Signal Processing for Internal Phase Probe in the TRIUMF cyclotron

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ABSTRACT

In the TRIUMF cyclotron, the beam cavity is sandwiched between the rf resonant cavity, with several parasitic modes that are in the vicinity of the operating frequency. Rf fields that are present in the beam cavity are orders of magnitude higher than cyclotrons of other designs. Phase probes in this region must be able to extract the beam signal from the significant amount of contaminating rf noise that is present. With a combination of hardware and software adaptive noise cancelling techniques, it is possible to obtain accurate beam phase information at a signal-to-noise ratio of less than one, corresponding to a beam current of 5 μA.

INTRODUCTION

In the TRIUMF 500 MeV H^- cyclotron the beam induced signals from the internal phase probes are completely masked by the pick up of extraneous signals due to rf fields generated through excitation of parasitic modes and random electrical discharges in the accelerating dee structure. The cavity in which the beam travels can support parasitic modes that can be excited through misalignments of the resonators at the dee gap. These parasitic mode fields with frequency components consisting of 23.06 MHz fundamental dee excitation frequency plus its harmonics and the inherent wide band noise due to discharge lead to extraneous fields ranging from 1kV/m to more than 10 kV/m depending on dee alignment. These fields generate interfering signals on the capacitive probes used for non-intercepting detection of the beam. By signal processing at the second rf harmonic the interference is reduced significantly while still permitting a wide operating range of 180° for beam phase measurement. Direct conversion from the 46 MHz harmonic into base-band using a vector demodulator is used to extract beam phase information. The effect of residual rf leakage is removed by pulsing the beam so that the phase of the beam can be obtained from subtracting the beam-on vector from the beam-off vector. The beam-off vector is continuously updated to allow for long time drifts in the system. Using the combination of the above techniques, we have been able to obtain beam phase information for peak current as low as 5 μA at 50 % duty cycle.

PHASE PROBE FRONT-END

A non-intercepting phase probe is simply a metal plate over which a charged beam bunch passes. The beam induces a voltage on the plate which is proportional to the amount of charges in the beam pulse. Stray electric fields that are present near the plate also induce voltages in the plate, contaminating the beam signal. To improve the signal-to-noise ratio, an opposing upper and lower probe pair is used. Most of the rf leakage picked up by the two probes have vertical electric fields that induce voltage in the upper and lower probes that are 180° out of phase. On the other hand, the beam induces voltages in the probes that are in phase. Therefore, by summing the two probe signals the leakage component will be suppressed and the beam component enhanced. The existing probe pair is located inside the vacuum tank behind the resonator, starting at a radius of 272 inches. The front surface of each plate is covered with aquadag to suppress electron emission from occurring at its surface. The plates are surrounded by grounded shields, isolated from ground by ceramic stand-offs and connected to the detection electronics by 50 Ω coaxial cables. The turn separation of the beam at the radii of the phase probes is of the order of 1.5 mm, so the induced voltage is the sum of more than 60 turns. For a 100 μA beam, the measured second harmonic component of the signal is 10 mV_{p-p}. This is close to the predicted value when cable losses are taken into account. The second harmonic component of the rf leakage voltage is typically 10 mV_{p-p}, with noise bursts up to 30 mV_{p-p}. Due to the presence of non-vertical fields, cancellation of rf leakage by this standard method is not complete. The residual noise consists of random bursts of less than 1 μs in duration (Figure 1). The origin of these noise bursts is discharges in either the rf resonator or the rest of the vacuum tank which generates rf noises that are able to propagate to the phase probes. Vibrations of the resonator support structure further modulate the amplitude of the residue noise with a 5 Hz component. The amplitude of the residual noise is typically 2 mV_{p-p}, which can still pose a significant interference to the beam signal at lower beam current.

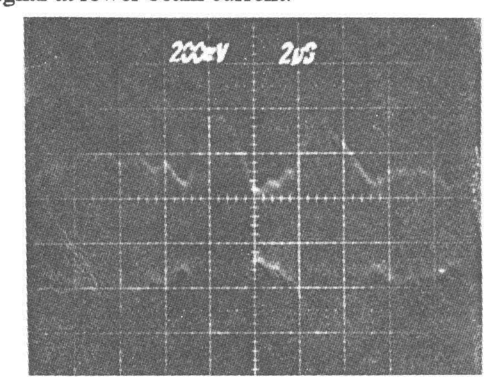

Figure 1. 46MHz component of noise bursts from a single phase probe. The signal is amplified 30 times. The average amplitude is 600 mV_{p-p}, with a modulation of greater than 50 %.

