Interleaved Wide and Narrow Pulses for the KAON Factory 1 MHz Chopper

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Abstract

A beam chopper is required in the transfer line between the 1 GeV/c TRIUMF cyclotron and the Accumulator ring of the proposed 30 GeV/c KAON Factory synchrotron. The beam chopper must generate pulses with a magnitude of at least 9.5 kV with rise and fall times of less than 38 ns (corresponds to kick rise/fall time of less than 39 ns) at a repetition rate of 10^6 pulses per second at a 100% duty cycle. The pulse pattern must be synchronized to the 23 MHz RF system for the TRIUMF cyclotron. Two different pulse widths are required to deflect a total of 5 beam bursts out of every 45 beam bursts that are extracted from the cyclotron. The inter-leaved pulses will have flattop durations of more than 48 ns and 92 ns. Results of measurements on a prototype chopper are presented where pulses of two different widths are synchronized to an RF synthesizer and stored in a low loss delay cable. Rise and fall times of 20 ns to 40 ns have been achieved with 12 kV to 15 kV wide and narrow pulses at 1.9×10^6 pulses per second continuous operation.

I. Introduction

The TRIUMF cyclotron will be used as an injector for the KAON Factory synchrotron. The beam chopper will create holes of 108 ns duration in the 100 μA, 1 GeV/c H^- beam in the accumulator ring to allow enough time for the magnetic field to be established in the kicker magnets [3,4] in each of the 5 rings. The H^- burst period within the cyclotron is 43.5 ns and the burst width is 2.4 ns with a jitter of approximately 2.4 ns. Hence the effective gap between beam bursts within the cyclotron is about 39 ns. If the H^- beam were extracted with the same pattern, as is the case for H^+ extraction, then the chopper "kick" would require a rise and fall duration of less than 39 ns and a flat top duration of more than 48 ns and 92 ns on alternate pulses, as shown in Figure 1, so that 2 and 3 beam bursts would be removed alternately at approximately 1 μs intervals. However the H^- extraction scheme that has been developed for the KAON Factory performs in such a manner that every second burst is extracted [7]. Thus the period of the extracted H^- beam is 87 ns. In Figure 1 the cyclotron internal burst pattern and the extracted burst pattern are shown in relation to the chopper timing. The beam chopper pattern as shown in Figure 1 will deflect a total of 5 beam bursts with 4 deflector pulses over a period of exactly 4 accumulator periods of about 1 μs each. Ten beam bursts are un-deflected between each chopper pulse and these beam bursts are inter-leaved in such a manner that there are 40 consecutive beam bursts in the accumulator ring and 5 consecutive missing beam bursts.

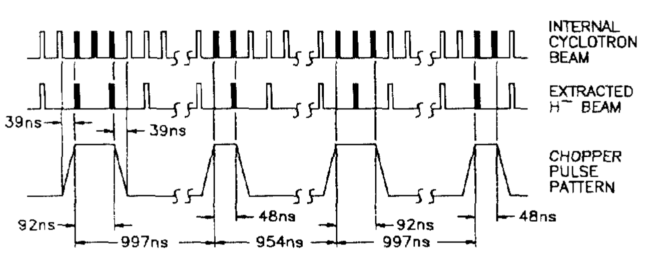

Figure 1: Beam Chopper pulse pattern synchronized with internal cyclotron beam and extracted beam

The angle of deflection Θ, from an electric field is

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

where $\beta \times c$ is the particle velocity and p is the beam momentum. The required deflection of 1 mrad can be achieved with a set of plates 5 cm (d) apart in which the product of voltage, V and plate length, ℓ is 37.7 kV·m. Thus 9.5 kV pulses are required for 4 m long deflector plates. The deflected H^- beam bursts will impinge on a stripper foil and emerge as H^+ and be further separated from the un-deflected H^- beam by a dipole magnet and directed to a 10 μA beam dump.

II. Chopper Design Concept

The 1 MHz chopper design concept has been described extensively (see [5,8,9] and references cited therein). The cathode of an EEV [6] CY1170J 75 kW tetrode is connected to a negative high voltage power supply. The anode

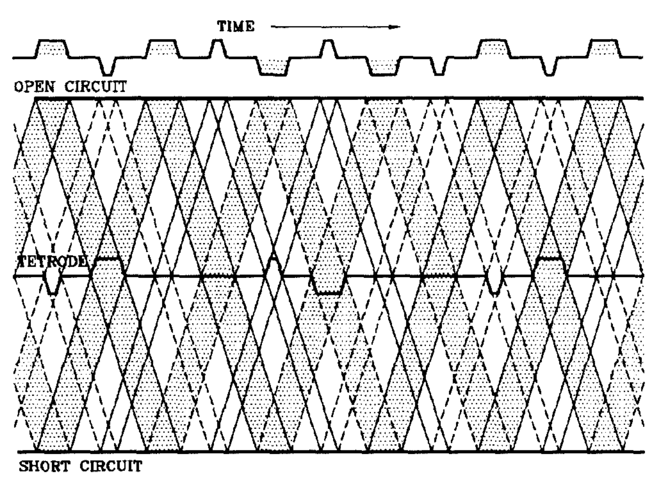

Figure 2: Lattice diagram of inter-leaved chopper pulses.

