A DEVICE FOR BUNCHING RELATIVISTIC ELECTRONS*

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Introduction

A device to bunch a longitudinally uniform beam of relativistic electrons has been designed, built, and operated successfully. The bunching results from a path length difference that is achieved by first modulating the energy of the beam particles and then passing the beam through a particular static magnet system. The buncher consists of an input beam transport employing solenoids, air-core quadrupole magnets, and n=0 bending magnets followed by a strong focusing magnet ring arranged in an FDO configuration. Subsequent beam transport consisting of quadrupoles, bending magnets, and solenoids recombines the beam and transports it to the experimental area.

Operationally, the results indicate that bunching ratios, I_{peak}/I_{ave}, of approximately two are rather routinely achieved with negligible beam loss. Single particle effects are consistent with the theory of simple phase-space dynamics. With regard to the all-important area of high intensity accelerator physics, observations have been made within the buncher system of coherent beam effects. Growth of very high frequency modulation has been measured for the unbunched, continuous beam. The growth appears to be intensity dependent; that is, the modulation grows faster with higher injected beam current. Qualitatively this beam behavior is consistent with well-established theory of coherent effects.

Design and Theory

The buncher system consists of two basic components. The first is the energy modulating RF cavity, and the second is the static magnet ring and beam transport system. The electron beam from the Astron linear accelerator,[1] yielding a beam of approximately 5 MeV kinetic energy, 100-500 A beam current, and 300 ns duration, is directed through the modulating cavity where a sinusoidal energy variation of about ±4% is imparted to the beam at a frequency of 120 MHz. This beam then passes through an input beam transport section into a strong-focusing magnet ring where the energy variation translates into a path length difference. This coherent path length difference is the mechanism for achieving beam bunching. The beam then enters the downstream beam transport system where it is spatially recombined and focused into the desired beam and transported to the experimental gas tank. The general layout of the entire system is shown in Fig. 1.

The computer program SYNCH[2] was used to determine the basic design of the magnet ring itself. As designed, the magnet ring is an eight cell structure with each cell being a simple FDO design. Each cell is 3.6 m long with 1.8 m of each cell being drift space and the remaining 1.8 m being equally divided between the focus and defocus functions. The nominal Q value or tune is 1.75 for both transverse planes; however, the Q values may be varied over a range $1.5 \leq Q \leq 2.5$ by appropriate tuning of the gradient magnets. Transition gamma is 1.65 at the nominal Q value.

The transport systems for entrance into and exit from the ring for the matched configuration were designed using the computer program TRANSPORT.[3] The input transport system takes the beam from the accelerator to the ring and prepares the beam so as to have the proper matched betatron amplitudes, and also places each particular energy on its proper equilibrium orbit. The output transport is required to perform somewhat in reverse of this by recombining and focusing the beam so as to be round in real space and additionally have all particles at the various energies pass through the same focus. These requirements allow for production of useful beams for further transport to the experimental area.

The theory of the bunching process is a slight modification of standard klystron theory. A particle with the mean energy E_0 has a path length ℓ_0 through the entire system. A particle energy $E_0 + \delta E$ has a path length $\ell = \ell_0 + \delta\ell$, where $\delta\ell$ is proportional to δE, the proportionality constant being a function of the parameters of the ring and two transport systems. A path length difference is encountered in the ring itself, where a $\delta\ell$ of 11.45 cm for a $\delta E/E_0$ of 1 percent can be achieved with the proper magnet settings. The value of $\delta\ell$ encountered through the ring and both transport systems is slightly less than this value since a small amount of debunching occurs in the beam refocussing process. Theory and numerical examples presented here deal with passage through the ring only.

The energy of particles entering the ring varies with time according to the relation

$$E(t) = E_0 - \delta E \sin \omega t, \tag{1}$$

where δE is the peak energy deviation provided by the RF cavity. A particle entering the ring at time $t = t_1$ will exit from the ring at a time t_2 given by

$$t_2 = t_1 + \frac{\ell_0}{v} - \frac{\delta\ell}{v} \sin \omega t_1, \tag{2}$$

where $\delta\ell$ is the path length deviation corresponding to δE. The variation of the speed v with energy is neglected. The number of particles entering the ring during a time interval dt_1 is $I_0 dt_1$, where I_0 is the current in the longitudinally uniform beam. The number of particles leaving the ring in a time interval dt_2 is $I dt_2$. Requiring conservation of charge, the current leaving the ring is given by

$$I = I_0/(dt_2/dt_1). \tag{3}$$

From Eqs. (2) and (3) we then have

$$I = I_0/(1 - \chi \cos \omega t_1), \tag{4}$$

in which the quantity $\chi \equiv \omega\delta\ell/v$ corresponds to the bunching parameter in the klystron theory. A value of $\chi \geq 1$ corresponds to some particles overtaking others. The theory is slightly more complicated if $\chi \geq 1$ since the function $t_1(t_2)$ becomes multivalued; that is, particles that enter during different intervals dt_1 exit during the same interval dt_2. The appropriate

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modification of Eq. (4) to include values of $\chi > 1$ is

$$I = I_0 \sum |1 - \chi \cos \omega t_1|^{-1}, \qquad (5)$$

in which the sum extends over the pertinent values of t_1.

