HIGH POWER OPERATIONAL EXPERIENCE WITH THE LANSCE LINAC*

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Abstract

The heart of the Los Alamos Neutron Science Center (LANSCE) is a pulsed linear accelerator that is used to simultaneously provide H+ and H- beams to several user facilities. This accelerator contains two Cockcroft-Walton style injectors, a 100-MeV drift tube linac and an 800-MeV coupled cavity linac. This presentation will touch on various aspects of the high power operation including performance, tune-up strategy, beam losses and machine protection.

INTRODUCTION TO LANSCE

LANSCE is a multi-beam, multi-user facility that produces intense sources of pulsed, spallation neutron and proton beams in support of national security and civilian research. LANSCE is comprised of a pulsed, high-power 800-MeV proton linear accelerator (linac) and a proton storage ring and has been in operation for over 30 years. The facility, previously known as LAMPF, provided an 800 kW beam for the meson physics program. Presently, the LANSCE user facilities include:

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

The heart of the facility is a pulsed linear accelerator which operates at a repetition rate of 120 Hz. The H+ and H- beams are created and then accelerated up to 750 keV using Cockcroft-Walton technology. The H- 750 keV transport also contains a beam chopper to impress the requisite intensity modulation upon the various beams therein. Both H+ and H- beams share a common transport prior to injection into the drift tube linac (DTL). This transport includes a single gap buncher and four quadrupole magnets.

The beams are accelerated up to 100 MeV with an DTL. The 201.25 MHz DTL is comprised of four tanks that are powered by separate amplifiers. Tranverse focusing is provided by electromagnetic quadrupoles located inside the drift tubes and arranged in a FODO lattice. Following the DTL is a 100 MeV beam transport system, the transition region (TR), that allows independent matching, steering and phasing of both H+ and H- beams into the coupled cavity linac (CCL). It also contains a kicker magnet in the H+ section which allows beam to be delivered to IPF at any repetition rate in DC mode or up to 30 Hz in pulsed mode. The 800 MeV CCL is comprised of 44 modules. Each module consists of either two or four tanks that are powered by a single klystron. Transverse focusing is provided by quadrupole doublets arranged in a FDO lattice. Following the CCL, the linac beams are separated using a combination of DC and pulsed magnets and directed to their respective facilities, i.e. pRad, WNR, UCN, or the PSR to produced the short, high-intensity pulses for Lujan. Presently, LANSCE does not produce the 800 MeV, 1 mA high power H+ beam. Table 1 contains a summary of the typical beams parameters for the various user facilities presently in operation.

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]**
pRad	~1	300	60 ns bursts every ~1 μs	< 1	< 1
WNR (Tgt4)	100	625	1 μpulse every ~ 1.8 μs	5	~ 4
Lujan	20	625	290ns/358ns	100-125	80-100
UCN	20	525	Lujan-like to none	< 2	< 1.6
IPF	30 in pulsed mode	625	NA	250	25

LINAC OPERATIONS

The LANSCE linac first reached 800 MeV operation on June 9, 1972. It took approximately 10 more years to reach 1 mA average current at 800 MeV. Since the mid-1990's the facility's mission has evolved from predominantly one of nuclear physics to one of neutron science.

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Performance

The linac has historically operated at 120 Hz with a beam macropulse length of 625 µs, which results in a beam duty factor of 7.5%. Typical H+ peak current was 16.5 mA. This required the linac rf to operate at ~10% duty factor. Both H+ and H- beam operation can occur during the same rf cycle so long as rf power is adequate to accelerate the full beam load. This aspect has been exploited to increase the utilization of the linac duty factor.

Present day operation has been limited to 60 Hz due to recent performance shortcoming of the 7835 power triode which is used in the final power amplifier for the DTL. Typically, the peak beam currents within a macropulse are ~13 mA. Occasionally, it becomes necessary to run extended beam gates, up to 1225 µs, at low repetition rate for pRad or PSR studies.

