ENERGY SWEEP COMPENSATION OF INDUCTION ACCELERATORS

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Abstract

The ETA-II linear induction accelerator (LIA) is designed to drive a microwave free electron laser (FEL). Beam energy sweep must be limited to ± 1% for 50 ns to limit beam corkscrew motion and ensure high power FEL output over the full duration of the beam flattop. To achieve this energy sweep requirement, we have implemented a pulse distribution system and are planning implementation of a tapered pulse forming line (PFL) in the pulse generators driving acceleration gaps. The pulse distribution system assures proper phasing of the high voltage pulse to the electron beam. Additionally, cell-to-cell coupling of beam induced transients is reduced. The tapered PFL compensates for accelerator cell and loading non-linearities. Circuit simulations show good agreement with preliminary data and predict the required energy sweep requirement can be met.

Introduction

Linear induction accelerators (LIAs) are used for the production of high average power charge particle beams. These accelerators have been operated at high current (greater than 1 kA), moderate energy (order 10 MeV) and at high repetition rates (order 5 kHz) [1-3].

An LIA consists of an injector used to generate the initial charge particle beam pulse, multiple accelerator cells, and a pulse generator with a pulse distribution system [4]. The injector normally consists of multiple accelerator cells with an internal conductive structure, which in the case of ETA-II, contains an electron source on a "cathode shank" and a re-entrant anode structure. This injector geometry sums the energy gain of individual cells and allows achievement of the required beam qualities.

Energy sweep is defined as the quantity dE/E, and represents the variation of the beam energy about some mean value. In the LIA, non-linear loading at the accelerator cell is inherent. Consider a simplified model of the pulse generator and accelerator cell (Fig. 1). The energy gain at the accelerator cell, proportional to V_b, is a function of the cell current, i. e., current through C_{gap}, the ferrite current, and the beam current. As ferrite current is a function of the integral of the voltage at the cell, a non-linear accelerator cell response results [5].

From the circuit equations, the effect of the ferrite non-linerity takes the form:

$$\frac{dV_b}{V_b} \simeq \left[\frac{Z_0}{Z_f}\right]\left[\frac{dZ_f}{Z_f}\right] \tag{1}$$

As an example, ETA-II uses PE-11B NiZn ferrite and a cell source impedance of Z_o=40 ohm. From previous data [5], dV_b/V_b, which is proportional to the energy sweep, is calculated to be 6% when 75% of the volt-second product of the ferrite cores is used.

For the simplest case, compensation of the energy sweep contribution at an accelerator cell, on the s-plane, requires:

$$\frac{V(s)}{H(s)} = \frac{V_0}{s}\left(1 - e^{sT}\right) \tag{2}$$

where H(s) is the pulse distribution system and cell response, V(s) is the applied pulse, T is the pulse width, and V_o is the accelerator gap voltage.

To compensate the energy sweep contribution at an accelerator cell, H(s) and V(s) may be adjusted. For an ideal V(s), i. e. $V(s) \propto s^{-1}$ and a non-perturbing pulse distribution system, H(s) can be made to approach a constant by modifying the total cell current to eliminate non-linearities. This modification of H(s) can be done by adjusting the beam current profile or by introducing additional components at the accelerator cell, i. e. non-linear components [6], RLC filters, etc. Modification of V(s) for a defined H(s) requires modification of the pulse generator.

Minimum total accelerator energy sweep requires minimum energy sweep at the injector or the use of compensating accelerator cells. The latter assumes the energy sweep associated with the injector is fixed and the initial accelerator cells are used for compensation. That is, the sum of the injector and these accelerator cells result in a minimum total energy sweep. Although slightly less than ideal for minimum corkscrew motion [7], this technique is considered here.

