SIMULATION STUDY AND INITIAL TEST OF THE SNS RING RF SYSTEM *

Y. Zhang, H. Ma, M. Champion, P. Chu, S. Cousineau, V. Danilov,
T. Hardek, J. Holmes, M. Piller, M. Plum
Spallation Neutron Source, ORNL, Oak Ridge, TN 37831, USA

Abstract

The *rfsimulator* code was developed for the study of the Spallation Neutron Source (SNS) dual-harmonic ring RF control. It uses time-domain solvers to compute beam-cavity interactions and FFT methods to simulate the time responses of the linear RF system. The important elements of the system considered in the model include beam loading, dynamic cavity detuning, circuit bandwidth, loop delay, proportional-integral controller for feedback and adaptive feed forward, stochastic noise, width-in-turn loop parameter change, beam current fluctuation, and bunch leakage. As the beam power increases, beam loss in the ring goes up and thus precise control of the bunching RF phase and amplitude is required to limit beam loss. The code will help in the development of a functional RF control and in achieving the goal of minimizing beam loss in the accumulator ring.

INTRODUCTION

The SNS accumulator ring is designed to deliver 1-GeV proton beams of up to 1.4 MW onto a mercury target for neutron production. The tolerable fractional beam loss in the ring is very low, about 10^{-4} [1]. Precise control of the dual-harmonic ring RF phase and amplitude is critical to maintaining a clean gap for extraction kicker rise time while lowering the peak beam current to prevent coherent instabilities and the space charge stopband related beam losses [2]. The effects of beam loadings for high-intensity beams on RF control and beam bunch leakage were studied during the ring RF system design [3, 4].

Dynamic detuning was proposed to compensate for the heavy beam loadings. (For more details, see Brookhaven National Laboratory tech notes, quoted in the Refs. [1–4].) In the beam commissioning, however, performance of the ring RF system in the initial test was not satisfactory. Dynamic detuning was not functioning, and the RF control system could not properly handle heavy beam loadings, which caused severe beam bunch leakage and beam loss in the ring for high-current circulating beams. We have improved and will continue the study of the dual-harmonic RF system control [5, 6]. In the meantime, we also developed a simulation code, *rfsimulator*, to help understand the problem and for the future upgrades of the RF system. Development of the code and some simulation results from it are discussed in this paper. The initial measurements of the dual-harmonic RF system with the commissioning beams are briefly introduced.

* SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

SIMULATIONS

A few models simulate the control of RF cavity and the collective effects of beam longitudinal transport in an accelerator [7–9]. Because of the complexities involved in the simulations, a code based on numerical approximation is needed to join the state-of-the-art SNS Low-Level RF system [10] with the high-intensity circulating beams. The *rfsimulator* code was developed in Java; it utilizes some of the applications and GUI tools found in XAL [11].

A general RF loop, including an RF cavity, a coupler, and a generator, is represented by a parallel resistor-inductor-capacitor (RLC) circuit driven by the generator current, I_G, and the beam imaging current, I_B. The complex impedance of the network is

$$\frac{1}{Z} = \frac{1}{R_b} + i\omega C + \frac{1}{i\omega L} \tag{1}$$

where

$$\frac{1}{R_b} = \frac{1+\beta}{R_s} \tag{2}$$

R_s is the shunt impedance and β is the coupling factor. The inductance, L, and the capacitance, C, determine the resonant frequency, ω_r, of the cavity. When the cavity is detuned, the impedance becomes

$$\frac{1}{Z} = \frac{1}{R_b} \cdot (1 + iQ\frac{\omega^2 - \omega_r{}^2}{\omega \cdot \omega_r}) \tag{3}$$

where Q is the loaded quality factor of the cavity.

The generator voltage and current are no longer in phase due to the cavity detuning:

$$V_G = \frac{R_b \cdot I_G}{1 - i \cdot \tan\varphi} \tag{4}$$

where φ is the detune angle.

