beam in the main cyclotron. A minimum of 100 nA of 90 MeV H_2^+ beam is required to efficiently perform circulating beam studies of the Cooler.

A list of the present cyclotron beam properties is given in Table III. The only significant change this year is the maximum ^3He beam energy achieved. Cyclotron beam development in 1987 will be directed at meeting the beam stability requirements of the K600 spectrometer and the H_2^+ and polarized proton beam intensity requirements of the Cooler. As during the past two years, manpower limitations brought on by the Cooler construction project will not allow much more than this.

1) 1985 IUCF Scientific and Technical Report, p 99.

2) Crossing the $\nu_z = 1$ Resonance in the IUCF Main Stage, D.L. Friesel, and J. Dreisbach, Proc. 9th Int'l. Cyclotron Conf., p. 445 (1981).

3) 1985 Scientific and Technical Report, p. 117.

4) Beam Splitting, this report. p. 141.

LABORATORY DEVELOPMENT

Accelerator Improvements - D. Friesel, J. Hicks, J. Taylor

In spite of the large manpower commitment dedicated to finishing the Cooler, a significant number of improvements were made to the existing facility this year. Much of this work was done by the operations and ion source groups who are committed to machine support.

One of the largest Cyclotron upgrade projects completed this year was done by the power supply group. A new 600 kV power supply stack (resonant cascade voltage multiplier) was constructed using parts and designs provided by the vendor who no longer sells the complete unit. We have two positive potential stacks in service for biasing the ion source terminals. With the increased use of H^- beams, the eight hour job of reconfiguring a stack for negative polarity had become burdensome. The new stack with negative polarity can now be installed in 30 minutes.

Inflection into the Injector cyclotron is accomplished with two high voltage electrostatic elements which are positioned by translation and rotation using stepping motors. These transport mechanisms were rebuilt using brass and stainless steel bushings instead of Delrin which suffered heat and radiation damage during the last ten years of operation The resulting improvement in position accuracy and ease of operation was significant. In addition element #2 has been redesigned and rebuilt to simplify repair and alignment and a spare element was constructed.

In order to increase cooling to the poleface trim coils and to improve the vacuum pressure in the Injector cyclotron, the water cooling circuits at the rear of sectors A and D were reworked to eliminate plastic tubing and to simplify the feedthroughs. Twenty water cooling vacuum feedthroughs were replaced with two larger water feedthroughs and the length of the cooling lines inside the vacuum tank was reduced. This successful operation will be repeated on sectors B and C when a suitable shutdown period is available.

Several rf systems have been improved. The previous year's major rebuild of the Injector rf system (new input stage and the addition of interstage tuning) left many small circuit clean up and repackaging jobs to be done. These have now been accomplished. In the Main Stage rf pre-driver system, an old 30 watt drive amplifier has been replaced with a modern 40 watt unit to increase system reliability. The rf distribution system has had ALC modules added to the rf and the harmonic generator channels. Development work continues offline on a new, higher voltage, f buncher. Low power Q and frequency tests have been completed in air and the unit is now being installed in its vacuum chamber for high power tests.

Vacuum system improvement efforts were focussed on the Main cyclotron this year. One of our residual gas analyzer heads was rebuilt and installed permanently to monitor tank vacuum. This has saved time in the diagnosis and understanding of vacuum problems. In the Main Stage vacuum control system, a number of solid state relays had proved to be unreliable and all have been replaced by e/m relays. For all three sizes of cryogenic cold heads, new (stronger) stepping motor shafts have been designed, built and installed, with a resultant increase in reliability. The magnets in these motors had been found to weaken with use and a plan has been developed for remagnetizing them.

