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EMITTANCE GROWTH AND BEAM LOSSES IN LANSCE LINEAR ACCELERATOR *

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Abstract

The LANSCE Accelerator facility currently utilizes four 800-MeV H- beams and one 100-MeV proton beam. Multi-beam operation requires careful control of the accelerator tune to minimize beam losses. The most powerful 80-kW H^- beam is accumulated in the Proton Storage Ring and is extracted to the Lujan Neutron Scattering Center facility for production of moderated neutrons with meV- keV energy. Another H^- beam is delivered to the Weapon Neutron Research facility to create un-moderated neutrons in the keV - MeV energy range. The third H^- beam is shared between the Proton Radiography Facility and the Ultra-Cold Neutron facility. The 23-kW proton beam is used for isotope production in the fields of medicine, nuclear physics, national security, environmental science and industry. Minimization of beam losses in the linac is achieved by careful tuning of the beam in each section of the accelerator facility, imposing limitations on amplitudes and phases of RF systems, control of H- beam stripping, and optimization of ion source operation. This paper summarizes experimental results obtained during accelerator tuning and identifies various sources of emittance growth and beam losses.

LANSCE ACCELERATOR FACILITY

The LANSCE Accelerator facility has been in operation for more than 40 years. Currently it delivers 800-MeV H^- beams to four experimental areas and one 100-MeV proton beam (see Fig. 1 and Table 1). The accelerator facility is equipped with two independent injectors for H^+ and H^- beams, merging at the entrance of a 201.25-MHz Drift Tube Linac (DTL). The DTL accelerates the two beams to 100 MeV. After the DTL, the Transition Region (TR) beamline directs the 100-MeV proton beam to the Isotope Production Facility (IPF), while the H^- beam is accelerated up to the final energy of 800 MeV in an 805- MHz Coupled Cavity Linac (CCL). The H^- beams, created by different time structures of a low-energy chopper, are distributed in the Switch Yard (SY) to four experimental areas. Minimization of beam losses is one of the main criteria of successful operation of the accelerator facility.

BEAM LOSS IN ACCELERATOR

Beam losses in the LANSCE accelerator are mostly determined by the two most powerful beams: the 80-kW H^- beam injected into Proton Storage Ring, and the 23-kW H^+ beam, which is used at the Isotope Production Facility. The main sources of beam losses in the linac are mismatch of the beam with the accelerator structure,

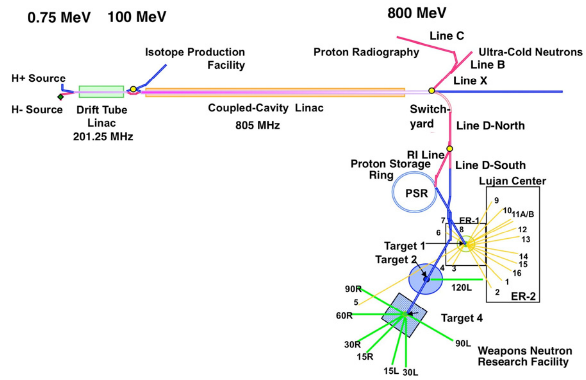

Figure 1: Layout of LANSCE Accelerator Facility.

Table 1: Beam Parameters of LANSCE Accelerator

Area	Rep. Rate (Hz)	Pulse Length (µs)	Current/ bunch (mA)	Average current (µA)	Average power (kW)
Lujan	20	625	10	100	80
IPF	100	625	4	230	23
WNR	100	625	25	4.5	3.6
pRad	1	625	10	<1	<1
UCN	20	625	10	10	8

variation and instabilities of accelerating and focusing fields, transverse-longitudinal coupling in the RF field, misalignments and random errors of accelerator channel components, field nonlinearities of focusing and acceleratirng elements, beam energy tails from un-captured particles, particle scattering on residual gas and intra-beam stripping, non-linear space-charge forces of the beam, excitation of high-order RF modes, and dark current from unchopped beams.

