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THE IUCF PHASE PROBE

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Abstract

A non-intercepting, charge-sensitive, sampling beam probe has been developed for use in internal beam phase measurements in the variable-energy, separated sector injector cyclotron at Indiana University. The two probe pickup plates of 10mm by 16mm are located above and below the median plane with sampling diodes in close proximity. The probe head is mounted on a movable assembly permitting continuous observation of phase history from inflection radius through extraction radius, at interval beam currents of 100 nanoamperes or greater with pulse rise times of less than one nanosecond. Over a two-year period the phase probe has proved relatively reliable and easy to use for confirming trim coil adjustments and orbit dynamical isochronization procedures. The probe display, in addition to providing data on phase group width and centroid versus radius, has on occasion shown up ion source ripple and radio frequency parasitic generation which might otherwise have been overlooked.

University Cyclotron Facility (the injector and the main stage) will have several properties which have dictated the design features of our phase probe. The rather large orbit separation, averaging about 2-1/2 orbits per radial inch, the average beam current, about one microampere, coupled with the relatively small number of orbits per trim coil region, about 12, require a high pick-up sensitivity but a rather small pick-up area. The beam burst length, of the order of 0.2ns, requires a wide bandwidth pick-up circuit, if details of the beam burst structure are to be observed. A good signal to noise ratio is required, and as a consequence immunity to RF pickup is essential. Finally, a non-intercepting pickup probe is desirable for the following reasons: to minimize heat and radiation production thereby prolonging the lifetime of the probe components and to allow phase measurements to proceed compatibly with use of the facility by experimenters.

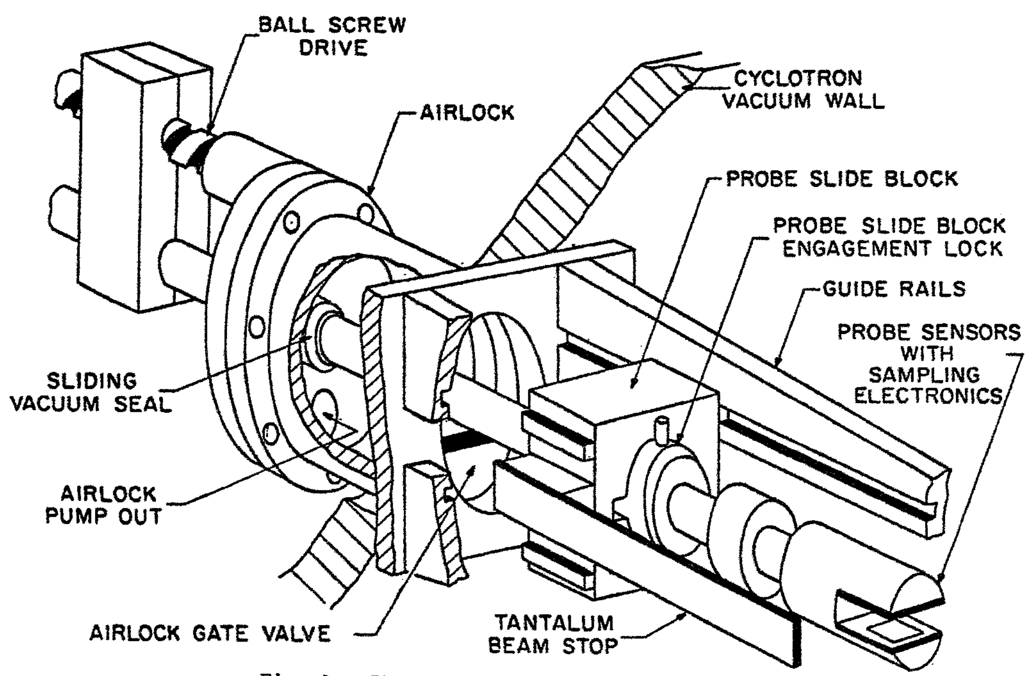

Fig. 1: Phase Probe Mechanical Assembly

Introduction

The use of a sensing device to measure the phase relationship between beam bursts and the RF in a cyclotron has proven to be a valuable aid in tune-up and isochronization[1-3]. The two cyclotrons of the Indiana

These requirements led to the development of a non-intercepting, charge-sensitive sampling phase probe system which has been in operation at IUCF for about 2-1/2 years. In this report the mechanical and electronic aspects of the probe are described and some of the results obtained with it are discussed.

