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A FAST CHOPPER FOR PROGRAMMED POPULATION OF THE LONGITUDINAL PHASE SPACE OF THE AGS*

J.M. Brennan, L. Ahrens, J. Alessi, J. Brodowski, J. Kats, W. van Asselt

AGS Department, Brookhaven National Laboratory
Associated Universities, Inc., Upton, NY 11973 USA

Summary

A fast beam chopper has been built that can produce an arbitrary pulse program of the 200 MeV H^- beam for synchronous injection into moving rf buckets in the AGS. The chopper will eliminate rf capture losses and can be used to tailor the initial distribution in longitudinal phase space by varying the pulse parameters, width and phase, on a bunch-by-bunch time scale, during multi-turn injection. The chopper also serves as a studies tool since it can provide controllable beam intensity with fixed longitudinal emittance (and conversely) and/or missing bunches. It is an electrostatic deflection device with 15 pairs of plates located above and below the 35 keV H^- beam between the ion source and the RFQ preinjector. The plates are spaced 26 mm apart in the beam direction and connected as a slow-wave structure by coaxial cables. They are driven to ± 760 V by dc-coupled pulse generators. Beam current rise and fall times are less than 10 ns.

Introduction

Injection, rf capture, and early acceleration are crucial steps to successful operation of the synchrotron, in particular, the vast majority of particle losses in an acceleration cycle occur during these steps. Rf capture losses could, in principle, be eliminated by an adiabatic turn on of the rf voltage. But for a high intensity machine such as the AGS, the long time required for adiabatic capture would be prohibitive, because other loss mechanisms, such as transverse stopband losses, driven by large betatron tune spreads due to space charge at low energy, would defeat the advantage of effective rf capture. Optimized non-adiabatic capture schemes have been used with some success,[1] but efficiencies are limited. In order to eliminate the rf capture process altogether, a fast chopper has been built that can prepare the rf bunch structure of the beam before injection into phase stable buckets in the AGS. The elimination of rf capture losses may relax some of the constraints on optimizing other facets of the early acceleration process. Moreover, the presence of time structure on the injected beam allows investigation of the causes of other early losses by enabling ac-coupled instrumentation devices to see the beam at injection.

To be effective, the chopper must have complete controllability of the injected pulse program (see below). This controllability also opens the possibility for using the chopper as a studies tool. A specified longitudinal emittance can be obtained by populating only the appropriate area of phase space while the beam intensity can be independently controlled by the number of turns injected. Conversely, at fixed intensity, the initial distribution in phase space can be programmed to study such effects as the dependence of betatron tune depression on longitudinal bunching factor and the stability of hollow distributions in the presence of beam control feedback loops.[2] Zero is an allowed value of the width, which gives bunch-to-bunch intensity control, useful for studies of transient beam loading on the acceleration cavities.

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Applications Program

Injection into the AGS is done while the magnetic field is rising at a rate of 0.5 T/s.[1] This is done to minimize the time that the beam must spend at the lowest energy where space charge effects are greatest. Also, the power supply ripple would be excessive at the low voltage needed for zero rise rate at the injection field level (250 Gauss). The synchronization energy (E_s = the energy of a particle that does not change phase with respect to the rf), therefore, depends on time during the injection process. The time dependence is governed by the two controlled variables $\dot{B}$ and $\dot{f}$ ($\dot{f} = df/dt$) through[3]

$$\dot{E}_s = \frac{\beta^2 E_s}{-\eta} \left(\dot{f}/f - \frac{1}{\gamma_{tr}^2} \dot{B}/B\right)$$

where β is the normalized particle velocity, and $\eta = \gamma_{tr}^{-2} - \gamma^{-2}$. One normally chooses $\dot{f}/f = \gamma^{-2}\dot{B}/B$ so that the radius of the orbit of the synchronous particle is constant. In that case, $\dot{E}_s = 7.0$ MeV/ms. At the other extreme, a capture strategy could choose $\dot{f}/f = \gamma_{tr}^{-2} \dot{B}/B$ so that the synchronous energy is constant. The radius of the synchronous particle will change then at the rate of -3.5 cm/ms. Since the linac energy is constant, the former choice implies that the phase coordinates of the separatrix at the injected beam energy will change continuously during injection. While for the latter case one is injecting into a stationary bucket at the synchronous energy and the boundaries are always $\pm \pi$.