In addition, a number of beam and machine development activities have taken place over the years that have demonstrated various increased capabilities of the linac, such as higher duty factor or peak and average current operation. One such test was a development related to developing a long-pulse spallation source at LANSCE. During this demonstration [1] the linac delivered a 21 mA peak, 315 µA average current beam at 800 MeV to Area A for ~12 hours. Beam reliability was over 88% and linac beam losses were higher than usual but acceptable.

Operating Schedule

The CY2008 schedule is representative of operations in recent years. This year began with extended maintenance through May 5th. At that time facility start-up/turn-on began and lasted for approximately one month. Following start-up is production beam operation which is divided into six blocks containing an average of ~24 contiguous days of beam to the user facilities. This time also includes "sole-use" time, which precludes one or more facilities from receiving beam due to particular operating mode, e.g. PSR to WNR. Between any two blocks of production beam is a maintenance period which in typically preceded by 1-2 days of beam/machine development. The maintenance activities include an H- ion source recycle. The average time between blocks of production beam in 2008 is ~11 days. Extended maintenance is scheduled to begin around mid-December.

Beam Reliability

During production operation beam reliability (hours-delivered divided by hours-scheduled) is carefully tracked for each user facility. A semi-automated logging system is used to keep track of beam-off events and their durations, with a resolution of 1 minute. Operations personnel provide area and system assignments to those downtime events. The data are then post-processed on a daily basis using automated routines to produce the detailed summary of beam and system downtimes.

The Lujan beam is presently the highest power beam with the most complex beam delivery system, i.e. linac plus PSR plus target, at LANSCE. In CY2007 the Lujan beam reliability was 81.2% which covers a total of 3255 hours of scheduled operation. During this same time the linac reliability was 93.4%. Figure 1 shows the percent of Lujan beam downtime attributed to each system for CY2007 operations. DC magnets and the Lujan target were the most significant sources of beam downtime.

The frequency of beam trips of various durations is also informative. For the Lujan beam in CY2007 the average number of beam trips per day with a duration greater than 1 minute, 1 hour and 3 hours was 5.3, 0.64 and 0.20, respectively.

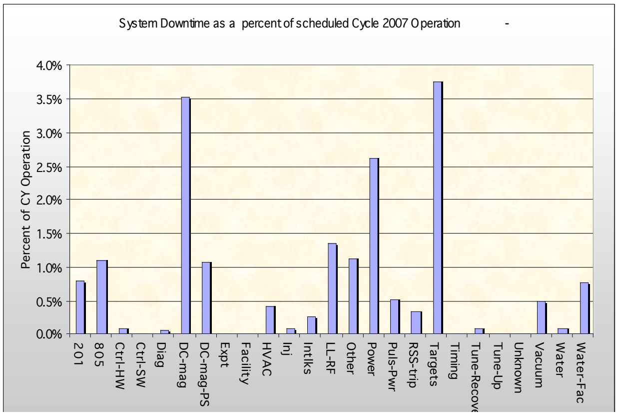

Figure 1: Percent of Lujan beam downtime by accelerator system for CY2007 operations.

ANNUAL FACILITY STARTUP/TUNE-UP

The annual facility startup/tune-up process basically has two goals. The first is to achieve low-loss, stable, beam operation to all experimental areas. This process begins with all accelerator systems in the powered-off state following an extended maintenance period. The tune-up process begins with a physics-model based procedure and finishes with empirical tweaking to reach high power operation. The second goal is to recertify the personnel safety and machine protection systems related to beam operation at the facility. The radiation safety system (RSS) must be recertified every 6 months. The RSS has 80 checks which on average require two hours per check to complete. To help reduce the maximum number of checks that need to be performed at any one time, the LANSCE operations staff is now moving to a rolling recertification program. The machine protection systems, i.e. run permit (RP) and fast protect (FP), are recertified once per year during startup. The RP system has over 49 interlock checks and 40 Albatross neutron detector checks while the FP system includes over 24 interlock checks that are performed during this time. All interlock checks are executed using approved formal procedures.

