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ABSTRACT

A sampling oscilloscope has been used to display beam pulses of the Berkeley 88-inch cyclotron. The beam impinges on a water-cooled copper target that is partially enclosed in a water-cooled rf shield. An hydraulic cylinder drives the probe radially. Satisfactory signals relative to the noise were achieved with an average beam current of 1 μ A. The phase of the beam with respect to the dee rf can be resolved to better than 5 deg. Plans for further development of the probe are discussed.

MEASUREMENT OF BEAM PHASE OF THE BERKELEY 88-INCH CYCLOTRON†

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April 9, 1962

1. Introduction

The problem of determining sets of trim-coil current for satisfactory field shapes in the Berkeley 88-inch cyclotron is being attacked on two fronts:

(a). Garren¹⁾ and Young²⁾ have described how such current sets can be predicted by manipulating measured effects of individual trim coils.

(b). A probe containing a water-cooled copper target is being developed to display beam pulses on a sampling oscilloscope. We will observe the phase of the beam pulses as a function of radius and modify the predicted trim-coil currents to obtain an optimum function of phase vs radius.

Konrad³⁾ used a sampling technique to measure ion phase on the Birmingham cyclotron. During the past three years, sampling oscilloscopes⁴⁾ have been put into mass production. The availability of these commercial oscilloscopes makes the measurements of beam pulse phase and pulse shape relatively simple.

The initial development work of the 88-inch cyclotron phase probe was conducted at the Berkeley 60-inch cyclotron⁵⁾. This work established that it was possible to attain high resolution of phase at relatively low average beam current. It also demonstrated that it was relatively easy to shield a water-cooled target from the high rf voltage on the dee.

† Work done under the auspices of the U.S. Atomic Energy Commission.

A probe was built for the 88-inch cyclotron. Figure 1 is a block-diagram representation of the phase-probe instrumentation. A water-cooled copper target, which is shielded from the rf voltage of the dee by a water-cooled shield, is connected to a sampling oscilloscope through a 125- Ω coaxial cable. The cable is terminated with its characteristic impedance at the oscilloscope. The oscilloscope is triggered in synchronism with the dee voltage through a loop coupled to the rf field of the cyclotron. (Examples of phase signal oscillograms are shown in Figures 6 and 8.)

2. Sampling Oscilloscope

Sampling oscilloscopes examine the detailed wave form of recurrent phenomena by extracting a small amount of information from each of the recurrent events. A familiar example of an application of the sampling principle is the stroboscope. The human eye has a limited frequency response and retains visual sensation for a fraction of a second after an image is removed from the retina. When a fast-moving object is viewed the image seems blurred. If the motion is recurrent and the object is illuminated for only a brief period at the same position during each recurrence, the object appears to be clear and stationary. If the illumination occurs at successively later (or earlier) increments of time after the beginning of each period the object appears to move slowly through a cycle of its recurrent motion. A similar effect is achieved even when the pulse of illumination occurs only once in several periods.

Sampling oscilloscopes are equipped with very fast switches which permit the sampling of a small portion of each of a series of recurring wave forms. A holding circuit preserves the voltage information until the next sample is taken during a subsequent period. The sampling switch can be

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Fig. 1. Phase probe block diagram.

controlled by the recurring wave form in such a way that the entire wave form is scanned. Only the input circuits of a sampling oscilloscope must have a high frequency response in order to examine the details of recurrent high-frequency phenomena. Because the switches that are used are relatively free of noise, low-amplitude wave forms can be studied. The noise of commercial sampling oscilloscopes† is of the order of 1 mV; the minimum rise time is approx 0.5 nsec.

3. Probe

The phase probe is designed to move rapidly over a wide range of radii. A metal bellows is used for the moving vacuum seal to assure reliable leak-free operation. Figure 2 shows how the metal bellows is incorporated in the probe. Each end of the bellows is sealed to a flange. The flange at the end near the probe head allows the probe shaft to slide through it. The probe shaft is sealed to the outer flange. The space outside of the shaft and inside of the bellows is evacuated. The free length of the bellows is 90 in. and it is designed to operate over the range 60 to 140 in. The probe is moved by an

†Representative manufacturers specifications for dual-channel sampling oscilloscopes:

Hewlett-Packard Model 185A/187B : :

rise time: Approx 0.4 nsec, sensitivity:
3 mV/cm, noise: approx 0.5 mV ("smoothed").

Lumatron Model 120 : : rise time: approx 0.35 nsec, sensitivity:
2 mV/cm, noise: less than 0.5 mV (smoothed)

Tektronix Type 661/4S1 : : rise time: 0.35 nsec, sensitivity: 1 mV/cm,
noise: approx 0.5 mV (smoothed)

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Fig. 2. Phase probe.

hydraulic cylinder with a piston travel of 54 in. As the probe moves, a chain drives an energized potentiometer. The voltage output of the potentiometer is brought to the control room to indicate the position of the probe.