Mechanical Design

The injector cyclotron phase probe assembly Fig. 1 consists of the probe sensor and the support and drive mechanism. The probe sensor Fig. 2, composed of two

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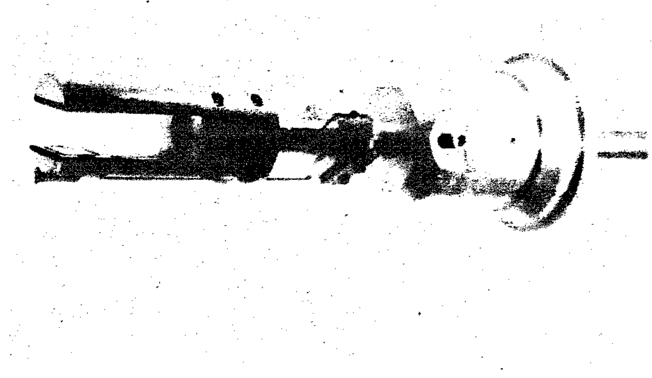

Fig. 2: Phase Probe Sensor Head With Dual Pick-Up Plates and Sampling Electronics, Followed By Position Limit Switch and Guide Rail Lock.

independent pickup plates and associated sampling electronics 1/2" apart above and below the median plane is mounted on a 50" long by 1/2" diameter stainless steel tubing. This tubing carries the signal cables and allows the probe head to be positioned along the injector cyclotron radius in the extraction valley. The external probe end contains the vacuum seal and signal feedthrough with an easily decoupled electronics module containing signal summing and gate amplifiers. The probe can be installed or removed from the cyclotron without breaking vacuum in about 5 minutes via an airlock. When in the machine, the probe head engages a set of guides on which the probe slides. The guides maintain the probe sensor position above and below the median plane to within 2mm.

The probe is driven externally by a Slosyn drive motor using a ball screw drive mechanism; the motor is controlled by the Sigma2 control computer. A tantalum beam stop mounted on the slide mechanism intercepts the beam at a radius 1 inch greater than that of the sensor edge. This protects the probe tubing, which is on the median plane, from beam damage. Mounting the upper and lower beam sensors on a single tube in this manner provided us with a simple probe and drive mechanism, which was adequate for our initial tune up operation. Before routine operation of the facility begins, if desirable, separate probe drives for upper and lower sensors will be built to enable simultaneous phase sensing and user operation.

Electronics

A block diagram of the phase probe electronics is shown in Fig. 3. The two pickup plates, each a rectangle 10mm radially x 16mm azimuthally provide two signals which are summed to increase the signal to noise ratio and afford a good structure for RF shielding. There was no evidence in our machine that the RF signals induced into the sensors were of opposite phase or even slightly shifted. As a consequence, the induced RF would not naturally cancel when summed. The pickup plates were made as an etched out island on a double copper clad circuit board, with the surrounding area of the copper clading acting as a RF shield for the sampling electronics below. The copper clading on the opposite side of the pickup island was also isolated from ground to provide the second plate of a parallel plate capacitor of about 5pF. This capacitor is the repository of the charge induced by the beam and provides a means of supplying a differential signal having a high degree of common mode rejection of unwanted signals from RF, power supply ripple or sparking; see Fig. 3.

The two plates of the pickup capacitor are tied to each other through a 50 ohm termination resistor and a gate diode which acts as a switch, closing each time a negative pulse is applied. This allows the capacitor to charge and hold its charged state as influenced by the charge distribution of the circulating

