PULSERS FOR THE INDUCTION LINAC EXPERIMENT, MBE-4*

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Summary

The MBE-4 proof-of-principle experiment uses an induction linac to accelerate four Cs+ beams from injection at 200 kV to almost 1MV. When completed in the summer of 1987 it will be 17.2 meters long and have 24 acceleration gaps and 6 diagnostic gaps. Careful tailoring of the accelerating voltage waveforms at each gap is required to accelerate the beam, amplify the current and provide longitudinal focusing. The ideal voltage waveforms required at the first 4 gaps are almost triangular with an amplitude of about 20 kV and an approximate width of 3 μsec, becoming flatter and shorter with an amplitude of 30 kV at subsequent gaps as the beam current increases and the pulse width narrows. These waveforms [1] are shown in Fig. 1. Pulser voltage waveforms at each gap are adjusted in both amplitude and firing time in conjunction with beam experiments to determine the required voltage waveforms of the subsequent pulsers. Existing cores and previous experience with thyratron pulsers provided the basis for the pulsers for the first half of the machine. During this fabrication period, additional cores and spark gap pulsers capable of generating higher voltages than the thyratron pulsers became available and a combination of both types of pulser will be used to complete the apparatus.

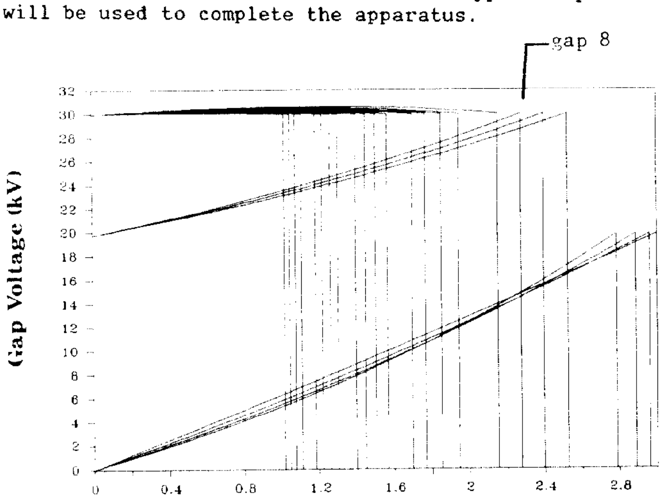

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Fig. 1 Ideal Accelerating Voltage Waveforms for all 24 Gaps

Introduction

MBE-4, when complete, will have 24 accelerating gaps. The initial complement of available cores consisted of 92 nickel-iron tape wound cores [2] capable of 6.8 mVsec/core and 26 silicon steel tape wound cores [3] capable of 24 mVsec/core. Groups of these cores were used with an appropriate number of thyratron pulsers to provide the necessary accelerating voltage waveforms at the first eight gaps together with the required voltage waveforms which provide the longitudinal control of the beam ends. Additional silicon steel tape wound cores capable of nominally 60 mVsec/core became available and some of these were used in conjunction with the existing cores to provide the necessary accelerating voltage waveforms at the next four gaps (#11 - 14) using thyratron pulsers. Four different pulser circuit types were identified as possible solutions for generating the required waveforms. These pulsers are typically identified by their generated voltage waveforms which are either parabolic, (1-cos ωt), trapezoidal, or capacitor discharge. Basic circuits were established to generate the required voltage wave-forms using thyratron pulsers and at the same time basic performance characteristics were established for the cores. In order to generate the parabolic waveform it was necessary to connect a resistor in parallel with the core so that it dominated the load resistance. This introduced additional circuit losses that are undesirable, therefore this circuit configuration has not been pursued. The computer program Spice [4], together with some basic characteristics for each type of core, has been used to predict the performance of any proposed circuit configuration. This has enabled the number and type of thyratron pulser circuits required for each gap to be defined so that they generate the specified voltage waveforms. A standard pulser package, including reset, was established which could operate at a maximum voltage of 30 kV, with the pulser output waveform characteristics being determined by the pulse-forming network installed internally in the designated area.

