ZGS INJECTOR OBSERVATIONS

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In considering the design of multicavity, high current linacs, the effects of beam loading on the cavity gradient are matters of greater concern as the beam currents become increasingly large. Presented in this discussion will be observations of these effects made on the ZGS, 50 MeV injector. Also some comments will be made on observations of group velocity and cavity phase acceptance.

Beam Loading

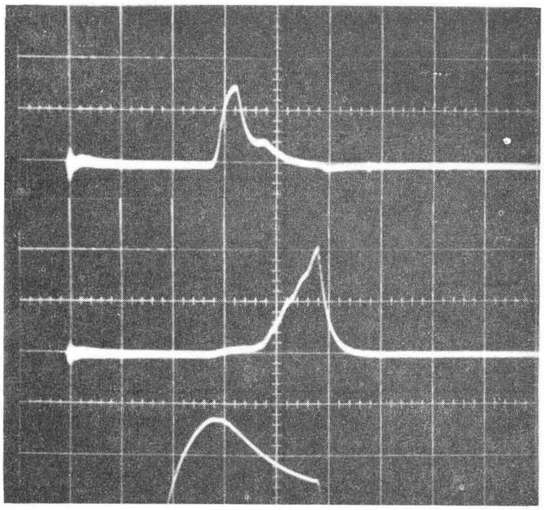
The 50 MeV beam from the ZGS injector is bent into the synchrotron through a 107° achromatic magnet system. At the center of the second bending magnet of the system there is a focus at the same point where the energy dispersion is greatest.[1] Therefore, by arranging to have a narrow (0.010") vertical slit (i.e., a slit which confines the beam to a vertical line) which can be positioned at any point in the transverse plane across the center of this magnet, it is possible to make analysis of the distribution of energies in the beam. The dispersion at this position is $\frac{\Delta E}{E} = 4.6\%$ per inch. Since the absolute value of the fields in the magnets have not been precisely determined, only relative observations can be made.

In using this slit for orbit measurements in the synchrotron under conditions of limited energy spread in the injected beam, it had been noted that there was a distinct variation of energy with time during the pulse under conditions of large beam loading as shown in Fig. 1.

This observation led to investigation of the variation of the mean energy and energy spread with rf gradient in the cavity. Figure 2 is a typical energy distribution as determined by sweeping the slit under a given set of conditions. The results of these measurements of the energy distributions at various rf levels are shown in Fig. 3.

By observation of the high energy and low energy extremes of the distriubtions (see Fig. 1) measured at each rf level, one can observe the variation of total energy spread with cavity gradient. This variation is shown in Fig. 4.

The operating conditions of the entire linac system were maintained constant while taking the data represented in Figs. 3 and 4; that is, there were no changes of preaccelerator conditions or focusing magnets made to



Beam pulse through slit on High Energy side of energy distribution.

Beam pulse through slit on Low Energy side of energy distribution.

Expanded rf pulse under heavy beam loading condition.
2% of rf gradient/cm,
100 μ sec/cm.

