THE RF SYSTEM FOR THE AGS LINAC INJECTOR*

J.F. Sheehan, R.F. Lankshear and R.L. Witkover
Brookhaven National Laboratory
Upton, New York

A new 200-MeV proton linac is to be built for the AGS at Brookhaven National Laboratory to increase the beam intensity. The RF system for the linac will power 9 accelerator cavities at a frequency of 200 Mc. It must be capable of maintaining the correct accelerating gradient in each cavity during the loading caused by injection of a 100 mA proton beam. This requires the delivered RF to double in power during the pulse. A 400 microsecond, 10 pps, RF pulse will allow multiturn injection at maximum AGS repetition rate, with intermediate pulses available for linac diagnostics.

The first cavity requires 1.5 megawatts of RF power. This will be supplied by two identical 750 kW tetrode RF amplifiers feeding separate RF coupling loops. Cavities 2 through 9 require about 5 megawatts each for a 100 mA proton beam. About one-half of this is losses in the cavities and one-half is energy added to the beam.

The RF systems for cavities 2 through 9 are identical. Each system consists of: (1) 5 MW RF-amplifier, (2) plate power supply, (3) capacitor bank and crowbar, (4) charge control amplifier, (5) 350 kW RF-amplifier, and (6) modulator.

A common RF oscillator-amplifier feeds all systems at a 10 watt power level. This consists of a General Radio type 1162A frequency synthesizer with output at 50 to 51 Mc, and two Hewlett-Packard untuned frequency doublers. This allows a tunable frequency range of 200 Mc to 204 Mc with very good spectral purity. No phase jitter or sideband frequencies have been found above -60 dB.

The 5 MW RF output amplifier uses an RCA 7835 tube in a Continential Electronics cavity. Preliminary tests on this unit at 6.5 megawatts have been limited by problems in some of the auxiliary equipment (resistive load and modulator, etc.).

The plate power supplies will be silicon rectifier type of about 60 kV, 100 kW capacity for each RF-amplifier.

The capacitor bank of 40 μF-60 kV limits the modulator plate voltage droop to less than 10% during the 300 ampere plate output pulse. This large stored energy necessitates using a crowbar system to prevent destruction of the modulator or RF tube during a sparkover. The crowbar system uses a National Electronics type NL-1039 EHV ignitron as a shorting device. Over-all crowbar firing delays of 1.1 to 1.3 microseconds are obtained with the prototype systems. A major problem has been the availability of a good crowbar resistor which will last more than a few hundred pulses.

Isolation between the main plate power supply and the capacitor bank is provided by a series vacuum tube. This triode and its associated circuitry form the Charge Control Amplifier (CCA), which provides constant charging current to the capacitor over the full interpulse period. Variations in pulse rate and bank voltage at start and end of a recharge cause the constant current level to change on a pulse-to-pulse basis such that the desired capacitor voltage is reached just prior to modulator discharge. At this time the series tube is driven sharply to cut-off, providing high impedance isolation.

This fast switching, of the order of 10 μs, allows the circuit to provide good regulation of the capacitor bank voltage. The rapid cut-off capability allows the main power supply to be disconnected in the event of a crowbar, preventing re-ignition of the fault and speeding recovery. In addition, the need for crowbar refiring circuits is eliminated and the main power supply contactor need not be opened with each fault, thus increasing its life. Having a fast switch also permits the use of a single power supply to charge several capacitor banks on a completely independent basis if desired. Each bank can be charged and discharged between any voltage, even experience a fault, without affecting the others.

A wide flexibility in programming voltages on a pulse-to-pulse basis is performed at constant and thus minimum current, providing the minimum variation in demand upon the power lines.

The question of charging efficiency was investigated. Since the charge-control tube is basically a variable resistor there was some concern that it would not operate with the high efficiency found in the usual inductive resonant charging systems. However, it can be shown that for the general case of a capacitor which was discharged to a voltage V_1, being recharged to a voltage V_2, the efficiency is given by

$$\eta_{max} = \frac{\text{Energy Delivered to Capacitor}}{\text{Energy from Supply}} = \frac{V_1 + V_2}{2\ V_{PS}}$$

where V_{PS} = the power supply voltage.

