PHASE SHIFT OF BEAM BUNCHES AS A FUNCTION OF LINAC ACCELERATING GRADIENT*

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Introduction

In an earlier report[1], it was shown that an unexpectedly large phase shift occurs in beam bunches from the ANL 50 MeV, 200 MHz linac when the rf gradient is allowed to fall due to beam loading, and that this phase shift does not occur when the gradient is held constant. No corresponding shift of phase of the rf fields in the linac cavity were observed; and, since there was a reduction of beam current accompanying the phase shift and the gradient reduction, it was not made clear by deliberately reducing the current whether the current or the rf gradient is the independent variable since the two were interdependent. There was also some question regarding the possibility of phase shift of the rf field on axis relative to the field at the cavity wall. Further measurements have, therefore, been made in an attempt to resolve some of these questions.

Instrumentation

With minor modifications, the equipment used in these measurements is the same as formerly used. A block diagram of the system is shown in Fig. 1. Beam from the linac is collected inside the inner conductor of a modified, open-ended, 90° elbow mounted on a short section of 3-1/8" rigid coaxial line. The collecting target is 45" downstream from the linac end wall.

Voltage signals produced by the individual beam bunches are transmitted via a 7/8" Heliax cable, terminated into 50 ohms at the end which connects to the vertical plates of a Type 519 Tektronix CRO.

The CRO horizontal sweep circuit is set for continuous tracing at a 400 kHz rate; but the CRO beam is off except during a gated interval when an external unblanking gate is activated by the linac pre-trigger pulse, with an appropriate delay. From the delayed gate of the CRO, a sweep generator gate is turned on to start a sawtooth generator which feeds a voltage ramp to the vertical position control of the CRO, thus causing each successive sweep to appear at a different vertical position on the scope face during the gate interval. At the end of the ramp, a turn-off signal cuts off both the unblanking gate and the sweep generator gate until the next linac trigger pulse arrives.

Each horizontal sweep of the CRO is triggered by a 200 MHz signal from the same oscillator that drives the linac power amplifier chain. Thus, the timing of individual beam bunches on the target is referenced to the 200 MHz triggering of the CRO sweep. Any variation of bunch timing during a beam pulse, therefore, appears as a horizontal shift of the signal on the screen. Time and/or phase shifts during a beam pulse interval are measured in the horizontal direction in relation to the 5-nsec interval between two successive bunches. Longer time intervals are measured in the vertical direction in terms of the 2.5-sec interval between successive CRO traces, or in relation to the total length of the vertical sweep which can be varied from 25 μsec to 200 μsec.

Experimental

A. RF Phase Shift Measurements

A typical beam bunch pattern is shown in Fig. 2, for open-loop conditions in which the gradient is allowed to droop with beam loading. In this instance, a shift of about 82° was measured from the beginning of the pulse to the region where the gradient became stable. This is nearly three times the synchronous phase angle. In order to determine whether there is a shift of the rf phase on the beam axis, a special rf probe was inserted into the last accelerating gap in the linac. Typical rf patterns from this probe are shown in Fig. 3, in which the top pattern is with the gradient about 13% above normal, the middle pattern for normal gradient, and the bottom at about threshold accelerating gradient. In each case the gradient was held constant (nearly) by the closed loop control during the beam pulse. No measurable lateral shift is observed with change in gradient as seen by the fact that all three patterns are equidistant from a fiducial line faintly visible in the photograph. In the lower pattern a "phase rattle" is noticeable,

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due to the fact that there was significant oscillation in the gradient control circuit at this level. The same type of results were obtained from the rf probes inserted at various positions along the linac cavity, both under open-loop conditions and with the gradient varied over considerable range but automatically stabilized during the beam interval. Thus, there is no evidence that there is any significant phase shift in the rf fields under any conditions examined and in many positions in the cavity.