The interlock checks and tune-up activities are interleaved to make better use of limited resources. They progress in a natural order from low-energy injectors to high-energy beam transports and targets. This allows maintenance activities to continue in downstream areas for as long as possible. Approximately one month is scheduled for annual startup. This one month period is also used to accommodate equipment problems/failures that inevitably occur during startup.

LINAC TUNE-UP

The linac physics-based tune-up strategy was developed over many years of high-power, multi-beam operation. It is a multi-step process that includes the use of a "zero" current beam, i.e. a beam with minimal space-charge and beam loading effects, and previous results from single- and multi-particle beam dynamics models to establish the desired phase and amplitude set points for the DTL and CCL cavity fields. These models use ideal accelerating structures that, for example do not include any measurements of relative field profiles. The zero current beam (1-mA is typically used) also mitigates complications from space charge. Transverse beam emittance is extracted from either slit & collector or combined wirescanner measurements. All tune-up activities performed with interceptive diagnostics in the linac are done with very low-duty factor beam, e.g. 4 Hz x 150 μs macropulse, which limits damages to those diagnostics and beam spill during manipulation of machine parameters. The pulse length is chosen to provide stable, reproducible measurements under steady state conditions.

The LANSCE linac has a wide array of beam diagnostics that are used extensively during the tune-up process. Transverse measurements are made with slit & collector, multi-wire harp and wirescanner devices. To establish the desired tune along the LEBT, several emittance stations are available. Beam emittance is measured in the LEBT and TR to match beam into the DTL and CCL, respectively. Multiple wirescanners per module at the front of the CCL provide independent check on the match. Transverse profiles are available at each module throughout the rest of the linac. Longitudinal measurements in the DTL employ absorber/collector devices to determine beam intensity above an energy threshold. Longitudinal measurements in the CCL consist of an absorber/collector to measure the phase width of the 100 MeV beam and capacitive pickups to measure beam phase for the delta-T procedure. Current monitors are implemented at every module. Scintillator based beam loss monitor are used in the linac. DTL tanks 3 and 4 each have one, the TR has several and the CCL has them evenly spaced at a frequency of two per module.

The first step in the tune-up is to establish the full-peak current tune in the LEBTs. The peak currents are set by source performance, experimental beam requirements and available beam duty factor. This is performed using a combination of emittance measurements at several locations along the ~12 m long transports and a 2D beam envelope model. Space charge neutralization plays a role in the beam evolution along the LEBTs. The Cockcroft-Walton Injectors produce unbunched beams during a macropulse. Microbunching is applied starting ~1/3 of the way through the beam line. Significant bunching is only applied in the last 1.8 m of transport. With LEBT vacuum in the mid-10^{-7} T range the compensation is about 10-20 % for H+ beam and almost complete for H- over much of the transport. Estimates of the effective beam current for matching purposes is determined by comparing measured beam profile sizes to envelope model predictions at the emittance measurement stations.

The next step in the tune-up process is to establish the correct RF phase and amplitude operating set points in the linac. This is done using an unchopped 1-mA peak current beam. This beam is transversely matched into the DTL design lattice using target values derived from envelope models. The phase and amplitude settings for the 201 MHz LEBT bunchers and DTL tanks are set using a phase-scan procedure which employs the absorber-collect devices. The target values for the phase-scans were derived from multi-particle beam dynamics simulations with a 1 mA peak current beam. Once the operating set points for the DTL are established, the 1 mA beam is transversely matched into CCL. The operating set points for the first several CCL quadrupole doublets have evolved away from the design to improve the match and operation of the high-power beams. The longitudinal tune of the CCL is then established using the delta-T method with a solution derived from a single-particle model.