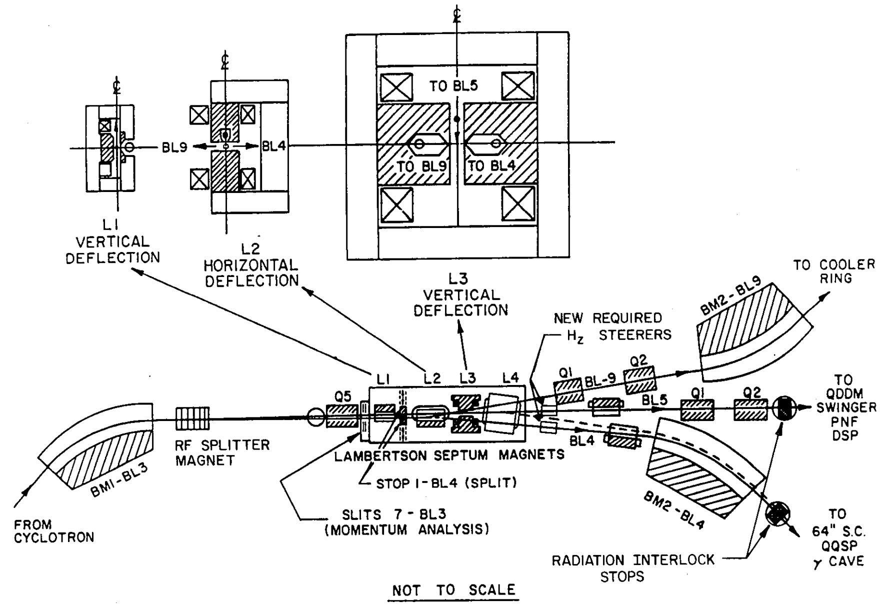
A new grounding system has been installed in high voltage terminal B to minimize the RFI created by sparkdown of the terminal. An improved rotating ground connection has been devised for the Injector and Main Stage turn pattern wire scanners.

The following accelerator improvements are discussed in separate sections of this report: polarized ion source, water tower system, stripper loop, and beam splitting.

Beam Splitting Development - D.L. Friesel, T. Ellison and T. Sloan

The beam splitting apparatus described in the 1984 IUCF Scientific and Technical Report[1] was completed during the 6 week Cooler construction shutdown in May of this year, and was successfully used to deliver beams to two experimental areas simultaneously for both research and equipment development activities. The magnetic elements were actually installed as manpower and access to the beam line 3 area permitted during accelerator shutdown periods in both 1984 and 1985, but performance difficulties with the ferrite f/3 kicker magnet prevented beam testing to begin until this year. The design problems of this kicker magnet, which was incapable of cw operation at the design frequencies of 8.5 to 11.8 Mhz, are detailed in the 1984 report. Because of manpower limitations imposed by Cooler and K600 construction activities, these problems were never satisfactorily resolved. However, in 1986, a slower (< 1 kHz) ferrite audio frequency splitter magnet and control system was designed to provide beam splitting on a macroscopic time scale, and the third Lambertson septum magnet (L3) was installed in the splitter vacumm chamber. These achievements brought the beam splitting system into an operational state, and split beam operations were begun on July 2nd. A plan view of the beam splitting apparatus in beam lines 3 and 4 is shown in Fig. 6.

The audio frequency splitter magnet is located immediately following the momentum analysis magnet in beam line 3 and produces an oscillating magnetic field of about ± 60 Gauss ($\pm 2.6 \times 10^{-3}$ Tm). The magnet is

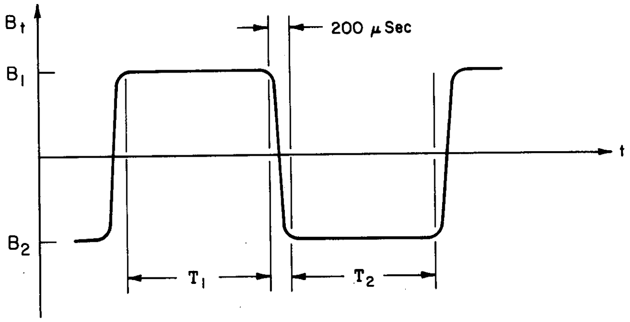


NOT TO SCALE

Figure 7. Plan view of the beam splitting system.

constructed with high frequency ferrite material salvaged from a surplus kicker magnet obtained from the Fermi National Accelerator Laboratory Experimental Cooling Ring. It is driven by a commencial 400 watt bipolar audio operational amplifier power supply, which limits the rise time of the resulting magnet fields to about 200 μsec. The field response of the magnet, which has a continously variable rf period from 1 to 40 msec for each field polarity, is shown in Fig. 8. The variable period permits a continuous adjustment of the beam intensity ratio of the split beams. The amplitude of the fields are also independently adjustable from 0 to 60 Gauss to account for the wide range of rigidities of the cyclotron beams. Control of these magnet parameters is accomplished through a specially designed NIM logic module located in the cyclotron control console, which allows the cyclotron operator to instantaneously give all the cyclotron beam to either user, to split beam between the two users, and to adjust the ratio of the beam intensity given to each user.

