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

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## Abstract

A fast chopper has been built that can switch the beam injected into the AGS or AGS Booster on and off with rise and fall times in the order of 10 ns. The chopper will be used to control the initial population of longitudinal phase space in order to eliminate rf capture losses and achieve an optimal phase space density distribution. The chopper operates on the 35 keV $H^-$ beam between the ion source and the RFQ. The interaction between the electrostatic fields of the chopper and the space charge neutralizing ions in the beam has been seen to be a significant but manageable effect.

## Introduction

In the typical operation of a synchrotron, a continuous beam is injected for several turns and the program of rf voltage and frequency is adjusted to optimize the capture efficiency into and distribution within the stable region of the longitudinal phase space.[1] The beam dynamics at the very early stage of the acceleration process can be quite complicated because of several subtle effects such as space-charge tune depression and spread, magnetic field imperfections at low beam rigidity, and injection orbit errors. Operationally, one is led to a compromise between competing effects, such as rf capture losses and transverse losses, that yields the best overall performance. If, however, explicit control of the initial population of the longitudinal phase space were available, the problem could be more cleanly factored into the transverse and longitudinal variables. For example, if only the stable region of longitudinal phase space were populated, the rf capture losses, per se, would be eliminated and other loss mechanisms would be highlighted. Moreover, if the detailed distribution within longitudinal phase space were controlled (called "painting"), then the effects that depend on charge density could be studied and presumably optimized. Since most of the losses in the AGS occur at, or soon after, rf capture, any reduction in losses at this time would be very beneficial for reducing the irradiation of the machine.

The fast chopper described in this report is a device that will provide this type of control for the AGS and AGS Booster. The chopper is a beam switch that has rise and fall times in the order of 10 ns and has complete controllability of the phase and width of each beam pulse, with respect to the phase of the rf system of the synchrotron. To make full use of the chopper, it is necessary to be able to preprogram the parameters of each pulse and then fetch these parameters and synchronously trigger the chopper on a bunch-to-bunch time scale. This is 400 ns for the AGS. The chopper system is, therefore, equipped with a digital delay generator that stores 1K words of phase and 1K words of width (1 ns resolution) in a RAM that is clocked out to the chopper with a 2.5 MHz clock that is derived from the drive signal to the acceleration cavities in the AGS. With a typical beam intensity of 20 mA and an average duty factor of 50% these 1K pulses would fill the AGS with $2.5 \times 10^{13}$ protons.

When used in conjunction with a second sine wave chopper at 10 MHz, which will be located between the RFQ and Linac, the fast chopper will produce single micro-bunches from the Linac at a repetition period ranging from 50 ns to over 100 μs.

The fast chopper has been built and tested off-line on a test beam developed for the new RFQ pre-injector for the BNL 200 MeV Linac.[2] The principles of operation, details of the design, and results of the beam tests are presented in this report.

## Painting

There are two facets to the process of phase space painting that are relevant to using the chopper. First, is the elimination of rf capture losses and the consequent reduction of the radiation burden for the machine; second, is the attempt to tailor the density distribution of particles in phase space in such a way that improves the overall performance of the machine by mitigating those adverse multiparticle effects that are driven by high local charge density.

It is clear what must be done to accomplish the first goal: phase and size the injected pulses to guarantee that all particles are within the boundaries of the separatrix. A complication that can arise when one is injecting into a moving bucket with a fixed beam energy is that the boundaries depend on time during the injection. The parameters of each pulse, phase and width then must be uniquely controllable. The chopper has, therefore, been equipped with a programmable digital delay generator that stores unique values for each of 1K pulses. A standard digital delay generator has been modified (by the manufacturer)[3] to store the pulse program and fetch it out with a 2.5 MHz clock, which is the fundamental rf frequency of the AGS and Booster at injection. The clock will be derived from the "starting oscillator" of the AGS, which drives the cavities during injection. A trade-off must be made between eliminating losses in the machine and efficiently using the beam from the injector. Achieving the optimum trade-off requires good definition of the beam pulse edges. The chopper has been designed to provide the minimum practical rise and fall times on the beam pulse.