Fig. 1 Time Variation of Beam Energy Under Condition of Large Beam Loading

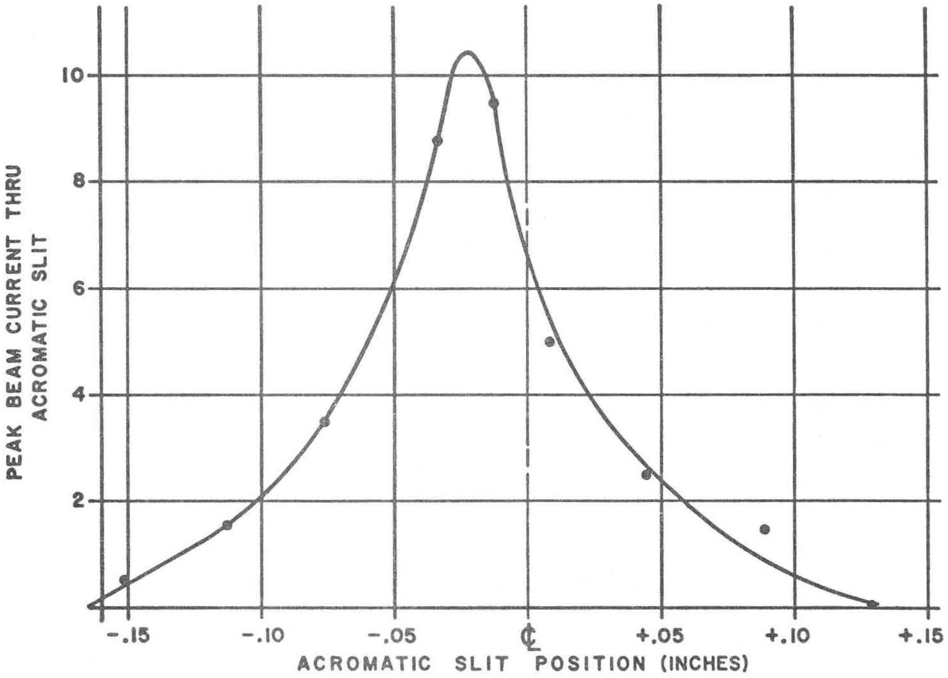


FIGURE 2 – ENERGY DISTRIBUTION AS OBSERVED BY SWEEPING ACROMATIC SLIT

adjust the injection matching conditions at the various rf levels. However, the cavity rf level was adjusted for each measurement so that there was no beam loading present.

We do not as yet understand the reasons that the mean energy and energy spread vary as observed, but will continue experiments to determine the reasons for this behavior.

Beam Loading Compensation

The ZGS injector rf system[2, 3] was designed with a series, hard tube modulator for regulation of the plate voltage to the output stage of the driven amplifier. This provides a means for delivering a variable amount of power to the linac cavity during the rf pulse for cavity voltage stabilization and beam loading compensation.

Ideally, the compensation is provided by a feedback system which regulates the power amplifier output for a constant rf cavity voltage through a closed loop servo system. Unfortunately, the servo loop of this system must include the final amplifier stage of the rf system and the characteristics of this stage are variable depending on tuning of the rf circuits. For this reason, the servo loop on the ZGS injector, as of this time, has been closed only under test conditions and not under operating conditions where its effects could be evaluated. This is not to imply that there is anything impossible about the task of establishing closed loop operation but rather that the tuning conditions of the power amplifier and the matching power amplifier to the cavity must be established as fixed conditions for the closed loop system to be satisfactory. This condition is being approached but has not yet been reached on the ZGS injector.

Beam loading is now compensated by an open loop system shown in the block diagram of Fig. 5. The operation of this open loop system is shown in the scope pictures of Figs. 6.1 through 6.8.

Measurements of pulse compensation voltages required for a cavity envelope which is flat during the time of the beam pulse with 50 mA of 50 MeV beam indicate that this should be within the capability of the system when such beam currents become available from the ZGS preinjector.

Questions had been raised from time to time of the ability of the beam loading compensation system to correct all parts of the cavity properly for beam loading. Figure 7.1 shows the cavity envelope near the low energy end, center and high energy end of the cavity under condition of heavy beam loading and Fig. 7.2 shows the same output loops under operation with the open loop correction of Fig. 5. These scope pictures

