CHARACTERIZING AND CONTROLLING BEAM LOSSES AT THE LANSCE FACILITY*

L. Rybarcyk#, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

Abstract

The Los Alamos Neutron Science Center (LANSCE) currently provides 100-MeV H^+ and 800-MeV H^- beams to several user facilities that have distinct beam requirements, e.g. intensity, micropulse pattern, duty factor, etc. Minimizing beam loss is critical to achieving good performance and reliable operation, but can be challenging in the context of simultaneous multi-beam delivery. This presentation will discuss various aspects related to the observation, characterization and minimization of beam loss associated with normal production beam operations in the linac.

INTRODUCTION

LANSCE is a multi-user, multi-beam facility that produces intense sources of pulsed, spallation neutrons and proton beams in support of US national security and civilian research. It comprises a pulsed 800-MeV room temperature linear accelerator and 800-MeV proton storage ring and has been in operation for over 37 years. It first achieved 800-MeV beam on June 9, 1972. The facility, formerly known as LAMPF, routinely provided an 800 kW beam for the meson physics program. Presently, the LANSCE user facilities include:

- Lujan, which uses the proton storage ring (PSR) to create an intense, time-compressed proton pulse that is used to produce a short pulse of moderated (spallation) neutrons (meV to keV range),
- Proton Radiography (pRad), which provides high resolution, time-sequenced radiographs of dynamics phenomena,
- Weapons Neutron Research (WNR) that provides a source of unmoderated (spallation) neutrons in the keV to multiple MeV range,
- Isotope Production (IPF), which is a source of research and medical isotopes for the US, and
- Ultra-Cold Neutrons (UCN), which is a source of sub-μeV neutrons for fundamental physics research.

A list of beam parameters for present day operation is shown in Table 1.

ACCELERATOR

The accelerator consists of separate proton (H^+) and H^- Cockcroft-Walton based injectors that produce 750-keV beams for injection into the drift tube linac (DTL). Each low energy beam transport (LEBT) contains magnetic quadrupoles for transverse focusing, a single-gap 201.25-MHz buncher cavity for initial bunching of the beam, and

Table 1: Typical Parameters for LANSCE Linac Beams Note: All beams are 800 MeV, H^- except for IPF, which is 100 MeV, H^+.

Area	Rep Rate [Hz]	Pulse Length [μs]	Chopping pattern	Iavg [μA]	Pavg [kw]
Lujan	20	625	290ns/358ns	100-125	80-100
pRad	~1	625	60 ns bursts every ~1 μs	< 1	< 1
WNR (Tgt4)	40	625	1 μ–pulse every ~ 1.8 μs	≤2	~ 1.6
UCN	20	625	Lujan-like to none	< 5	< 4
IPF	≤30 in pulsed mode	625	NA	230	23

an electrostatic deflector for "gating" beam into the linac or inhibiting beam when a fault condition occurs. The H^- LEBT also contains a 16.77-MHz buncher for producing single, high-charge, micropulses and a slow-wave beam chopper for modulating the intensity of the beams. The H^+ and H^- beams are merged in a common LEBT that contains a single 201.25-MHz buncher cavity, aka main buncher, which performs the majority of the bunching for the standard linac beams and four quadrupole magnets to achieve the final match into the linac.

The 100-MeV DTL is an Alvarez style 201.25-MHz linac comprised of four independently powered tanks for a total length of 61.7 m. The tanks contain electromagnetic quadrupoles in a FODO lattice. At the beginning of tank 3, the lattice transitions to a quad magnet in every other drift tube.

Following the DTL is a 100-MeV beam transport, aka the Transition Region (TR), which consists of separate paths (chicanes) for the two beam species, that allows for independent matching, steering and phasing of the H^+ and H^- beams into the subsequent structure. The split nature of this transport is required in order to have the flexibility necessary to simultaneously achieve proper phasing of both beams into the next linac. The H^+ segment of the TR also contains a kicker magnet for extracting 100-MeV beam to IPF. Since there are currently no users of 800-MeV H^+ beam, this magnet is operated in DC mode.

