Proceedings of the 7th International Conference on Cyclotrons and their Applications, Zürich, Switzerland

STATUS REPORT ON THE INDIANA UNIVERSITY CYCLOTRON FACILITY *

R. E. Pollock

Indiana University, Bloomington, Indiana, USA

Abstract

First operation of IUCF is described.

1. Introduction

The Indiana cyclotron design[1] has four radial (no spiral) magnet sectors that give adequate dynamic stability[2] for protons to about 200 MeV with 36° sector angle. Particle and energy variability is obtained by substantial field shape changes, the radial gradient coils being capable of supplying 20 to 30% of the main coil ampere-turns. The hollow center of the magnet ring gives an upper limit to the total radius increase in the acceleration spiral and leads to the requirement for an injector.

Internal beam operation of the main stage cyclotron began only a few days before the start of this conference. This report concentrates on a few preliminary results which may be of general interest. The reader is cautioned against extrapolations, as work is still in progress.

2. Operating Experience

The injection stages, consisting of ion sources, high voltage terminal, first beam line and injector cyclotron, have been in operation for some time and their performance characteristics have been previously described[3,4,5,6]. Typical extracted beam characteristics are 0.5 to 1.5 microamperes of protons up to energies of 10 to 12 MeV. A beam was first inflected into a coasting orbit in the main stage cyclotron on 13 June 1975 at a time when only half the trim coil and rf components were installed. The first acceleration attempt was made on July 16 with both rf systems tested, and trim coils installed but not interconnected. On this attempt the rf amplifier anode power supply crowbar failed. After parts were flown in and the trim coil hookup was completed, a series of 4 runs between July 22 and July 28 were made which showed evidence of a centering error of several millimeters, with loss of beam on the back of the inflector septum and very poor ($<10^{-3}$) transfer efficiency from the coasting beam into the acceleration spiral. We had chosen for these first tests a 127 MeV proton beam as an easy case in the middle of our energy range. This choice gave an rf frequency of 28.88 MH_z whose third harmonic by accident excited a previously unsuspected spurious resonance in the drive ball screws of the rf tuning panels. Five of the eight drives overheated and jammed. In the one week that it took to redesign, remove, rebuild and reinstall these drives (which now have no serious resonant modes) a central region field compensator for removing the perturbation induced by the yoke of the inflector magnet on the north valley field was installed and mapped, and some small corrections were made to the harmonic content of the magnet sectors as described in the next section. The largest extraction magnet was also installed at this time.

After rf conditioning and repair of some minor vacuum leaks, a run on 8 August gave acceleration of a few nanoamperes of protons to about 80 MeV with the predicted trim current settings, and a less intense beam to 120 MeV, within several centimeters of the extraction radius. This run terminated with a rf screen power supply failure.

The electrostatic inflector position was checked on August 10, and the lower limit to the remotely-operated radius travel was changed by 5mm. In the final run of this series on August 12, an inflected beam of up to 0.32 microamps was obtained. Using the modified radial position of the inflector, about 10% of this beam was transferred to the acceleration spiral. With a few small adjustments to the field compensator and trim coil currents, a well-behaved beam of 10 to 15 nanoamps was accelerated to 130 MeV at a radius about 3 cm beyond the nominal extraction point. Coherent radial and axial betatron oscillation of about 3 mm amplitude could be observed on a BeO phosphor mounted on the south probe and viewed with a television monitor as the probe radius was increased. Figure 1 shows the first integral probe current plots as a function of radius for several starting phases. The injector rf phase is shifted to obtain the different arrival times. There is no significant beam loss (except at inflection) over a 30° phase interval. A bump in the phase history is evident in the -20° curve which can be removed by a trim current change. The sides of the phase acceptance curve measured at the extraction radius give a phase width of ~5°.

The main stage cyclotron is open to air during the week of the conference for installation of the remainder of the extraction system and the differential current probe. Extraction tests are scheduled to begin on Sept. 3. A radiation check after opening showed that the beam loss beyond the extraction radius was caused by a coil spacer in the extraction magnet which will be shadowed by the electrostatic deflector[7] when that is installed. The beam had passed completely through the spacer and had made a hot spot on the sector down stream. This beam loss occurred only in the 2 or 3 minutes in which the turn patterns were being made, but the aluminum spacer had a surface activity >20 mR/hr some 16 hours later. Some of the vault roof had already been removed for crane access during the extractor component installation. The neutron flux from skyshine on the balcony was ~30 mRem/hr during operation.

