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NEW NONDESTRUCTIVE BEAM DIAGNOSTICS FOR THE IUCF CYCLOTRON

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New nondestructive cyclotron beam diagnostic systems which have been developed at IUCF include a beam time of flight system having a kinetic energy resolution of less than $\pm 5 \times 10^{-5}$ (1σ) and improved electronics for our beam phase detector and beam position monitoring system. New beam diagnostics under development include a cyclotron beam turn counter, a new extensive Beam Position Monitor system, and high voltage terminal bunchers.

Beam time-of-flight (TOF) system

Two 7.5 cm length Q-electrodes, separated by 8.515 m, are mounted in a straight section of beam line immediately after the main cyclotron. This system, which is used with pulse-selected beams, measures the relative phase between the RF voltages induced by the beam on the two electrodes using a HP4195A network analyzer. The measurements are made at about 270 MHz at a harmonic of the beam pulse repetition frequency which is not also a harmonic of the cyclotron RF system frequency, making the system absolutely free from RF interference.

A measurement with $\pm 0.5^\circ$ precision at this frequency (± 5 ps), which is easily obtainable, gives an energy resolution of about ± 18 keV for a 100 MeV proton beam (about $\pm 1 \times 10^{-4}$ $\Delta p/p$). In actual use, with beams with intensities ≥ 80 nA, we can resolve momentum changes 5 times smaller than this. For example, a recent series of 22 cyclotron beam energy measurements taken over a period of 1/2 hour for an 80 nA 135 MeV proton beam had fluctuations with a standard deviation of 5.5 keV (2×10^{-5} $\Delta p/p$). The high precision of this system is shown in Fig. 1, which is a copy of the network analyzer display which is made available to the operators.

This system is now used as the standard for setting the beam energy for Cooler runs where the precise setting of the beam momentum ($< \pm 2 \times 10^{-4}$) is essential. Besides being extremely precise and repeatable, the system is easy to use. For example, it is not necessary to precisely set slits and adjust the beam position and angle at the entrance and exit of an analyzing magnet in order for this system to give a valid measurement.

Although the precision of this system is extremely high, there is an uncertainty of about 6×10^{-4} ($\Delta p/p$) in this system's accuracy. The system calibration was checked by measuring the energy mismatch of the cyclotron beam to the Cooler using Schottky signals and qualitatively looking at how the beam behaves as it is transferred bucket-to-bucket into the Cooler. Here we find that we must add about 52 ps delay as an error term in order to provide the Cooler with an optimal energy 45 MeV beam. This corresponds to an error of about 54 keV (6×10^{-4} $\Delta p/p$). This may be due to an error in measuring the distance

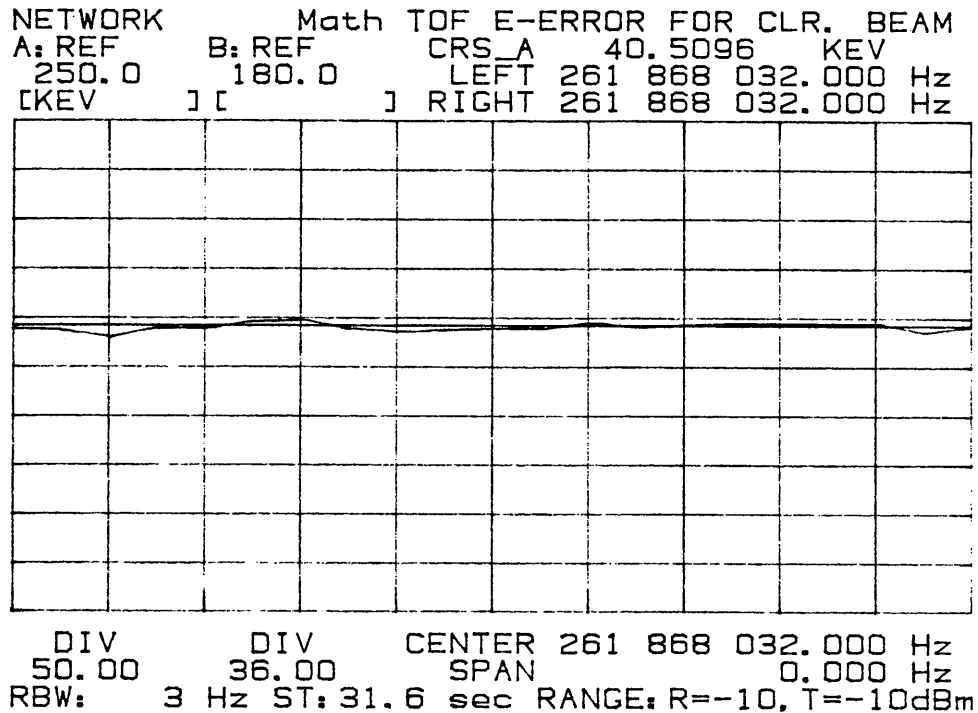


Figure 1. Display for time of flight energy measurement for a 1.5 μ A 108 MeV proton beam. The jagged line connects 20 separate measurements made at 1.5 second intervals. The straight line centered on the jagged line is the average value. The desired energy is at the vertically-centered horizontal graticule. The number printed in the upper right hand corner (40.5096 keV) is the average energy error. The vertical scale is 50 keV/div.

between pickups, the electronic delays in the system, or an error in our knowledge of the actual Cooler circumference by about 5 cm (5×10^{-4}). We have observed that the Cooler circumference can be changed by an amount on this order by making certain changes in the closed orbit, and we presently suspect that our value for the nominal Cooler circumference is in error. Further comparison of the beam energy as measured by the TOF system and by matching to the Cooler for beams of different energies (and thus velocities) will tell us whether this error is an electronic error, or an error in either the distance between pickups or Cooler circumference. Another system with a much longer flight path may be installed in the beamline to the spectrometer. If installed, this system should be able to tell us what the actual Cooler circumference is.

