ENERGY FLOW AND HIGH REPETITION RATE ISSUES FOR THE ETA II MAGNETIC MODULATOR SYSTEM

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Abstract

ETA II is a linear induction electron beam accelerator designed to operate at high repetition rates (<5 kHz) and high average powers (<3 MW). The 2 kA electron beam is accelerated with 70 ns, 100 kV pulses generated by a system of magnetic modulators. There are a number of critical issues associated with high repetition rate and high average power operation of the magnetic modulators in a linear induction accelerator power conditioning system. A discussion of the initial investigation into the high repetition reset issues is also presented.

Introduction

High average power operation of electron beam accelerators requires the ability to generate drive pulses efficiently and precisely at high repetition rates[1 2 3]. ETA II uses magnetic modulators (MAG 1-D s) to generate 100 kV, 70 ns drive pulses into 2 Ω at repetition rates up to 5 kHz. Magnetic modulator efficiency and reset become significant issues at high average powers and high repetition rates. Modulator inefficiencies which can be tolerated during low average power operation, result in major cooling problems in the magnetic core materials during high average power operation. In addition, this thermal load causes changes in the temperature dependent component characteristics throughout the modulator. The greater the temperature change the greater the component changes and the more difficult it becomes to generate a precise pulse train. Measurements were made to evaluate and understand the energy flow through the magnetic modulators on ETA II. The results of the investigation will be presented in this paper.

Reset also becomes an issue at high repetition rates because the magnetic cores in the magnetic modulators must be reset before each pulse. Stable and precise reset can be easily accomplished at low repetition rates but as the repetition rate increases and the time available for reset decreases, maintaining a precise reset condition becomes much more difficult. Precise reset is required because of the requirement to maintain a drive pulse jitter of less than 1 - 2 ns.[4] This paper will briefly describe the measurements that have been performed on the MAG 1-D to evaluate the reset issue.

System Description

The ETA II accelerator is driven by four magnetic modulators (MAG 1-D s)[5]. Each modulator drives twenty accelerator cells with a maximum output voltage of 100 kV. The MAG 1-D consists of three stages of magnetic pulse compression which compress a 3.8 μs charge pulse to a 70 ns output pulse with approximately a 20 ns risetime. The input voltage is also stepped-up from 25 kV at the input to 100 kV at the output with an auto-transformer in the MAG 1-D. A diagram of the MAG 1-D is shown in Figure 1.

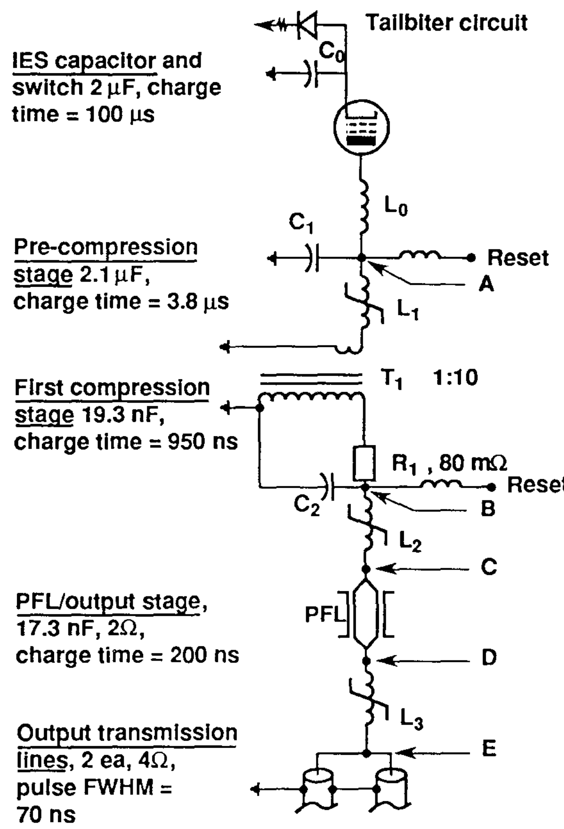

Fig. 1. Schematic of MAG 1-D magnetic pulse compression modulator.