In order to obtain the function $I(t_2)$ from Eq. (4) it is necessary to insert $t_1(t_2)$ from Eq. (2). Although not possible analytically this operation is easily performed numerically.

Of particular interest is the Fourier series representing $I(t_2)$. In terms of $\tau = t_2 - \ell_0/v$, this series takes the form

$$I(\tau) = I_0 \left[1 + 2 \sum_{n=1}^{\infty} J_n(n\chi) \cos n\omega\tau \right]. \qquad (6)$$

As it stands, the series converges very slowly, the coefficients $J_n(n\chi)$ decreasing as $n^{-1/3}$. In practice, however, the series will converge more rapidly because of effects that have been neglected in the simple theory presented here. The finite emittance of the beam and the resulting spread in ℓ_0 are examples of such effects.

Buncher Hardware

A photograph of part of the buncher system is shown in Fig. 2. This figure shows some of the features of the ring and transport sections. The magnet ring and transport consists primarily of a vacuum vessel and associated magnets. The main ring, fashioned as a one-turn helix, is fabricated of aluminum with an ID of 60 cm. Each of the eight cells of the ring is made up of a section of a torus with a major radius of 2.29 m and an arc length of 1.8 m along the center followed by a 1.8 m long straight section. The focus,defocus and bending magnets are positioned on the toroidal section of the beam pipe leaving the straight section free for diagnostic use, vacuum pump access, etc. This arrangement makes up the basic 3.6 m cell structure. The input and output transport adjacent to the ring is 45 cm ID with quadrupoles and bending magnets appropriately placed around the beam pipe.

Vacuum on the ring and transport is provided by five mercury diffusion pumps placed appropriately throughout the system. Typical operating pressures are in the range of $1\text{-}3 \times 10^{-6}$ torr.

The magnets on part of the buncher system are rather unique. Since the vacuum tank in the regions where magnetic fields are required on the ring is a section of a torus, it is necessary to design coils which will yield the desired magnetic field in a toroidal geometry. In addition, it was desired to produce this magnetic field without using magnetic materials. The design of these air-core magnets is described in detail in Ref. 4. Each cell of the ring consists of an n=0 dipole magnet coupled with superposed focusing and defocusing quadrupole magnets designed in the above manner. This provides the FDO configuration.

Magnets on the input and output transport sections are powered by individual current-regulated supplies. Magnets on the ring itself are connected in series for a given function (focus, defocus, or bend) and individual magnets on the ring may be varied 5% by means of a system of resistive trimmer shunts.[5]

The RF system which supplies the energy modulation operates at 120 MHz and is capable of supplying an energy spread of up to approximately ±300 keV to the beam. The details of this RF system are described in these proceedings.[6]

Buncher System Operation and Development

The basic hardware components of the vacuum and magnet system were completed and installed in November 1971 with the energy modulating RF system being installed in January 1972. Initial debugging and development was completed in March 1972 with the initial optimization of the system being complete. Since that time operation has been generally routine; early difficulties have been resolved; new diagnostics and techniques have been developed; new and interesting phenomena have been observed and are being studied.

Typical results for the buncher system of operation are shown in Fig. 3. The oscillogram at the top of Fig. 3 shows the beam current at the end of the downstream transport system as measured by the so-called resistive beam bugs.[7] The peak current in the bunches is approximately 600 A. These results corresponded to accepting 300 A of the beam at the entrance to the buncher system and transporting approximately 280 A average to the output of the buncher system. These results yield a bunching ratio, I_{peak}/I_{ave}, of about 2.1. Minimum current between the peaks is about 120 A, yielding a beam current modulation ratio, I_{peak}/I_{min}, of approximately 5. These results should be considered as being conservative due to frequency response limitations of this diagnostic device.

The oscillogram at the bottom of Fig. 3 shows more details of the bunch structure. This particular measurement was made using a small, 50Ω Faraday cup that sampled only a small portion of the total beam. Frequency response of this system has been verified to at least 500 MHz; therefore, the Faraday cup should give a true representation of the structure over at least the first four harmonics of the basic 120 MHz modulation frequency. The Faraday cup was located after the output beam transport system where the beam is circular with ~1 cm diameter. This size is in contrast to the beam in the buncher where the energy modulation creating the path length variations causes the time averaged beam to have an observed 15 cm breadth and 4 cm height. As seen on the oscilloscope recordings of the Faraday signals, the output beam current has higher harmonic structure in addition to the basic 120 MHz content. This higher harmonic content is a strong function of the voltage on the 120 MHz cavity and also the detailed tuning of the magnet system.

