A 1 MHz BEAM CHOPPER FOR THE KAON FACTORY

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Abstract

The proposed Kaon Factory at TRIUMF requires a high repetition rate beam chopper for the injection process into the accumulator ring. Prototype studies on a novel design for an energy efficient 1 MHz (10^6 discrete pulses/s) beam chopper are described. In the low voltage prototype 20 Volt electrical pulses are stored in a low loss transmission line which is open circuited at the far end. Testing has just begun on high voltage prototype in which 7 kV pulses have been produced at the end of 10 cm diameter, 50 Ω coaxial cable. In the final version the voltage may be as high as 20 kV and the low loss transmission line will be coupled to an open circuited set of deflection plates through which the beam passes. Results on the performance of the low voltage prototype are presented as well as a description of the first test results from the high voltage prototype.

Introduction

Kicker magnets will be required for all ring-to-ring transfers in the 5 proton accelerator rings (A, B, C, D, E rings) in the Kaon Factory[1,2]. The circulating beam will be present in a series of bunches in the accumulator ring (A ring) at the synchrotron RF frequency of 46 MHz. The field in the kicker magnets must rise from 1% to 99% of full strength during the time interval between the gaps in the beam so that the beam can be transferred with minimum losses.

The purpose of the chopper is to remove 5 bunches from the beam so that there will be a gap[3] of 108 ns at 450 MeV in the accumulator ring (A-ring) and 80 ns in the 30 GeV beam in the driver ring (D-ring). This gap will be of sufficient duration to permit the kicker magnets of conventional design[4,5] to be switched on or off. The extracted beam from the TRIUMF cyclotron, when set up as an injector for the KAON Factory, will consist of a 100 μA of 1 GeV/c H^- particles at a repetition rate of approximately 23 MHz. The accumulator ring for the Kaon Factory can store 45 bunches in two complete revolutions or equivalently it will store 22.5 bunches in one revolution. The accumulation procedure will continue for 20,000 turns[1] at which time the stored beam will be transferred to the B ring. The chopper repetition rate will be 1.022 MHz with alternate pulse widths of 49 ns and 92 ns so that 2 and 3 bunches will be removed alternately at approximately one μsec intervals. The field in the deflector plates must effectively rise and fall in less than 39 ns which is the time between beam bursts from the cyclotron. The chopper will deflect the 1 GeV/c H^- particle beam by 1 mrad and the deflected beam bunches will impinge on a stripper foil and be further separated from the H^- beam in a downstream dipole magnet. Thus 5 out of 45 bunches will be removed from the beam before being injected into the accumulator.

The angle of deflection θ_e due to the electric field is given by

$$\Theta_e[rads] = arctan\left[\frac{V \times \ell}{d \times p \times \beta}\right] \quad \left[10^9\mathrm{V/GeV}/c\right] \qquad (1)$$

where V is the deflection plate voltage, ℓ is the length of the deflection plates, d is the plate separation, $\beta \times c$ is the particle velocity and p is the beam momentum.

The required chopper kick angle of 1 mrad can be achieved, from equation (1), with a set of plates 5 cm apart in which the product of plate voltage and plate length is 37.5 kV·m. The gap between beam bursts is 39 ns so that the rise time of the pulse (τ_{pv}) and the propagation time of the H⁻ (τ_{beam}) through the center fed deflection plates must satisfy[9] ;

$$\tau_{pv} + \tau_{beam} \le 39ns \qquad (2)$$

where $\tau_{beam} = \frac{\ell}{\beta \times c}$. Thus as the plates are made longer the effective rise time of the voltage pulse must be decreased to allow for the increased transit time of the beam through the deflector plates.

Chopper Design Concept

The proposed method for generating high voltage pulses at a 1 MHz rate with a reasonable power dissipation in the driving circuits involves the storage of electrical pulses in a very low loss transmission line that has a one way propagation time of approximately 1 μs. Similar devices in other laboratories[6,7,8] operate either at a low repetition rate or at a low macro-duty cycle. The schematic for the KAON Factory chopper is shown in figure 1.

