OPERATIONAL EXPERIENCE WITH THE ZGS INJECTOR

J. Abraham, R. W. Castor, P. V. Livdahl, W. Myers, R. Perry
Argonne National Laboratory, USA
(Presented by P. V. LIVDAHL)

I. INTRODUCTION

The 50 MeV injector for the Argonne National Laboratory, Zero Gradient Proton Synchrotron is a quadrupole focussed, Alvarez type linear accelerator. This linac is patterened after the Brookhaven AGS injector [1]. For this reason, only those items which are significantly different from the Brookhaven injection system will be discussed. Fig. 1 is a photograph of the 750 keV pre-accelerator. The 800 kV Cockcroft-Walton power supply is to the right and the horizontal accelerating column is to the left of the photograph. Fig. 2 is a photograph of the linear accelerator taken from the top of the enclosure for the pre-accelerator.

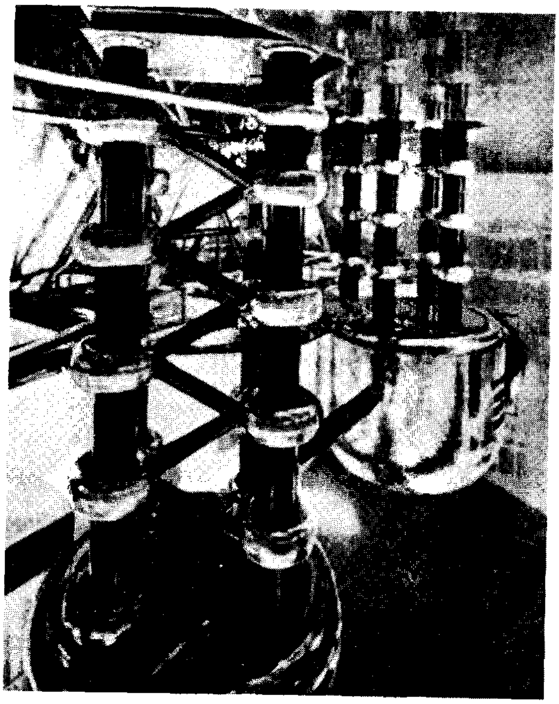

Fig. 1. ZGS 750 keV pre-accelerator.

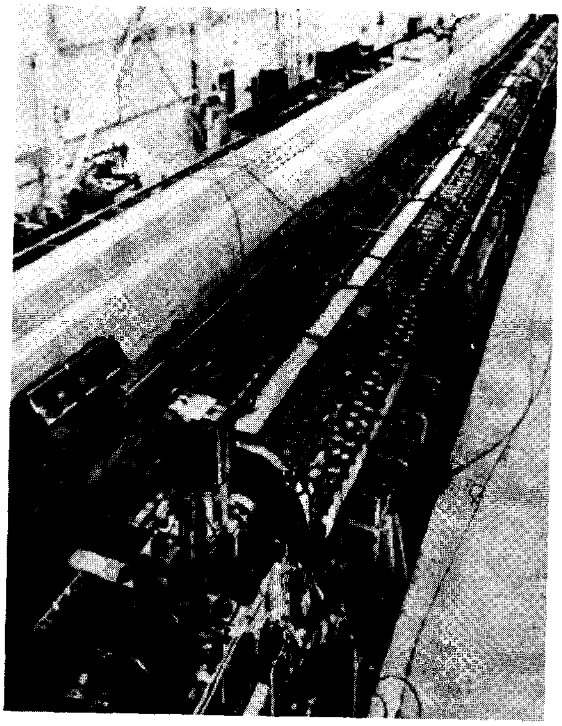

Fig. 2. ZGS 50 MeV linear accelerator.

II. LINEAR ACCELERATOR RADIO FREQUENCY POWER SYSTEM

The 200 MH_Z RF system, which excites the accelerating electric field in the linac cavity, is the most significant departure of the Argonne linac from other linear accelerators in the 50 MeV energy range. Fig. 3 is a photograph of the system. Fig. 4 is a block diagram of the system. Auxiliary sections such as the power distribution units, the water distribution unit, and the control console are, of course, necessary but are not shown in the block diagram.

