

THE EFFECT OF DTL CAVITY FIELD ERRORS ON BEAM SPILL AT LANSCE*

L. J. Rybarczyk[†], R. C. McCrady, Los Alamos National Laboratory, Los Alamos, NM, 87545 USA

Abstract

The Los Alamos Neutron Science Center (LANSCE) accelerator comprises two (H⁺ and H⁻) 750-keV Cockcroft-Walton style injectors, a 201.25-MHz, 100-MeV drift-tube linac (DTL) and an 805-MHz, 800-MeV coupled-cavity linac (CCL). As part of the LANSCE Risk Mitigation project a new digital low-level radio frequency (LLRF) control system is being deployed across the linac, starting with the DTL. Related to this upgrade, a study was performed where specific cavity field errors were simultaneously introduced in all DTL tanks about the nominal stable, low-spill, production set points to mimic LLRF control errors. The impact of these errors on the resultant beam spill was quantified for the nominal 100 μ A, 800-MeV Lujan beam. We present the details of the measurement approach and results that show a rapid increase in total linac beam spill as DTL cavity field phase and amplitude errors are increased.

INTRODUCTION

The LANSCE facility employs a room temperature 800-MeV linac to produce both proton and H⁻ beams for several user programs. The linac consists of a 100-MeV, 201.25-MHz, four-tank DTL structure followed by a 800-MeV, 805 MHz, 44 module CCL structure. During normal operations, beam spill along the linac, proton storage ring (PSR) and beamlines to the target can be attributed to several factors, one of which is cavity field error. During normal operation, linac machine parameters are usually tweaked to achieve a stable, low-loss tune. These tweaks include adjustments to many of the linac RF phase and amplitude set points. Although these new set points result in relatively low beam spill during operations, cavity field errors can introduce deviations about these nominal values and may result in excursions in beam performance, including increased spill along the linac.

An effort is currently underway to upgrade the linac LLRF control system with a modern digital equivalent. The legacy analog system used along the linac has provided nominal amplitude and phase control estimated to be better than 0.1% and 0.1°, respectively, during the steady-state portion of a typical 625 μ s beam macropulse. During the beam turn-on transient, LLRF amplitude and phase errors typically exceed these values but remain below the fast-protect trip point of 1% and 1°, respectively. Although the new digital system is expected to achieve same or better performance, the question arose about the impact of larger control errors, i.e. cavity field errors, on beam spill during operations. The work reported here was

aimed at quantifying the beam spill associated with larger cavity field errors in the DTL.

EXPERIMENT DETAILS

The experiment was conducted on the LANSCE linac and beam lines that provide 800-MeV beam to PSR and the Lujan Center neutron spallation target. The “Lujan” beam, nominally 100 μ A with a duty factor of 20 Hz x 625 μ s, is “chopped” in the 750-keV low-energy beam transport (LEBT) to provide an extraction gap for the PSR. The chopping results in a typical beam “minipulse” with 290 ns out of 358 ns. During these measurements, we used the duty factor and the minipulse countdown, i.e. “1-of-n” to reduce the average beam current well below the 100 μ A in order to keep the beam on when spill was excessive and interruptions would have otherwise occurred. All results were renormalized to an average beam current of 100 μ A.

Beam current and loss monitors along the CCL and downstream beam lines were used to document the average current and spill levels, respectively. We also recorded the status of the beam fast-protect system to ensure that beam was uninterrupted during the measurements.

