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Preprint

Induction Linac Energy Regulation Via Injector Current Modulation

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INDUCTION LINAC ENERGY REGULATION VIA INJECTOR CURRENT MODULATION

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Abstract

A 16-MW, 30-MHz electron beam current modulator has been built and tested at Lawrence Livermore National Laboratory. The modulator utilizes the transconductance of an array of 32 planar triode tubes to shunt a voltage regulation cell which will be added to the electron beam injector of an induction linac. The modulator exerts analog control over the top 5% of the injector current pulse. It will operate on a 60-ns beam pulse up to a 0.1% duty cycle.

Proper operation requires that the modulator be as small as possible and be tightly coupled to the accelerator cell. The 25-kV prototype module consists of a 16-tube coaxial array made up of eight dual-tube submodules. The tubes are placed in a 14-in.-diam × 7-in.-tall freon-filled can that is directly connected to the accelerator cell. Each cell accepts two 16-tube modules in a bilateral arrangement. Controlled power density is >10 kW/in^3. Additional circuit details are given in Ref. 2.

Introduction

Induction linacs used for free-electron laser experiments are required to produce electron beams that have minimal intrapulse energy variations. This has required an active method of intrapulse beam energy control to compensate for the accelerator gap voltage droop caused by a time- and temperature-dependent magnetization, or leakage, current in the accelerator cell's ferrite cores.[1] Since the beam current represents a significant load to the pulse line driving the cells, it is possible to regulate the accelerator cell voltage by controlling the beam current. This method of regulating the output beam energy by using the injector to vary the beam load in the subsequent accelerator cells has been reported elsewhere.[2]

Since the injector cathode is operated in the space-charge-limited regime, any modulation of the injector's voltage will vary the output current according to Child's Law. The modulator will vary the injector voltage by controlling the voltage drop across each of two regulation cells added to the injector. This paper focuses on the 16-MW, 30-MHz current modulator which, on the left side of Fig. 1, can be seen installed on each of two regulation cells added to LLNL's high average power (HAP) injector. Operating parameters of the injector are intended to be 750 kV, 750 A.

Since each induction cell acts as a 1:1 pulse transformer, a current equal to the beam current is induced in each regulation cell. The transconductance of the planar triodes shunting each cell provides a variable resistance for this current, and thereby a variable voltage is produced across the cell. Details of this concept are shown on the right side of Fig.1.

Circuit Description

Each individual module which makes up the regulator circuit (four are shown in Fig. 1) is a coaxial array of 16 planar triode electron tubes in cascode connection with a microwave packaged field effect transistor (FET). The FET is driven by a 50-MHz bipolar radio-frequency (rf) transistor in an emitter follower configuration. Each tube is shunted by a 1000-Ω, 500-W resistor to provide a fixed value of maximum resistance; this fixes the maximum voltage when the nominal current is run through the cell. This circuit, configured as a linear amplifier, has also been used for intrapulse beam position correction on the Advanced Test Accelerator (ATA) at Lawrence Livermore National Laboratory.[3]

