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AN ELECTRON BEAM BUNCHER TO OPERATE OVER THE FREQUENCY RANGE 1-4 GHz*

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Summary

We present a description of an electron buncher to be installed in the terminal of a Van de Graaff, which is to produce a modulated beam over the frequency range 1-4 GHz. The modulator geometry has been optimized so that the modulation amplitude should be nearly constant over the frequency ranges 1-2 GHz and 2-4 GHz. Preliminary results indicate the device works as predicted.

Background and Theory of Operation

One of the simplest schemes for producing a bunched electron beam is that employed in the klystron: A pre-accelerated electron beam is velocity modulated by passing it through a gap across which there appears a time-dependent electric field (parallel to the beam velocity); the beam then enters a field-free drift space in which the initial velocity modulation evolves into a spatial or density modulation.

Because a klystron is basically a single-frequency device, its basic scheme has several features which are undesirable in a broad-band bunching device. In a conventional klystron, the use of a single modulating gap is made possible by making the gap part of a resonant input cavity, a structure which is inherently unsatisfactory for a broad-band device. A non-resonant bunching structure is made possible using two modulating gaps connected by a short drift tube (not to be confused with the drift space referred to above) mounted at the mid-plane of the buncher cavity (see Fig. 1). The buncher cavity and drift tube can be designed so that they act as extensions of the outer and inner conductors, respectively, of the transmission line which furnishes the modulating signal. The far side of the drift tube assembly is connected to an impedance matched monitoring port. Hence the modulating structure has the characteristic impedance of the input transmission line and is as broad-banded as the termination of the line will allow.

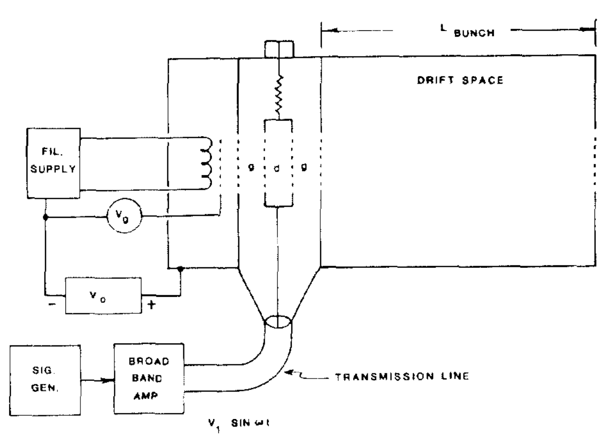

Fig. 1 Schematic representation of buncher

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The bunching characteristics for the two-gap modulator are obtained in a manner similar to that used for the conventional klystron.[1] If the applied modulating signal is of the form $V = V_1 \sin \omega t$, the effective modulating voltage experienced by an electron is $\langle V \rangle = V_1 M(\omega) \sin \omega t$. For the two-gap modulator,

$$M(\omega) = \frac{2 \sin(\theta_g/2) \sin[(\theta_g+\theta_d)/2]}{\theta_g/2} \tag{1a}$$

where

$$\theta_d = \omega d/v_0 \qquad \theta_g = \omega g/v_0 \tag{2a,b}$$

g,d = gap and drift-tube lengths (respectively)

V_0 = pre-acceleration voltage

v_0 = velocity resulting from V_0

For the case of equal gaps (d=g)

$$M(\omega) = \frac{2 \sin(\theta_g/2) \sin \theta_g}{\theta_g/2} \tag{1b}$$

The spatial bunching which the beam undergoes after having traversed a drift space of length L (in the present setup, the beam is rapidly accelerated immediately upon exiting the drift space, thereby "freezing" the existing bunching from that point on) can be expressed in terms of the bunching parameter X, which is given by

$$X = \frac{M(\omega)V_1}{2 V_0} \frac{\omega L}{v_0} \tag{3a}$$

If the modulated beam current is expanded in a Fourier series with fundamental frequency ω, the modulation amplitude of the n^{th} harmonic is given by

$$I_n = 2 I_0 J_n(nX) \tag{5}$$

where I_0 is the d.c. beam current. From Eq. (5) we see that the maximum modulation for the n^{th} harmonic is obtained when nX corresponds to the maximum of J_n. This is also the condition for the minimum variation of the modulation.