B. Programmed Gradient Change

By delaying the application of the gradient correction signal, and then applying a positive ramp to the correction, it is possible to allow the gradient to droop some sizeable amount from beam loading and then to restore it to its initial value during a beam pulse. In Fig. 4a, the shape of the gradient variation is shown in the lower trace, with the linac beam current shown in the upper trace, under these conditions. Fig. 4b are typical beam bunch patterns under such conditions. Here the upper pattern shows the beginning of the beam pulse at the bottom, whereas the bottom pattern has the beam pulse ending at the bottom. The maximum phase shift amounts to about 60° in these patterns, and it is evident that the phase returns nearly to the original value as the gradient is restored. The middle pattern is the 200 MHz rf sync signal, and gives an indication of scope sync reliability under good conditions.

C. Phase Change with Controlled Gradient

The next step was to determine whether gradient change alone would produce a phase shift. To accomplish this, the accelerating threshold gradient was carefully determined, making use of the achromatic deflecting magnets to assure that we were observing full energy beam. Then, making use of the gradient stabilizing system to maintain constant gradient at any chosen level and holding the buncher voltage at its normal level, beam patterns were recorded for many gradient values; and the lateral positions of the patterns were determined relative to a fiducial line on the photographs.

With this procedure one must rely upon the stability of the CRO sync, which can be influenced by amplitude of the 200 MHz sync signal, by sync adjustments, etc. It is difficult to ascertain to what extent such factors may have affected the results. Most of the data presented, however, were taken under as nearly identical conditions as could be obtained, i.e. sync knobs in extreme positions, rf level not changed, etc., during the measuring period.

Typical beam patterns are shown in Fig. 5, where the upper, middle, and lower patterns are taken with successively decreasing gradient. It is clearly evident that large phase shifts are involved. However, there is also a change in the beam current, particularly as the gradient approaches accelerating threshold. Consequently we undertook to determine to what extent current magnitude affected the phase shift.

D. Phase Change with Reduced Current

In order to determine the effect of beam current upon the phase shift, a perforated metal absorber was inserted into the beam ahead of the linac so as to reduce the beam by about 50% without changing the beam emittance or other properties significantly. Unfortunately only one useful photograph was obtained under these conditions before other difficulties arose which prevented further measurements; hence, the statistics are not good for this case. Nevertheless, our opinion, based on this result, is that beam amplitude, per se, does not enter into the matter of phase shift.

Discussion

The results of the measurements compiled for both gradient and current changes are shown in Fig. 6a where each of the three values of phase on a given photo are designated by a particular symbol, the three for reduced current being identified by a large asterisk (*). The solid line is the locus of the synchronous phase as a function of rf gradient, where

$$\cos \psi_s = \frac{\text{Threshold Gradient}}{\text{Operating Gradient}} .$$

By coincidence, threshold gradient was exactly 1.00 on the particular readout used. All phase values were normalized to that of the highest gradient; and since this corresponds to $\psi_s \doteq -40^\circ$, the zero was arbitrarily set 40° to the left of the intercept of the ψ_s locus with the threshold line. The data is presented in this way in order to compare with the sine curves in Fig. 6b, where, on a smaller gradient scale, the extremes of voltage shown in Fig, 6a are shown.

From this comparison, it is clear that very great phase shifts occur as the gradient is reduced to near threshold--as much as three times the expected value of the synchronous phase angle. Since the deviation of the measured phase shifts from the locus of the synchronous phase begins at the highest gradient, one can hardly attribute the effect to reduced energy of the beam, even though the effect becomes progressively worse with decrease in gradient. Nor can it be attributed to beam excitation of other modes in the cavity because the modes should not be excited differently at one gradient than at another under stabilized gradient conditions. Indeed shifts of nearly the same magnitude are observed with controlled and uncontrolled gradient. Moreover, since the effect is not beam amplitude sensitive, the anomolous phase shift appears to be only a function of rf accelerating gradient.

