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STUDY OF THE RF CAPTURE PROCESS IN THE ARGONNE RAPID CYCLING SYNCHROTRON*

Yanglai Cho, Charles W. Potts, Antanas V. Rauchas,
Seung-Ai Shin,** and Harunori Takeda
Argonne National Laboratory
Argonne, Illinois 60439

Summary

The 500-MeV Rapid Cycling Synchrotron (RCS) guide field is energized by a dc-biased, 30 Hz sinusoidal ac power supply, and the field strength varies between 2.81-9.81 kG. During the acceleration period, the $\dot{B}$ varies in a half-sine function from zero to a maximum of 670 kG/s and back to zero. Although the average $\dot{B}$ during injection is not equal to zero, efficient capture has been obtained experimentally by adjustment of the RF voltage program and the injection timing.

In this paper, we describe a simulation study of the capture process in order to understand the experimental results.

Introduction

The injection into the RCS utilizes the H^- charge exchange method from a 50-MeV linac, with a pulse length varying between 50-200 μs. After the injection is over, the RF system forms a single bunch in the accelerator, which has an average radius of 6.83 m and a bending radius of 3.68 m. The RF programming consists of a few hundred volts during the injection period. After injection, the voltage is raised rapidly to about 10 kV. This programming, together with timing of the RF, has been critical in achieving high efficiency.

The following results were obtained by a numerical simulation study that includes space charge. The steep rise of the RF voltage amplitude at the beginning induces a highly nonlinear bunch motion, and the bucket expands to three times the initial coasting beam bunch area. The bunch information at this period is so strong that neither the initial particle distribution nor the initial momentum error byte of a factor of two deteriorates the capture efficiency seriously. The 2×10^{12} particles per bucket induce a 5.5% bucket shrinkage in average, although it reaches 17% at the initial period. However, the space charge effect on the capture efficiency is not significant at this beam intensity, since we allow the phase space to be diluted by a factor of three.

Capture Simulation and Optimization

Optimized conditions for the injection process and the RF voltage amplitude function are obtained by a Monte-Carlo program (RFSIMulation), which traces space charge interacting particle trajectories in longitudinal phase space. The space charge term is calculated from the particle density gradient in a bunch for each macroparticle at each integration step. The integration is performed by a turn basis, using recurrence equations obtained from the following equations. For a j-th particle:

$$\frac{dW_j}{dt} = e\hat{V}_{(t)} \left(\sin \phi_j - \sin \phi_{s(t)}\right) + \frac{e^2 \frac{N}{n_o} g_o}{2\varepsilon_o \gamma_j{}^2} \frac{\partial \lambda}{\partial \phi_j}$$

$$\frac{d\phi_j}{dt} = - \frac{h\eta_{(t)}\omega_{(t)}}{2\pi R_s P_{s(t)}} W_j \qquad g \sim 2.6$$

where:

ϕ_s, R_s, and P_s = synchronous particle phase, radius, and momentum,

W_j = a conjugate variable to ϕ_j,

N = the number of real particles per bunch,

n_o = the number of macroparticles per bunch,

g_o = a geometric factor,

λ = the macroparticle line density, and

η = $1/\gamma^2 - \alpha$.

The shrinkage of a bucket due to space charge below transition ($\gamma_y \sim 2.2$) is included in the separatrix:

$$W = 2\pi R_s \Delta P = - \frac{2\pi R_s}{h\eta_{s(t)}\omega_{s(t)}} \left\{ 2 \frac{\Omega^2}{\cos \phi_{s(t)}} \left[(\cos \phi + \phi \sin \phi_{s(t)}) - (\cos \phi_{1(t)} + \phi_{1(t)} \sin \phi_{s(t)}) - \frac{k_{(t)}}{e\hat{V}_{(t)}} \left\{ \lambda_{(\phi)} - \lambda(\phi_1) \right\} \right] \right\}^{\frac{1}{2}}$$

where:

$$k(t) = \frac{e^2 \frac{N}{n_o} g_o}{2\varepsilon_o \gamma^2 (t)} \ , \qquad \phi_{1(t)} \sim \pi - \phi_{s(t)}$$