Optimal DTL field levels for high power beam operation are quite different than the design values. Originally, 1-mA beam was used to establish the design field in the DTL tanks for high-power beam operation. However, these design fields resulted in unacceptably high beam losses in the CCL for high power operation. Better operating levels were discovered through empirical tweaking. Although the actual solution was not always the same, the tendency was. A snapshot of the field levels in the DTL tanks during one period of high power operation showed amplitudes relative to design of 98%, 96%, 94% and 98% for tanks 1 through 4, respectively. The effect of operating the DTL tanks at reduced amplitudes is to reduce the longitudinal acceptance and thereby removes "tails" early in the acceleration process, i.e. beam spill occurs at lower rather than higher energy.

The last step in the physics tune of the linac is to restore the nominal high-peak current beam in the LEBT and rematch at the entrance to the DTL and CCL. The high-current match into the DTL is complicated by the evolving longitudinal emittance and the lack of complete knowledge of the space charge neutralization that occurs between the matching quadrupoles and the DTL [2]. A simple approach that has been used to perform the matching is to employ a 2D envelope model with a scaled-up effective current. This procedure is adequate and removes the requirement for accurate knowledge of the longitudinal beam emittance. The delta-T procedure is used to make longitudinal adjustments to ensure the correct beam energy out of the DTL and beam phase at the input to the CCL. At this point the model-based physics tune of the linac is complete.

Following the physics tune-up, the linac is capable of delivering high-peak, low-power beam. At this stage the tuning process becomes empirical and is driven by the off-energy components and transverse tails in the beam. The tuning is focused on reducing beam losses and raising the average current to the target value. Phosphors located at dispersive points in the 800 MeV beam switchyard immediately following the linac are used to reveal off-energy components. The beam spill monitors along the linac provide relative beam loss information. When the 800 kW H+ beam was in operation, beam currents of a few hundred microamps were readily achievable following the physics tune. It would typically take a few days of empirical tweaking to reach low-loss 1 mA operation.

BEAM LOSSES, ACTIVATION AND PROTECTION

The empirical tuning performed on the machine is aimed at producing a low-loss tune. The largest source of beam loss (~20%) occurs early in the DTL and is a result of the incomplete bunch formation prior to beam entering tank 1. The next area is the TR transport between the DTL and CCL structures. Off-energy and transverse tails results in ~0.1% beam spill as measured by current monitors. Beam spill along the CCL is typically less then 0.1%. Transverse mismatch contributes to higher than average spill near the beginning of the CCL. Longitudinal tails not captured by the CCL contribute to higher than average losses near module 13 where the period of the transverse focusing lattice doubles. Activation levels along the linac following two operating periods with different beam conditions are shown in Figure 2.

Simulations of beam losses along the linac were performed as part of a larger study that looked at beam performance for both the 1 mA H+ and 75 μA H- beams in operation at the time [3]. These were multiparticle beam dynamics simulations that included initial distributions constructed from transverse emittance measurements and longitudinal simulations of the beams in the 750 keV LEBTs. Estimates of the space charge neutralization were also included in this portion of the simulation. The DTL tank fields used in the simulations were estimated from phase-scan measurements, while the CCL fields were set to design values that were installed by the delta-T program. The magnets in the transverse focusing lattice of the LEBT, DTL, TR and CCL were set to operational values.

The results of the simulations were in reasonable agreement with the measurements. The measured longitudinal capture of the complex beam bunches was well reproduce by the simulation and is shown in Table 2. The collective beam losses along the linac tended to be slightly over estimated by the simulations but are similar and are presented in Table 3. Qualitatively, the loss profile along the CCL shows similarities to the measured profile. However, the interpretation of the measured profiles is complicated by lack of knowledge of the actual energy distribution of lost particles along the linac.

Table 2: Simulated and measured beam capture LANSCE DTL.