The design requirements for the RF system are:

1. Frequency	200 MHz±2 MHz	
2. Peak Power	5 MW	
3. Pulse Width	50 to 500 μs (continuously variable)	
4. Pulse Rep. Freq . .	1 to 10 Hz (continuously variable)	

The low level stages of the RF drive chain are conventional applications of high frequency tubes in resonant cavity circuits. However, the final stage, or power amplifier, is unique in an accelerator application. To provide the required 5 MW of peak power, a single RCA-7835 (formerly the A 2346 F) vacuum triode was chosen. This tube is a double-ended, super power triode which is ceramic sealed and liquid cooled. The tube employs a double-ended principle [2] with symmetrically spaced ceramic insulators and coaxial contact terminals on either end of the tube structure. This feature permits operation of the tube at frequencies higher than are possible with single-ended tubes of comparable power capabilities.

Requirements for 5 MW output from the 7835 are:

1. Peak Drive Power	160 kW
2. Peak Plate Voltage	35 kV
3. Peak Plate Current	260 A
4. Filament Current	6,600 A
5. Filament Voltage	3.8 V
6. Anode Cooling	45 gpm water

The 7835 is operated as a cathode driven linear amplifier. The input and output circuits of the power amplifier are coaxial line cavities symmetrically placed on both ends of the double-ended tube. The RF power is coupled from the lower output cavity through a $\lambda/4$ coaxial impedance transformer to the wave guide.

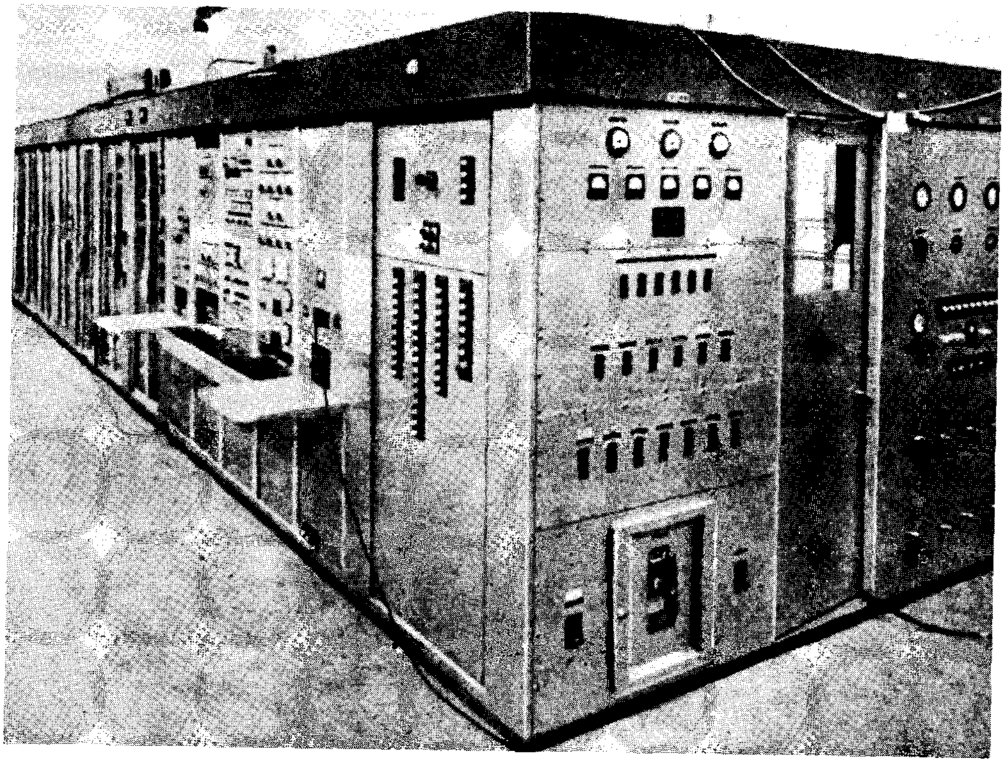

Fig. 3. ZGS injector 5 MW RF system.