The rf magnet causes the beam extracted from the main cyclotron to be alternately switched between the two gaps of the first Lambertson septum magnet (L1) located approximately 3 meters down stream in beam line 4. The oscillating field amplitude of 60 gauss gives a beam separation of nearly 8 mm at the entrance of this magnet for 200 MeV protons. The two beams are further separated via Lambertson magnets L1, L2, and L3, and directed to their respective beam lines as illustrated in Fig. 7. The design and development of the IUCF Lambertson septum magnets, which have high and low field regions separated by only several mm, was previously reported.[2] With these magnets, cyclotron beams can be delivered to any one of the experimental areas in beam line 5, 6, 7, or 8 (beam swinger, PNF, K600 spectrometer, and general purpose BL 5 areas) simultaneously with any one of the three experimental areas in beam line 4 (QQSP pion spectrometer, 64" scattering chamber, or low intensity gamma cave). Similarly, the cyclotron beam can be delivered to the Cooler via beam line 9 simultaneously with any of the



$1\,\text{mSec} \le T_1 \le 40$ mSec

$0 \le B_1 \le 60$ Gauss

-~~800~~ 60 $\le B_2 \le 0$ Gauss

Figure 8.

experimental areas in beam line 5, 6, 7, or 8. At the moment, it is not possible to split beams between the cooler beam line 9 and the experimental areas in beam line 4. A fourth Lambertson magnet (L4), which is shown in Fig. 7 but not yet installed in the beam line, is required for this combination. While this magnet has been designed, there are no immediate plans for its installation. This limitation is expected to have a minimal affect on the use of beam splitting because we expect the new K600 spectrometer in beam line 8 and the Cooler to be the most heavily used experimental systems in the near future, and beam sharing between these two systems is allowed.

The set up of the high energy beam lines was also modified during the last several years to make the use of split beams not only possible, but convenient for the user. Many of the high energy beam line elements which shared a common power supply via load switches required separate supplies so that elements in two beam lines could be powered simultaneously, and independently adjusted. Modifications to the laboratory radiation interlock system were required to allow beams to enter two experimental areas simultaneously, and new radiation interlock stops were installed in beam lines 4 and 5 so that each user could enter his experimental area without disturbing the beam on the other target. This also made it possible for the cyclotron operator to continuously monitor the beam intensity available to each user.

Beam development studies demonstrated that the operation of the beam splitting system was straight forward, with excellent transmission of the split beams through the septum magnet chicanes to the selected targets. Approximately 2% of the beam extracted from the cyclotrons was lost on the Lambertson magnets as the splitter magnet field switches polarity, which is consistent with the 200 μsec rise time of the magnetic field for rf oscillation periods of 40 msec. However, the beam lost here does not reach the target areas, and the quality of the beam at each selected target location is nearly identical to that achieved when the beam splitting system is not used. No problems with beam haloes, for example, attributable to the use of the beam splitting system have been observed. The only significant difference in the properties of the split beams is the pulse structure. Because the beams are split by alternately switching the beam from one target room to another with the ferrite audio frequency magnet, the beam at the target has the usual cyclotron pulse period (about 33 nsec) superimposed on the switching magnet frequency. The magnet operates between 0.025 and 1 kHz, hence the instantaneous beam on target can be up to 40 times larger that the average intensity monitored in the faraday cup. This is an important consideration for coincidence and other classes of experiments.