Using the fast Faraday cup a measurement was made of the bunched current versus voltage on the energy modulating cavity. As noted in the bunching theory above, bunching increases with increasing χ up to a value of $\chi = 1$. Then for $\chi > 1$ the beam is over-bunched and peak current is reduced. Moreover, as χ is increased into the over-bunching regime, the single sharp current peak passes over into a characteristic double peak structure familiar to simple klystron theory. Figure 4 shows the results of this measurement where peak beam current is plotted versus voltage on the 120 MHz cavity. As seen from the figure, the peak current occurs at approximately 220 kV on the cavity and is a relatively steep function of the cavity voltage. These results are in good agreement with theoretical predictions from the above analysis.

With regard to beam emittance, measurements indicate that the Astron accelerator beam emittance is ~20π mrad-cm. For an unbunched beam the emittance at the output of the buncher system has been observed to be ~30πmrad-cm. This increase in beam emittance is probably due to nonlinear effects. Results indicate that the beam is straying sufficiently far from the equilibrium orbit in some regions of the ring and transport so as to enter the nonlinear regions of the magnetic fields. These and other nonlinear effects would lead to a growth in the beam emittance. For bunched beam operation the emittance at the output of the buncher system is approximately 100 π mrad-cm. This increase in emittance is also consistent with the concept of nonlinear effects since the energy-modulated beam would be straying even deeper into the nonlinear areas of the magnetic field. The problem of chromatic aberrations, especially in the output transport, probably contributes to this degradation of emittance.

Since the lattice ring itself is strong focusing, the amplitude and orientation of the transverse and longitudinal phase space parameters are dependent upon the detailed setting of the ring focus and defocus magnets. By injecting an unbunched, essentially monoenergetic beam off of its proper equilibrium orbit, it is possible to observe the centroid of the beam executing betatron oscillations about the equilibrium orbit. In this manner the Q value or tune for both the horizontal and vertical motion can be determined directly. Utilizing this technique, a survey was made of Q values versus ring quadrupole settings. As determined, the Q values of the ring were readily tunable over a range of $1.3 \leq Q \leq 2.3$ with the quadrupole settings being in reasonable agreement with the numerical computations.

Observed Collective Effects

Observations of collective beam effects have been made within the buncher system. All observations reported here pertain to the Astron accelerator beam being transported through the buncher system while the energy modulating 120 MHz cavity is turned off and the gap internally shorted. For such conditions, a high frequency current modulation becomes detectable on the continuous beam as it passes through the input buncher transport and nears the ring. Around the ring itself the amplitude of this modulation (the frequency of which ranges from 700-1100 MHz) grows by as much as a factor of 4 to 6. At the end of the output transport the level of this undriven modulation often reaches 10-15% of the average current level. The amplitude and frequency of these fluctuations, as well as their growth rate, are strongly dependent on accelerator tuning. Considerable time is spent tuning the accelerator to minimize these high frequency fluctuations. During this final tuning process the accelerator operator is guided only by the quality of the signals appearing on the diagnostics at the buncher system output.

Figure 5 shows the percentage of high frequency current fluctuations at the buncher system exit versus the average output current. Average output current is always >90% of the input current. The buncher current may be varied in two ways. Curve A in Fig. 5 depicts results obtained by varying the extracting voltage of the electron gun and thereby varying the current in the accelerator as well as the buncher. Curve B depicts results obtained when the accelerator current was held constant (at 400 A), but the average buncher current was varied by using constant emittance attenuators located before the buncher input.

A very appealing interpretation of this data, accounting for the substantial amplification of the amplitude around the ring would postulate a coherent momentum modulation on the beam at the exit of the accelerator. This coherent fluctuation would convert to density modulation because of the design of the buncher system. Momentum fluctuations of the order of ±0.25% at approximately 1 GHz have been measured. This is sufficient to account for the observed density modulation at the exit of the buncher system. Apparently this initial high frequency momentum fluctuation is a strong function of the current in the accelerator and also of the detailed tuning of the accelerator. These observations strongly suggest that the momentum fluctuations arise from coherent effects in the accelerator.

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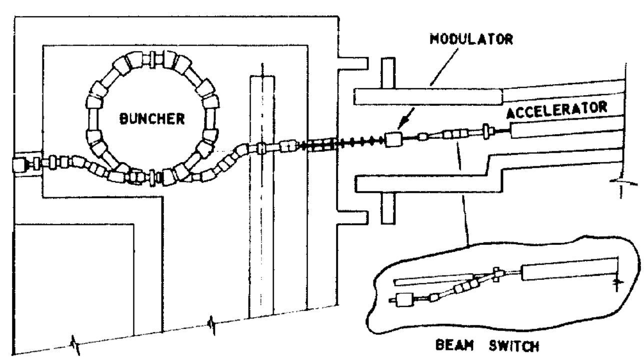


Fig. 1. Schematic layout of beam research facility.