Variation of the modulation amplitude with frequency can be further reduced as follows. Let us substitute Eqs. (1a) and (4) into Eq. (3a), and replace the θ_g in the denominator by Eq. (2b). We then have, for the equal gap case

$$X = \frac{2 V_1}{V_0} \frac{L}{g} \sin(\theta_g/2) \sin \theta_g \tag{3b}$$

where the frequency dependence of X is contained entirely in θ_g. Hence we can further minimize the variation of J_n with frequency by operating in the neighborhood of the maximum of $\sin(\theta_g/2)\sin \theta_g$, which occurs at $\theta_g/2 = .9553$, and is equal to

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.7698. If one wishes to operate over a one-octave range, from ω_1 to $\omega_2 = 2\omega_1$, about a mid-band frequency ω_0, then for minimum frequency variation of X,

$$g = \frac{1.911\ v_0}{\omega_0} \tag{6}$$

In seeking to minimize the frequency variation of J_n over the entire octave, rather than maximizing $J_n(nX)$ at midband, one should choose the remaining parameters so that $X(\omega_0)$ and $X(\omega_1) \approx X(\omega_2)$ are roughly equidistant from the optimum X. The method is illustrated graphically in Fig. 2 for the case of $n = 1$. ($[J_1(X)]_{max}$ occurs for $X = 1.841$.) The curve in the lower graph illustrates the underlying frequency dependence of X. The constant A has been adjusted to show the condition for minimum frequency variation. This situation obtains when $J_1(X)$ is at a maximum where $\sin(\theta_g/2)\sin\theta_g = .86 \times .7698$; Eq. (3b) then yields

$$\frac{V_1\ L}{V_0\ g} = 1.390 \tag{7}$$

If one were in practice able to realize the situation described, it would be possible to keep the output modulation amplitude constant to ± 1.5% over a one-octave frequency range.

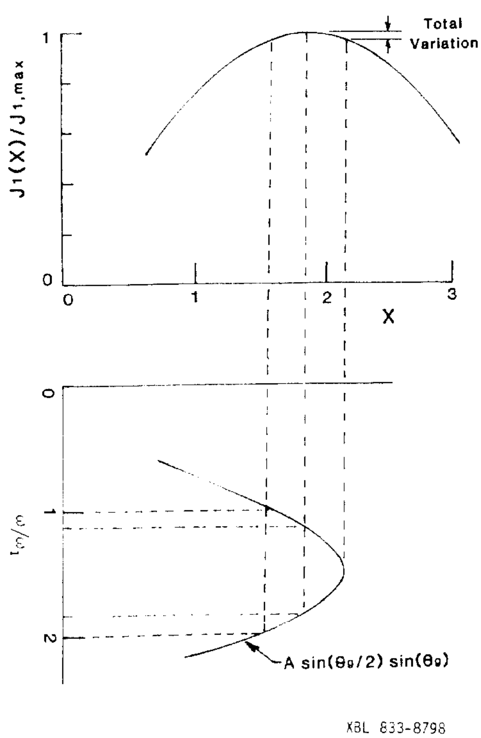

Fig. 2 Graphical representation of method for minimizing frequency variation of modulation amplitude

To extend the frequency range over two octaves, i.e., from ω_1 to $4\omega_1$, two approaches are possible. Using the above method, and optimizing the system for a two-octave range, one can achieve a modulation amplitude which would vary by ± 19%. An alternate approach would be to make use of the harmonic spectrum of the output beam. One still maximizes $\sin(\theta_g/2)\sin\theta_g$ at $\omega_0 = 1.5\omega_1$, but obtains the bunching between $2\omega_1$ and $4\omega_1$ by optimizing X for $n = 2$, i.e. operating in the neighborhood of the first maximum of $J_2(2X)$, namely $2X \approx 3.05$.