We have still to locate and fix a component positioning error which is preventing 100% transfer of the inflected beam into the acceleration spiral. We must be more careful to avoid incidental beam spills before we dare to accelerate or try to extract the intensity which will then be available. Component behavior has shown that we will have no problem producing energies in a 60 to 150 MeV range, the temporary upper limit being still set by the ion source terminal voltage.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 27-32

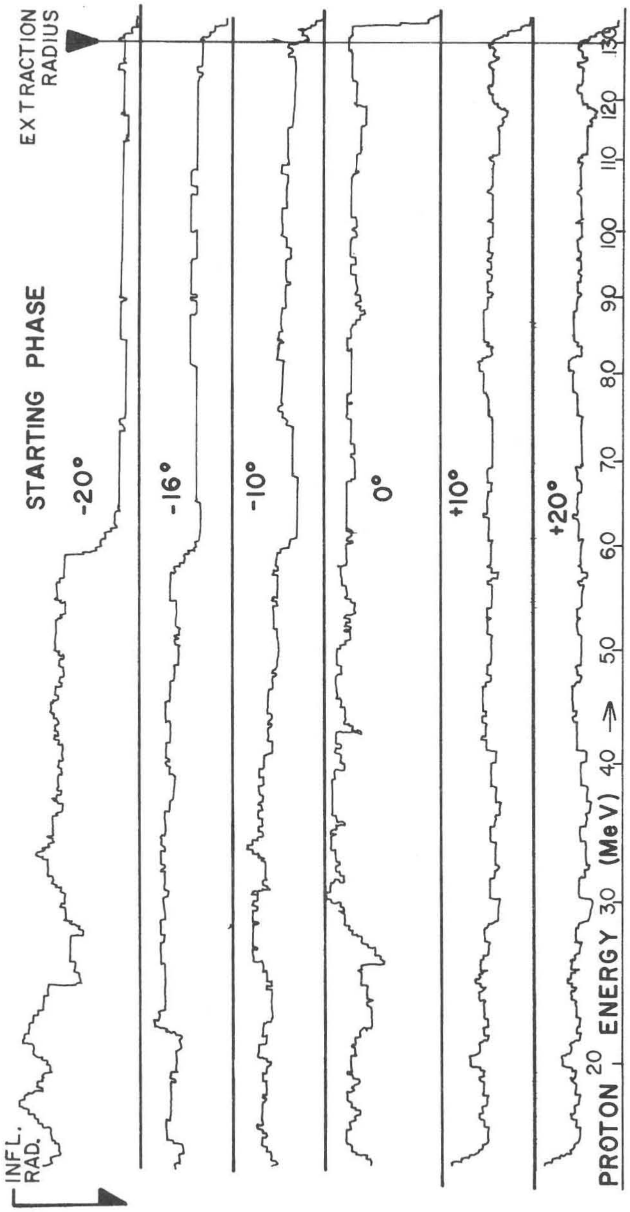

Figure 1. First turn patterns. Note beam loss at 13 MeV with positive phase and at 59 MeV with negative phase

3. Main Stage Magnetic Fields

The base magnetic field is uniform except for a 4% central region shim. The field is made isochronous,for the wide design range of particle masses and energies, by 21 radial gradient ("trim") coils. The trim coil design, the mapping procedures and results have been previously described[8,9,10]. The field can be made isochronous even for the high rf harmonic numbers which correspond to heavy ion acceleration.