The second goal, to control the distribution within phase space, is more ambitious. The problem is far from straightforward because the period of the synchrotron motion is comparable to the injection period. Furthermore, since one is trying to fill a large fraction of the bucket, particles at different phases have different synchrotron frequencies. It is necessary to not only establish a uniform density, but also to create a distribution that is stable; that is, matched to the bucket. A

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simulation program has been used to investigate some schemes of programmed filling of the bucket. Figure 1 shows the results of a simulation of the filling scheme described by the pulse program of Figure 1a, where the parameter w is varied as shown. A mountain range display of the charge line density is given in Figure 1b, with 10 turns per line. This distribution is relatively flat. It has a bunching factor of 0.7 and is stable. This program delivers $2 \times 10^{13}$ protons at 25 mA into an emittance of 1 eV$\cdot$sec, is within the capability of the fast chopper, and is one candidate for experimental study.

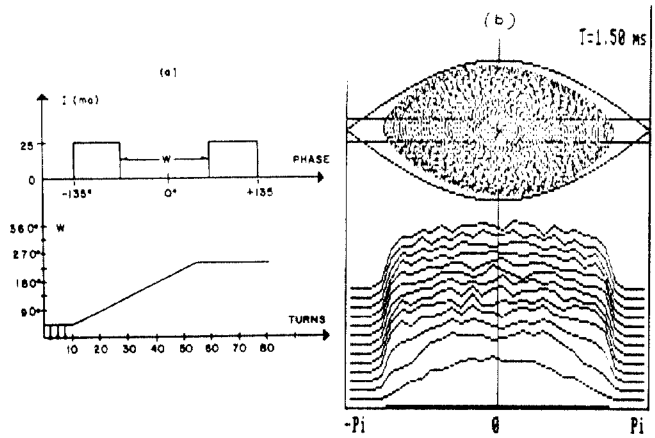


Fig. 1. Painting scheme; a. pulse program, b. longitudinal phase space and line charge density.

## Design of the Chopper

The chopper is located between the ion source and the RFQ, where the $H^-$ beam energy is 35 keV. There are two focusing solenoids, separated by about 1 m, that match the beam to the RFQ acceptance. The beam is approximately 8 cm in diameter and essentially parallel between the solenoids where the chopper is located. The chopper is an electrostatic deflection device that applies a 135 mrad kick to the beam via a complementary pair of high-voltage plates. The kick displaces the image formed by the second solenoid to outside a 17 mm diameter circular aperture located just at the entrance of the RFQ. The large angular kick is required because the rejection aperture cannot be located at the beam waist which is inside the RFQ. Since the plate separation is given by the beam diameter, the size of the kick is proportoinal to the voltage applied times the length of the deflection plates. A practical limit to the high voltage, consistent with the requirement for complete flexibility, is $\pm$ 1 kV. The plate length then must be 38 cm.

The beam velocity at 35 keV is only 26 mm/10 ns, making the transit time through the plates 150 ns. The rise time on the beam pulse cannot be less than the transit time, so in order to achieve a rise time in the order of 10 ns, the plates are segmented into transverse strips on 26 mm centers. The voltage is applied to the strips sequentially at a rate that matches the beam velocity. This type of traveling- wave, or slow-wave, chopper has been used previously for protons at higher energy.[4] The delay between successive strips is made by connecting the strips with coaxial cables of the appropriate length. Voltage is applied to the plate only when beam is being rejected, so that geometric aberations caused by the fringe field of the plates does not affect the usable beam.