Following the TR is the 805-MHz coupled-cavity linac (CCL) that accelerates beams up to 800 MeV. It consists of 44 independently powered modules, which have either two or four tanks, for a total length of 727 m. Each tank

*Work supported by DOE under contract DE-AC52-06NA25396.
#lrybarcyk@lanl.gov

ISBN 978-3-95450-118-2

consists of a large number of identical accelerating and side-mounted coupling cells. The magnetic quadrupole doublets, which are located between tanks, are arrayed in a FDO lattice. A transition occurs in the lattice at module 13 (211 MeV) where the period doubles. Beam steering magnets are located in LEBT, TR and post-linac beam transports.

Immediately following the linac is a beam switchyard that employs DC magnets to separate the H^+ and H^- beams. During some macropulses, pulsed kicker magnets are used to direct H^- beam to the pRad or UCN facilities. Otherwise, the H^- beam pulses are directed toward the PSR and Lujan or WNR facilities.

Except for devices in the LEBTs, dedicated collimators are not used at the LANSCE facility. The LEBT collimators consist of sets of movable "jaws" and selectable fixed-size circular apertures. The jaws are used for scraping tails, beam-intensity reduction and as chopping apertures, while the circular apertures are used in several locations to prevent direct beam impingement on buncher-cavity noses, slow-wave chopper helices and as chopping apertures.

BEAM LOSS OBSERVATIONS AND CHARACTERIZATION

This paper will focus predominantly on the highest power beam presently in operation at LANSCE, the 80 kW Lujan Center beam, although some WNR and high-power H^+ data from present and past operation are used for comparison. Data presented are representative of typical high-power operation.

Beam Loss Measurements

There are three different beam-loss measurement devices in use at LANSCE. The hardware transmission monitor (HWTM) system is based upon precise beam current measurements between successive locations. This system has a 0.1µA resolution for 1000 µA current and is more suited to estimating moderate to large losses, those that occur during the capture stage or when a beamline device malfunctions.

The other two devices are beam spill monitors that detect radiation produced when beam particles strike the accelerator or beamline structures. LANSCE employs both liquid scintillator and ionization chamber type devices. Each pint can of liquid scintillator is viewed by a photo-multiplier tube and is coupled to electronics to provide both instantaneous loss levels and values averaged over macropulses associated with a particular beam. They are fast enough to provide the time variation of beam loss across a macropulse and serve as input to the machine "fast" protection system. They are used throughout the facility. The other type of device is an ion chamber that contains 160 cm^3 of N_2 gas at 1 std. atm. The ion chambers are coupled to electronics to provide average beam loss but are also capable of generating a trip within a few µs of a large loss of beam. These devices are distributed in most of the high-energy beam lines and in the PSR, since they are well suited for measuring spill associated with the high-intensity, narrow pulse generated therein. They are used both as input to the machine protection system and to the radiation safety system.

LEBT and Beam Formation

For the LANSCE linac, beam losses therein are intimately related to beam formation in the LEBT. Both H^+ and H^- utilize a two-buncher scheme to transform the DC beams from the Cockcroft-Walton injectors into partially bunched beams for injection into the DTL. It is the partially bunched beam that results in increased losses and operational set points that deviate significantly from design.

DTL Losses

Only a fraction of the partially bunched beam injected into the DTL is captured and accelerated to 100 MeV. Typical capture for the well-tuned beam is 80 to 82%. The beam that is not captured remains at low energy (~750 keV) until it strikes the drift tubes in tanks 1 and 2 and is lost. This beam loss amounts to a few 10's of Watts for the Lujan beam. Much smaller beam loss occurs at the higher energy end of the DTL, as evidenced by small levels of radio-activation of the structure. The magnitude of this spill is less than the combined loss of 0.2%, which includes the region from the middle of the DTL (40 MeV) to the 211 MeV point in the CCL (module 12).

During simultaneous IPF(H^+)/WNR(H^-) operation, the LEBT main buncher is typically adjusted to improve capture (from approx. 30 to 40%) for the few µA WNR micropulse beam at the expense of the 230 µA IPF beam capture (from 80 to 72%). Any further reduction in IPF capture also results in rapidly increasing high-energy beam losses for the IPF beam.

