DESIGN OF A BEAM BUNCHER USING A HALF-COSINE DRIVING FUNCTION

R. C. Rogers
Cyclotron Institute, Texas A&M University, College Station
Texas, 77843-3366, U. S. A.

ABSTRACT

A beam buncher design for the axial injection system on the K500 cyclotron is described. The buncher uses a unique, easily generated, driving waveform of repetitive half cycles of a cosine function. The effect on the beam velocity profile is to mimic the action of a true saw-tooth waveform. Considerations of single and multiple gap performance and their effect on the velocity profile and power demand are presented.

1. INTRODUCTION

The K500 cyclotron uses an external Electron Cyclotron Resonance Ion Source (ECRIS) and axial injection system to provide particles for acceleration. Figure 1 is a schematic drawing of the axial injection transport line showing the major elements of the system. The particles are extracted from the ECRIS by a d. c. voltage that provides a continuous current to the cyclotron. The particles can be more efficiently used if they are collected into "bunches" that are injected into the machine in synchronism with the accelerating voltage. As shown in the figure, the buncher is the last active element before the particles enter the hole through the upper pole cap of the cyclotron.

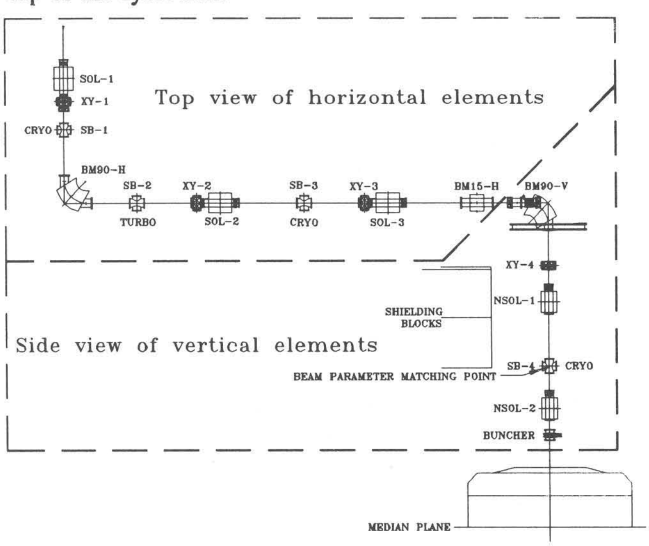

Fig. 1. Schematic of the axial injection system for the K500 cyclotron.

The action of a buncher using a sawtooth waveform has been previously described.[1] Efforts to generate and support this waveform on several types of bunching structures have met with little success owing to the wide bandwidths and power requirements of the final amplifier. Most successful bunching has been achieved through the use of single-gap devices, using either a single sinusoidal waveform or two waveforms[2] operating on the first and second or first and third harmonics. Multiple-gap systems that use several harmonics to construct the sawtooth waveform have also been successful.[3] Single-frequency devices typically recover about 30% of the original d. c. current while multiple-gap systems can recover as much as 70-80%, depending upon the number of harmonics used.

The bunching structure described here is a single gap type using a driving waveform that is more easily generated than a sawtooth while yielding the same result.

2. BUNCHER GAP EFFECT

Figure 2 shows a sectional drawing of the bunching structure with an active gap constructed of two closely spaced grids with attached field shaping cones, driving voltage inputs and load resistors. The gap voltage is a sinusoidal waveform operating at the frequency of the cyclotron and at some fixed phase relative to the dee voltage.

