A Variable Duty Factor Beam Chopper for a 300 keV Injection Beamline

M.J. Barnes, G.D. Wait
TRIUMF
4004 Wesbrook Mall, Vancouver, B.C., Canada
and
C.B. Figley
XILLIX Technologies Corporation
2339 Columbia Street, Vancouver, B.C., Canada

Abstract

A new beam chopper has been developed for the 300 keV H^- beam injected into the 500 MeV TRIUMF cyclotron. The beam chopper controls the duty factor of the beam between 0.1 % and 99.9 %. The chopper consists of a high-voltage modulator incorporating two stacked Field-Effect Transistor switches, operating in a "push-pull" mode, and a set of deflector plates. The required pulse magnitude is 5 kV at 3 kHz (continuous) with rise and fall times of less than 44 ns. The deflector plates are 12.7 cm long with a separation of 3.2 cm and are installed in the 300 keV injection line to the cyclotron. The circuit performance and the results of beam test measurements are presented.

1 INTRODUCTION

The Ion Source Injection System (ISIS) for the TRIUMF 500 MeV cyclotron has several H^- ion sources which feed a common 300 keV beam line. A high intensity ion source, capable of several hundred μA of current, can be pulsed at 1 kHz with a variable duty factor before accelerating the H^- beam to 300 keV. Time of flight measurements, using pulsed beam, are required for tuning purposes. Another ion source, capable of several μA of polarized ions, is not pulsed. In order to vary the duty factor of the polarized beam it is necessary to "chop" the 300 keV beam. In addition, to maintain a constant power load for the cyclotron RF system it is desirable that the frequency of the pulsed beam in the cyclotron is approximately 3 kHz[1]: the period of the 3 kHz duty factor corresponds to the transit time through the cyclotron.

Specifications for the beam chopper call for a 5 kV pulse, with duration continuously variable in the range from 333 ns to 1 ms, a continuous repetition rate variable between 1 kHz and 3 kHz, and rise and fall times (10 % $\rightarrow$ 90 %) not to exceed 43.4 ns. The period of the micro duty factor of the cyclotron is 43.4 ns.

The beam chopper utilizes a set of deflector plates 12.7 cm long with a separation of 3.2 cm. The angle of deflection (Θ_e) due to an electric field is given by:

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

where V is the deflector plate voltage, ℓ is the length of the deflector plates, d is the plate separation, $\beta \times c$ is particle velocity, c is the velocity of light, and p is the beam momentum (eV/c). From Eq. 1, the 5 kV pulse results in a 33 mrad deflection for the 300 keV H^- beam.

2 DESIGN

A solid state switch consisting of two stacks of high voltage Field Effect Transistors (FETs), operating in "push-pull" mode, has been designed, built and successfully tested. The design of these switches is based on a stacked FET switch developed at Saskatchewan Accelerator Laboratory (SAL)[2]. However the design has been modified considerably. The SAL design, which is used to drive a klystron load, does not actively pull the capacitive load to ground and hence the fall time is approximately 1 μs[2]. The SAL design also has a limited requirement for pulse duration, which is in the range 500 ns to 6 μs[2].

The 300 keV beam chopper consists of three stages to convert a TTL timing signal, from the ISIS control system, to a 5 kV pulse. The first stage converts the TTL signal to 60 V; the second stage converts the 60 V signal to $\pm$250 V; and the final stage generates a +5 kV pulse. The beam chopper is designed to be reliable. The chopper is modular and hence easily maintainable. The two stacks of the final stage each consist of 7 modules (Fig. 1). The 7 modules of the pull-up stack are labelled UP1 through to UP7 in Fig. 1; UP1 is at the +5 kV DC end of the stack, and UP7 is at the deflector plate end.

The details of switch modules UP1 through to UP7 and DN1 through to DN7 are shown in Fig. 2 of reference[3]. The high-power FET utilized in each switch module of the power modulator is the APT1004RBN[4]. At 25°C the APT1004 FET is rated at 1 kV and a pulsed drain current of 17.6 A (at a 10 % duty factor). A detailed circuit description is presented in reference[3].

The pulse transformer associated with each module must have high voltage isolation, low inter-winding capacitance and good bandwidth[2]. The transformers used have single turn primary and secondary windings on a ferrite core. The parasitic capacitance to ground from each module (typically 4pF[3]) significantly affects the the transient voltage grading down the stack[3, 5].