Because of the late delivery date for the trim coils, the field mapping was completed in December 1974 using a prototype trim coil set in one magnet sector (SW sectorB). The first two trim coil sets were installed in early June and the last two in early July 1975. The intricate interconnection operation was completed on July 19, 1975. The variation from sector to sector has since been checked with trim coils excited to give an isochronous field for 127 MeV protons, by hill centerline scans with an nmr probe. Earlier tests had shown that the absence of significant azimuthal variation permits a one-dimensional check in this way. The largest variation was a uniformly higher field by about 0.35% in the two west sectors A and B. This effect was removed by a pair of small bypass resistors across the main coils, as it is roughly invariant with excitation and radius. The next largest variation was a 0.4% weakness in the nose of NE sector D. This was actually first found by a centering error in the inflected beam in the first acceleration attempts and confirmed by field measurements. This has been temporarily corrected by bypassing two trim coils but will later be adjusted by a shim modification. With these changes the variation in the observed field, relative to the isochronous hill centerline prediction, is shown in Figure 2.

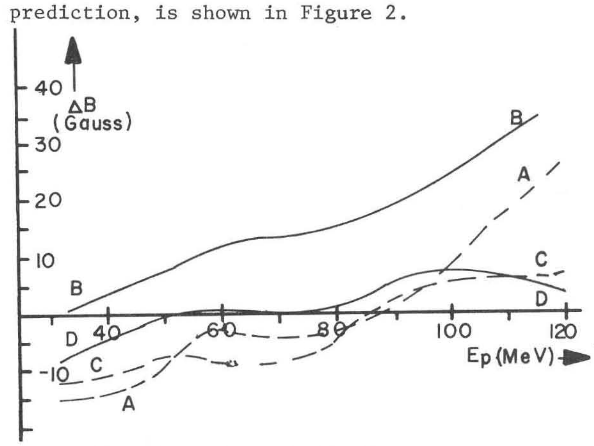

Figure 2. Comparison of the four magnet sectors. Note similarity to $\pm$ 10 gauss and common upward trend

The main field is about 11 Kg and the isochronous rise with radius is about 1.3 Kg so the observed variations on the order of 10 gauss are relatively small. There is a consistent trend of the average of the four sectors to lie below the isochronous value at small radii and above it at large radii. This is apparently a small but real change in the field shape of each sector due to the excitation of trim coils in adjacent sectors. It is equally prominent in the mapped sector on which the prediction is based and in the previously unmapped sectors. Ignoring this observation, the field was found to isochronous enough to accelerate the beam from 10 MeV to 80 MeV using the predicted current distribution. A small adjustment in two or three coils as suggested by the nmr scans brought the beam to full radius (130 MeV) with a starting phase acceptance$\gtrsim$ 30°.

*Work supported in part by the NSF and by IU

4. Main Stage Vacuum

The ring chamber is constructed of eight segments; four chambers which form part of the magnet structure and which are largely filled with pole tips and main coils, and four "valley" chambers which link the magnets. Two cryogenic vacuum pumps, each consisting of a 5 watt 20 K cold surface surrounded by an 80K radiation shroud are suspended in non-valved appendages below the rf valleys with a honeycomb baffle to suppress rf heating. A small auxiliary high vacuum pump (~1000 ℓ /second) is mounted in one of the other valleys to take care of the H, He and Ne gas load. The narrow magnet gap limits the conductance between valleys. The trim coil structure with its sidewalls reduces the magnet gap