Similarly, the beam-induced voltage seen by the cavity is

$$V_B = -\frac{R_b \cdot I_B}{1 - i \cdot \tan\varphi} \tag{5}$$

More work is needed to model an RF loop that includes a vector feedback controller and an adaptive feed-forward (AFF) control mechanism. For example, it should properly deal with loop delay, circuit bandwidth, loop gain (including proportional gain and integral gain), stochastic noise, and some imperfections of a realistic accelerator RF system, such as beam current and beam phase fluctuations, calibration errors of the cavity pickup probe, variations in the cavity-loaded quality factor due to dynamic detuning, and drifting of the internal impedance

 1-4244-0917-9/07/$25.00

and nonlinearities of the amplifier in an RF pulse etc. However, no detailed algorithm has been implemented to maintain a certain degree of generality for the model and to save CPU time. Figure 1 shows a simplified diagram of the RF control model.

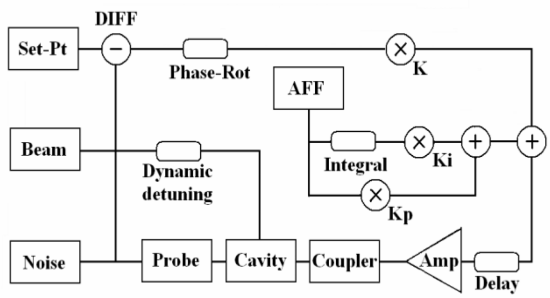


Figure 1: Schematic diagram of the RF control model

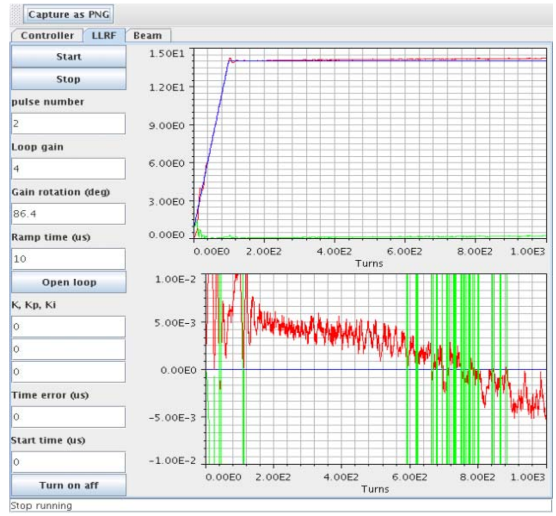
Usually, frequency domain solvers are applied in linear RF circuits, as it is easier to derive analytic solutions of the differential equations that represent the RF loop. However, as long as numerical approaches are involved, the exact analytic formula for a specific solution is less important, and time domain solvers may work as well. Because we are interested in an arbitrary RF waveform and changing beams, it could be more complicated with frequency domain solvers: different formulas are needed for "RF on" and "RF off" for a constant voltage and a ramped current in the simulation. Meanwhile, Laplace transforms and Fourier transforms are necessary. Instead, the time domain solvers utilized in the model appear to be much simpler. FFTs and inverse FFTs are utilized to simulate the time and frequency responses of the linear RF circuit.

A ring longitudinal model is introduced into the code to give the RF loop proper beam-loading kicks while simulating beam longitudinal transport in the ring with corresponding modulations from the dual-harmonic RF loop. The ring model is simplified by

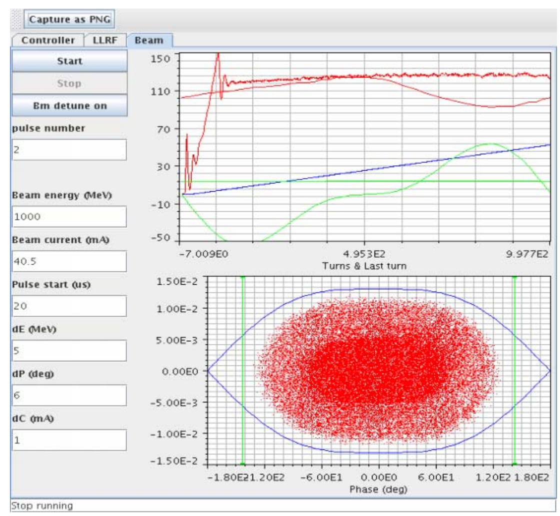
$$\begin{pmatrix}\theta\\ dE\end{pmatrix} = \begin{pmatrix} 1 & \dfrac{(\frac{1}{\gamma^2}-\frac{1}{\gamma_{tr}^{2}})\cdot C}{\beta^2\cdot mc^2} \\ \sum_h qV_h & 1\end{pmatrix}\cdot\begin{pmatrix}\theta_0\\ dE_0\end{pmatrix} \qquad (6)$$

where C is the ring circumference, β, and γ are particle relativistic parameters; γ_{tr} is the transition gamma; mc^2 is the total energy; q is the charge; and V_h is the complex voltage of each harmonic, which consists of the generator voltage and the beam-loading-induced voltage.

