A 475.76 MHz LINAC CHOPPER

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Summary

The Cambridge Electron Accelerator uses an 'S' band (2854.56 MHz) linac as an injector, and a UHF (475.70 MHz) synchrotron rf acceleration system. A chopper is used to eliminate five out of the six linac bunches, and the sixth bunch can be injected at the optimum phase with respect to the synchrotron rf voltage. This reduces synchrotron oscillation, and reduces beam loading on the rf, thus allowing for much larger accelerated currents.

The linac uses constant phase velocity waveguides (v_p=c). The energy of the electrons introduced into the linac determines the trapping efficiency and the phase angle of the electron bunch with respect to the linac traveling wave. The chopper, situated between the gun and the linac waveguide, is a cylindrical 475.76 MHz cavity operating in the TM_{010} mode. It provides one half of the injection voltage(70 kv) for the selected electrons. The other half is provided by the gun pulse.

Besides increasing the synchrotron intensity, the chopper system produced many other additional benefits.

Introduction

The C.E.A. uses a frequency of 476 MHz in the accelerator cavities to accelerate electrons in the synchrotron ring. The electrons are injected from an S-band linear accelerator, which operates on the 6th harmonic of this frequency (2856 MHz).

There are various strong reasons for wanting to chop the linac beam so that only one out of every 6 linac bunches is injected into the synchrotron: in the synchrotron the amount of current which can be accelerated is limited by the beam-cavity interaction. If the beam-induced voltages in the rf acceleration system become large compared to the voltages produced by the transmitter, beam loading effects may lead to a complete loss of accelerated particles. One way of improving the situation would be to increase the voltage impressed by the transmitter so that beam-induced voltages become comparatively small; however, large rf voltages at injection would lead to large amplitudes of synchrotron oscillations for those particles which are injected at wrong phase angles with respect to the accelerating voltage. Only one out of 6 linac bunches can be placed at the correct phase angle; the other 5 bunches would get lost after very few turns, but the amount of beam loading they produce before they get lost would still be appreciable. A chopped linac beam would allow the injected bunches to be placed at the correct phase angle with respect to the synchrotron rf, this then would put no restriction on the applied rf voltage and would minimize synchrotron oscillations. It also would avoid contributions to the beam loading from particles which are injected at wrong phase angles and will get lost later.

Additional Benefits

1. By chopping at the injection end of the linac, the beam loading in the linac is reduced. This gives a higher output energy from the linac without reducing the useful current injected into the synchrotron. Higher injection energy seems to improve the performance of the synchrotron.
2. Electrons which cannot be accelerated do not enter the injection chamber, therefore less radiation damage occurs to the synchrotron vacuum chambers.
3. The gun is operated at a lower voltage. This eases the gun arcing problem, reduces the requirement for tank pressurization and invites the possibility of operating the gun from a regulated DC supply instead of from the present pulsed source.

Synchronization

To allow pre-selection of linac current pulses, the linac and synchrotron rf must be operated from the same master oscillator. But since each of these systems is a separate high "Q" system, extremely elaborate temperature control would be necessary to maintain each system at its appropriate frequency--during injection. Fortunately, injecting at a frequency slightly higher than the cavity resonant frequency tends to reduce beam loading; the exact amount "off frequency" is not critical. The solution was to provide a frequency synthesizer[1] which can be adjusted so that the 108th harmonic is at the linac waveguide resonant frequency during injection time; then after approximately one millisecond the frequency falls so that the 18th harmonic is at the rf accelerating cavity resonant frequency. The synchrotron rf is thus locked--during injection--to the linac rf. See Fig. 1.

The Principle of Chopper Operation

The linac used for injection into the C.E.A. synchrotron has two 10 foot waveguides with constant phase velocity. With an rf power input of 5 Mw into each of the two waveguides, the peak amplitude of the rf field is about $E_o = 10$ Mv/m at the injection end. Electrons are injected at a voltage of approximately 140 kv through a prebuncher into the first linac waveguide. A chopper cavity, resonant at one sixth of the linac rf frequency has been added between the gun and the prebuncher and supplies now half of the 140 kv injection voltage.