Figure 2 shows the complete slow wave structure. There are 15 strips above and 15 below the beam. The symmetrical arrangement reduces the extent of the fringe field by a factor of two. Each strip is 160 mm long (transverse to the beam) by 17 mm wide. The delay lines are made of 50 Ohm 141 semi-rigid coaxial cable. An electrostatic shield separates each pair of strips and eliminates cross talk between the strips. The height of the strips above the ground plane was adjusted to make the characteristic impedance of the strips equal to the 50 Ohms of the delay lines. Because there are 15 strips, a small reflection at each one can significantly reduce the magnitude of the pulse reaching the last strip. An overall transmission coefficient of 90% requires the impedance mismatch at each strip-cable interface to be less than 0.7 Ohm. The mismatches were measured with an HP8753A network analyzer used in the Time-Domain-Reflectometry (TDR) mode.

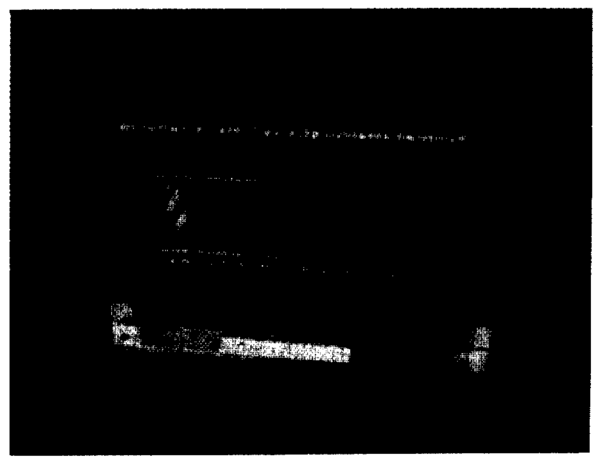

Fig. 2. Slow-wave structure of the chopper.

Figure 3 shows a measurement of the impedance of a section of the slow-wave structure, as a function of distance, before the adjustments were made when the mismatches were as much as 10 Ohms.

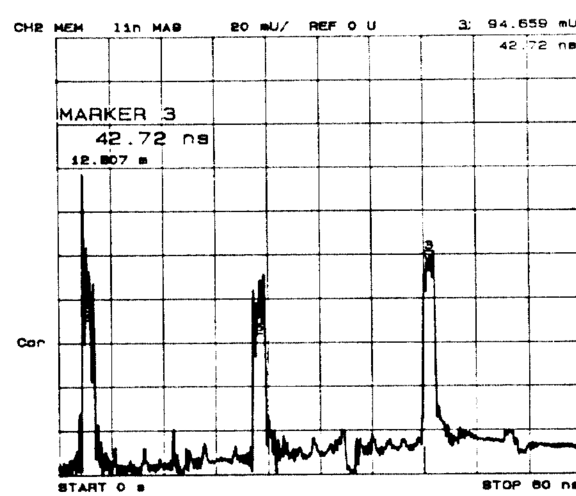


Fig. 3. TDR measurements of the impedance of three strips.

The final mismatches were less than the sensitivity of the measurement, about 0.5 Ohm. The height of the strips above the ground plane was 4.0 mm. The TDR measurements also gave a precise determination of the delay between strips. At the end of the structure, a power attenuator terminates the lines and serves as a monitor port. The vacuum in the chopper vessel is good, $3 \times 10^{-7}$ Torr, despite the large amount of material within the vacuum.

## Pulse Generators

The chopper is 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.[5] Each generator is capable of producing ± 1000 V pulses, with rise and fall times measured to be less than 7 ns, into a 50 Ohm load for up to 1 ms. Four MOSFETS are used in the output stage, in a totem-pole configuration, which makes the rise and fall times symmetrical. They have d.c. coupled output stages, and therefore the output voltage level in the "off" state is always zero, independent of the duty factor of the pulse program. This feature is essential for the operation of the chopper because the output voltage in the "off" state affects the usable beam and must not be allowed to fluctuate when a complicated pulse program is applied.