TR Losses

Beam losses in the TR arise from low energy and transverse tails on the beam. Furthermore, the H- beam also experiences additional losses as seen in Fig. 1. Comparing average losses normalize to average current for the IPF(H^+) and Lujan(H^-) beams, one sees the H^+ spills near two large bends in the transport (TRAP1 &

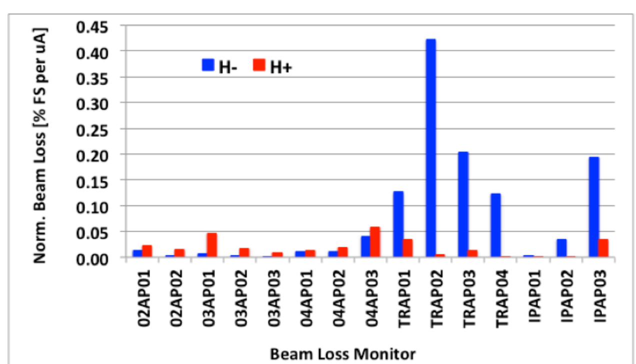

Figure 1: Comparison of H^- and H^+ average beam losses normalized to current in the vicinity of the TR.

ISBN 978-3-95450-118-2

IPAP3), where H^- spill appears on both the H^- and H^+ sides of the TR (TRAP1-4, IPAP2&3). Since the magnetic chicane precludes H^- from reaching IPAP1-3, this suggests that H^- stripping occurs and is responsible for additional spill observed in the TR and IPF transports during an H^- beam pulse. The magnitude of the overall spill in the TR is not well determined, due to the complicated geometry, but is within the 0.2% regional loss mentioned above.

Species Independent CCL Losses

The beam loss profile in the CCL has distinct features. Localized and higher than average spill is observed for both H^+ and H^- beams at the lattice transitions. Near the entrance to the CCL, beam spill is attributed to transverse mismatch, while at M13 where the quad spacing doubles, the spill also arises from off-energy beam. These observations are reproduced for both species with multiparticle simulations [1]. Fractional loss between modules 3 and 12 is estimated to be <0.2%. Assuming 100 MeV, this would correspond to a few 10's of W.

Additional H^- Losses in the CCL

The last feature in the CCL beam loss profile however, is only present for H^- beam and is shown in Fig. 2. The increasing H^- loss signal along the linac is attributed to stripping of an electron(s) from an H^- ion, which is subsequently lost. To understand the source and magnitude of this contribution, an analysis was performed considering residual gas (RG), intra-beam (IB) and Lorentz field stripping contributions [2].

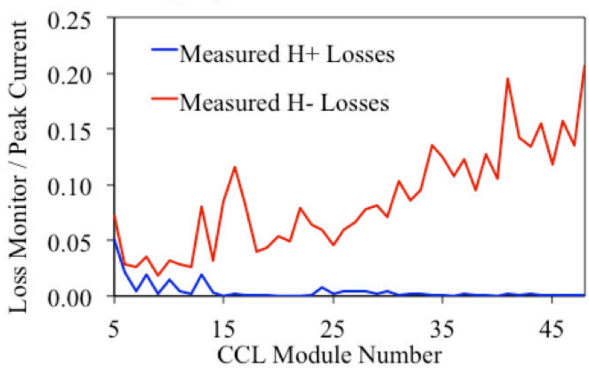

Figure 2: Measured loss monitor signals normalized to peak current for H^+ (blue) and H^- (red) beams accelerated to 800 MeV in the CCL.

Residual gas stripping arises from H^- ions that scatter off the background gas atoms within the evacuated structure. For the purpose of the analysis, a single representative average pressure of 1×10^{-7} T was used throughout the CCL. It was based upon a limited number of pressure readings along the structure and a residual gas analysis for composition. Integrating the fractional loss per meter, which is proportional to the energy dependent cross-section and the residual gas density, produced a total fractional loss from RG stripping of $\sim2.1\times10^{-4}$.

Intra-beam stripping can result from collisions between H^- ions within a bunch. Unlike the residual gas stripping, the fractional loss rate for intra-beam stripping depends upon the particle density within the bunch. Employing the results of the work by V. Lebedev *et al*. [3] for the fractional loss due to IB stripping, and utilizing a beam envelope calculation for the beam size and divergence information along the linac, the integrated fraction loss is estimated to be $\sim1.6\times10^{-4}$, which is comparable to the RG stripping.