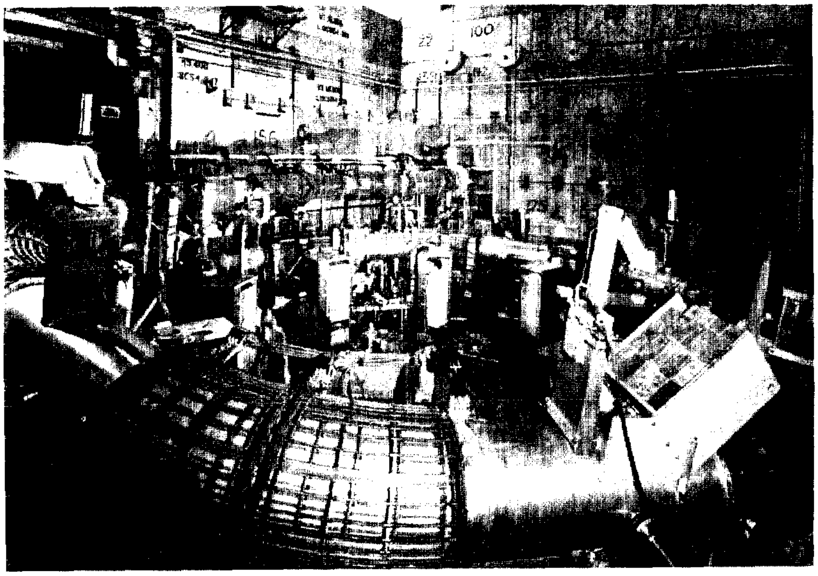
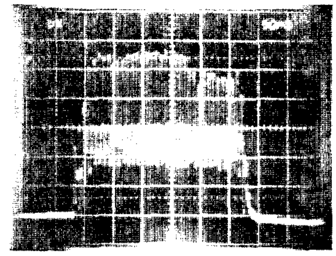
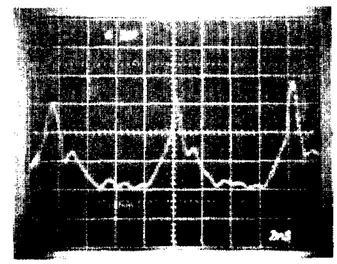


Fig. 2. Photograph of buncher system showing part of the ring and transport system.



Fully modulated current at buncher output. 100 A/Div, 50 ns/Div.



Detailed structure of individual bunches. 150A/Div, 2 ns/Div.

Fig. 3. Modulated beam profile

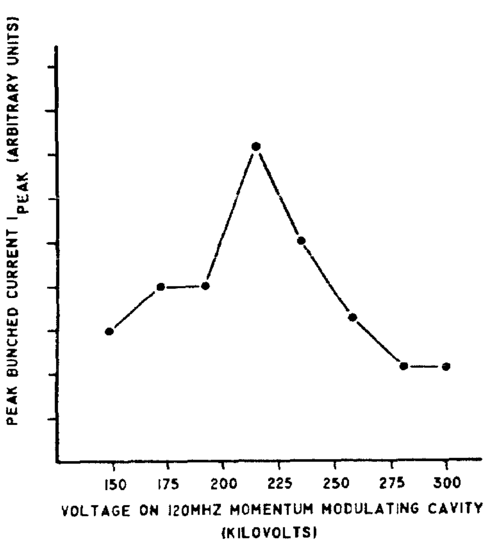


Fig. 4. Peak bunched current versus voltage on 120 MHz RF cavity.

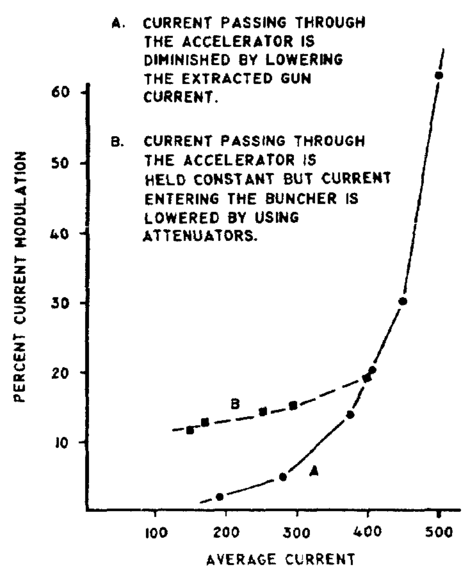


Fig. 5. Percent current modulation of a continuous beam versus average buncher current.