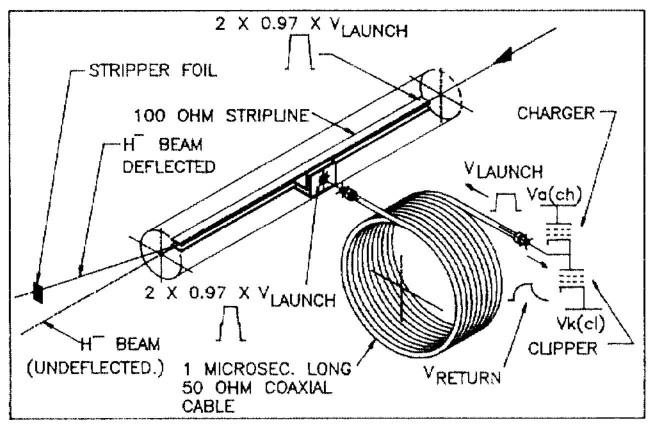

Fig. 1: Schematic Diagram of the 1 MHz Chopper

At the sending end of the cable there will be two tetrodes. One tetrode will be used as part of the charging circuit (charger) to form the rising edge of the pulse and the other tetrode will be used as part of the clipping circuit (clipper) to form the falling edge of the pulse and clamp any voltage level that would otherwise appear between the pulses. The first pulse will travel along the cable for 1 μs until it reaches the open circuit at each end of the deflection plates. An open circuit causes a reflected pulse of the same magnitude and polarity as the incident pulse. The voltage on the deflection plates will be doubled and the reflected pulse will travel back along the cable. If the pulse has a perfect flat top there will not be any magnetic kick once the plate are charged since the currents in the incident and reflected pulses cancel. Two μs after being sent down the cable the reflected pulse arrives back at the charging end of the cable reduced in amplitude due to attenuation in the cable and spread in time by dispersion. At that moment the charger will be launching another pulse which will add to the reflected initial pulse. The magnitude of the pulse will build up to an equilibrium level[10] in a time period that depends on the circuit parameters.

Every 2 μs a pulse of 49 ns flat-top (to deflect 2 beam bursts) will be re-launched down the cable. Alternate pulses with a 92 ns flat-top (to deflect 3 beam bursts) will also be launched every 2 μs but delayed by 1 μs from the 49 ns wide pulses. These pulses will reflect back and forth in the cable passing each other at the center of the cable where the voltages will add and the currents will almost cancel.

The deflector plates will be center fed to reduce the fill time.[9] Center feeding requires that the deflector plate impedance be twice that of the storage cable ie: 100 Ω plates for a 50 Ω storage cable.

Power Considerations

Ideally only a small amount of current is required from the charging circuit to reshape a pulse which has been distorted by dispersive effects in a 10 cm coax cable[11]. However the current required to charge and discharge the stray capacitance of the tetrode circuits is considerably larger than the current required to reshape each pulse on the cable. Table 1 shows a summary of the timing, voltages, currents, and power requirements for various sizes of deflector plates and a stray capacitance of 320 pF for 2 CY1172[13] tetrodes of 125 pF each plus an estimated additional 70 pF from floating power supply connections. The current (I) required to charge a capacitance C_{st} to V volts is given by

$$I = C_{st} \times \frac{V}{\tau_{pv}} \qquad (3)$$

assuming that the voltage pulses are trapezoidal. The power (P) required to charge the capacitance at 1 MHz is determined from

$$P = \frac{1}{2}CV^2 \times 10^6 \qquad (4)$$

If one uses a low loss coaxial cable which is 10 cm in diameter then the attenuation of a pulse with a 20 ns rise time would be 3% after travelling 600 meters[(11)]. Thus the power dissipation in the cable would be 6% of the average power as shown in table 1. Calculations[12] show that the temperature rise between the inner and outer conductor of a 10 cm diameter 50 Ω coaxial cable storing a 5 kV pulse (which doubles to 10 kV at the deflector plates) is about 11 degrees Celsius and thus no cooling is required. However cooling may be required at much higher voltages as the temperature rise will increase in proportion to the square of the voltage.