A spark gap pulser built by Ford Laboratories was modified to operate in conjunction with four of the nominal 60 mVsec cores. This pulser arrangement is used at two of the acceleration gaps to provide most of the acceleration voltage specified for four of the gaps. Corrections to the generated acceleration voltage waveform and the voltage waveforms required to provide longitudinal control of the beam ends are obtained using four thyratron pulsers.

Thyratron Pulser Development

An analytically derived model for magnetic induction cores [5] is, in its simplest form, a resistance in parallel with an inductance and this is used with the other appropriate circuit elements to predict pulser performance. The values of resistance and inductance used to represent a specific core is voltage-level dependent; core package measurements were made to determine these resistance values. An initial value of inductance was calculated and used with the appropriate core resistance equivalence at specific charge voltages to generate computed voltage and current waveforms. The inductance value was modified using the measured current waveform as reference until the computed waveform matched the measured waveform up to saturation level. This was carried out for all the different core packages to establish the core model [6] for any core/circuit combination.

The computed and measured characteristics for a

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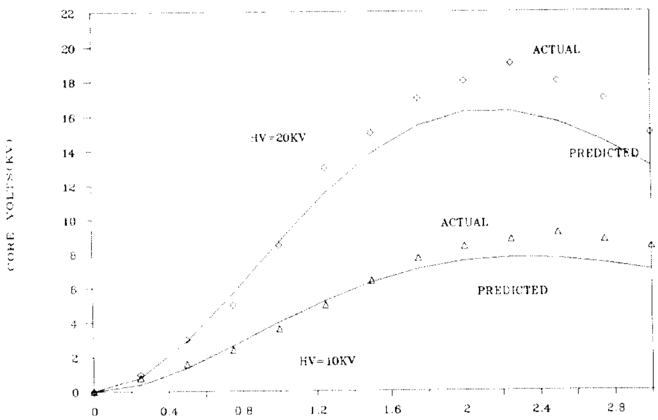

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Fig. 2 Computer predicted and measured core voltage for a core package containing two 24 mVsec silicon steel cores and a (1-cos ωt) pulser at a charge voltage of 10 kV and 20 kV.

core package containing two 24 mVsec silicon steel cores and a (1-cos ωt) pulser at charge voltages of 10 kV and 20 kV are shown in Fig. 2. All the (1-cos ωt) and capacitor discharge circuit arrangements used on MBE-4 were evaluated in the same way and showed reasonable agreement between the measured and computed waveforms. The computed and measured results for a trapezoidal waveform pulser using a core package containing two 24 mVsec silicon steel cores has been demonstrated. This circuit configuration has not yet been used on MBE4 because it is not compatible with an optimized pulser arrangement for the required accelerating voltage waveform schedule.

Selection of the core package arrangements, type of pulsers and number of pulser circuits is carried out by matching these to the accelerating voltage specified for a given gap. The number of pulser circuits is kept to a minimum and the core package usage is maximized. Computed voltage waveforms, within the limits of the standard thyratron pulser, for each of the proposed pulser circuits are generated. A composite of these waveforms is also produced so that it can be compared with the specified waveform. A capacitor discharge pulser and a (1-cos ωt) pulser each using a core package containing two 24 mV sec silicon steel cores was proposed for gap 8 and the computer predicted waveforms are shown in Fig. 3. This can be compared to the ideal accelerating voltage waveform for gap 8 as shown in Fig. 1.

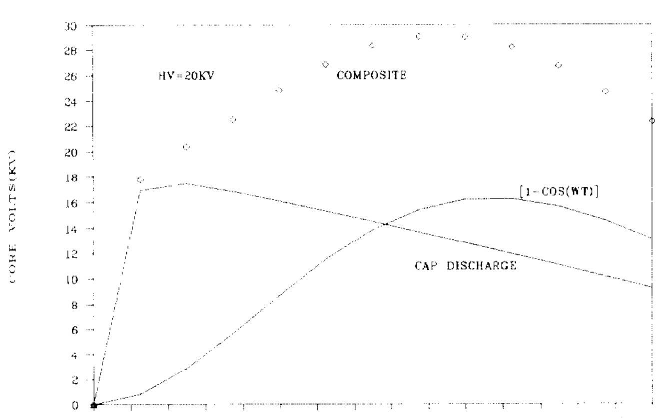

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Fig. 3 Predicted individual and composite voltage waveforms for a (1-cos ωt) pulser and a capacitor discharge pulser for a charging voltage of 20 kV each. The core package for each pulser contains two 24 mVsec silicon steel cores.