The tune up of the beam lines for beam splitting after extracting beam from the cyclotrons is only slightly more time consuming than usual. Beam is transmitted through the momentum analysis system in beam line 3 to the left half of the split Stop 1-BL4 (shown in Fig. 7) with the splitter magnet off. The magnet is then switched on and the momentum analysis magnet is adjusted until half the beam appears on each of the left and right halves of this stop. This stop is removed and beam is transmitted to both the radiation interlock stops in beam lines 4 and 5. From here, beam is tuned to the target area of the primary user as would any beam from the cyclotrons. Beam is tuned to the secondary user only after the primary user is satisfied with the quality of his beam. As may be expected, the beam requirements of the primary user take precedence over the needs of the secondary user. Several split beam combinations were run by users last year which both demonstrated the utility of the system, and indicated that for some beam lines, additional steering elements are required immediately following the Lambertson magnet chicane. Beam splitting between the K600 spectrometer and the pion spectrometer in beam line 4 has been the most requested combination to date. An additional horizontal steerer in beam line 4 immediately following the splitter box is needed to simplify the procedure of getting a halo free beam to the QQSP pion spectrometer. This is normally a meticulous task without beam splitting, and the small trajectory difference introduced by the splitter system aggravates the tuning of this line. Use of this line has been successful without the new steerer, but tune up would be less critical with it. Similarly, when splitting between the PNF and the beam line 4 areas, another horizontal steerer is needed after the splitter box to permit centering of the beam on the high energy polarimeter in beam line 5 before proceding to the PNF target. Both new steerers are required to compensate for small trajectory changes in these beam lines induced by the fringe fields in the Lambertson magnets.

The use and refinement of the beam splitting capability at IUCF will continue as time and schedules permit. Meanwhile, beam splitting has become a reality at IUCF which is gaining in acceptance and utilization. Procedures for the orderly scheduling and delivery of secondary beams is still being developed. Presently, requests for split beams are made through the director of the facility. Cooperation of the primary user, of course, is required as well. We are now beginning to indicate the scheduling of split beam on the quarterly cyclotron run schedules, and primary beam time suitable for split beams operations is rapidly becoming scarce. As the new Cooler accelerator and experimental equipment development activities increase this year. it is possible that the scheduling of split beam time usage will become as tight as the primary beam time scheduling has been for some time.

1) Beam Splitting, 1984 IUCF Scienfific and Technical report, p. 148.

2) End Effect Corrections in a short Lambertson Septum Magnet, R.E. Pollock, Proc. 10th Int'l. Conf. on Cyclotrons and their Applications, (East Lansing, MI, April 1984) F. Marti, Editor, p. 111.

New Cooling Tower - C. Foster

As reported in the 1985 annual report, the evaporative-cooling tower to provide cooled water for the cyclotron is in operation. This tower was used successfully throughout 1986. It maintains the temperature of the water on the primary side of the cyclotron and Cooler heat exchangers stable to within ±0.5° Farenheit. Such temperature stability has been shown to be essential to efficient cyclotron operation with stable beams of high quality for long runs.

There have continued to be difficulties with tower operation which, nevertheless, have had minimal impact upon the cyclotron operation schedule. In early

January, a relay failed in the north pump controller causing an over temperature excursion. In February, a pump to motor coupling failed. In March, it was determined that the tower and sump valves were operating slightly out of timing with one another, momentarily dead heading the pump. Restriction was added in the air line to the tower valve to slow its operation to match the speed of operation of the sump valve.

In July, several power outages occurred blowing the tower control chip. Upon replacement an improved controller card and battery backup module was installed. No chip failures have been observed since this replacement.

Coupling wear was still excessive. In November, both pumps were removed and returned to the manufacturer for tests. Bearings were changed on both pumps even though no indication of improper operation of the pumps was observed. A meeting of all parties involved to determine the cause of these failures is to be held in early 1987. The suspicion is that the pump/motor base is not rigid enough and will need replacement.

There also remains a problem when all water is suddenly switched from circulating through the sump to going over the cooling tower. The water is sufficiently delayed by passing through the tower before returning to the sump that the water level in the sump is lowered below the top of the intake opening to the pumps causing cavitation for several minutes. An additional trough was added to carry water from the tower to the sump to reduce this delay.

Plans exist to extend the readouts of the control tower from the panel located in the east wall of the high bay to the cyclotron control console to expedite monitoring tower operation.

Efforts are being made to resolve these problems before warranties expire in May, 1987.