The phase angle ϕ_∞ at which an electron will come to rest with respect to the linac traveling wave, which propagates with a phase velocity $v_p = c$ (the velocity of light) is a function of the injection voltage U_{inj} and the phase angle at injection ϕ_{inj}.

If ϕ_o is the phase angle (measured at the 476 MHz frequency) at which an electron goes through the chopper cavity, the phase angle ϕ_B at which this electron will go through the prebuncher (measured at the S band frequency) is given by the expression:

$$\phi_B = 6\phi_o + \frac{2\pi \ell_1}{\lambda\sqrt{1-\left(\frac{U_o}{U_1+U_o}\right)^2}} + \alpha \qquad (1)$$

Where:
ℓ_1 = 12cm = distance from chopper cavity gap to prebuncher gap.
λ = 10.5cm = the S band wavelength.
U_o = 511kv = the rest energy of an electron divided by its charge.
$U_1 = U_{DC} + U_{CH} \cos \phi_o$.
U_{DC} = 70kv = the gun DC voltage.
U_{CH} = 70kv = the 476 MHz chopper cavity peak voltage.
And α is a phase angle which is adjusted so that the "ideal" electron which goes through the chopper at $\phi_o = 0$ will go through the prebuncher at $\phi_B = -\pi/2$.

The electron which leaves the prebuncher at the angle ϕ_B now has a voltage U_{inj} where:

$$U_{inj} = U_1 + U_{BN} \sin \phi_B \qquad (2)$$

Where:
U_{BN} = 11.3kv = the peak voltage in the prebuncher which has been chosen to give best bunching to 140kv electrons.

The phase angle ϕ_{inj} at which an electron arrives at the linac waveguide is then given by an expression similar to that for ϕ_B. (In this calculation ℓ_2, the distance from the prebuncher cavity to the linac waveguide, is 36 cm.)

The fixed phase-shift between prebuncher and waveguide is adjusted so that the ideal electron is injected 90° ahead of the peak of the traveling wave. Knowing the injection voltage, U_{inj}, and the injection phase angle, ϕ_{inj}, one can compute the final phase angle ϕ_∞.

$$\sin \phi_\infty - \sin \phi_{INJ} = \frac{2\pi U_o}{\lambda E_o}\left[\sqrt{\frac{U_{INJ}^2}{U_o^2} + \frac{2U_{INJ}}{U_o}} - 1 - \frac{U_{INJ}}{U_o}\right] \qquad (3)$$

Where:
E_o is the maximum field strength of the linac rf wave, and the other symbols are defined as above.

This equation (for ϕ_∞) can easily be derived, and is accurate for constant rf amplitude along the waveguide; actually the amplitude is not constant, but since the final phase angle is approached closely before the amplitude of the rf voltage has changed significantly, this equation can be considered a good approximation.

Figure 3 shows the results of this calculation for ϕ_o from 0 to 360 degrees. Since the amount of charge within a certain final phase angle interval is proportional to the corresponding ϕ_o, by using Figure 3, one can easily derive a graph which shows the actual bunching. Figure 4 shows the amount of current in terms of ϕ_o (note that $\Delta\phi_o = 360^\circ$ corresponds to 100 percent of the gun current) which is within 2.5° of final phase angle.

Associated with the linac output there would be 6 bunches per synchrotron rf cycle. The largest bunch, called Bunch I includes more than 10 percent of the gun current.

