SIMULATION OF THE CAPTURE PROCESS IN THE FERMILAB BOOSTER

S. Stahl and C. Ankenbrandt
Fermi National Accelerator Laboratory*,
Batavia, Illinois 60510

Summary

A progress report on efforts to understand and improve adiabatic capture in the Fermilab Booster by experiment and simulation is presented. In particular, a new RF voltage program for capture which ameliorates transverse space-charge effects is described and simulated.

Introduction and Overview

The Fermilab Linac accelerates H^- ions to a kinetic energy of about 204 MeV. The emerging beam is a stream of bunches equally spaced at the Linac RF frequency of 201.242 MHz. The full Linac momentum spread of about 0.4% is reduced to about 0.16% in the beam transport line to the Booster by a bunch-rotating RF cavity called the Debuncher. Using H^- charge-exchange injection, one or more turns are injected into the same region of 6-dimensional phase space, except that the Linac frequency and the Booster revolution frequency are in general incommensurate, so that Linac bunches usually do not coincide with previously injected ones. However, there is no high-frequency chopper and no scheme to "paint" the beam into longitudinal phase space per se. The Linac beam current of about 35 mA corresponds to 6×10^{11} protons per turn.

The guide field B, resulting from a f=15 Hz resonant circuit, is approximately harmonic with a DC offset:

$$B = B_{min}(1+C)/2 + B_{max}(1-C)/2,$$

where $C = \cos 2\pi f(t-t_{min})$.

There is no "flat-bottom" on the magnet waveform; the injection time t_{inj} is close to t_{min}. Acceleration by the 18 RF cavities takes place at a harmonic number h=84, corresponding to an initial RF frequency of about 30.315 MHz. At the start of the cycle, the injected protons must be captured in one of the 84 stable areas or buckets in longitudinal phase space, a process usually called adiabatic capture.

Among the readily variable parameters affecting capture are the minimum magnetic guide field, the injection time, the amplitude and phase of the Debuncher RF voltage, the initial value of the Booster RF frequency, and the time dependence of the amplitude and phase of the Booster RF voltage. Experiments and simulations intended to shed light on how these parameters affect Booster performance and how to optimize them are described here. The time-honored empirical approach of varying the parameters to optimize performance amounts to a (time-consuming!) search in a multidimensional parameter space; numerical simulations provide invaluable guidance for this search. Conversely, experiments help to determine the parameters used in the simulations; the two approaches are thus complementary.

Several previous simulations of adiabatic capture in the Booster which neglected space-charge effects have been reported [1-4].

The Simulation Method

The simulations reported here, which include longitudinal space-charge effects, used the longitudinal tracking program ESME, described in another paper at this conference [5-6]. In order to check the correspondence of these simulations with reality, the results have been compared in detail with several experimental observations. Figure 1, for example, shows real and simulated "mountain range" pictures of a single turn injected into the Booster with an RF voltage program like the one described below and shown in Figure 4. The high-frequency "noise" in the simulation is caused by statistical errors resulting from the finite number of particles simulated. There are 25 oscilloscope traces, with successive traces taken every second turn, starting at injection time. The horizontal scale is 5 nsec/division and there are ten divisions. Attempting to reproduce such complicated patterns provides stringent tests of the simulation and helps to determine the injection and capture parameters. For example, the patterns of Figure 1 are sensitive to the injection energy, the initial Linac phase space distribution, the injection time with respect to the magnetic field waveform, and the Booster RF voltage program. In fact, the comparison suggests that the injection time with respect to the minimum of the guide field is about 100 μsec earlier than a dB/dt signal available in the control room indicates.

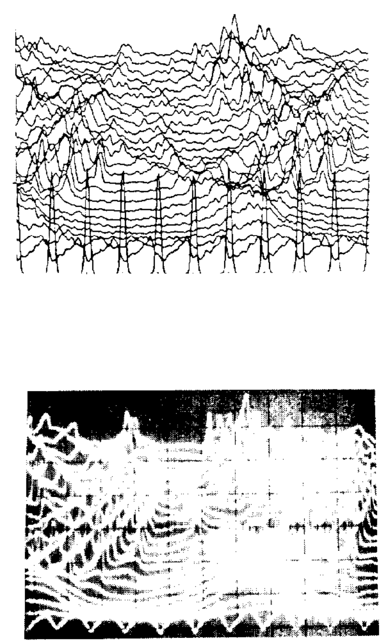

Fig. 1. Simulated (above) and real (below) "mountain range" pictures showing the time development of the beam current when a single turn is injected into the Booster.