Ion Sources - H.R. Petri

Most of the ion source work effort went into making improvements on the polarized source during 1986. Early in the year, pumping speed measurements of the 1200 L/S Perkin Elmer ion pump, which pumps the ionizer region, were made. The pumping speed was low and it was decided to remove the pump and send it back to Perkin Elmer for rebuilding. There it was discovered that the pump still had some Argon pumping elements in it. It was decided to rebuild the pump with hydrogen pumping elements only, in an effort to improve the hydrogen pumping speed and reduce the background hydrogen in the ionizer. While the ion pump was being rebuilt two new gate valves were purchased and installed, one which isolates the ion pump from the ionizer, the second which isolates the titanium sublimation pump from the electrostatic mirror region. These valves had been leaking through, and had been causing problems. In addition the titanium sublimation pump itself, which never seemed to do much to improve the vacuum, was removed and replaced with a 500 liter/sec Balzer's turbomolecular pump. Finally, after reassembly, the ionizer elements E1, E2, E3, etc. and the lens assembly E5, E5.6, E6, and the electrostatic mirror, were removed and cleaned in an orthophosphoric acid solution. All of this work has helped reduce the unpolarized background from the ionizer, which had been increasing and was lowering the polarization of the source.

Another very welcome improvement to the polarized source was the replacement of an old belt drive mechanical pump which backs the diffusion pumps on the

Atomic Beam section. This pump used conventional oil which hydrogenated and had to be changed every 200 hours. Even with this frequent oil changing, which was a headache operationally, the pump leaked through its seals and was very messy. The pump was replaced with a Leybold-Heraeus Trivac D90A which is charged with Fomblin oil. This direct drive pump is very quiet and smooth and finishes the complete conversion of the diffusion pump mechanical pump arrangement to non-hydrogenating Fomblin oil. After about six months this conversion seems to be an operational success.

All tantalum parts in the ionizer are currently being reproduced. They will replace our old deteriorating parts sometime in 1987.

A cooled accomodator nozzle was designed and tested briefly in 1986. The system was cooled to 150° K using the 80° K shield of a cryohead. It produced 10-12 microamps of beam (a factor of 1.5-2 improvement) for twelve hours before the glass nozzle of the dissociator bottle melted. This initial test was encouraging but much development work needs to be put into this system to get it to work reliably. Cooled accommodators in DC sources are difficult to keep cold. Our current operations schedule makes it very difficult to develop this system, but some further tests are planned in 1987.

Control System Software - J.C. Collins

Following the installation of the PDP-11/44 cyclotron control computer (herein referred to as DIANA, its Decnet node name) last year, a significant effort has been devoted to improving its functionality, removing low cross-section bugs, adding new features, and allowing remote operations initiated via Decnet. The control software staff has been expanded to include two operators (part-time as other duties allow) and a full-time hourly programmer.

Under the heading of improved functionality, we have finally found a source of inexpensive, reliable 40 character alpha-numeric display strips for use with the attachable meters. The operator station displays now have bar graph capability, which has been used in data logging and, especially, the beam current reporting system. A new prediction/device setup algorithm using ADC values has been developed. Using it for energy/particle changes, the operator begins tuning from a "generic" condition. The current use of sets of DAC values from previous runs tends to perpetuate past errors. A program has been written to set main stage trimcoil values, a complex operation involving three power supplies and 19 shunt controls, some one of which, depending on particle and energy, is in voltage, rather than current, regulating mode. Long term beam drifting may now be partially compensated by a program which periodically searches through a few-parameter space for maximum beam on target.

The beam polarization state can be specified by the primary data acquisition computer through messages sent to DIANA over Ethernet. The XSYS system uses this capability now and Q will be modified to do so in the near future.

A new mode of operation is required because the K600 spectrometer data acquisition area is physically removed from the control room and this device requires significant tailoring of the beam to reach optimal resolution. A set of cooperating programs for DIANA and the VAXs has been created to allow experimenters, while sitting at their VAX terminals, to read any cyclotron device and control a (highly restricted) subset of magnets and quadrupoles directly related to K600 spectrometer operation. Also, the K600 vacuum system is the first IUCF system to use an industrial controller and an IBM PC as integral components. While the industrial controller use made control construction faster, easier and more flexible (and expensive), the PC as human interface seems not worth the development effort required and will not be used for the Cooler.

