THE PRODUCTION OF INTENSE NANOSECOND AND SUBNANOSECOND BEAM PULSES FROM TANDEM ACCELERATORS

H. Naylor[+], K. H. Purser and P. H. Rose
High Voltage Engineering Corporation
Burlington, Massachusetts

Abstract

A short review is presented of the factors involved in the production of intense bursts of ions having nanosecond duration from tandem accelerators. For the specific example of the High Voltage Engineering Corporation's model MP tandem it is shown that, if velocity modulation is applied to the beam at the appropriate point and if a non-dispersive arrangement of elements is used in the post-acceleration beam-transport system, the existing source and the injection optics should permit pulsed beams of the hydrogen isotopes to be available at several target positions with energies up to 20 MeV, burst widths of ~ 1nS and peak intensities of ~ 500μA. The advantages are emphasized of having ions of variable energy available at the modulator and it is shown that this feature can permit the use of sources of large inherent energy spread and also the production of pulsed beams from a variety of heavy ions. The concept of multiple bunching is introduced and it is shown that the use of this technique would allow the production of burst intensities of several milliamperes and also ultra-short pulses ($\tau \sim 5 \times 10^{-11}$ secs).

Introduction

Time-of-flight techniques have found widespread application in nuclear structure studies for the direct measurement of neutron velocities as a determination of energy[1] and as a monochromator[2] for the selection of neutrons having a specific energy. Extensions of these same timing methods make possible mass-identification of charged particles in a manner complementary to the well-known $E.\,dE/dx$ techniques [3, 4]; the rejection of background pulses caused by unwanted radiations when these radiations arrive at the detector at a time which is known to be different from the expected arrival times of the wanted events[5]; the direct measurement of isomeric lifetimes with $\tau \sim 10^{-10}$ sec.[6, 7]; trajectory determination permitting kinematical corrections and simultaneous angular distribution measurements at multiple angles (see figure 1).

Although a number of authors have described instrumentation for the production of pulsed beams from d. c. accelerators (see reference 8), only two groups have reported apparatus which was designed specifically for tandem Van de Graaff accelerators [9, 10]. Because these tandem systems are somewhat limited in usefulness, as the peak burst currents are much less than the intensities needed for many experiments and also because of a growing general interest in time spectroscopy, a study was conducted with the following aims in parallel with the design of the ion-optical system of the High Voltage Engineering Corporation's model MP tandem accelerator:

(i) To investigate pulsing techniques which would be compatible with the MP optical components and be capable of providing pulsed beams of the hydrogen isotopes at energies up to 20 MeV, with burst-widths of approximately 1nS and peak intensities of several hundred microamperes.

(ii) To arrange that the chosen pulsing components be capable also of providing nanosecond bursts of a large variety of particle species.

(iii) To investigate ways in which the system might be extended in the future to provide intensities of several mA and ultra-short bursts ($\tau \leq 10^{-10}$ sec.).

The present paper discusses the more important conclusions from this study and proposes a pulsing system for tandems which should provide considerably higher pulse intensities than have been previously available.

Ion Optics of the MP Tandem Accelerator

Figure 2 is a schematic diagram showing the major optical components chosen for the d. c. beam transport system. An intense beam of atomic ions from a duoplasmatron source is passed through a gas target where a small fraction is made negative by charge exchange. These ions are focused, momentum analyzed (to remove unwanted masses and the fractions derived from the molecular components of the primary beam) and inflected onto the tandem axis where they are accelerated to an energy suitable for tandem injection.

As the beam must be focused to a crossover of small diameter to pass through the stripping canal in the high voltage terminal, a positive lens is needed close to the entrance of the low-energy

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[+] Present Address: University of Auckland, New Zealand tubes. In previous tandem designs this lens action was provided automatically by the focal properties of the low-energy acceleration tubes. Unfortunately, however, the focal properties of acceleration tubes are severely energy dependent, and the axial motion with terminal voltage of the injection point which is conjugate to the terminal stripper together with a consequent change in the magnification across the low-energy tubes, introduce serious ion-optical matching problems. In practice, the conventional arrangement of einzel lenses permits the optical acceptance of the accelerator to exceed the emittance of the source over only a small range of terminal potentials. In the MP design, these optical problems were eliminated by shaping the boundary of the field at the entrance to the acceleration region by a plane conducting grid, having a high transmission (88%) for charged particles, and by the use of a lens whose strength is independent of the terminal voltage. The grid terminates the electrostatic fields in a controlled manner, rather than by the bulge which is inherent in a free-space solution of Laplace's equation, and eliminates from the transport system a strong focal element whose strength varies greatly with changes in the terminal potential.