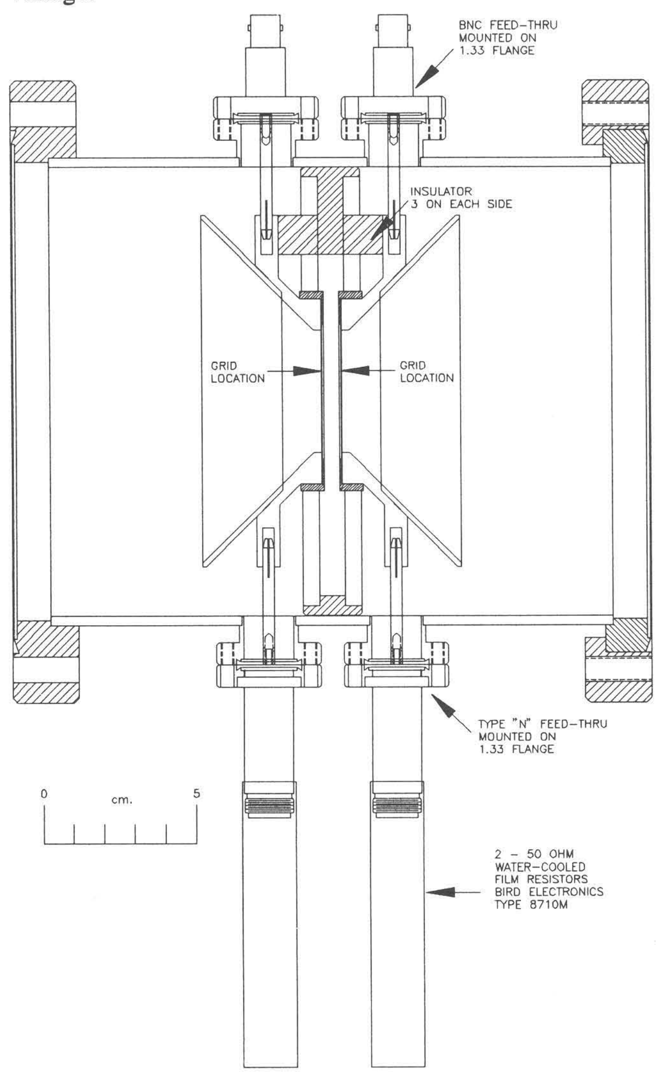

Fig. 2. Sectional view of the single gap buncher.

The K500 cyclotron accepts the external beam through a helical inflector that has an output aperture at a fixed radius from the center of the machine. The velocity of the beam is adjusted to match the central magnetic field of the cyclotron and the radius of the inflector aperture. From this a beam wavelength can be defined as

$$\lambda_b = \frac{v_i}{f} = 2\,\pi r_i \qquad (1)$$

where v_i is the injection velocity, r_i is the radius of the inflector aperture and f is the cyclotron frequency. Since r_i is fixed the beam wavelength is constant. It is useful to discuss some features of the buncher in terms of this number λ_b.

The velocity of the particles after exiting the gap is given by

$$v_g = v_o \frac{V_g}{2V_e} \frac{\sin\frac{\pi}{\lambda_b}s}{\frac{\pi}{\lambda_b}s} \sin\left(\omega f + \frac{\pi}{\lambda_b}S\right) \qquad (2)$$

where v_g is the output velocity from the gap, v_o is the input velocity, V_g is the peak voltage across the gap, V_e is the ECRIS extraction voltage, s is the distance across the gap and ω is the radian frequency of the gap voltage. This result assumes that the change in velocity in the gap is very small compared to the input velocity and that the electric field in the gap is uniform.

A normalized plot of the effect of the gap as a function of the gap distance, in terms of λ_b, is shown in Fig. 3. Any single gap buncher of the type shown in Fig. 2 has, in fact, three gaps. There is a long input gap, a short active gap and a long output gap. From Fig. 3 it is apparent that the long gaps, e.g., five wavelengths or more, have very little effect on the beam velocity. This effect can be further reduced if the grids are driven in a bi-phase or push-pull mode. In most cases the fields in the input and output gaps are not uniform, so the actual effect of these gaps must be evaluated on a cases-by-case basis.

