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PRECISION INTENSE PARTICLE BEAM ACCELERATORS USING IN-SITU TUNING TECHNIQUES

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Summary

Modern superpower accelerators are capable of up to 15 MeV and over 10 TW in 100ns pulses using oil or water insulated pulselines. Previous pulseline accelerators[1,2] have generally had to accept a pulse shape somewhat different than the design based on computer simulation (due to unpredictable load dynamics in many cases). This paper presents an iterative perturbation theory approach to accelerator design. The approach utilizes a transmission line whose taper can be adjusted in-situ, thereby permitting corrections to the voltage waveform during operation with the actual dynamic particle beam load. Two successful examples of this iterative perturbation theory approach are: (1) the achievement of a ramped voltage pulse to bunch a light ion beam ICF driver. The ORCA-I 1 MeV - 200ns accelerator[3] with ± 1% precision has been tested and is now used in low emittance light ion beam ICF driver research[4], (2) the suppression of voltage droop in a field emission diode with plasma induced gap closure. A precise (± 1%) voltage plateau is achieved for use in high rep-rate generators[5] for pre-ionizing high energy gas laser chambers.

Application to Distributed Pulselines

For short (200ns or less) high voltage pulsers, it is customary to use a water insulated pulseline.[1,2,3] The 1 MeV - 250ns ORCA-I accelerator[3] has proven uniquely capable of producing precision ramp voltage pulses for ion beam bunching applications. In this section the in-situ perturbation method of tuning the voltage ramp to a desired shape is described. An in-house computer code, PCTLINE, has been developed for use in initially characterizing a given waveform and subsequently determining the effect of a perturbation.

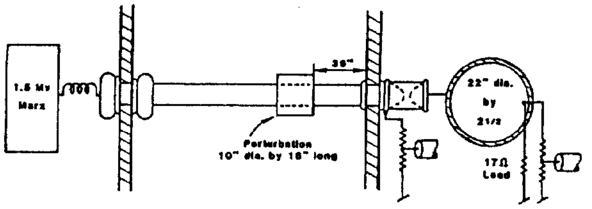


Fig. 1: An example of an impedance modification to the pulseline.

Consider the 250ns ORCA-I pulseline which is simply sketched in Fig. 1. Note the short larger diameter sliding stub on the center conductor. As shown in Fig. 2, the location and effect of this stub on the load voltage waveform has been determined quite similar for both an ORCA-I shot and a PCTLINE simulation. The ramp has been achieved by switching the pulseline onto the load about 200ns prior to and at about 60% of maximum resonant charge transfer. By appropriately adjusting the number, size, and location of these perturbations, higher order transient oscillations on the load voltage, such as seen in Fig. 3, can be suppressed as exhibited in Fig. 4. As described in more detail elsewhere,[3] the ramp in Fig. 4 matches a desired theoretical ramp (for 20:1 beam bunching) to within ± 1%. This procedure can readily and economically be used with the same accelerator to tune-in other desired voltage ramps and/or plateaus.

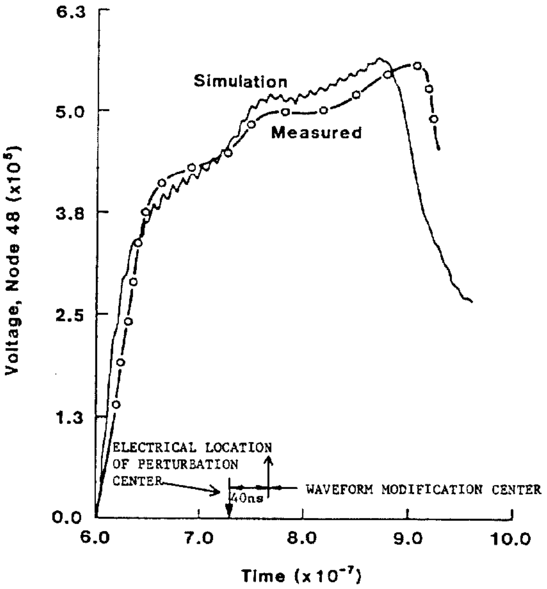
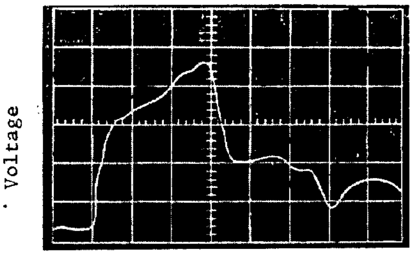
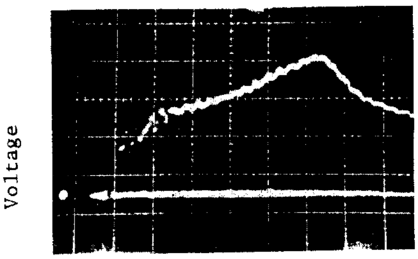


Fig. 2: The effect of an impedance perturbation on a simulated and measured load voltage waveform.



