A BEAM PHASE MEASURING SYSTEM FOR THE TRIUMF CYCLOTRON

R. Burge and R. Vader

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3
Kernfysisch Versneller Institute, Universiteitcomplex Paddepoel, Znerikelaan 25, Groningen, The Netherlands

Abstract.- A technique similar to the one used at the KVI cyclotron has been adapted to measure the beam phase at TRIUMF. Here the problem is complicated by the high level of RF interference which is present over all the beam region. Also, the front end electronics of an active pick-up probe cannot survive in the high radiation field. The method is based upon modulating the beam intensity in order to retrieve the beam signal from the RF interference. A FET mixer is used to detect the bipolar signals from passive non-intercepting capacitive probes in the cyclotron. As the low frequency intensity modulation of the beam is recovered in a quadrature phase detection system, the beam phase measurement is independent of the phase of the beam modulation with respect to the phase of the external beam pulser. As a consequence, this new system can be applied to a moveable non-intercepting phase probe with a signal to noise ratio of the same order as that obtained with a single stationary probe. The system has been tested with 7 fixed non-intercepting probes at various radii and has measured beam phase for currents of 200 nA in RF noise levels of 1 volt.

1. Introduction.- To help study the machine stability a beam phase measuring system has been designed to work with both fixed and moveable non-intercepting capacitive pick-up probes in the TRIUMF cyclotron.

In order to avoid radiation damage passive pick-up probes are used. The signals from the fixed probes are sent over 30 m of FM8 coaxial cable to the phase probe electronics located outside the cyclotron vault.

The moveable probe will consist of a single pick-up above the median plane. This makes construction of the moveable probe relatively simple and avoids the interception of high energy, high current beams (500 Mev, 100 μA). The system does not allow cancellation of unwanted RF pick-up by the addition of signals from pick-up probes mounted above and below the median plane [1,2]. As a consequence, very high levels of RF interference occur with this arrangement. The RF interference on fixed phase probes in the TRIUMF cyclotron can reach 2V p-p, but most probes average 800 mv p-p of RF disturbance.

A beam pulser, installed in the ion source, is used to vary the pulse width of the beam injected into the cyclotron from 0% to 99% at a 1KHZ repetition rate [3]. This external beam modulation allowed us to adopt a phase detection system similar to that developed at KVI [4,5]. The system at KVI, which uses a synchronous detector, has been shown to be very insensitive to RF disturbance. The detector separates beam signals from the RF interference by identifying the external modulation imposed on the beam. Low frequency fluctuations of the RF interference, which are separate from the 1KHZ beam modulation frequency, can also be rejected by this system.

2. Phase measurement system.- Figure 1 shows the basic phase detection system. The signal from a capacitive pick-up probe in the cyclotron consists of unwanted RF interference and modulated beam signal. The phase probe signal is multiplied by an RF reference signal in the HF mixer. The time invariant RF disturbance from the phase probe will appear at the mixer output as a DC signal plus harmonics of the cyclotron RF frequency. The AC signal due to the 1 KHZ modulated beam will appear at the output of the AC coupled low frequency amplifier. When the RF phase shifter is adjusted to null this signal, the relative phase between the beam and the RF reference can be measured across the RF phase shifter.

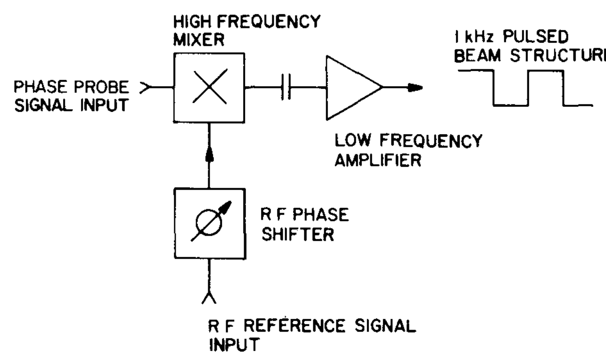


Fig. 1 : Recovery of the pulsed beam structure from the phase probe signal.