More than 50 percent of the total charge in this bunch is within 5° and about 70 percent is within 10°. This in itself demonstrates the very good bunching which one gets just by using a prebuncher cavity in conjunction with a $v_p = c$ waveguide. (The energy spread due to bunch width varies as the cosine. The energy spread due to a phase width of 10° is less than 0.4 percent.) The only two bunches (beside Bunch I) which carry any significant amount of charge and have large energy, are Bunches II and V. The charges in Bunches II and V are less than 25 percent of the charge in Bunch I, and the charges in the top 10° phase angle width are less than 12 percent. Moreover the final phase angles of Bunches II and V are more than 10° lower than that of Bunch I, meaning that the peak energy also is lower and consequently most of those electrons will not be accepted in the synchrotron. Two remarks should be made at this point:

1. From Figure 3 it is clear that with an injection energy of about 140kv no electron can be placed at the crest of the rf-wave in the linac. In order to obtain maximum voltage and to minimize energy spread one has to reduce the phase velocity in the first waveguide to allow the bunch to drift over the crest of the wave. This is done by running the waveguide at a slightly higher temperature. The result is almost identical with the case in which one places the bunches exactly at the crest of the wave and has exactly $v_p = c$.

2. The long tails of these bunches, shown in Figure 4, do not contribute significantly to beam loading in the linac. They seldom are observed because their entirely different energy makes focusing and steering conditions for those electrons wrong. For this reason one may expect an even better performance of this injection system than the calculations would indicate.

Cavity Design

The chopper cavity is a cylindrical reentrant cavity operating in the TM_{010} mode and is located between the linac-gun and the S-band prebuncher (see Figure 2.) The cavity, being short, could be added to the existing linac without changing the injection geometry appreciably. The cavity was constructed of stainless steel for mechanical strength. The interior of the cavity was silver plated to reduce the energy loss. The temperature of the cavity is tied to that of the linac by use of a common temperature-controlling water system.

The cavity was machined to frequency immediately prior to the final assembly braze. A vernier tuner provides a tuning range of one MHz. The cavity gap is 3/4 inch.

The cavity has a measured loaded Q of 10,000, and a shunt impedance of about 0.66 megohm.[2]

Amplifier Design

The pulsed rf amplifier that is used can produce 100 kv peak at 476 MHz at the cavity gap. The amplifier specifications are:

1. 20 kw peak power output at 476 MHz.
2. 40 db gain above available drive.
3. 10μsec pulse. Filling time = $2xQ/2x\pi xF = 6.66\mu$sec.
4. Regulation to 0.1 percent to minimize variations in particle energy. (A peak detector acting on a voltage variable attenuator regulates the amplifier output.)
5. Repetition rate 60 pps, i.e., the synchrotron rate.
6. Remote control, with expected life exceeding 1000 hr. mtbf.

A choice had to be made between a multi-stage gridded tube amplifier and a single stage klystron. As a commercial television type klystron Eimac 3 KM 3000 LA was available at a competitive cost, it was selected, although its average power rating far exceeded our requirements. (Rated at 3 kw, used at 20 w.) This klystron has a modulating anode, therefore for fast rise and flat pulses, a floating deck modulator using Eimac 4 PR 60's was designed and built.[3]

Experimental Results

Initial calculations indicated that the cavity could "multipacter"[4] at about 5 kv. In fact, multipactering appeared as a relaxation oscillation whose frequency was dependent upon impressed rf power. After approximately one week of "processing" near the multipactering threshold, the surfaces improved, so that it is possible to go through the multipactering level (5 kv) without breakdown and operate reliably at voltage from 10 to 100 kv.

Conclusion

Operation of the synchrotron with the chopped linac beam conformed to expectations. By varying the phase shift between the synchrotron and the linac, only one bunch can be detected. The other bunches are apparently of such different energy as to be lost along the injection path.

Now that the cavity voltage can be increased to lessen the effect of beam loading, it is possible to accelerate about twice as much current as compared to the unchopped case. At the present time the C.E.A. accelerates up to 4.8 x

10^{12} electrons per second.

Acknowledgement

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References

1. J. Maddox, Master R.F. Oscillator, C.E.A. Dwg. #13E-56A.
2. D.R. Hamilton, J.K. Knipp, J.B. Horner Kuper, Klystrons and Microwave Triodes M.I.T. Radiation Laboratory Series, Vol. 7, page 78, Fig. 4-10.
3. L.Law, Floating Deck Modulator, C.E.A. Dwg. #14E-62A, 14E-63A, and 14E-64A.
4. W.C. Brown and R.H. George, Rectification of Microwave Power, Vol. 10-64, p96.

