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A LOW-COST RF SYSTEM FOR A 2-MEGAHERTZ HEAVY
ION LINEAR ACCELERATOR

R. T. Sanders

January 10, 1979

ACCELERATOR DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY, ASSOCIATED UNIVERSITIES, INC.
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ABSTRACT

A low-cost radio-frequency power source for a low beta linear accelerator (Linac) is described. Details of the conversion of a 30-kW, 4- to 30 MHz communications transmitter to a 2-MHz parallel line resonator driver are included. Typical calculations required for the modifications and anticipated line dissipation are given. The results of actual high level operation are discussed and power output requirements when driving a Wideroe linac are determined.

I. INTRODUCTION

Because of today's limited funding for research programs, careful budgeting of both time and money is demanded. The Heavy Ion Fusion program at Brookhaven National Laboratory (BNL) is bound by such constraints.

It was necessary to build a low-cost rf system for a 2-megahertz low beta linear accelerator (Linac), without the need for expensive long lead time, or prototyped items. An old, but working, high frequency transmitter was purchased, modified, and rebuilt at a fraction of the time and cost required to prototype a similar rf system. A transmission line/resonator that would deliver the accelerating voltage to the Linac was designed to utilize readily available materials and simple construction without the need of expensive machining.

The mechanical and electrical parameters of the transmission line/resonator are discussed in detail in a design study and will not be presented here.¹ However, certain line measurements are included.

Details of the transmitter modification and start-up are included.

This rf system was planned to provide up to 30 kW for transmission line losses and beam loading, and an accelerating gap voltage of up to 100 kV peak.

II. GENERAL

Transmission line/resonator calculations showed a need for about 15 kW of driving power where the line Q was calculated to be over 2600. A suitable rf power source was needed, and instead of going through a lengthy design and prototyping program for such a source, a 4- to 30-MHz Gates transmitter was purchased from a deactivated short-wave transmitting station.

This transmitter had been out of service for eight years and required an extensive cleanup to return it to a suitable operating condition. It had been used mostly at 13 MHz. Plans were to operate it initially in this region and then to tune it down to its lowest frequency, 4 MHz. Finally, tank circuits would be changed to lower it to the planned operating frequency of 2 MHz.

After operating at 2 MHz into a dummy load, with good stability, the final tank circuit would be removed and replaced by the transmission line/resonator.

III. TRANSMITTER MODIFICATIONS

The transmitter was designed with a matching network that would allow it to drive balanced load impedances from 300 to 800 ohms though not necessarily at its rated full output power capability of 30 kW. The dummy load used for testing was two water-cooled 150-ohm single-ended coaxial units, shown in Figure 1, originally built as 50-ohm terminations. Because of this low impedance, the maximum output was limited to 22 kW at all frequencies.

Before proceeding from 4 to 2 MHz, it was necessary to analyze the driver and final amplifier stages and determine the proper modifications so that the actual performance would not differ at the lower frequency. This entailed measuring tank circuit LC values, calculating circulating currents and plate swings, and for the maximum output power, estimate the loaded Q.

The following calculations were made for the final push-pull amplifier,² where

$$E_{bb} = \text{plate voltage} = 7500 \text{ Vdc},$$

$$E_p = \text{plate swing (per tube)} \sim 0.9 \times 7500 = 6750 \text{ Vpk},$$

$$E_t = \text{tank voltage} = 2 \times 6750 = 13500 \text{ Vpk},$$

$$E_t \text{ rms} = 13500 \times 0.707 \sim 9540 \text{ Vrms}.$$

Also

$$f_o = 4 \text{ MHz}.$$

$$L \text{ tank (measured)} = 10 \text{ } \mu\text{H}.$$

Then for Figure 2, as seen from the primary side,

$$I_t \text{ rms} = \frac{E_t \text{ rms}}{\sqrt{R_L^2 + X_L^2}}.$$

But for a properly designed tank circuit:

$$X_L^2 \gg R_L^2,$$

or

$$I_t \text{ rms} \sim \frac{E_t \text{ rms}}{X_L} = \frac{9540}{2\pi f_o L} = \frac{9540}{2\pi \times 4 \times 10^6 \times 10 \times 10^{-6}},$$

$$I_t \text{ rms} = 37.95 \text{ or } 38 \text{ amperes,}$$

where

$$P_o = \text{power output} = 30 \text{ kW,}$$

$$R_L = \frac{P_o}{I_t^2 \text{ rms}} = \frac{30 \times 10^3}{(38)^2} = 20.8 \text{ ohms.}$$

Also

$$Q_L = \frac{VA}{P_o} = \frac{E_t \text{ rms} \times I_t \text{ rms}}{P_o} = \frac{9540 \times 38}{30 \times 10^3} = 12.$$

A loaded Q of 12 is an acceptable midrange value that is typical for high frequency transmitters. Lower values of Q allow for too much harmonic content, while higher values result in excessive tank circuit losses.³

The new tank inductance value is now found retaining the same value of loaded Q but at 2 MHz. Thus

$$L = \frac{QR_L}{2\pi f_o} = \frac{12 \times 20.8}{2\pi \times 2 \times 10^6} = 19.86 \text{ or } 20 \text{ } \mu\text{H.}$$

This is twice the inductance used at 4 MHz, and the tank capacitance is also doubled.

Figure 3 shows the output stage with the new 2-MHz tank inductor in place.

Similar calculations followed by the necessary tank circuit modifications were also made for the driver stage. Earlier stages were originally built to tune as low as 2 MHz so it was not necessary to modify them.

The transmitter tuned and operated as well at 2 MHz as at the higher frequencies. Again, the maximum output power was limited to 22 kW. Heavier loading would cause the plate overload relays to trip.