We used a simplified approach to introduce errors in the DTL cavity fields during these measurements, where the errors are static offsets in amplitude and phase from the nominal production set points. For the purpose of these measurements we assumed that the same LLRF controllers would simultaneously allow a distribution of errors with the same maximum magnitude in percent of amplitude and degrees of phase on all DTL modules, e.g. 0.5% and 0.5°, respectively. Initially, we used HPSim [1] to simulate beam spill along the CCL due to these types of DTL cavity field errors. In the model the linac was configured to approximate the linac operating at production levels. A typical set of simulations consisted of 1000 different combinations of random, uniformly distributed errors up to the maximum amplitude and phase, respectively on all DTL modules. The simulated beam losses were extracted from all runs so that rms and maximal values could be determined. From these data, we observed a correlation between the extreme beam loss and maximal cavity errors. Initially, we considered the above approach for the experiment, i.e. 1000 different error combinations. However, limited beam-development time and risk of failure to the existing mechanical phase-shifter packages led us to choose a different approach. Instead, we introduced only maximal static field errors in each DTL cavity as deviations about their nominal production set points. For each maximal static error a total of 2⁴ different combinations consisting of either same-sign (+, + or -, -) or opposite-sign (+, - or -, +) intra-tank (amplitude, phase) errors were applied to the DTL. Although limited

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[†] lrybarcyk@lanl.gov

in depth and detail, this approach still provides a measure of the sensitivity of the beam spill to cavity field errors.

Python and PyEpics scripts were used to perform the data acquisition and analysis of the experiment. This made it very easy to calculate and introduce the various error combinations into the DTL LLRF controls as well as record and analyze the various data sets in a systematic and repeatable fashion. Because of potential mechanical lash issues associated with setting the phase shifters, we always approached the new phase set point from the same direction.

RESULTS

The data collected were analyzed by area: CCL, Switchyard, beam transport to the PSR, PSR, and the beam transport to the Lujan target. *From each data set the error combination with the largest total spill was used to represent the worst case spill associated with the X% and X° error.* The results presented below use these worst-case values.

CCL

There are 88 CCL spill monitors, aka APs, located adjacent to quad doublets at the middle and end of each of the 44 modules. An example of the typical spill pattern observed during normal Lujan beam operations is shown in Fig. 1. The spill observed near the entrance to the CCL,

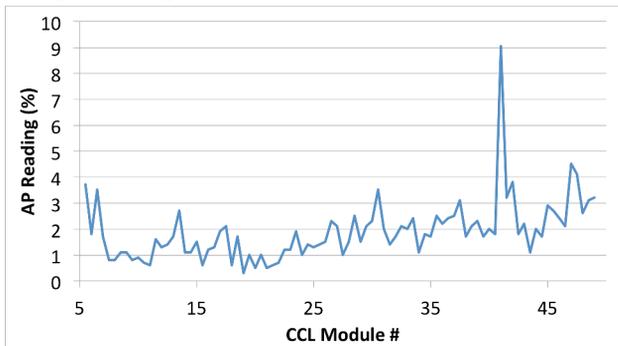


Figure 1: Usual Lujan beam spill pattern along the linac.

i.e. modules 5 and 6, is typically associated with mismatched/mis-steered beam, while a peak near module 15 is typically due to off-energy/uncaptured beam. The slow rise in spill with increasing module number is predominantly a result of intrabeam stripping losses [2]. Figure 2 shows the CCL spill monitor readings for the two cases of no additional errors and an additional 0.2% and 0.2° amplitude and phase errors, respectively. There is a noticeable increase in several of the spill monitors indicating sensitivity to even small DTL cavity field errors. The trend in the spill-monitor readings integrated over the CCL reveals a very strong dependency on DTL cavity field error for the same-sign error cases, whereas the opposite-sign error cases exhibit less sensitivity as shown in Fig. 3. This difference can be understood by looking at the differential energy change about design for a proton in a single DTL cell with regard to RF field amplitude and phase errors. Same-sign errors produce a deviation that moves the proton away from design energy.

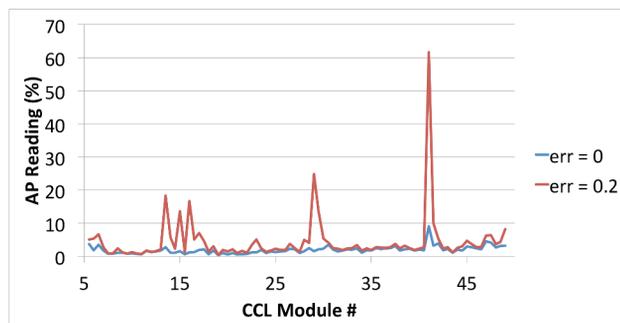


Figure 2: CCL spill monitors for baseline and 0.2%, 0.2° same-sign error cases.