200 ns/div

Fig. 3: An ORCA-I voltage pulse demonstrating transient oscillations on the voltage ramp.



50 ns/div

Fig. 4: An ORCA-I voltage pulse without transient oscillations on the voltage ramp.

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Application to Pulse Forming Networks

In certain applications, such as electron beam pre-ionization of large volume gas lasers, long pulses (over 1μs) are desirable. Instead of the distributed line discussed in the previous section, it is more practical to use a pulse forming network, or PFN. The required voltage is obtained by combining a series of identical PFN's into a Marx generator.[5] The desired average power is achieved by rep-rating the Marx in excess of 100 Hz. One of the main concerns is that the electron diode suffers from gap closure due to plasmas created by electron field emission.[5] This causes the diode voltage to droop well below the desired voltage plateau (should be flat to within ± 5%) for uniform gas ionization. To demonstrate that this problem can be alleviated, this section treats a PFN Marx design for both a constant 35Ω load and a worst case Child's law load and demonstrates how the voltage plateau can be tuned in-situ.

An example circuit for a pulse forming network is shown in Fig. 5. Note that there are effectively eight T-line sections of 20nF and 500nH each (i.e. 250nH on each leg of the Tee with the ends lumped into required larger inductances). The characteristic impedance is thus 5Ω, which represents a 35Ω source impedance for a typical 7-stage PFN Marx (e.g. with 50kV/stage charge voltage). The electrical length of each section is 100ns which ideally relates to a 1.6μs pulse width.

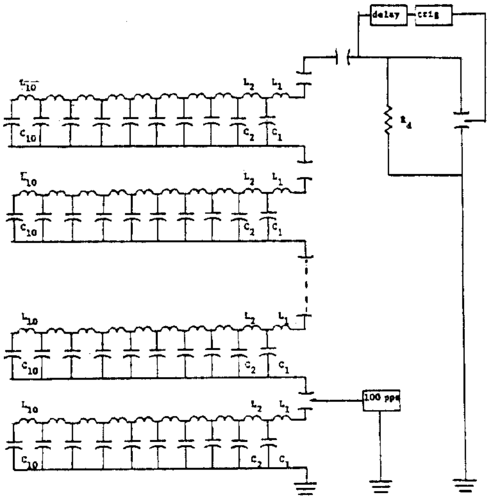

Fig. 5: 600 kV PFN Marx Generator

The PCTLINE computer code was used to simulate a 7-stage PFN Marx terminated in a 35Ω load. The load voltage waveforms are exhibited in Fig. 6. The solid line waveform is seen to have a 125ns 10% to 90% risetime, a 350kV voltage plateau that is flat to within ±2% over a 1.2μs duration, and a 290ns 10% to 90% falltime. The risetime infers an effective source plus load inductance of

$$L = \frac{\tau R_L}{2.2} = 8\ \mu H$$

which can be divided among the diode envelope (~1μH) and the prompt inductance of the erected PFN Marx. Note that this is ~1μH/stage, whereas the T-line symmetry would require only 250nH/stage for a total of 1.75μH prompt inductance. The lower prompt inductance induces ringing, however, which occurs because the related 46ns risetime is too fast for the 100ns electrical length PFN section to follow. As indicated by the ringing at the leading edge of the dashed waveform in Fig. 6, a prompt inductance of 3.8μH is also insufficient. The other dashed line shows the plateau degradation induced by too much (10μH) prompt inductance. Obviously, the risetime effects can be optimized by tuning the prompt inductance in each stage of the PFN. If a faster risetime were desirable (say 62.5ns 10-90%), then the number of PFN sections must be increased (e.g. doubled) thereby increasing the system cost and size, and making the allowable system packaging tolerances more stringent.

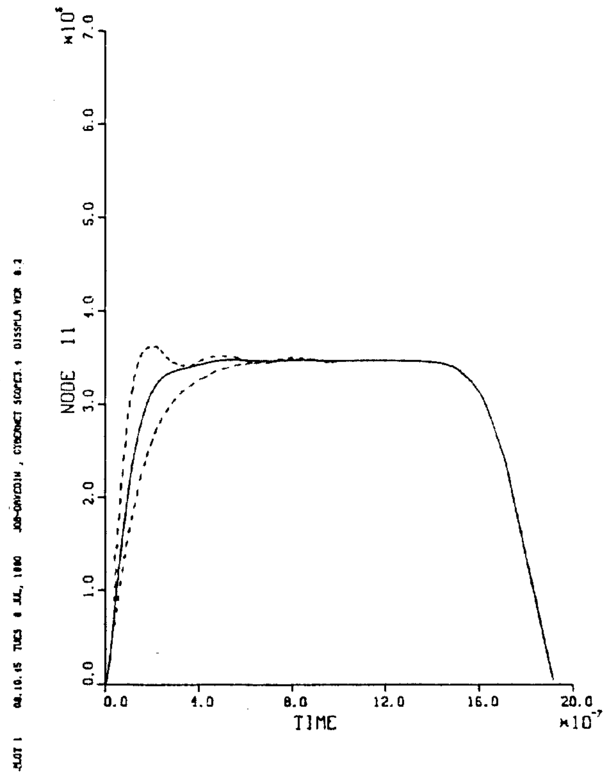

Fig. 6: Simulated voltage waveform for a 35Ω load.