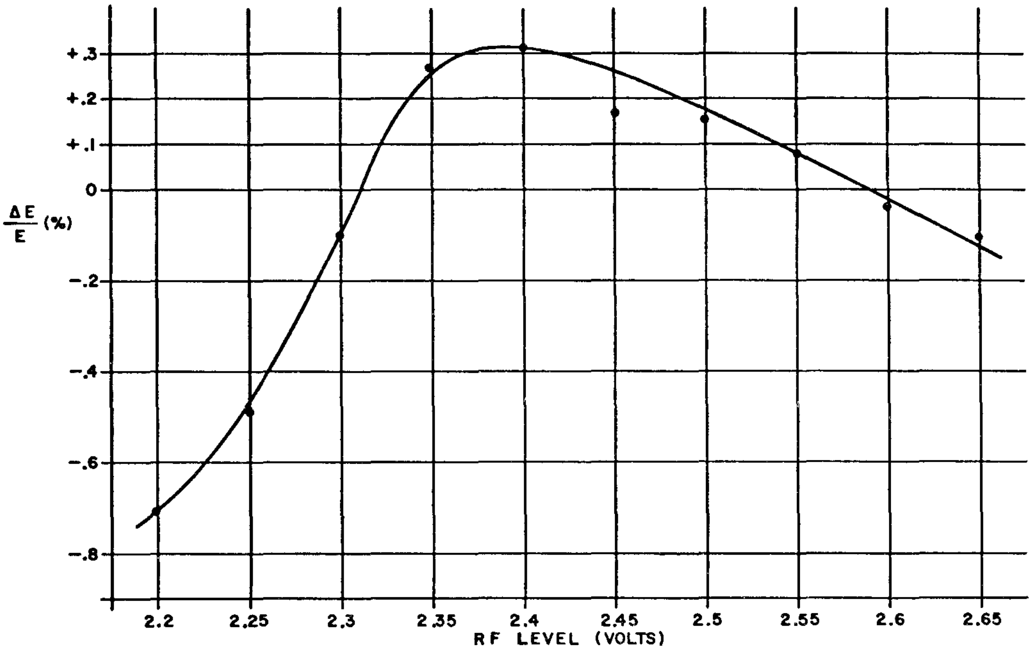


FIGURE 3 – VARIATION OF MEAN ENERGY WITH RF GRADIENT

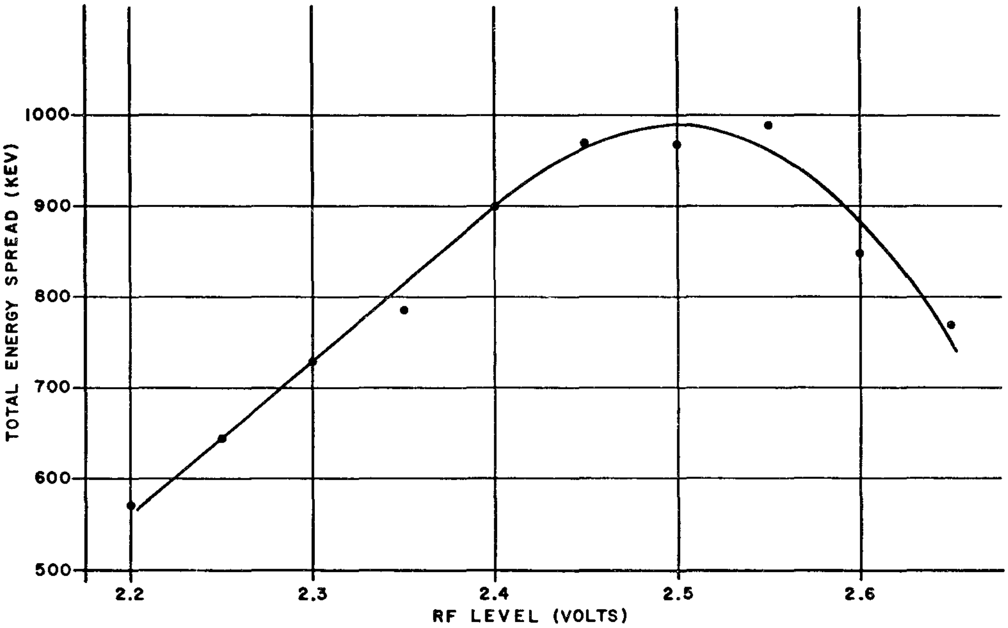


FIGURE 4 – VARIATION OF TOTAL ENERGY SPREAD WITH RF LEVEL

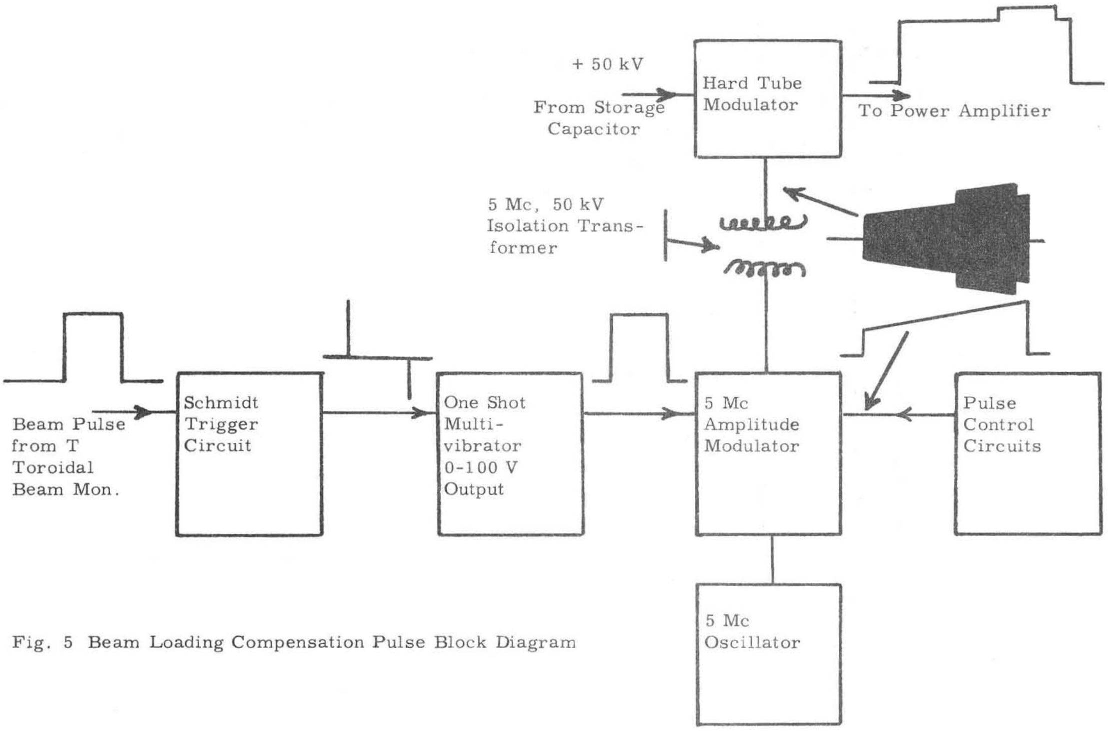
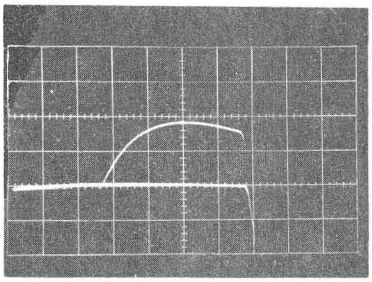


Fig. 5 Beam Loading Compensation Pulse Block Diagram

Fig. 6.1 No Beam through Cavity
No Compensation Pulse



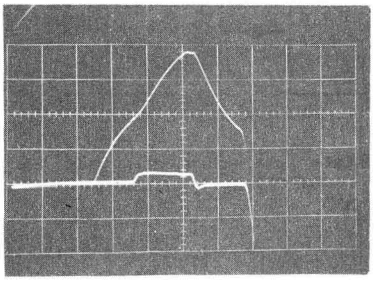
Top Trace

Rectified cavity rf voltage.
.05 v/cm - zero suppressed.
(2.4 v is accel. gradient.)

Bottom Trace