Time Compression

Although various methods of introducing time information have been proposed[5, 12, 13, 14, 15], the basic theory of pulsing indicates that in general time information cannot be introduced into a beam without reducing the quality of some other property of the beam[8, 11]. For example, the Mobley bunching system adds time-information to the beam at the expense of the angular homogeneity at the target; this increase in radial phase space is not negligible and excluded consideration of this bunching method from the present design study, when considered together with the large physical size of the magnet required for compressing proton beams at 20 MeV and the fact that pulsed beams can be delivered easily to only one target location. This loss of quality is also true of velocity bunching where time information is introduced by modulating the velocity of the particles along their momentum direction so that at a later time the faster particles catch up with the slower, producing at some point a bunched beam; with this technique time information is impressed on the beam at the expense of energy homogeneity. In a d. c. accelerator velocity modulation has the important practical advantage that in many situations the chromatic effects introduced by the optical elements because of the energy inhomogeneity and the emittance increase produced by the velocity modulator can both be neglected, and the accelerator can be operated when pulsed, in the conventional manner. An additional advantage is that several target stations can be used for pulsed experiments.

Velocity modulation was chosen in this design study and figure 3 shows schematically the arrangement of components which have been proposed for the MP pulser. The d. c. beam from the source would be chopped to provide 20-50 nS bursts at 2. 5 Mc/S, passed through a diverter[8] to remove unwanted pulses, and velocity modulated by the buncher to provide bursts of current at the target. Practical considerations suggested that the most effective location for the buncher would be at ground potential in the region between the injector and the tandem accelerator. This location has several advantages; first, at this point velocity modulation can be introduced at a fixed beam crossover; secondly, the ion energy can be adjusted to optimize the final time spreads arising from the inherent source energy inhomogeneities; finally, variable bunching energy permits compression of a variety of masses. Velocity modulation within the injector was not considered acceptable as the pre-injection momentum analysis needed for d. c. and heavy-ion work would interfere with any single-gap arrangement. Post-acceleration bunching is not of general use since for 16 MeV protons approximately 500 keV modulation would be required to compress a 10nS burst over a 40 meter drift length.

Velocity Modulation

The principles of velocity modulation of electrons have been reviewed by Spangenberg[16] and of positive ions by Neiler and Good[5]. In figure 4, where we neglect transit time through a modulator, the transit time, t_o across a field-free drift region of length L is

$$t_o = L \sqrt{m/2E_o}$$

and for small ΔE,

$$\Delta t = L \sqrt{m/8E_o^3} \cdot \Delta E \text{ ------- (1)}$$

where m is the mass of the ions
E_o is the energy of the ions arriving at the modulator.

Equation (1) can be viewed from two different points which are equivalent but serve to illustrate complementary aspects of the problems of velocity modulation. First, if Δt_2 is considered as the difference in time, measured at the target, between two particles which leave the modulator simultaneously, then ΔE_1 represents the difference in energy between the particles. Thus, if ΔE_1 represents the inherent energy inhomogeneity of the beam leaving the source and the experimental requirements set a maximum value for Δt_2, the burst width at the target, then equation (1) may be used to determine either the maximum bunching length L which can be used when E_o is fixed, or alternatively the minimum beam energy at which the modulation can be applied when mechanical constraints have established the length L. The second point of view is that if Δt_1 is the time-length of the section of beam which is to be compressed, ΔE_2 is the energy modulation which must be impressed on the beam to achieve the maximum time-compression in the length L.

If the initial conditions are Δt_2 and ΔE_1 we have

$$\frac{\Delta E_1}{\Delta t_2} = \frac{1}{L}\sqrt{\frac{8E_o^{\,3}}{m}} = \frac{\Delta E_2}{\Delta t_1} \text{-------} (2)$$

so that $\Delta E_1 \Delta t_1 = \Delta E_2 \Delta t_2$

This expression will be obeyed in the ideal case and the extent to which the product $\Delta E_2\ \Delta t_2$ approaches $\Delta E_1\ \Delta t_1$, without loss of particles from the bunch and without changing the other coordinates and momenta at the target, may be used as a figure of merit for the bunching system.