Additional References

A. Allen J. Litchtenberg, Phase Prebunching, CEA-21.

B. G.A. Voss and A.E. Barrington, 475 mc/s Modulation of the Linac Current, CEA-79.

C. J. Cerino, Linac Prebuncher, CEAL-TM-142.

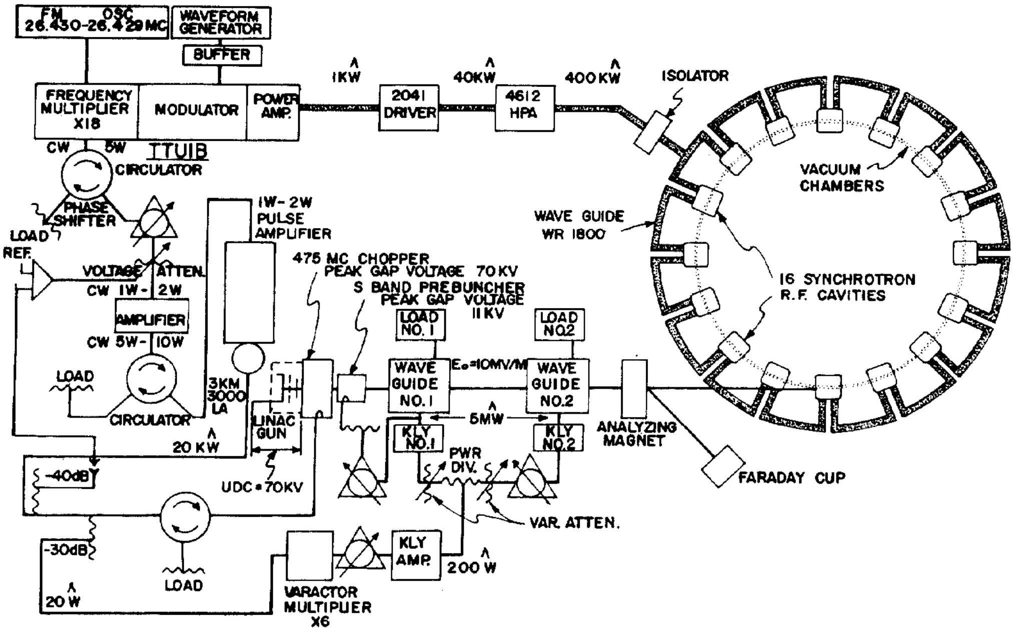

Fig. 1. Diagram of RF flow from Oscillator to LINAC and Synchrotron cavities.