Since no high power cavity was avaliable for testing the RF power capability of the system, a resistive wave guide load was used. Fig. 5 shows how the resistive load power increases as a function of peak power amplifier plate voltage. One of the tubes tested onto the resistive load reached a peak power of 6.2 MW at 35 kV plate voltage and the design duty cycle.

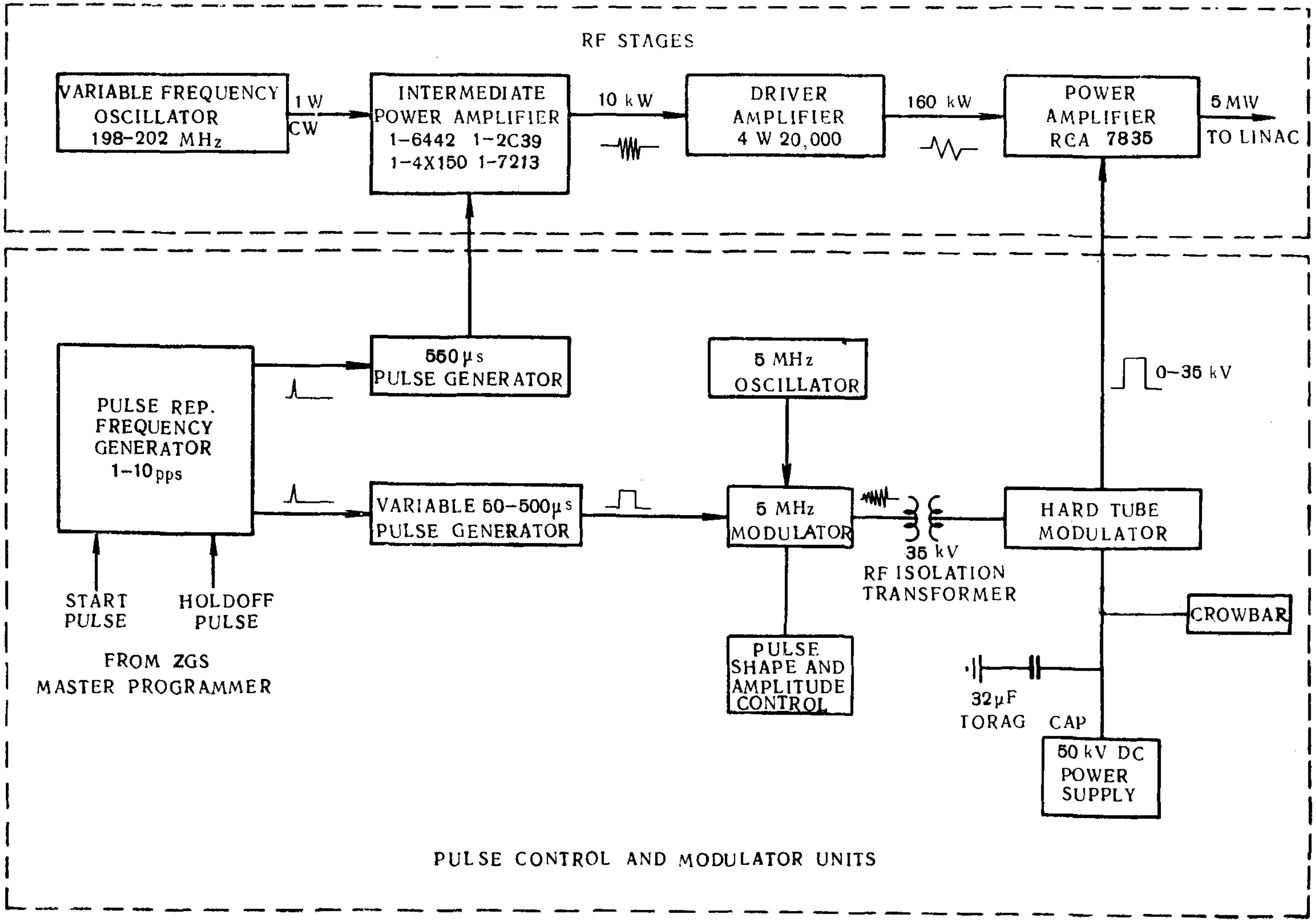

Fig. 4. Block diagram of 200 MHz linac RF power system.

