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EXPERIMENTAL AND THEORETICAL STUDY OF THE AGS INJECTION AND CAPTURE

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Introduction

Over the past couple of years a computer model for longitudinal dynamics has been developed to simulate and interpret particle behavior in the AGS during injection and capture. This report describes the study which recently has been done comparing the computer model and experimental results at the AGS.

The goal of this study was:

- to determine the area of practical applicability of the model as a tool for diagnosis of injection and capture conditions in the AGS, and
- to plan the next computer and machine experiments in order to prove model reliability and to improve AGS production.

Three capture scenarios were explored both via experimental runs at the AGS and via computer runs for the model. Each run can be interpreted in terms of the position of injected beam relative to capturing bucket and bucket position relative to aperture. The diagnostic tools used to compare experiment and model tools were the so-called "mountain range" and the beam intensity as a function of time.

The mountain range is a series of curves representing particle intensity distribution versus phase angle from $-\pi$ to $+\pi$ and versus revolution turns. In the experiment the mountain range was constructed onto the oscilloscope screen from a signal taken from the wall monitor (F20). The signal represents the variable part of current with no d.c. In the computer model, the mountain range is constructed during the tracking of 2000-4000 particles and graphically displayed on the computer screen.

The intensity curve is the total number of particles at each instant or total charge vs. time. In the experiment, the signal is taken from the L20 current transformer normalized by the revolution frequency. In the model we introduced aperture limits. Those are distances $\Delta R = \pm 2$ cm from the design orbit of radius $R_o = 128.5$ m. During the tracking each particle is subject for counting provided the particle orbit radius R satisfies $R_o - \Delta R < R < R_o + \Delta R$. If this condition is not satisfied, then the particle is lost (hit aperture) and removed from further calculations.

All experimental and all computer runs had the following common conditions.

1.	Magnetic field rate of change	$\dot{B} = 4.9$ Gs/ms;
2.	Radio frequency rate of change	$\dot{f} = 28$ kHz/ms;
3.	Peak voltage	$V = 200$ kV;
4.	Injectin energy (kinetic)	$E_{lin} = 200$ MeV;
5.	Injection energy spread	$\Delta E = \pm 0.4$ MeV; (not measured)
6.	Duration of the injection	$T_{in} = 0.25$ ms.

Thus the initial conditions varying from run to run are the field B(0) and radio frequency f(0). In the computer runs they were simply assigned before each run started. Experimentally the time of injection could be shifted relative to the magnetic field by changing the variable delay between the Gauss clock autodet functioning as the "injection peaker" and the start of the Linac pulse. This also shifts the beam relative to the rf frequency since the frequency is referenced to the field. In setting up the experimental parameters it was useful to adjust $\dot{f}$ to allow beam to survive a while beyond capture--allowing the experimenter to clearly distinguish between captured and uncaptured beam. Since the $\dot{f}$ required to match $\dot{B}$ and R_o changes rather rapidly with time and since the starting oscillator controls allow only a single slope, a compromise value resulted which was significantly less than the correct value at injection, 28 MHz/sec instead of 33 MHz/sec. Nevertheless, this value of 28 was used for the machine experiment, and consequently applied to the simulation.

The Results

The results are presented for each run separately in Figures 1, 2, and 3. Each figure has three sections. The right section with the black background represents experimental results. The left and central sections represent results from computer modeling. The experimental section shows intensity curve and mountain range. They should be compared with mountain range in the central section and with the intensity curve I(t) in the left section.

Particle positions in phase space (energy E vs. phase ϕ from $-\pi$ to π) are shown in the central section at the end of injection. Each dot is a particle. Some of the particles are within the bucket, some are not. Those which are out of the bucket will be lost ultimately. Two rectangles crossing the bucket represent injected beam at two different times. The upper rectangle is the beam just at the beginning of injection, the lower rectangle is at the end of injection. The height of the rectangles corresponds to the energy spread of 0.8 MeV. In the model, injection starts when time T = 0 finishes when T = 0.25 ms. That last time is shown on the left section by the vertical line crossing all the graphs. The same time is shown on the central section by two short lines connecting the mountain range with vertical frame. These two time pointers separate the mountain range area (below the curve connected to the pointers) which was created during injection. We will refer to that mountain range as the "injection mountain range".