*Operated by the Universities Research Association, Inc., under contract with the U. S. Dept. of Energy.

CH2387-9/87/0000-1117 $1.00 © IEEE
PAC 1987

A Beneficial New RF Voltage Program

During the capture process, the RF oscillator is locked to a programmable frequency synthesizer. Control of the RF voltage during capture is accomplished by holding the cavity voltages approximately constant (to avoid multpactoring) and varying the RF phase between two equal groups of cavities called A and B so that $\phi_A=-\phi_B=\phi(t-t_{inj})$. This process is called paraphasing and ϕ is called the paraphase angle. Conventional wisdom and tradition maintain that injection should occur with the two groups exactly out of phase, that is, with the initial paraphase angle $\phi(0)=90°$. Capture is accomplished by reducing ϕ smoothly to zero, allowing the effective ring voltage to rise gradually to typically 400 kV 400 μsec after injection.

Recently J. Crisp and J. Lackey of Fermilab discovered that the overall transmission is improved at high intensity if the initial paraphase angle is not 90°. The results shown in Figure 2 are typical. The upper curve shows the beam intensity shortly after injecting 8 turns and the lower one is the intensity just before extraction. The abscissa is linear in the initial paraphase angle, with the dip in the final intensity occurring at $\phi(0)=90°$. Usually $\phi(0)>90°$ gives slightly better performance than $\phi(0)<90°$, but either is significantly better than $\phi(0)=90°$, even though the last choice usually results in slightly higher capture efficiency. It is interesting to note that starting with $\phi(0)>90°$ results in formation of initial buckets which are displaced by half the bucket spacing from the location of the final buckets.

The Booster performance is limited by transverse space-charge effects early in the cycle, the deleterious effects of which are discussed in another paper at this conference [7]. Thus it was immediately surmised that the observed improvement results from a reduction of the peak bunch current, which lowers the incoherent space-charge tune spread. Verifying this hypothesis was one of the goals of the simulations and experiments described in the next section.

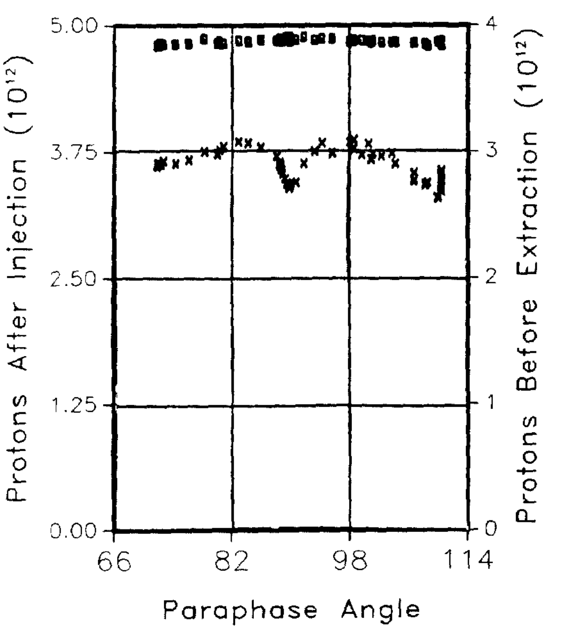

Fig. 2. The beam intensity shortly after injection (upper curve) and shortly before extraction (lower) as a function of the initial paraphase angle.

Comparison of the Two RF Voltage Programs

It is known from past experience and prior simulations [1-2] that the traditional capture method, with RF voltage rising smoothly from a very low initial value, results in little dilution of the longitudinal phase space in the absence of space-charge effects. If the Linac beam is captured efficiently without dilution, the resulting longitudinal emittance containing about 95% of the beam is 0.02 eV-sec per Booster bunch, corresponding to the area in longitudinal phase space of a rectangle whose length is 1/84th of the Booster circumference and whose full momentum spread is 0.16%. The bucket area is limited by the available RF voltage to about 0.04 eV-sec a few msec after injection; larger bucket areas are achievable later in the cycle. This factor of two difference between the minimum bunch area and the available bucket area provides some leeway to modify the longitudinal phase space distribution of the beam in order to reduce space-charge transverse tune spreads. It was suspected that the new RF voltage program was causing such a beneficial modification.

