of future operation as many experiments went into production mode with longer runs. The performance highlights included 160 MeV at 100 nA on target in September, 500 nA on target in November, 82% main stage extraction efficiency, numerous new energies, the first $^{4}He^{++}$ beams, and a decreasing need for beam physicist intervention in routine operation.

One may define two fundamental modes of operation for the accelerator system. The high definition mode is conceptually simpler although it has proven more difficult to maintain in practice. In this mode, the beam from the ion source is prepared during transmission through the low energy beam line into the optimum phase space configuration for acceleration and transmission to the target. The most difficult requirement to meet is the narrow phase width ($\sim$2.4° fwhm) although the transverse emittance (typically 0.3 π cm rad eV$^{\frac{1}{2}}$ radial by π cm rad eV$^{\frac{1}{2}}$ axial), properly matched for uniform acceleration, is not a trivial requirement. This mode has been used primarily in development tests. It is characterized by large intensity reductions during pulse preparation from the DC beam, with high transmission thereafter. With the diagnostic devices currently available, the operator has relatively little information feedback and the beam is easily lost by drifts or minor adjustments.

The low definition mode is one in which as few constraints as possible are applied, and beam transmission is maximized from source to target. This mode is characterized by noticeable beam loss at each of some 11 slits or narrow gap devices as the phase space contour is formed into the desired shape by successive approximations. Current pickoffs and simple transmission ratio measurements enable the operator to obtain and maintain an acceptable tune. The most intense beams are obtained with losses distributed among the constraints so that a quasi-exponential survival profile is observed, yielding about 0.2% of the DC source intensity on target. Despite its operational simplicity, this mode is acceptable only for low to moderate intensities, beyond which heating and activation problems ensue. While the 1976 performance figures apply to this mode, the future operational limits will be determined by the behaviour in the high definition mode.

The phase acceptance factor leads one to expect about 0.6% of the DC beam to reach the target, enhanced by the buncher by a factor of 5 as explained in the next section. With the duoplasmatron source in use now giving 50 to 100 μA, it should be possible to increase intensity on target to one microampere. Further improvements can come from the use of more intense sources in the new ion source terminal now under construction, but present experimental area shielding is adequate only for the sub-microamp level.

A nominal beam current of 150 nA was used in the planning of early experiments. By the end of the first year this figure was being reached for protons frequently, but not on every tuneup. To obtain the highest resolution in spectrograph experiments, slit settings in the high energy beam line were used which reduced the beam by a factor of three (low definition mode), suggesting the need for better phase width and/or emittance constraints prior to the main stage.

Harmonic numbers near the optimum energy gain ($h = 4, 5, 6$ for protons; $h = 13, 14, 15$ for ^{6}Li) are used as required, and exhibit similar performance characteristics. The harmonics $h = 7$ and $h = 12$, for which the energy gain falls below 75%, have been somewhat more difficult to tune, with best intensities about a factor of three lower. This behaviour was not expected from orbit calculations and is still under study. Harmonics 8 and 11, with energy gain below 50%, have not yet been used, although required eventually to fill an energy gap 18-32 MeV/amU.

Beam such as lithium which are stripped to a higher charge state prior to acceleration are of lower intensity due to the equilibrium fraction for the conversion. Just prior to the conference, beams of 50 pnA of ^6Li at 65 MeV on target were recorded.

Pulse Preparation

The DC beam from the ion source is processed to match the rf phase acceptance of the cyclotrons. For most experiments, one beam pulse per rf cycle is desired, giving h pulses per orbit, where h is the rf harmonic number. For flight-timing experiments, one pulse per orbit is required for clean suppression, obtained from one pulse per h rf cycles.

The pulsed beam intensity is increased by about a factor of five, using an rf velocity modulator ("buncher") in the low energy beam line, followed by a 5 meter drift space before inflection into the injector cyclotron. The modulator is a two-gap linear accelerator. The accelerating electrode is mounted on a low-capacity ceramic vacuum feedthrough connected to an adjustably-tuned quarter-wave helical resonator line. The gap separation is made effectively equal to the first-turn dee width so that the buncher works over the same frequency range as the cyclotron rf. At most a few kilovolts amplitude is required.

The buncher parameters are set by the following calibration procedure. The beam in the injector cyclotron may be viewed by a TV camera and a pneumatically-activated quartz plate which stops the beam $\frac{1}{4}$ revolution after the first dee and $\frac{1}{2}$ revolution after inflection. With all rf off, a spot is observed at the coasting radius. With the cyclotron rf on, the spot is spread into a line of several centimeters length. Some of the DC beam is accelerated and some decelerated in the first dee and the following magnet sector is dispersive. If the beam is vertically displaced from the electrical symmetry plane of the dees, the line opens into an ellipse. When the buncher is turned on, the ellipse exhibits an intensity modulation around its periphery. The buncher amplitude and phase are then set respectively for one bright spot of minimum width at the phase of maximum energy gain. The method is simple and accurate to a little better than 10° in phase width and phase position.