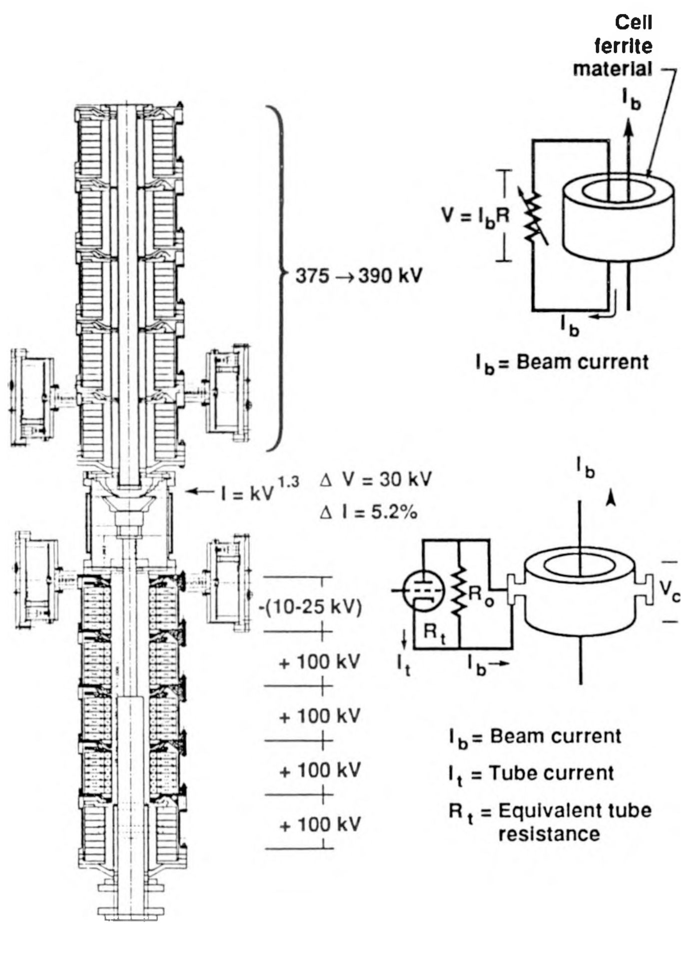

Fig. 1. Injector control concept, with the regulation cells shown on the injector at left.

Figure 2 is a photograph of two 16-tube modules with two of the dual-tube submodules in the foreground. Figure 3 is a cutaway drawing of a tube module with a simplified circuit schematic of a dual-tube submodule. Individual dual-tube submodules were tested with the test circuit indicated in Fig. 4; the output waveform is shown following the 5-V input waveform with a frequency response of >50 MHz.

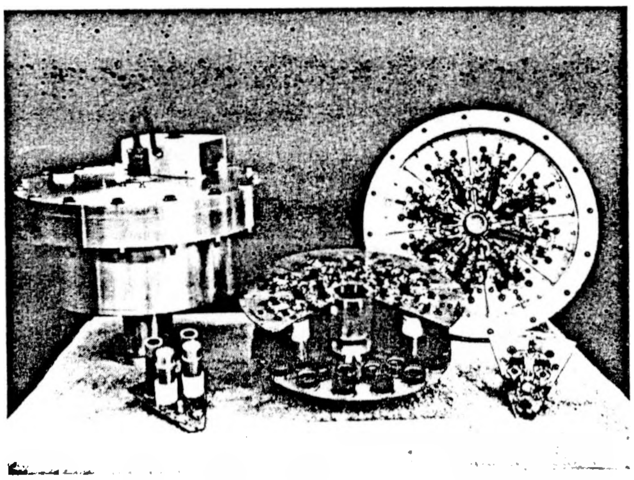

Fig. 2. Photograph of the tube modulator assemblies.

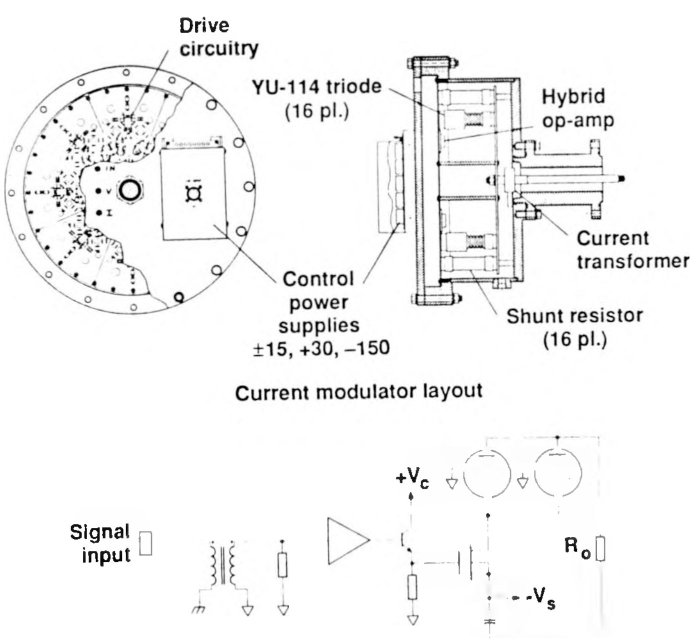

Fig. 3. Cutaway drawing of a modulator module and a simplified schematic of a dual-tube submodule.