Equation (2) is a special case of the limitations inherent in the various methods of beam chopping and bunching discussed by Fowler and Good[11]. These authors have shown that by including t and -H as additional canonically conjugate coordinates, on equal standing with the generalized coordinate q_i and p_i, it is possible to extend Lagrange's differential invariant to read:-

$$\left.\Delta p_x\,\delta x - \delta p_x\,\Delta x + \Delta p_y\,\delta_y - \delta p_y\,\Delta y - \Delta E\delta t + \delta E\Delta t\right|_a^b = 0 \text{---------------} (3)$$

where the x and y coordinates are mutually orthogonal with the axis of z, which coincides with a reference ray, and the p_i are canonically cononically conjugate momenta. Δ, δ refer to variations on each of two rays with respect to the reference ray.

The form of equation (3) shows the direct correspondence which exists between time plots in the (t, z) plane and conventional ray-diagrams in the (x, z) or (y, z) planes. The analogy can be easily pictured if one plots the time difference from some reference ray against distance, as in figure 5. Here, the single-gap buncher becomes a positive "time-lens" and the time spread in the compressed burst is seen to be proportional to L and to the source energy spread. The energy inhomogeneity in the final bunch, θ, is proportional to the time-length of the burst before compression. The time diagram is instructive as it emphasizes the importance of establishing the optimum distance between the buncher and point of minimum time confusion (which in practice will be arranged to be at the target); if this distance is made too great for the inherent energy inhomogeneities in the beam, there is no value of the energy modulation which will make the burst-length adequately short. In a practical situation the parameters of the system can be adjusted effectively by altering the energy of the ions at the modulator. This is an important reason for using a variable energy ion beam.

Chromatic Effects in the Low Energy Acceleration Tubes.

When the energy of the ions entering the accelerator is changed incrementally by ΔE, with no corresponding change in the voltage ratio across the bipotential lens at the entrance to the low energy tubes, the focal length of this lens increases and the ion beam is no longer focused to a crossover at the stripper. Clearly, for a particular stripper diameter there is a maximum value of the modulation depth, $\Delta E/E_o$, which can be applied if the beam is not to be intercepted at the terminal. Table I lists, for the MP tandem, the acceptable values of $\Delta E/E_o$ which can be imposed on the beam if the diameter at the terminal is not to grow by more than 0.1", the maximum acceptable increase for a canal diameter of 0.3". The final column shows the length of beam which can be compressed without exceeding these limits.

Table 1
Acceptable Values for $\Delta E/E_o$ (MP Tandem)

Terminal Voltage (MV)	$\Delta E/E_o$ (maximum) (%)	Introduced Energy Inhomogeneity (E_o = 125 keV) (keV)	Δt_o (nS)
1	4.8	12.0	30.5
3	6.1	15.2	38.5
5	6.9	17.2	44.0
8	7.3	18.2	46.0
10	7.8	19.5	49.4
12	8.1	20.5	52.0

Velocity Modulator

The charging currents necessary to drive the proposed MP modulator are sufficiently great that the buncher must be part of a high-Q tuned circuit; application of shaped waveforms by means of a hard-tube modulator is impractical. The modulator must be driven at some multiple of the base frequency which was chosen to be 2.5 Mc/S because of many practical considerations. Figure 6 shows a comparison between the ideal bunching waveform[17] and sinusoidal modulation at 5 Mc/S; it can be seen that the two waveforms differ only slightly near t = 0 and that a prebunched beam length of about 40 nS can be used without introducing excessive time error. Thus, from an injector capable of producing d. c. negative ion currents of 30 μA, peak burst intensities of about 1 mA should be available which, at a repetition rate of 2.5 Mc/S represent mean beam currents of 3 μA.