Coupling the power from the wave guide into the linac cavity requires matching the wave impedance of the guide to the admittance of a transition section which couples the power to the cavity. The coaxial transmission line in this transition section is 1/2 wavelength long and is terminated by the coupling loop in the cavity on one end and a tunable short on the other. The admittance of this section was measured using a slotted line and an iris was then designed to match the load to the guide. Since the effective admittance will vary with the amount of beam being accelerated through the cavity, it is necessary to be somewhat mismatched at accelerating gradient without beam in order to match the beam loaded cavity properly. Thus the iris presently used must be checked empirically at beam levels requiring close to the 5 MW capability. Fig. 5 shows how the power into the cavity increases with the plate voltage. Below 2.5 MW the cavity is unloaded. Since the match improves with beam loading the slope of the curve increases above the operating gradient. These measurements verify the theoretical cavity excitation power as 2.4 MW with an accuracy of $\pm 10\%$. The cavity excitation power measurements are made by measuring the electrical power input to the power amplifier and the thermal power dissipation in the 7835. To achieve reasonable accuracy it is necessary to operate at maximum repetition rate (10 pps) and pulse length (500 μs). Fig. 6 is a photograph of the power amplifier taken from above the RF equipment enclosure. Also visible is the wave guide and its connection to the linac cavity.

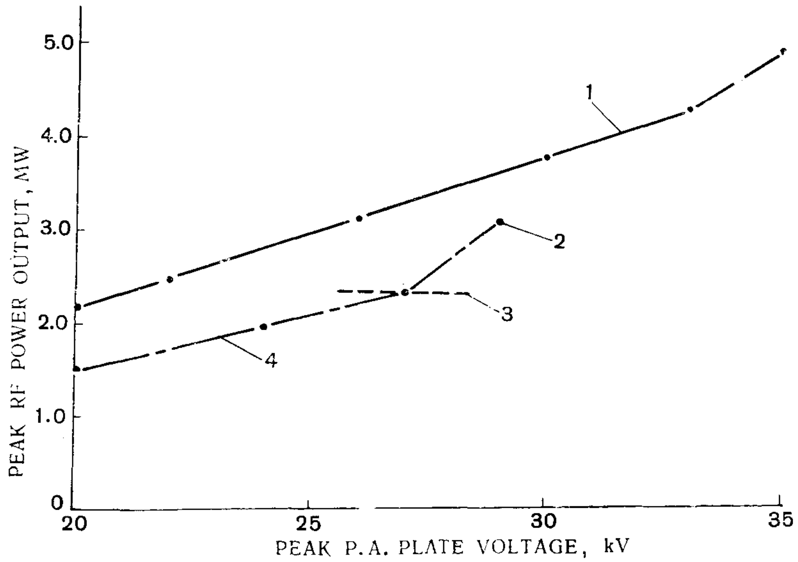

Fig. 5. Measured power amplifier output power vs. plate voltage: *1* — resistive load; *2* — with 10 mA beam; *3* — accelerating gradient excitation power; *4* — power into cavity.

Another unique unit of the RF system is the hard tube modulator which performs three basic functions: a) provides a continuously variable plate voltage pulse from 0 to 35 kV for the power amplifier; b) regulates the output voltage pulses by controlling the voltage drop across the modulator and c) provides fast fault protection for the power amplifier by immediately removing the plate voltage in case of a load fault. The regulation of the output level of the power amplifier during the pulse can be accomplished by controlling the output voltage of the modulator. Plans have been made to automatically regulate the output power by sensing the deviation of cavity voltage from a fixed RF level. This fast regulation system has not been incorporated into the equipment as yet. However, it is anticipated that this will by necessary to compensate for beam loading before much higher beam currents are accelerated through the linac.

