RF Capture Studies for Injection into a Synchrotron*

E. S. Lessner, Y. Cho
Argonne National Laboratory, 9700 So. Cass Ave., Argonne, IL 60439

Abstract

The capture process for a rapid cycling protron synchrotron is studied by numerical simulation. The rf programming is optimized to allow efficient capture such that minimum particle losses and reasonable capture voltage are attained. The total capture time is constrained to be less than 700 μseconds. Two methods of trapping the injected beam by the synchrotron rf system are examined: by stationary adiabatic capture and by synchronous injection in a standing bucket of the ring. In the adiabatic method, the non- linear function of Lilliequist and Symon is employed. The simulation allows the "tracking back" of the original distribution of any set of particles, in particular of those not captured at a given time, which is useful in studying injection alternatives such as shaping the phase-space density prior to injection. The simulation results will be used to design a chopper system to facilitate loss-free injection.

I. Introduction

A One Megawatt Spallation Neutron Source is being proposed for the upgrade of Argonne's Intense Pulsed Neutron Source. An overview of its conceptual design is given elsewhere in these Proceedings [1]. The new accelerator system (a 400–MeV linear accelerator and a 2.2–GeV rapid cycling synchrotron) will deliver a time-averaged current of 0.5 mA at a 30–Hz repetition rate. At such high intensity beams, it is essential to minimize beam losses to avoid problems with the ensuing induced radioctivity. In this paper, we present the results of preliminary studies of the injection and capture processes and possible ways of maximizing the capture efficiency. We examined two methods of trapping the injected beam by the synchrotron rf system: by stationary adiabatic capture and by synchronous injection in a standing rf bucket of the ring.

The guide magnetic field has a flat-bottom of 0.5–0.7 msec duration, a rising field of 20 Hz, and a falling field of 60 Hz to maintain the overall required 30–Hz repetition rate. The introduction of a constant magnetic field during injection allows for easier manipulation of the capture process. The rf voltage is programmed such that it is minimized during injection and capture and maintains an approximately constant bucket area determined by the bucket area at B_{max}. The minimum voltage at capture insures that one does not have a larger bucket area at the small synchronous phases and high dilution of the phase-space. The capture efficiency is calculated at 2 msec after the start of the acceleration. Our simulation code tracks a number of macro particles in longitudinal phase-space. A pair of Hamiltonian difference equations is solved for each macro particle for each turn. The phase-space coordinates are the total energy and the phase angle measured with respect to the energy E_s and phase angle ϕ_s of the synchronous particle. The equations of motion for particle i, on turn n, are [2]:

$$E_{i,n} = \frac{\beta_{s,n}}{\beta_{s,n-1}} E_{i,n-1} + e\hat{V}(sin\Phi_{i,n-1} - sin\Phi_{s,n-1}) \quad (1)$$

$$\Phi_{i,n} = \Phi_{i,n-1} + \frac{2\pi h \eta_{s,n}}{\beta_{s,n}^2 E_{s,n}} E_{i,n} + (\Phi_{s,n} - \Phi_{s,n-1}) \quad (2)$$

where h = harmonic number, and $\eta = \alpha - \gamma^{-2}$. These equations are sympletic to first order.

For a given final particle distribution, the program can "track back" the initial distribution of any set of particles, which is very useful in determining the initial coordinates of lost particles. A particle is considered to be "lost" if it is outside the separatrix at a specified time.

II. Adiabatic Capture

In the stationary adiabatic capture method, the nonlinear function of Lilliequist and Symon [3] is employed. At any given time t, the rf voltage amplitude is given by:

$$V(t) = \frac{V_2(t_2)}{(\sqrt{\frac{V_2}{V_1}} - \alpha\frac{t-t_1}{\tau_{p2}})^2} \quad (3)$$

where V_1 is the initial voltage at time t_1, V_2 and τ_{p2} are the final voltage and the phase oscillation period at time t_2, respectively, and α is a constant that determines the degree of adiabaticity.