In order to reduce the severity of the voltage transients in the stack, fast-grading capacitors (Cfg) are connected between the drain and source of the APT1004 FETs at several levels of each stack. In order to avoid excessive

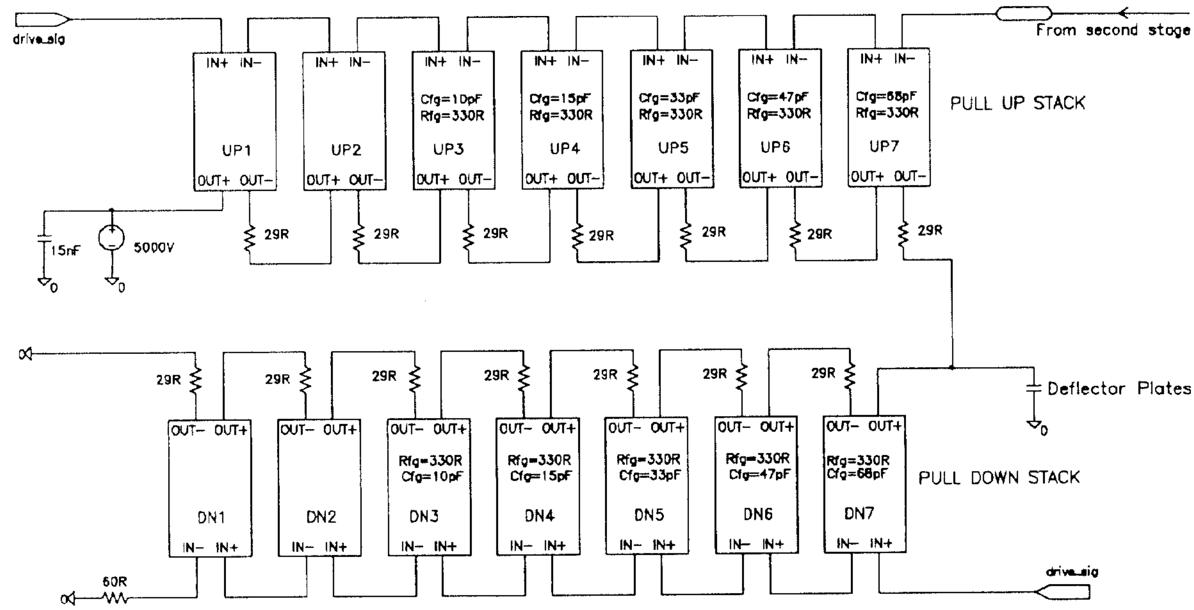

Figure 1: Schematic diagram of final stage of beam chopper

drain current in the APT1004 FET during turn-on it is necessary to connect a fast-grading resistor (Rfg) in series with each fast-grading capacitor. The fast-grading capacitors and resistors are connected on the back-plane, and not on the PCB cards. This ensures that, although the value of the fast-grading capacitor varies down the stack, the PCB cards in the two stacks are all identical. The nominal value of the fast-grading components used are shown on Fig. 1. Modules UP1, UP2, DN1, and DN2 do not require fast-grading components. The values of the fast grading capacitors vary from 68 pF at the deflector plate end of the stack to 10 pF across modules UP3 and DN3 (see Fig. 1). The method of determining these component values is described in reference[3].

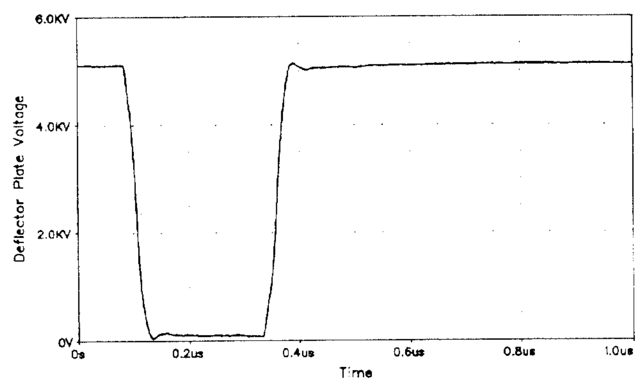

Figure 2: Pulse; frequency=2.5 kHz; width=399.75 μs

3 MEASUREMENTS

The beam chopper has been tested at up to 20 kHz with pulse voltages up to 6 kV[3]. The FET stacks are capable of being operated at frequencies considerably higher than 20 kHz with some minor circuit modifications[3].

Fig. 2 shows the deflector plate voltage for operation at 5 kV, at 2.5 kHz, and a nominal pulse width of 399.75 μs. Both the rise and fall-time of the pulse voltage is 30 ns and is virtually independent of repetition rate or pulse-width, while operating in the frequency range 1 Hz to 20 kHz (pulse widths from 250 ns to 1 s)[5]. Similarly rise and fall times are virtually independent of the DC high voltage in the range 1 kV to 6 kV[5].

The voltage per module for 5.5 kV tests varied by about $\pm$100 V, from a nominal value of 786 V[3]. The peak current for 5 kV operation is about 9.5 A[3], and is well within the rating of the APT1004[4]. The measured voltage distribution and FET current are presented in reference[3].