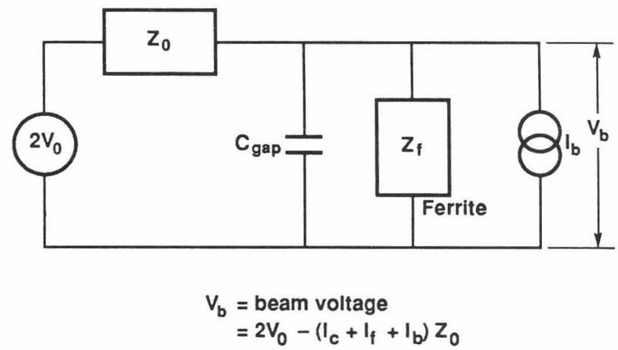

Figure 1. Simplified Pulse Generator and Accelerator Cell Model.

Energy Sweep Compensation on ETA-II

The predominant factors on ETA-II which influence H(s) are: beam and applied high voltage pulse phasing, accelerator cell feed structures, and the non-linear effects of the cell ferrite. In the initial stages of development on ETA-II, the accelerator cell feed structures were dominant in the determination of H(s).

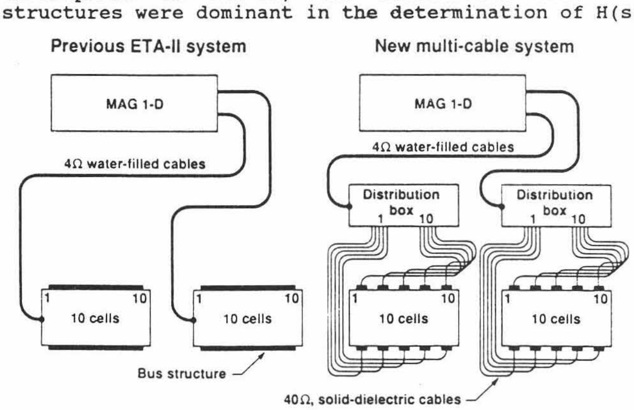

Figure 2. ETA-II Modifications. Previous ETA-II bus structure (left). Modified ETA-II "two cell" bus structure (right).

The high voltage pulse on ETA-II was previously applied to the accelerator cell through two bus structures on each side of a module of ten accelerator cells (Fig. 2). The pulse generator, i. e. MAG1-D [8], was connected to the 10 cell module through a single cable. Two effects were associated with this structure. First, the capacitance associated with each accelerator cell combined with the bus structures to form a slow wave structure. Second, the beam return current introduced transients on this slow wave bus structure with a polarity opposite to the applied high voltage pulse. Improper phasing of the high voltage pulse with the beam and severe distortion of the MAG1-D pulse resulted. Compensation was much more difficult since the total response of the feeds, cells, and their interaction needed to be considered.

A new accelerator cell feed was developed and implemented. The slow wave bus structure was replaced with a bus connecting two accelerator cells. This "two-cell" feed structure placed the cell capacitance across the bus termination. Slow wave transit time effects were eliminated. Distribution to each two cell structure was done with individual transmission lines properly timed to the beam transit. Thus, this new system only introduced a time delay and nearly isolated the response of a single cell.

In this new system, compensation can be accomplished by adjustment of V(s). This compensation may be done in two ways. The first method relies on the output characteristics of the MAG1-D at various voltages, i. e., the output pulse shape varies with output voltage [9]. By properly adjusting the output voltage pulse amplitude, a minimum energy sweep may be obtained. This technique, however, confines the accelerator to a single operating point in our energy range of interest. We present the modeling, sensitivities and preliminary test results in the section Single Operating Point Compensation.

The second method requires the use of a variable taper PFL [10], i. e., a PFL with an adjustable impedance variation along its length. The impedance variation results in an output pulse shape required to meet the cell impedance non-linearities with minimum energy loss. This method allows energy sweep compensation at any accelerator operating point. We present our initial analysis and sensitivity calculations in the section Multiple Operating Point Compensation.

Single Operating Point Compensation

Cell response modeling using SCEPTRE [11] and prototype verification were performed to determine the performance of the two cell structure. The model included the non-linear effects of the ferrite and was implemented by a function derived from experimental data. Typical performance of the model compared with measurement is shown in Figure 3.

The combined effect of the bus structure connecting the two independent cells was taken into account by directly measuring the voltage across a two cell structure. Agreement between the measured and calculated two cell voltage pulse shape was within 1% in an area surrounding the peak. Absolute amplitude was in agreement within 10%.

