THE INVESTIGATION OF INJECTION TIMING FOR THE IPNS RCS*

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Abstract

The Rapid Cycling Synchrotron (RCS) of the Intense Pulsed Neutron Source (IPNS) at ANL accelerates $> 3.0 \times 10^{12}$ protons from 50 MeV to 450 MeV with 30-Hz repetition frequency. During each acceleration cycle, the rf frequency varies from 2.21 MHz to 5.14 MHz. In order to improve capture efficiency, we varied the injection timing and the early rf voltage profiles. The experimental results are compared with simulation results obtained with the 1-D tracking code, CAPTURE. This allowed us to optimize injection time and the rf voltage profile for better capture efficiency. An optimized injection time and rf voltage profile was found that resulted in raising the capture efficiency from 85.1% to 88.6%. These studies have now also been expanded to include second harmonic rf during the capture and initial acceleration cycle in the RCS.

INTRODUCTION

The RCS accelerates protons from 50 MeV to 450 MeV. Until recently, this was by two single-gap, ferrite-loaded, harmonic number one, coaxial rf cavities [1]. A third cavity has recently been added, able to operate at the second harmonic for the first 4 ms of the acceleration cycle. The schematic diagram of the RCS is shown in Fig. 1. H- beam from the linac (50 MeV, 200 MHz) is stripped to H+ (protons) in a carbon foil and injected into the RCS, filling about 130 turns during the ∼75-μs injection period. Protons circulate and fill the whole ring during this injection period. As the rf voltage starts to increase, the particles are bunched and start to gain energy. While the majority of circulating protons are captured in the rf bucket, some losses occur (12% - 15% of the beam prior to the addition of the second harmonic system). Because of the relatively low energy and high bunch charge, space charge significantly affects the bunching/capture process.

CAPTURE PROCESS

The orbit guiding magnetic field oscillates at 30 Hz according to:

$$B = B_0 - B_1 \cos(2\pi \cdot 30 \cdot t). \tag{1}$$

Each time the magnetic field ramps up, one bunch of protons is accelerated. For each acceleration cycle, we set the moment when this ramping magnetic field is at minimum to be time zero. The starting point of the 75-μs injection period can be varied from 50 to several hundred microseconds before time zero. Since the duration of injection is very short compared with the variation of the ramping magnetic field, we consider the ramping magnetic field before time zero to be flat when the injection is close to time zero.

Without the rf voltage, protons uniformly distribute

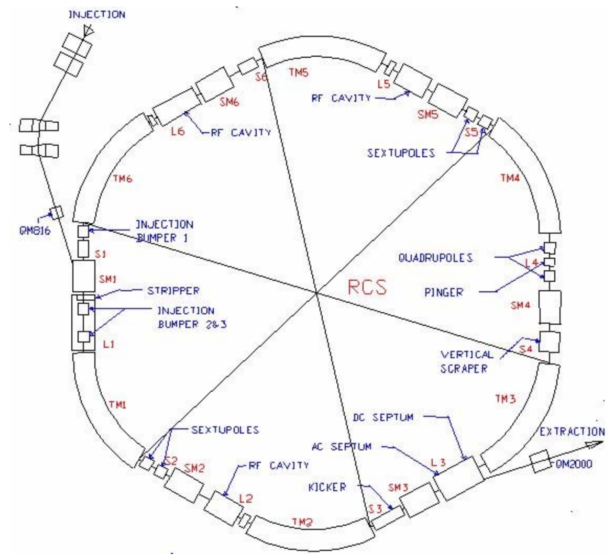

Figure 1: Schematic diagram of the RCS.