It is conceivable that the effect may be due to some peculiar tune condition of the ANL linac; but no clue has yet been found which would suggest such a condition. Plans are being made to install additional tuners in the linac cavity so as to achieve a better gradient distribution. Facilities are now available for examining the field distribution pattern many times during a beam pulse.[2] Hence, with the additional tuners and the fast readout of the field distribution it should become possible to determine whether internal peculiarities have any bearing on the anomolous phase shift.

References

1. R. Perry and J. Abraham, Sixth International Conference on High Energy Accelerators, Cambridge, Massachusetts, September 1967, ANL Internal Report RP/JA-1, November 1967.

2. L. G. Lewis, M. J. Knott and R. Perry, Sixth International Conference on High Energy Accelerators, Cambridge, Massachusetts, September 1967.

DISCUSSION

(J. Abraham & R. Perry)

DICKSON, RHEL: Have these phase shifts, discussed at the end of your talk, been correlated with energy changes?

PERRY, ANL: We have so far only determined that we have a full energy beam, at threshold rf gradient by passing the beam through our achromatic bending system.

LEE, BNL: Concerning the last slide, what did you use as phase reference?

PERRY, ANL: The scope is triggered by a 200 Mc sine wave and each trace presumably begins at the same point on the sine wave. One can check this by seeing whether successive sine waves on the scope line up with each other. This is a measure of the jitter of the scope trigger. This is a difficult thing to set up, but the triggering is fairly reliable once it is established. The speed of the trace makes it necessary to use photographs to detect synchronism jitter.

LEE, BNL: In regard to my previous question, when you use an external trigger to trigger the scope, is this signal obtained from the cavity or a reference line?

PERRY, ANL: This trigger signal is taken from the same oscillator that drives the linac.

LEE, BNL: It might be better to define your phase as that between beam and the cavity field.

NISHIKAWA, U. of TOKYO: Could I make sure whether your phase measurement refers to the amplifier or to the driving point of the cavity?

PERRY, ANL: Referring to Fig. 1, the 200 MHz oscillator which drives the linac amplifier chain and thus feeds the cavity also supplies a signal to the synchroscope which triggers the scope sweep. The two remain locked together in this respect. I am not saying there is no phase shift between the oscillator and the linac cavity. There may be phase shift in the rf amplifier chain but changes in such phase shift are not observed during a beam pulse, i.e., during a change of rf gradient.

NISHIKAWA, U. of TOKYO: I am just afraid that the beam causes reactive loading and not pure resistive loading. Thus the phase of the cavity field may shift from the generator driving field due to the reactive loading.

PERRY, ANL: Would you expect a shift as large as 100 degrees or more?

NISHIKAWA, U. of TOKYO: No, probably order of 10 degrees. However, if you use a buncher, the reactive loading effect in the buncher may be stronger.

VOICE: I don't know whether it will clarify the situation or make it worse, but the greatest scatter of results was with the beam just over the threshold and hence a low current beam. One would suppose that for a low current beam the beam excitation effects are very small.

MARTIN, ANL: Let me try to clarify this problem. The trigger to the scope was always from the oscillator. There exists in the linac tank 55 probes on which one can pick up the 200 Mc signal. One is in the end gap and one can look at the phase shift of that with respect to the oscillator and know that there is no phase shift under these conditions, so when you see relative phase shift of the beam bunches this means a phase shift with respect to the rf signal.

LAPOSTOLLE, CERN: I think this is normal, especially near threshold. Particles tend to slip over the rf field and lose phase. At low level there is a phase shift that can be rather large. They are no longer stable but they still gain energy over the rest of the tank. In this case, however, the energy spread goes up.

PERRY, ANL: I am sure individual particles can shift and in this case the distribution of the beam bunch has a much broader peak, near rf threshold and the shape is roughly symmetrical for a given bunch, but still particle bunches are observed from which large phase shift measurements can be made.

