SIMULATIONS OF RF ERRORS IN THE SNS SUPERCONDUCTING LINAC *

Y. Zhang and S. D. Henderson,
Spallation Neutron Source, ORNL, Oak Ridge, TN 37831, USA

Abstract

Minimizing beam emittance growth in the SNS superconducting linac due to RF errors, either correlated or uncorrelated, is essential since it can lead to beam loss in the linac and in the downstream accumulation ring. From multi-particle simulation studies of both matched and mismatched lattices, for the design peak beam current of 38 mA, as well as a typical commissioning beam current of 20 mA, we conclude that the linac may tolerate much higher non-correlated RF errors, especially in the second half of the SC linac, where errors in synchronous phase up to 10 degrees and that of cavity field amplitude up to 10% is acceptable. However, tolerance to correlated RF errors in the linac is within only 0.5 degree and 0.5%, from simulations using a simple linac model. Beam parameter measurement results acquired during the commissioning confirmed the simulations.

INTRODUCTION

The Spallation Neutron Source superconducting linac and accumulation ring was successfully commissioned [1 -3]. Maximum beam energy of the linac reached 950MeV with a peak beam current approximately 40mA. But in the initial beam commissioning runs, static RF setpoints of the superconducting linac did not reach the desired accuracy of synchronous phase ±1° and field amplitude ±1%, instead, static RF errors of a few degrees and a few percent were usual, presumably from calibration errors of relevant devices, noise and drifting of upstream cavities. However, beam transverse emittances measured in and at exit of the linac are preserved and beam losses in the linac are moderate. In this situation, studies are needed to understand the performances of the RF system for the full power beams and to improve linac tuning algorithm.

Besides static RF setpoint errors, dynamic RF errors also exist in a linac. Either phase or amplitude variations of a cavity in the proton linac will change the beam arrival time to all downstream cavities, and the correlations of dynamic RF errors in the linac is greatly concerned as it could cause more damaging. Appropriate tools are needed in the study of dynamic RF errors in the SC linac, such as the multi-particle tracking code IMPACT [4]. With an aid from a simple linac longitudinal model developed for the superconducting linac (SCL) [5], we also simulated dynamic RF errors with the PARMILA code [6].

SC LINAC MODELS

PARMILA code has been successfully bench marked with the SNS warm linac and used in the baseline SCL design. But because it does not include computation of the absolute phase for a SC cavity, it could not directly simulate dynamic RF errors in the SCL, which is different to the IMPACT code.

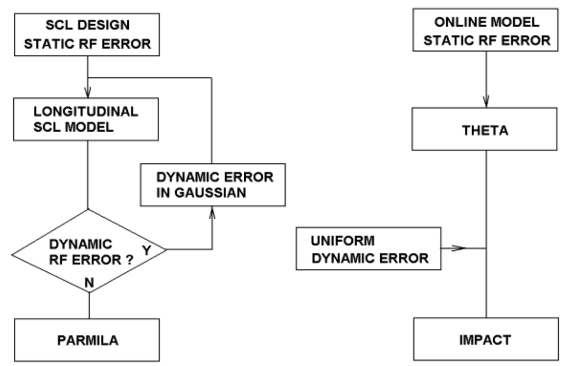

Figure 1: SC linac models built for simulation study.

Figure 1 shows the linac models built for this study. Dynamic RF errors are computed in the longitudinal SCL model developed in C++ and input into PARMILA for simulations. While IMPACT handles dynamic RF errors directly, we modified a python script provided by J. Qiang – one of the authors of IMPACT, to accept parameters of the real linac from the on-line model which is included in the XAL infrastructure [7]. Simulation of static RF errors is straight forward in both models.

STATIC RF ERRORS

Two cases are simulated: matched baseline SCL design lattice for 1 GeV and 38 mA beams with PARMILA, and a mismatched commissioning lattice (one of medium beta cavities turned off and field amplitude of several high beta cavities reduced by 10% without any re-matching) for 910 MeV and 20 mA beams with IMPACT. RF errors of the warm linac are not included in the simulation to save computational time.

Figure 2 shows beam emittances in both transverse and longitudinal planes with a standard linac error: static RF setpoints ±1° and ±1%, dynamic RF errors ±0.5°, ±0.5%, quadrupoles ±1%, from 1,000 PARMILA simulation runs. Normalized transverse emittances (x and y) are 0.31, and longitudinal emittance is 0.38 π·mm·mrad. Compared with the design of 0.5 π·mm·mrad, there is room for more static RF errors in SCL, especially for those downstream cavities where RF error influences beam energy but has little to do with beam quality. In PARMILA simulation, the maximum tolerable static RF setpoint errors of the SCL is 3° and 5%, which reasonably agrees with the

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simulation results of up to 30% random amplitude errors but with the correct synchronous phase [8].