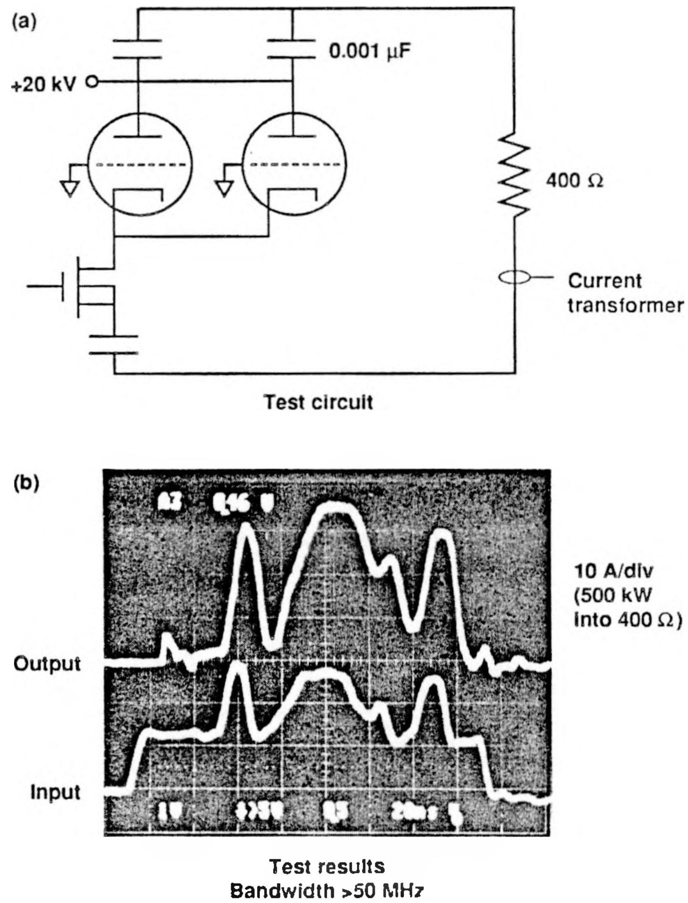

Fig. 4. (a) Schematic of the test circuit, and (b) the input (5 V) and output (30 A) waveforms of a dual-tube submodule operating at the 500-kW level.

Test Results

To validate the concept and insure proper operation, the current modulator was installed and tested on a two-cell test stand. A regulator cell with two current modulator modules was attached to an accelerator cell driven by a 80-kV Blumlein pulse line. A conductive rod traversing the middle of each cell simulated the injector beam current. Figure 5 is a schematic diagram of the two-cell test stand, and Fig. 6 is a photograph of the test stand with the regulation cell and two modulator modules in the foreground.

The shunt impedance of the cell ferrite, in parallel with the fixed resistors of the current modulator, provided a total shunt resistance of 16 Ω. This resistance produced 25-kV voltage drop across the cell when a 1550-A current was induced in the circuit. The uncorrected regulation cell voltage waveform in Fig. 7a shows this 25-kV peak voltage when the 1550-A peak current is passed through the cell. Since the cell load is purely resistive, the current waveform has a shape that is nearly identical to the uncorrected cell voltage waveform. The inductance of the external resistor causes the circuit to have a predominant left-to-right risetime. While this shape is poor by accelerator standards, it was adequate for these tests.

The objective of the current modulator is to vary the voltage drop across the regulation cell in an arbitrary manner. This ability is demonstrated in Figs. 7b and c, where the tube circuit is employed to flatten the dynamically changing pulse. This demonstration was

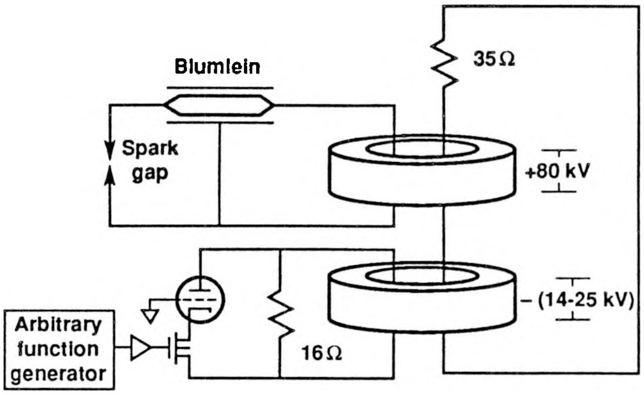

Fig. 5. Simplified schematic of the two-cell test stand used to test the shunt regulation concept.