In the case of discharge to zero, V_1 is zero and for resistive charging the maximum efficiency is 50%. (For this same case the theoretical maximum efficiency with inductive resonant charging is 100%, since $V_{PS} = 1/2\ V_2$.) But in the present system, the hard tube modulator does not discharge the bank to zero. For the case of a 10% discharge of the capacitor voltage the efficiency for resistive charging has a maximum value of 95%, which is quite acceptable.

---

*Work performed under the auspices of the U.S. Atomic Energy Commission.

The charge-control amplifier circuit is shown in Fig. 1. The series passing tube is a Machlett ML-8041, selected for its high voltage hold-off, high amplification factor and favorable drive requirements for high current at low plate voltage.

The driver for the charge-control tube has an output range of -700 V to + 100 V (at 600 mA). The negative voltage allows cut-off even when the full power supply voltage is across the tube, and the positive voltage permits 3 A of plate current to flow when there only is about 1 kV across the tube.

The output stage, consisting of the 4CX250R and 4CX1000A, provides the bipolar drive capability. To obtain linear operation into the nonlinear load (8041 grid circuit from negative to positive region), negative feedback was employed from the output (8041 grid) through a non-inverting transistor amplifier (A_2). This matches the input requirements of the 4CX250R to the available output range of the operational amplifier, A_1. A signal proportional to the charging current [$V_I = - I(t) R_K$] is developed across the current-viewing resistor R_K and compared to a reference signal ($V_{ref} = I_c R_K$) at the operational amplifier (A_1) summing junction. The error signal is amplified and applied to the grid of the 8041 to keep the charging current constant.

The charge-control amplifier is designed to charge the bank under such conditions that (a) the desired final bank voltage may be changed from pulse to pulse, (b) the residual bank voltage at the end of the previous discharge may vary from pulse to pulse, and (c) the PRF is not fixed. This may be accomplished by the circuit shown in Fig. 2.

The voltage divider observes the capacitor bank voltage. The lowest value, V_F, which occurs just after modulator discharge is read and stored in the sample-and-hold circuit for the duration of the charging cycle. This value is subtracted from the capacitor voltage required at the end of charging, as set on the "V_0-set" potentiometer. The difference is amplified by the operational amplifier whose gain is adjusted proportional to the pulse rate. The output is "V_{ref}" and is telemetered to the charge-control deck. Basically the circuit implements the equation

$$V_{ref} = R_K C \ (V_0 - V_F) \ (PRF) = I_c R_K$$

which determines the minimum charging current required for complete recharge in the interpulse period.

Voltage regulation is provided by a parallel telemetering system which closes a gate at the charge control deck when the capacitor bank voltage reaches the value set on the "V_0-set" potentiometer. This function is performed by the voltage comparator in Fig. 2. Thus, voltage regulation and minimum level constant current charging are accomplished with only two external parameters required: the pulse repetition frequency, and the desired bank voltage. All other variables are internally monitored so that the appropriate minimum current is computed.

The low level control circuitry of the presently operating (prototype) charge-control amplifier has been rearranged to perform all sensing and adjustment functions on the floating deck while a suitable optical data link is being developed. The prototype circuit configuration is shown in Fig. 3. Measurements made with the prototype CCA recharging the modulator-discharged bank verified the linear operation of the circuit as it passed into the positive grid region of the 8041. Bank voltage was regulated to 0.1% even when the power supply voltage was increased by 30% over its original setting. If modulator pulsing stopped, the voltage was held for extended periods to within 0.5%, the observed droop being set by the Schmitt trigger hysteresis.

The modulator (Figs. 4 and 5) uses three Machlett type ML-8618 magnetically focussed triodes as output tubes. The high efficiency, low drive requirements of this type tube are desirable for the fast analog modulation control required to correct for the 100% change in loading of the accelerator cavity during beam injection. The modulator ON-OFF command is telemetered to the floating deck with a solid state infrared optical system. The analog level control information is directly coupled to the deck through a high voltage dc amplifier. The level control system has been tested at 90% modulation with a 20 kV per microsecond slewing rate.

Maintaining fast linear analog response from the modulator is a major goal in attempting to stabilize correct accelerating gradient during beam injection. This permits open as well as closed servo loop signals to be used to control modulator output power.