Experience with the RF system has been very gratifying. To date there have been no major component failures. Three power amplifier tubes have been tested, of which one has been operated only into the resistive load. A total of 2600 h of operation have been experienced with no reliability problems becoming apparent. The hard tube modulator has proven to be a very useful and practical switching device. The simple controls for pulse shape, pulse length and repetition rate, as well as the anticipated pulse regulation feature, have been most satisfying. No multipactoring has ever been encountered in the linac. Contributing factors are believed to be: a) the very fast rate of rise of RF power from the power amplifier (less than 5 μs to full power); b) very good, clean operating vacuum (1.5×10^{-6} or less) and c) use of oxygen-free high conductivity copper.

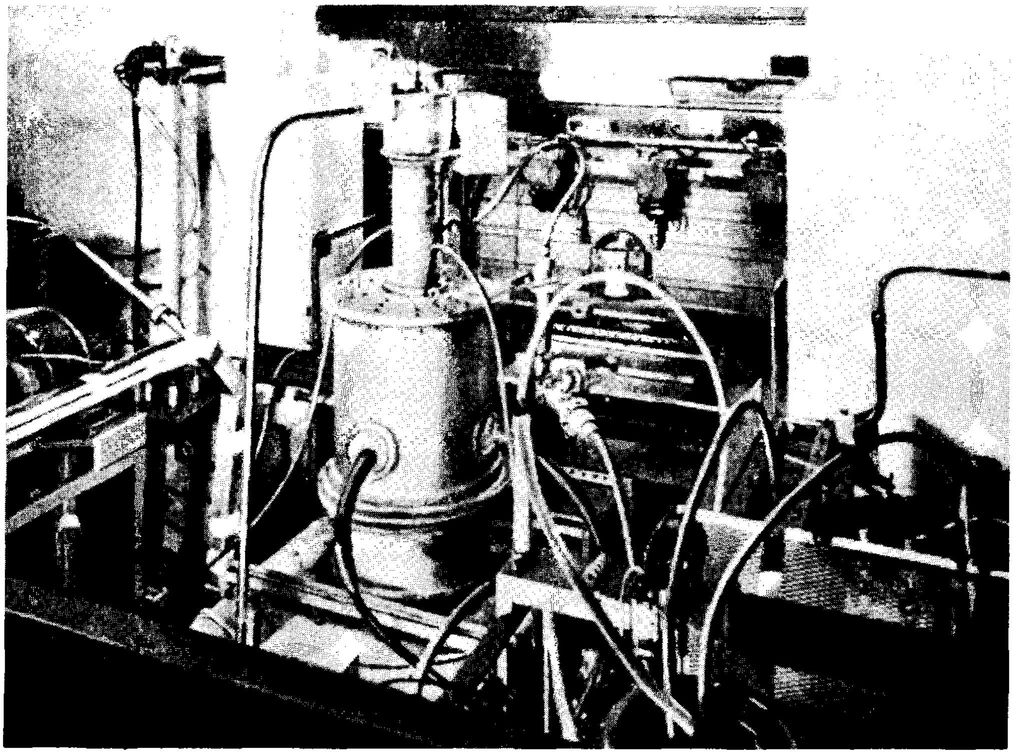

Fig. 6. 200 MHz 5 MW power amplifier.

III. VACUUM SYSTEM

The linac cavity is pumped by nine 2000 l/s Vac Ion pumps spaced along the cavity. The effective pumping speed to the cavity is only 9000 l/s due to the impedance of the pump-out holes through the cavity wall. The inherent starting problems of the electromagnetic pumps are circumvented by using a high capacity, low pressure roughing system which includes a single liquid nitrogen trapped mercury diffusion pump as the final roughing stage. The beam pipes, both pre-linac and post-linac, and all associated auxiliary equipment are pumped by 400 l/s VacIon pumps. The accelerating column is evacuated by a liquid nitrogen trapped mercury diffusion pump. This was included when it was found that electromagnetic ion pumps reach a condition of hydrogen saturation, which results in pump instability, after prolonged pumping of relatively large quantities of hydrogen.