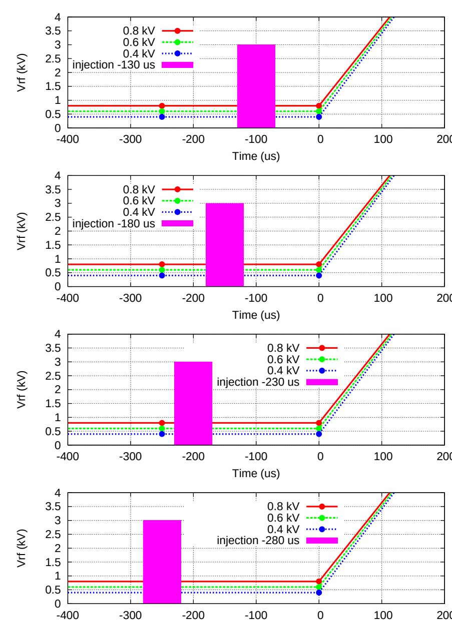

Figure 2: Injection scheme 1 of different injection timing; the purple blocks indicate the injection period.

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Table 1: Efficiencies with Constant V_{rf} before Time Zero

Injection Time (μs)	0.4 kV	0.6 kV	0.8 kV
-130	85.9%	86.3%	85.3%
-180	87.2%	82.6%	82.7%
-230	86.1%	85.3%	83.6%
-280	78.9%	85.8%	85.1%

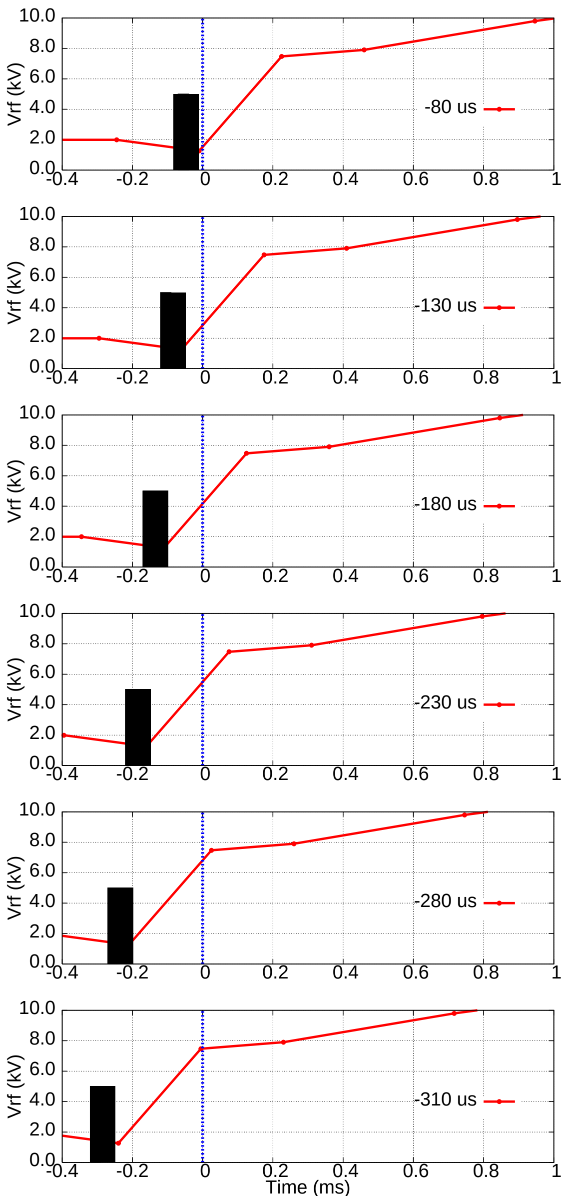

Figure 3: Injection scheme 2 of different injection timing; the black blocks indicate the injection period.

around the full circumference. Once the magnetic field starts ramping, the rf voltage needs to increase fast enough to bunch the beam and provide sufficient energy gain. For acceleration, the rf bucket length is far less than the ring circumference. Since the protons initially distribute around the full circumference, they need to be efficiently concentrated to fall in the rf bucket. We did both experiments and modeling to look at the effect of rf amplitude and injection timing on capture efficiency. The first cases studied experimentally are shown in Fig. 2. The experiment results are shown in Table 1.

