SLAC-TN-65-43
E. L. Chu
May 1965

A SIMPLE SCHEME FOR OBTAINING VERY INTENSE BURSTS OF HIGH ENERGY ELECTRONS

In some future experiments with the SLAC linac it will be desired to accelerate intense current pulses of very short duration. Such experiments as neutron time-of-flight measurements and K_2^0 measurements have been mentioned by Panofsky.[1] According to Neal[2], the accelerator will be able to deliver 7.4×10^{10} electrons of 20 ± 0.5 BeV energy per pulse of 10 nsec duration. It appears clearly from Ref. 2 that the factor limiting the electron current in a sharp burst will be the amount of energy spread tolerable. Any useful scheme to increase the number of electrons per pulse must not at the same time enlarge the energy spread. The purpose of this note is to describe a simple scheme by which the accelerator may be loaded much heavier than normal for this kind of operation. It should be possible for the machine to accelerate 7N to 15N electrons per pulse $(N = 7.4 \times 10^{10})$ to an energy of 0.7V to 0.5V (V = 20 BeV).

The scheme to be described requires an electron beam injector system designed and operated at a frequency slightly below the accelerator frequency $\nu_0 = 2856$ Mc/sec. In view of the scope and the importance of the above-mentioned experiments, the use of a special injector system may not seem economically unfeasible or unjustifiable.

Let $(1-\delta)\nu_0$ be the bunching frequency of the proposed injector system. Then, the electron bunches injected into the main accelerator in successive rf bunching cycles will be spaced from each other by a distance $c/(1-\delta)\nu_0 \cong (1+\delta)\lambda_0$, λ_0 being the accelerator guide wavelength. This spacing between two neighbouring bunches will persist as the bunches travel along the whole two-mile length of the accelerator because they all enter with the same injection energy and are to be accelerated to the same output energy within a small energy spread.

If the first (earliest) bunch of electrons in a pulse travels at a phase angle φ, (say, $\varphi_1 = \pi/4$) ahead of the rf wave crest, the second bunch will find itself at a phase angle φ_2 which lags behind φ_1 by $2\pi\delta$ radian. Each successive bunch will lag behind the preceding one in phase angle by the same amount, $\varphi_n = \varphi_{n-1} - 2\pi\delta$.

In a beam pulse of duration $\tau = 10$ nsec there are altoghere m rf bunches, $m = \nu_o \tau \cong 28.5$. Let us say $m = 29$. The mth bunch will lag behind the first in phase angle by $(m-1)2\pi\delta$ radians. The value of δ will be so chosen that the last or the mth bunch will travel on the crest of the rf wave ($\varphi_m = 0$). Thus

$$(m-1)2\pi\delta = \varphi_1 = \pi/4,$$

i.e.,

$$\delta = \frac{1}{8\ (m-1)} = \frac{1}{224}$$

The difference between the accelerator frequency and the injector frequency (called the "beat frequency") is

$$\delta\nu_o = (2856/224) \times 10^6 \cong 12.75 \text{ Mc/sec.}$$

Without making detailed calculations we may assume, for the time being, that the successive shifting of phase will more or less compensate for the transient beam loading effects. The earlier bunches interact with stronger rf fields at less favorable phase angles while the later ones interact with weaker rf fields at more favorable phase angles. Therefore, each rf bunch of electrons will gain approximately the same amount of energy equal to $V_o \cos\varphi_1$, V_o being the zero-current beam energy. The total charge in one pulse is $N'e$ and the total amount of energy gained is $N'eV_o\cos\varphi_1$. If U is the total rf energy stored in the accelerator prior to the injection of the beam pulse, then $(1-\cos^2 \varphi_1)U$ will be the usable amount of rf energy. We thus require:

$$(1 - \cos^2 \varphi_1)\ U = N'eV_o\cos\varphi_1,$$

i.e.,

$$N' = (U/eV_o)\ \sin \varphi_1\ \tan \varphi_1\ .$$

Taking $\varphi_1 = \pi/4$, we obtain $N' = 0.707\ (U/eV_o)$.

In the case of normal operation $(\delta = 0)$, we have $U_o = U = 2380$ joules, $\tau_o = 1.67$ μsec, $V_o = 20$ BeV, and $N_o = 2.6 \times 10^{11}$ electrons per pulse. In this case, $N_o = 0.350(U/eV_o)$. We obtain the following ratios by comparing the two cases.