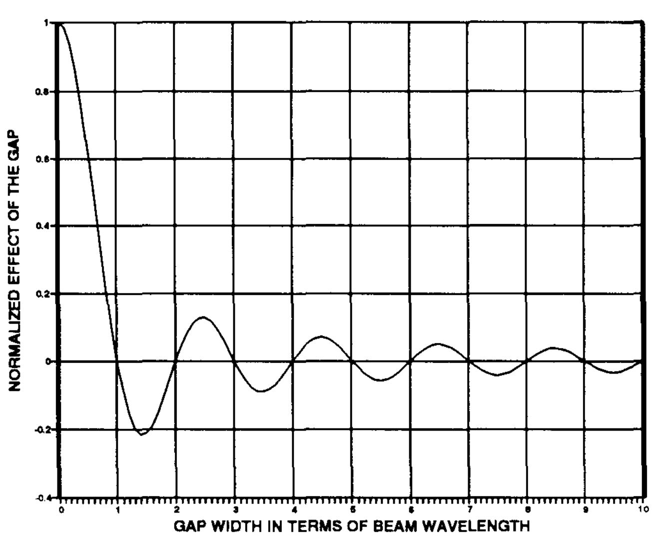

Fig. 3. Normalized gap effectiveness as a function of gap width.

3. WAVEFORM ANALYSIS

The arguments for using a sawtooth waveform for bunching were presented in Ref. 1. However, this waveform is generated at small signal levels and must be amplified. The fast risetime and amplitude that are required for effective bunching place very large demands on the amplifiers in terms of power output capability and bandwidth. An alternative to the sawtooth waveform is that of a half cycle of a cosine wave. This signal is simple to generate at low power and a scheme will be presented for high power generation.

Figure 4 shows a comparison of an ideal sawtooth waveform to an ideal half-cosine wave. The peak amplitude of the cosine wave is 0.7854 times the peak amplitude of the sawtooth. This amplitude gives the least average error fit of the cosine to the sawtooth over the period. Figure 5 shows more realistic signals with nominal risetimes of 10% of the period for both signals and the same amplitude relationship. It is clear that the half-cosine wave very closely approximates the sawtooth.

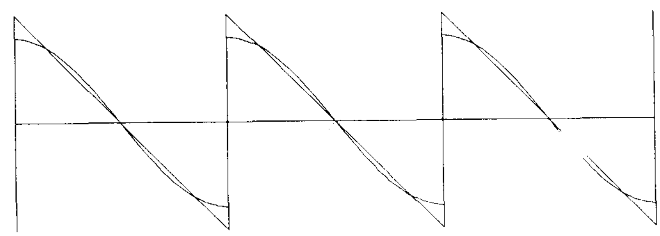

Fig. 4. Idealized sawtooth and half-cosine wave forms.

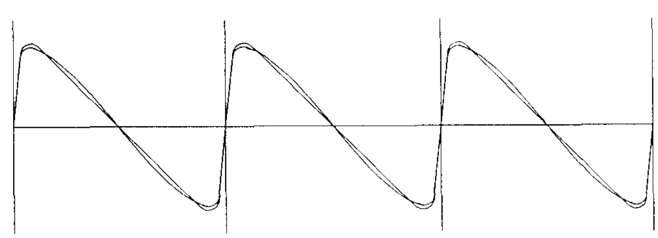

Fig. 5. Sawtooth and half-cosine wave forms with 10% risetimes.

Fourier decomposition of the two signals with 10% risetimes gives the following relation between their harmonic components.

Table 1.

Harmonic	Sawtooth	Half-cosine
1	0.777	0.836
2	0.344	0.314
3	0.190	0.181
4	0.113	0.116
5	0.070	0.075
6	0.046	0.048
7	0.030	0.030
8	0.018	0.017

The harmonic content of the two waveforms is almost identical with the higher harmonics being virtually equal since both signals have equal risetimes.

Equation 2 can be modified to include the harmonic terms as

$$v_g = v_o \frac{V_g}{2V_e} \frac{\sin \frac{n\pi}{\lambda_b} s}{\frac{n\pi}{\lambda_b} s} \sin\left(n\omega t + \frac{n\pi}{\lambda_b} S\right) \qquad (3)$$

where the term n represents the harmonic number. The effect of the gap on each of the harmonic components can therefore be evaluated and the components recombined to give the resulting velocity profile.

The active gap in the buncher under consideration is 0.25 inches long which is equal to $0.126\lambda_b$ for the K500 cyclotron. The gap effect for each of the harmonics above is shown in the following.

Table 2.