Lorentz-field stripping is a relativistic and quantum mechanical effect. It can be ignored for the Lujan beam in this energy range as the integrated fractional loss for a typical LANSCE linac beam was estimated to be $<10^{-8}$.

The simulated particle loss profiles based upon RG and IB stripping were individually transformed into corresponding spill monitor readings using the results of a series of MCNPX [4] radiation transport model calculations. For each spill monitor, a distribution was generated of charged-particle energy deposited vs. location of the lost proton along the linac. In the model the CCL was represented as a solid copper cylinder with a diameter chosen to preserve the mass per unit length. The tunnel was included with 30 cm thick concrete walls. A proton was started on axis at design energy for the z location. For convenience, each distribution was fit with a three-parameter Lorentzian line-shape. Finally, for each beam spill monitor, this response function was folded with each particle loss profile over distances of ±20 m to produce the simulated loss monitor profiles.

The relative contribution to beam losses from RG and IB stripping was estimated by comparing simulated and measured losses for different final energy beams and applying overall scale factors to reproduce measured spill profiles. For final energies below 800 MeV, where the beam coasts to the end of the linac after the last accelerating module, the RG and IB stripping mechanisms behave differently. Whereas RG stripping rates remain constant once the beam energy stops changing, the IB stripping rate drops quickly as the beam bunch length increases and the H^- ion density decreases. A comparison of measured and simulated loss for two final energy H^- beams is shown in Fig. 3. Based upon this analysis for the nominal Lujan beam, the total fractional loss in the CCL from the stripped beam contributions is $\sim4\times10^{-4}$. By combining the loss particle rates and energies for the Lujan production beam, the average stripped-beam power deposited along the CCL is estimated to be a few 10's of mW/m.

800 MeV Protons from Stripped H Linac Beam

An experiment [5] was performed that showed some H^- ions lose both electrons and appear as protons at 800 MeV. This was motivated by a proposed physics experiment that would use the 800-MeV H^+ beam. The experiment is sensitive to background beams, one source of which could be 800-MeV protons originating from an H^- beam pulse. This background beam measurement used a sensitive image plate detector located in a post-linac 800-MeV H^+ chicane to quantify the fraction of H^+ reaching that location during an H^- beam pulse. The CCL-

ISBN 978-3-95450-118-2

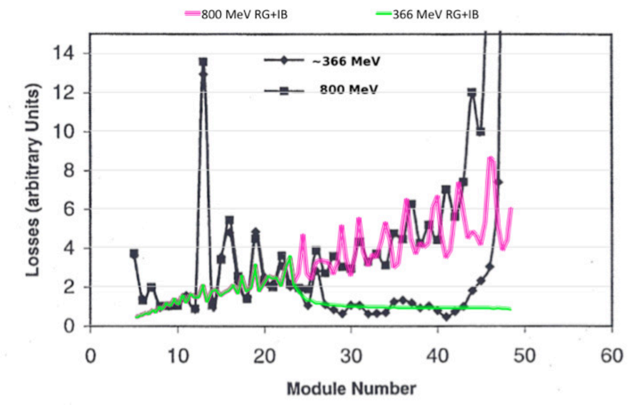

Figure 3: Comparison of measured (black) and simulated beam loss profiles for 800 (pink) and 366 (green) MeV H^- beams.

only loss fraction, which likely only comes from stripping in the high-energy end of the CCL was 0.38×10^{-6}. The total linac loss fraction starting from the common 750-keV LEBT, where a vacuum issue at the time of the measurement resulted in 10x higher background pressure, was measured to be 9.2×10^{-6}. To reach 800 MeV, the phasing requirements dictate that the source of the stripped H^- is likely to be the common LEBT. Under normal operating pressures of 10^{-7} T, this two-step RG stripping process would drop below the CCL only estimate, so the total loss fraction would be $\sim0.4\times10^{-6}$.