The low level (10 volt) command signal from an operational amplifier is amplified in a solid state linear amplifier to a level (300 volt) sufficient to drive the main high-voltage amplifier (DP-15) to a maximum output of 40 kV. A bootstrapped cathode follower stage (4CW10,000A) is used to supply the grid current, mainly reactive, of the three parallelled output tubes.

The two main parameters which limit the high frequency response of the modulator system are: (1) the grid-to-plate capacity of the output tubes, which must be charged and discharged by the cathode follower (4CW10,000A). (2) The grid-to-plate capacity of the voltage amplifier stage (DP-15) which must be charged by the cathode follower.

This requires the use of a larger tube (4CW10,000A) than would have been needed if there were only a resistive component of grid current. The 3 ampere plate current required by the DP-15 amplifier is only 1% of the modulator output current. Response times of 1 microsecond for an output voltage change of 40 kV have been obtained.

The maximum deviation from linear response is 4% thus allowing first order RF amplitude corrections to be programmed open-loop. The open-loop command signals, and the servo feedback information obtained from detected samples of RF accelerating gradient are combined in the first stage operational amplifier.

The screen of the 4CW10,000A stage is driven by a tube-transistor amplifier with output diode-clipping. The input to this amplifier comes from the main control panel, using an infrared fiber-optics telemetry link to cross the high voltage interface. This unit can be overdriven to insure an adequate turn-on signal since its linearity does not affect the analog control system. Either this system or the analog control system can be used to turn off the modulator in the event of an RF amplifier fault. Turn-off times of 400 nanoseconds have been obtained by using both systems in parallel.

The 350 kW driver amplifier (Fig. 6) provides the grid drive power for the RCA 7835 final power amplifier used for tanks 2 through 9. With minor changes these units will be used directly to provide the 1.5 MW RF power to excite the first cavity.

The auxiliary equipment and circuits for the driver were developed and tested using BNL designed cavities. This system employs two RCA type 7651 tubes and one RCA type 4616 tube. A system of this type (Fig. 7) is presently being used for supplying RF drive power, to allow tests to be made on the 7835 amplifier system.

A second driver amplifier was developed using similar components but with amplifier cavities developed and supplied by RCA. Most of the recent driver work has been with this combination. The three RF tubes and their associated cavities are designated RCA Amplifier Chain type Y1068. Minor mechanical changes in the water cooling connections have allowed an identical electronics package to be used with both amplifier systems. RF output is taken via 3-1/8" EIA 50 ohm rigid coaxial line.

Screen modulation of the 4616 is necessary at the 350 kW power level. A pulse of 0.5 A at 2 kV is provided by a hard tube bootstrap-modulator which also forms a convenient source of positive pulses for the 7651 control grids.

Bias supplies for the 4616 control grid and the 7651's are arranged using conventional regulated power supplies.

Low level (10 watt) pulsed RF with fine frequency control is supplied to the grid of the first 7651. This tube drives the second 7651 which in turn drives the grid cavity of the 4616 output stage.

A block diagram of the complete 350 kW driver is shown in Fig. 8.

The plate power supply for the 4616 is continuously adjustable to 30 kV at 500 mA. It is regulated to 1% against 10% changes in line or load, with 5% ripple. This supply charges a capacitor bank of 18.75 μF constructed of ten 7.5 μF capacitors in a series-parallel arrangement. With a peak plate current of 25 A for the 4616, the voltage droop is approximately 500 V for a 400 μs pulse width.

A 6 kV, 300 mA power supply is used to provide 5 kV at 10 mA to number two 7651 and 100 mA to the 3 kV screen-voltage regulator. It is electromechanically regulated to 1% for 10% changes in line or load. The 3 kV regulator reduces the supply voltage to a preset level depending upon the pulse amplitude at which the 4616 screen is to be operated. The unit feeds a capacitor bank of 125 μF to supply the 3 A of modulator current with 1% voltage droop.

The screen modulator is designed around a 3-400Z triode whose anode is ac-coupled to the grid of a 4CX1000A cathode follower (see Fig. 9). A grid bias supply maintains the 4CX1000A at cut-off during the quiescent period. The 3-400Z is fully conducting due to a resistor returned from plate-to-grid.