Analysis of the accelerator performance was similarly performed using MAG1-D output pulse and previous beam current data (Fig. 4). Significant energy sweep, however, associated with the injector is present in the ETA-II system. Elimination of this energy sweep required intentionally introducing additional sweep at the accelerator cells which countered that of the injector.

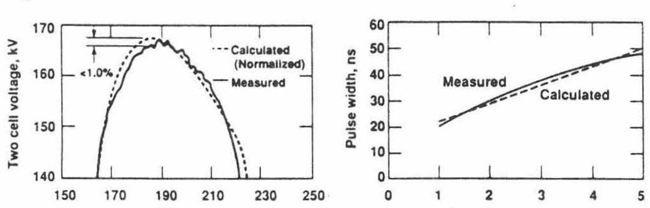

Figure 3. Circuit Model and Prototype Measurement

The parameters of Injector Timing (injector pulse to accelerator cell voltage pulse arrival timing) and MAG1-D input Charge Voltage, $\propto V_o$, were varied to obtain a maximum pulse width (total accelerator energy sweep) of 38 ns, ± 1% energy sweep (Fig. 5). The optimization curve exhibits the property of being relatively insensitive to both parameters.

In our present experiment of 20 accelerator cells, the minimum total energy sweep occurred at an accelerator cell gap voltage of 80 kV. We are presently planning a 60 cell experiment. The sensitivity of the energy sweep at individual cells to timing jitter at this voltage, however, was found to be unacceptable. Further analysis showed that this sensitivity was significantly less at 90 kV without degradation in the total energy sweep. Thus, consistent with the objective of maximum pulse width at the cell and minimum sensitivity, we plan to operate the remaining 40 accelerator cells at this gap voltage of 90 kV.

Simulations were also performed using the BREAKUP code [12] to predict the resultant corkscrew amplitude. Results from the calculation indicated an amplitude on the order of ± 250 microns. Comparison with simulations developed for the previous ETA-II bus structure (Fig. 6) indicate that the corkscrew amplitude will be reduced by at least an order of magnitude.

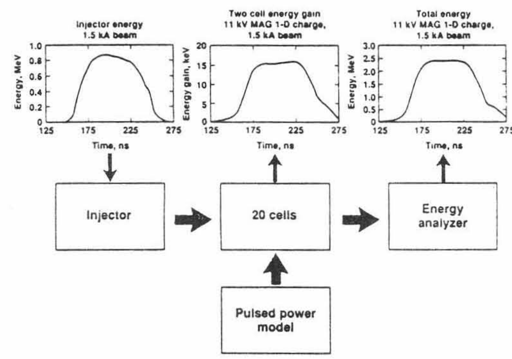

Figure 4. Compensation of the ETA-II 20 cell experiment.

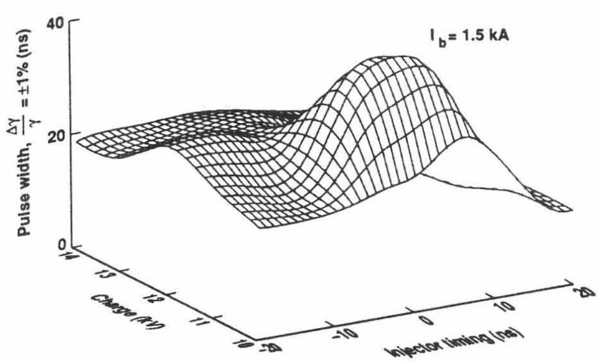

Figure 5. ETA-II 20 Cell Experiment Pulse Width Optimization Surface. Pulse width values are for dE/E= ± 1%, I_{beam}=1.5 kA.

Multiple Operating Point Compensation

Additional calculations were performed to evaluate the performance of a variable taper PFL in the MAG1-D pulse generator. Physically, the device is a tri-plate transmission line. This configuration allows two objectives to be met. First a more uniform constant impedance transition can be made from the PFL to the coaxial output switch, and second, mechanical actuators necessary to control the impedance taper can be easily implemented.