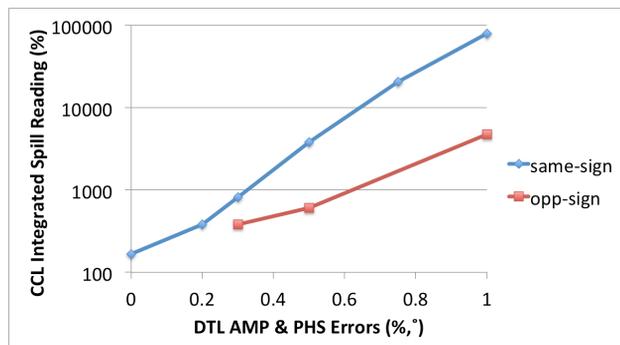


Figure 3: CCL integrated spill versus magnitude of DTL amplitude and phase errors for same- and opposite-sign combinations.

However, contributions from opposite-sign errors partially cancel each other resulting in smaller energy deviations for the same size errors. Since we are interested in the maximum spill, we will focus on the same-sign errors for the rest of this work.

Figure 4 shows the exponential-like response of several selected CCL AP's. That trend for six of the CCL AP's with the largest increase overall shows 3 to 4 orders of magnitude rise in beam spill when 1% and 1° errors to the amplitude and phase, respectively, were introduced.

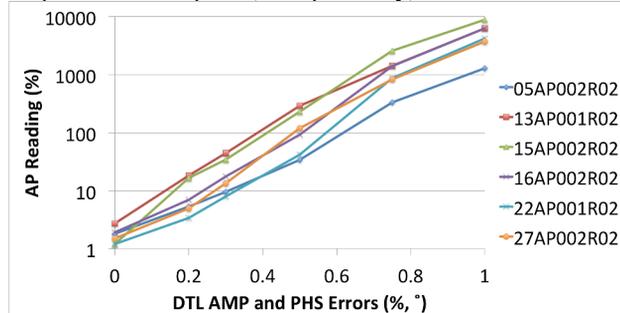


Figure 4: Selected individual CCL AP readings versus DTL amplitude and phase errors.

Switchyard

The beam Switchyard, located just beyond the CCL, is the area where the proton and H- beams are directed to the various user facilities. This is also a place where off-energy beams, between ~200 and 800 MeV that travel down the linac, fall out of the pipe and are lost. For these measurements we selected 13 spill monitors in this area to

represent the overall beam loss here. Many of these AP's also showed an exponential increase with DTL cavity field error. When compared to the baseline, the integrated Switchyard spill rises more rapidly than the integrated CCL spill as shown in Figure 5. This is likely due to more beam falling out of the "bucket" in the CCL as the magnitude of the errors increases and that those off-energy particles just coast down the linac and eventually dump out in the switchyard.

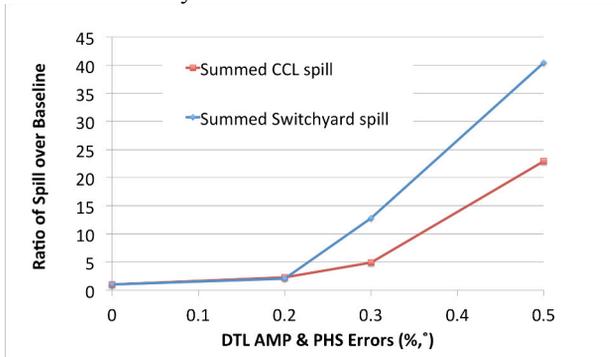


Figure 5: Ratio of beam spill with error to baseline for summed CCL spill and summed Switchyard spill.