Figures 3 and 4 confirm this interpretation. They show the bunch current distributions observed and simulated with the two RF voltage programs shown, which correspond to initial paraphase angles of about 90° and 100°, respectively. Each picture shows 50 traces, one trace every three turns, with successive traces displaced upwards. The horizontal scale is 5 nsec/division. In Figure 4, the effective ring RF voltage undergoes a phase flip when the amplitude is at the minimum. It is apparent that injecting with the new RF voltage program of Figure 4 results in longer, flatter bunches. Further simulation results, not shown, indicate that the center of the two-dimensional longitudinal phase space distribution of the bunch is somewhat depleted with the new RF voltage program, explaining the flatter projection on the longitudinal position axis.

The simulation program reports the following results for the two capture programs at the same final voltage. For the traditional RF voltage program, the rms emittance is 1.1×10^{-2} eV-sec, the rms bunch length is 4.0 nsec, and the simulated capture efficiency is 98%; for the new RF voltage program, the results are 1.5×10^{-2} eV-sec, 4.8 nsec, and 96%, respectively.

Conclusions

The ability to simulate adiabatic capture, complemented by experiments to verify the accuracy of the simulations, has already proved a valuable tool to enhance understanding of the capture process and to guide efforts to optimize the process. The simulations confirm that transverse space-charge effects can be reduced by modifying the RF voltage program during adiabatic capture, suggesting that there may be simple alternatives to the ingenious but complicated longitudinal phase space "painting" schemes recently invented for several proposed machines.

Acknowledgments

We are grateful for the support and cooperation of our colleagues in the Booster group and in the Accelerator Division at Fermilab.

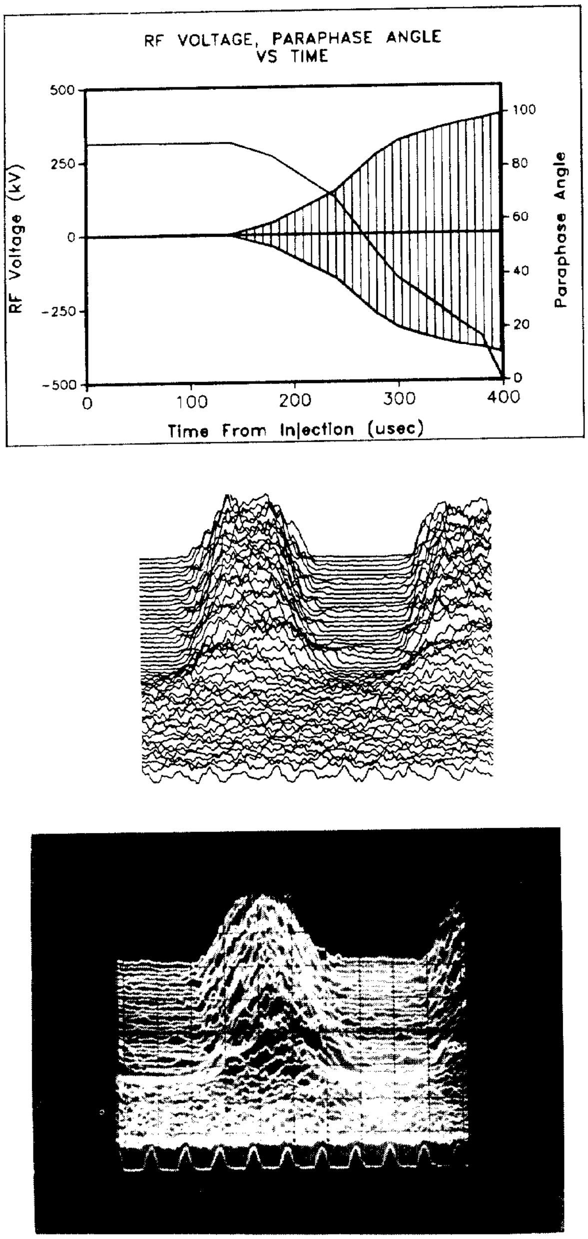

Fig. 3. Simulated (middle) and real (bottom) "mountain range" pictures showing the time development of the beam current with four turns injected into the Booster using the traditional RF voltage program shown at the top.