As is well known, most circular accelerators exhibit only minor bunching efforts due to internal accelerating structures because a velocity increase leads to a proportionately larger orbit circumference and little or no change in transit time. In the Indiana configuration however, the situation is different because the rf structure of a dee contains two accelerating gaps separated by a nearly magnetic-field-free drift across the rf valley. On the inner orbits beam crossing the upstream dee gap is velocity modulated, then drifts an appreciable distance to the downstream gap. The effect is a maximum for rf phase 90° away from that corresponding to maximum energy gain and is clearly observable during the calibration procedure described above. The buncher voltage giving minimum spot width at the viewer, for buncher phase displaced 90° on one side of the value for best acceleration, is appreciably different from the buncher voltage for minimum width observed for the opposite 90° phase displacement. Calculation shows that the correct buncher voltage setting is close to the geometric mean of the two values obtained for the ±90° displacements. Note the complication introduced into isochronization procedures by the coupling between buncher settings and starting phase.

The beam entering the injector is bent by the field in the valley, and this bend is compensated by a 5° magnet at the tank wall. This scheme introduces two further buncher complications. The beam width is several centimeters at the magnet, with the beam converging toward the inflector gap. In the bend an appreciable path length difference between the extreme rays is introduced, corresponding to a phase spread of several degrees which appears to limit the bunching improvement factor. Furthermore the magnet dispersion spreads the bunched beam across the inflector slits in such a way that maximum inflected intensity corresponds to incorrect buncher phasing and magnet setting.

Two orthogonal transverse rf deflectors ("choppers") can be operated to sweep the beam across a set of beam lines slits at a narrow waist. For pulse selection the two plates are operated at 90° relative phase at a frequency of (h-1)/h relative to the cyclotron rf. This produces a ring pattern at the slit. The beam is steered magnetically to the side by one radius to obtain transmission and the pulse adjusted to pass beam at the proper time for acceleration. Pulse suppression ratios as high as several thousand are observed. The chopper system can also be operated at the cyclotron frequency to produce phase groups of selected width prior to bunching, or one electrode pair operated at each freqnecy to produce a variety of Lissajous patterns for simultaneous pulse selection and phase clipping. Transmission of the selected beam using the choppers has been only 20 to 50% of the expected value thus far.

Charge Changing

The vapor stripper in the low energy beam line which is used to remove one electron from Li^+ and He^+ ions consists of a cylindrical chamber fed with a fluorocarbon vapor of high molecular weight. The beam entrance and exit apertures are placed at the narrowest waist in the beam line to limit the gas outflow and the effect of multiple scattering upon beam emittance. Three cold traps at LN_2 temperature reduce the vapor load on the rest of the vacuum system. The flow of vapor to the stripper is adjusted with a needle valve for best internal beam in the injector stage. A definite maximum is observed; the beam loss on the high pressure side apparently resulting from electron pickup in the residual vapor in the 5 meter section of beam line between stripper and cyclotron rather than from the emittance increase. At 400 keV the maximum observed particle current ratio ($^6Li^{++}/^6Li^+$) is 1/7, which is not inconsistent with published charge equilibrium fractions for other stripping materials.

Carbon foils (3-5 $\mu g/cm^2$) in the beam line between cyclotrons convert more than 90% of the Li^{++} to Li^{3+}.

Isochronism

Trim coil settings change smoothly with energy so that new energies can be obtained by interpolation. The main stage coil currents agree quite well with the predictions based on a single sector map, although adjustments of a few gauss are observed to be necessary, even in reproducing an energy previously developed. The field shape is affected by sudden changes in main coil or trim coil current, for example if a power interruption or interlock trip occurs. Transient shape changes take 10 minutes to die away. A magnet cycling procedure to restore the profile takes about 20 minutes with settling. Often small trim current changes are required to restore comparable isochronism following such a perturbation. While the main magnet changes, isochronism in the injector stage is lost due to the transient fringe field.

A simple measure of the quality of the main stage tune is obtained by changing the relative rf phase of the two cyclotrons while observing the full radius beam current. The half loss points occur at values from ±15° for a marginal tune to as much as ±40°. The inflected beam must clear the inflector septum on the first few turns and this requirement limits the starting phase acceptance as can be seen by repeating the measurement at a small radius.

On two occasions when an rf amplifier failed at an inconvenient hour, the experiment has been continued by operating with only one dee excited after minor profile and centering readjustments. Performance does not appear to be noticeably worse in this mode.

The control computer provides for seven "super knob" adjustments in which different sets of four or more trim coil currents are changed simultaneously in the appropriate ratio to introduce phase excursions localized in radius. With the aid of these convenient parameters, the phase history can be made flatter until the starting phase acceptance is invarient with radius.

Accelerator Improvements

An ion source terminal of 750 kV to accommodate a variety of sources is being assembled. With the resulting increase of incident energy, it should be possible to provide proton beams of 190 MeV or more by the end of 1977. A commercial polarized proton/deuteron source will be installed early in 1978. The terminal provides a magnet, power and cooling for an arc source of several kilowatts which can in future make available intense Helium beams and multiply-charged ions such as 170 MeV $^{20}Ne^{4+}$.

A substantial number of improvements to accelerators and beam lines are underway to improve the matching of beams, to extend performance limits, to improve diagnostic information and control. Space precludes a fuller description of work in progress.

Conclusion

Although IUCF has now been in operation for more than a year, it has been possible to realize in that time only a small fraction of the full potential of this extremely flexible facility. The fundamental performance limits are clearly much broader than those reported here.

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