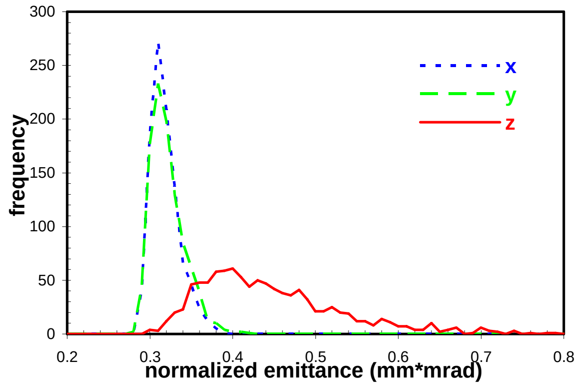

Figure 2: Output beam emittances with standard errors.

It will be helpful to know the tolerance of downstream cavity errors as some RF changes may not need to retune the entire linac, which is quite time consuming. So we assume that medium beta SCL has standard errors, while static RF errors in high beta section change. Figure 3 shows the results of beam emittances versus static RF errors in high beta cavities from PARMILA simulations. When errors near 12° and 12%, longitudinal emittance begins to increase rapidly. But up to 10° and 10%, static RF errors in high beta cavities are still acceptable.

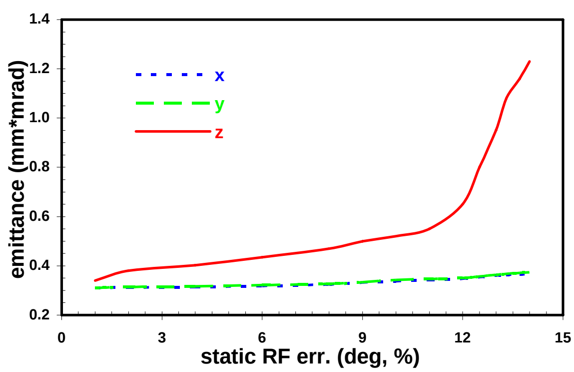

Figure 3: Beam emittances versus static RF errors in SCL high beta section.

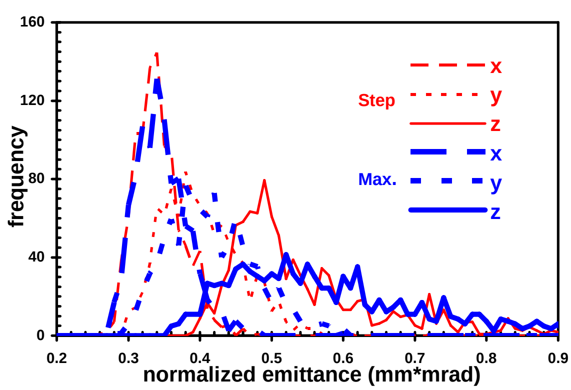

Figure 4: Beam emittances with the maximum acceptable static RF errors: 3° and 5% (Max.) and with the high beta cavity errors: 10° and 10% (Step).

IMPACT simulations of a mismatched SCL lattice for a typical commissioning case with beam energy 910 MeV, current 20 mA, and from 1,000 runs have a similar result, as shown in figure 4. In the slightly mismatched SCL lattice, the maximum acceptable static RF setpoint is close to 3° and 5%. The high beta section may up to 10° and 10%, which agrees with the PARMILA simulations for the matched lattice; uniform and Gaussian distributed RF errors are applied in the two models respectively. The result is important to the tuning as well as to the routine operation of the superconducting linac; e.g., a rough but fast linac tuning algorithm may apply in the high beta SCL. When amplitude of a few high beta cavities changed no more than 10%, and/or cavity phase is shifted up to several degrees in high beta SCL, it is not necessary to retune the SC linac so that beam availability maintains; though it may need to adjust the last cavity for a correct beam energy.

DYNAMIC RF ERRORS

Dynamic RF error in the linac plays a more important role in normal operations, and significantly influences beam losses in the downstream accumulation ring. Due to correlations of dynamic RF errors in a proton or a heavy ion linac, beam quality is more sensitive to dynamic RF errors at SNS. Figure 5 shows beam energy distributions for static RF errors of ±1°, ±1%, and for dynamic RF errors of ±1°, ±1%, each from simulations with the linac longitudinal model for 10,000 particles. Beam energy spread (or jitter) is approximately 1.3 MeV for the static RF errors, while the same amount of dynamic RF errors yield 2.4 MeV (rms) and nearly doubles.

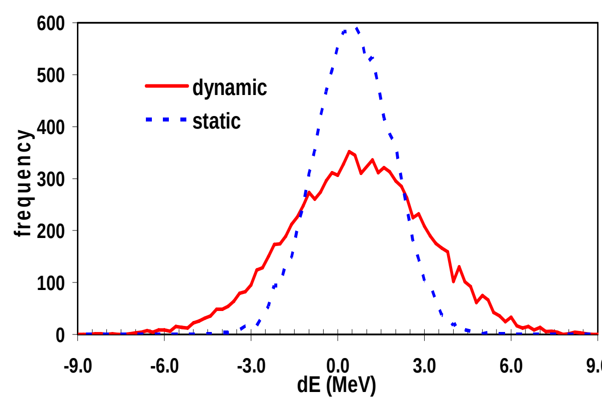

Figure 5: Beam energy jitters for dynamic RF errors and for static RF errors, both of ±1°and ±1%.

