© 1973 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

# SUBNANOSECOND HIGH-INTENSITY BEAM PULSE

G. MAVROGENES, W. RAMLER, W. WESOLOWSKI, K. JOHNSON and G. CLIFFT Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439

#### Summary

We have completed the design and installation of a new bunching system for the Argonne electron linear accelerator originally placed into operation in 1969. It now routinely produces a pulse as short as 40 ps in duration with a charge of at least 7 nC (180A in amplitude) for use with experiments in the very "short" time reaction region. Such a pulse is produced over an energy range of 4 to 20 MeV with an accompanying total energy spread of 300 keV. Frequency of production is variable from one single pulse up to a PRR of 800 P/s. Efficiency of acceleration from the gun to the output of the accelerator is 50 percent.

Details of the bunching system, including the method of calculation with space charge inclusion, geometrical factors and hardware, and operational results are given.

#### Introduction

The Argonne Linac is a two-section "L" band traveling wave electron linear accelerator.<sup>1</sup> The original bunching system consisted of two traveling-wave (TW) prebunchers and a tapered TW buncher ( $\beta_W = 0.6$  to 1), produced a nominal trapping efficiency of 80% (I gun/I output accelerator) for the transient mode of operation (10 A, 10 ns) and 90% for the steady state mode (2A, 0.6 to 10 µs). It is these components that were used and axially repositioned along with the addition of a subharmonic (SH) buncher to achieve the subnanosecond-single-pulse bunching system to be described.

The design goal for this new system was twofold; first, produce a single pulse of electrons with a time structure in the picosecond time domain with a contained charge equivalent to that existing in one "fine" structure (PRR 1300 MHz) pulse produced by the Linac. For example, the 10 ns, 10 A burst of electrons contains 13 "fine" structure pulses with each containing a nominal charge of 8 nC. Second, since the energy spread within such a pulse does not exceed 300 keV, such resolution must be conserved in the formation of the single pulse for both the purposes of experimentation and transporting.

Various methods of achieving these goals were considered with "gating" of the original bunching system and SH prebunching being considered to be the most practical. It would appear that since the "fine" structure does indeed exist, one need isolate only one of these pulses. Several techniques were considered such as "gating" the buncher system by the use of crossfield filters or by means of RF deflection. Gating was discarded in favor of SH bunching because it provides for greater charge acceptance, a more compact beam-line, less complexity in hardware and, in general, greater flexibility in the time formation of the pulse.

\*Work performed under the auspices of the U.S. Atomic Energy Commission.

### Method of Calculation

The effects of space charge in the formation of an electron bunch of subnanosecond duration with a mean energy of 100 keV and having to contain 10 nC or more of charge cannot be neglected. To facilitate the calculations, the Tien<sup>2</sup> model was applied which represents the injected electrons as a series of finite disks of equal charge. The differential equations of motion of such disks within a circular conducting beam pipe have been previously developed,<sup>3</sup>,<sup>4</sup> and are the basis from which our calculations have been derived. For completeness, these equations are as follows:

$$\frac{d\gamma_{i}}{d\zeta} = -\psi \sin \delta_{i}$$

$$+ \frac{2e\lambda^{2}In}{m_{o}c^{2}b^{2}\pi} \frac{1}{N} \sum_{j}^{N} \sum_{n}^{\infty} \left[ \frac{J_{1} \frac{\beta_{on}b}{a}}{\beta_{on}J_{1}(\beta_{on})} \right]^{2}$$

$$\frac{e^{-\left|\frac{\beta_{on}\beta_{w}\lambda(\delta_{i}-\delta_{j})}{\gamma_{i}^{2}}\right|}}{\gamma_{i}^{2}}$$

where:

relates to the energy change of the disk caused by its interaction with the accelerating field and the forces created by space charge and image effects. Now, the resulting change in phase of the disk to the field because of its change in energy is given by

$$\frac{\mathrm{d}s_{\mathbf{i}}}{\mathrm{d}\varsigma} = 2\pi \left(\frac{1}{\beta_{w}(\varsigma)} - \frac{s_{\mathbf{i}}}{\sqrt{\gamma_{\mathbf{i}}^{2}-1}}\right)$$