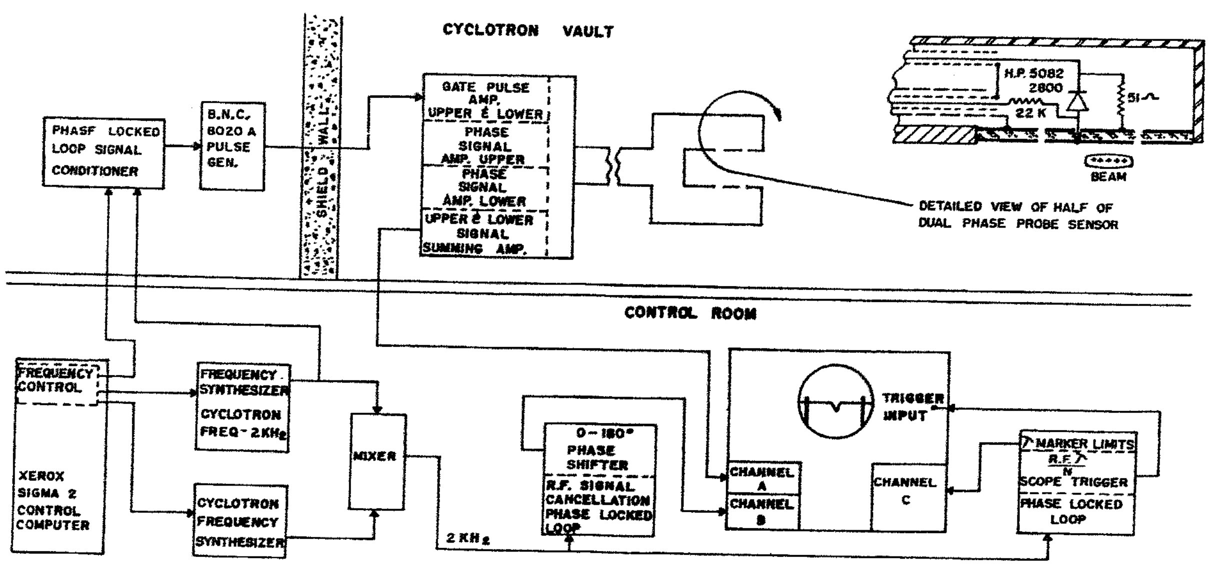

Fig. 3: Phase Probe Electronics

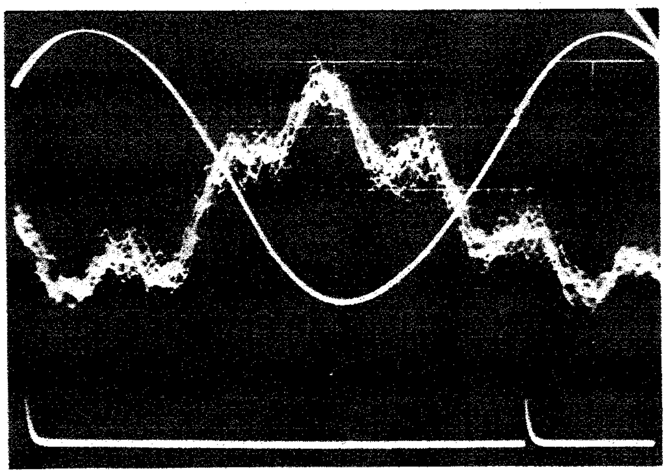

Fig. 4: Phase Probe Signal of RF Fundamental and 5th. Harmonic With Superimposed RF Cancellation Signal. Scope: 40 RF Degree/cm, 0.2V/cm.

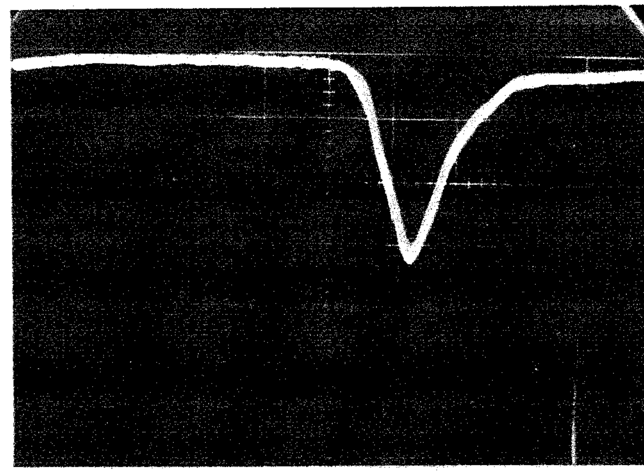

Fig. 5: 1μA Proton Beam With Minimized Ion Source Ripple. Scope: 40 RF Degrees/cm, 1V/cm.

beam outside the pickup plate. The charge across the sensor plate slowly bleeds off through a 22 kΩ resistor to charge the signal cable capacity of 180pF. This resistance and the cable capacitance act as a low pass filter allowing only the slowly varying average charge on the pickup plate to pass to an FET differential amplifier with a gain of 160. A microdot mininoise triaxial cable is used to reduce microphonics. The outermost shield is grounded and does not act as part of the signal carrying inner coax, thus eliminating capacity modulated signals induced on the inner coax differential signal carrier caused by small machine vibrations.

The amplified signals from the upper and lower pickups are summed and amplified 6.6 times. The combined gain is 2100 with a noise figure of 50 mV as measured with an oscilloscope. One of our current noise sources is being reduced by the installation of low noise metal film resistors. Another source of noise is small amplitude modulation of the gate pulse. These problems will be investigated further since a better signal-to-noise ratio will be required when we construct a second phase probe system in the main stage cyclotron in the near future.