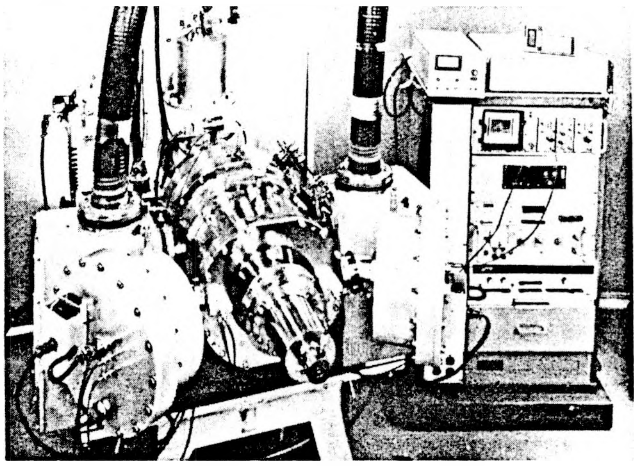

Fig. 6. Photograph of the two-cell test stand.

accomplished by entering the required correction, point by point, with an arbitrary function generator which has a 5-ns-per-point resolution. Figure 7b shows the waveform with correction on the first half of the pulse, while Fig. 7c is the fully corrected waveform. Figure 7d is the point-by-point correction input into the computer controlling the arbitrary function generator. Figure 7e is the output of the arbitrary function generator, showing the effects of the 5-ns risetime of the instrument.

During the middle of the correction in Fig. 7c, the current modulator was full on. The 25- to 14-kV voltage variation at that point reflects the maximum power output swing of the modulator. Since this waveform is flat to <5% and the total voltage swing of the modulators will be <5% of the injector voltage, the total injector voltage should be accurate to <0.025%. We are hoping to obtain energy regulation better than 1%.

Power dissipation occurring in the regulator circuit was varied from 39 MW (tubes off) to 23 MW (tubes on), for a controlled power swing of 16 MW (8 MW for each of the two modules). When used on the HAP injector, the lower current (750 A) will