The longer pulse falltime is due to risetime slowing in the PFN due effectively to the total series inductance in the erected PFN Marx (of 32μH) and the 1.2μH load inductance, and to the non-ideal 40nH simulation of an open circuit (which is a requirement of the resonant charging circuit). The best way to estimate this slow falltime is to crowbar the electron diode at the end of the voltage plateau.

Whereas the voltage exceeds half its peak value over the effective 1.6μs electrical length, the plateau is flat to within ±2% only over 1.2μs. The risetime and falltime are thus shown to be part of the justification for making the PFN electrical length longer than the ideal 1μs length.

By adjusting the inductance between capacitors (simply done experimentally by appropriately shorting turns or fractions of turns), the plateau accuracy could be improved. This will be necessarily and more dramatically demonstrated for the example dynamic load equation

$$Z_L(t) = 36(d - vt)^2\ \Omega$$

which is an empirical simulation of a space charge limited electron beam impedance profile[5] of initially 36Ω (for a 6cm vacuum gap) and a cathode plasma expansion velocity of 2cm/μs (producing 16Ω 1μs after onset). Note that any impedance characteristic deduced experimentally could be used in place of the above empirical formula.

The PCTLINE simulated waveform for the empirical Child's Law load is represented by the solid line in

Fig. 7. Note that the voltage plateau droops to about 50% of its initial peak value, which is quite drastic relative to the constant 35Ω plateau shown dashed in Fig. 7. This droop can be compensated by producing an increasing voltage taper in the PFN. The simplest way to do this is to reduce the inductance in each successive section by an appropriate amount (in practice by shorting the required number of turns or fractions thereof). The result is a shortening of the plateau duration because the effective electrical length of each section has been made successively shorter. The resulting pulse (shown dashed in Fig. 7) equals 300kV to within ±1% over 750ns even for this worst case dynamic load. If the inductance and capacitance of the last two sections in the PFN were doubled, then this flat-top would be extended to 1μs and then restored to within ±1% with minor inductance adjustments.

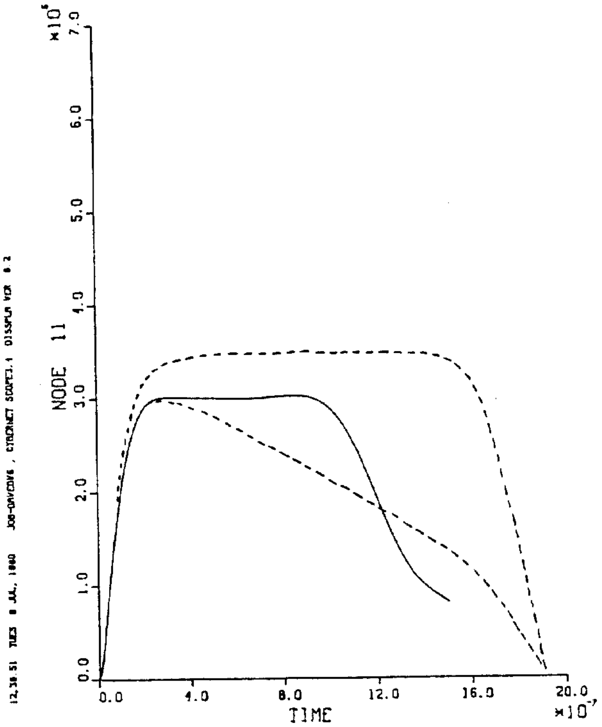

Fig. 7: Simulated voltage waveforms for a Child's Law load.

Note that there has been an energy penalty paid in producing this flat-top pulse with the dynamic load. Whereas the minimum matched load energy transfer would be 3.5kJ (e.g. 500 J/stage for an ideal 0.5μs electrical length, 5-section and 5 J/stage capacitor PFN), the dynamic load requires 8 sections and 10 capacitors/stage or 7 kJ stored energy. This 50% transfer efficiency to the electron diode is still better than driving the load with a stiff Marx generator (say 35kJ, or ten times the energy delivered to the load) and the PFN Marx plateau variation is also better than the (10% or more) inherent droop of a simple Marx.

Conclusion

A technique has been described for using a transmission line computer code to initially design a desired voltage wave shape on a transmission line and subsequently to improve the match of this wave shape with a desired theoretical requirement using an iterative perturbation technique. Application of the method to a distributed pulseline and a pulse forming network has been presented.

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