IV. TRANSMISSION LINE MEASUREMENTS

Low level measurements were made on the transmission line/resonator to verify the design calculations. The unloaded Q was measured by loosely coupling a signal generator and rf voltmeter to the line as shown in Figure 4. The measured Q value was 2000. This is lower than the original calculation of 2600 and would tend to indicate that the shunt resistance value is lower than originally estimated.

$$R_p (\text{calc}) = 170 \text{ kilohm.}$$

The real value of R_p is then

$$Q_0 = \omega_0 R_{p0} C_0,$$

and

$$Q_1 = \omega_1 R_{p1} C_1,$$

$$\omega_1 = \omega_0,$$

$$C_1 = C_0;$$

then

$$\frac{R_{p1}}{Q_1} = \frac{R_{p0}}{Q_0},$$

$$R_{p1} = \frac{Q_1}{Q_0} R_{p0} = \frac{2000}{2600} \times 170 \text{ k} = 130.8 \text{ kilohm.}$$

The calculated line driving power to obtain 100 kV peak at the open end of the line was 14.7 kW for a Q of 2600. Obviously, with a lower value of shunt resistance the drive requirements will be higher.

Thus where the measured Q is 2000, the necessary drive is

$$P_0 = \frac{V^2}{2(2R_p)} = \frac{(100 \times 10^3)^2}{4 \times 130.8 \times 10^3} = \frac{10^{10}}{5.23 \times 10^5} = 19.12 \text{ kilowatts.}$$

V. HIGH LEVEL OPERATION

The first plan for driving the transmission line was to tap the line at a nominal 600-ohm impedance point and connect it to the transmitter output without any modifications. But, in order to simplify the circuitry even more, it was decided to drive the line directly from the plates of the output tubes at a higher impedance point as shown in Figure 5.

Figure 6 shows the final amplifier after the 2 MHz tank inductor was removed and replaced by a center tapped rf choke and plate voltage blocking capacitors. The output leads from the blocking capacitors to the bell-shaped output lead insulators at the top of the enclosure are also visible.

The estimated push-pull tank impedance was

$$R_{sh} = R_L (1 + Q^2) = 20.8 (1 + 12^2) = 3016 \text{ or } \sim 3000 \text{ ohms.}$$

The line driving point tap location is then

$$\tan \beta l = \left(\frac{2R_p}{R_{sh}} \right)^{\frac{1}{2}} = \left(\frac{2 \times 130.8 \times 10^3}{3000} \right)^{\frac{1}{2}} = 9.34,$$

$$\beta l = 83.9 \text{ degrees (from the open end of the line).}$$

During the rf system testing, the transmission line had not been extended into the Linac tank so that the resonant frequency was actually 2.3 MHz.

Thus

$$\lambda = 130.4 \text{ meters,}$$

$$\frac{\lambda}{4} = 32.6 \text{ meters.}$$

Then the calculated tap point from the shorted end is

$$32.6 \text{ m} \times \frac{90 - 83.9}{90} = 2.21 \text{ m, or } 7.25 \text{ ft.}$$

The tap locations were moved for maximum loaded Q and thus maximum voltage at the open end of the line. The final locations were about 8 feet from the shorted end.

Figure 7 shows the transmitter in its final location, permanently attached to the transmission line/resonator at the upper right.

The anticipated repetition rate for the Linac is low, so for testing purposes the transmitter was keyed "on" for approximately 1 millisecond with about a 1% duty cycle. The final amplifier plate power supply voltage stayed at 8.5 kV dc (during cw operation it droops to 7.5 kV dc). Under these conditions, the peak resonator voltage was 135-kV peak rf. The peak power output was then

$$P = \frac{V^2}{4R_p} = \frac{(135 \text{ kV})^2}{4(130800)} = 34.8 \text{ kW.}$$

The voltage at the transmitter tap point was then

$$V_{\text{tap}} = 135 \text{ kV} \cos 84.9^\circ = 14.3 \text{ kV.}$$

VI. CONCLUSION

The high level operation of this system included the line/resonator but not the Linac drift tubes or their mounting plates. It is anticipated that when the Linac is driven, additional line length and capacitive loading will be presented to the system, thus lowering the resonant frequency by about 300 to 400 kHz. The line Q will be lowered to about 1700 requiring about 23 kW to obtain 100 kV at the accelerating gaps. The test results indicate that this should not be difficult to obtain.

The total time from the beginning of transmitter refurbishing, including modifications, troubleshooting, and transmission line assembly and low level tests, through to the final high level tests, was about four months.

ACKNOWLEDGMENTS

All of the engineering and technician staff of the BNL Heavy Ion Fusion group contributed to the successful completion of this 2-megahertz rf system. Particular recognition is given to John Keane for the electrical design and John Brodowski for the mechanical design of the transmission line/resonator.

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Figure 1. Transmitter output power amplifier, output matching network and dummy load.

Figure 2. Tank inductor and load.

Figure 3. Transmitter output stage with 2 MHz tank coil in place. Output tubes are located in box-shaped air ducts at the right. At the upper left is the output matching network with a coupling link extending down into the tank inductor.

Figure 4. Low level test setup for transmission line resonator.

Figure 5. Schematic diagram of final amplifier with transmission line/resonator tank circuit.

Figure 6. At the left is the final stage with the tank circuit removed and the rf choke and blocking capacitors added. At the right is the driver/exciter compartment. Driver modifications are not visible externally.

Figure 7. The transmitter as viewed from the power supply end. Note that plate transformers are external. The unseen side has all controls and instruments. The aluminum duct at the upper right is the transmission line/resonator which is joined mechanically to the output amplifier compartment.

N O T I C E

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