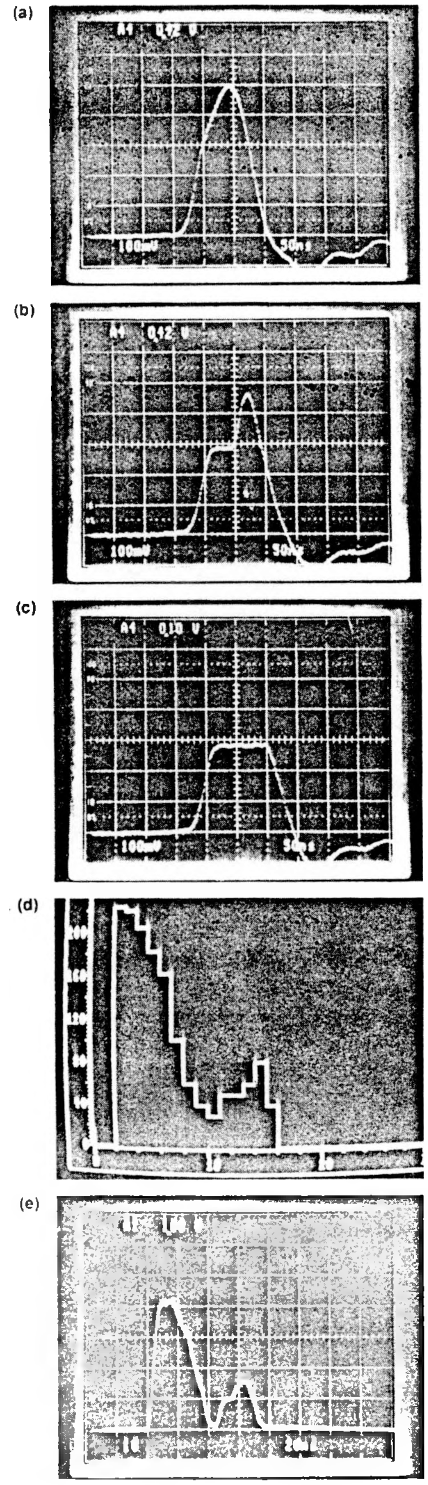

Fig. 7. (a) The uncorrected waveform is successively corrected (b,c) by a point-by-point correction input (d) into a computer and by (e) output to the modulator from the arbitrary function generator. Vertical scale for (a), (b), and (c) is 5 kV per division.

allow a larger voltage swing (15 kV) with a 12-MW power swing.

To insure an adequate safety margin on the 25-kV-rated input voltage, the cell current was increased until 40 kV was successfully dropped across the tubes. This was the tube manufacturer's (Eimac's) estimate of the tubes' internal breakdown voltage, and it was not deemed prudent to push any further. While the higher voltage allowed nearly twice the maximum tube current to flow and more than doubled the power swing (up to 18 MW per can), cathode lifetime and mean time between failures would suffer; this approach is therefore not considered. The modulator performance at rated voltage exceeded requirements, and no component failures were observed in the 100 hours of testing performed.

Frequency Response

While the modulator bandwidth in a small test circuit was found to be >50 MHz, some degradation was expected when the modulator was mated to the ferrite regulation cell. Figure 8 is an attempt to ascertain the modulator's bandwidth, including the cell response. The full power response shown in Fig. 8 has a 10–90% fall time of 16 ns and a 10–90% risetime of 12 ns. When one deconvolutes the effect of the changing pulse shape and the bandwidth-limited input of the arbitrary function generator from modulator response, a power bandwidth of >30 MHz is obtained.

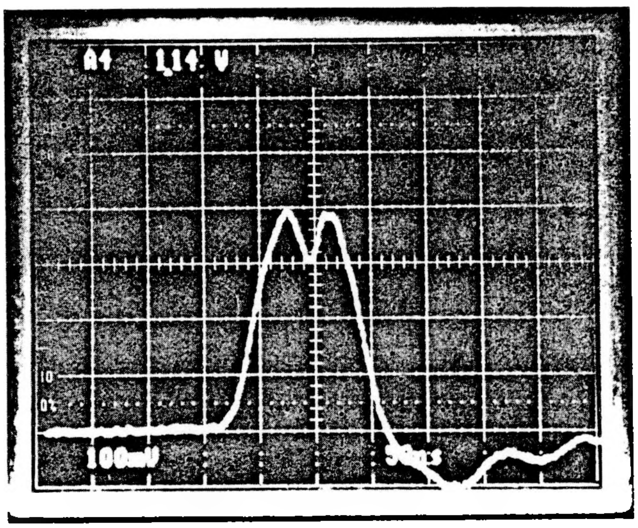

Fig. 8. A 30-MHz frequency response is inferred from notching the peak of the waveform.

Conclusion

Active intrapulse control of the gigawatt output of an induction linac electron beam injector can be obtained in a robust and cost-effective manner through shunt modulation of series cells. With the circuit described in this paper, large arrays of planar triode tubes can be paralleled to the required power levels. Output energy regulation of the subsequent accelerator cells can be obtained with the current variations produced with this modulator.

Acknowledgments

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References

[1] D.S. Prono et al., "High Average-Power Induction Linacs," in *Proc. 1989 Particle Accelerator Conf.*, March 20–23, 1989.

[2] E.E. Bowles and W.C. Turner, "50-MHz, 12-MW Induction Linac Current Modulator," in *Proc. 7th IEEE Pulsed Power Conf.*, June 11–14, 1989.

[3] K. Whitham et al., "Fast Correction Coils for Induction Accelerators," in *Proc. 7th IEEE Pulsed Power Conf.*, June 11–14, 1989.

Reference Documents

LEA 88-1913-01	Circuit Schematic
LEA 88-1913-02	Parts List
LEA 88-1913-03	Printed Circuit Board Art
LEA 88-1913-19- through -36	Piece Parts

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