Optimum impedance tapers were calculated for two experimental beam currents (Fig. 7). A resultant pulse for the matched cell case, i. e., Z_{cell}=40 ohm is shown in Figure 8. It was determined that

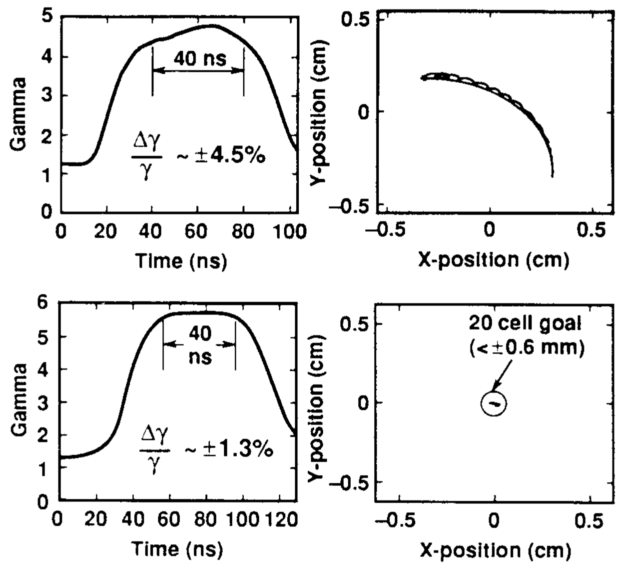

Figure 6. BREAKUP Simulations. Corkscrew motion is plotted for 40 ns as shown in each accompanying plot. ETA-II simulations for previous bus (top). Simulations of expected results (bottom), dE/E= ± 1.3%.

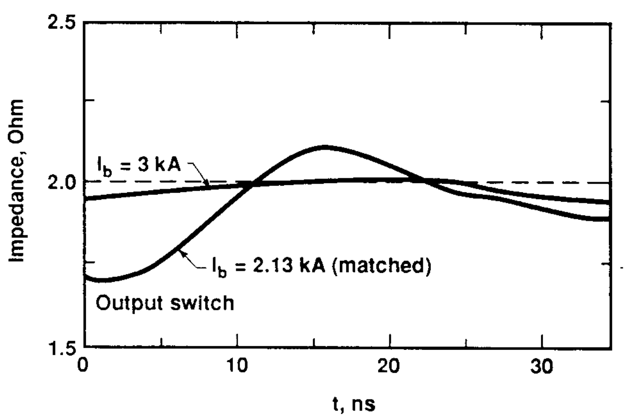

Figure 7. Optimum impedance tapers for specified beam currents.

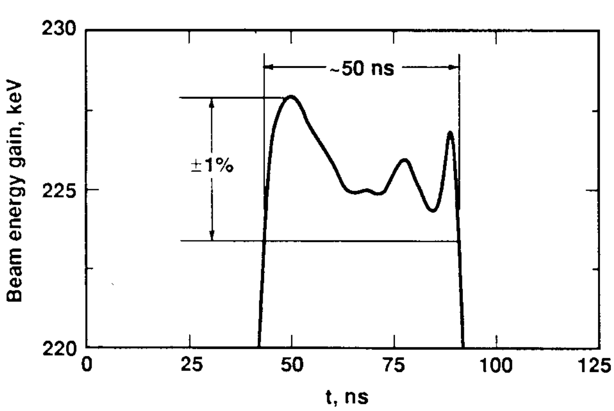

Figure 8. ETA-II "Two-cell" Acceleration Gap Voltage Pulse. I_{beam}=2.13 kA.

increased beam currents required less impedance taper. Reduced pulse width resulted, however. We speculate that the reduced impedance taper results from the self compensating effects of the beam current profile toward the peak and trailing edge of the pulse.

Development

Further refinements in the modeling effort are required. In addition to refinements in modeling magnetic materials, i. e. accelerator cell ferrite and the MAG1-D output switch, investigation into design centering of the PFL taper is required. We are pursuing each of these areas.

We are also considering the alternate implementation of the tapered PFL in the MAG1-D driving the injector on ETA-II. This implementation would allow compensation of the cell response by adjusting the beam current profile.

Acknowledgments

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