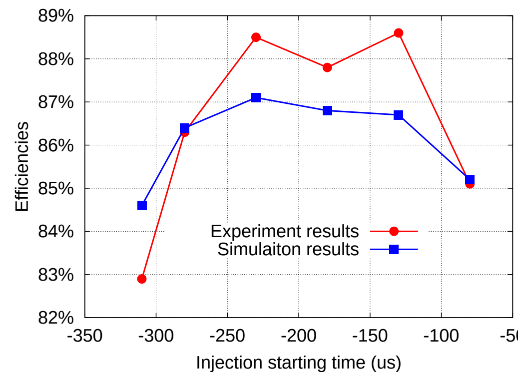

Figure 4: Comparison of the experiment and simulation results for injection scheme 2.

From Table 1, we can see that no obvious trend exists for increasing the relatively low amplitude V_{rf} before time zero or injecting the beam earlier. After observing the beam dynamics from simulation results, we understand that this is because:

- when forming the bucket in phase space, the small amplitude of the V_{rf} is mostly canceled by the space-charge effect; the bucket collapses, so we need to increase the amplitude.
- the introduction of V_{rf} will increase the energy spread once particles start to rotate in phase space; we need larger V_{rf} to hold the bunch, so we need to move from the constant amplitude V_{rf} to increasing V_{rf}.

Then we tried a second set of injection parameters as shown in Fig. 3. We increased the amplitude of V_{rf} before time zero and let it keep going up after injection. When we vary the injection time, the V_{rf} profile is also shifted relative to time zero.

Besides experiments, we also used the 1-D code CAPTURE [2] to simulate this bunching process. The results are shown in Fig. 4. We can see that both the experiments and simulation results indicate that there exists an optimized region for injection, between -130 and -230 μs. The capture efficiency increases from about 85% to about 88.5%. This optimization is a compromise between the particle motion in the phase space and the potential shape that combines contributions from space-charge effects and rf voltages. If the beam is injected too early, the variation of the magnetic field must be included in the calculation (a flat field assumption is not valid). The space-charge effects can be mitigated somewhat by the application of the second-harmonic cavity.

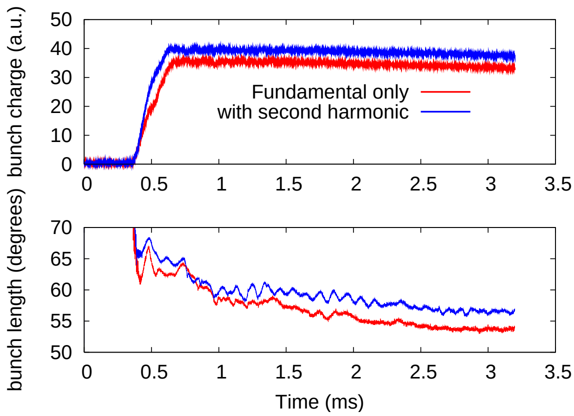

Figure 5: BPM measurement results of bunch length and charge showing the effects of second harmonic voltage. Bunch charge is obtained by integrating the beam position monitor (BPM) signal so only AC current is obtained. The bunch length is the standard deviation of the longitudinal intensity distribution in rf phase.

2ND HARMONIC CAVITY UPGRADE

A third rf system has been installed in the RCS that operates at the second-harmonic mode during the first 4 ms of the acceleration cycle combined. With the original two rf systems operating in the fundamental mode, the addition of the second-harmonic rf voltage will change the total V_{rf}. By choosing a proper phase for the second-harmonic rf voltage relative to the fundamental rf voltage, the total potential can be shaped and is able to hold a longer bunch. Since the total charge can be distributed in a longer bunch, the space-charge effects can be reduced, and more protons can be accelerated.

We are presently seeing a $>$10% increase in accelerated current when we add second-harmonic rf. The measured bunch length and bunch charge are shown in Fig. 5.

CONCLUSION

We have tried to improve the capture efficiency of the RCS of IPNS by adjusting the injection timing and profile of the rf voltage before time zero. Both experiment and simulation indicate that a certain level of low amplitude rf voltage before time zero helps the bunching process and improves the capture efficiency. The addition of second harmonic further improves the capture efficiency by lengthening the bunch and reducing the space-charge effect.

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