The sampling diodes mounted on the pickup plates are strobed with a gate pulse that is accurately advanced icrementally along the RF by providing a second stable accurate frequency synthesizer which is tuned to a frequency exactly 2kHz different from the RF frequency synthesizer. The gate pulse is supplied by a Berkeley Nucleonics Corporation Model 8020A Pulse Generator triggered by the output of a computer-tuned phase-locked loop, locked onto the signal from the 2 kHz difference frequency synthesizer. The phase-locked loop acts as a signal conditioning buffer to provide a clean fast rising trigger to the pulse generator, the output of which is a pulse of -2.2V into 50 ohms with a rise and fall time of 1.3ns, FWHM of 3ns and jitter of less than 50ps.

The rise time of the probe has been determined in bench tests to be less than 1.0ns and jitter to $\pm 2^{\circ}$ at 30 MHz. This value reflects the rise time of the equipment used to simulate the beam burst; the actual value may be lower.

The position of the pickup plates in the extraction valley, the pickup lead shielding, the care taken in bypassing and isolating the phase-probe system and the use of common-mode rejection serve to minimize RF pickup, which has been a serious problem at other laboratories. Fig. 4 is a phase probe display showing pickup of RF fundamental with harmonic content at about the maximum level encountered; the ordinate is 0.2 V/cm. This should be compared to a display with RF cancellation, Fig. 5.

In order to provide a low frequency signal to trigger the display oscilloscope at the sampling repetition rate, RF phase angle markers on the scope, and a phase shiftable sine wave of the same frequency as the RF which can be summed with the phase probe output at the scope to give RF fundamental cancellation, the RF synthesizer and gate pulse synthesizer are mixed to provide the 2 kHz phase coherent difference frequency. The mixer output is fed into two phase-locked loop circuits. One circuit provides the phase shiftable RF cancellation signal, and the other provides the scope trigger and RF phase angle markers.

Results and Discussion

The phase probe system has been in operation in the IUCF injector cyclotron for about 2 1/2 years. The probe has proved to be very useful in isochronization. It has been reliable with no damage to the sampling head by radiation yet observed. Fig. 5 is an example of the phase probe display under optimum conditions: 1μA beam, 1 V/cm, 40° of RF phase/cm, protons. Beam burst phase relative to the RF has been measured to $\pm 4^{\circ}$ at currents as small as 100 ± 10nA. Even at this small average current only about 16% of the beam burst of one turn was being sampled. Fig. 6 shows the profile for this 100 nA beam at 0.1 V/cm, 40° of RF phase/cm, extraction radius (after the electrostatic deflector), 20° of chopping and using 10 MeV protons. These displays were obtained using the RF cancellation technique described above.

The results of a phase history measurement are shown in Fig. 7. This data required about 4 seconds per radial point to obtain, or about 3.6 minutes for the complete scan. This compares quite favorably to the estimated 40 minutes to obtain the same data with the Smith Garron method, which cannot give the details

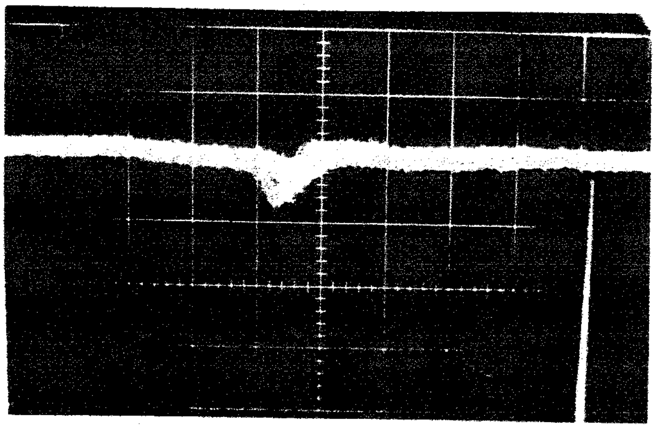

Fig. 6: 10 MeV Proton Beam In Extraction Orbit. Average Beam Current of 100± 10 nA, with ~16% of One Beam Bunch Over Phase Pick-Up Plates. Scope: 40 RF Degrees/cm, 1V/cm.