The pre-compression stage of the MAG 1-D is charged from an intermediate energy storage (IES) capacitor C_0 through a thyratron switch. As the pre-compression stage capacitor reaches its peak voltage, the pre-compression stage reactor, L_1 saturates, discharging C_1, through the 10:1 step-up transformer, T_1, into the 1st stage water capacitor C_2. C_2 is charged in approximately 1 μs and discharges in about 200 ns when the 1st stage reactor, L_2, saturates. The PFL is charged in 200 ns and as the PFL voltage reaches its peak, the output switch, L_3, saturates and delivers the PFL energy to the load. The component values are listed in Table 1.

TABLE 1
Component values for MAG 1-D

Components	Values
C0	2.0 μF
C1	2.1 μF
L1 (sat)	87 nHy
T1	10 : 1 step-up
C2	19.3 nF
L2 (sat)	614 nHy
PFL	2 ohms, 35 ns
L3 (sat)	23 nHy

All cores in the MAG 1-D are wrapped with 2605 CO Metglas with the exception of the transformer which is 2605 SC. Mylar, .25 mil thick, is used for the interlaminar insulation in the cores.

Capacitive voltage dividers were installed on each of the capacitor stages in the MAG 1-D and on the output switch. Each of the capacitive voltage dividers were calibrated against a Tektronix P6015, 1000:1 high voltage probe. Each probe was calibrated in place in the MAG 1-D by inserting the high voltage probe through access ports at a symmetric locations on the modulator housing. The capacitive probes were then used to measure the voltages in the MAG 1-D under various circumstances to evaluate efficiency and reset.

Energy Flow Measurements

The voltage waveforms at each stage of the MAG 1-D were recorded at a constant input voltage but not simultaneously. The maximum energy stored in each stage was defined at the peak voltage of each stage. Table 2 shows a summary of these voltage measurements and the calculated maximum energy storage of each stage. From Table 2 it is easy to see that the losses increase dramatically near the output stage of the MAG 1-D. Approximately 236 joules are lost during the transfer of energy from the 1st stage water capacitor, C_2, to the PFL. This is not unexpected because the output switch sees the highest $\partial B/\partial t$ (~15 T/μs) This is nearly 36% of the energy stored in the IES capacitor, C_0. The overall efficiency of the MAG 1-D was measured to be approximately 58%.

TABLE 2
Summary of measurements on MAG 1-D

Stage	Voltage	Energy
IES capacitor	25.5 kV	655 J
Pre-compression stage	23.7 kV	592 J
1 st stage capacitor	246 kV	583 J
PFL	200 kV	347 J
Output pulse	103 kV	380 J

Further experiments were performed to attempt to understand the loss mechanisms in the last two stages where the majority of the losses appear to be. These experiments focused specifically on the transfer of energy to the PFL stage and magnetic losses in the output switch. In one experiment, the output switch was removed and the energy in the MAG 1-D was allowed to oscillate through the MAG. The voltage on the PFL was measured at its peak to determine the amount of energy that was transfered to the PFL with no output switch in the circuit. This value was then compared with the measurements taken with an output switch shown in Table 2 to determine the losses due to the output switch. A summary of the distribution of the energy losses in the MAG 1-D resulting from these measurements is shown in Table 3.

TABLE 3
Energy Balance Summary

1.	Energy dissipated in charging pre-compression stage	30 J
2.	Energy dissipated in water capacitor (1st stage)	37 J
3.	Energy dissipated in the PFL charge	32 J
4.	Energy dissipated in output reactor	85 J
5.	Energy dissipated in discharge of PFL	21 J
6.	Energy reflected into MAG 1-D	70 J
7.	Energy dissipated in load	380 J

The losses in Table 3 were further categorized as 120 joules in effective series resistance losses, 85 joules in the output reactor magnetic losses and 70 joules of energy reflected at the output stage back into the MAG 1-D.

Reset Issues

The magnetic cores in the MAG 1-D magnetic modulator must be reset before each pulse. This reset requires the application of a reset voltage, $v_r(t)$, across the core windings such that the integral of the reset voltage, $\int v_r(t)\,dt$, is equal to that of the integral of the main pulse voltage, $\int v_p(t)\,dt$. If these two integrals are not equal, then the core will not be fully reset before the next pulse. Timing variations in the output pulse will result from inadequate reset. It has been estimated that in order to maintain output pulse jitter of less than or equal to 1 ns, the core must be reset to within $1*10^{-3}$ Tesla[6]. Maintaining this type of accuracy becomes very difficult at high repetition rates where there is less time for reseting the cores. Presently dc reset is used to reset the cores.