Beam tests were carried out with the new beam chopper installed in the 300 keV injection line with various duty factors from 0.1 % to 99.2 %. The range of duty factors is limited by the ISIS control system. The beam current was approximately 250 μA, and the FET pulser was operated at 2.25 kHz and voltages from 1.25 kV to 5 kV. Fig. 3 shows the measured signal from a capacitive beam pickup in the ISIS beamline, and the integral of the signal, for the start of the pulse-train of undeflected beam bunches. The phase of the beam chopper was adjusted so that the first beam bunch is not distorted, confirming that the 'kick' has a rise time less than the beam bunch spacing. Fig. 4 shows the measured signal when the beam chopper is being operated at a 50 % duty factor. Fig. 5 shows the measured signal, and the integral of the signal when the beam chopper is being operated at 0.1 % duty factor (444 ns) and a 1 in 5 selector is operating. The 1 in 5 selector increases the 43.4 ns period of the beam micro structure by a factor of 5 to 217 ns. Two beam

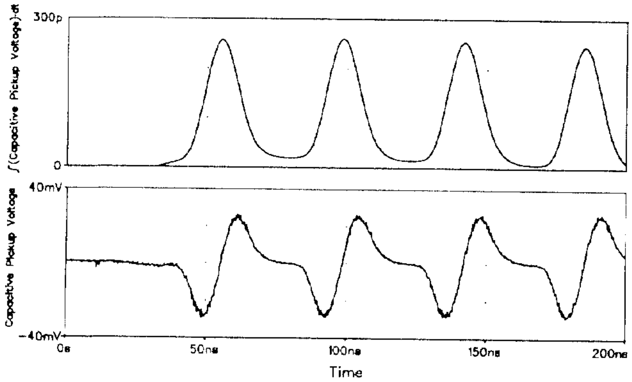

Figure 3: Capacitive beam pickup; start of train of beam-bunches; 75% duty factor

bunches are injected into the cyclotron for each pulse period of the ISIS beam chopper. The apparent width of the beam bunches is approximately 13 ns full-width half maximum (see Figs. 3 and 5). This width is mainly determined by the length of the capacitive pickup installed in the beamline (8.6 cm), which takes 12 ns for the 300 keV H^- beam to propagate through[1]. The signal from the capacitive beam pickup will also be distorted as it propagates through more than 30 m of RG213 and 5 m of RG58 coaxial cable.

Wire scanners which are downstream of the beam chopper were used to determine the position of the beam. The position of the beam corresponded to a deflection angle 25 % greater than that calculated using nominal values in Eq. 1. However because the deflector plates are relatively short, end-effects will have a significant effect on the beam deflection. Opera-2d[6] has been used to simulate the deflector plates. The simulation confirms that, at the center of the plates, the effective length of the deflector plates is approximately 25 % greater than the nominal length.

4 ACKNOWLEDGEMENTS

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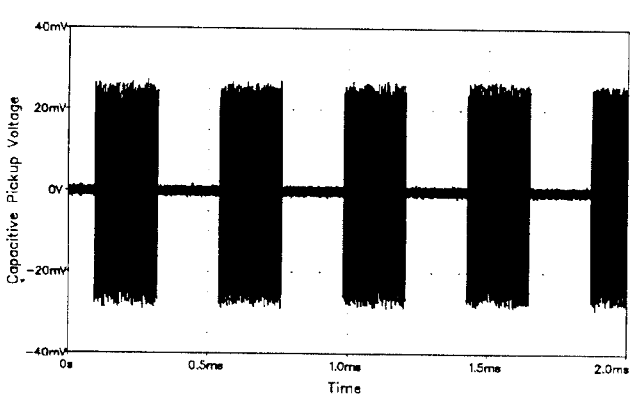

Figure 4: Capacitive beam pickup: 50% duty factor

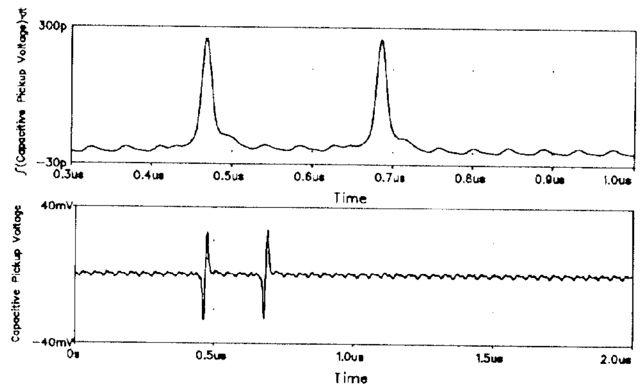

Figure 5: Capacitive beam pickup; 1 in 5 selector operating and 0.1% duty factor on beam chopper

5 CONCLUSION

An economical, frequency and duty factor agile, pulse generator has been designed, built and tested at TRIUMF. The beam chopper has been tested at a pulse voltage of 6 kV, and over a frequency range of less than 1 Hz up to 20 kHz. Pulse widths from 250 ns to 1 s have also been demonstrated. Rise and fall times of about 30 ns have been achieved over the complete range of frequencies and duty factors. Beam tests have confirmed the successful operation of the system. All of the design specifications for the ISIS 300 keV beam chopper have been achieved. Further developments are planned to improve the circuit performance to increase the frequency to 1 MHz and to raise the pulse voltage to 15 kV for other applications[3].

6 REFERENCES

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