Heavy Ion Bunching

The simplest form of velocity modulator that can be used is the two-gap buncher consisting of one driven electrode with a grounded electrode close to either end. Such a device accelerates each ion twice; once when entering the modulator and again when leaving. If the shape of the modulating waveform at entrance and exit are to be identical and time aberrations minimized, the oscillating voltage must change phase by $(2n + 1)\ \pi$ radians during the time that particles take to travel the distance between the accelerating gaps (where n is zero or a positive integer). Thus, if τ_o is the period of the modulation waveform, v the velocity of the ions, and ℓ the length between the modulator gaps the following relationship must be satisfied:-

$$\ell = \sqrt{\frac{2E_o}{m}} \cdot \frac{\tau_o}{2} \cdot (1 + 2n)$$

Clearly, if the period of the modulator and its length are fixed, bunching can be made to occur for a variety of masses by changing the values of the injection energy and the parameter n. Figure 7 shows the manner in which these parameters can be adjusted to permit bunching of a variety of particles. This graph emphasizes a second advantages of variable energy injection.

Optical Effects of Velocity Modulator

As each gap of the modulator can be regarded as an equi-diameter two-cylinder immersion lens, the optical distortion introduced into the beam by the modulator may not be negligible. These lens effects cannot be removed by adjusting the strength of another d. c. lens as they are dependent upon the phase of the particles. Although, in principle, they can be reduced by using grids at the modulator gaps, an unfortunate consequence is that the "facet lenses"[18, 19] formed by the apertures between the grid wires produce a considerable effect upon the beam. Such grids may be essential, however, to reduce transit time effects if the diameter of the modualtor electrodes is large. For these reasons it was considered essential to place the bunching gaps close to a beam waist and make the electrode diameter as small as possible.[20] An incidental advantage is that the modulating electrode is small and has a small capacitance to ground. At the location of the MP modulator the beam diameter is less than 0.20"; and even if the modulator has this diameter the focal length of each lens is sufficiently great that shifts in the position of this crossover at the injection point are negligible. Furthermore, as the modulator is at a beam waist the confusion which is introduced does not change the diameter of the beam at the conjugate point at the entrance to the stripping canal.

Post Acceleration Debunching

The difference in path-length through the post-acceleration beam transport components represents the most serious cause of debunching in the MP accelerator. The extreme path-length differences expressed as time are listed in Table II for the MP tandem 90°-analyzer.

Although the beam which leaves the 90° analyzer is debunched, time-space correlations still exist within the beam. Thus, if the particles which leave the 90° analyzer are passed through a second bending field, where the previously shortened trajectories are now the paths of greater length, the debunching effects can be reduced. Such an arrangement is shown in figure 8.

Detailed calculations of the time-properties of the arrangements of lenses and bending elements are facilitated when beams of finite emittance are being considered by extending the matrix formulation discussed by Penner[21], to a 4 x 4 vector space[22]. The additional parameter to theradius, angle and momentum spread is the incremental trajectory length, ΔL. Using Penner's notation the appropriate four-dimensional matrix transformation for a uniform-field magnet is given in equation (4).

Figure 9 shows the principles of a new post-acceleration beam transport system which is isochronous at multiple target locations and is also nondispersive[23]. In this system, a cross-over is formed at the symmetry planes of each of the deflecting elements. In this way all particles in the beam travel almost equal distances between the buncher and the target, irrespective of their location in the beam and irrespective of the location of the final target. Computer calculations, which include the finite emittance of the beam leaving the model MP tandem, indicate that this isochronous system will introduce time spreads of approximately 0.05 nS.

Multiple Bunching

If the output from the negative ion source is to be used most efficiently and the fraction of ions which are rejected is to be kept small, the bunching waveform must be useable over a much larger fraction of 2π radians than is possible with sine-wave modulation. In effect, this means that the rate-of-change of potential on the modulating

Table II
Time Spreads Introduced by 90° Magnet

Particle Energy	H_1	D_2	T_3	O_{16}	S_{32}	I_{127}	U_{238}
5 MeV	2.1 nS	3.0 nS	3.7 nS	------	------	------	------
10 MeV	1.5 nS	2.1 nS	2.6 nS	------	------	------	------
20 MeV	1.1 nS	1.5 nS	1.7 nS	4.2 nS	6.0 nS	------	------
30 MeV	0.9 nS	1.2 nS	1.5 nS	3.4 nS	4.9 nS	------	------
50 MeV	------	------	------	2.7 nS	3.7 nS	7.5 nS	9.8 nS
100 MeV	------	------	------	1.9 nS	2.7 nS	5.3 nS	7.3 nS
200 MeV	------	------	------	------	------	4.6 nS	6.3 nS
300 MeV	------	------	------	------	------	3.1 nS	4.4 nS