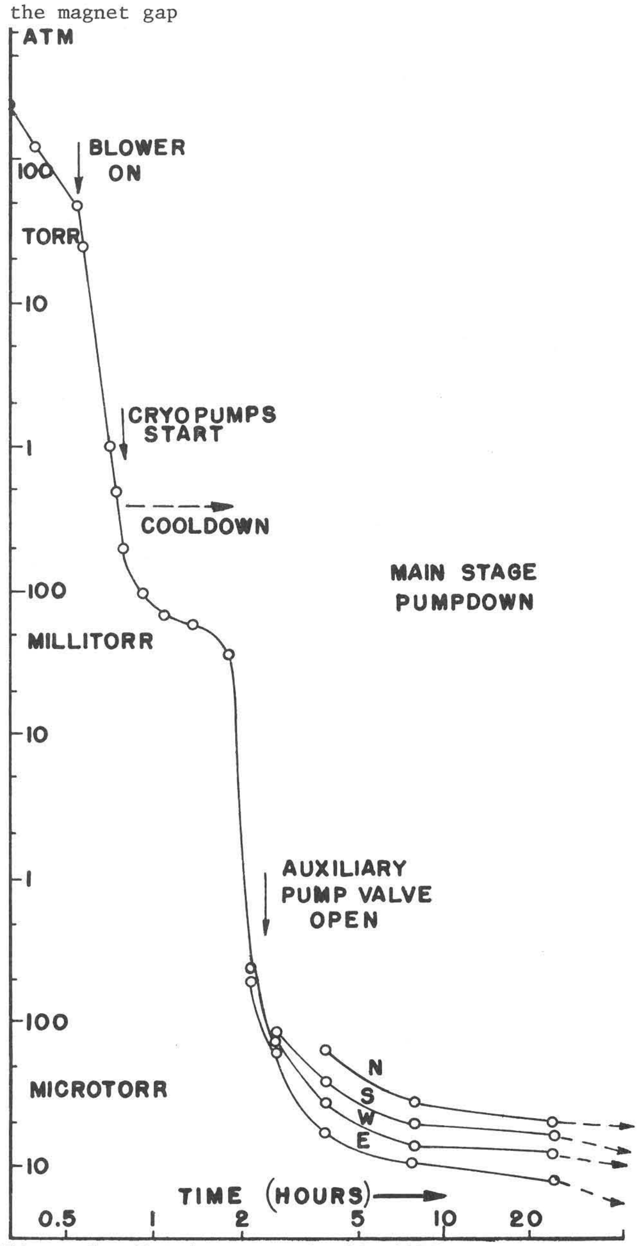

Figure 3. Pumpdown on July 12, 1975

from 7.6 to 3.5 cm, but gives the future option of separating the coil region in each hill chamber from the high vacuum beam region. At present, for simplicity of early operation, the blowout foils are not installed and the ring operates as a single chamber.

The chamber is roughed out with two well-trapped mechanical pumps with a combined speed of 120 ℓ /sec. At about 25 Torr, a Rootes blower of 350 ℓ /sec. comes on and the cryogenic cooling cycle is started. Figure 3 shows a typical pumpdown curve. Note that the unpumped north valley has the highest base pressure. In leak chasing, the small conductance between valleys has helped to localize the search.

The first rough vacuum was obtained on 6 March 1975 and the first cryogenic pumping on 2 April. At that time none of the rf, trim coil, inflection, extraction or diagnostic components were installed and base pressures of 4 μ Torr were obtained. In early May one valley chamber was removed to repair a welded seam which had been temporarily sealed for the first tests. With dees, trim coils and inflection hardware installed, the base pressure has become about 8 μ Torr in the rf valleys and 12 μ Torr in the valleys without cryopumps. This change was expected from the increase in exposed surface and from the reduction in gap conductance.

At the highest rf power used to date, the temperature rise of the 20K cryopump as measured by the hydrogen vapor pressure thermometer has been less than 0.2 K.

5. Main Stage Radiofrequency

Two resonant structures, in opposite magnet ring valleys, driven by 100KW amplifiers provide the necessary energy gain per turn in four gap crossings. The dee, dee stems and liner form a high Q, low capacity, self-contained mechanical structure which is easily rolled into or out of the vacuum chamber. The amplifier is mounted on the vacuum chamber back plate and drives the dee with a coupling capacitor through a vacuum penetration. Frequency tuning over the 30 $\pm$5 MH_z range is accomplished with hinged panels acting primarily as variable capacitors, driven mechanically by two pairs of ballscrew/stepping motor devices for each resonator. Many of the design parameters of the system have been previously described.[11)] The present remarks will be limited to a discussion of early rf operation.

When the east resonator was first placed under vacuum late in April 1975, the amplifier was not able to drive it through multipactoring. From our experience with the injector cyclotron rf, we knew that the design is very sensitive to the coupling capacity. With too little coupling, multipactoring is a problem. With too much coupling the turnon is easy but the amplifier sees too much voltage at the highest drive levels. To assist the cleanup of the fresh dee surfaces we therefore increased the coupling substantially above the design value and on the next attempt (May 9) produced a bright glow discharge followed by high voltage breakthrough after the vacuum recovered. The coupling was gradually reduced in successive runs to the design value without recurrance of the "hard start" condition even after several day's exposure of the dee to air. Based on this experience the west resonator was installed with a small drive capacitor gap, driven through the first intense gas-loaded discharge without difficulty on July 6 and the coupling readjusted in one step to the design value for high voltage operation. When this system was rolled out for inspection during a recent shutdown, some solder flux contaminants were removed from a tuning panel and from a portion of the dee surface and the hard start condition was again observed, caused apparently by residue of the cleaning solvents on the copper. This time high voltage breakthrough was restored by exciting the main magnet to about 10 kilogauss. The field changed the character of the gas loading, producing a very bright glow discharge for several minutes followed by vacuum recovery and high voltage operation.