New beam phase meter electronics

A new set of electronics has been designed for the beam phase meter.¹ The HP 8405A Vector Voltmeter which was used as the phase detector, has over 5 times the noise (white) to signal ratio that one would expect in a given bandwidth due to the signal-to-noise ratio of the input signal. This poor signal-to-noise ratio prevented the system from working reliably for beam currents less than 20 nA. The Vector Voltmeter was replaced by a modified beam position detector.¹ By merely bypassing the amplitude-to-phase conversion portion of the

circuitry, we have a synchronous phase detector having a signal-to-noise ratio which is over 5 times greater than that obtainable with the HP Vector Voltmeter. This allows the system to lock onto beams with intensities as low as about 4 nA.

The coherent RF interference at the second harmonic of the cyclotron RF, which varies from the equivalent of 0.2 to 2 nA depending upon the RF frequency, is now our major problem. We are going to make a small effort at reducing this RF interference by another order of magnitude. If these efforts are unsuccessful, we have a number of ideas for electronic circuitry which we can install fairly easily in order to compensate for this RF interference.

New beam position monitoring (BPM) system

We have developed a new simplified beam position electrode amplifier which increases the signal to incoherent-noise ratio by 6 dB with respect to our previous design. The previous design was optimized for the Cooler frequency range of 1 to 20 MHz and used high input impedance FET buffers to give a flat response over this range. The frequency range used by the cyclotron BPM system, however, is from about 40 to 50 MHz (the 3/2 harmonic of the cyclotron RF system, and the third harmonic of the beam which is pulse selected 1:2). By using 50 Ω input impedance amplifiers the signal is reduced by about a factor of two (since the low frequency cutoff is about 90 MHz), but the incoherent noise voltage is reduced by about a factor of 5, from approximately 3.5 to 0.75 nV/ $\sqrt{\text{Hz}}$. We are now in the process of producing 50 units (as was previously done for the Cooler) to instrument the beamline from the cyclotron to the K-600 spectrometer.

Terminal bunching system

Measurements have shown that the IUCF injector cyclotron injection system has an energy acceptance of about ± 2 keV. The present bunching system (which bunches the 600 keV beam from the terminals), however, puts about a ± 20 keV energy spread in the beam. We are therefore building bunchers for installation in the terminal where the 20 keV beam can be bunched with as little as 100 V. In principle, we expect this system to improve the beam transmission through the cyclotrons (presently about 2.5%) by a factor of 2.5. However, the energy spread of the beam coming from the source might be so large as to make this system ineffectual.

Beam turn counter

A simple beam turn counter which is now under construction makes use of the buncher phase modulators.² In this case, the buncher phase modulator will modulate the beam current at a 100 kHz rate. This current modulation is detected at two nondestructive current monitors – one before and one after the cyclotron, and the phase difference of this modulation is detected using a network analyzer. A single turn in the cyclotron nominally takes about 120 ns, or about 4° at 100 kHz – an easily detectable phase shift. This system is similar in principle to the system used at GANIL,³ except that we will deliberately modulate the beam with a single coherent frequency, rather than relying on the random beam current modulation frequencies already present.

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2. Mark Ball, Timothy J.P. Ellison, and C. Michael Fox, "New nondestructive beam diagnostics for the IUCF Cyclotron and Cooler", Proc. 12th Int. Conf. on Cyclotrons and their Appl., (8-12 May 1989, Berlin).
3. F. Loyer, "On line beam diaganostics at Ganil", Proc. 11th Int. Conf. on Cyclotrons and their Applications, edited by M. Sekiguchi, Y. Yano, K. Hatanaka (Ionics, Tokyo, Japan, 1986) 449-452.

CONTROL SYSTEM SOFTWARE

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Since the Cooler was the development project for the lab last year, it is natural that almost all control software efforts were aimed at Cooler operation. The largest job was improvement in our treatment of ramps. The ramp generation program was modified to sub-divide RF frequency vectors at the beginning and end of the ramp to allow for finer control and to handle "retro-grade" steerers, where the field must decrease with energy, rather than increase. A ramp modification program was created allowing the user to change any ramp, accumulate or remove changes, archive and restore sets of changes and apply changes collectively or singly. Some facility for archiving complete ramps was installed, although this is rudimentary at present: calculation of a ramp set takes about 10 seconds, fast enough not to be a burden on operations. Since acceleration is now only about 10% efficient in terms of beam current, much more work is sure to be done on the ramping programs.

The second major project was the timing system. The present timing system consists of Jorway 221 CAMAC modules, a timing database and event definition program and a timing server task which allows any program access to timing information and control functions. The user can specify assertion and removal times for any timing signal, change the 'zero' time and obtain a graphical depiction of the timing events. Both the ramp execution and stacking injection control programs make heavy use of the timing server. Stacking control, in particular, creates up to 75 repetitions of the timing events needed to perform the stacking injection operation. (Some details of stacking injection are presented elsewhere in this report.) However, the entire timing system will be replaced in the near future because it cannot meet demands we foresee, particularly for cycle lengths greater than the current 16 2/3 second limit while retaining 1 micro-second resolution.

COMBO capabilities were substantially expanded. COMBOs are linear combinations of real devices which the control system can treat as single pseudo-devices for most purposes. The COMBO control code was made recursive, enabling COMBOs of COMBOs. (Now all cyclotron and Cooler devices could be simultaneously controlled by a single knob!)