Power amp. plate voltage.
10 kv/cm.
Sweep - 50 μ sec/cm.

Fig. 6.2 No Beam through Cavity with
Compensation Pulse 3 kv

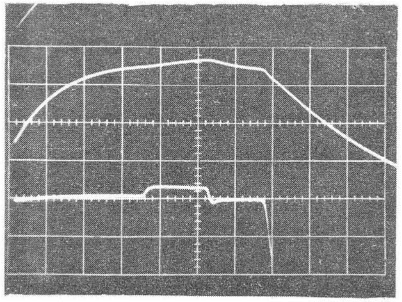


Top Trace

Rectified cavity rf voltage.
.05 v/cm - zero suppressed.
(2.4 v is accel. gradient.)

Bottom Trace

Power amp. plate voltage.
10 kv/cm.
Sweep - 50 μ sec/cm.



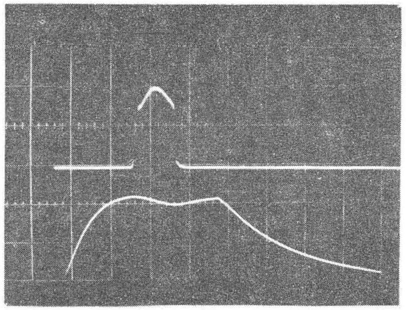
Top Trace

Rectified cavity rf without
zero suppression.
1 v/cm.

Bottom Trace

Power amplifier plate voltage
with 3 kv compensation.
10 kv/cm.
Sweep - 50 μ sec/cm.