Harmonic	Gap effect
1	0.974
2	0.899
3	0.781
4	0.632
5	0.464
6	0.292
7	0.131
8	-0.008

Figure 6 shows both the reconstructed half-cosine wave and the resulting velocity profile with each compared to its ideal waveform. The loss of risetime in the velocity profile is the result of the gap effect attenuating the higher frequency components. This effect is discussed in Ref. 1 and is repeated in this form to provide quantifying values for this particular buncher configuration.

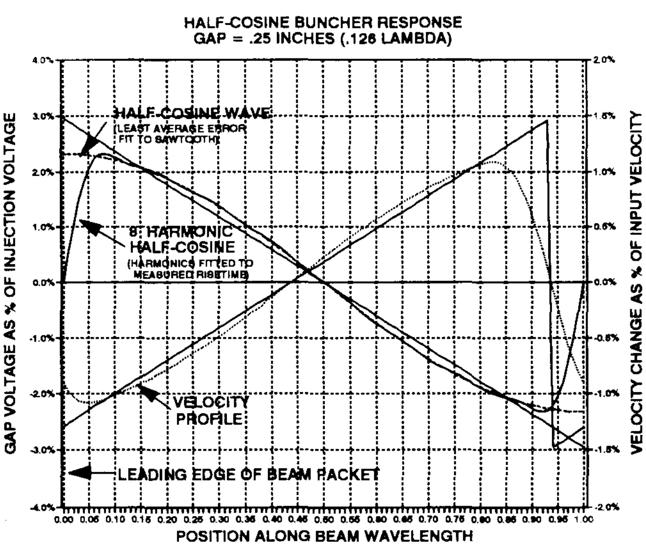

Fig. 6. Half-cosine voltage wave form and particle velocity profiles reconstructed from Fourier components. Velocity profile is constructed from gap effect modified components.

4. POWER CONSIDERATIONS

The power required for the buncher grids is dependent on the ECRIS extraction voltage and the distance to the inflector aperture, i.e., the drift path over which the bunching action takes place. For the location of the buncher shown in Fig. 1, the drift path is approximately 34 wavelengths. For an ideal sawtooth waveform that is symmetric about zero volts, this implies a peak voltage across the gap of 2.96% of the ECRIS extraction voltage. For the half-cosine wave a peak voltage of 2.32% (0.7894 x 2.96 from Section 3 above) would be required. Because the grids are driven in a push-pull manner the peak voltage for each grid is then 1.16% of the ECRIS extraction voltage.

From Fig. 2 above or from the block diagram shown in Fig. 7 below, it can be seen that a 50Ω load resistor is connected to each grid of the buncher. This resistor provides the wide bandwidth load required to match the multi-harmonic driving voltage. The maximum extraction voltage required to match the K500 center region is approximately 18 kV. From the voltage calculated above, this leads to a maximum power requirement of 435 watts per grid.

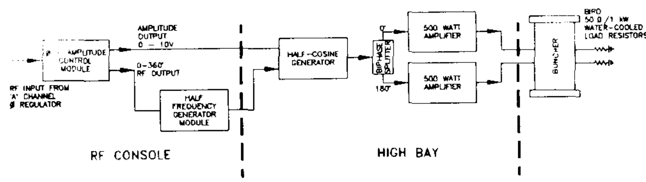

Fig. 7. Block diagram of buncher electronics system.

The power demand can be reduced by half by adding a second active gap one wavelength away. This will result in further degradation of the risetime of the velocity profile to the point where the result is little different from the use of a single frequency driving voltage.

5. LOW POWER SIGNAL GENERATION

Figure 7 shows the overall view of a buncher control system. The driving R.F. signal is derived from the phase regulator for the initial accelerating dee. This insures that the buncher signal has a properly phased signal for injection. The first module provides an amplitude control to the half-cosine generator and an adjustable phase R.F. signal to the half-frequency generator. The half-frequency generator divides the frequency of the input signal by two and provides a high purity sine wave of f/2 to the half-cosine generator.