The capture efficiency for several degrees of adiabaticity and phase-space dilution was studied extensively. However, it has been observed experimentally that in adiabatic capture processes that are constrained by time and capture voltage values (a high capture voltage implies high dilution and particle losses when the bucket shrinks during acceleration), there is always a "band" of particles that is not captured. Their initial distribution extends from the unstable fixed points to the energy extreme values, with a roughly linear variation in phase angles (see Figure 2). One possible way of avoiding these losses is to paint the longitudinal phase-space by injecting a beam of small energy spread, with its central energy modulated during the injection period to match the bucket area of the ring and chopped at appropriate phase angles. In our simulation of injection by painting, we have assumed the following conditions:

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.

0-7803-1203-1/93$03.00 © 1993 IEEE

- the magnetic guide field is kept constant during injection and capture, giving a maximum bucket area for a given voltage;
- the linac pulse duration is 0.5 msec long;
- injection stacks of 100–keV energy spread; and
- the central energy is raised linearly during the injection period.

In the simulation, stacks are sampled at 25 μsec intervals. The rf programming is shown in Figure 1. The initial voltage is kept constant at 1 kV during injection and raised rapidly to 7 kV in 1/4 of the final oscillation period (0.2 msec), right at the start of the acceleration period. The capture voltage of 7 kV is determined by the requirement that the bucket area at $\dot{B} = 0$ be equal to the bucket area at $\dot{B}_{max}$, corresponding to a bucket area of 3 eV-sec. For a momentum deviation $\Delta p/p = 1.5E\text{-}3$ and without beam chopping (bunch length equal to the circumference length), the capture efficiency measured at 2 msec into the accelerating regime ($\Phi_s = 26°$) is 88%. The initial distribution of the uncaptured particles can be seen in Figure 2. To avoid these losses, we injected stacks with the lower energy particles chopped at the end of the bunch (positive phase angles) for increasing periods of time, and the higher energy particles chopped at the beginning of the bunch (negative phase angles) for decreasing periods of time (see Figure 2). With this procedure all of the beam is captured, but 25% of the total beam area must be chopped, requiring a higher duty factor and a dilution of the order of two. The particle distribution at the end of 2 msec can be seen in Figure 3.

For comparison, we examined the case when the voltage is raised immediately from 1 kV to 7 kV, in a "step-like" fashion, thus shortening the flat-bottom field duration requirement. For a momentum variation of 1.5E-3, as before, the capture efficiency at 2 msec of acceleration drops to 80%. To avoid losses, the beam would have to be cut slightly more than 25%, using a more complex scheme than in the previous case, since many of the particles of higher energy and phase angles which are captured in the adiabatic process are lost in the non-adiabatic one. We also examined the capture efficiency for particles injected with lower momentum spread, namely, $\Delta p/p$=1.2E-3 and 7.0E-4. The capture efficiency for all the cases examined is displayed in Table 1.

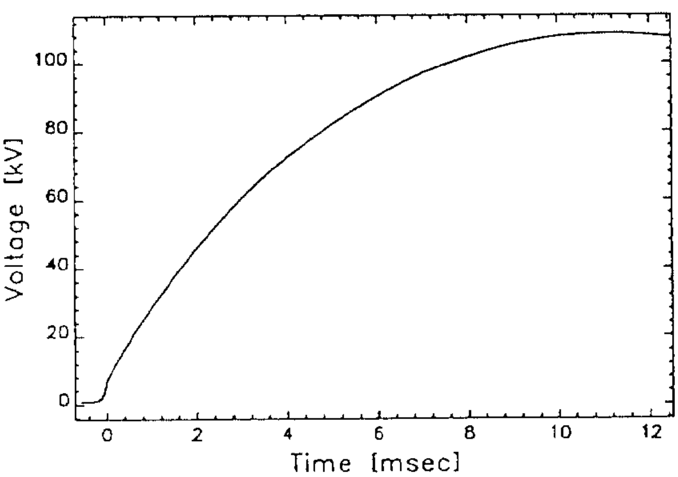

Figure 1
RF voltage programming from the start of injection to the end of acceleration. The magnetic field is held constant for 700 μsec; the beginning of the accelerator clock is set at t=0.