Fig. 6.3 Same as 6.2, but without Expanded RF Scale



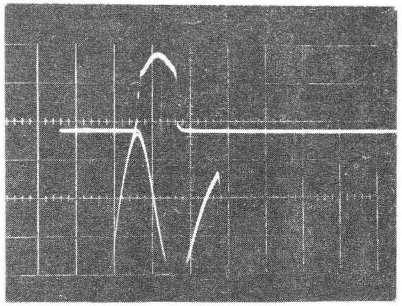
Top Trace

Beam pulse - 10 mA/cm.

Bottom Trace

Rectified cavity rf voltage.
1 v/cm.
Sweep - 100 μ sec/cm.

Fig. 6.4 20 mA Peak Beam Pulse RF Loading without Compensation



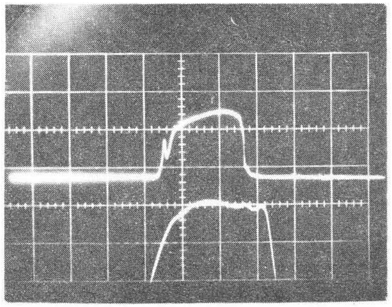
Top Trace

Beam pulse - 10 mA/cm.

Bottom Trace

Expanded rf voltage.
.05 v/cm.
Sweep - 100 μ sec/cm.

Fig. 6.5 Same as 6.4 with Expanded RF Voltage



Top Trace

Beam pulse - 10 mA/cm.

Bottom Trace

Expanded rf voltage.
.05 v/cm.
Sweep - 50 μ sec/cm.

Fig. 6.6 Beam Pulse and Expanded RF Voltage with Compensation

(NOTE: Beam pulse shape changes from pictures 6.1 through 6.5, is not due to rf compensation but rather different injection conditions. 6.6 and subsequent pictures were taken on a different day.)

indicate that the cavity envelope is compensated everywhere, minor differences in the corrected waveform are due to the fact that they are not taken on the same pulse and there is some pulse-to-pulse variation when operating with the open loop system.

Group Velocity in the Linac Cavity

The group velocity, or rate of transfer of rf energy from the coupling loop to the extreme ends of the cavity, was observed in the following way. Using a dual beam scope, the output of the monitoring loops at the high and low energy ends of the cavity were compared at the time of initial cavity build-up with the rectified rf signal from an identical loop at the center of the cavity. (In this linac the rf feed loop is located at the center of the cavity.)

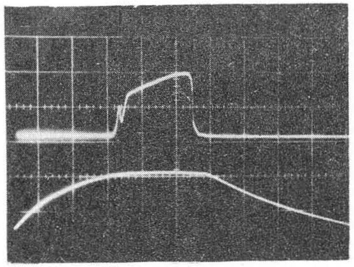
Figures 8.1 and 8.2 show the build-up of rf at the initial rise of the pulse. Figure 8.1 compares the center of the cavity (upper trace) with the low energy end. It is noted that the build-up of the field in the center of the cavity is very small until the rf energy has been propagated to the ends of the cavity where the initial build-up is much more rapid. The length of cavity between the two loops is 17.3 meters and the delay to start of build-up at the low energy loop is 9 μ seconds, giving a group velocity of 1.9 meters/ μ second.

No explanation for the apparent initial negative slope of the center loop has been found; changing detectors, cables, etc., has not shown the reason to lie in the detection equipment.

Figure 8.2 compares similar waveforms at the high energy end. The length of cavity between loops is 15.7 meters and the delay of build-up to the high energy loop is 3 μ seconds. This results in a group velocity in this end of the cavity of 5.2 meters/ μ second.

These observations raise the question of whether or not these numbers are characteristic of an unfilled cavity or if they do indeed remain the same in a cavity which is already excited. To observe this, the compensating pulse was applied to the power amplifier plate voltage after accelerating gradient in the cavity has been achieved and similar observations are then made of the changing rf level in the cavity due to the increased drive power. Figures 9.1 and 9.2 show the same loops as in Figs. 8.1 and 8.2 under excited cavity conditions using high gain, zero suppression plug-in units with delayed sweep.