Figure 3 shows details of the construction of the probe head. The figure contains an arrow representing a beam impinging on a water-cooled target 1/2 in. high. The target is recessed in a water-cooled shell that serves to reduce the magnitude of the rf field at the position of the target. It is supported on its copper cooling-water tubes in an insulating disk that serves as the vacuum seal. A transition from copper tubing to polyethylene tubing is made just beyond the vacuum seal. The center conductor of a flexible coaxial cable is connected to one of the short copper tubes; the braid is connected to the metal probe body.

4. Phase Relations

As the probe is moved to stop the beam at different radii the phase of the trigger signal remains constant. The relative phases of the beam pulses at different radii can thus be determined. The dual-channel oscilloscope inspires confidence by displaying the trigger wave form simultaneously with the target voltage.

If a small piece of metal is clipped to the target (to increase its capacitance to the dee) and the probe is moved near the dee, a few millivolts of rf will be induced on the target. This rf signal can be used to establish the phase difference (at the oscilloscope) between the trigger rf signal and the dee voltage.

Adjusting the trigger-circuit controls on the sampling oscilloscope shifts the phase of the target signal trace. The triggering phase also shifts with time. However, when the trigger signal is displayed on the second

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Fig. 3. Phase probe head.

channel of the oscilloscope it will maintain its phase relative to the signal trace and thus preserve a phase calibration. Figure 4 is an equivalent circuit for the rf voltage induced on the target. Because the capacitive reactance of the dee-to-target capacitance is very much greater than the characteristic impedance of the cable, the rf voltage on the cable leads the dee voltage by almost exactly 90 deg.

Figure 5a introduces the effect of the probe position into the question, and fig. 5b shows the phase relations of the dee voltage and the voltage induced on the probe. The rf voltage on the probe is shown combined with the voltage induced by a packet of in-phase ions. In-phase ions are defined as those which are entering the dee-side semicircle at the time of minimum (maximum negative) voltage on the dee. In this paper beam phase is reported in terms of phase lag. Therefore, with increasing phase the beam pulse would appear farther to the right on a wave form such as the one in fig. 5b. Because the ions arrive at the azimuthal position of the probe in the 88-inch cyclotron 60 deg before the reference position, the pulse corresponding to in-phase ions appears 60 deg to the left of the dee-voltage minimum. This corresponds to a position 30 deg to the right of the minimum value of rf voltage induced on the target. The target-voltage wave form does, of course, shift its phase as it travels down the coaxial line. However, the phase relations are maintained.

W. B. Jones (private communication) has suggested an alternate method for referring the beam phase to the dee voltage. When the dee frequency is varied the beam pulse moves along the trace. When the probe is near the center of the cyclotron the amplitude of the pulse remains nearly constant until it reaches the ends of a range which should be 180 deg wide. The center of this range should then correspond to 0-deg phase lag.

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Fig. 4. Phase probe equivalent circuit.

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Fig. 5. Beam and rf phase relations.

5. Results

At the time this is being written very little phase information from the probe has been used to tune the 88-inch cyclotron. However, we have had enough experience with it to demonstrate that it will give us the phase information we want.

Figure 6 contains oscillograms from the dual-beam sampling oscilloscope taken with the probe at several radii. These pictures were made when the probe had a less effective rf shield than at present and the target picked up some noise. Harmonics of the rf are exaggerated by the probe because the reactance of the dee-to-target capacitance is, of course, inversely proportional to frequency. The three traces on each oscillogram represent (top to bottom): (a) Target voltage with the arc on, (b) Target voltage with the arc off (no beam), and (c) Trigger voltage signal (not to be confused with the dee voltage shown in a similar position on fig. 5).

The average beam current at the time of the photographs was under $10\mu\text{A}$ at 30 in. radius. Figure 6a corresponds to a probe position close enough to the dee to pick up some dee rf on the target. Note that although it takes some imagination to see a beam pulse, fig. 6a does establish the phase relation between the trigger rf and the dee rf (taking into account the 90 deg phase lead described under "Phase Relations"). The minimum instantaneous trigger voltage happens to almost coincide with the minimum rf induced on the target, which in turn corresponds to the position of a -30-deg (leading) pulse. The target signal in fig. 6b contains two humps which seem to indicate two separate beams. The distance between the humps is a function of the rf.

The phase information from several oscillograms such as in fig. 6 was plotted (fig. 7) on a graph of Garren's prediction of phase as a function of radius

Abscissa = 10 nsec/div.
Ordinate = 3 mV/div.

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Fig. 6. Phase signal oscillograms.

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Fig. 7. Predicted and measured beam phase.

for an optimal set of trim-coil currents. Note that positive values of $\sin\phi$ correspond to lagging phase. The magnitudes of the cyclotron frequency and the coil currents at the time of the phase measurements were very close to those used in the prediction calculations.