Two pulsers are normally provided at each gap with additional pulsers being provided at the gaps requiring more complex waveforms. With the capability to control the pulser charge voltage and the trigger time to 10 nsec, it has been possible to minimize the error between the calculated and generated acceleration voltage waveforms. The voltage specified for gap 11 was considered complex and a considerable amount of flexibility was requested. Computer waveform simulation was carried out and from this a four pulser configuration was selected. The ability of this group of pulsers to match the calculated acceleration voltage waveform, which is based on the measured performance at the previous gap, for gap 11 is shown in Fig. 4. [7]

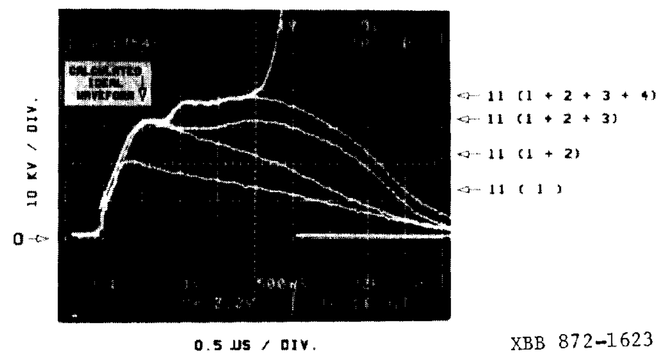

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Fig. 4 Comparison of the calculated ideal voltage waveform with the actual composite voltage waveform at gap 11 using four thyratron pulsers.

Spark-Gap Pulser Development

In the spring of 1986 we learned that a project to build an electron induction linac by Ford Laboratories had been discontinued. We then purchased enough of their fabricated silicon steel cores to complete MBE-4, and embarked on a study of their pulser design to see if their excess pulsers could be usefully incorporated in MBE-4. This, indeed, proved to be the case but at the cost of minor modifications to the planned accelerating schedule in the last half of MBE-4. It was pleasing to find that the induction linac design proved flexible enough to accommodate a rather different core arrangement, and quite a different pulser design. The incorporation of the new pulsers, switched by spark-gaps rather than thyratrons, gives a broader base to our pulser technology development.

The results of these tests indicated that the desired flat waveforms in the high energy end of the accelerator could be approximated by the waveform in Fig. 5, augmented by low amplitude (1-cos ωt) pulsers. Whereas the initial design of MBE-4 was based on a maximum voltage of 30 kV per gap and one or more pulsers per gap to obtain the voltage, the new design is 60 kV across each of two adjacent gaps, all driven by one higher power pulser. To achieve this, 4 cores are driven in a series parallel configuration as shown in Fig. 7.

Without correcting networks, the core voltage is a monotonically decreasing function of time as the pulser capacitors are discharged. To flatten the voltage pulse, we added a small series inductance to the existing self inductances of the capacitors, spark gap, and wiring, to obtain a 2:1 voltage divider between the core impedance and the rest of the circuit. Then, to counteract the pulse droop, we added across each of the cores an LC circuit whose function is to take some energy out of the main energy storage capacitor at the beginning of the pulse, and put it into the core near the end of the pulse.