These pictures indicate a delay of at most 2 μ seconds at the low energy end and about 1 μ second at the high energy end which would



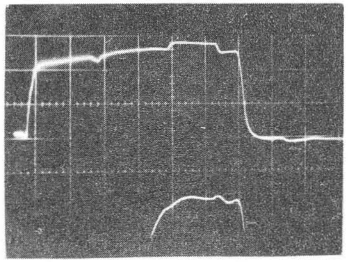
Top Trace

Beam pulse - 10 mA/cm.

Bottom Trace

Sweep - 50 μ sec/cm

Fig. 6.7. Same as 6.6, but without Expanded RF Waveform



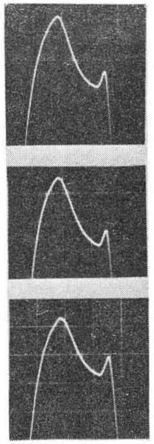
Top Trace

Power amplifier plate voltage
with compensation pulse.
10 kv/cm.
Sweep - 50 μ sec/cm.

Bottom Trace

Rectified cavity rf voltage
.05 v/cm.

Fig. 6.8. RF Voltage Pulse and Plate Voltage Waveform with Compensation for Beam Loading

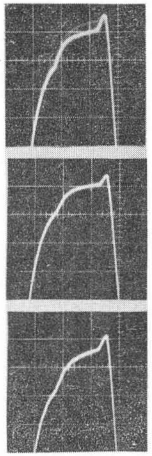


Low Energy End of
cavity. Loop 9.2%/cm,
50 μ sec/cm.

Center of cavity.
Loop 42, 2%/cm.
50 μ sec/cm.

High Energy End of
cavity. Loop 58, 2%/cm,
50 μ sec/cm.

Fig. 7.1. RF Envelope at 3 Cavity Positions Under Heavy Beam Loading Conditions



Low Energy End of
cavity. Loop 9, 2%/cm,
50 μ sec/cm.

Center of cavity.
Loop 42, 2%/cm,
50 μ sec/cm.

High Energy End of
cavity. Loop 58, 2%/cm,
50 μ sec/cm.

Fig. 7.2. RF Envelope at 3 Cavity Positions With Open Loop Beam Loading Compensation

indicate group velocities which are greater by about a factor of 5 (8.6 meters/ μsecond) at the low energy end and 3 (15.7 meters/μ second) at the high energy end under the condition where the cavity is excited.

Linac Phase Acceptance

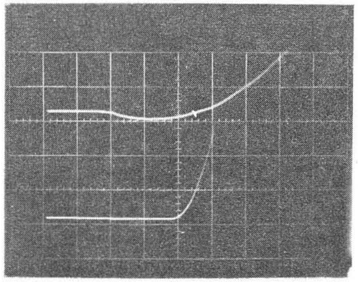
Phase acceptance measurements are made as the ratio of the peak beam current entering the bore of the first drift tube, as measured by a shielded toroid which measures only those particles which enter the bore of the first drift tube, to the peak beam current accelerated through the linac (as measured by either stopping the beam or by a toroid). The expected phased acceptance without buncher at the design synchronous phase angle and accelerating gradient is $\frac{3 \times 26^\circ}{360^\circ}$ or 22.6%. This phase acceptance, or transmission efficiency, is observed at an rf level of 2.35 volts (see Fig. 1) and the threshold for acceleration is 2.15 volts. Raising the rf level beyond 2.45 volts has not ever been observed to raise the transmission efficiency without buncher beyond 25%. One would expect it to continue to rise as the gradient is increased, provided appropriate compensation of quadrupole focusing fields were made. Efforts to achieve this have not been successful.

Measurements of phase acceptance as a function of preaccelerator injection energy have confirmed those measurements made at BNL.[4] Use of the first harmonic buncher has yielded transmission efficiencies as high at 65% (68% is the design expectation) but 55% to 60% is the usual day-to-day operating condition.

These phase acceptance measurements make no correction for proton percentage. In the ZGS system the two sets of triplet quadrupole matching lenses serve to separate such a large percentage of the molecular hydrogen and other heavy ions which are produced in the ion source that only a negligible amount of these ions are injected into the linac.

Conclusions

These observations show that very precise rf level control is necessary to meet the design requirements of a multicavity system to maintain the required injection energy as the beam progresses from section to section. In connection with the use of this particular linac as the injector for the ZGS, the data shows that by an appropriate programming of the rf level, it may be possible to use the changing energy characteristic to an advantage by providing an increasing injection energy with pulse length.