The electromagnetic pumping system has proven to be very satisfactory. Only minor maintenance has been required on two of the nine 2000 *l* pumps, although they average more than 500 days of continuous pumping since they were delivered. The 400 *l* pumps have been slightly more troublesome, but recent modifications have resulted in trouble-free operation. The normal operating pressure in the linac cavity is from 5×10^{-7} to 1.5×10^{-6} mm of mercury.

VI. CONTROL SYSTEM

Fig. 7 is a photograph of the linac control console in the main ZGS control room. In order to conserve control console space, as well as to eliminate a great deal of long run wiring, a telephone type, two digit dial system is used to select variables for control from a common set of push buttons. Also a secondary, single digit system is provided for control of items which often require operation or adjustment concurrent with variables on the two digit system. Portable control units are available which can be patched into the dial system to operate any equipment at any location in the linac building. The flexibility resulting from this feature of the control system has proved to be extremely useful and quite an economy of technician and operator time has resulted.

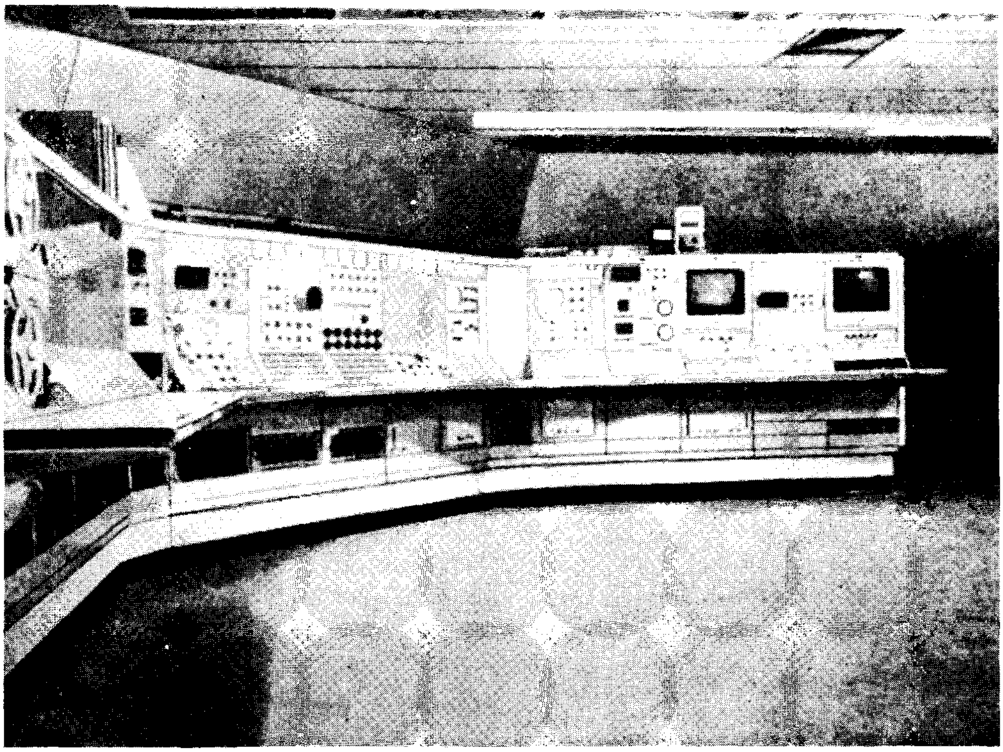

Fig. 7. ZGS injector control console.