BEAM LOSS CONTROL

LANSCE is a mature facility with a long history of high-power beam delivery. The operation of the linac has evolved over time to a production tune with relatively low beam losses (excluding initial DTL capture). This has been accomplished mostly through empirical tweaking on various machine parameters. Compared to design the most significant changes occurred with the DTL cavity fields. The DTL quadrupole magnets are generally maintained at their design values, with the exception of the last few, which are used to enhance the matching of beam from the DTL to the TR. Most CCL quadrupole magnets also tend to follow the design with small, non-systematic variations from year to year. However, several located at the upstream end, which are used to enhance the match from the TR to CCL, and again at the transition in the CCL quad lattice, deviate from design by up to ~15%. These changes were arrived at through empirical tweaking and not by any matching algorithm.

DTL Operational Changes and Benefits

One of the biggest changes made in the way the linac is operated occurred many years ago. During the LAMPF era, it was recognized that operating the DTL at design cavity field settings would not result in low-loss operation for the high power beam. The accelerator operators found that it was necessary to undo the DTL "physics tune" in order to achieve a low-loss operation. Analysis of post-production DTL phase-scan data revealed the DTL cavity fields to be at reduced amplitudes. The results of the analysis on that particular data set indicated that at that time tanks 1 – 4 were operated at approximately 98, 96, 94 and 98% of design, respectively. Subsequently, the tune-up procedure was modified to make the post physics-tune DTL cavity fields closer to low-loss production values.

The benefit of these operational changes has been consistently lower beam spill along the linac and in the switchyard (from low momentum tails). However, the reasons behind it are not apparent. With a lack of experimental data to indicate the source of this benefit, multiparticle beam dynamics simulations have been used to evaluate the beam performance under design and production-like conditions, i.e. reduced DTL amplitudes, to see what, if any, improvements result. The results showed that the simulated "production" beam at the entrance to the CCL has better qualities. The rms longitudinal emittance is smaller by 23%, while the energy and phase spread of the beam are smaller by 25 and 21%, respectively. A slight improvement was also seen in the number of off-energy particles exiting the DTL. These simulated distributions are shown in Fig. 4. Qualitatively, a smaller emittance beam should more easily fit into the acceptance and result in lower losses, which is what is observed.

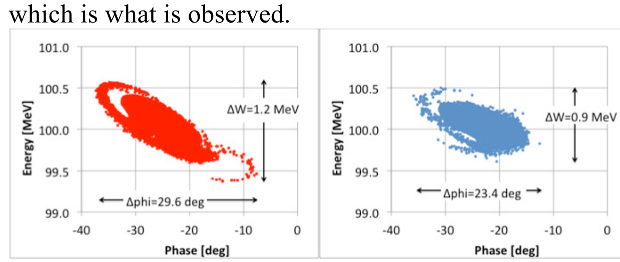

Figure 4: Comparison of simulated 100 MeV H^- beam at entrance to CCL. The result for DTL at design set points (left panel) shows a larger beam longitudinally than with the DTL at production set points (right panel).

High Performance Simulator as a Virtual Diagnostic

One way to work towards better control of losses is to develop a better understanding of the beam evolution in the linac. For example, many combinations of a DTL tank's RF field phase and amplitude set points will produce the same energy gain but different longitudinal acceptance and transverse RF defocusing, which affects the beam distribution, including size, tails, etc., as alluded to above. At present, our detailed knowledge of the beam in a production setting is limited. Machine parameters are tweaked to reduce spill, without knowledge of the impact these changes have on the beam distribution along the linac. Since the DTL input distribution is not completely bunched, an envelope model is insufficient to properly represent the beam formation and evolution. Bridging the gap between the low-power physics tune and the high-power production tune is presently accomplished with

ISBN 978-3-95450-118-2

poorly understood changes to machine parameters. A more satisfying approach would be to incorporate more relevant information into the process.

Although several different options may provide the pertinent information to some degree, a high-performance, pseudo real-time, multi-particle tracking simulator could serve as a "virtual' beam diagnostic during production operations and lead to better control of beam losses. Information from real beam diagnostics is desired but these devices are typically expensive, may be incompatible with production beam operation and provide only limited information. Offline analysis can provide a wealth of information, but due to the slow response is not valuable in a real-time control-room environment where rapid feedback is vital. However, a high-performance multi-particle beam dynamics simulator that contains the necessary physics and communicates with the accelerator control system could provide continuous, realistic simulations of the beam evolution in the linac and therefore lead to valuable insight into operational changes that improve beam performance.

