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PULSED BEAM CHOPPER FOR LAMPF*

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Summary

A pulsed beam chopper has been designed and tested for use on the 750 keV proton injector transport line of LAMPF. The deflection structure, which is 1 m long, is similar to the traveling wave beam deflector in a high speed oscilloscope. The proton beam travels between two deflection "plates" each consisting of the closely spaced turns of a helical delay line. A 5 ns long positive pulse on one helix with a simultaneous negative pulse on the other helix creates a transverse electric field in the beam region which travels with the beam. The longitudinal velocity of the electric field is matched to the proton beam velocity (~1 cm/ns) by the pitch of the helices. This scheme allows the 5 ns (5 cm) long "micropulses" of LAMPF to be chopped into or out of the linac with 1 ns transition times. This method avoids the constraints of resonant chopping systems and will permit completely arbitrary patterns of LAMPF micropulses to be selected and accelerated. One exotic application is the generation of pseudo-random pulse sequences for neutron time-of-flight measurements.

Introduction

This chopper is designed to accomplish two basic tasks. The first and simpler requirement is to insert a few microseconds gap near the end of the 500 μs long LAMPF proton macropulse. The gap will allow a fast pulsed kicker magnet in the LAMPF switchyard to turn on without spilling beam. This magnet steers the remaining few microseconds of the LAMPF macropulse down a new beam line to a thick neutron producing target at the Weapons Neutron Research facility. Neutron beams from this target will be used in experiments which will utilize time-of-flight techniques.

The proton beam is naturally broken into a fine structure of micropulses by the accelerating process. These are derived from 5 ns long portions of the D. C. beam from the injector, bunched in the transport line for improved acceptance into the accelerator, and at the exit of the accelerator have a length of about 80 ps and a 5 ns spacing. Usually beams destined for the neutron area will consist of single micropulses or a fixed number of adjacent micropulses repeated at a fixed rate. A less common mode might be to chop the beam into a repetitive pseudo-random binary sequence of micropulses.

A relatively unsophisticated pulsed chopper can provide the beam gap for the kicker magnet to turn on, since rise times are not crucial. Certain combinations of single or adjacent micropulses at a few repetition rates can be provided by resonant circuit chopping systems such as the one already in use on the H^- transport line at LAMPF. However, in order to obtain complete flexibility in number of micropulses and frequency of repetition, or to provide pseudo-random sequences, a very fast pulsed system must be used.

Design

To completely fill one time "bucket" of the linac with protons and not have any protons in the adjacent time buckets, a perfect 5 ns long "square wave" of protons through the chopping aperture would be required. As the transition time between beam on and beam off approaches 2 ns, one must either pass a partially filled micropulse into the linac, or allow transmission of some particles in adjacent micropulses. Transition times of 1 ns are possible for a pulse amplifier delivering several hundred volts into 100Ω at a high instantaneous duty factor, allowing for complete isolation of a single micropulse with some reduction in the protons delivered to the accelerator.

The voltage required to deflect the 750 keV proton beam onto the chopping aperture depends on the length of the deflection structure through which the beam passes. To reduce the voltage requirement to the several hundred volt level, the length of the structure must be on the order of 1 meter. The velocity of a 750 keV proton is about 1 cm/ns, and the requirement that the flight time of the beam through the deflection plates be less than the transition time of the chopped beam means this 1 meter long deflection structure must be broken into one hundred 1 cm long plates. This is not required for resonant deflection systems but is for pulsed systems, assuming one does not have extra voltage for "overpulsing."

This concept is shown schematically in Fig. 1 as a 100 element lumped constant line. The L's and C's would be chosen to provide the proper time delay per element to match the propagation of a voltage pulse on the line to the velocity of the beam. As the beam passes down between the plates of the capacitive elements of the line, it will see an electric field across them only if it is in phase with the voltage pulse. If it preceeds or follows the pulse by 1 ns (1 cm) then it will see no electric field across any capacitive element and will pass through all elements undeflected.

In practice, lumped element lines cannot be constructed with this number of elements without intolerable degradation of the 1 ns risetime. Ideally the plates should be incorporated as parts of a transmission line, where distributed elements rather than lumped elements allow the 300 MHz bandwidth required.