Beam losses at LANSCE are controlled by various types of loss monitors. The main control is provided by Activation Protection (AP) detectors, which are one-pint size cans with a photomultiplier tube immersed in scintillator fluid. AP detectors integrate the signals and shut off the beam if the beam losses around an AP device exceed 100 nA of average current. The same devices are used as beam loss monitors (LM), where the signal is not integrated and therefore one can see a real-time of beam loss across the beam pulse.

Another type of loss monitor are Ion Chamber (IR) detectors, which are used in the high energy transport lines (Line D, PSR, 1L, WNR). They are usually located in parallel with Gamma Detectors (GDs) that feeds into the Radiation Safety System. An advantage of the IRs is that they do not saturate at high loss rates like the AP devices.

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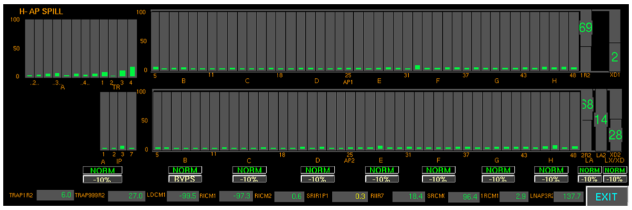

Figure 2: Beam loss along linear accelerator.

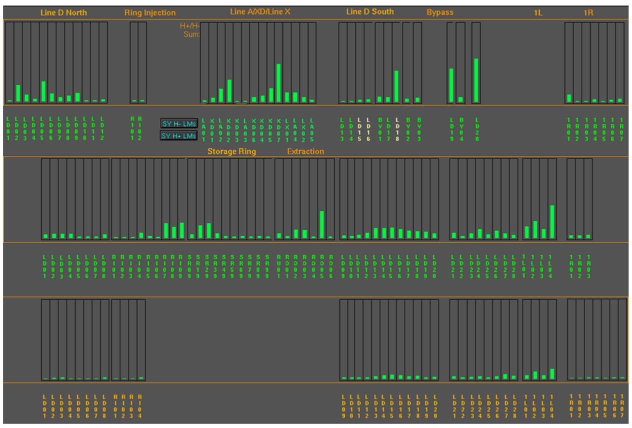

Figure 3: Beam losses in high-energy beam transport.

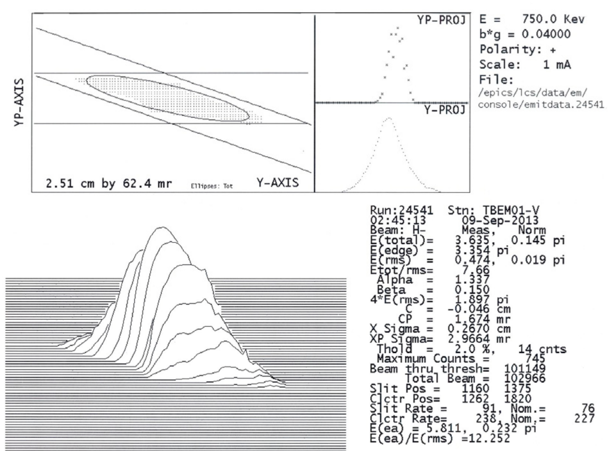

Figure 4: Emittance measurement of H^- beam at the beginning of Low Energy Beam Transport.

The third type of beam loss monitor are Hardware Transmission Monitors (HWTM). The HWTM system measures the beam current losses between current monitors and can limit beam current to a value at one current monitor.

Distribution of beam losses along the accelerator facility are presented in Figs. 2, 3. Typical averaged beam losses along the linear accelerator are $2x10^{-3}$ which corresponds to loss rate of $3x10^{-6}$ m^{-1}, or 0.2 W/m. In the high-energy beamlines (HEBT), the total beam losses are 4x 10^{-3} which corresponds to a loss rate of $2x10^{-5}$ m^{-1}, or 1.6 W/m. Higher beam losses in the HEBT are explained by smaller transverse acceptance and the dispersive nature of the beamlines, which generates additional losses due to longitudinal (energy) tails in the beam. Typical average losses in Proton Storage Ring (PSR) are at the level of 0.3%.