A negative going 50 V pulse from a Hewlett-Packard 214 pulse generator turns off the 3-400Z causing its plate to rise, thus turning on the 4CX1000A. The rising cathode voltage of the 4CX1000A is fed to the plate of the 3-400Z, raising it above its normal potential. A hold-off diode in the plate lead prevents loading by the plate supply during this period.

The bootstrapping action is maintained until the end of the pulse when the 3-400Z again conducts, returning the 4CX1000A to its cut-off state.

The screen modulator delivers 2.7 amperes into a 750 ohm load resistor which when connected to the 4616 allows 500 mA of screen current without significant loading of the pulse. Rise time is limited by a 18000 pF screen bypass capacitor built into the 4616.

The large stored energy in the capacitor bank supplying the 4616 plate makes fault protection a necessity. This is accomplished by a crowbar system which discharges the bank in 5 microseconds from the sensing of a fault. The fault signal is obtained from a zener diode which is connected to a current viewing transformer in the 4616 plate circuit. An arbitrary threshold of 100 A was selected. Using this system, a 1 mil aluminum foil was unpunctured when the plate lead was shorted to it. Both 30 kV and 3 kV capacitor banks are discharged in the case of 4616 over-current, to prevent the application of screen voltage in the absence of plate voltage. A logic circuit is under development which will allow a fixed number of crowbars in a given time interval without requiring the high voltage supplies to turn off.

Results of operation using the RCA Y1068 amplifier chain are summarized below.

Duty Cycle	0.4% (400 μs at 10 pps)
Frequency	202.204 Mc
Peak Power	590 kW (A peak of 650 kW was reached but occasional arcing was observed in the load)
Cavity Pressure	30 psi (Air)
4616 Plate Efficiency	60%
System Bandwidth	4.4 Mc
RF Rise Time	< 2 μs (into matched resistive load)

Having exceeded the 350 kW design requirements by such a large amount (650 kW peak), an 800 kW version of this amplifier system is being constructed. This will involve replacement of the type 4616 tube with an RCA type A2771 and require plate modulation to be used for the higher plate power required. The cavities and associated electronics will remain essentially the same. Two of the higher power units will be used to supply RF power to accelerator Cavity #1 instead of the originally planned 7835 system.

Tests have been successfully conducted on all of the prototype subsystems. The results obtained indicate that a complete RF system based on this design will provide the necessary capabilities to compensate for expected beam loading of the cavities.

Acknowledgements

The authors would like to acknowledge the associated work performed by J. Keane, R.B. McKenzie-Wilson, J. Aggus and A. McNerney of the Accelerator Department.

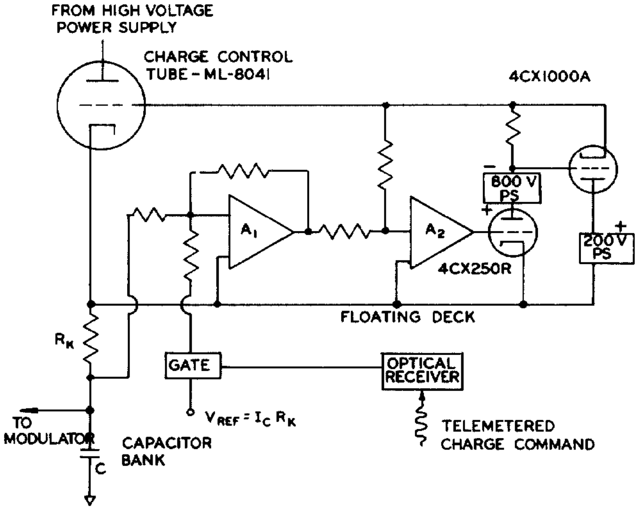

Fig. 1. Charge Control Amplifier—floating deck circuits.