If the reflected pulse is trapezoidal with the required rise time then only about $\frac{1}{2}$ of the peak current in the pulse will be available within the rise time period τ_{pulse} to charge the stray capacitance. The remaining current of about 100A must be supplied by the charging circuit. If the stray capacitance is reduced or the cable impedance is reduced then the stored pulses will be much more effective in charging the stray capacitance within the required rise time. Detailed calculations have been performed on the timing and power dissipation, including an representative model of the tetrodes and tracking of beam particles through the deflector plates [14,16]

Defl. Plate Length (m)	1	2	3	4	5	6
Beam Transit Time (ns)	4.5	9	13.5	18	22.5	27
Pulse Rise Time (ns)	34.5	30	25.5	21	16.5	12
Defl. Plate Voltage (V)	37.5	18.75	12.5	9.4	7.5	6.25
Stored Pulse Current (A)	375	188	125	94	75	63
Cap. Charge Current (A)	347	200	156	143	145	167
Ave. Pulse Power (kW)	703	176	78	44	28	20
6% Loss in Cable (kW)	42	10.6	4.7	2.6	1.7	1.2
Cap. Charge Power (kVA)	225	56	25	14	9	6

Table 1. Power and Timing for Various Lengths of Deflector Plates.

Low Voltage FET Prototype

A low voltage (20 volt) FET 1 MHz chopper was built and tested as shown schematically in figure 2. The 50 Ω coax cable was .95 cm in diameter and had a one way propagation time of 1 μs. A 4 m long 100 Ω strip line was fabricated out of plates 8 cm wide and 5 cm apart in a copper lined cardboard coaxial housing 75 cm in diameter and 5m long. The output impedance of the charger and the clipper FET circuits were 50 Ωs to match the cable impedance. 320 pF was added from the center of the cable in an attempt to simulate the stray capacitance expected in the high voltage prototype. Voltage measurements were made at various points along the deflector plates and at the charging end of the cable. The pulse shape and height at the end of the deflector plates was essentially the same as that observed at the charging end of the cable as expected from calculations[10]. The rise time of the pulse at the center of the plates was observed to be about 10 ns longer than the rise time observed at the end of the deflection plates. This is due to the 13 ns delay from the center of the plates to the end of the plates and back to the center. This is indicated in the pulse at the center of the plates in figure 1.

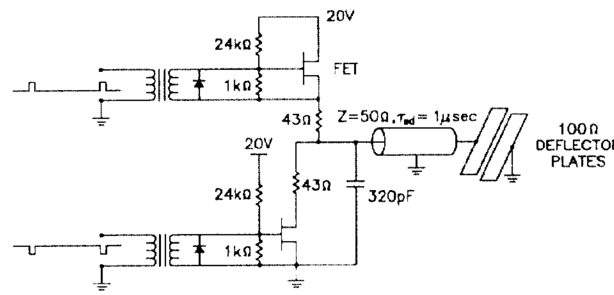

Fig. 2: Schematic Diagram: Low Voltage FET Prototype of 1 MHz Chopper

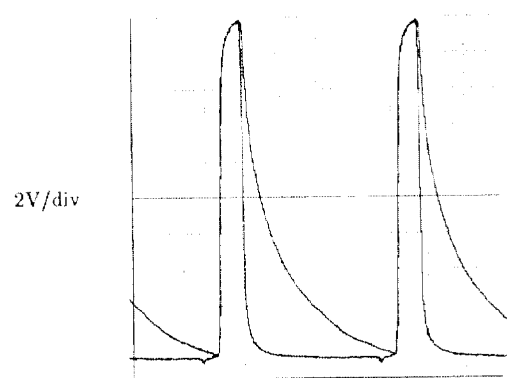

Fig. 3: Influence of Clipper on Stored Pulses.