In the SNS accumulation ring, the maximum acceptable injection beam energy tails is no more than 5 MeV, and for linac beams, it is only approximately 4 MeV, because of the space charge effects and stripping foils used in the ring injection, beam energy spread still increases downstream of the linac. On the other hand, electron-proton instability (EP) is a critical obstacle in a high current proton ring like SNS, and beams with larger energy spread and less tails are needed to increase the threshold of EP instability, while at the same time, reduce beam losses and activations in the ring. Detuning the last linac cavity and making it an energy spreader cavity could produce the required large energy spread and meanwhile, not increase the beam tails too much [9]. However, it depends on the quality of linac beams; especially energy jitters.

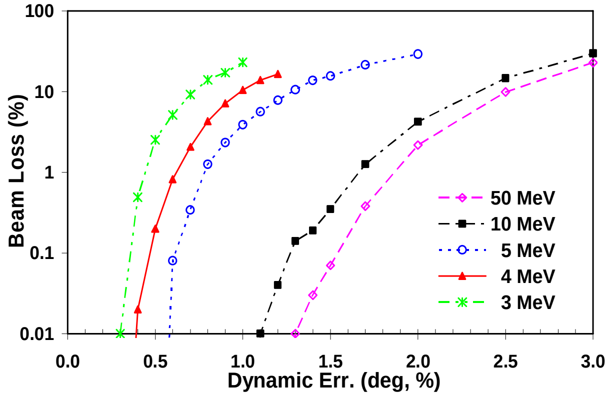

Figure 6: Beam loss in various energy tails depends on dynamic RF errors of the superconducting linac.

Figure 6 shows beam losses in different energy tails versus dynamic RF errors from simulations with the linac model. To keep the beam tails at a 10^{-3} level [10] for a maximum of 4 MeV, dynamic RF errors in the SC linac should not exceed ±0.5°and ±0.5%. This was achieved in the commissioning, with a measured stability of cavity phase and field amplitude ±0.5°and ±0.5% of all the linac cavities. However, it may not be enough for the SNS upgrade power of 3 MW.

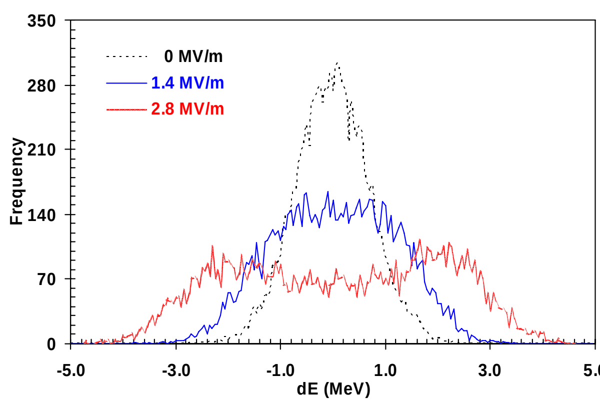

Figure 7: Beam energy distributions with the last cavity as an energy spreader, for dynamic RF errors of ±0.3° and ±0.3% in the superconducting linac.

From simulations for the SNS linac dynamic RF errors of ±0.5°and ±0.5%, to maintain a reasonable beam tails, amplitude of the last SC cavity, which detuned by several tens to a hundred kHz to serve as the energy spreader cavity, is limited to less than 0.5 MV/m, and is little help to EP instability. Much less dynamic RF error is required, e.g., ±0.2° and ±0.2%, but needs to improve the linac LLRF system and optimize each individual linac cavity. Figure 7 shows simulation results for dynamic RF errors of ±0.3° and ±0.3%, with the last linac cavity detuned and at different amplitudes. From 2~3MV/m modulations with the cavity, beam distributions changed significantly.

MEASURED BEAM PARAMETERS

In the 2005 commissioning, measured beam energy jitter was approximately 1.3 MeV, agrees with the model predicted of 1.2 MeV for dynamic RF errors of ±0.5° and ±0.5%. Static RF setpoint error was usually 2° to 3° and 5%, exceeded the design of ±1° and ±1%, presumably caused by drifting of the upstream cavity and calibration errors of relevant devices as the linac tuning algorithm is ±1° for each individual cavity. The measured beam transverse emittance both in and at the exit of the linac is usually 0.3 π·mm·mrad with a maximum measured value of 0.36 π·mm·mrad and agrees with the simulation results for static RF setpoint errors of ±3°and ±5% - 0.3 to 0.4 π·mm·mrad. In the simulations, longitudinal emittance is more sensitive to RF errors of the linac, which could be a better analysis for static and dynamic RF errors of the superconducting linac. But unfortunately, up until now, no longitudinal beam diagnostic instrument is available in the SNS superconducting linac.

CONCLUSIONS

In our simulation studies with numerical linac models, static and dynamic RF errors in the SNS superconducting linac were investigated. Dynamic RF errors may cause more damaging to the linac beam and to the accumulation ring due to correlations of the RF errors in the proton linac. Therefore, studies are needed to reduce the correlated RF errors in the linac and to improve the LLRF performance as well as to increase the linac beam quality for power upgrade.

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