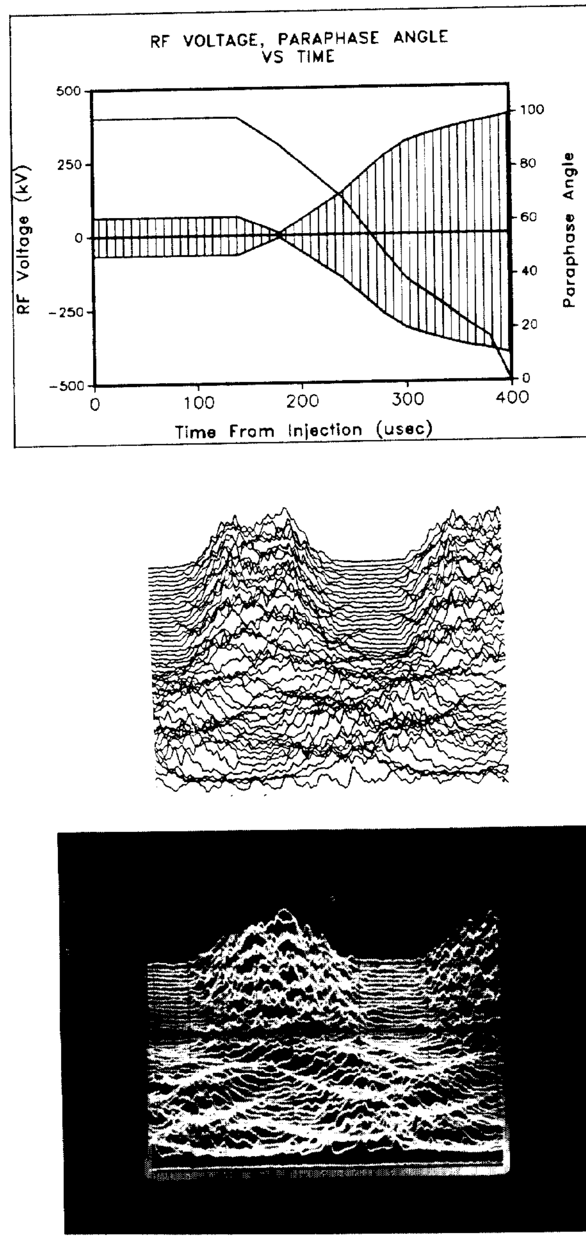

Fig. 4. Simulated (middle) and real (bottom) "mountain range" pictures showing the time development of the beam current with four turns injected into the Booster using the new RF voltage program shown at the top.

References

[1] J. A. MacLachlan, "RF Capture in the NAL Booster", Fermilab Technical Memo TM-303, May 1971.

[2] W. W. Lee and L. C. Teng, "RF Capture with Acceleration in the NAL Booster", Fermilab Technical Memo TM-473, January 1974.

[3] J. E. Griffin and E. R. Gray, "A Console Program for Examining Beam Capture in Stationary Booster Buckets", Fermilab Technical Memo TM-719, March 1977.

[4] C. Ankenbrandt, E. Gray, J. Griffin, and R. P. Johnson, "Reappearance of Linac Bunch Structure on Booster Bunches During Capture and Acceleration", IEEE Transactions on Nuclear Science, vol. NS-24, pp. 1455-1457, June 1977.

References (continued)

[5] J. A. MacLachlan, "ESME: Longitudinal Phase Space Particle Tracking- Program Documentation", Fermilab Technical Memo TM-1274, May 1984.

[6] P. Lucas and J. MacLachlan, "Simulation of Space Charge Effects and Transition Crossing in the Fermilab Booster", in these proceedings.

[7] C. Ankenbrandt and S. D. Holmes, "Limits on the Transverse Phase Space Density in the Fermilab Booster", in these proceedings.