In the presented model, effects of the space charges and wakes in the ring generated by the high-intensity circulating beams are not included because their influences to the RF control are small and can be ignored in this study. Each turn is sliced into 128 bins in the simulations to analyze the RF performance and to meet the FFT requirement. Approximately 50,000 particles are simulated in each beam pulse for up to 1024 turns to quantitatively compute the beam bunch leakage and beam loss caused by any imperfection in the RF control. Figure 2 shows one of the simulations for dynamic detuning.



(a) Low-Level RF tab—RF voltage and phase



b) Beam tab—RF power and beam phase space

Figure 2: Preliminary simulation for dynamic detuning

In the preliminary model, an infinite bandwidth of the feedback loop and constant Q and R_s are assumed. Under that condition, dynamic detuning is a perfect AFF: voltage and phase are precisely controlled, RF power keeps almost constant during beam accumulations, and the extraction kicker has a clean gap. However, in further studies, the loop had a limited bandwidth, and the loaded Q of the ferrite-core cavity was reduced from 50 to 10 when the bias current was ramped up to detune the cavity by 200 kHz. The internal impedance of the tetrode also dropped in an RF pulse. When those elements were introduced into the model, the simulation results were no longer perfect. Figure 3 shows a loop with a bandwidth of 10 kHz. Figure 4 shows the Q and R_s variations in a pulse. In both cases, RF errors increased. Particularly, phase errors up to 10° due to variations of Q and R_s cause intolerable beam bunch leakages and losses in the SNS accelerator systems.