In order to null the detected beam modulation signal it is necessary to recover the DC beam phase information that is lost by the AC coupled low frequency amplifier. The DC beam phase information can be obtained by multiplying the detected beam modulation signal with a appropriate beam modulation reference signal [4]. This correlation with the external beam modulation signal also gives a very high degree of noise immunity to the phase measuring system.

The 300 μs time of flight through the TRIUMF cyclotron is of the same order as the 1KHZ pulser period. An external beam modulation reference signal cannot be easily used to recover the DC beam phase information from a moveable phase probe or a fixed phase probe which experiences large changes in the

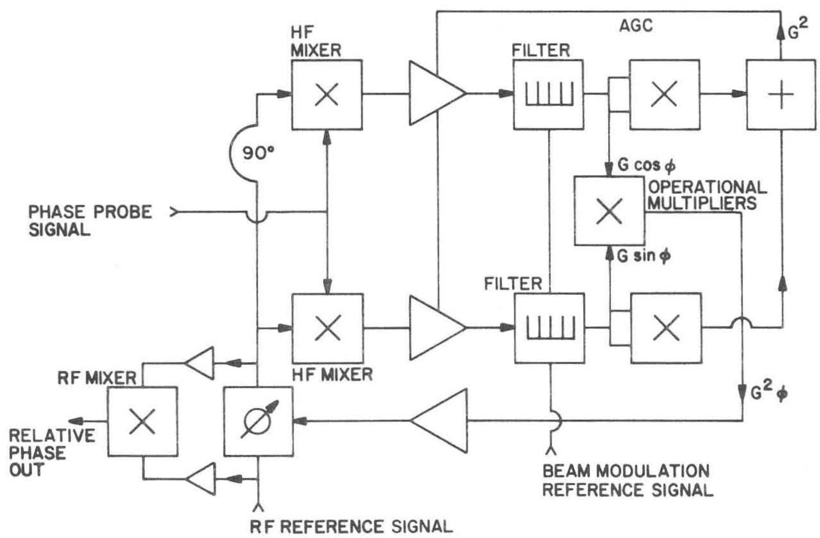


Fig. 2 : Block diagram of the phase measuring system.

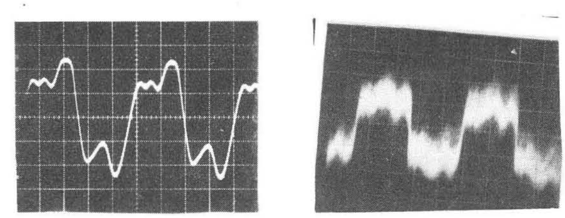
cyclotron time of flight. This problem has been overcome by using quadrature detection and autocorrelation.

A block diagram of the actual phase measuring system is shown in figure 2. The quadrature detection circuit consists of two high frequency mixers where the phase probe signal is multiplied by two RF reference signals of equal amplitude but shifted 90° in phase with respect to each other. In a fixed frequency cyclotron, such as TRIUMF, the 90° phase shift in the RF reference signal can be easily accomplished with a fixed cable delay. The two low frequency AC signals obtained from the mixers are proportional to $G\cos\phi$ and $G\sin\phi$; where G is the modulated beam signal and ϕ is the phase angle between the beam signal and the RF signal from the electronic phase shifter. These signals are processed in a signal averaging filter and then are multiplied together. The output of the operational multiplier contains the necessary DC information and is used to drive the RF phase shifter.

The circuit acts like a phase locked loop and seeks to null the $G\sin\phi$ signal. At null, the error signal is $G^2\phi$. When the system is out of lock the error signal is $G^2/2 \sin 2\phi$. This signal contains the gradient information necessary to bring the system into lock.

An automatic gain control (AGC) signal is derived from the detected signal power, G^2. The AGC is used to keep the system response constant so that the tracking error is independent of the modulated beam intensity. It is also used to shut down the circuit when the beam signal power falls below a threshold value. The system has remained locked with peak beam currents of 200 nA in 50% mode. Tests to determine the minimum beam required to measure the beam phase have not been performed yet.