Figure 8 is a schematic diagram of the half-cosine generator. The half-frequency signal is applied to the input of a quadrature hybrid signal divider to provide two signals that are 90° out of phase. One signal is then

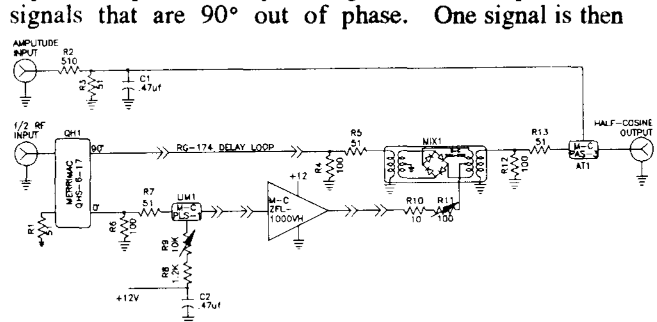

Fig. 8. Schematic diagram of half-cosine wave generator.

applied to a limiter to generate a square wave that is amplified and applied to the i.f. output terminal of a mixer. Note that this square wave is operating symmetrically about zero volts. The other signal from the quad hybrid is applied, through a delay line, to the r.f. input of the mixer. The delay is required to account for the delay in the limiter and amplifier. The half-cosine wave is then available at the l.o. input terminals of the mixer. The square wave first biases the ring modulator diodes in a direction so that the output from the l.o. terminals is in-phase with the r.f. input signal. When the square wave switches, it biases the diodes so that the output is 180° out-of-phase with the input signal. Because the switching takes place at the peak of the input signal and happens each half cycle, the resulting signal is a half-cosine wave with a period equal to the period of the original r.f. signal. Another way of looking at this is that two signals of equal frequency, f/2, have been mixed with the result that the signal of cyclotron frequency, f, has been recovered. Further, the high frequency harmonics necessary for the fast risetime were supplied by the square wave. The final circuit provides amplitude control of the half-cosine signal.

From Fig. 7 above, it can be seen that the half-cosine wave is split in a 180° power divider to provide the bi-phase or push-pull driving signals to the amplifier chain and thus to the buncher grids.

The design of this system was based on the proliferation of wide bandwidth high power amplifiers designed around the Motorola MRF151G power MOSFET. Although many amplifiers of this basic design are available and are advertised as being "linear" amplifiers, none that have been tested to this time should be represented as "linear". In fact, all the amplifiers of this design are operating in a Class AB mode and cannot support the half-cosine waveform. One amplifier has been found which can provide the proper amplification, Amplifier Research Model 1000L. However, this amplifier, available at a list price of $44,000 (U. S. currency) each, is prohibitively expensive for this application.

6. HIGH POWER SIGNAL GENERATION

Because of the extreme cost of amplification of the small signal waveform some design work has been done on methods of generating the half-cosine wave at high power levels. Fig. 9 is a diagram of a circuit that uses the MRF151G in a switching mode. This takes advantage of the device's high current capability and fast switching speed without the demand for wide bandwidth linear gain.

The operation of this circuit is to apply a high power full-wave rectified signal to the center tap on the switching transformer. The gate switching waveform is applied so that the switching takes place when the current through the switching transformer is at a peak. This reverses the current through the transformer and gives the fast reversal of phase necessary to produce the risetime required for the half-cosine waveform. The rectification of the input signal is required to maintain positive voltage on the drain inputs of the N-channel MOSFET. The transformers for this type of application follow the design given in Ref. 4.

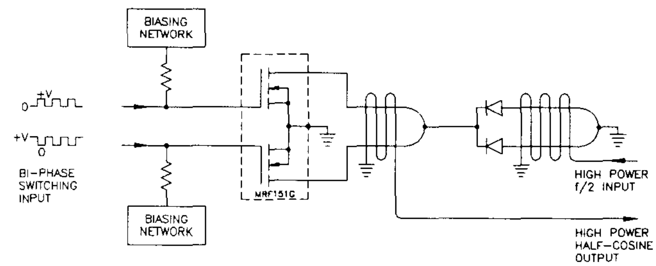

Fig. 9. Preliminary circuit design for a high power half-cosine generator.