To calculate the effects of SH prebunching, both equations were referenced to the downstream side of the buncher gap. Initial conditions for solution were established as follows: Each disk was assigned a phase position relative to the buncher's field and an equal phase difference existed between each disk. The magnitude of this difference was dependent upon the number of disks and the time width of injection. The energy modulation experienced by each disk was then calculated by

$$\gamma_{i} = 1 + \frac{e(V_{0} + V_{i} \sin \omega t)}{m_{0}c^{2}}$$

where:

V is voltage of Gun  $V_1^0\sin\omega t$  is modulation voltage of SH. B.

£

Simplicity was achieved by assuming (a) effect of gap transit time is negligible, (b) radial size of the disk remains unchanged during the process of bunching, (c) electrons emanate from the gun in a burst with zero rise and fall times, and (d) electron emission from the gun is of constant amplitude throughout the duration of the injection.

For the quantity of charge used in these calculations, ( $\sim$ 15 nC) it was found that partitioning the burst of electrons from the gun into 21 disks, one center disk with 10 upstream and 10 downstream, presented a reasonable representation and use of any additional disks did not significantly contribute to the accuracy of the results.

It was these equations and assumptions that were used to study the interrelated effects of duration of injection, quantity of charge, subharmonic bunching parameters, and axial distances required to achieve the design goals.

This method of calculation was extended to the fundamental frequency prebuncher and buncher and the details of such calculations, including programming, are given in Ref. 5.

# Results of Calculations

Since the existing housing for the linac presented a physical constraint in regard to the drift distance for bunching, we had to first relate to this problem and achieve a compromise with the interrelated parameters.

The data of Table I illustrates the change that occurs in drift distance as the subharmonic index is varied; distance decreases with decreasing index. Unfortunately, as the index decreases, the requirements on the "gun" as related to both charge and shortness of injection increase. Index numbers as great as 10 were quite attractive to "gun" operation,<sup>6</sup> but drift distances were too great. In fact, 155 cm was the maximum distance that could be allowed, therefore, the choice of the 6th index for our design. Requirements for the gun were then feasible, and commercial components<sup>7</sup> were then available.

Axial positioning of the 1302 MHz prebuncher and buncher and the required electrical parameters were established by performing a series of trajectory calculations for various combinations of injection time and charge, electric fields and component positions. Parameters for SH Buncher are given in Table II.

Figure 1 illustrates a typical calculation in which the assumed injection is 2.5 ns (rectangular) in duration, electrons are 100 keV in energy and the total charge is 19 nC. At the entrance to the buncher, these electrons are bunched to about 0.12 ns (I rad for 1302 MHz) with a capture efficiency of 50%. Of course, in reality the shape of the injected burst is almost triangular in shape with the end disks containing less charge; efficiency of the bunching will increase. The buncher provides full acceptance and provides a further compression to about 0.05 rad and increases the mean energy of the electrons to 2 MeV. Injection into the accelerator then occurs. As the duration of the injection is increased, for example >3 ns, satellite bunches will appear and the charge contained in the main pulse will be enhanced. Fig. 2 establishes the axial position of components in the finalized system.

### Operation

Only the beam from the accelerator has been studied to determine the performance of the bunching system. Fig. 3 illustrates performance when the gun provides a 3 ns burst of electrons, estimated charge input of 15 nC, and the SH prebuncher is not energized. With the SH prebuncher energized, bunching occurs with one main pulse formed (Fig. 4); trapping efficiency is about 50%. When the charge of the main pulse is increased from 7 to 12 nC, satellite pulses appear (Fig. 5). All of these measurements were accomplished by passing the beam through a thin window Xe gas cell (1 atmos.) and the resulting Cerenkov light monitored by a fast diode<sup>8</sup> circuit. Fig. 6 is a typical profile of the axial magnetic field.