BEAM EMITTANCE MEASUREMENTS

Beam emittance is measured using the slit-collector method for beams with energies not exceeding 100 MeV. There are seven beam emittance measurement stations in the low-energy beam transports, and three stations after the DTL. A threshold of 2% out of the peak value of the beam distribution is added to remove experimental noise (see Fig. 4). After measurement, both rms emittance and total emittance of the beam are calculated. For energies higher than 100 MeV, beam emittance is measured using a combination of wire scanners, while emittance is recalculated using a matrix method. Evolution of transverse beam emittance along accelerator is presented in Tables 2, 3.

Determination of longitudinal beam emittance is performed through measurement of the longitudinal beam size after Tank 3 in the DTL at a beam energy of 70 MeV [1], and measurement of momentum spread of the 800-MeV beam in a high-dispersive point of Line D. The typical value of the phase length of the bunch at 70 MeV is 7^o, which corresponds to a half-bunch length of 5 mm. The typical value of the beam size at a high-dispersive point of the high-energy beam transport is 5.8 mm and is mostly determined by the beam momentum spread of $\Delta p / p \approx 10^{-3}$. Due to adiabatic damping of phase oscillations in a linear accelerator, the momentum spread is changing as

$$\frac{\Delta p}{p} \sim \frac{1}{\beta^{5/4}\gamma^{1/4}} \quad . \tag{1}$$

A combination of the beam size and momentum spread gives an estimate of the longitudinal normalized beam emittance at 70 MeV as $4\varepsilon_{rms\_long} \approx 0.7$ π-cm-mrad.

ION SOURCES

Proton Ion Source

Optimal operation of the accelerator facility critically depends on the emittance and brightness of the beam extracted from the ion sources and beam formation in the low-energy beam transport (LEBT). The proton ion source is a duoplasmatron source with a Pierce extraction geometry. Presently the source delivers a proton beam with a current of 5-7 mA at 100 Hz x 625 μsec pulse length. An intrinsic limitation in particle-source beam-emittance comes from the finite value of the plasma temperature in the ion source. The normalized emittance of the beam, extracted from a particle source with aperture radius *R* and plasma ion-temperature *T*, is estimated as:

$$\varepsilon = 2R\sqrt{\frac{kT}{mc^2}} \quad . \tag{2}$$

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Besides the emittance determined by Eq. (2), additional sources contributing to beam emittance are irregularities in the plasma meniscus extraction surface, aberrations due to ion-source extraction optics, non-linearity of the electric field created by the beam space charge, beam fluctuations due to ion-source instability or power regulation. A typical value of the normalized rms proton beam emittance is ε_{rms} = 0.002 - 0.003 π·cm·mrad.

H- Ion Source

The H^- beam injector includes a cesiated, multicusp-field, surface-production ion source. Negative ions are created as a result of charge exchange at a molybdenum surface converter, in the presence of a thin layer of cesium. The generated H^- particles are then accelerated towards the extraction aperture. Correspondingly, the normalized beam emittance of this type of source is estimated as the phase space area comprised by a converter with radius R_{conv}, extractor aperture with radius R_{ext}, and distance L_{conv} between them (admittance of source) [2]

$$\varepsilon = \frac{4}{\pi}\sqrt{\frac{2eU_{conv}}{mc^2}}\frac{R_{conv}R_{ext}}{L_{conv}}, \tag{3}$$

where U_{conv} is the voltage between the converter and the source body. In the LANSCE H^- ion source, R_{conv} =1.9 cm, R_{ext} = 0.5 cm, L_{conv} =12.62 cm, U_{conv} = 300 V, which yields a normalized beam emittance of ε = 0.076 π cm mrad. This quantity is close to the experimentally observed value of four-rms normalized beam emittance $4\varepsilon_{rms}$ = 0.072 π– cm-mrad.