The upper graph on the left section has three curves. The middle curve $E_s(t)$ represents an evolution of synchronous energy with the time. Roughly speaking, it characterizes the energy of the bucket as a whole. After each 0.1 ms, the curve E_s is crossed by a vertical line representing the height of the bucket at that time. Two other curves below and above E_s are the aperture limits in energy units. If the height of the bucket reaches one of those limits, then the bucket hits the aperture and part of the bucket particles will be lost as it was explained in the Introduction. Thus, the upper and lower aperture curves are the aperture corridor where the bucket is moving. In this corridor, the solid horizontal line ending at the vertical time line represents constant injection energy.

In the central section we also marked the aperture corridor. Two black boxes (their upper side) at the frame just below the bucket denote the level of low aperture, while two pointers at the top of the frame show the level of high aperture. The numbers above the bucket are as follows. T is the duration of tracking, Nptcl is the number of captured particles, Nmax is the total number of injected particles, DT is the revolution period at the end of the run, Nphi, Ne are the numbers of particles homogeniously distributed (Nphi-horizontally, Ne-vertically) within the injection rectangle during injection. After each turn, a new portion of 23 x 3 = 69 particles is placed in the rectangle which is moving down relative to the bucket.

All other numbers on the figures are self-explanatory.

First Run (Figure 1) - Symmetrical Injection

This run was made to compare the theory and experiment in the case of "symmetrical injection" This is the case when injected beam at the beginning of injection is placed in the bucket symmetrically with the beam injected at the end of injection.

The main features are:

a. Single mountain range due to injection symmetry;
b. Intensity curve slightly deviate from linear during injection; it could happen if the bucket was placed close to the lower aperture. At the beginning of injection all the particles are in the upper half of the bucket and far from the aperture either they are within or out of the bucket. Near the end of injection, unstable particles form flow (see Figure 2) hitting the aperture.
c. Symmetrical injection is the best way to reduce particle losses compared to all other non-symmetrical cases.

Second Run (Figure 2) - Upper Injection

This is the case when injected beam is placed onto the upper half of the bucket.

The main features are:

a. Double mountain range; this means the center of the bunch has lower (if any) particle density than other parts of the bunch.
b. Injection mountain range (which is the single range created during injection) is situated on the right-hand side of the double mountain range; it could happen only if injection has started onto the upper (not lower) half of the bucket when particles are moving counter clockwise about the bucket center.
c. Linear character of intensity I(t) during injection; this tells us that even if the bucket was not very far from the lower aperture, the spacing was adequate. This is another indicator of upper injection.
d. Because this is the non-symmetrical case, the losses are bigger then in the first run.

Third Run (Figure 3) - Lower Injection

This is the worst case when injected beam is placed onto the lower half of the bucket.

The main features are:

a. The double mountain range tells us that this is non-symmetrical injection and injection mountain range being on the left-hand side tells us that this is the lower injection.
b. Non-linear behavior of the intensity curve during the injection shows that particles start to hit the aperture before injection has finished.
c. Losses in the lower injection are greater than losses in the two other cases because the injected beam is closer to the lower aperture.