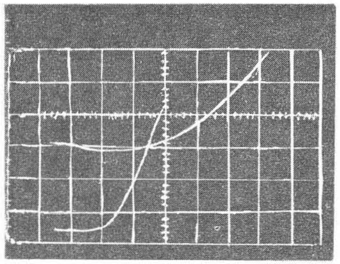
Top Trace

Loop 34 (center of cavity) time base 5 μ sec/cm.

Bottom Trace

Loop 1 (low energy end of cavity) time base 5 μ sec/cm.

Fig. 8.1 Initial Cavity Build Up at Center and Low Energy End of Cavity



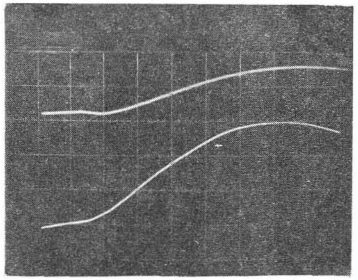
Top Trace

Loop 34 (center of cavity) time base 5 μ sec/cm.

Bottom Trace

Loop 64 (high energy end of cavity) time base 5 μ sec/cm.

Fig. 8.2 Initial Cavity Build Up at Center and High Energy End of Cavity



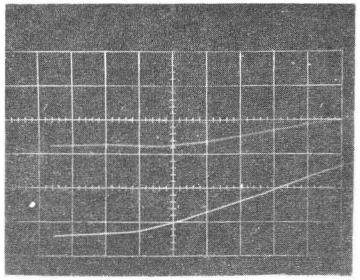
Top Trace

Loop 34 (center of cavity), 10 μ sec/cm.

Bottom Trace

Loop 1 (low energy end), 10 μ sec/cm.

Fig. 9.1 Change of Cavity RF Envelope Due to Spike on Power Amplifier Plate Voltage at Center and Low Energy End of Cavity



Top Trace

Loop 34 (center of cavity), 5 μ sec/cm.

Bottom Trace

Loop 64 (high energy), 5 μ sec/cm.

Fig. 9.2 As in Fig. 9.1 except comparing center and high energy end of the cavity.

Beam loading control with long pulse length at high beam current is certainly feasible but all of the engineering problems on our particular machine are not as yet solved.

SHAYLOR: I presume you are using a Tektronics 555 Scope for the double display work.

LIVDAHL: That is correct.

SHAYLOR: Until recently I was at Birmingham (England) and there we have very great difficulties with earth loops, due to certain peculiarities of our synchrotron. The 555 is particularly difficult to use in this respect since you can't selectively earth both signal inputs simultaneously unless you are using differential input amplifiers. So now one question is: Are you using differential input plug-ins? If not, what is the voltage you have at your probes so as to give us a feel for your pickup problems. Another question is, have you tried testing with the offending loop that goes negative short circuited, but still earthed in the normal way? I am looking for cross talk or trouble between the amplifiers. I am deeply suspicious of the negative-going curve, and if in fact the kick-off point is not where it starts to go negative but where it starts to go positive, then the time schedules of all these things are going to be significantly different.

LIVDAHL: In answer to your first question, differential plug-in units were not used. As a matter of fact, type Z, zero suppression plug-in units were used. I am not sure what type of units were used for the initial build-up.

CASTOR: They were the type Z used without the slide back.

LIVDAHL: In connection with the cabling to the loops, neither loop is grounded anywhere in the system. There is a teflon shield around the loop where it penetrates into the cavity so that there are no ac or grounding problems. It is a floating system all the way to the scope.

SHAYLOR: The type Z unit, the slide-back unit, has in fact a lot of hook diodes on its input, and I think that feeding a bit of the 200 Mc rf into it may produce some interesting effects.

ROWE: I would like to make a couple of remarks on this--an old user of Tektronics Scopes--I never noticed this particular difficulty with the type Z plug-in, but the CA plug-in has an obnoxious habit of ringing at very high frequency, far beyond the response of the scope proper. This seems to be associated with the input attenuator and the first stage of the amplifier. And you can get some truly magnificent results under some condition; I was thinking along the same lines this gentleman was and I was wondering if maybe that might be the trouble. We got around some of these problems once by buying intentionally a poor scope.