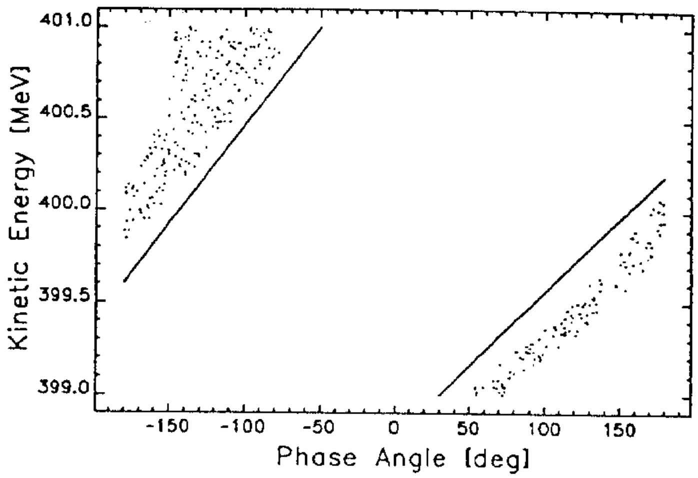

Figure 2
Schematic initial phase-space distribution of particles not captured at t=2 msec of acceleration for an adiabatic capture and unchopped beam. To ensure total capture, the beam is chopped prior to injection along the indicated continous lines.

Table 1
Capture Efficiency measured at 2 msec

	$\Delta p/p$		
	1.5E-3	1.2E-3	0.7E-3
Unchopped Adiabatic	89.17	89.99	90.56
Unchopped Non-Adiabatic	82.68	83.56	84.20
Chopped Adiabatic	100.00	–	–
Waiting Bucket	99.60	99.82	99.98

III. Stacking in a Standing RF Bucket

In the second study, we injected stacks of 100–keV energy spread cut at +/- 120° into a standing bucket of area 3 eV-sec and momentum spread of $\Delta p/p$=1.5E-3. As in the adiabatic process, the central energy of the stacks is modulated during the injection period. Figure 4 depicts the phase-space configuration right after injection, showing a dipole distribution, with a hot core of particles around 401 MeV which remains even after several synchrotron oscillations. Since space charge effects are likely to be maximum at the beginning of acceleration [4], this configuration is

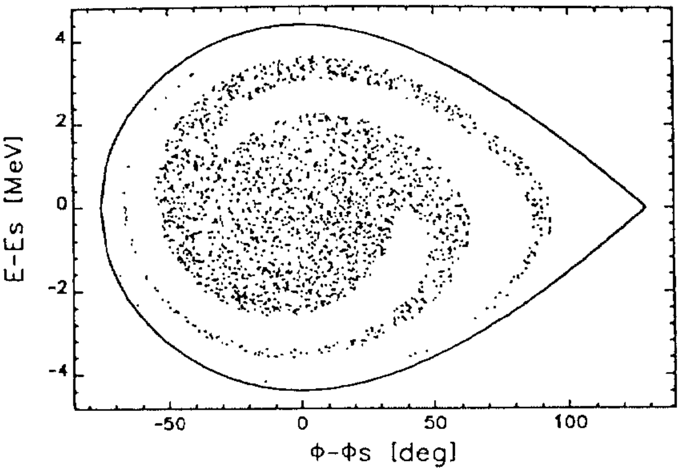

Figure 3
Phase-space distribution at the end of 2 msec of acceleration for the chopped beam.

not desirable. As an alternative, we examined the injection of stacks with no modulation of the central energy and for the three values of momentum deviation. As previously, the stacks are chopped at +/- 120°. For the higher momentum spread case, the phase-space distribution, right after injection, is fairly uniform in energy and phase angle, as shown in Figure 5. Tracking back the initial distribution of the lost particles indicates that chopping the beam at +/- 100° (55% cut) would insure total capture.