V. BEAM MEASUREMENTS

The design of the ion source and 750 keV accelerating column have been described by A. Yokosawa [4] and R. Perry [5]. These units deliver total ion currents as large as 200 mA, of which about 70% are protons. However, the optimized electrostatic lens voltages produce a beam facus in the accelerating column about one meter from the ground end. The consequence of this is an inefficient transport of beam the linac with the present quadrupole matching system. The beam into the first drift tube is presently limited to about 35 mA of protons. The existing matching system consists of two quadrupole triplets, one on each side of the buncher. Modification of these lens elements should increase the available beam to the linac since the measurements of emittance area of the current from the ion source indicates that virtually all of the beam lies within the linac acceptance area in the +—+—mode. Horizontal and vertical defining slits are used for the measurements of beam phase space figures at 750 kV and 50 MeV. Fig. 8 is a block diagram of equipment used to record data for these measurements which is fast and permanent.

The system utilizes an $x - y$ plotter which records beam intensity through the second slit as it is scanned across the beam pattern at a constant rate of speed. Thus, a recording of position of the first slit. The first slit is then repositioned to a second radius and another traversal of the second slit determines the intensity distribution at the new radius. By

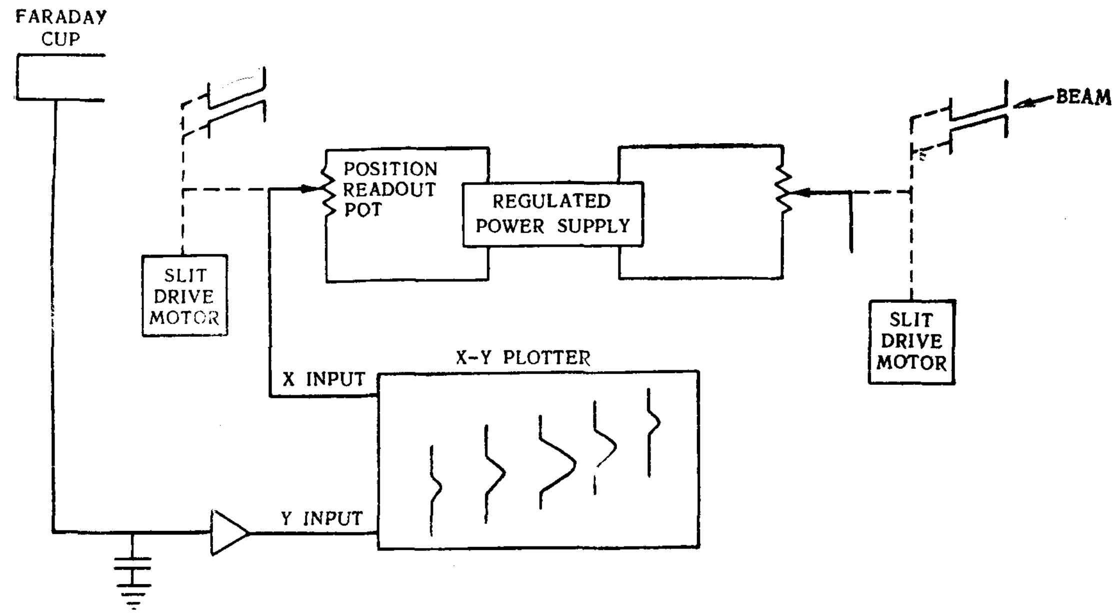

Fig. 8. Schematic of phase space recording equipment.