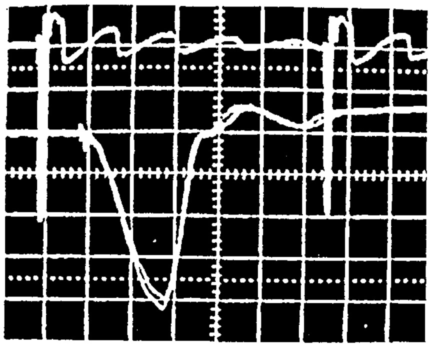

Fig. 2. Pre-compression stage voltage showing reflected energy that appears as reverse voltage on C_1.(Upper trace 50 µs/div, Lower trace 2 µs/div)

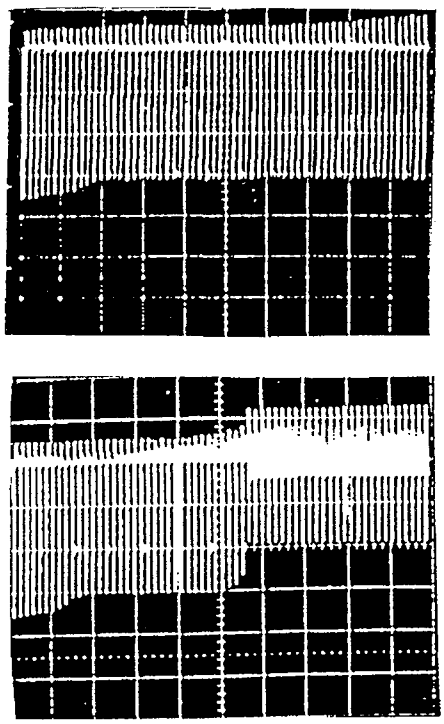

Fig. 3. Pre-compression stage voltage waveforms during bursts at 3 kHz in the top photo and 5 kHz in the bottom photo.

A preliminary investigation of high repetition rate reset was conducted on a MAG 1-D. One of the issues associated with the MAG 1-D that makes reset more difficult is the 70 joules of reflected energy that does not get delivered to the load. Figure 2 shows the reflected energy that appears at the pre-compression stage after the inital discharge pulse. This energy oscillates in the MAG 1-D for greater than 200 µs after the main pulse. These oscillations make it nearly impossible to maintain a stable reset condition at high repetition rates (3-5 kHz)

This reflected energy can easily be dissipated when it returns to the pre-compression stage of the MAG 1-D. The tailbiter circuit shown in Figure 1 was installed to dissipate this reflected energy in a few microseconds. Preliminary evaluations of the magnitude of the reset problem were made with the tailbiter installed. Figure 3 shows the effect of insufficient reset on the amplitude stability in the pre-compression stage during a burst of 62 pulses at repetition rates of 3 and 5 kHz.

From Figure 3 it is obvious that the present reset scheme is inadequate for repetition rates of 3 - 5 kHz. The problem seems to be less severe at 3 kHz than at 5 kHz as indicated by less amplitude variations, but neither is acceptable. This preliminary investigation shows that considerably more effort will be needed to fully understand and solve the reset problems.

Conclusions

Investigations have been conducted to study the efficiency and reset issues of the MAG 1-D. Voltage measurements on each stage indicate that although losses are distributed through out the entire MAG 1-D, a large fraction of the losses occur during the transfer of energy from the 1st stage water capacitor to the PFL. This can be partly explained by the losses in the output switch due to the high $\partial B/\partial t$ that the output switch sees.

A preliminary investigation of the reset problem was conducted in which significant variations of amplitude on the pre-compression stage capacitor were observed. The measurements indicate that the present system cannot produce stable pulses at repetition rates above 3 kHz. Additional work is needed to characterize the output pulse behavior at high repetition rates and to fully understand the reset dynamics.

Acknowledgements

All measurements described in this paper were conceived and executed by David Barrett.

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