LOW ENERGY BEAM TRANSPORTS

Both beams are transported in 750-keV beamlines and merged before injection into the Drift Tube Linac. Each beamline is 11 m long containing 18 quadrupoles. After merging, both H^+ and H^- beams are transported in a common 2.5-m-long beamline containing 4 quads for matching into the DTL. Both beams experience emittance growth in the LEBTdue to RF bunching. The relative increase of proton beam emittance is around 1.9, and that of the H^- ion beam is 1.2. Space charge induced emittance growth in the transport beamlines is insignificant. Additionally, the 36-ns H^- WNR beam experiences 30% emittance growth due to chopping.

The proton beam dynamics is sensitive to beam alignment in the LEBT. Matching of the proton beam with the transport lattice requires beam waists at the entrance of the RF cavities and in the middle of the beam deflector. Typical relative beam emittance growth in the beamline was observed to be approximately a factor of 3. A beam based steering procedure was implemented to minimize emittance growth in the LEBT [3]. It included the determination of beam offset and beam angle upon entering a group of quadrupoles, which requires a subsequent correction of the beam centroid trajectory to minimize beam offset. Application of this procedure resulted in a reduction of up to a factor of 2 in emittance growth.

Dynamics of the H^- beam in the LEBT is significantly affected by space charge neutralization. Typical spectra of residual gas in the 750-keV H^- transport channel indicate that the main components are H_2 (48%), H_2O (38%) and N_2 (9%), while the residual gas pressure is 10^{-6} Torr. Measurements show that space charge neutralization of the H^- beam along the LEBT varies between 50%-100%. Knowledge of the effective beam current under space charge neutralization allows precise beam tuning in the structure. Neutralization of H^+ beam does not exceed 20%. Typical beam losses in each beamline are within 0.5 mA peak current.

DRIFT TUBE LINAC

The Drift Tube Linac consists of 4 tanks with output energies of 5 MeV, 41 MeV, 73 MeV, and 100 MeV, respectively. Originally designed for operation with a synchronous phase of -26°, the linac was historically retuned for -32°, -23°, -22°, -32° tank synchronous phases with field amplitudes of 98%, 96%, 94%, and 98% of nominal values to minimize beam spill. Both H^- and proton beams are captured with efficiencies of 75%-80% into the Drift Tube Linac, so initially 20%- 25% of the beam is lost in the beginning of Tank 1. Subsequent beam losses of 0.1%-1% in the DTL result due to additional uncaptured particles and by expansion of the phase-space volume occupied by the beam (emittance growth). Figure 5 and Tables 2, 3 illustrate the increase of beam emittance of H^- and H^+ beams in the DTL. Rapid emittance growth of the total beam is observed while the beam core is changing at a smaller rate. The H^- beam emittance is observed to increase by a factor of 1.8-2.3, while the H^+ beam emittance increases a factor of 5-6. These values agree with earlier simulation results [4]. While beam distributions and beam currents are significantly different at the entrance of DTL for the two beam species, the distributions of all beams at the end of DTL tend to be the same. It reflects the fact that during acceleration the beam tends to occupy the full available phase space acceptance.

The dominant cause of beam emittance growth at low energy is transverse-longitudinal coupling in the RF cavity fields. Estimated beam emittance growth due to this process is [5]

$$\frac{\varepsilon}{\varepsilon_o} = 1 + \frac{\Phi}{\tan\varphi_s}\left(\frac{\Omega^2}{4\Omega_{rs}^2 - \Omega^2}\right), \tag{4}$$

where Φ is the phase length of the bunch, φ_s is the synchronous phase, Ω is the longitudinal oscillation frequency, and Ω_{rs} is the transverse oscillation frequency in presence of RF field. In the 201.25-MHz DTL Φ ~ 1.57 rad, φ_s ~ 30°, Ω/Ω_{rs} ~ 0.75. The expected emittance growth from Eq. (4) is $\varepsilon / \varepsilon_o$ = 1.62.