DETECTION ELECTRONICS

The second harmonic of 46 MHz is chosen for phase probe signal processing because of its low leakage values as well as its wide operating range. A schematic of the vector demodulator is given in Figure 2. Direct conversion of the phase signal from rf to base-band is employed. The reference signal is derived directly from the rf system itself. Since the rf accelerating field is amplitude controlled but not phase controlled, vibrations in the support structure of the resonant cavity changes the tune of the cavity and causes a time-varying phase shift between the amplifier and the cavity. The reference phase for the detector is obtained from an electric field probe located inside the resonator near the accelerating gap where the electric field is

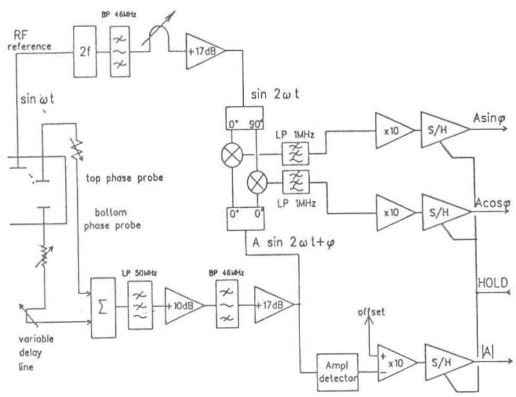

Figure 2. Block diagram of vector demodulator for the phase probe.

in phase with the accelerating field. Since the probe is located inside the resonator, the induced voltage consists of the 23 MHz signal with all other frequencies at least 60 dB weaker. For this reason no filtering is needed before the dee probe signal is frequency doubled by mixing with itself to obtain a 46 MHz phase reference. The other mixing products are removed by bandpass filters. The reference 46 MHz signal is amplified and split into two equal parts : the I (in-phase) and Q (quadrature) components. The signals from the upper and lower phase probes are bandpass filtered to accept only the 46 MHz components. These consist of the Fourier component of the beam signal, the second harmonic rf leakage and the 46 MHz component of wideband discharges. The relative amplitudes and phases of the filtered signals are adjusted to obtain the maximum cancellation of the rf leakage. Filtering before combining the two signals enables each of the signal to be monitored individually with an oscilloscope. The relative amplitudes and phases of the two signal can then be adjusted for cancellation. The combined signals are monitored by a directional coupler installed after the combiner. Fine cancellation is performed by minimizing the voltage at this point with the beam switched off. A small amount of the signal is tapped off to a tuned amplitude detector for beam intensity measurements. The main portion of the signal is split and mixed with the I and Q reference signals. A pair of diplexers at the output of the mixers provides constant terminating impedance in order to minimize inter-modulation products. The 500 KHz low frequency branches of the diplexers extract the I and Q information of the phase probe signal. The I,Q and amplitude signal are then amplified and digitized. Track-and-Hold amplifiers are used before the digitizer to assure that the digitized information from all the channels are acquired simultaneously. The information at this stage is the vector sum of the leakage and the beam pick-up phasors. Frequency response at this stage extends from dc to the response of the post detection amplifiers which are approximately 100 KHz.

Using the I,Q information, Figure 3 shows the two clusters of sampled data in the I-Q plane with a 180 µA beam pulsed at 50 % duty cycle. The beam-off cluster is located at the centre of the picture and the beam-on cluster at the right side.

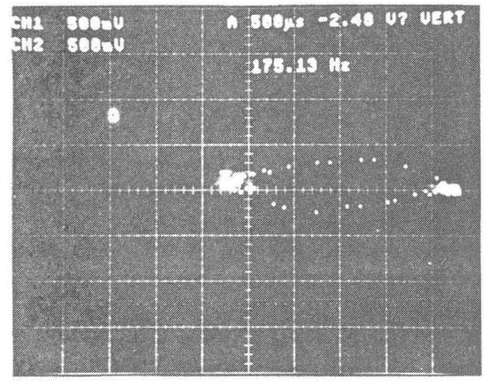

Figure 3. I-Q diagram showing the data clusters of demodulated beam phase signal. The distance between the two clusters is proportional to the magnitude of the beam current and the angle the beam phase.

The sizes of clusters are indications of the amount of noise that is contaminating the measurements. The 5 Hz AM noise from the resonator support structure vibration can cause the centroid of the cluster to move in unison without affecting the angle between them. Actual beam phase modulation due to the vibration can cause the beam-on measurement to rotate about the beam-off measurement. It is apparent from the figure that the phase resolution of the phase probe is determined by the size of the clusters and their separation. The cluster sizes depend on the noise generated by the rf system and on the effectiveness of the cancellation. The separation between the cluster is proportional to the beam intensity. For a given cluster size, when the beam intensity is reduced, the beam-on cluster moves towards the beam-off cluster, and the uncertainty in the beam phase angle increases almost linearly with the reciprocal of the separation until the two clusters overlap, at which point the uncertainty in beam phase is approximately 45°. Generally speaking, this uncertainty can be reduced by averaging the data points for each of the clusters at the expense of the frequency response. This is performed in software as described in the next section.

SIGNAL ANALYSIS SOFTWARE

After digitization, the beam signals are processed by software. The signals are digitized in a CAMAC module and read by a general purpose computer through a CAMAC branch highway, with the consequence that real time information of the signal is lost. The main objective of the software is to calculate the phase angle and to remove the time varying background noise. To accomplish this, the software consists of two main parts: the adaptive beam detection logic and the angle calculation. The main logic blocks are indicated in Figure 4. During angle calculation, the code keeps running averages of the sines and cosines during beam-on and beam-off intervals as determined by the beam detection logic, and uses these values to calculate the actual beam phase angle ϕ. The averaging are performed by one pole Infinite Impulse

Response filters. More sophisticated filters can be used if necessary.