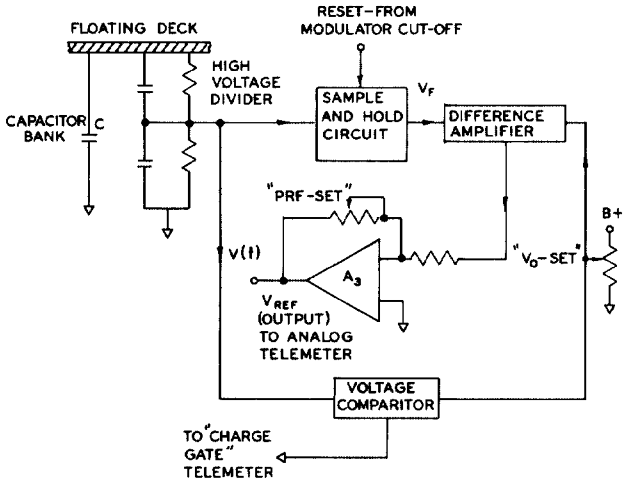

Fig. 2. Charge Control Amplifier—ground level sensing circuits.

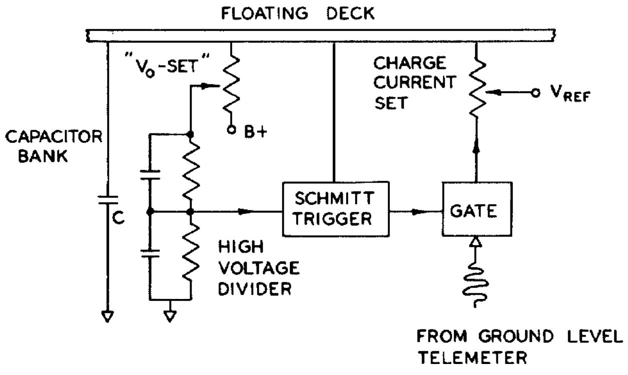

Fig. 3. Charge Control Amplifier—prototype sensing circuits.

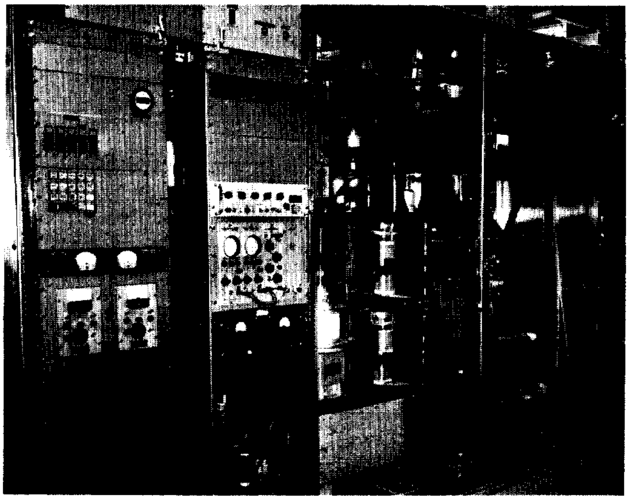

Fig. 4. Photograph of RF modulator.

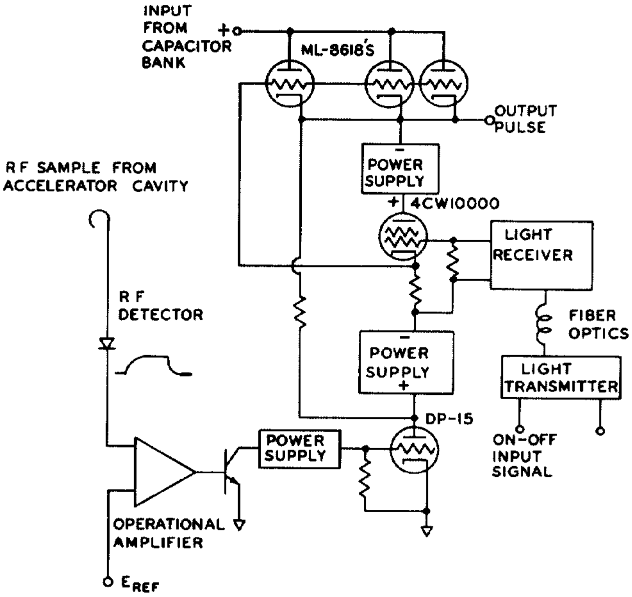

Fig. 5. RF modulator.