The RCS operates with a 30 Hz sinusoidal B field, with h = 1. The conditions for the simulations are 2×10^{12} protons/bunch, 1200 simulated particles, and a bunch size 0.13 eV-s of a multiturn, continuously-injected coasting beam with $\Delta P/P = \pm 0.15\%$. The beam is injected around B = 2.81 kG ($\dot{B} = 0$). The beam distribution is quadratic in $\Delta P/P$, and is uniform in ϕ. A particle is defined to be lost if it is outside of the separatrix for an instant. This definition of particle loss is applied after the rapid RF voltage rise period. Then, the capture efficiency is calculated at 2 ms after injection. The RF voltage is radically raised from 0.5-10 kV in 400 μs immediately after injection for the efficient capture. The timings between $\dot{B} = 0$ (t = 0), injection time t_i, and that of the radical rise of the RF voltage t_s are crucial for the efficient capture. They must be within a time window of ±100 μs to keep inefficiency below one percent. The inefficiency grows rapidly outside of this window.

At the best optimized condition ($t_i \sim -0.1$ ms, $t_s \sim -0.05$ ms), the loss is about 0.1% at t = 2 ms.

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**On leave of absence from Ewha Women's University, Seoul, Korea.

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Capture Process Under Rapidly Varying Voltage

The capture process is strongly determined by the RF voltage radical rise period. Although the space charge effect is the strongest during this period, the bunch and the bucket evolution is determined mainly by the RF voltage. The radical expansion of the bucket accompanied by the accelerating synchrotron frequency (4.7-6.9 kHz) forms the bunch. The bunch formation is seen clearly with space charge turned off. Figure 1 shows the typical "s" shape reflecting a sinusoidal RF voltage structure. Both tails of the bunch are pulled into the separatrix after almost one synchrotron period (Fig. 2). The RF voltage is increased by a factor of 2.1, the bucket height is increased by a factor of 1.43, and the synchronous angle is kept between 2.75-3.87° so that the bucket expands in $\Delta P/P$ with a wide phase angle acceptance available.

Space Charge Effect

The gradient of charge density varies rapidly at the first 400 μs. The effect of space charge is strongest at this period. Figures 3 and 4 show the results with space charge turned on, corresponding to Figures 1 and 2, respectively. The space charge diffuses the distribution and reduces the bucket height according to local charge density. A large difference in distribution is seen between Figs. 2 and 4. The bucket size is reduced over 10% for Fig. 3.

An optimization of the RF voltage function is performed, extending after the first few ms of the capture period. Figure 5 shows a loss-minimized, nearly achievable RF voltage function. The stabilized separatrix at the acceleration stage reduced its size by 5.5%. This is consistent with an estimate of bucket shrinkage from uniform charge distribution.[2] We observed a uniformization of particle density along the longitudinal dimension ϕ during this period.

Effect of Initial Distributions

The simulated particle distribution at injection along the ϕ axis is uniform but, for the $\Delta P/P$ axis, uniform and quadratic distributions are both tested. The capture efficiency at t = 3 ms differs by one percent. The variation of the initial momentum error byte from 0.15-0.3% introduces a half percent inefficiency variation.