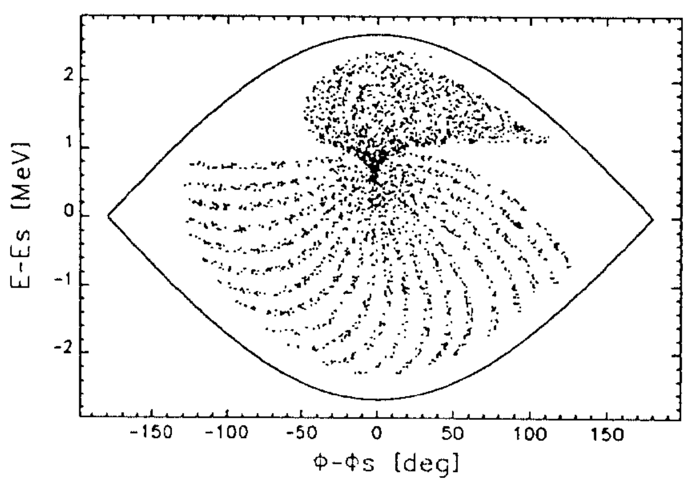

Figure 4
Distribution at the end of injection for energy modulated stacks injected into a waiting bucket of the ring, showing a high density of particles around 401 MeV.

IV. Conclusions

Several options for the injection and capture into a stationary bucket of a synchrotron are studied by numerical simulation. In the adiabatic case, within the time and voltage requirements, 100% capture efficiency can be achieved

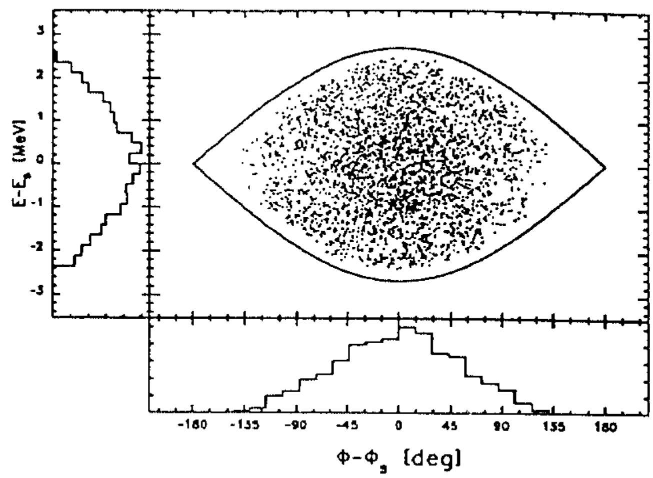

Figure 5
Distribution at the end of injection for stacks injected without energy modulation. The particle distribution in Φ and E space is shown respectively at the bottom and sides of the figure.

by modulating the central energy and chopping the beam prior to injection. In the synchronous capture by a standing bucket case, modulation of the central energy leads to an undesirable phase-space distribution after injection. If the stacking is done without energy modulation, with the injected beam spread to fill the rf bucket acceptance, however, the phase-space distribution is acceptably uniform but requires a higher duty factor than the adiabatic process. In this case, if the energy spread is further reduced by a factor of two, the capture efficiency is nearly 100%.

V. References

[1] Y. Cho *et al*, "Conceptual Design for a One Megawatt Spallation Source at Argonne National Laboratory," these proceedings.

[2] S. R. Koscielniak, "The Long1d Simulation Code," *European Particle Accelerator Conference*, 743-745 (1988).

[3] C. G. Lilliequist and K. R. Symon, "Deviations from Adiabatic Behaviour During Capture of Particles into an R.F. Bucket," *MURA-491* (1959).

[4] Y. Cho, "Capture and Acceleration Considerations in the SNQ-SRA," *ANL-83-13, AAD-N-5* (1982).