We have taken an aluminum plate of dimensions 6 mm x 90 mm x 1 m for use as a ground plane. A copper ribbon is wound helically around the ground plane, spaced 2 mm away from the ground plane to make a strip transmission line of 100Ω impedence and adquate bandwidth. The 0.85 cm pitch of the helical winding

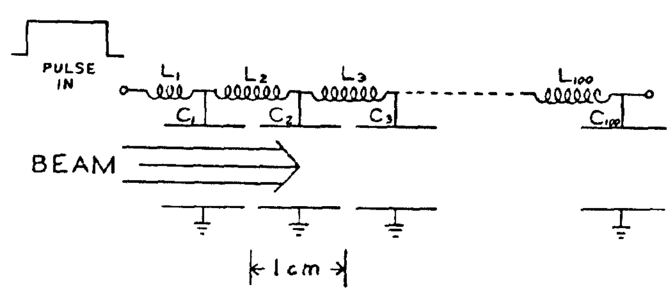

Fig. 1. Schematic of a lumped constant delay line. The capacitive elements double as the electrostatic deflection plates of a beam chopper. Beam which is in phase with the voltage pulse on the line will be deflected.

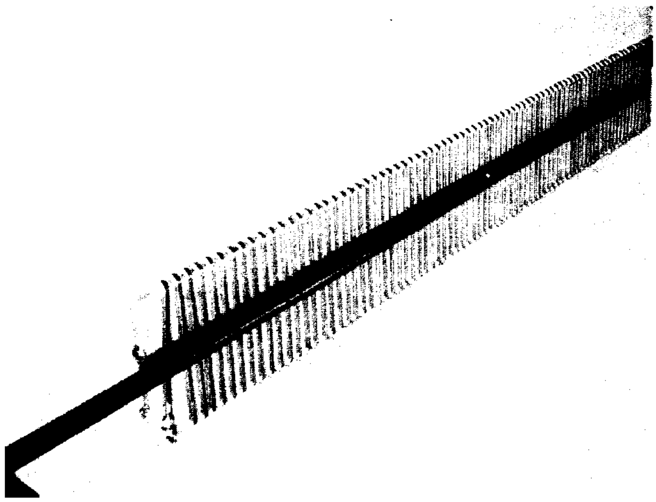

Fig. 2. Photograph of Helix II. Copper tape, 3 mm wide, is wrapped around an aluminum ground plane, 6 mm x 90 mm x 1 m, with Teflon insulators. A 10 mm diameter dowel rod represents the proton beam location.

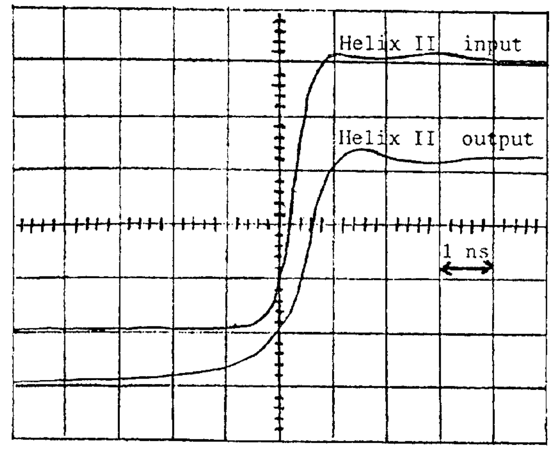

Fig. 3. Test pulse at the input and output of Helix II.

matches the pulse propagation velocity down the line to the beam velocity. Figure 2 shows this device along with a dowel rod which simulates the position of the proton beam. An electric field may be applied across the beam region by applying a voltage pulse on the copper conductor, and placing on the other side of the beam either a ground plane or another similar deflection structure with a voltage pulse of opposite polarity. This device is capable of applying a transverse electric field to a proton in the beam for its entire flight time through the structure while leaving a proton 1 cm in front or behind undeflected as it passes through the 1 m long structure.

Impedance mismatches and rf dissipation (both from radiation and losses in the insulator-spacers) each time the conductor wraps around the corner of the ground plane are very important for these relatively long structures (120 turns). Semi-circular Teflon pieces at each corner hold the copper ribbon to a smooth radius of curvature around the corner while minimizing the impedance mismatch and rf losses due to the low dielectric constant and dissipation factor of this material. Investigation of ceramic insulators as a substitute is contemplated, because of the difficulty in disipating the beam induced heating of the copper ribbon with Teflon insulators in vacuum.

Another problem is that the turn-to-turn spacing must be larger than conductor-to-ground-plane spacing in order to minimize the turn-to-turn capacitive coupling which degrades the rise time. For shorter lines these spacings can be about equal, but Helix II, shown in Fig. 2, has 3 mm wide ribbon with a 5.5 mm gap between turns and a 2 mm spacing between conductor and ground plane. Less spacing to ground reduces the impedance of the line, requiring more current for a pulse of given voltage, and less than the 5.5 mm turn-to-turn gap would increase the turn-to-turn capacitive coupling above tolerable levels. Increasing this 5.5 mm spacing reduces the average E field seen by the beam for a given voltage pulse by the "aspect ratio," ribbon width divided by pitch (3 mm/8.5 mm or .35 for Helix II). These trade-offs must be evaluated for individual applications.