Apart from the behaviour of a new or contaminated resonator, we have observed several other phenomena associated with the turnon characteristics in normal use. After any vacuum tank opening the dee structure will evolve gas after turn on, and after each voltage increase up to 100 KV amplitude, the tank pressure rising from about 10 μTorr to perhaps 50 to 100 μTorr and recovering in a few minutes. The resonator will sustain a high voltage up to ~75 μTorr but will not recover from a spark until the pressure drops below ~35 μTorr. At dee voltages above 160 KV the structure exhibits the characteristic high voltage conditioning behaviour in which each voltage increase leads to sparking at a frequency which reduces with time. At the highest voltage sustained to date (280 KV on the east resonator) the structure appears to be still well below the practical voltage-holding limit.

With the cyclotron magnetic field off, the resonator exhibits not only the normal multipactoring voltage stop-band between 300 volts and 3 KV, associated with the acceleration gap but also a weaker clamp between 40 and 80 KV apparently due to the largest cavity dimension. See Figure 4.

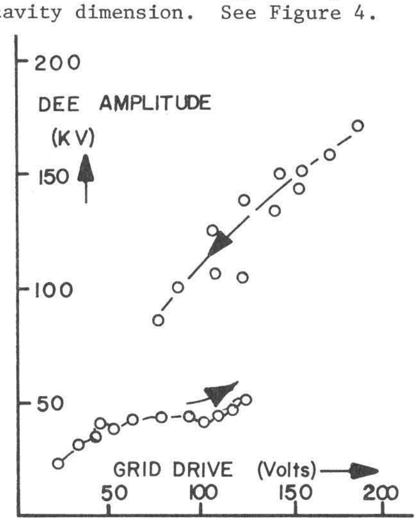

Figure 4. High voltage multipactoring

It is possible to turn on the voltage at this 40 KV level then detune slightly and increase the drive to obtain operation above 80 KV as shown in the figure. With the cyclotron magnetic field on, this higher voltage stop band is less apparent. However, the outgassing procedure mentioned above is field sensitive and the conditioning process must be repeated at several field levels. The presence of magnetic field makes it noticeably more difficult to drive through multipactoring, for reasons which are not yet understood. It is likely that modification of the pulse wave-form will permit the turnon following a spark to be as easy with field as it is at present without field.

The resonator is a copious X ray source, the total radiation flux at the plastic viewing windows exceeding 3 Roentgen/hr. Figures 5 and 6 show the voltage dependence of this radiation intensity and a preliminary absolute dee voltage calibration using the X ray end point energy measured with a Ge (Li) detector. The rf power delivered at a given dee voltage has been measured by subtracting the heat delivered to the amplifier cooling water from the DC plate power. We find 20 KW at 29 MH_z at 165 KV, somewhat below the expected value, and no obstacle to 250 KV operation.