Dual Spectrometer Controls - W. Manwaring

The Spectrometer project gave us the opportunity to try a number of new designs:

- New thermocouple monotoring chassis. This chassis reads and displays eight channels and compares each vacuum read to a setpoint value. Eight logic level outputs (used as interlocks) give the relative status of the readouts and setpoints.
- Gould 884 Programmable Controller used for vacuum valve and pump control. An IBM PC programs the ladder logic in the 884, and also acts as vacuum control panel via a hi-res graphics screen.
- New 16-bit parallel bus data transfer system from the PDP-11, using noise-immune differential drivers to cross the building (400').
- Two new Digital-to-analog converter cards with analog isolators.
- A new 'circulating' ADC chassis that samples 16 channels continuously and stores and results in computer-accessible two-port memory.
- A new 15-bit dual-slope integrating ADC card with on-board isolator for high-precision readouts (costs less than $200).
- A new beam current amplifier chassis with front-end active filter.

Cyclotron Beam Diagnostic Systems - T.J.P. Ellison M. Fox, and S. Koch

Introduction

Noninterceptive beam position monitiors developed for the Cooler have been installed just upstream of the high energy polarimeters in Beam Lines 4 and 5. After a brief testing period, this system was connected to the cyclotron controls computer, and software steering loops were implemented to stabilize the beam position at these locations.

A new phase probe was also installed in the Main Stage Cyclotron, though this system has not yet been commissioned.

Beam Position Monitoring System:

The electrode amplifiers and beam position detector electronics are shown schematically in Figures 9 and 10, and are described elsewhere.[1-3] Figure 11 summarizes the performance of this system.

The Elimination of rf Noise:

The BPM system operates with beam currents in excess of about 10 nA. In order to make position

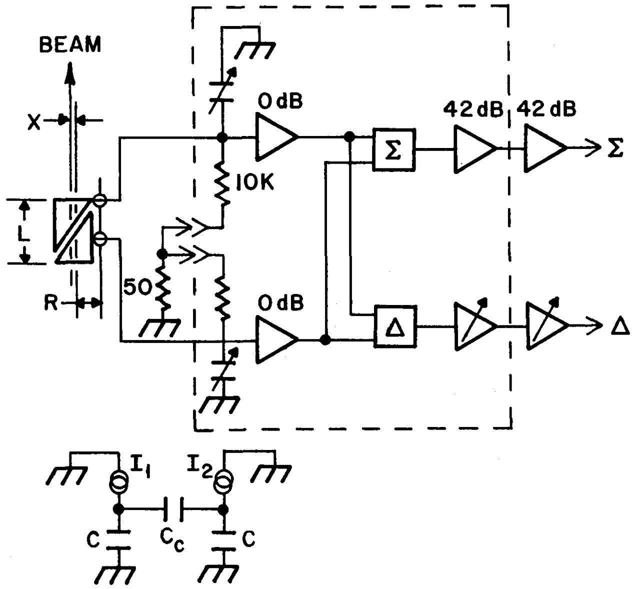


Figure 9. Schematic of, and equivalent circuit for, a beam position electrode and block diagram of electrode amplifiers.

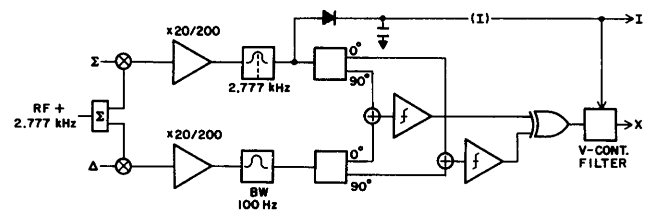


Figure 10. Block diagram of beam position detector electronics.

measurements with an accuracy of 1% of the pick-up radius with beams of such low intensities, the amplitude of the rf interference at the electrode amplifier input must be less than about 3.4 nV. This coherent noise power is equivalent to the FET amplifier input noise power in the electrode sum and difference channels within a 0.3 Hz bandwidth. Thus our detectors are sensitive to rf noise interference which is below the level which can be measured even with our most sophisticated test equipment. Previous experience has shown that it is not possible, regardless of the care taken, to achieve such a high level of shielding from cyclotron rf systems.

However, by bunching the beam at half the cyclotron rf frequency, ($f_c/2$), the effect of the rf noise can be elliminated, providing the beam rf signals are measured at an an odd harmonic of $f_c/2$: there is rf power from the beam at all harmonics of $f_c/2$ due to the delta function-like beam time structure, while the cyclotron rf interference appears only at harmonics of the cyclotron rf frequency (i.e. the even harmonics of $f_c/2$). The beam may be bunched in this manner without significantly reducing the beam intensity.