Figure 3 shows the ability of Helix II to pass a fast rise time pulse. The input pulse has a 10%-90% rise time of about 0.8 ns. The output pulse shows 15% attenuation and a rise time of nearly 2 ns, due to a ramp precursor arising from turn-to-turn capacitive coupling. The 20%-90% rise time is still about 1 ns.

Beam Optics and Voltage Requirements

An interesting feature of electrostatic deflection of a particle beam of emittence, ε, is that the voltage required to separate deflected from undeflected beam is independent of beam diameter.

$$V = \frac{8T}{e\ell}\ \frac{\varepsilon}{\pi} \tag{1}$$

where:

T = kinetic energy of beam

e = charge

ℓ = length of deflection structure.

This equation holds for minimum separation of beam envelopes in phase space, in the zero space charge and low frequency limits.

Space charge forces are important in high intensity beams such as LAMPF's. However, these forces can aid in separating beams, or cause mixing depending on the exact beam optics. The other important consideration for the short pulse deflection such as required in this application is the frequency dependence of the E field. The E field strength in the region between the deflection structures depends strongly on the frequency component of the voltage pulse on the line which gives rise to it.

$$E_y = \cos(K_z Z - \omega t)\left(\frac{V}{h}\right)\left(\frac{d}{s}\right)\ \frac{\sin\left(K_z \frac{d}{2}\right)}{K_z\ d/2}\ \frac{\cosh(K_y Y)}{\cosh(K_y\ h/2)} \tag{2}$$

where:

d = width of copper tape

s = center-to-center spacing of tape (pitch)

h = spacing between helix structures (beam diam)

K = wave number for frequency ω

Z = distance along beam axis

Y = distance transverse to Z in deflection plane.

The first term is the familiar Z and time dependence of an alternating field. The next term is just the voltage drop across the gap. The third is the aspect ratio discussed earlier, which is the fraction of the total deflection structure which is at potential V. The fourth term is a frequency dependent term, but its value is very close to one for our parameters. The last contains the variation of the field intensity across the gap, h, between the plates. Very close to either plate, at $Y = \pm \frac{h}{2}$ this fraction is equal to one. In the center, however, at Y = 0, this factor is 0.9 for a frequency of 200 MHz and a separation, h, of 1 cm. At h = 2 cm the factor drops to 0.65 and at h = 4 cm it drops to 0.25. The fundamental frequency for deflecting a 5 ns micropulse is 200 MHz and, clearly, plate separations of greater than 2 cm cause disastrous losses in deflection field intensity. Therefore, though the deflection voltage required in the low frequency limit is independent of h, for fast pulsing the beam width in the deflection region must be minimized.

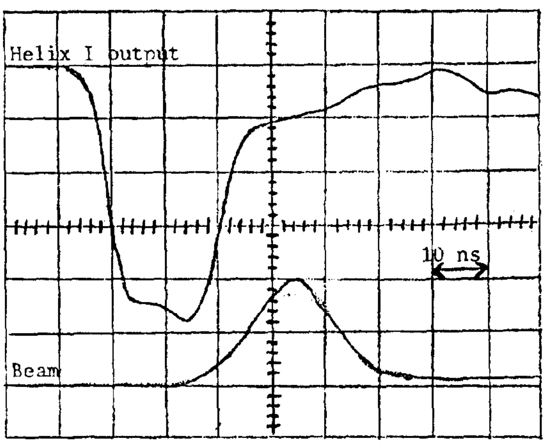

Fig. 4. Negative pulse at output of Helix I at 20 V/div. Lower trace is chopped beam in Faraday cup at 400 $\frac{\mu A}{div.}$.

Beam Tests

In Fig. 4 are some results of beam tests on an early model deflector called Helix I. Due to inferior design, the rise time of the output voltage pulse from helix is about 10 ns, as shown by the upper trace. With this device, 30 ns long beam bursts were obtained from the chopper, as seen on the lower trace.

Confirmation of the calculated beam deflection per volt of pulse amplitude was made. For a plate separation, h, of 2 cm we obtained a deflection sensitivity of 20 $\frac{\mu rad}{volt}$ at this lower frequency. Confirmation has not yet been obtained for the deflection sensitivity at the higher frequencies attainable by Helix II.

Conclusion

A deflection structure capable of chopping LAMPF micropulses in arbitrary patterns has been designed and bench tested. Beam tests with a device of somewhat lower bandwidth confirm most relevant calculated characteristics. Voltage, rise time, and duty cycle requirements for this application are within the capabilities of state-of-the-art pulse amplifiers (not the subject of this article). Requirements on the beam optics in the transport line of the accelerator are somewhat restrictive but will not conflict with optimum performance of the accelerator.

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