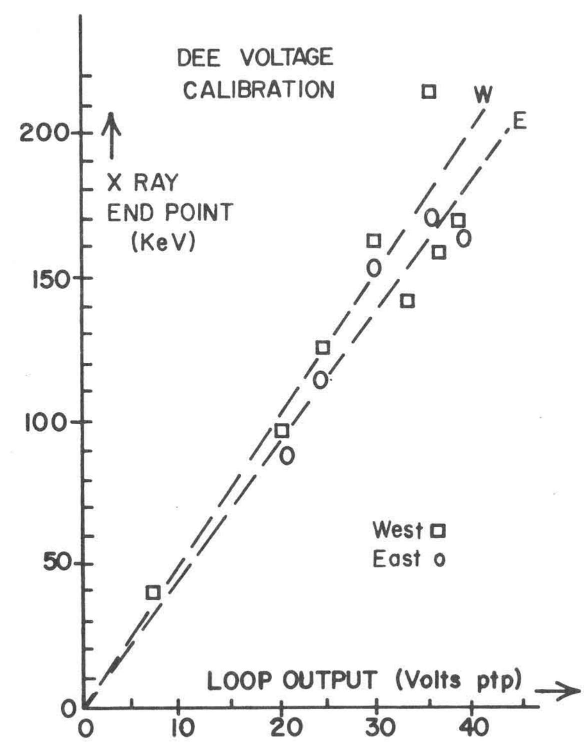

Figure 5. Dee voltage calibration. On this first attempt, the detector jammed at the higher voltages and had to be moved away from the window, the lower voltage points are more reproducible.

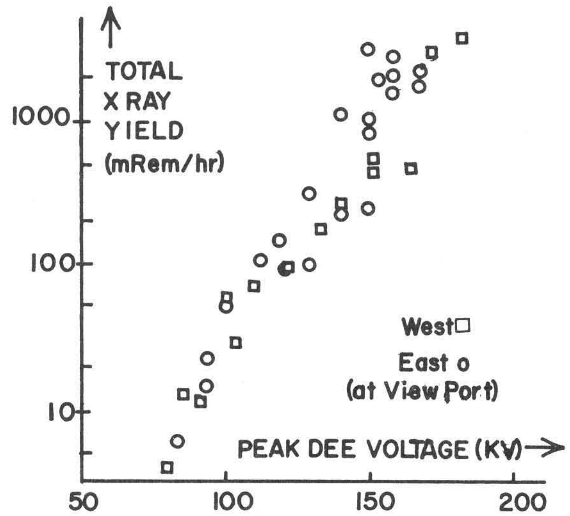

Figure 6. Radiofrequency radiation measured at the vacuum tank windows. The general room level stays between 2 and 10 mR/hr, permitting limited access during rf conditioning. Flux increases above 20μ Torr.

6. Comment on Procurement

A common rule of thumb in making up construction schedules is to make careful estimates and then to double them. Because we have had some recent relevant experience in purchasing a substantial number of diverse components I have included Figure 7 showing the procurement schedules in which the "firm" promised delivery date is compared to the actual arrival. The reader will notice that the factor of two rule is well established by the data. Figure 8 shows a general review of IUCF recent history.