The only way to switch back and forth from first to second harmonic operation without changing hardware or affecting the optimization of $\sin(\theta_g/2)\sin\theta_g$ is by changing V_1; denoting the modulating voltages for first and second harmonic operation by $V_1^{(1)}$ and $V_1^{(2)}$ respectively, the requirement for optimizing both modes is

$$V_1^{(2)} = .833\ V_1^{(1)} \tag{8}$$

Analysis similar to that described above indicates that the 2nd harmonic amplitude of the bunched beam will vary by < ± 3.5% over the (output) frequency range $2\omega_1$ to $4\omega_1$. The one drawback to this scheme arises from the fact that $[J_2(x)]_{max} \approx .83[J_1(x)]_{max}$, so that the modulation amplitude suffers a 17% discontinuity as one switches from first harmonic to second. Notwithstanding this effect, the overall variation in the output amplitude is still only about 20%, roughly half as much as in the alternate scheme. An additional practical consideration favoring the 2nd harmonic scheme is that in the frequency range of interest, electronics capable of supplying constant output voltage over a two-octave frequency range are either very expensive or unavailable, and sometimes both.

Experimental Results

An electron buncher was designed based on the above considerations. An electron gun, consisting of a thoriated tungsten filament, a control grid and a combination focussing and pre-acceleration electrode (V_0 = 400–500 V) produced the electron beam. The beam then passed through a 3 mm collimating aperture into the buncher cavity at the center of which was mounted the cylindrical drift tube on which the modulating signal appeared. A second collimator was placed at the exit of the buncher cavity and this was followed by a stainless steel tube which served as the drift space. Fine rectangular grids of 1 mil tungsten wire spaced at roughly 0.5 mm were placed over the entrance and exit collimators and both ends of the drift tube in order to maintain planar equipotential surfaces at these locations.

Figure 3 shows a photograph of the buncher cavity (left) and electron gun assembly. Of the latter, only the final aperture, i.e. the entrance collimator to the buncher cavity is visible. In the photograph, the buncher cavity is supported by a mounting flange attached to the "downstream" end of the drift space. The drift tube modulator is visible in the center of the cavity and is supported by the leads connected to the signal input port at the right and a 50 ohm monitor port which is just visible at the left.

The buncher is to operate over the frequency range 1-4 GHz, so that ω_0, the midband frequency (for 1st or 2nd harmonic operation), is 1.5 GHz. The modulating signal is supplied by a power amplifier driven by a voltage-controlled 1-2 GHz YIG oscillator. Using a pre-acceleration voltage of 400 V, Eq. (6) gives for the gap spacing g = 2.4 cm. With V_0 and g now fixed at the above values, Eq. (7) shows that optimization of X requires that V_1L = 133 V-cm.

Since the buncher is to be installed in the terminal of a Van de Graaf accelerator, it is desirable to maintain L at a reasonable length. To minimize the

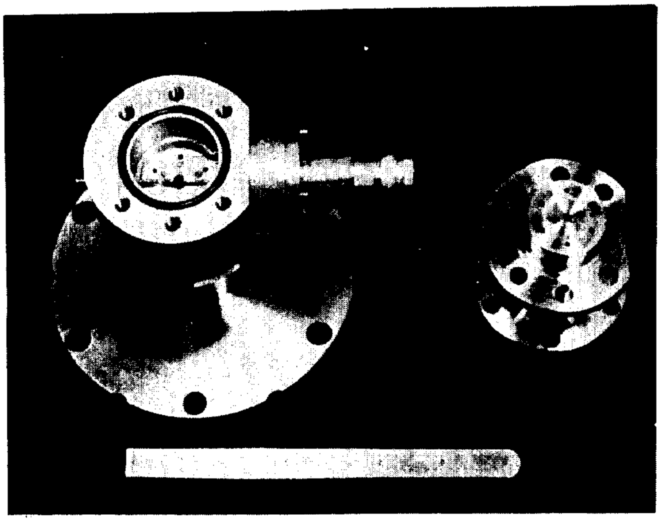

Fig. 3 Buncher cavity (left) and electron gun assembly (right)

power requirements for the amplifier one wants to keep V_1 small. A reasonable compromise seemed to be $V_1 = 10$ V and $L = 13.3$ cm. For a given V_1, the power requirements can be reduced by using a higher impedance input transmission line (and designing the buncher cavity accordingly). For example, with a 125 Ω impedance, a 10 volt (peak) modulating signal only requires 0.4 W. The input power requirement can be reduced further, at the expense of a varying input level, by using a mismatched input transmission line. Because of the difficulties in obtaining adequate amplifier performance, we elected to take this latter approach in the present series of tests, driving the 125 Ω cable with a 50 Ω source, and terminating it in 307 Ω, i.e., a 257 Ω resistor in series with the 50 Ω monitoring port.