(Equation 4)

$$\begin{bmatrix} x_2 \\ \theta_2 \\ \dfrac{\Delta p}{p_o} \\ \Delta L_2 \end{bmatrix} = \begin{bmatrix} \dfrac{\cos(\alpha-\beta_1)}{\cos\beta_1} & \rho\sin\alpha & \rho(1-\cos\alpha) & 0 \\ \dfrac{-\sin(\alpha-\beta_1-\beta_2)}{\rho\cos\beta_1\cos\beta_2} & \dfrac{\cos(\alpha-\beta_2)}{\cos\beta_2} & \sin\alpha+\tan\beta_2(1-\cos\alpha) & 0 \\ 0 & 0 & 1 & 0 \\ \sin\alpha+\tan\beta_1(1-\cos\alpha) & \rho(1-\cos\alpha) & \rho(\alpha-\sin\alpha) & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ \theta_1 \\ \dfrac{\Delta p}{p_o} \\ \Delta L_1 \end{bmatrix}$$

electrode must be sufficiently low that the charging currents can be supplied by a hard-tube modulator. However, the values of $\frac{dV}{dt}$ which are technically feasible using a hard-tube modulator may not be sufficiently great to reduce the debunching effects produced by the source energy spreads and it may prove impossible to satisfy, simultaneously, the requirement of large acceptance angles from the source ans short bursts at the target. Basically, this difficulty represents a matching problem in phase space and the analogous difficulty in light-optics would be overcome by the addition of extra lenses. It is interesting to consider the advantages of using several velocity modulators arranged sequentially through the beam transport system. The potential advantages can be seen from figure 10. The first modulator operates on the beam at the lowest possible energy, consistent with space-charge and other effects, allowing the charging currents to be small. The second modulator is situated so that the necessary time-rate-of-change of voltage for short burst time is achieved. The condition which must be satisfied by such a bunching system may be written:

$$\frac{1}{L_2} \cdot \sqrt{\frac{8\,eV_2^3}{m}} >> \frac{1}{L_1}\sqrt{\frac{8\,eV_1^3}{m}}$$

where the subscripts 1 and 2 refer to the first and second modulators respectively.

This inequality can be satisfied if an acceleration stage is present between the modulators or if the distance between the target and the second modulator is much smaller than the distance between modulators.

Recent work on high intensity negative ion sources indicates that d.c. currents of several hundred microamperes can be obtained at energies of about 10 keV with a very low emittance and good energy homogeneity [24,25]. If usch a source were installed within the MP injector, it should be possible to compress 60% of the particles leaving the source into 20 nS bursts. If further modulation was then applied at ground potential, bursts should be available at the target having nanosecond duration and intensities of many milliamperes. The principles of this technique are also applicable to the production of ultra short bursts (Δ T ~ 0.05 nS) using an auxiliary post-acceleration modulator to further compress the high energy particles. The high modulation voltages needed might be obtained by making the second modulator part of a high-frequency resonant cavity.

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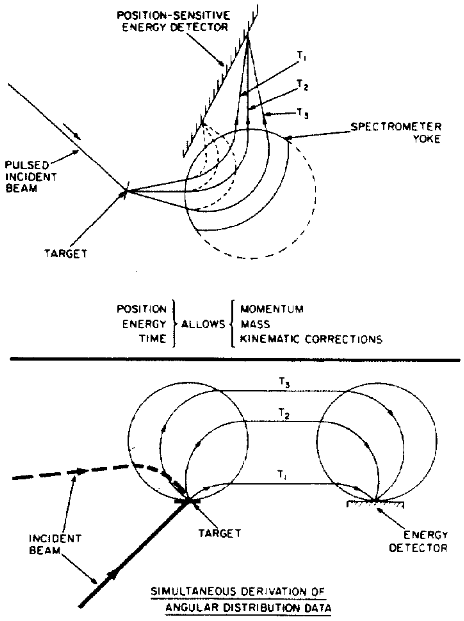


Figure 1.