The oscillograms in fig. 8 were made after the present more effective rf shield had been installed on the probe. Figure 8a corresponds to an average beam current of $2.5\mu\text{A}$. The average current was measured by connecting the phase probe to a D. C. microammeter, and it is in agreement with the value computed by dividing the area under the pulse by 125Ω (the characteristic impedance of the cable). Figure 8b, made at 4.4 in. radius demonstrates the effectiveness of the new rf shield. From oscillograms such as these the phase of the pulse can be resolved to better than 5 deg. It is apparent that an average beam current of $1\mu\text{A}$ yields a useful signal.

6. Further Plans

Tentative plans for the phase probe include:

Display of phase vs radius. The hydraulic drive system of the phase probe was designed to move the probe rapidly and repeatedly along a radius of the cyclotron. It is part of a plan for making quick adjustments of ion phase as a function of radius. The other elements of the plan are the oscilloscope display, and a method of adjusting the circular trim coils in pairs.

The present plan for the oscilloscope display is to move the trace vertically a distance proportional to the radius of the probe. The cathode-ray-tube screen will be dark except for the duration of one or two sweeps at each of a selected set of radii. A long-persistence phosphor will then display phase as a function of radius in the form of a nest of traces, each similar to the top trace of fig. 8a. When the probe is set to sweep from 4-1/2 to 39 in.,

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Fig. 8. Phase signal oscillograms.

the 13 traces--made at 4-1/2 in., 6 in., 9 in., etc.--may be spaced vertically at least 1 mm for each inch of radius. The resolution of phase and radius information will be better when the probe is set to sweep a fraction of the machine radius.

A method of adjusting circular-trim-coil currents has been suggested by Garren and was reported by me in ref.⁶). If, whenever the current in a circular trim coil is changed, an appropriate change in the opposite direction is made in an adjacent coil, the phase of the ions inside of the selected coils will be affected relatively little. "Appropriate" is defined as that magnitude corresponding to zero net change of flux density at the machine center. The pair of currents will give a circular bump of flux which will give ion phase changes approximately zero inside the coils and approximately constant (non-zero) outside.

What is needed, then, are rapidly repeated displays of phase vs radius, and a convenient set of controls to achieve the combinations of trim-coil-current adjustments described above. It should then be possible to match a desired function of phase vs radius from the center outwards with very little interaction between adjustments.

Operation with a low duty factor. Small water-cooled copper targets can withstand at least 100 μ A at 50 MeV continuously. If tuning is to be done with higher beam intensity, or if it is desired to limit the amount of induced radioactivity, the cyclotron may be pulsed to generate a series of separated short trains of beam pulses. The oscilloscope we are now using is a Hewlett-Packard Model 185A/187B, which has a maximum sampling rate of 100 000 cps. A maximum of 1000 samples make one trace. If the probe moves approximately 3 in./sec and one trace is made for each 3 in., a duty factor of 0.01 is sufficient to get a complete phase-vs-radius function in about 15 sec. Higher sampling rates⁷)

are possible and will permit much lower average beam power. A plan for interrupting the beam follows.

Generation of short trains of beam pulses. We have observed that the cyclotron takes a second or two to "settle down" after the arc power supply is turned on. Because the dee rf circuit has a high Q , much higher than the steady-state power is required to modulate it at a high repetition rate. Here is a third method for modulating the beam: Two or three of us have independently suggested that we can destroy the beam near the center of the machine by pulsing a pair of small electrodes to deflect the beam vertically. It will be necessary to consider the effect of the electrodes on the focusing conditions at the center, but if it is successful this method will permit the cyclotron to be tuned at high peak beam currents while the average beam current is very low. And we will then have a C. W. cyclotron with a beam something like a synchrocyclotron.

Measurement of average beam current. If the resistor terminating the coaxial cable at the sampling oscilloscope is connected in series with a suitable capacitor, then an averaging D. C. microammeter connected across the capacitor will read the average beam current.

Vertical blowup. E. Kelly has suggested that the phase probe be equipped with targets that interrupt ions at the radius of the center target but above and below the center. The one probe could then supply phase and focusing information when the auxiliary electrodes are connected to D. C. microammeters to indicate vertical blowup of the beam. It would be difficult to shield the auxiliary electrodes from the rf but fortunately that is unnecessary.

Improved frequency response. Goodall and Dietrich⁷⁾ have described an "electrical stroboscope" with one order lesser rise time and two orders greater sampling rate than the sampling oscilloscope we are now using. The improved

resolution such an oscilloscope would permit may be of interest. Their instrument will not display pulses which are repetitive in shape but random in time. But, the ability (which our present instrument has) to display pulses random in time is not needed to display cyclotron beam pulses. In order to use the frequency response such an instrument would offer, the probe would have to be redesigned. The target should form the center conductor of a coaxial transmission line, with the rf shield forming the outer conductor. The characteristic impedance of that line should be nearly constant and should be equal to that of the flexible transmission line connected to the target. The transition between the target and the flexible transmission line must be carefully made. A large part of the line between the cyclotron and the control room should have air dielectric, in order to preserve the high-frequency information.

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