Figure 3 shows the voltage measured at the charging end of the cable for the circuit shown in figure 2 without the 320 pF capacitor added. The repetition rate was adjusted to match the cable delay time and minimize the pulse rise time. The exponential tails on the pulses were observed without the clipper circuit operating. The clipper circuit was switched on and the timing was adjusted to minimize the fall time. The rise and fall time was adjusted to 30 ns. The peak amplitude was less than 20 volts due to the attenuation of the .95 cm diameter cable. Without changing the rise and fall time of the pulses on the gates on the FETs a 320 pF capacitor was added as shown in fig 2. The effect of this capacitance was to increase the rise and fall times to 45 ns. The power dissipation on the charging circuit was measured with and without 320pF. The difference is the additional power required to charge the stray capacitance. The result was scaled to a deflection voltage of 37.5 kV giving a result of 190 kW consistent with the estimates in table 1.

Figure 4 shows the slow decay of pulses reflecting freely in a 150 m long 10 cm diameter 50 Ω coaxial cable. The first pulse in figure

4 is the pulse launched from the charging circuit. The second pulse has reflected from the other end of the cable and has almost doubled in amplitude because the charger is off and is thus a high impedance circuit. The remaining pulses are due to subsequent reflections. The voltage losses measured from figure 4 are about 2% per μs.

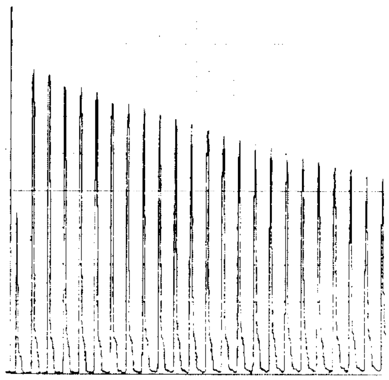

Fig. 4: Decay of Pulses Stored in 10 cm Coax Cable.

High Voltage FET Prototype

A high voltage prototype of the chopper is presently being built[15] in which CY1172 tetrodes are used in the clipper and charger circuits and a 10 cm diameter coaxial cable 150 m long is used as a storage cable. Initial testing has been done at a low macro-duty cycle with the charging circuit anode voltage varied in the range from 3 to 9 kV. The three tetrode power supplies for the screen grid, control grid and the filament supply are all on the 'pulse deck'. The filament power supply has been decoupled with a ferrite loaded inductor and there was a modest effort to decouple the other floating power supplies with inductors. The clipper circuit is not yet completed. Figure 5 shows a 3.3 kV pulse launched down the cable and the buildup of the pulse train reinforced by the charger circuit on each return for an anode voltage of 9 kV. The rise time of the grid pulse was 30 ns. The rise time of the 3.3 kV pulse is about 40 ns and the rise time of the reflected pulses are about 50 ns. The rise time of the reflected pulses with an anode voltage of 5 kV was about 40 ns. The action of the clipper will be expected to suppress the pulses in the tail.

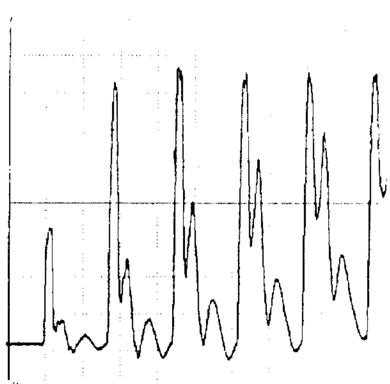

Fig. 5: Initial Test Results from the High Voltage Chopper Prototype.

Conclusions

Extensive tests will be carried out when the clipper circuit is installed and the measurements will be compared with calculations in which the timing is optimized and the grid pulse amplitude and rise time and circuit parameters are varied systematically. Preliminary prototype measurements are promising and it is expected that the results will supply us with the tools required to design a final version that will meet the specifications.

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