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of the tetrode is connected to two 50 Ω storage cable cables of approximately equal length. One cable is short circuited at the far end. The far end of the other cable is connected to the center of a set of deflector plates which are configured as a 100 Ω strip-line and are center-fed to match the impedance of the 50 Ω storage cable. The deflector plates are open circuit. The propagation delay in the two cables can differ by ±3 ns without any measurable degradation in performance. Thus as the cables temperature changes, the system can be synchronized precisely to the cyclotron by simply changing the position of the short circuit stub. However the sum of the delays of the two cables must be accurate to within about 1 ns.

Figure 2 shows the lattice diagram of the double width pulse pattern at the tetrode and at the open circuit end of the pulse storage cable. Alternate wide and narrow pulses are shown in Figure 2 at the deflector plates. Since the deflected beam will strike a stripper foil in either direction the polarity of the deflector voltage is not important.

In Figure 2 the path of negative pulses is indicated by dashed lines and the path of positive pulses is indicated by solid lines. The pulses reflected from the short circuit are reversed in polarity and those reflected from the open circuit maintain the same polarity. There are actually two narrow pulses and two wide pulses on the cable travelling in opposite directions. Alternate reflections from the remote ends of the cables cause a voltage null at the anode when the pulses are of opposite polarity. When the two narrow (or wide) pulses add together as a single negative pulse at the anode of the tetrode, then the tetrode is pulsed on to restore the leading edges (charge). When the two narrow (or wide) pulses add together as a single positive pulse, the tetrode is pulsed on to restore the trailing edges (clip). The magnitude of the stored pulses are doubled at the deflector plates. Storage cables which have a total delay of 2 μs are required so that four pulses (2 wide and 2 narrow) can be stored to give a repetition rate of 10^6 pulses per second at the deflector plates. Note that the repetition rate at the tetrode is 1/2 of the repetition rate at the deflector plates since the pulses arrive at the tetrode in pairs.

III. Measurements

The prototype tests which were reported in Hamburg [5] were carried out at 2.2×10^6 pulses/s, with one width of pulse. The prototype was upgraded with a new pulse sequencer [2] and with an increased length of the storage cable. The base of the tetrode was re-configured and the screen power supply and the grid driver circuit were redesigned to reduce the inter-pulse ripple [1]. The wide and narrow pulses were controlled independently using the new timing control system which can be synchronized to the 23 MHz cyclotron pulse pattern. The length of the storage cable was ≃double that used for the previous results [5] so that both wide and narrow pulses could be stored simultaneously. This keeps the repetition rate at $\simeq 2 \times 10^6$ pulses/s and maintains the power dissipation at a reasonable level. The two cables were connected to the tetrode as described in reference [5] as a lumped element 50 Ω transmission line with a delay of 5 ns. The total one way delay of the storage cables, including the 4 m long deflector plates and the tetrode connection, was 1079.8 ns when the short circuit position was adjusted so that the delays on either side of the tetrode were equal. This corresponds to a fundamental resonant frequency of 926.1 kHz.

The pulse sequencer [2] counts the number of RF cycles and generates timing signals that are used to synchronize the charge and clip timing for two different widths of pulses. The synthesizer was set to a frequency that is 45 times the required chopper frequency. The synthesizer frequency was 41.79 MHz rather than 23 MHz (cyclotron frequency) due to the available length of the storage cable. The high voltage power supply voltage was set to -15 kV and the grid drive timing was tuned independently for the narrow pulse and then for the wide pulse at 928.7×10^3 pulses/s (41.79/45). The voltage pulses shown in Figure 3 were measured at one end of the 4 m long deflector plates. The top two traces in Figure 3 show the narrow and wide pulses obtained independently on the deflector plates. The first negative and the first positive pulse in the narrow (wide) pattern is actually one pulse delayed by twice the total cable length. See Figure 2 . The second negative and second positive pulse in the narrow (wide) pattern is the other pulse. These two pulses differ in magnitude by about 2 kV. Part of this is due to a baseline 2.5 kV peak to peak, 232 kHz oscillation which is due to excitation of the $\lambda/4$ resonance of the total delay of the cables. However there is still an asymmetry in pulse amplitudes of about 1 kV which is present and is under investigation.

