PERFORMANCE CHARACTERISTICS OF THE ZERO GRADIENT SYNCHROTRON LINAC AUTOMATIC GRADIENT STABILIZER

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Shortly after the Zero Gradient Synchrotron became operational in late 1963, the need for a more stable LINAC beam became apparent; beam loading caused severe reductions in the gradient (Figure 1) resulting in excessive energy spreads at 50 MeV during injection into the synchrotron. In addition, pulse-to-pulse jitter, caused by inherent instabilities in the 200 megacycle radio frequency equipment, aggravated the situation.

The equipment configuration, shown in Figure 2 in its entirety, is characterized insofar as the discussions to follow by Unit 4, the RCA 7835 200 Mc 5 Megawatt Power Amplifier; Unit 5, the 10 megawatt Modular (a series-parallel combination of four ML 5682s driven by two ML6696s); Unit 6, the 5 Megacycle Pulse Driver, the function of which was to telemeter pulse commands to the Modulator; and Unit 7, the Pulse Generator and Synchronizer, which functioned as a low level command generator and system timer.

Programmed Beam Compensation

The obvious advantages of a hardtube modulator were utilized early in 1964 to program (increase) the plate voltage applied by the Modulator to the Power Amplifier during the beam period. The scheme was as shown in the simplified block diagram of Figure 3. Numerous timing and shaping arrangements were investigated, but at this point the system was essentially open-loop and the inherent instabilities caused by beam and radio frequency equipment fluxuations were still present and uncorrectable.

Nevertheless, system response to such programs proved of interest as is shown in Figures 4 and 5. One important factor which is not shown in the aforementioned figures is the system delay between the application of the compensation pulse and the tank response as viewed by the H-Field Pickup Loop. Much of this delay, which becomes extremely important when efforts are made to close a feedback loop upon the system, was built into the equipment in the form of stage biases, etc.

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In any event, the steep rise in TANK GRADIENT characteristic of a stepfunction on PA Ep was encouraging. The fact that the match between the Final Amplifier and the LINAC appeared less favorable during the beam pulse was also noted not without concern. With the CAVITY pre-excited to accelerating gradient, system bandwidths, particularily that of the CAVITY, apparently broadened by the loading effect of the Final Amplifier under power, seemed to promise some measure of success in closing a feedback loop upon the system.

The 5 Megacycle Automatic Gradient Stabilizer

The first, or 5 Megacycle Automatic Gradient Stabilizer, was installed in November of 1965. The system was as indicated in Figure 6. Note that this system consisted essentially of modifications within the limitations dictated by existing equipment, namely the 5 Megacycle Pulse Driver and the Two-Deck Modulator. Although every effort was made to broadband wherever possible, built-in bias delays and the 5 megacycle carrier ultimately determined the measure of success. System performance was as indicated in Figure 7 for a beam current of 20 milliamperes.

A 20 milliampere beam caused

1. A 1.4% drop in gradient.
2. A 0.52% gradient droop during the beam pulse.
3. Approximately a 6% change in Modulator loading (from 100 to 106 ohms).

The 1.4% drop in gradient coincident with a 1.0 megawatt beam demand required a 2.31 megawatt (33.5%) increase in PA Plate Input Power (from 6.9 mW to 9.2 mW).

1. The ratio $\frac{\text{PA Forward Power}}{\text{PA Reverse Power}}$

   decreased from 2.24 to 1.70 under the same conditions indicating a LESS Favorable mismatch during beam acceleration.

2. Pulse-to-pulse jitter in gradient was 0.344%

The frequency of the damped oscillations appearing during initial cavity excitation is approximately 32 kilocycles which, perhaps coincidentally, corresponds very closely to that predictable by the measured open-loop gain-phase relationships. The response of the 5 megacycle telemetry and pulse generating equipment into a matched resistive load exclusive of the 5 Mc isolation transformer and the Modulator was satisfactory to approximately 100 kilocycles. As installed and operating in conjunction with the ZGS, the open-loop system gain was 26 db. Closed-loop, this system reduced the energy spread at 50 MeV from 500 keV to 250 keV (on the basis of 50% total beam availability).

It is interesting to note that the "scalloping" frequency appearing during the excitation period, which may or may not be attributable to Cavity TM_{011} moding (there has been some evidence that several other distinct difference frequencies corresponding to the spacing of even higher order modes, TM_{012}, TE_{211}, TE_{212}, etc., may also be present), is present only during periods when the Final Amplifier is under power driving the Cavity. Furthermore, it is damped to the point of non-existence by beam loading and can be aggravated or reduced by appropriate adjustments to the radio frequency drive parameters, principally Final Amplifier Plate Tuning.