## Space Charge

The 35 keV $H^-$ beam is normally fully space charge neutralized by ionization of the residual gas in the transport line. The electrostatic deflecting field of the chopper can sweep out the neutralizing ions and strongly affect the optics in the line. Loss of neutralization can have two effects; one is a change in the tune of the line due to the defocusing effect of space charge, and the other is an emittance growth due to the non-linearities of the space charge force when the beam distribution is not uniform.

To investigate these effects, a series of experiments were done on a test beam line using a mock-up of the chopper with long plates instead of the slow-wave structure. Beam emittances were measured while a square-wave voltage was applied to the plates. By pulsing the plates between zero and high voltage, and with the sampling time of the emittance measurements long compared to the period of the voltage pulse, the emittance of both the deflected and undeflected beam could be observed simultaneously. The effects on the emittance due to space charge and those due to aberation could be distinguished because the time for neutralization to build up is much longer than the off-time of the voltage. The measured emittances showed two beams, completely separated in phase space. Figure 4 shows beam emittances measured at the location of the RFQ with the square wave voltage on and off. The available beam energy was limited to 17 keV. The intensity was 20 mA, which gives the same perveance as 50 mA at 35 keV. One can see a significant defocusing effect on the undeflected beam, but only a small emittance growth (less than 20%). The defocusing effect implies that the tune of the line must be changed when the chopper is in operation.

## Results With Beam

The performance of the chopper was measured by observing the 750 keV output beam from the RFQ with

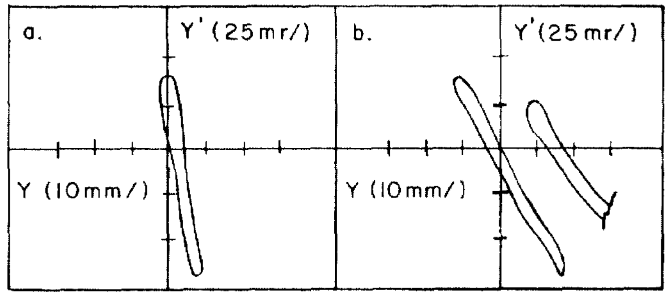


Fig. 4. Emittances with test chopper; a. chopper off, b. 0 to 500V, 0.5 MHz square wave on chopper.

a fast 50 Ohm coaxial Faraday cup, which has a bandwidth greater than 2 GHz. Figure 5 is a single-trace oscillograph (Tektronix 7104 and 7A29 vertical amplifier) of the beam signal when the chopper (beam) was pulsed on (off) for 150 ns and off (on) for 300 ns. This approximates a program that could be used for injection into a stationary bucket in the AGS. The average current during the on time was approximately 30 mA. Fluctuations during the on time are caused by rf noise in the discharge current of the ion source. The 200 MHz microstructure from the RFQ is well within the bandwidth of the instrumentation and individual microbunches can be resolved at the edges of the chopped pulses. The rise and fall times comprise two microbunches, implying transition times of 10 ns. The current during the off time was less than 1% of the average. Emittances of the 750 keV beam were measured. These measurements show a negligible emittance growth, but a 30% reduction in intensity is typically seen. The chopper will be commissioned during the next proton run at the AGS in late 1988.

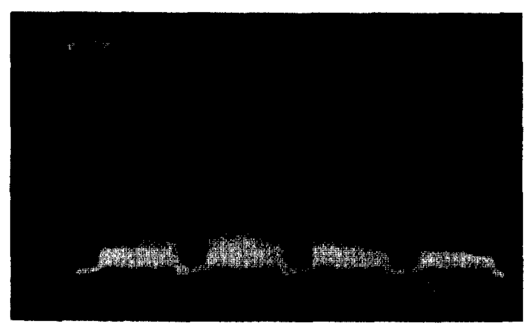

Fig. 5. Chopped 750 keV $H^-$ beam. The 200 MHz micro-structure from the RFQ can be seen.

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