The chopper accommodates this variety of choice by using pre-calculated phase coordinates for the edges of each pulse that is injected. The coordinates are fetched out in real time from a fast memory and used to trigger the high voltage pulsers that switch the beam on and off. The memory contents are calculated by an interactive applications program in the AGS Apollo-based computer control system. An example of the graphic output of the program is shown in Figure 1. The input variables are: rf voltage/turn, $\dot{B}$, $\dot{f}$, injected synchronous energy, beam current, and number of turns to inject. The output is a graphic display of the separatrix and the area into which particles will be injected.

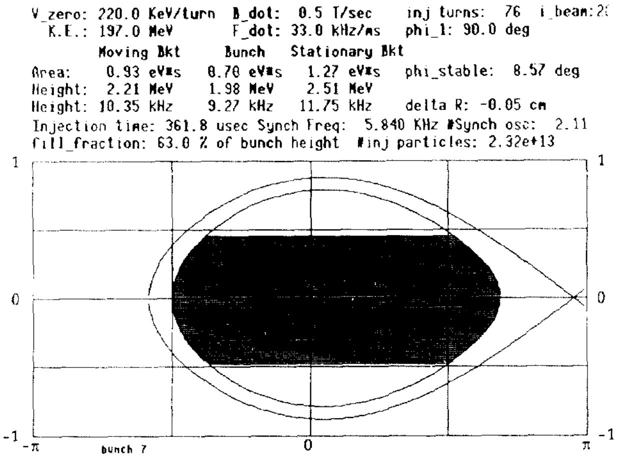

Figure 1. Chopper control program output; bucket, bunch, and area into which particles are injected.

Numerical outputs are given for the parameters of phase space and several other relevant quantities, such as: the variation of radius of the synchronous particle, the total number of particles injected, and the synchrotron oscillation frequency. Individual pulses can be switched on and off by changing values of the elements of a bunch-X-turn matrix from one to zero.

Construction of the Chopper

The feasibility of implementing a chopper with the necessary flexibility follows from the change of the AGS preinjector from a Cockcroft-Walton to an RFQ linac.[4] This made the beam accessible at ground potential while it is at a low enough energy (35 keV) so that it can be effectively deflected with practical voltages. The chopper is a pulsed electrostatic deflector, located between the ion source and the RFQ, midway between two focusing solenoids that match the beam to the RFQ acceptance. The beam diameter is 80 mm at that point. Unwanted beam is rejected by deflecting it outside the opening of a 14 mm diameter circular aperture which is located at the entrance of the RFQ, 22 mm upstream from the vane tips. The beam is rapidly converging at this point with a waist inside the RFQ. The Twiss parameters are $\alpha = 5.0$ and $\beta = 0.27$ m and the beam emittance is 133 π mm mrad. With a parallel beam in the chopper, the deflection that is needed to displace the beam outside the aperture is 44 mrad, five times what would be needed if the aperture were at the waist. Furthermore, when the chopper is in operation, the space charge neutralization by ionization of the residual gas is lost, and the beam becomes divergent in the chopper, increasing the required deflection to 65 mrad. Given the size of the beam and the desire to keep voltages low, the array of deflecting plates was made 380 mm long in the beam direction.