NOTE: In the ZGS Linac Cavity the TM_{011}, TM_{012}, TE_{211}, TE_{212}, etc. mode frequencies have been measured to be 26 Kc, 62 Kc, 130 Kc, 328 Kc, 512 Kc, etc. above the TM_{010} operating frequency.

"Scalloping" is present regardless of whether the system is operating open or closed loop so loop oscillation in itself cannot be the entire cause; it appears to be more closely associated with system matching and the degree of coupling between the Final Amplifier and the Cavity.

In the ZGS Linac, the cavity is driven at the center through a single port; the Automatic Gradient Stabilizer feedback of necessity is taken from an H-Field pick-up loop which, because of its location along the cavity, tends to be somewhat mode sensitive. The effect of loop position relative to Automatic Gradient Stabilizer operation is yet to be investigated.

The 26 Megacycle Automatic Gradient Stabilizer

At this point in time, the Single-Deck Modulator (a single Westinghouse 8461 driven by a ML6696) was under consideration as a replacement for the Two-Deck configuration. Rather than utilize the existing 5 megacycle telemetry and pulse equipment with its inherent restrictions, the telemetry equipment was redesigned at 26.125 Mc to operate Class AB_1. Its radio-frequency bandwidth was extended to approximately 6 megacycles. The pulse generating equipment, error amplifier, etc., were likewise modified to be as wideband as appeared consistent with the overall system requirements. This configuration, including the Single-Deck Modulator, was installed as indicated in Figure 8 in July of this year.

System open-loop gain is 37.7 db. Closed loop delay at operating Cavity gradient is 1.5 microseconds and is lumped in the Single-Deck Modulator; i.e., the time delay between the "Beam" disturbance on the 26 megacycle Carrier and the Modulator Output response thereto (delta PA Ep) is 1.5 μsecs. This delay is somewhat excessive and appears to be associated with the 26 megacycle isolating networks used to transfer the carrier from ground to the Modulator's high voltage platform.

Many of the performance characteristics of the 26 Megacycle Automatic Gradient Stabilizer are similar to those of the 5 megacycle system as a comparison of Figures 7 and 9 will show. It must be recognized that entirely new system gain-bandwidth-phase relationships now exist; many of the opportunities now present for additional improvement have yet to be explored consistent with ZGS operational schedules.

Acknowledgements

The contributions of N. Sesol, A. Tummillo, and D. Mendenhall towards the developments reported herein cannot be overlooked for it was they who built the necessary hardware.

DISCUSSION

R. W. CASTOR, ANL

VAN STEENBERGEN, BNL: At Brookhaven the problem of linac field stabilization has been attacked in the past by G. Keane, A. Otis, and myself to a lesser extent. It was found that because of the close proximity in frequency of the other field modes, the stabilization loop could not be closed in a practical fashion with the linac cavity included in the loop. Only with very small loop gain and low-frequency cut-off could this be done realistically. At present the approach is to operate a closed rf power loop excluding the linac cavity but to include an rf level program directly derived from the preinjector beam intensity.

CASTOR, ANL: I don't think our operators would be happy with such an arrangement. What they like to do is to look at the gradient and see that it's flat during the beam pulse, and they're not convinced unless they actually see this. They're not intrigued by programming of any sort.

ALLISON, LRL: We observed this moding. It's quite predominant on our tank. We do close the loop on our tank. The moding is eliminated in our system by means of a notch filter which is very critical to adjustment but at least it seems to work reasonably well.

CASTOR: We have tried filters of this nature, but generally when we put them in, this frequency just goes someplace else.