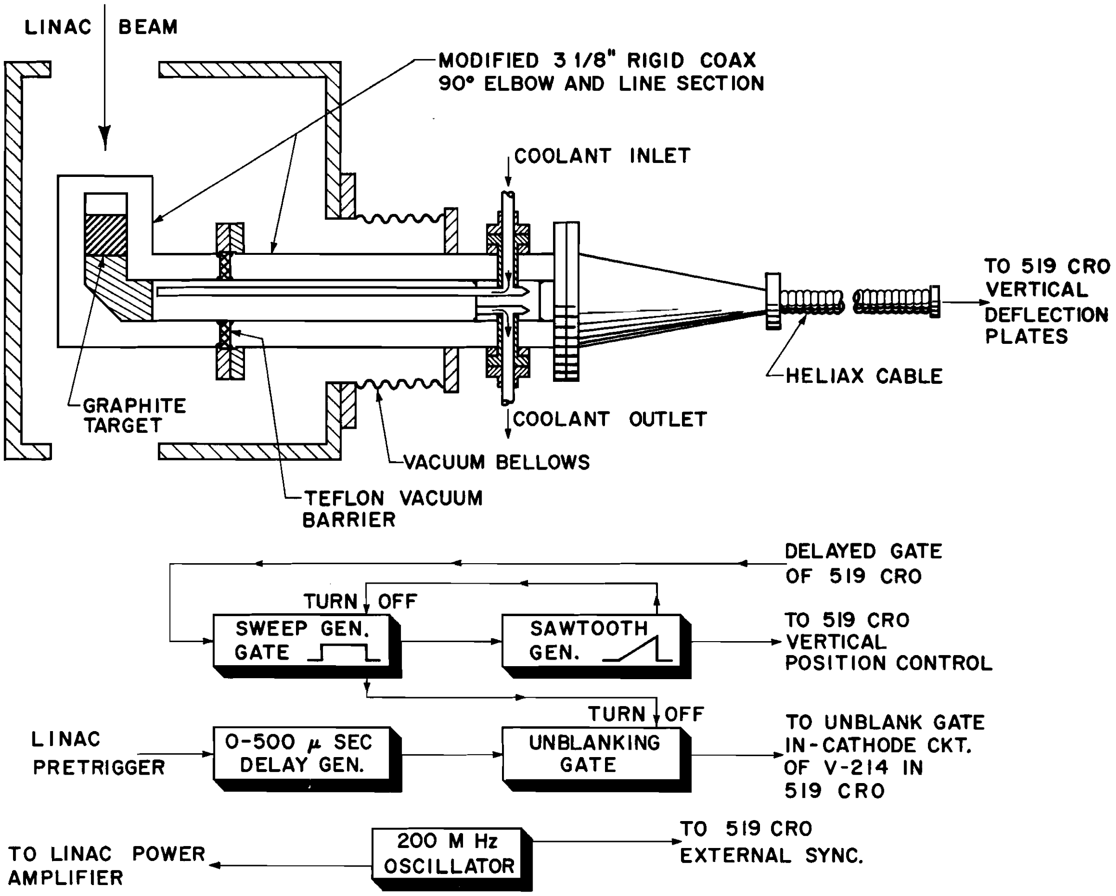

Fig. 1 Schematic of System for Linac Beam Bunch Phase Shift Measurements

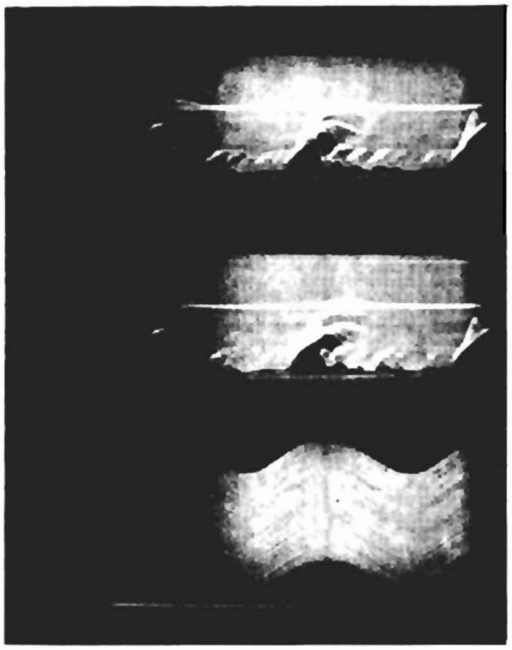

Fig. 2
Typical Beam Bunch Pattern
with rf Gradient Stabilizer off.
Gradient Droop = 7%
Pulse length 110 μsec.
Vertical Sweep 200 μsec.

Fig. 3
rf Signal from probe in
last linac accelerating gap.
Top: Gradient 13% above normal
Mid: Normal Gradient