3. HF mixer.- An active mixer is used as the phase detecting circuit. It offers improved conversion efficiency over a passive mixer since it can function as a demodulator and a preamplifier. Each of the two HF mixers uses a matched dual n channel J FET in a balanced mixer design [6]. The circuit has a wide dynamic range and large signal handling capability and can accommodate the levels of RF interference found on sigle pick-up probes in the cyclotron.



a b

Fig. 3a : RF interference on stationary pick-up Vert. scale: 200 mv/div; horizontal scale: 10 ns/div.
3b : HF mixer output for bipolar pick-up pulses from 20 μA beam in 50% mode. Vertical scale: 200 mv/div; horizontal scale: 0.2 ms/div.

The configuration can be used for quadrature detection of unipolar and bipolar beam pick-up pulses. Figure 3b shows the output of the HF mixer in response to bipolar pick-up pulses from a single stationary phase probe. The RF interference on the probe (figure 3a) was 1v p-p.

4. Matched beam modulation filter.- A commutating filter [7], shown in figure 4, is used to filter noise and low frequency RF fluctuations common to both signal paths of the HF mixer outputs shown in figure 2. The filter operates in the same manner as a signal averager.

The circuit is clocked at n times the 1KHZ beam modulation frequency f_o, where n is the number of sections in the filter. Since each capacitor is connected for 1/nth the time, the filter time constant is increased to $\tau \doteq nRC$, where R is the series resistor in figure 4. The number of individual signal samples taken in this time is $nRCf_o$. The effective averaging time is 2τ and the improvement in the signal to noise ratio for a white noise background is $N/\sqrt{N} = \sqrt{2nRCf_o}$. The improvement in signal to noise ratio of the $G\sin\phi$ signal in figure 2 is limited by the desired response time of the beam phase measuring system.

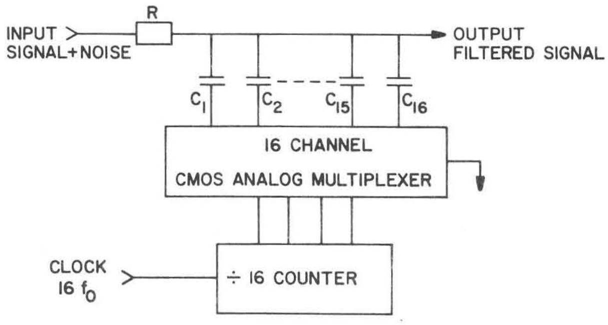


Fig. 4 : 16 section commutating filter.

The commutating filter has the same frequency response as a comb filter in that it transmits frequency bands centered on the harmonics of the beam modulation frequency up to half the clock frequency. For very low frequencies it acts as a simple RC filter. The bandwidth of the frequencies passed through the filter is inversely proportional to the time constant, nRC. Very low frequencies and frequencies above 8KHZ are rejected by the AC coupled amplifier preceeding the filter in figure 2.

The filter provides a means of signal processing suitable for a moving phase probe or a fixed probe which must correlate the external beam modulation through large changes in the cyclotron time of flight. The system works with the variable duty cycle beam pulser and can also take advantage of the 50% on-off beam modulation. This is the maximum modulation that can be applied to the beam and it gives the best signal to noise ratio for phase measurement.

Figure 5 shows the reduction in noise in the 1KHZ beam modulation signal when filtered by the 16 section commutating filter. The peak beam intensity is 7 µA in a 30% mode.