PSR and high-energy beam transport lines

The remainder of the beamlines to the PSR and Lujan target saw increased losses with increased DTL cavity field errors. However, they were not as dramatic as the CCL and switchyard trends.

A few spill monitors in the large 89° arc following the switchyard dominated the collection of ten spill monitors in that area. The rest exhibited far lower increase in spill as shown in Figure 6.

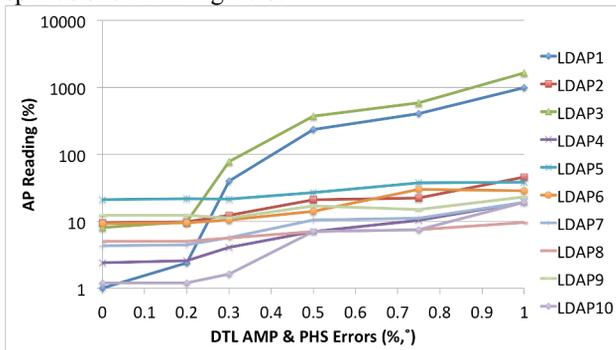


Figure 6: Beam spill in Line-D following Switchyard versus DTL cavity field errors.

The PSR beam loss is measured by summing all the loss monitors readings from around the ring. The fraction of beam lost grew by ~2.8 times the baseline as the DTL cavity fields amplitude and phase errors were raised to 1% and 1° as shown in Figure 7. The PSR appeared to be far less sensitive to these types of errors.

Finally, increases in beam spill along the beam transport from the PSR to the Lujan short-pulse spallation target, especially near the extraction region and around the 90° vertical bend to the target where observed. The integrated spill for this area is shown in Figure 8.

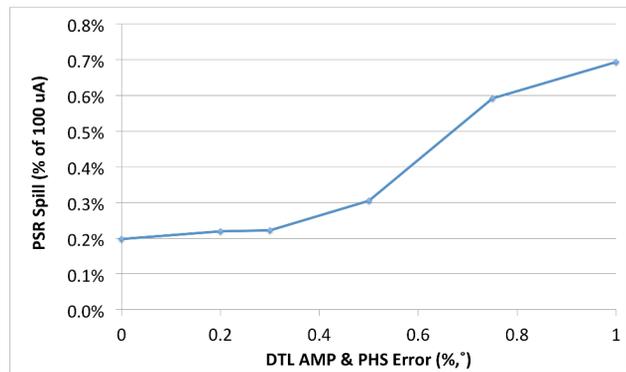


Figure 7: PSR beam loss versus DTL cavity field errors.

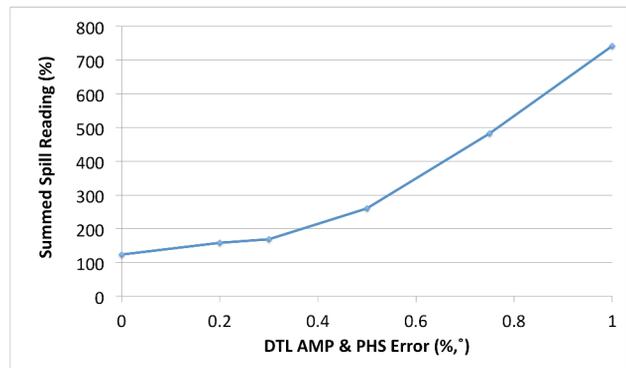


Figure 8: Beam loss versus DTL cavity field errors for beam transport from PSR to Lujan target.

CONCLUSIONS

The measurements performed have provided insight into the additional beam losses created by the Lujan beam at LANSCE when introducing DTL cavity field errors about nominal production set points. It is clear that the amount of Lujan beam spill in the LANSCE CCL and Switchyard areas is extremely sensitive to these errors while downstream areas are somewhat less sensitive. Extrapolating these results to LLRF performance requirements is difficult because of the lack of knowledge of the detailed distribution of control errors and associated spill. However, even small errors can increase the variability of pulse-to-pulse spill readings not seen in these time-integrated averages.

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