1-4244-0917-9/07/$25.00

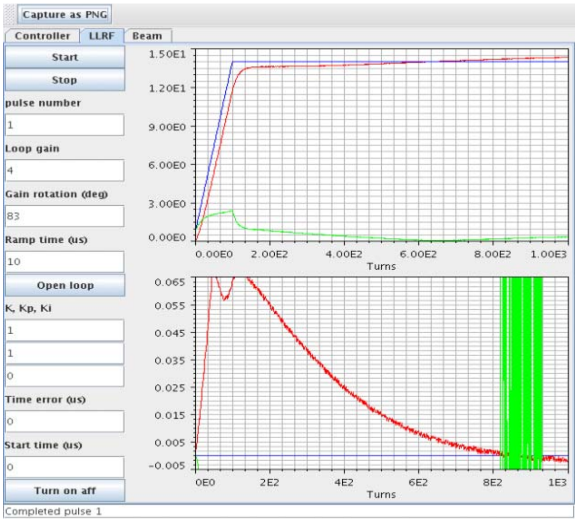


Figure 3: RF control with a loop bandwidth of 10 kHz

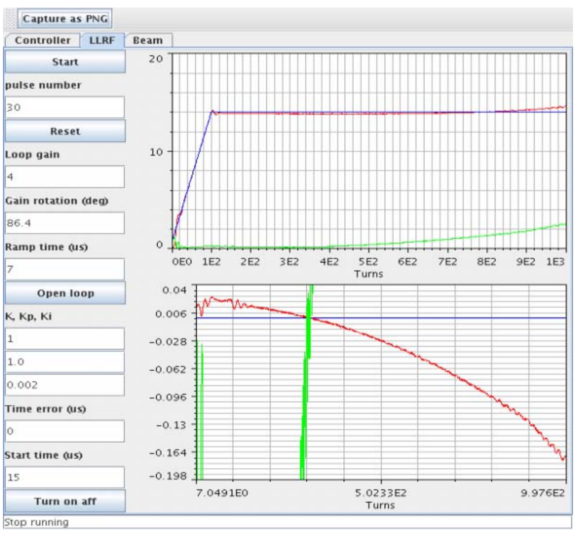


Figure 4: RF control for Q and Rs variations in a pulse

A simple algorithm for an RF system in a cavity heavily loaded with beams would be a feedback loop with a high gain. However, dynamic detuning may not be compatible with such a RF loop. Loop gain for dynamic detuning in the simulations is approximately 4, and the loop is not stable when Q and R_s vary. Dynamic detuning caused a large reduction of Q in an RF pulse and produced a ~2-kV voltage fluctuation per turn in each cavity (~14% of the cavity design voltage) for 1.4-MW beams. The voltage fluctuation caused beam distributions in the RF bucket to change significantly, although the voltage fluctuation alone did not obviously increase beam bunch leakage.

We studied other AFF algorithms with the simulation code, such as the SNS linac AFF. Although it worked for the linac, it helped little for the ring because the beam loading in the ring is much higher. In our simulations, a feedback loop only with a gain as high as 20 to 30, which needs a loop delay ≤ 0.95 μs, may stabilize the RF loop and may handle beam power up to 1.4 MW. However, it requires much more RF power than the dynamic detuning.

INITIAL BEAM TESTS

During the SNS beam commissioning, the initial test showed that the ring RF system could not handle heavy beam loadings, mainly due to the low loop gain. A lot of beam leaked into the extraction kicker gaps and were lost in the ring. Figure 5 shows one of the ring beam current monitor measurements against the simulations from the *rfsimulator* code. See Refs. [5, 6] for more information and for an update of the ring RF system studies.

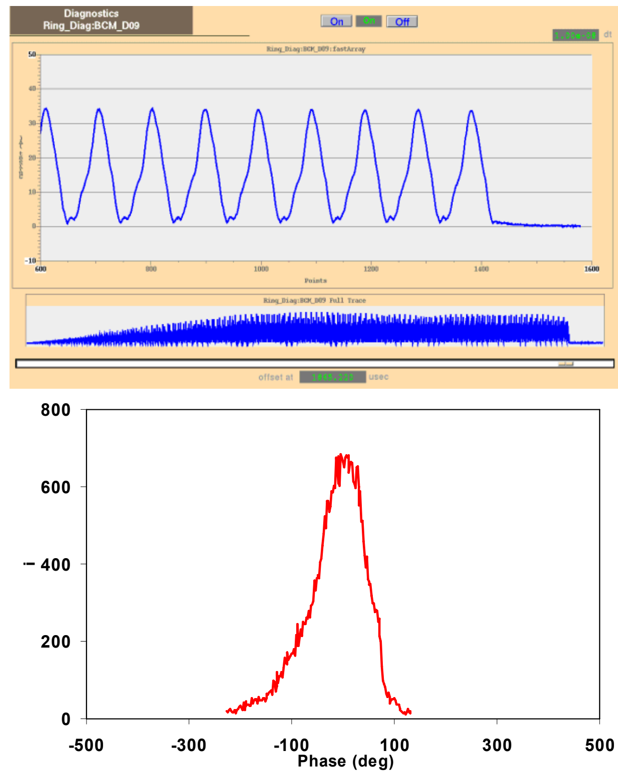


Figure 5: Beam measurement vs model simulation

CONCLUSION

A simulation code was developed to study the SNS ring RF system. It explains the failures in the initial beam tests and will be a helpful tool for future designs.

ACKNOWLEDGMENTS

The authors would like to thank J. D. Galambos, S. D. Henderson and J. Wei for useful discussions.

REFERENCES

[1] J. Wei et al., PRST-AB, **3**, 080101 (2000).
[2] M. Blaskiewicz et al., PAC 2001, 490.
[3] A. Zaltsman et al., EPAC 2002, 2202.
[4] W. T. Weng, S. Y. Zhang, EPAC 1998, 1136.
[5] T. Hardek et al., these proceedings.
[6] H. Ma et al., these proceedings.
[7] J. Tuckmantel, CERN-SL-Note-2000-053 HRF.
[8] S. Koscielniak, TRI-DN-97-12, TRIUMF Note.
[9] T. Czarski et al., TESLA Note 2003-06.
[10] H. Ma et al., PRST-AB, **9**, 032001 (2006).
[11] http://www.sns.gov/APGroup/appProg/appProg.htm