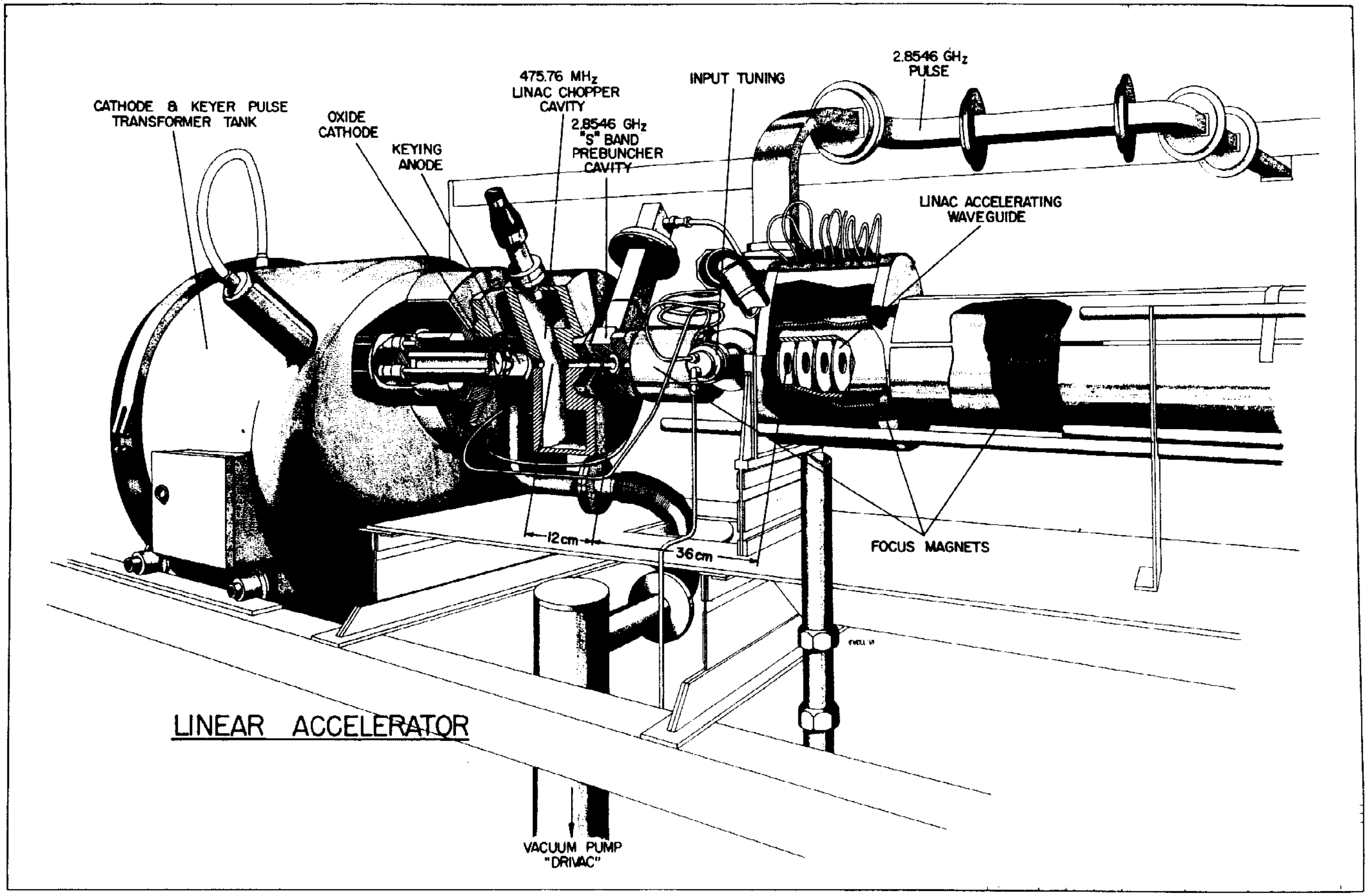
CATHODE & KEYER PULSE TRANSFORMER TANK
OXIDE CATHODE
KEYING ANODE
475.76 MHz LINAC CHOPPER CAVITY
2.8546 GHz "S" BAND PREBUNCHER CAVITY
INPUT TUNING
2.8546 GHz PULSE
LINAC ACCELERATING WAVEGUIDE
FOCUS MAGNETS
12cm
36cm
VACUUM PUMP "DRIVAC"
LINEAR ACCELERATOR

Figure 2.