Currently under development at LANSCE is just such a simulator [6]. The core of the simulator is based upon the PARMILA [7] code developed at Los Alamos to design and simulate ion linacs. The new code is implemented in C++ using NVIDIA's CUDA [8] technology for Graphics Processing Units (GPU). This technology provides a low cost solution (~$1k/card) to achieving a substantial speedup (~50x) required for this virtual diagnostic to be useful.

The linac layout is based upon a design created with PARMILA, but updated to reflect the as-built conditions. Real-time linac set points obtained through the EPICS control system are converted via an SQL database into model parameters that are used directly by the simulation engine. The simulation runs in a continuous loop with results presented graphically using OpenGL. A demo of the LANSCE DTL was performed with a GTX580 GPU (<$1K) containing 512 cores and 3GB of global memory. A screen shot of the simulation, which loops every ~2 sec. for 32k macroparticles is shown in Fig. 5.

SUMMARY

LANSCE provides pulsed proton and neutron beams to several user facilities whose missions include defense applications, isotope production and research in basic and applied science. Presently, the H^- and H^+ beams range in power from power from <1 to ~100 kW with varying pulse formats tailored to meet experiment requirements.

Beam losses along the linac arise from a number of sources. The DTL capture losses arise from injection of an incomplete bunch. Losses are observed near all transitions in the quadrupole lattice of the linac. H^- stripping losses are observed in the TR, CCL and SY areas.

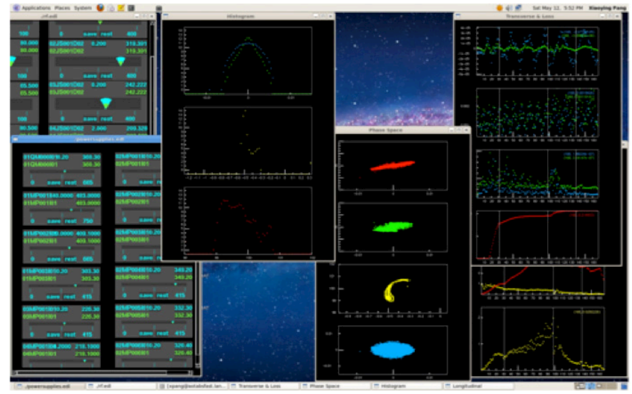

Figure 5. EPICS control sliders (left) and simulation output that includes profile, phase space, centroid, size, emittance and loss plots.

The most significant reduction in beam losses was the result of operating the DTL cavity fields away from the design values. This allowed the former 800 kW and subsequent 100 kW beams to operate with acceptable losses.

A virtual beam diagnostic in the form of a pseudo real time, high-performance tracking simulator could prove invaluable in understanding and controlling beam losses in high power linacs.

ACKNOWLEDGEMENTS

The author would like to acknowledge the following LANL staff whose work in include in this presentation: Frank Merrill, Charles Kelsey IV, Rodney McCrady, Xiaoying Pang and Scott Bailey.

REFERENCES

[1] F. Merrill and L. Rybarcyk, "Beam Dynamics Simulations of the LANSCE Linac," Proceedings of Linac98, pp. 839-841.

[2] L. Rybarcyk *et al.*, "H- Beam Loss and Evidence for Intrabeam Stripping in the LANSCE Linac," Proceedings of IPAC2012, pp. 3892-3894.

[3] V. Lebedev *et al.*, "Intrabeam Stripping in H- Linacs," Proceedings of the LINAC2010, pp. 929-931.

[4] D. B. Pelowitz, editor, "MCNPX User's Manual Version 2.6.0," Manual LA-CP-07-1473, Los Alamos National Laboratory, April 2008.

[5] R. C. McCrady *et al.*, "Stripping of H- Beams by Residual Gas in the Linac at the Los Alamos Neutron Science Center," Proceedings of Linac2010, pp. 908-910.

[6] X. Pang *et al.*, "High-performance Beam Simulator for the LANSCE Linac," Proceedings of IPAC2012, pp. 103-105.

[7] H. Tadeda, J. Billen, "*PARMILA*," LANL publication, LA-UR- 98-4478, 2005.

[8] NVIDIA, "*NVIDIA CUDA C Programming Guide," Version 4.0*, 2011.

ISBN 978-3-95450-118-2