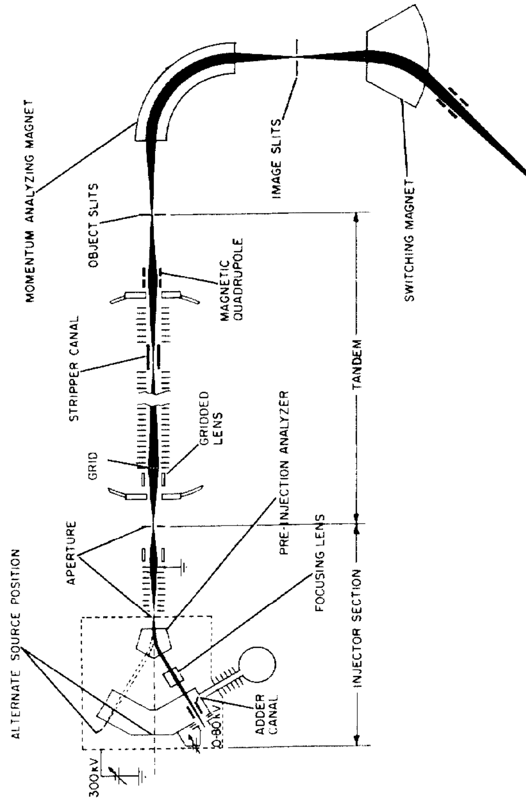


Figure 2.

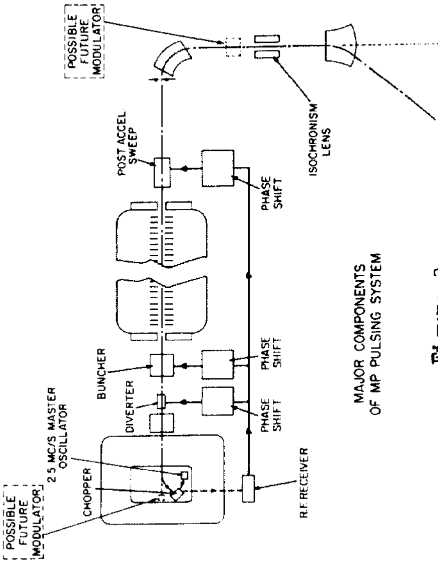
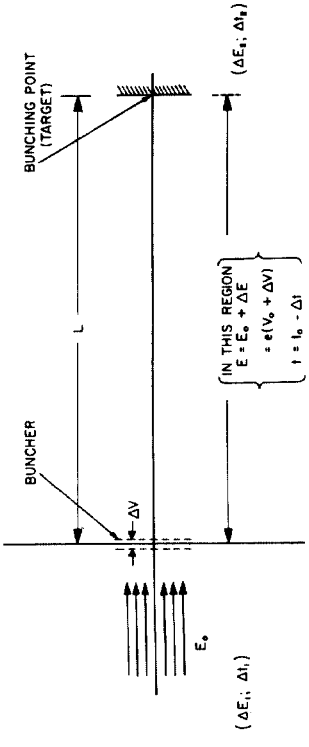


Figure 3.



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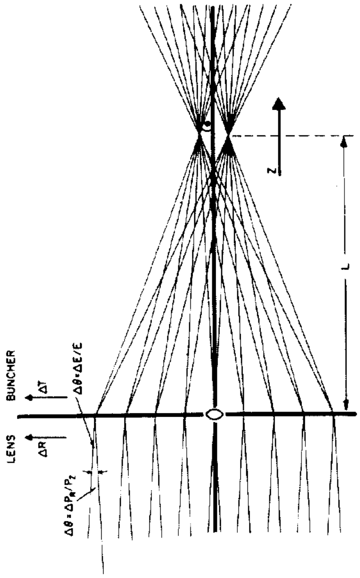

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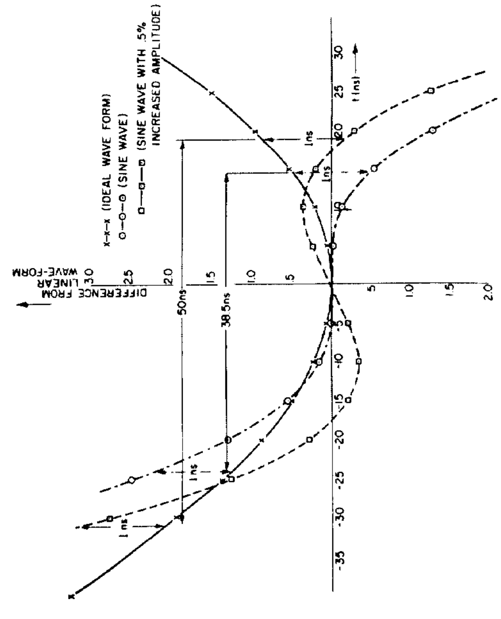