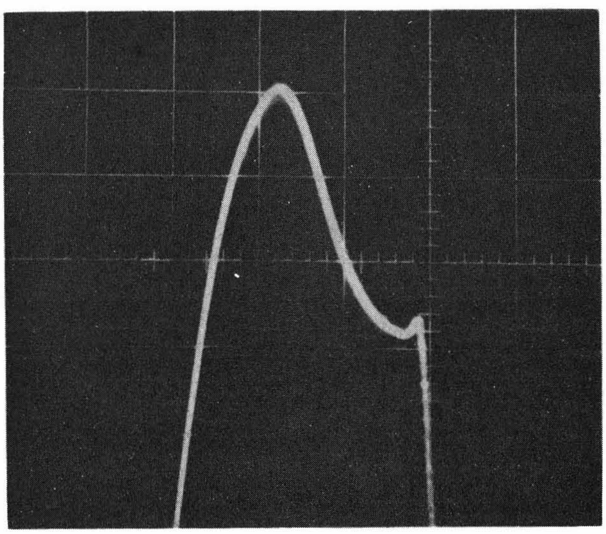


Fig. 1. Tank gradient, H-field loop No. 33: sensitivity, 50 mV/cm; time base, 100 μsec/cm; reference centerline, slideback 2.3 x 1, calibration 2.2%/cm.

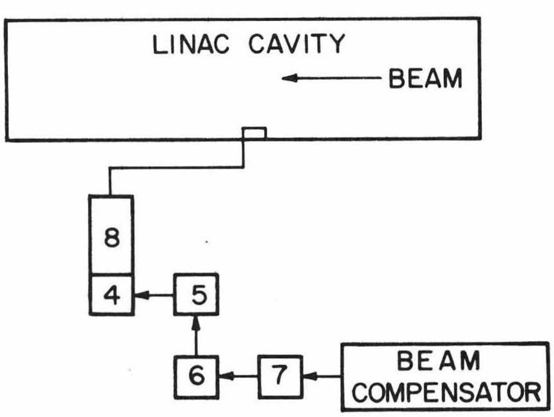
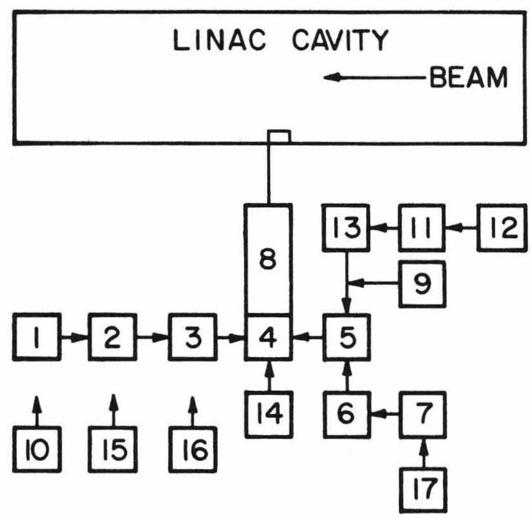


Fig. 3. Programmed beam compensation.



KEY:

1. 200 Mc EXCITER
2. IPA
3. DRIVER (4W20000)
4. PA (7835)
5. MODULATOR (4-5682s)
6. 5Mc PULSE DRIVER
7. PULSE GENERATOR & SYNCH.
8. PA-CAVITY TRANSMISSION LINE
9. FAULT DETECTOR & CROWBAR
10. CONTROL CONSOLE
11. 50 KV RECTIFIER
12. 50 KV TRANSFORMER
13. 32μf STORAGE CAPACITOR
14. 7000 A PA FIL. RECTIFIER
15. A C DISTRIBUTION
16. WATER DISTRIBUTION
17. PULSE EQUIP. POWER SUPPLY

Fig. 2. Initial equipment configuration.