Total spread (100% of electrons) in energy existing in the single pulse when containing 7 nC is 300 keV (FWHM 150 keV). Based upon this spread, time width of the pulse is estimated to be <40 ps. Measurements are now underway to determine this width by means of the time formation of the hydrated electron.<sup>9</sup>

This single pulse can also be repetitively produced with a rate as high as 800 PPS over the range of energy from 4 to 20 MeV. Operation is routine and requires no more than 5 minutes of additional tune-up time. Conventional linac operation is achieved by de-energizing the SH buncher and energizing prebuncher No. 1.

# Acknowledgements

We are indebted to G. Parker and L. Rawson for their efforts involving mechanical design and installation of components; and A. Hutton (Consiglio Nazionale Delle Ricerche of Bologna) who temporarily joined the group to study the design, and to participate in the installation and tune-up procedures.

# References

- W. Gallagher, K. Johnson, G. Mavrogenes, W. Ramler, "A High Current Electron Linac", IEEE Trans. Nuc. Sci. NS-18, 584 (1971).
- R. K. Tien, L. R. Walker, V. M. Wolontis, "A Large Signal Theory of Traveling-Wave Amplifiers", Proc. IRE 43, 260 (1955).
   C. B. Williams, M. H. MacGregor, "Space Change Effect in Wish Compart Linear
- C. B. Williams, M. H. MacGregor, "Space Charge Effect in High Current Linear Accelerator Systems", IEEE Trans. Nuc. Sci. NS-14, 581 (1967).
- G. W. Peterson, W. J. Gallagher, "An Analysis of Traveling Wave Prebunchers", IEEE Trans. Nuc. Sci. NS-16, 214 (1960).
   Internal Bldg. 211 (ANL) Eng. Rept., G.S.M. 32, (1971).

- 6. Applied Radiation Corp. Model No. 12 Electron Gun
- N. Norris, R. K. Hanst, "Velocity Modulating System for Enhancement of 50 Picosecond Radiation Pulse," IEEE Trans. Nuc. Sci. NS-16, 323 (1969).

# TABLE I

Subharmonic Index	Sub- harmonic Drift Distance cm	Width Injected Burst <sup>1,2</sup> ns	Injected Charge nC	Charge <sup>3</sup> Output Buncher System nC
4	110	1.5	10.5	7
6	155	2.5	18.5	8
8	221	3.0	22.5	9
10	276	3.1	23.3	9

8. I.T.T. F4014 Photodiode

9. C. Jonah, M. S. Matheson, Private communication, ANL.

# TABLE II

SH Buncher <sup>1</sup>		RF Amplifier <sup>2</sup>			
MHz Q R <sub>s</sub> (Ω) Mode	216.7 1000 200,000 TEM	Center Frequency Pulse width Repetition Rate Peak RF Output	216.7 MHz 10 µsec ± 1000 pps 12 KW	± 0.1 0.5µsec	

<sup>1</sup>Constructed by EG&G.

<sup>2</sup>Constructed by Microwave Cavity Laboratories.

<sup>1</sup>Zero rise and fall times are assumed.

<sup>2</sup>Amplitude of burst is 7.5 A.

<sup>3</sup>Results of trajectory calculations.



Fig. 1 Typical set of trajectories for SH bunching system



Fig. 2 Finalized layout of SH bunching system



Fig. 3 Accelerator output (12 nC) without SH prebuncher. Injection time is 3 ns & 15 nC



Fig. 4 Accelerator output (7nC) with SH prebuncher Injection time is 3 ns  $\beta$  15 nC



Fig. 5 Accelerator output (12 nC) with SH prebuncher Injection time is 3.7 ns & 25 nC



Fig. 6 Typical profile of the axial magnetic field