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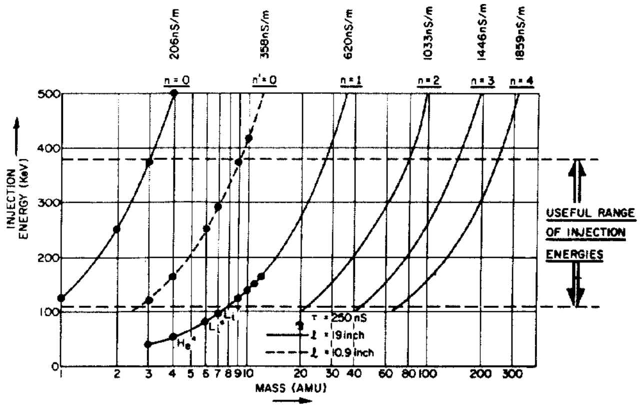
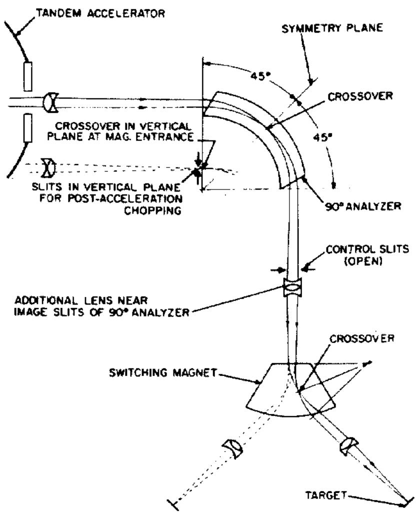


Figure 7.



ISOCHRONOUS BEAM TRANSPORT SYSTEM
FOR MULTIPLE TARGET LOCATIONS

Figure 9.

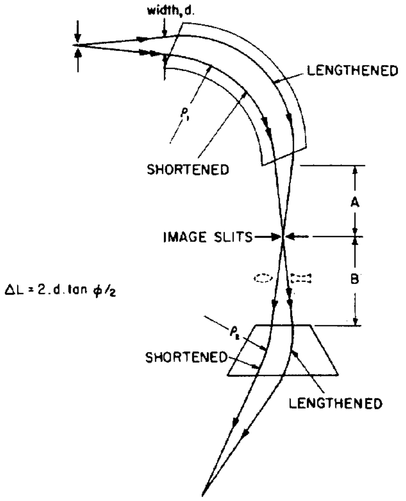


Figure 8.

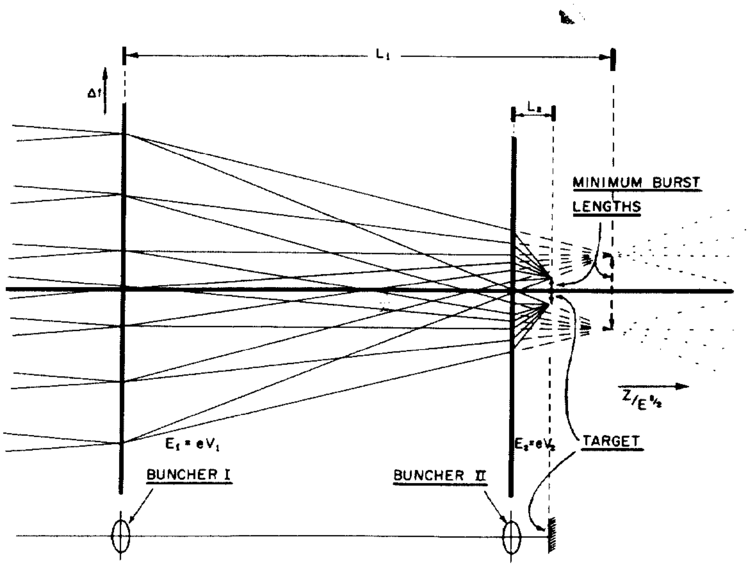


Figure 10.