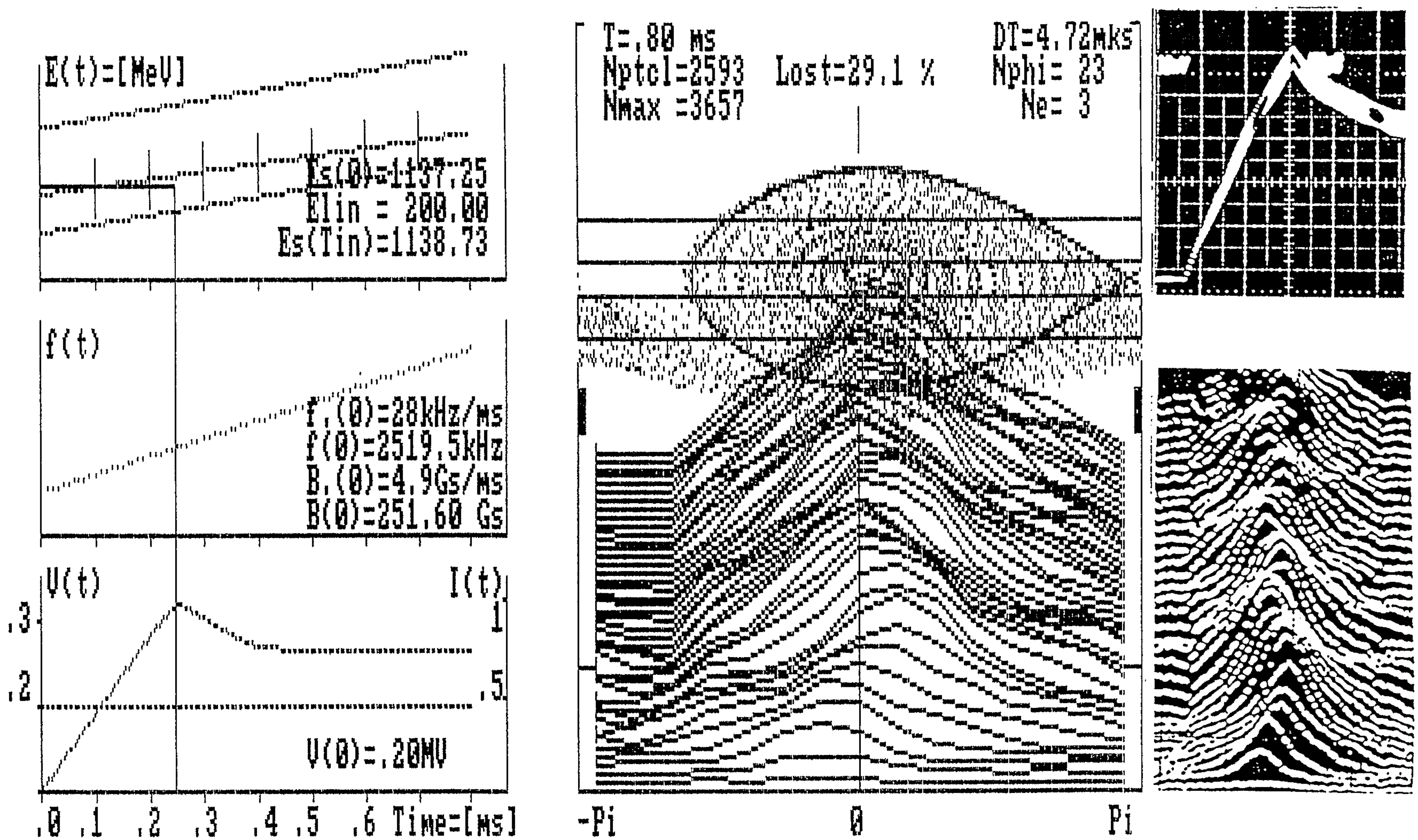

Figure 1. Capture under symmetrical injection.