The bottom trace in Figure 3 shows the wide and narrow pulses inter-leaved. The repetition rate for two widths of pulses was 1.8574×10^6 pulses/s. This is almost twice the required design repetition rate. The magnitude of the inter-leaved pulses is about 1 kV less than that of the independent pulses. The peak magnitudes of the various pulses in the 8 pulse pattern varied from 12 kV to about 15 kV so that the useful pulse voltage is only 12 kV. The kick angle

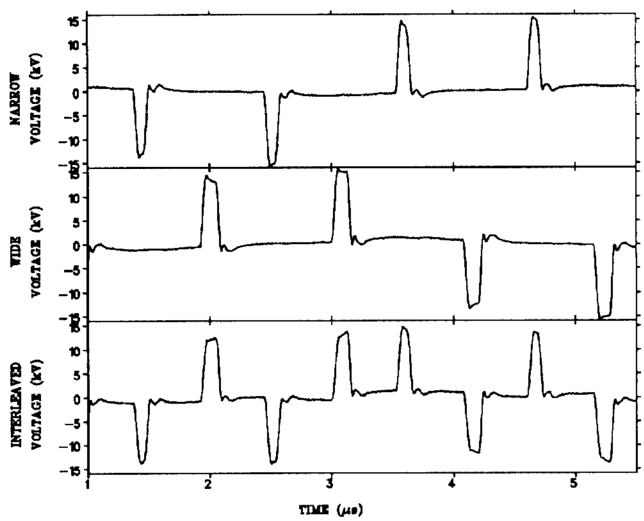

Figure 3: Measured wide, narrow and inter-leaved pulse patterns.

of the smallest pulse would be about 1.25 mrad with 4 m long deflector plates. The inter-pulse ripple which includes a 232 kHz component is about 3.0 kV peak to peak which is $\pm 13\%$ of the pulse magnitude for the 12 kV pulses. The variation in the kick strength from pulse to pulse is not important since the deflected beam is directed to a beam dump. The average current in the 75 kW tetrode was 3 A when both pulses were present giving a total dissipation of 45 kW.

Table 1.
Measured rise and fall times (including jitter) to ± 12 kV for the wide and narrow pulses independently and inter-leaved.

Pulse Edge	Measured Pulse Timing (ns) Independent $\lvert\text{Phase}\rvert + \Delta t$ 15-90%	Measured Pulse Timing (ns) Inter-leaved $\lvert\text{Phase}\rvert + \Delta t$ 15-90%
2^{nd} neg Narrow		
Lead	20.0	30.8
Trail	21.5	28.8
1^{st} pos Narrow		
Lead	23.9	28.6
Trail	25.9	26.0
2^{nd} pos Narrow		
Lead	24.2	35.5
Trail	23.2	30.9
1^{st} neg Narrow		
Lead	29.1	36.0
Trail	28.9	29.8
2^{nd} neg Wide		
Lead	21.0	28.2
Trail	17.5	19.9
1^{st} pos Wide		
Lead	25.0	32.0
Trail	20.8	22.6
2^{nd} pos Wide		
Lead	25.0	33.4
Trail	22.0	23.5
1^{st} neg Wide		
Lead	31.1	40.1
Trail	25.5	28.3

Table 1 shows a summary of the measured leading and trailing edge durations (Δt, 15% to 90% of ± 12 kV)) which includes timing jitter of the 8 voltage pulses for independent and inter-leaved pulses shown in Figure 3. The timing jitter was measured relative to the period of the grid drive and varied from 0 to 8 ns depending on the pulse edge being measured. The rise and fall times were all measured from 15% to 90% since the inter-pulse ripple shifted the baseline of one of the inter-leaved pulses to about 14% of 12 kV. The 10% to 90% rise and fall times were measured for all but one pulse and were found to differ from those shown in Table 1. by only 1 or 2 ns. The rise/fall times + jitter for the independent pulses are as much as 11 ns less than that measured for the inter-leaved pulses. This was due to the limitations on the grid pulser circuit which can not quite handle the higher repetition rates.

IV. Conclusion

The requirements for the prototype chopper are operation at 1.025×10^6 pulses/s continuously at 9.5 kV with kick rise and fall times (including phase jitter) of less than 39 ns. The measured results show that the prototype chopper can achieve operation at 1.9×10^6 pulses/s continuously at 12 kV or more with kick rise and fall times (including phase shifts) of less than 39 ns, with one exception. However the measurements show that at about 1×10^6 pulses/s the rise and fall times are all much less than 39 ns. The power dissipation in the CY1170J tetrode, with 12 kV stored pulses at 1.9×10^6 pulses/s is approximately 45 kW which is well within the 75 kW rated dissipation of the tetrode. This dissipation will be approximately halved at 1×10^6 pulses/s. The inter-pulse ripple is about $\pm 13\%$ and further study is required to reduce this to less than 10%. In future tests, the asymmetry in the pulse heights will be investigated and the long term stability of the system will be tested.

V. References

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