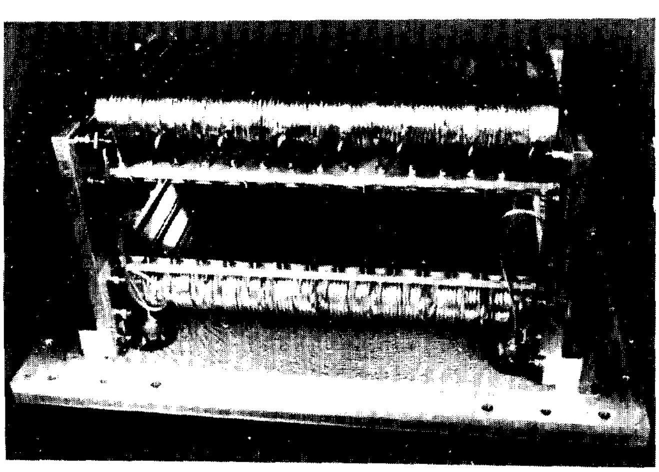

Figure 2. Chopper slow-wave structure.

A drawback of the low energy of the beam is the long time of flight through the deflecting plates, 150 ns. In order to get an acceptable rise/fall time on the beam pulse, it was necessary to segment the deflection plates into strips that are 17 mm long in the beam direction and 160 mm long transverse. The strips are located on 26 mm centers. The voltage is applied to the strips sequentially at a rate that matches the beam velocity as a slow-wave structure. The delay between the strips is obtained by connecting them one to the next with the appropriate length of coaxial cable. Figure 2 shows the mechanical assembly of the chopper. One can see that there are two sets of strips, located above and below the beam. There are two advantages to this arrangement; one, the magnitude of the voltage needed is halved and two, the extent of the fringe field in the beam direction for each strip is also halved. This results in reduced rise/fall time of the beam pulse. Details of the tuning of the impedance of the strips to the impedance of the coaxial cables have been published elsewhere.[5]

Pulse Generators

The slow wave structures are driven by a complementary pair of high voltage pulse generators. The pulse generators are commercial units and reflect the state of the art of fast high voltage pulse technology using power MOSFETS.[6] The generators have both pull-up and pull-down transistors in the output stage and, hence, have equal rise and fall times of the output pulse. The outputs are dc coupled to the MOSFETS so that the voltage level in the "off" state is always zero, independent of the duty factor of the waveform. This is an essential feature for the chopper since the usable beam is taken when the pulsers are "off". The output waveforms are shown in Figure 3, measured with a Tektronix 2467 oscilloscope via a 40.9 dB power attenuator. The rise and fall times (10% to 90%) are all less than 9 ns. The pulse amplitudes are ± 760 Volts.

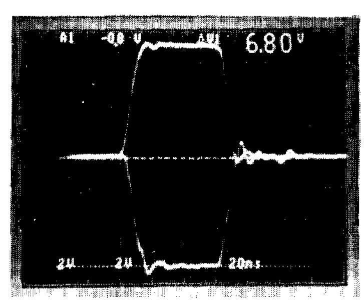

Figure 3. Outputs from high voltage pulsers. Center is zero volts, 20 ns/div.

Results with Beam

Space Charge. The electrostatic field of the chopper strongly affects the neutralizing ions in the 35 keV transport line. When the chopper is turned on, the beam intensity is reduced by ~15% and the rejection ratio is only ~80%. When the line is retuned for 100% rejection, the intensity is further reduced to 75% of the chopper-off value.

Rise/Fall Times. Figure 4 shows the beam current after the RFQ when the chopper is operating. The measurement was made with a wideband (> 2 GHz) 50 Ohm Faraday cup and a Tektronix 7104 oscilloscope. The 200 MHz microstructure from the RFQ can be seen. The rise and fall times comprise two periods at 200 MHz, implying transition times of 10 ns.