Bot: Threshold Gradient

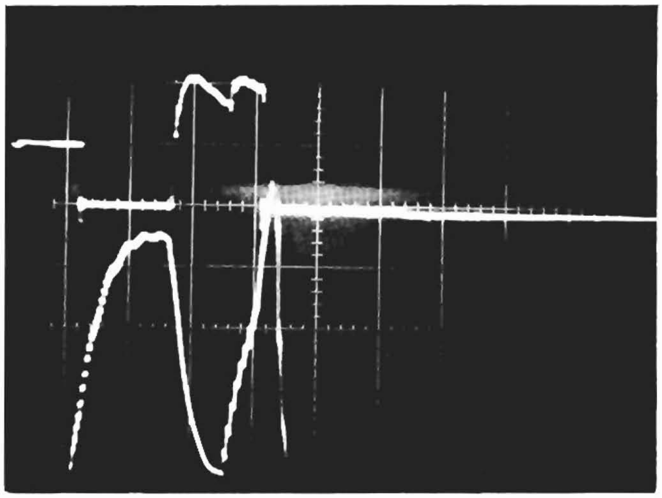

Fig. 4a
Top: Linac Beam Current 10 mA/cm.
Bot: RF Gradient droop (18%) followed
by corrective ramp.

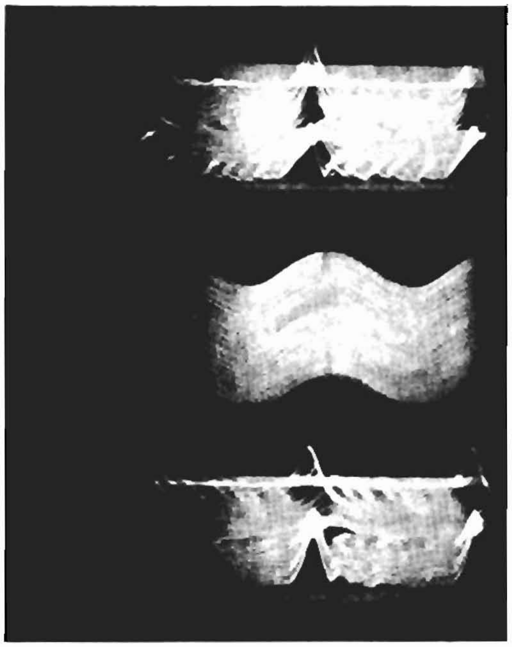

Fig. 4b
Patterns for Gradient Changing as in Fig. 4a
Top: Beam Beginning at Bottom
150 μ sec Pulse, 200 μ sec Sweeptime
Mid: 200 MHz rf Sync Signal
Bot: Same as top with
Beam ending at bottom.