A SPICE analysis of this circuit has been done and the important waveforms are shown in Fig. 10. Reading from top to bottom of the figure are the following signals:

1. Half-frequency high power input wave,
2. Rectified signal applied to switching transformer,
3. Gate 1 drive signal,
4. Gate 2 drive signal,
5. Half-cosine output signal.

Note that the gate drive signals are at frequency f, not f/2. Also, the output half-cosine wave has essentially the same peak amplitude as the input wave. This indicates that it may be possible to switch the power through the circuit with very low loss.

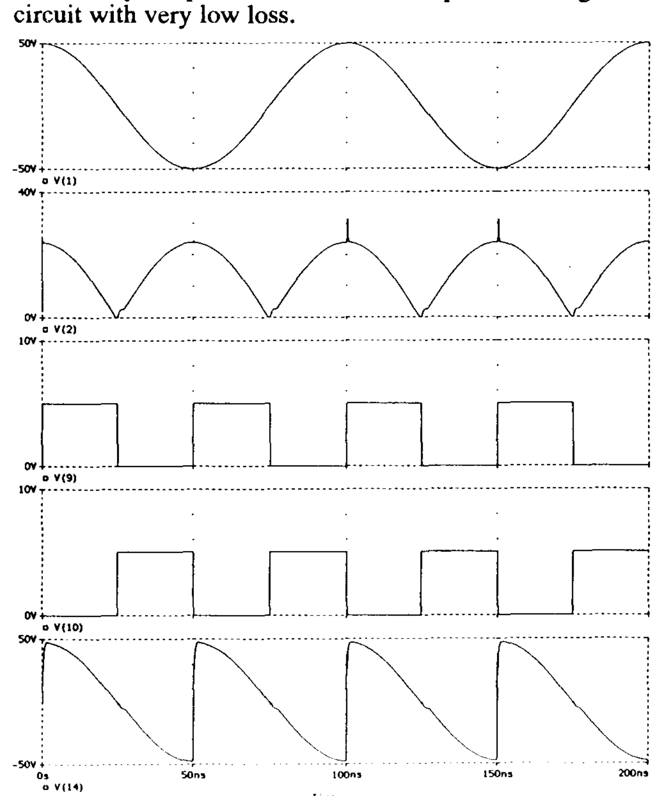

Fig. 10. SPICE analysis waveforms for circuit shown in Fig. 9.

The high power input for the signal generation is supplied from an amplifier of modest bandwidth. For the K500 cyclotron the amplifier need only cover the frequency range from 4.5 MHz to 13.75 MHz. Amplifiers of this bandwidth and nominal 500 watt capability are available at costs in the $10,000 price range.

There are a few different power MOSFET devices available and the MRF151G may not be the best choice but this remains to be investigated.

7. PRESENT STATUS AND CONCLUSION

The buncher mechanical structure shown in Fig. 2 is installed and operating with a push-pull sinusoidal wave while work continues on developing a high power half-cosine signal generator.

While the sawtooth waveform remains as an ideal choice for buncher applications, the half-cosine waveform must be considered because of its simplicity of generation. If high power generation techniques can be found, then the half-cosine waveform can potentially replace many expensive and complex multiple-gap, multiple harmonic systems.

8. ACKNOWLEDGEMENT

The author would like to thank Robert A. Gutierrez for assistance with the high power generation circuit design and SPICE analysis. Also, thanks go to John Vincent of the MSUNSCL for software for the Fourier analysis of the waveforms.

9. REFERENCES

1) Resmini, F. and Clark, D. J., "A Proposed Sawtooth Buncher for the 88-Inch Cyclotron Axial Injection System," UCRL-18125, University of California, Berkeley Radiation Laboratory, March 1968.
2) Lynch, F.J. et. al., "Beam Buncher for Heavy Ions," Nucl. Instr. and Methods **159**, 245-263 (1979).
3) Ratzinger, U. et. al., "The Three-harmonics Double-drift Buncher at the Munich Heavy Ion Postaccelerator," Nucl. Instr. and Methods **205**, 381-386 (1983).
4) Granberg, H. O., "Building Push-Pull, Multioctave, VHF Power Amplifiers," Motorola Application Note AR305 (1987).