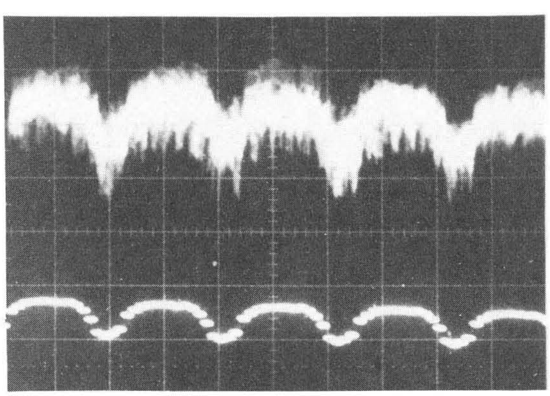


Fig. 5 : Matched filtering of the beam modulation signal. Upper trace: filter input; lower trace: filter output.

5. Input filtering.- Figure 3a shows that most of the RF interference is at the fundamantal Dee voltage frequency. When the phase probe signal is passed through a m-derived high pass filter, the fundamental component of the RF interference is reduced by 40 db and the RF voltage pick-up is reduced to 150 mv p-p. This reduced the noise due to RF fluctuations at the output of the HF mixer by a factor of 5. As analysis of the beam signal from passive pick-up probes shows that the amplitude of the beam signal frequency components is larger for the higher harmonics[1 4], rejection of all fundamental components at the input does little to reduce the beam signal power but it gives substantial improvement in the overall signal to noise ratio.

There exists a noise signal that is highly correlated with the beam modulation. It is a change in the RF interference caused by the 1KHZ beam discontinuity as it moves through the cyclotron. This effect is also reduced by rejecting the fundamental Dee voltage frequency at the input.

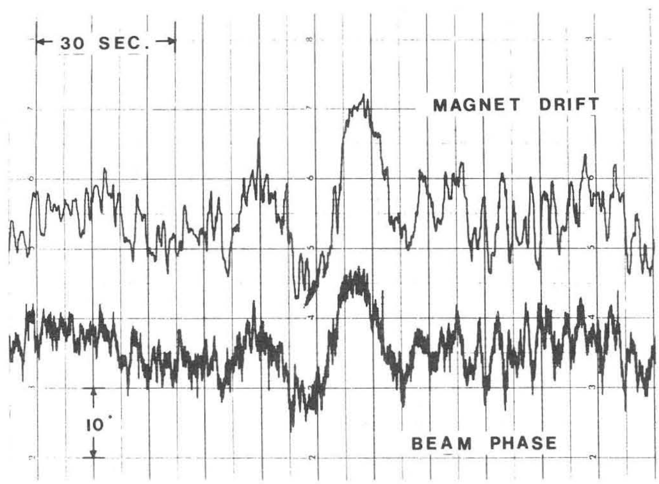


Fig. 6 : Magnet drift and beam phase signal.

6. Performance.- Bench tests with bipolar and unipolar signals show that the system can measure phase to less than 1°. Tests in the cyclotron with 15 µA of beam are shown in figure 6. It still remains to accurately test the system sensitivity and compliance with a wide range of cyclotron beams.

References.-

1. W. BRAUTIGAN *et al.*, Beam phase detection with a fixed intermediate frequency system at JULIC, Proc. 8th Int. Conf. on Cyclotrons and their Applications, Indiana, 1978, IEEE Trans NS-26 (1979) 2375.
2. R.J.VADER, H.W. SCHREUDER, KVI annual report 1976, p. 103.
3. G. DUTTO *et al.*, Achievement and control of the 100 µA beam at TRIUMF, Proc. 8th Int. Conf. on Cyclotrons and their Applications, Indiana, 1978, IEEE Trans NS-26 2320.
4. R.J. VADER, H.W. SCHREUDER, New methods for stabilizing Dee voltage and beam RF phase, Proc. 8th Int. Conf. on Cyclotrons and their Applications, Indiana, 1978, IEEE Trans NS-26 (1979) 2205.
5. R.J. VADER, Beam phase measurements at TRIUMF, TRIUMF report TRI-DN-79-21 and KVI internal report.
6. E. OXNER, FETs in balanced mixers, Siliconix Application Note AN 72-1.
7. B. BROEKER, Commutating filter techniques, Motorola Application Note AN-534.