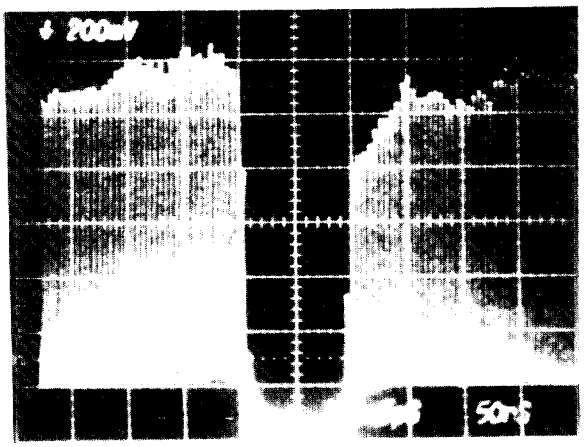

Figure 4. Beam current between RFQ and linac, with chopper on, single sweep, 50 ns/div. Zero at bottom of photo.

AGS Revolution Frequency. A precise measurement (0.01%) of the revolution frequency of the linac beam in the AGS was made by injecting one bunch with the rf system off and observing a mountain range display of the wall current monitor signal. The display was triggered by a stable oscillator whose frequency was adjusted to produce a constant phase pattern in the display. A measurement of the debunching time of this bunch also yielded a value for the energy spread of the linac beam, dp/p = ± 0.14 (1)%.

Linac Energy Spread. The linac energy spread was also obtained by observing bunch rotation of a single injected turn. The phase extent of the injected pulse was sufficiently small (± 45°) that the synchrotron frequency was constant throughout the bunch. Figure 5 shows a mountain range display as the bunch rotates in phase space. From the minimum width in time at one quarter of the synchrotron period, we infer the linac energy spread to be dp/p = ± 0.06 (3)%. The discrepancy with the debunching result is not understood.

Betatron Tunes versus Bunching Factor. Two different initial populations of longitudinal phase space with equal beam intensities were created by injecting 34 turns of 90° phase extent, one centered at the stable fixed point and one offset. The number of turns injected was chosen so that the duration of the injection process was equal to one synchrotron period. Although the number of particles injected was the same, the bunching factors were different, B = 0.18 and 0.24. Figure 6 shows the line charge

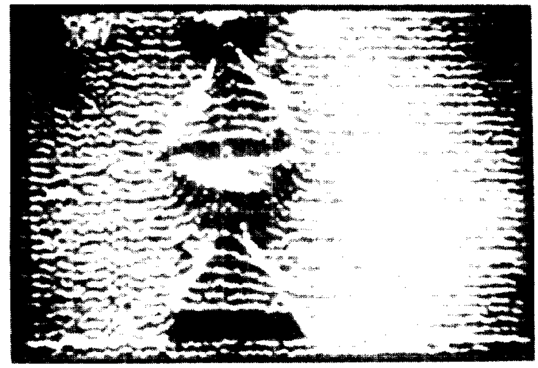

Figure 5. Mountain range display of wall current monitor showing synchrotron motion of single 90° bunch.

densities in the two cases. The coherent betatron tunes were measured for the two cases by the FFT technique. The results are: $\nu_x = 8.579$ and $\nu_y = 8.815$ for the former and $\nu_x = 8.590$ and $\nu_y = 8.825$ for the latter. Furthermore, the tune spreads, as derived from the line widths of the FFT spectra, indicate that the momentum spread had doubled.

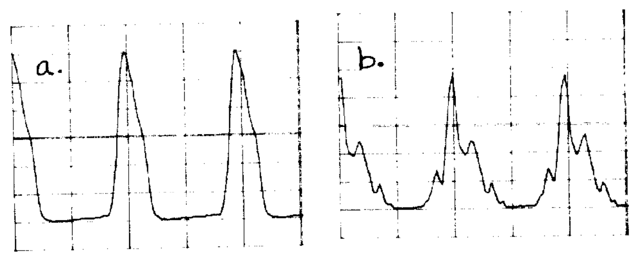

Figure 6. Line charge densities; (a) injecting about the bucket center, bunching factor B = 0.18, (b) off center injection, B = 0.24, 200 ns/div.

Acknowledgments

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