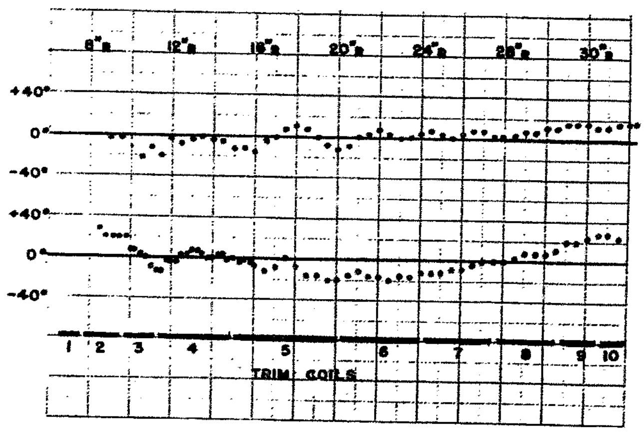

Fig. 7: Phase History Obtained with Phase Probe Showing Effects of Single Trim Coil Correction of Chopper Inflected Proton Beam. Lower Plot has Sag Over T.C. 5 and 6. Upper Plot, After Correcting T.C. 6 from 10A to 20A, Shows Removal of Sag.

of the physical structure of the beam burst.

In addition to providing phase information, the phase probe has also diagnosed some operational problems which would have been difficult to observe otherwise. Fig. 8 shows the beam burst profile resulting from an estimated 0.1% ripple on the preinjector terminal voltage, in conjunction with bunching of the preinjected dc beam which allowed a velocity modulation of individual beam bunches. Thus these beam bunches separated after a long drift space and arrived at the cyclotron inflector with a time variation of ±20° of RF phase angle. This effect was not suspected until the phase probe result was obtained.

The injector cyclotron has two independent RF accelerating structures which must be tuned separately. Early phase probe measurements were substantially more sensitive to mismatching of these elements than the RF tuning apparatus. Fig. 4 shows the phase probe output with the fifth harmonic of the RF generated by mistuning; the 15th. harmonic is displayed in Fig. 9.

As the system stands now, operation is quite satisfactory, but not completely automated. There are some improvements underway. We plan to eliminate the gate pulse frequency synthesizer, by constructing our

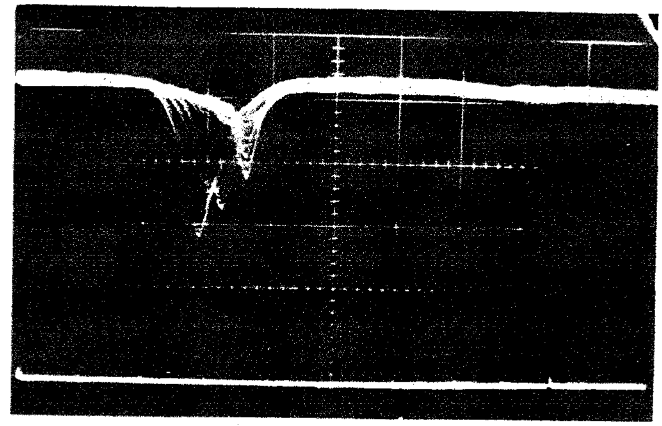

Fig. 8: Chopped Beam Exhibiting Phase Modulation Effects. Scope: ~40 RF Degrees/cm, 2.0 V/cm.

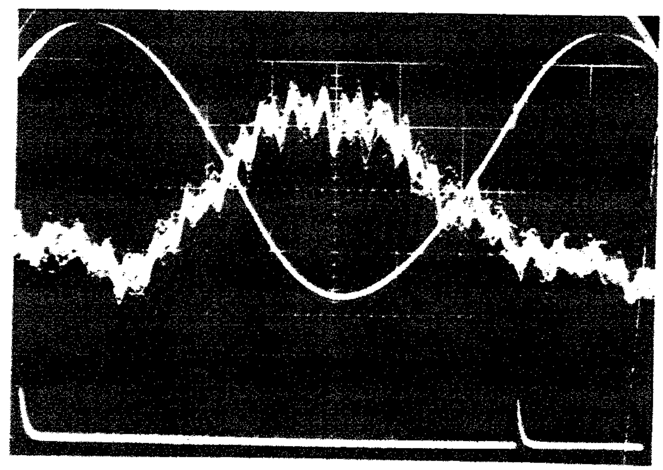

Fig. 9: Phase Probe Signal of RF Fundamental and 15th. Harmonic with Superimposed RF Cancellation Signal. Scope: 45 RF Degrees/cm, 2.0 V/cm.

own frequency translator.

Also we have underway the elimination of the gate pulse generator with a device which will reduce the gate pulse rise time ~100 ps and thereby provide better resolution of beam burst charge. Automatic RF cancellation and beam burst phase position readout for computer control are being examined to provide both digitized phase information for computer analysis and a large increase in signal to noise ratio by signal averaging techniques.

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