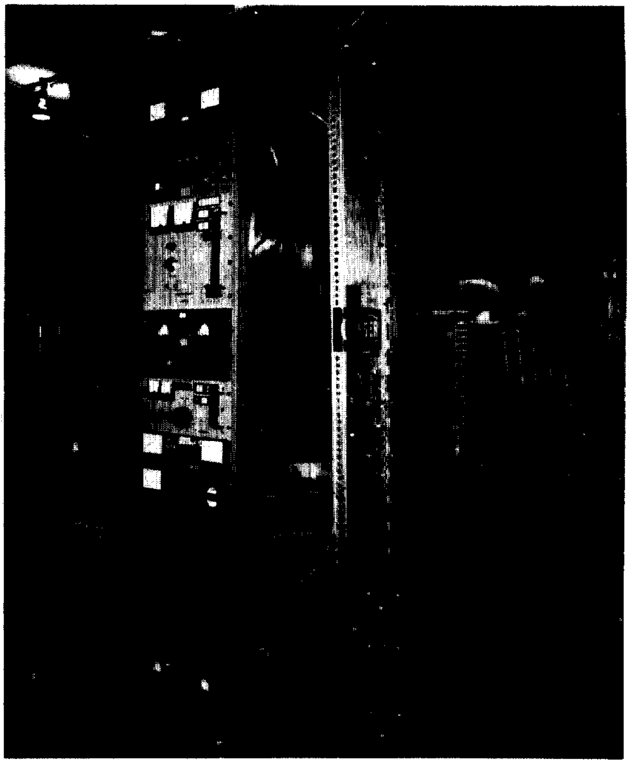

Fig. 6. Photograph of 350 kW driver amplifier module.

Fig. 7. Photograph of 350 kW driver amplifier cart.

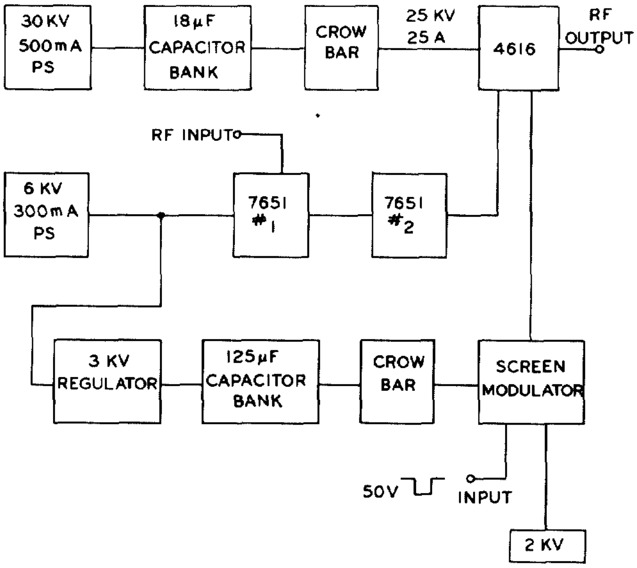

Fig. 8. Block schematic of 350 kW driver.

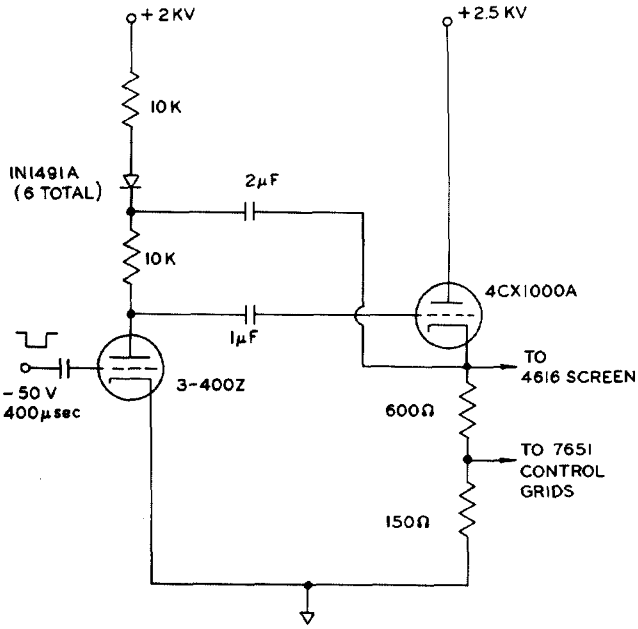

Fig. 9. Schematic diagram of screen modulator circuit.