(1) Output beam energy:

$$\frac{V'}{V_o} = \cos \varphi_1 = 0.707$$

(2) Number of electrons per pulse:

$$\frac{N'}{N_o} = \frac{\sin \varphi_1 \tan \varphi_1}{0.35} \cong 2.0$$

(3) Total beam energy per pulse:

$$\frac{N'eV'}{N_o eV_o} = \frac{\sin^2\varphi_1}{0.35} \cong 1.43$$

(4) Peak beam power:

$$\frac{N'eV'/\tau}{N_o eV_o/\tau_o} \cong 1.43 \frac{\tau_o}{\tau} \cong 240.$$

The output beam energy is decreased, but the other three parameters are increased. The peak beam power is strengthened by two orders of magnitude mainly because of the large factor of τ_o/τ.

The special injector system may have the same design as the present system except for a change of rf bunching frequency. The bunching frequency must be locked to the accelerator frequency ν_o by a beat frequency $\delta\nu_o \cong 12.75$ Mc/sec. This should be relatively easy to arrange. We may derive the beat frequency either by frequency demultiplication or from a separate crystal-controlled oscillator. One beat cycle contains 224 rf cycles. The electron gun must be triggered at the correct time in order that the first bunch of electrons in a pulse will arrive at the correct phase angle φ_1. The timing of firing the gun must be accurate to about one rf cycle in 224 rf cycles or one beat cycle, although it would not matter if the timing is wrong by a whole number of beat cycles. A misfiring of one rf cycle changes φ_1 by $2\pi\delta \cong 1.61^{\circ}$. It is clear that the firing of the electron gun must be controlled by the beat frequency with proper adjustment of the phase between the bunching frequency and the accelerator frequency. To maintain correct timing, the time jitter of the whole injector system must be no greater than a small fraction of one rf cycle.

Such strict discipline as just outlined was certainly not possible with yesteryear's pulse technique. The best figures available were found in a report by Hanst and Norris.[3] These authors have managed to decrease the pulse rise time to 1.5 nsec, which is a big improvement but still seems too large for the contemplated purpose. There is, however, no doubt in this writer's mind that the present figure can be further improved. The most significant result of theirs is that the overall time jitter was measured to be less than 0.1 nsec. Stability of this degree is sufficient for our purpose.

The proposed "off-frequency" injection system can also be used with longer beam pulses for increasing the allowable beam loading factor. It can be used in conjunction with or as a substitute of other schemes, such as "stagger timing." For example, if $\tau = 1.67$ μsec as in the case of normal operation, then $m = \nu_0\tau \cong 4770$.
Then,

$$\delta \cong 1/8m \cong 2.62 \times 10^{-5}$$

and

$$\delta\nu_0 \cong 1/8\tau \cong 74.85 \text{ Kc/sec.}$$

This small beat frequency is well within the passband of the accelerator waveguide. As suggested several years ago by R. B. Neal,[4] the slightly different bunching frequency may conveniently be obtained by phase or frequency modulation of the klystron power driving the buncher.

Quite recently, R. Miller[5] has suggested the use of "multiple bursts" in one normal pulse length to take advantage of the continuous flow of rf energy through the accelerator. Each burst is of 10 nsec duration. Ten to twenty bursts, equally spaced, may be accommodated in one pulse length of 1.67 μsec.

Miller's scheme may easily be adapted to the "off-frequency" system. For example, let the rf bunches in one burst of 10 nsec duration be properly phased so that $\varphi_1 = \pi/6$, $\varphi_{29} = 0$, and $\delta = 1/336$. Nine such bursts, spaced by an equal interval of 0.21 μsec, may be injected into the accelerator in one normal pulse length, thus increasing the number of electrons by a factor of 9 and increasing the accelerator conversion efficiency by a factor of 3. Operated in this manner, the accelerator may be expected to supply, in one normal pulse time, 1.93×10^{12} electrons of 17.3 BeV energy. More intense electron beams may be obtained at correspondingly lower energies.

In conclusion, it may be stated that the recent rapid progress in the art of generating short bursts of intense electron beams makes it possible to subject the injector system for the SLAC accelerator or similar machines to very strict discipline. The proposed "off-frequency" injector system presents to the multitude of existing injection and phasing schemes another companion, which may or may not be used in conjunction with others and which, in the opinion of this writer, can best exploit the advanced pulse technique already achieved and further improvements yet to be realized.

Acknowledgement

The writer of this note wishes to thank R. Helm, J. Jasberg, G. Loew, R. Miller, and R. B. Neal for helpful discussions prior to and during the course of preparing this note.

REFERENCES

1. Memo, W. K. H. Panofsky to R. B. Neal, April 27, 1965.
2. Memo, R. B. Neal to W. K. H. Panofsky, May 5, 1965.
3. R. K. Hanst and N. J. Norris, "Injector Pulser for Linac Picosecond Operation," EG&G 1183-2020, AP-0507, March 1965. (The writer of this note is grateful to G. Loew for a copy of the Hanst-Norris report.)
4. Private communication.
5. Memo, R. Miller to R. B. Neal, May 14, 1965.