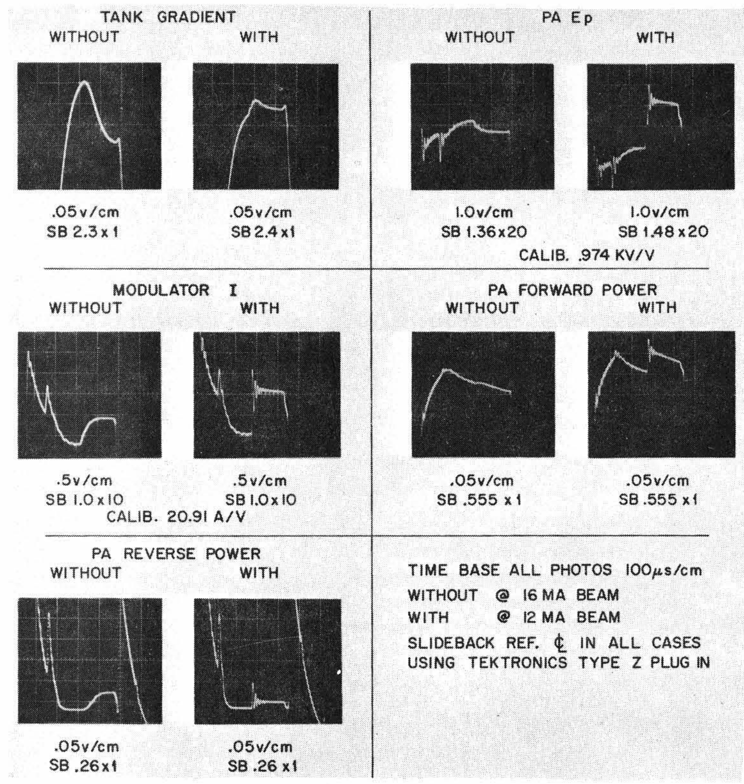


Fig. 4. System response without and with programmed beam compensation.

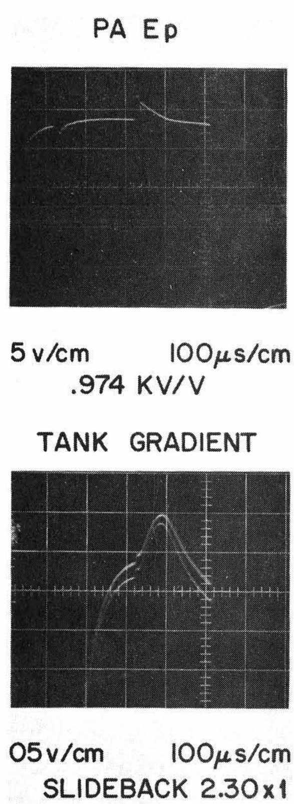


Fig. 5. System response to compensation w/o beam.

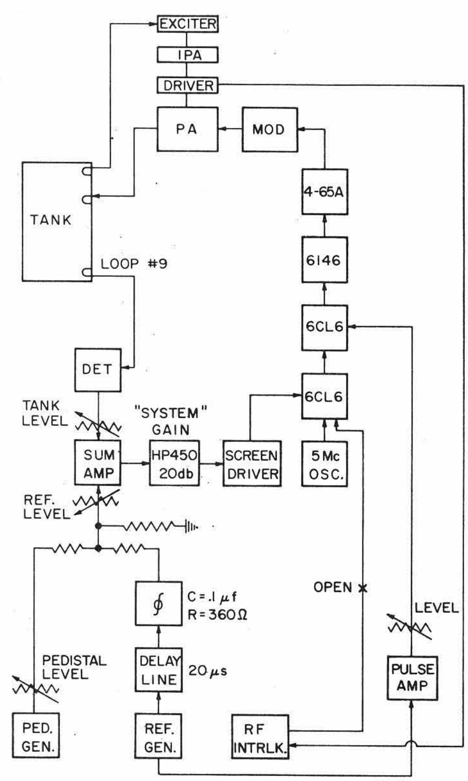


Fig. 6. Block diagram of system.

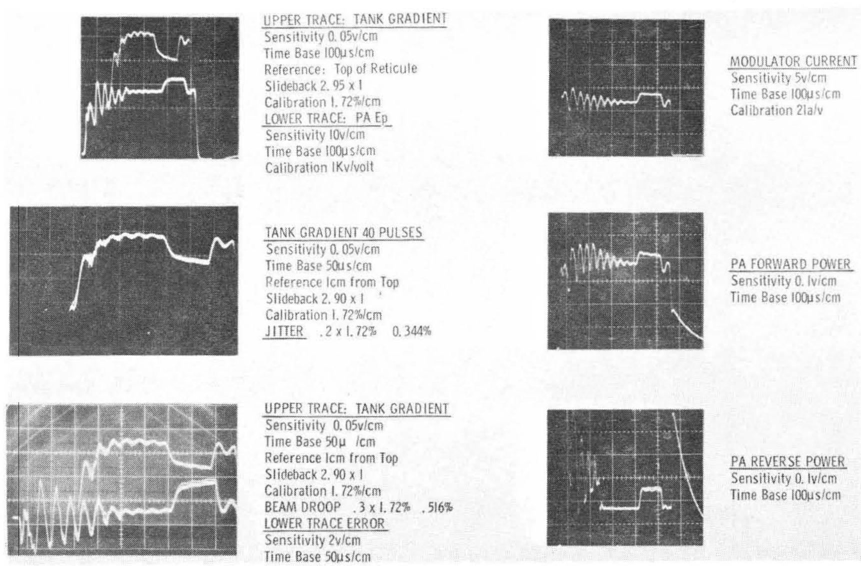


Fig. 7. Performance of 5-megacycle automatic gradient stabilizer for 20 MA beam.