The electrode amplifier operates to frequencies in excess of 100 MHz, though best operation is within the Cooler rf frequency range of 2 to 20 MHz. Initially, the system was designed to operate at $f_c/2$, but early tests showed, surprisingly, that there was more interference at $f_c/2$ from the buncher than at f_c from the cyclotrons! We found, however, that at $3f_c/2$ there was no detectable rf interference when using 80 dB gain at the electrodes.

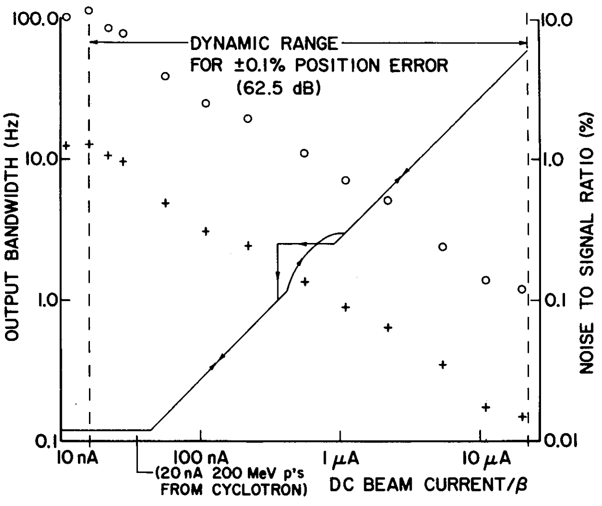


Figure 11. Performance of the BPM system showing the bandwidth (solid line), and measured rms (crosses) and peak-to-peak (open circuits) noise-to-full-scale signal voltage ratios for the beam position monitoring system.

System Operation:

The software steering loops have two adjustable parameters: the update period, which is set in 20 ms increments, and a sensitivity factor. The correction made each update period is proportional to the product of the position error and the sensitivity factor.

Although these monitors were used successfully in a number of experiments, the software control loops, developed for use with current integrators and split Faraday cups, were not optimized for use with the BPM detectors. For example, for beam currents of about 20 nA, the BPM detectors have a bandwidth of about 0.1 Hz (RC = 1.6 s). If the loops were initialized with an update rate of 0.02 s, the system could cause the beam to track the noise from the detector, or to overcorrect for position errors.

The programs are being improved to automatically set the update rate in accordance with the BPM detector output bandwidth (which an automatic bandwidth control circuit scales with the beam current), and scale the sensitivity factor with the beam rigidity. These changes will make the system trivial to operate, and will be tested with beam in 1987.

In 1987 pick-ups will be installed for the Charge Symmetry Breaking Experiment. In addition, a specially-modified position detector with an ouput bandwidth of 250 Hz will be tested and used to measure the amount of high frequency and line-related beam position movement.

1) T. Ellison and O. Dermois, IUCF Scientific and Technical Report 1985 p. 140.

2) Timothy J.P. Ellison, C. Michael Fox, Steven W. Koch, and Liu Rui, Proc. of the 1986 Int. Cyclotron Conf., Tokyo, 13-17 October (1986).

3) Timothy J.P. Ellison, C. Michael Fox, Steven W. Koch, Proc. of the Ninth Conf. on the Appl. of Acc. in Res. and Ind., Denton, TX, 10-12 November (1986) (to be published in NIM).

4) D. L. Friesel, this report, p. 137.

EXPERIMENTAL FACILITIES DEVELOPMENT

Facilities in Operation - C. Foster

1. Existing Beamlines

Beamline 4 to the 64 inch scattering chamber was realigned to improve transmission of beam to the target in that chamber. A multiscattering foil was installed in beam line 4 upstream of the switching magnet for use in providing low-intensity-diffuse beams in the gamma-cave.

The shielding penetration block at the beginning of beam line 5 was removed to provide access to the beam corridor after installation of beam line 9 to the cooler ring. This activity required realignment of a downstream section of beam line 3 and removal and re-installation of the high energy polarimeter on the polarized neutron facility beam line.

Efforts to maintain beamlines continued to be significant. In particular, difficulties with compressed air leaks from electrically operated air valves for actuators and air operated vacuum gate valves consumed much time until a solution was found late in 1986.

Last components to allow beam splitting were installed in beamline 4 in the summer of 1986 and split beam achieved in July. The advent of split beam has