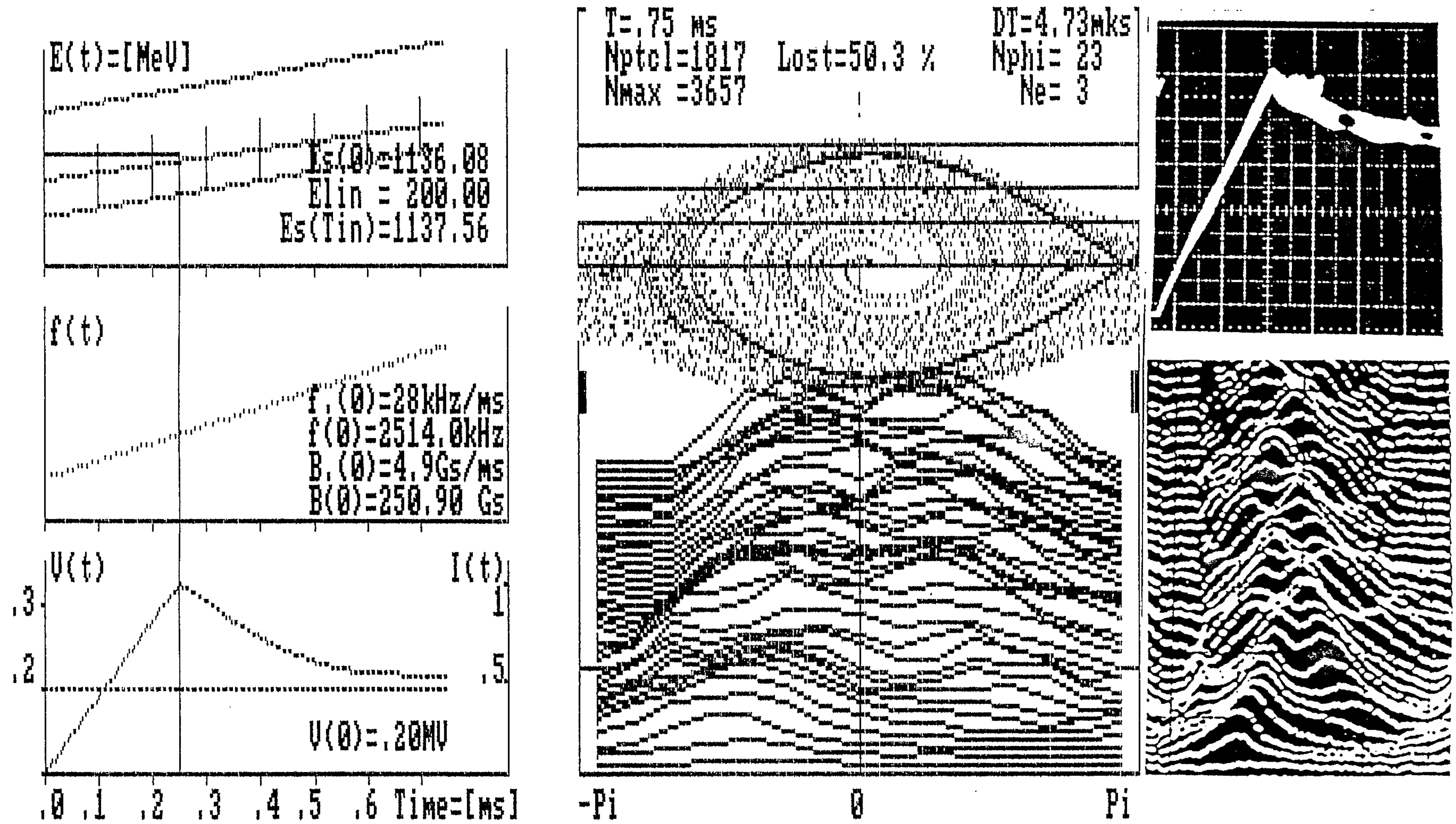

Figure 2. Capture with injected beam high in the bucket.