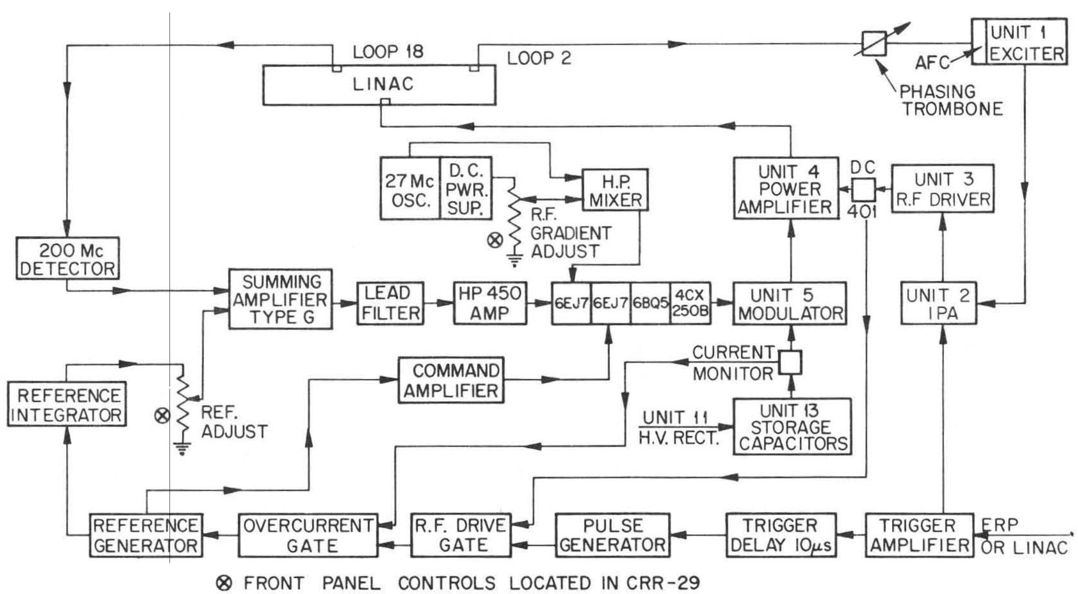


Fig. 8. Block diagram of automatic level control for 50 MeV linear accelerator.

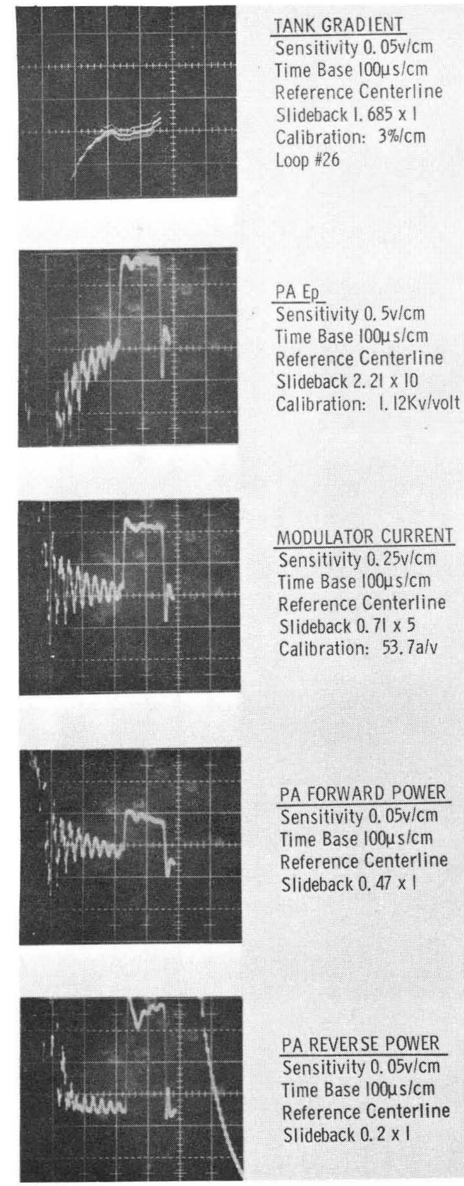


Fig. 9. Performance of 26-megacycle automatic gradient stabilizer for 20 MA beam--closed loop with beam.