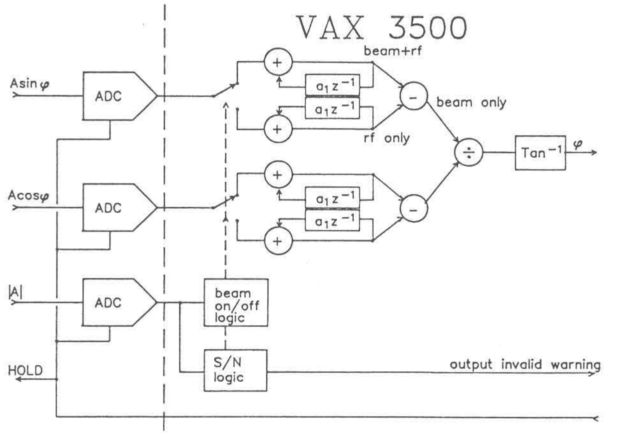

Figure 4. Software logic block diagram for the beam phase angle calculation.

The adaptive beam detection logic is used to determine the presence or absence of the beam signal. The signal which occurs during the absence of the beam is used for background subtraction. At the start of the measurement, a sample of beam intensity values which consists of both beam-on and beam-off values is collected. This set of numbers are histogrammed and their values smoothed by a 9-point quadratic smoothing routine[1]. The peaks corresponding to the maximum and minimum intensities are determined by fitting to Gaussian profiles, and their standard deviations determined. This information is used to set the centers and widths of windows of acceptance for the subsequent data. Spurious data caused by transients due to sparks in the ion source, the injection line, the main acceleration rf, as well as the rising and falling edge of the pulsing beam-on period which can result in intensity values falling outside the window of acceptance are rejected by the detection system. These data windows are not set a priori but are derived from the beam to compensate for the varying beam intensities and tuning conditions of the cyclotron, which tend to drift slowly. Furthermore, the centers and widths of the acceptance windows are updated in each data acquisition cycle in the form of running averages, which enable them to adapt the variations in the rf leakage or the beam intensity. In this way as long as the beam or the rf leakage does not suddenly change by more than two standard deviations within the averaging interval, the detection logic is able to track these changes and adjust the acceptance windows accordingly. Care must be taken in tracking the widths of the peaks since the acceptance/rejection process is intrinsically unstable for the width. The growth rate can be made very small, however, by an appropriate choice of the tracking parameters. The acceptance windows are chosen to be 3 standard deviations from the peaks to include 99 % of the valid data.

MEASUREMENTS

A series of measurement were performed at various beam intensities. It was found that the minimum current required for phase measurement depended on the stability of the rf system, since this is manifested in the amplitude of noise bursts picked up by the phase probes. During a period of stable rf operation, accurate phase information was obtained from beam currents as low as 3 μA.

Figure 5 shows the phase measurement when there were instabilities in the rf system during the course of the measurement. During this measurement the beam current was increased from 36 μA to 60 μA in 2 increments of 12 μA. The calculated phase remained stable at 59±2° for beam current of 36 and 48 μA. At approximately the 160th count, the current was increased to 60 μA. Shortly afterward a spark occurred and brought down the rf system. After it was restarted the rf became unstable and the rf leakage increased in amplitude and fluctuated wildly, as observed in the figure. Even though the signal increased as a result of the increase in beam intensity, the signal-to-noise ratio decreased by a large amount due to the wild fluctuation in the rf leakage. Correspondingly the calculated phase in Figure 5 became unreliable and showed phase fluctuations of more than 7°.

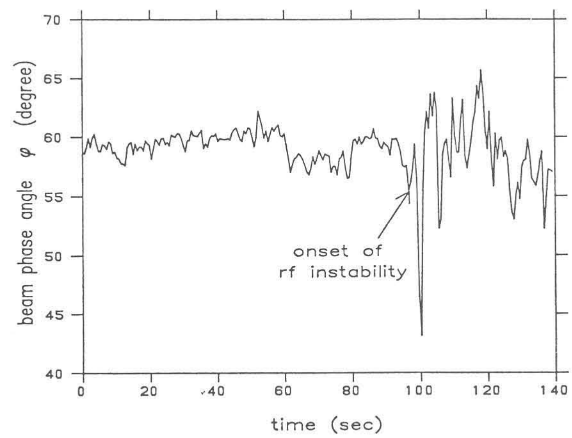

Figure 5. Beam phase angle before and after unstable rf operation.

CONCLUSION

It is possible to extract good beam phase information from a high rf leakage background by adequate signal processing. In order to track the time varying background for background subtraction, the beam must be able to pulse off regularly. Under stable rf operations, beam phase information can be obtained from contaminated signal with a signal-to-noise ratio of less than one, corresponding, for the TRUMF case, beam currents as low as 5 μA.

REFERENCE

1. A. Savitzky and M. Golay, Anal. Chem. 36,8, 1627 (1964)