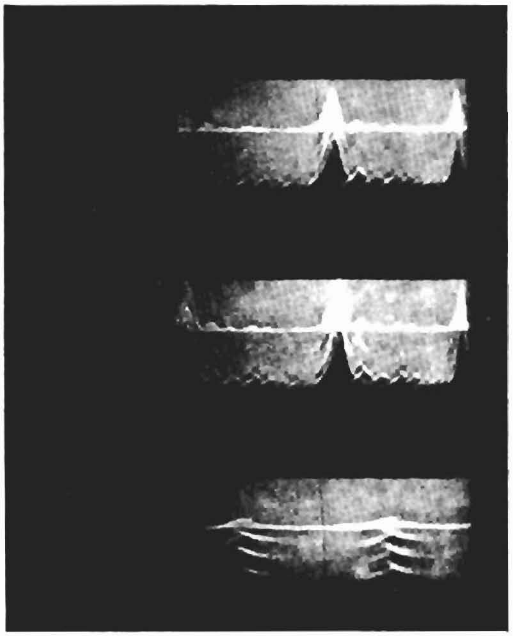

Fig. 5
Beam Patterns at Successively
lower (constant) gradients
Top: Gradient = 1.29
Mid: Gradient = 1.17
Bot: Gradient = 1.03

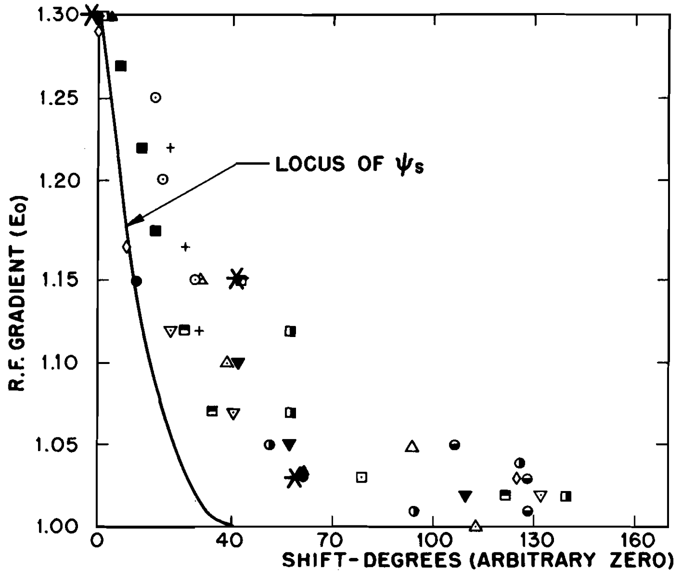

Fig. 6a Linac Beam Bunch Phase Shift vs Linac R. F. Gradient

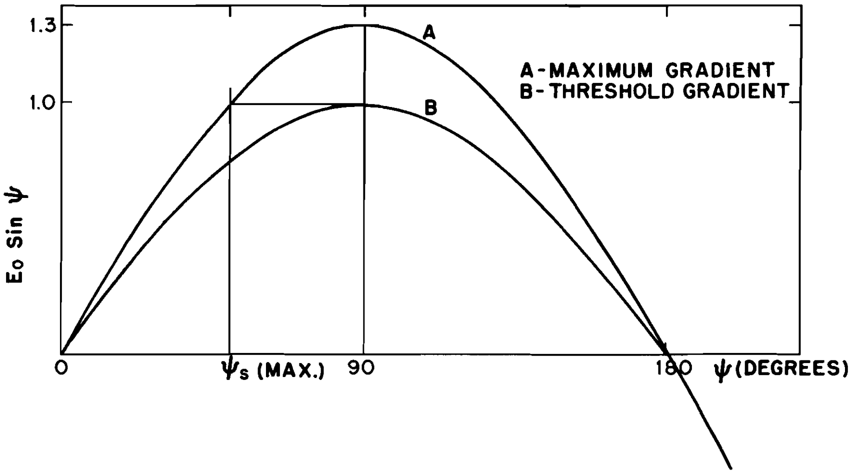

Fig. 6b R. F. Sine Waves