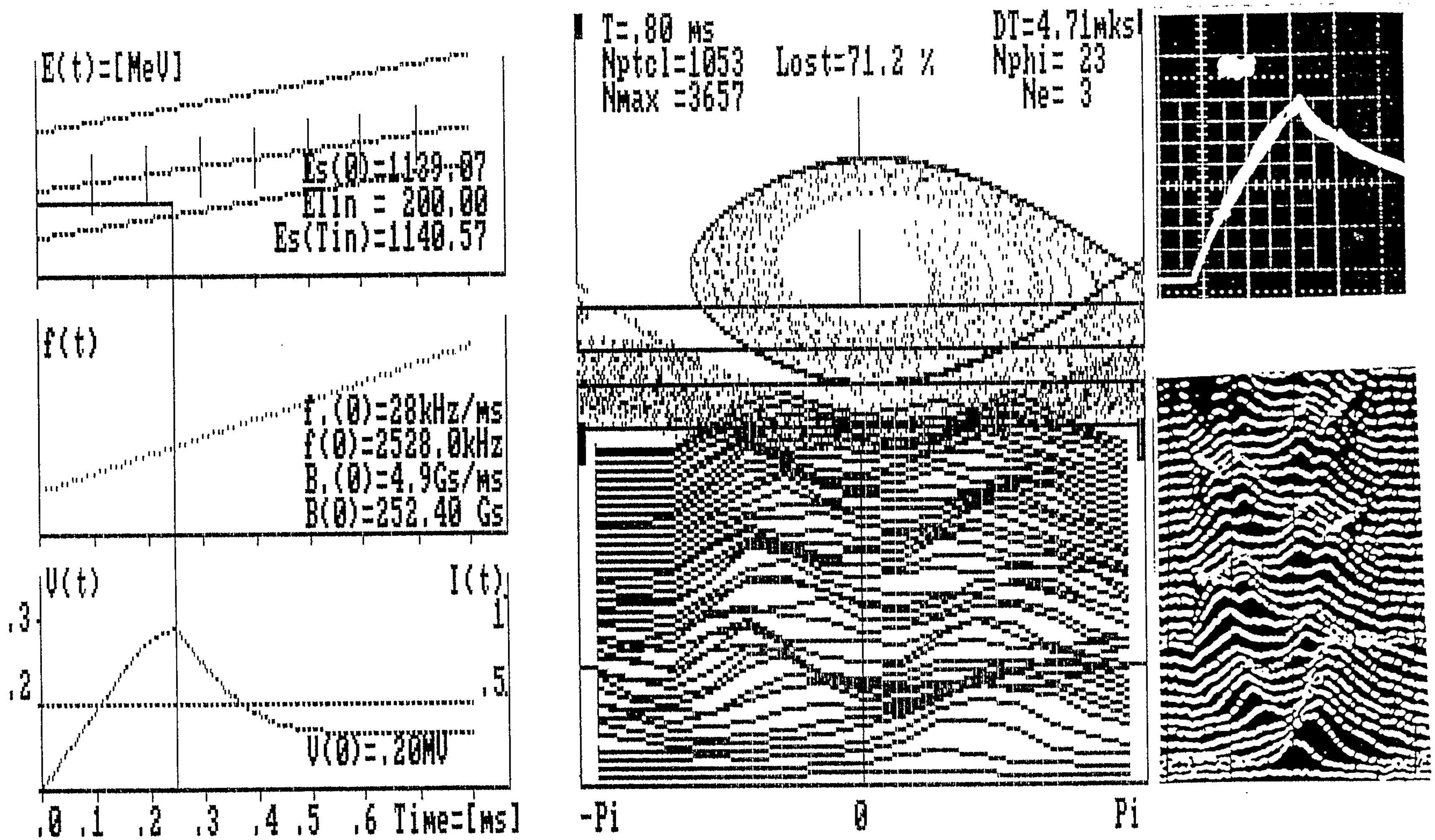

Figure 3. Capture with injected beam low in the bucket.

Conclusions

Based on excellent qualitative agreement between computer simulations and experiment, it can be concluded that:

a. Computer modeling of longitudinal dynamics even without betatron motion and space charge can be useful for interpretation of injection and capture conditions in the AGS. In particular, the model can predict and interpret:

   1. How close is the bucket to the aperture,
   2. Where the injected beam is relative to the bucket,
   3. What kind of losses we can expect on the above two conditions.

b. Because the best injection conditions are achieved by "symmetrical injection" the next experiment and modeling should produce more details on that case. Special efforts should be put on the issue of how to create a mountain range with flattop. In other words, how to organize injection with homogeneous particle distribution within the bucket.

Those questions could be answered if we break the limitations accepted for this study: constancy of $\dot{f}$, V, E_{lin}.

While those limitations are just technical for the computer model, the absence of consideration of transverse motion even in a simple and crude way (the only parameter reflecting the transverse focusing property in the model is the compaction factor, which is obviously not enough), is a basic limitation for the present model. The single parameter "physical aperture" we introduced in the model is in reality the result of horizontal and vertical acceptances and emittances, the latter depending on the betatron resonances and certainly on matching of injection emittances to betatron emittances and so on. Such a simplification of the model does not hurt too much while we are doing qualitative diagnostics, e.g., interpreting injected beam-to-bucket position through analysis of the mountain range. However, when we want to match the intensity curve from the model to the experimental one, we need more flexibility and in the above have used initial values f(o), B(o) as free parameters which, in fact, were not free in the experiment. If we would use these values from the experiment, we would get an intensity curve I(t) showing much better capture efficiency because the model does not know about losses due to resonances or other limitations from betatron motions. We hope to improve the model in the future by including elements reflecting transverse motion characteristics.

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