	H+ Capture		**H- Capture**	
	Sim.	Meas.	Sim.	Meas.
Capture	80%	82±1%	80%	81±1%

Table 3: Simulated and measured beam loss along LANSCE linac.

Between Modules	**H+ Losses**		**H- Losses**	
	Sim.	Meas.	Sim.	Meas.
3-12	0.04%	0.1%	0.15%	<0.1%
12-48	0.28%	<0.1%	0.24%	<0.1%

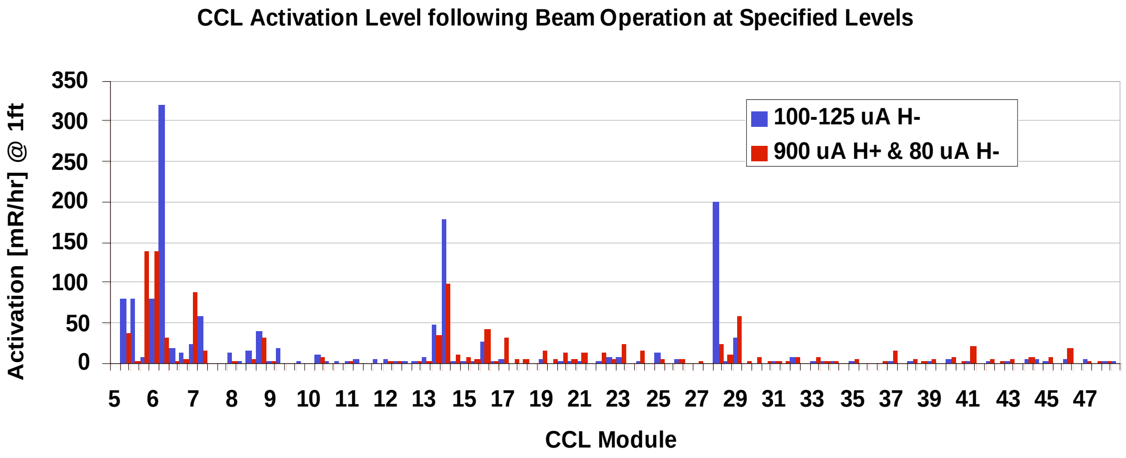

Figure 2: Activation levels along linac (measured at quad doublets) following two separation operating cycles.

The beam losses along the linac also show a variation with time within a macropulse. With high-peak current operation the beam turn-on transient can induce amplitude and phase errors in the cavity fields that result in increased losses during this time. Although the errors are not large enough to produce a beam trip (i.e. great than ±1% amplitude and ±1° phase), the transient losses are significantly greater than the steady state losses. The present LLRF control system does not contain an adaptive component that could further reduce the residual error over what is currently achievable. The reduced amplitude operation of the DTL tanks may also exacerbate these turn-on losses.

To mitigate beam induced damage to the accelerator structure and transports from errant beam, LANSCE employs a machine protection system, a.k.a. Fast Protect, that operates with a system response time of ~10 µs. The primary inputs to this system are:

- RF cavity field errors, with trip levels of ±1% in amplitude and ±1° of phase,
- Beam loss monitors which were initially setup to trip with 100 nA of beam spill in their vicinity, and
- Beam current transmission monitors which have adjustable set points and tolerance bands.

The faults are transmitted to chassis which inhibit gating of LEBT beam deflectors and/or ion sources which immediately suspends beam delivery. Depending upon the type and location of the fault, one or more beams may be affected. The affected beams remain off until the next beam gate after the fault has cleared.

SUMMARY

LANSCE is a multi-user, multi-beam facility that employs a high-power 800 MeV proton linac and storage ring. The facility has long history of 800 kW beam operation although present day operation occurs at more modest, 130 kW power levels. Current schedules include over 3000 hours of beam operation to several user facilities with typical availability of ~80%. Tuning the linac for high-power beam operation begins with physics model-based procedures to get the "rms" performance established but relies on empirical tuning to minimize beam spill.

REFERENCES

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