The buncher's performance was evaluated on a test stand which accelerated the beam to 30 kV and, with the use of appropriate magnets, steered and focussed it onto a Faraday Cup whose frequency response was relatively flat to 2 GHz and extended out beyond 4 GHz. The beam detection circuit is shown in Fig. 4. Since the power meter is a broad band device, a filter is necessary due to the presence of higher harmonics in the beam; to measure the frequency response over an entire octave, two different filters are needed. Because the Faraday cup is not back-terminated, an isolator is necessary to prevent reflected power from producing resonances in the detection circuit.

Figure 5 shows the experimental results. The dashed curve shows the input modulating signal measured at the monitoring port as a function of frequency. The resonant behavior of the mismatched transmission line is clearly evident. The falloff at the upper frequencies is due to the output characteristics of both the YIG oscillator and the amplifier. The lower curves show the output power associated with the first harmonic component of the bunched beam. The lower half of the spectrum was recorded using a filter with a 1.5 GHz roll-off; the upper half, with a 2.5 GHz roll-off. A slight difference in the insertion loss of the two filters is visible. Over roughly the lower 2/3 of the octave the double peaking of the output oscillation's relative to the input clearly shows the variation of X above and below its optimum value as V_1 varies. The smoothing effect of optimizing X is also evident: Variations of ± 40% in input power level result in output power variations of < ± 10%. The falloff at the highest frequencies reflects the falloff in the input. The falloff at the very lowest frequencies, and the peaking observed in the neighborhood of 1.7 GHz, appear to be at least partly due to the frequency response of the measuring circuit, and we are presently attempting to correct the situation.

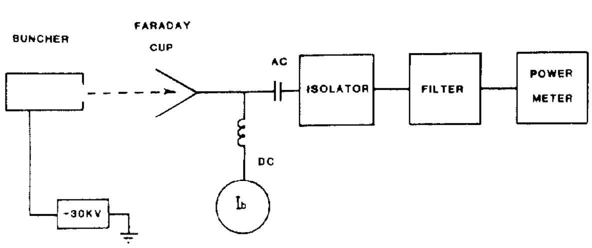

Fig. 4 Test Setup to Measure Beam Modulation

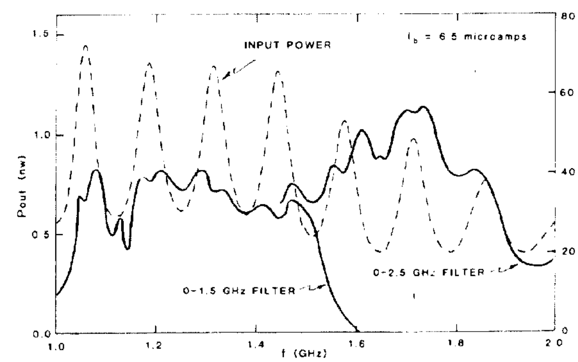

Fig. 5 Input and output modulation of buncher

Owing to the uncertainty of the Faraday Cup response above 2 GHz, no extensive measurements were taken over the 2-4 GHz region. However, preliminary measurements using a spectrum analyzer indicate the presence of output harmonics up to $n = 4$.

Conclusion

The present results are very encouraging. Driving the buncher with signal levels whose amplitude varied over a 2:1 range we were able to keep the modulation amplitude of the output current constant to ± 20% over nearly a one-octave interval. Based on this we intend to upgrade the modulation amplifier to reduce input signal varations and improve the response of the output measuring circuit. We also intend to do a detailed study of the second harmonic behavior. Finally, we note that the performance of the present version was deemed sufficiently satisfactory that it has been installed in the Van de Graaff, where it is currently operating.

Acknowledgement

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Reference

1. See, e.g., S.Y. Liao, Microwave Devices and Circuits, Prentice-Hall, p. 180.