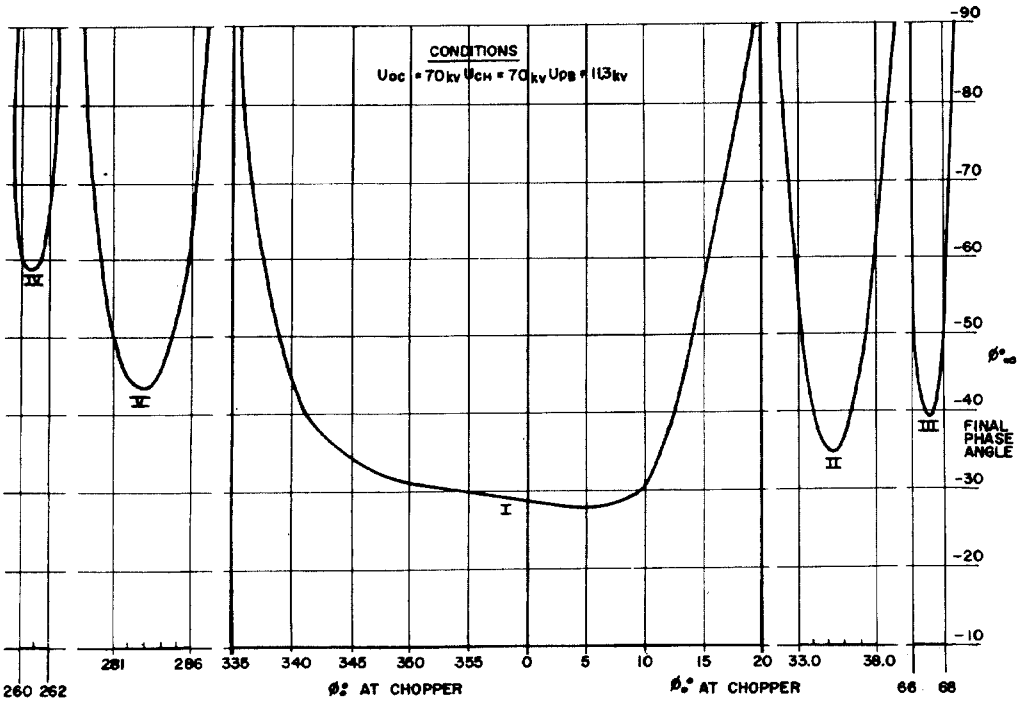

Fig. 3. Final phase angle of electrons as a function of the phase angle of the chopper RF.

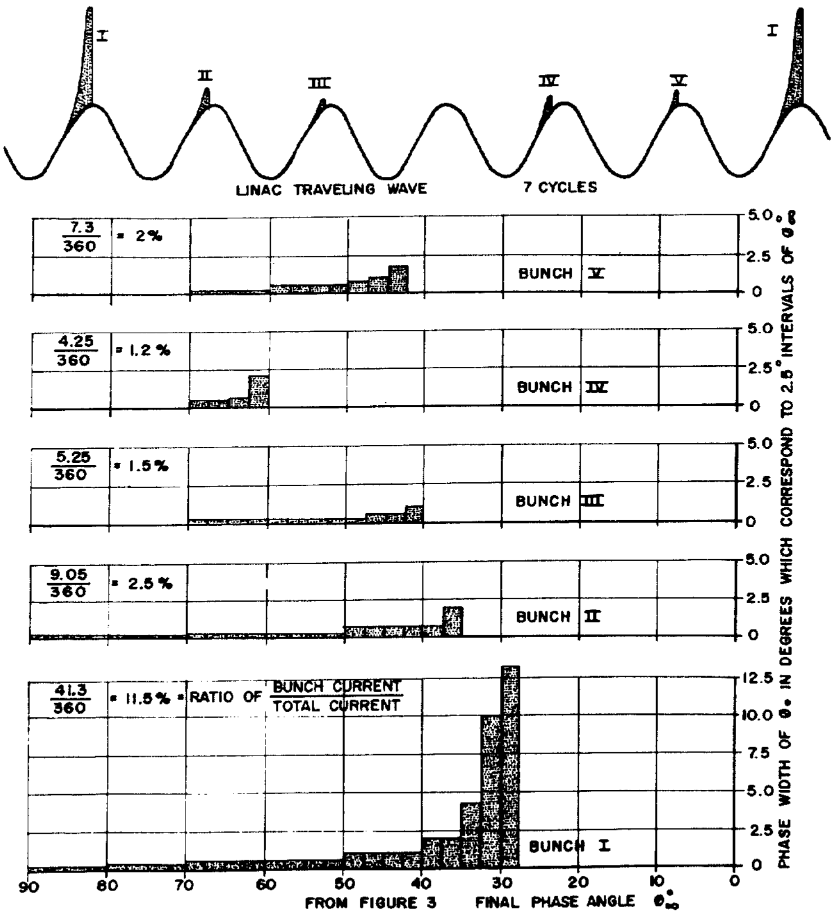

Fig. 4. Charge distribution of the LINAC beam.