By pulsing the induction cores from remanent B field to saturation in both directions, we found that a typical core has: B_s = 13.5 kG, B_r = 11.2 kG, I_r > 250 Amps, where B_s is the saturation flux density, B_r is the remanent flux density, and I_r is the current required to slowly reset the core. The radial packing fraction, f, which is the ratio of core lamination thickness divided by the lamination plus insulation thickness, was measured as 0.8. Combining these values with the cross sectional area, A_c, of the 11" x 4" core results in an available flux change, $\Phi = (B_r + B_s)fA_c$, of 54 mVsec, the usable fraction of which is determined by the core saturation characteristics and the drive circuit to be about 80% for the 1.4 μsec pulse in Fig. 5. The pulse excitation current, or "step" for these cores is about 1 kA, after which the core current shows a saturation wave-like linear increase up to about the 4 kA level. With the aid of this preliminary data the circuit shown in Fig. 7 was constructed and resulted in the voltage and current waveforms shown in Figs. 5 and 6 respectively. A good discussion on pulse magnetization is found in Chapter 15 of Reference [8].

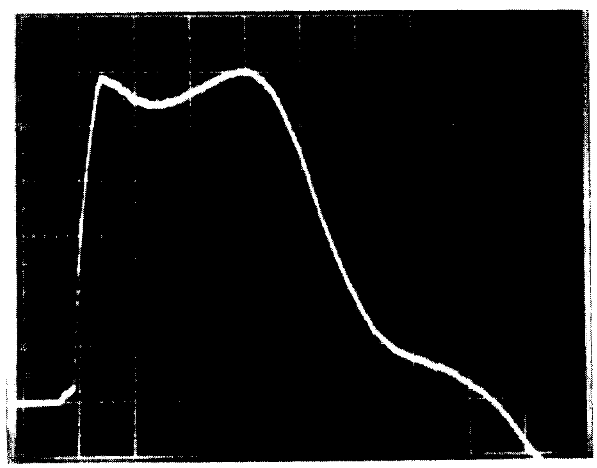

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Fig. 5 The accelerating voltage appearing across each of the four induction cores driven by one modulator.

Vert. scale: 5 kV/div. Horz. scale: 500 ns/div.

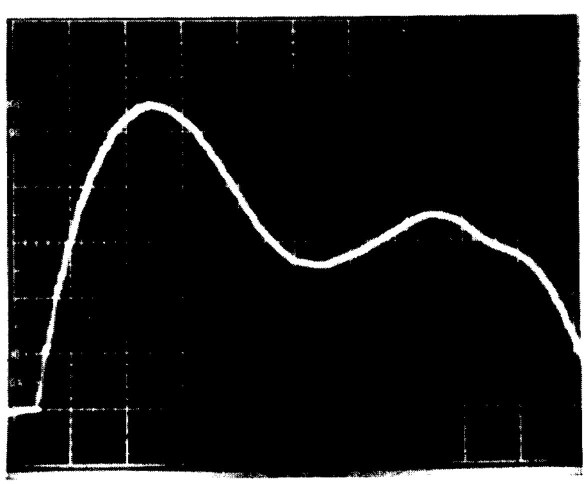

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Fig. 6 Modulator output current for the voltage pulse in Fig. 5. As the core enters saturation, near the center of the picture, most of the current is being supplied by the correcting network, whereas at the beginning of the pulse much of the modulator current is going into the correcting network.

Vert. scale: 600 A/div. Horz. scale: 500 ns/div.

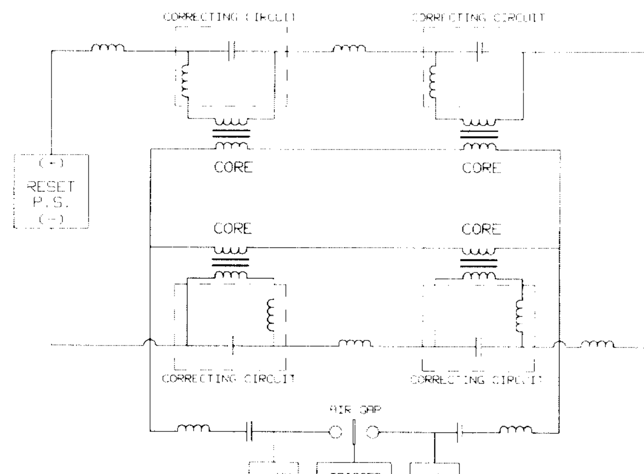

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Fig. 7 The spark gap pulser circuit

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