LIVDAHL: Nevertheless, I believe that where you saw this negative-going trace was the point at which the pedestal was placed on the plate voltage waveform. For this reason I didn't worry about this because that was not what I was attempting to look at. The fact that the top trace came up at a delayed time relative to the lower trace and that we knew that this was synchronized within less than a microsecond with the pedestal on the waveform just did not seem like there was any reason to worry too much about the negative undershoot.

SHAYLOR: You were not trying to interpret anything from the point where the top trace rose above the base line?

LIVDAHL: That is correct. All of the numbers that I gave you were from this point to this point.

KEANE: I might have a different explanation on this same topic. I think I have seen the same thing and I think it is moding. We have scalloping on our waveform. I am going to talk about this next, but essentially because you have a variance from probe to probe, I feel it is not the scope itself but rather the existing modes in the tank.

PRIEST: If that is the case, what Shaylor suggested would prove it, would it not; if you short circuit the loop or rotate it so that it doesn't couple, this negative thing will disappear whether it is a mode or not, if it is an rf effect, it will disappear, but if it is some kind of an extraneous spurious effect, it won't disappear. At least it would be a check.

LEISS: We are probably pushing this a little bit too much. However, it is quite possible that it actually represents one of the things which we have calculated in the extreme transit behavior of the machine. This is the following. You probably have before your main pulse, for example through the grid drive, a small amount of rf in the cavity. Now when you turn the pulse on, you get some very interesting transients and phase oscillations. What you detect in your diode is the total field vector, which can have oscillations on it and these oscillations have actually been observed. I would suspect that this is actually a real phenomena that one can predict in the extreme transient behavior on this machine as you start filling it.

LIVDAHL: I just cannot believe this, Jim, because this is nothing but the rectified output of an rf envelope and this says that this loop has got to be taking power out of the cavity.

LEISS: Well, the point is that if you have a small amount of rf in there, which I suspect you do, because your grid drive is probably on before the plate voltage, then you have an offset zero and it really has not gone negative; it has just gone down closer to true zero.

LIVDAHL: Yes, the drive does come on about 10 microseconds before the plate pulse and I do not know that we have looked for this.

LEISS: There is another interesting example you can predict and which has been observed on a lot of machines. When you turn the rf off, instead of the detected rf signal going down it initially has a rise. This is again precisely the same thing. This is the phase oscillation that is induced when you make a sudden change in the rf level of the cavity.

JAMESON: I might comment on this last statement. We did some measurements on a cell iris-loaded structure in which we put in a square wave input and looked at the build-up with a sampling scope. We took the pictures and measured the 63% rise time, and these indicated that the structure filled from the back end first. We also saw the transient that you spoke of at pulse turn-off. This effect was greater the further away you got from the drive. Now, these measurements that we did were done at signal generator power levels and I have some reservations about the techniques as far as quantitative results are concerned. One thing was that we were coupling out more than we should have been with the measurement loops. However, the observed results were qualitatively exactly as predicted by the equivalent circuit theorem.

VAN STEENBERGEN: May I make one comment on the closing of the loop? Mr. Otis, together with John Keane, has worked on the rf stabilization loop at Brookhaven. So far he has succeeded in closing the loop and keeping a stable system for the cut-off frequencies up to 20 kc and loop gains up to 5. When he exceeded these limits of cut-off frequency and loop gain, he saw strong excitation of extramoding of the tank. We just could not work with a loop stabilization system which had a wider frequency band which means that if there were to be any corrections, they had to be of a very slow variety in our particularly long tank.

FEATHERSTONE: I think everybody here who is interested in rf systems would like a status report on life and performance of 7835's.

LIVDAHL: I knew that question would be asked, so I looked at the clock last week. At the present time our mode of operation is to start up at midnight on Wednesday night and run through the following Friday morning, a period of 25 shifts, with operation on the succeeding days as we need for maintenance, observation, development, etc. At this rate we build up a maximum of 500 hours per month, so we really do not have an awful lot of data on it yet. However, last November 21, we put a 7835 in the power amplifier; it has been in there since. The power amplifier has not been apart in that time and we have operated for 4,400 hours in that time and the tube had a little over a 100 hours on it before that. The other two tubes that we own have 2,000 and 2,200 hours on them. There is no reason to believe that any of the three tubes have changed characteristics in that time.

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