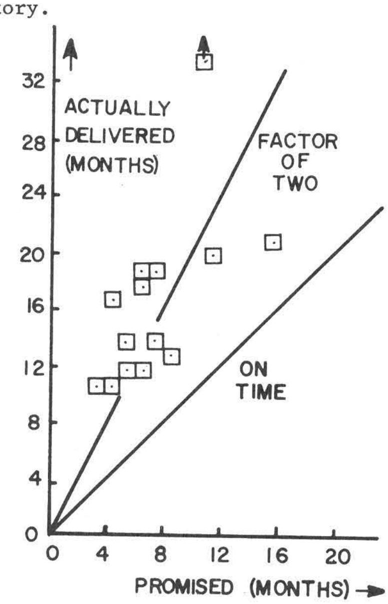

Figure 7. A comment on schedule reliability

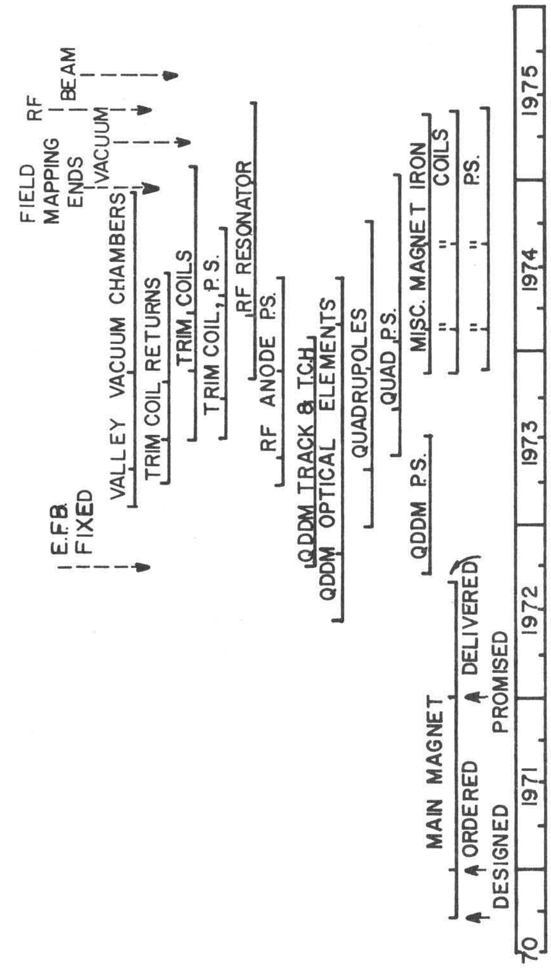

Figure 8. The last 3 or 4 years.

7. Summary

The Indiana University Cyclotron Facility has begun to produce proton beams in the 100 to 200 MeV region. The first experiments should be underway toward the end of 1975.

References

1) M.E. Rickey, M.B. Sampson, B.M. Bardin and D.W. Miller IEEE NS13 464 (1966)
2) M.M. Gordon ANN Phys 50 571 (1968)
3) M.E. Rickey A.I.P. Conf. Proc. #9, 1 (1972)
4) R.E. Pollock, P. Schwandt, and J.W. Hicks IEEE NS22 1049 (1975)
5) E.A. Kowalski, D.W. Devins and A. Seidman IEEE NS22 1505 (1975)
6) D.W. Devins, R.E. Pollock, J.W. Hicks and C.C. Foster IEEE NS22 1601 (1975)
7) R.E. Pollock, J. Dreisbach, J. Hicks, S. Lewis, D. Friesel, W. Smith, P.Schwandt and D. Madland IEEE NS22 1094 (1975)
8) D.L. Friesel, J.W.D. Sinclair, B.M. Bardin and R.E. Pollock IEEE NS22 1887 (1975)
9) D.L. Friesel and R.E. Pollock IEEE NS22 1891 (1975)
10) W.P. Jones IEEE NS22 1895 (1975)
11) W.J. Hoffert, G. Donica, H.J. Varga and H. Herman IEEE NS22 1265 (1975)

DISCUSSION

J. MARTIN: In the studies of transmission versus phase, what was the phase width of the injected beam?

R.E. POLLOCK: If you look at the transmission to full radius as a function of starting phase, and at the edge of the acceptance curve, the 25% to 75% points give 3.5 degrees of phase width, which is about 0.3 nsec. There does seem to be the appearance of a tail but the data is not conclusive yet, it is too early to say.

H.G. BLOSSER: I understand from your comment that a higher voltage pre-accelerator is required for high-energy protons. What is the schedule for this pre-accelerator? What are your plans for trying out other energies?

R.E. POLLOCK: We have picked what we thought would be the easiest energy to start with; we have experimental requirements for the early running with a range from 60-150 MeV, we will not go beyond 150 MeV in the first year of operation. From what we see of the operation of all of the components -- the radio frequency system, the inflector voltage-holding properties -- there will be no problem with any energy in this range. We will be trying something like 140 MeV in one of our next runs. The energies of up to 155 MeV are the ones that push the high-voltage terminal that I showed you near its sparking limit and we did not want that reliability problem on top of all the other problems in the first run. We see no difficulty from 50-150 MeV from the behaviour we have observed so far.

H.G. BLOSSER: Above 150 MeV, do you have to change the high-voltage terminal?

R.E. POLLOCK: We are in the process of building another high-voltage terminal alongside the one you have seen; we are not going to push that one, we are just going to leapfrog past it to one that will run easily at 700 kV instead of 500 kV. It will be coming into operation late in 1976.

C. MEYER-BÖRICKE: At what time do you expect to start with the experiments using the external beam?

R.E. POLLOCK: The first attempt to extract the beam will be on the 27 August. The beamline will be complete to the spectrograph by the last week of September. We have already had experimentalists in the vault measuring detector backgrounds and they will be ready to use the beam when it reaches the spectrograph. The first scheduled experiments, for which we will make a serious attempt to keep the machine operation on a schedule, begin the middle of November 1975.