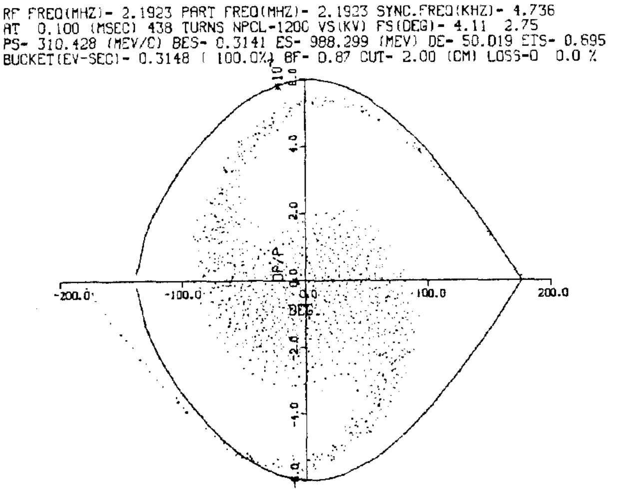

Figure 1

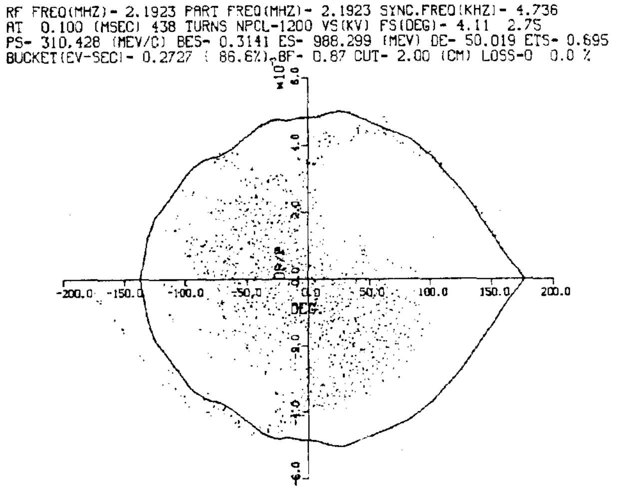

Figure 3

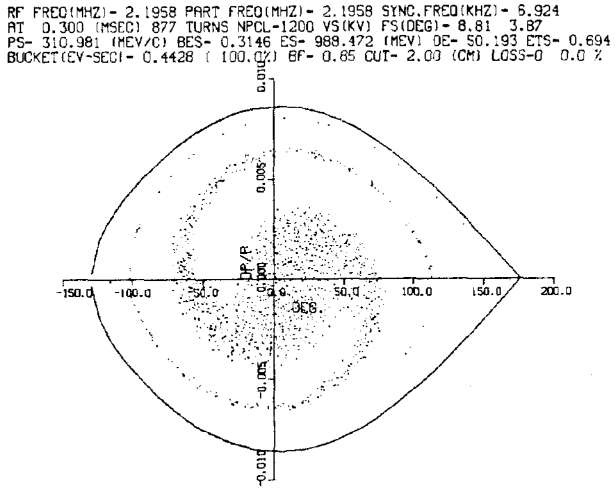

Figure 2

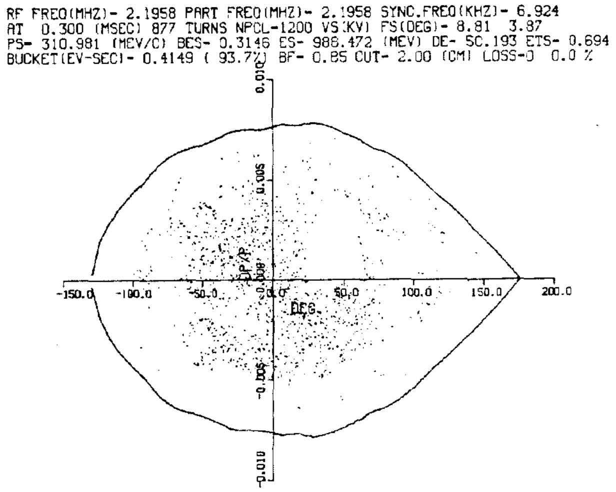

Figure 4

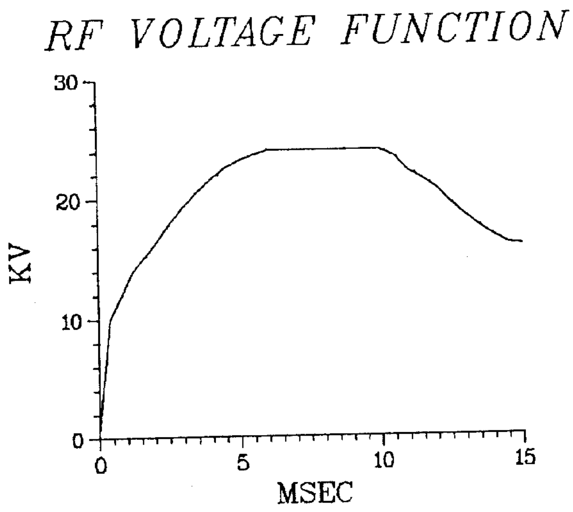

Figure 5

References

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2. C. Bovet et al., CERN/MPS-SI/Int. DL/70/4 (1970).