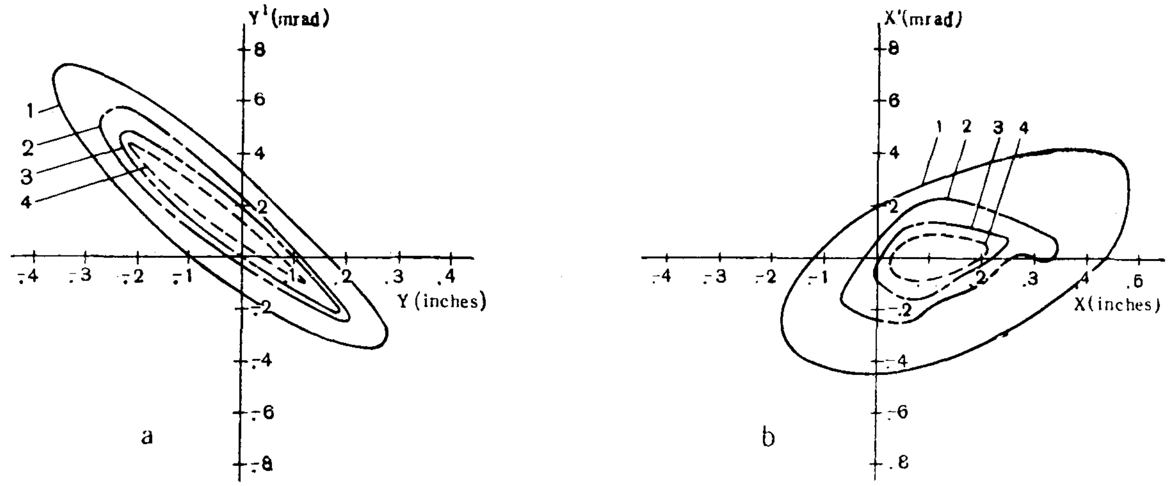

Fig. 9. 50 MeV emittance figures at 10 mA:
a — area = 0.73 π mrad·in.; *b* — area = 1.20 π mrad·in.; *1* — 100% contour; *2* — 75% contour; *3* — 50% contour; *4* — 25% contour.

the intensity profile for one position of the first slit is made in a matter of a few seconds. Determination of the extreme radii of the profile gives the divergence points on the ellipse including all of the beam at that radial off-setting the recorder base line for each position of the first slit, the plot for one plane can be recorded on one graph sheet. An idealized set of distribution curves are shown in the block diagram. Interior contours can be determined by integration of the recorded curves and subtraction of areas equivalent to percentages of beam at these radii.

Fig. 9 shows a representative set of 50 MeV emittance ellipses with 10 mA of beam. Irregularities of the $x - x'$ curves are thought to be due to frequent interruptions of beam operation during the measurement. The areas of the ellipses enclosing all of the beam is very close to that predicted from computer runs for the linac using $+-+-$ mode [3].

To date the largest peak 50 MeV beam accelerated has been 17 mA. The phase acceptance without the buncher is from 20% to 22% and the buncher gives an improvement of 2.5. These factors are reasonable but a higher buncher improvement factor was expected. A second harmonic buncher [6], which should theoretically increase the total phase acceptance to about 80%, is being tested but has not been incorporated into the linac.

REFERENCES

1. Accelerator Development Department Standards Book. Brookhaven National Laboratory, Section 1-7.
2. Hoover M. V. Advances in the Techniques and Applications of Very High-Power Grid-Controlled Tubes, Pub. No. ST-1423, Electron Tube Division of the Radio Corporation of America.
3. Cohen D. Radial Motions in the 50 MeV Linear Accelerator. Argonne National Laboratory Report, ANLAD-57.
4. Yokosawa. A. A Pulsed High Current Proton Source and Associated Focussing System. In: Proceedings of the International Conference on High Energy Accelerators (Brookhaven, 1961), pp. 385—394.
5. Perry R. Ion Source Developments. In: Proceedings of the Conference on Linear Accelerators for High Energies (Brookhaven, 1962), pp. 323—334.
6. Perry R. Multiple-Harmonic Buncher for a Linear Accelerator. Argonne National Laboratory Report, ANLAD-74.

DISCUSSION

N. V. Lazarev

1. What kind of vacuum tube is used in the modulator supplying the output RF stages?

2. In what manner is the feedback circuit for modulator control closed?

3. Is the correction for the amplitude of the RF pulse upon loading the resonator with a proton beam carried out?

P. V. Livdahl

1. Four tubes of type ML-5682 in a series parallel arrangement.

2. The RF envelope is detected and the corrected modulator control signal at 5 MHz is supplied to the grids of the above tubes through an isolating transformer.

3. Yes, we do, the system is used for this purpose.