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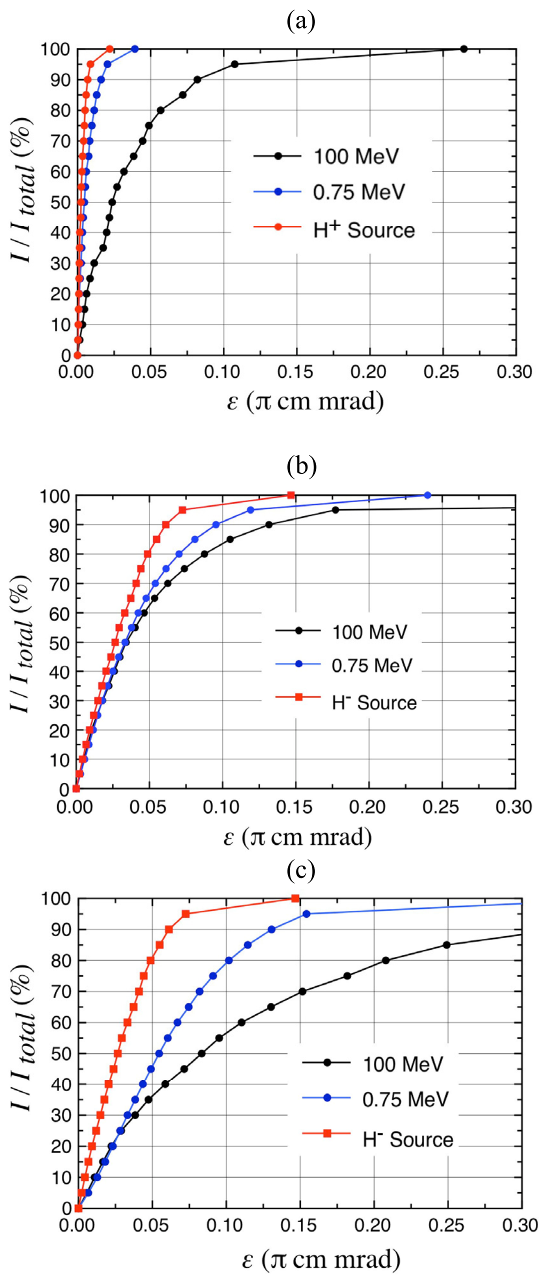

Figure 5: The distribution of the current in the phase space of the different beams in sources, LEBT (0.75 MeV) and after DTL (100 MeV): (a) H^+ beam, (b) H^- Lujan/pRad/UCN beam, (c) H^- WNR beam.

An important parameter, which characterizes the beam distribution is the ratio of total emittance to rms emittance. From Table 2 it follows, that for ion sources, this ratio is close to $\varepsilon_{total} / \varepsilon_{rms} \approx 6$, while at the end of the DTL this ratio is around $\varepsilon_{total} / \varepsilon_{rms} \approx 7...9$. It indicates that the beam distribution after the DTL becomes more diffusive with longer tails.

Table 2. Normalized Beam Emittance in LEBT and DTL (π cm mrad)

	H^- (Lujan / pRad / UCN)			H^- (WNR)			H^+ (IPF)		
	ε_{rms}	ε_{total}	$\frac{\varepsilon_{total}}{\varepsilon_{rms}}$	ε_{rms}	ε_{total}	$\frac{\varepsilon_{total}}{\varepsilon_{rms}}$	ε_{rms}	ε_{total}	$\frac{\varepsilon_{total}}{\varepsilon_{rms}}$
Ion Source	0.018	0.11	6.10	0.018	0.11	6.10	0.002	0.01	6.02
0.75 MeV	0.022	0.14	6.42	0.034	0.219	6.47	0.004	0.027	7.18
100 MeV	0.041	0.34	8.34	0.058	0.415	7.19	0.02	0.17	8.76

Table 3: Beam Emittance Growth in DTL

H^- (Lujan / pRad /UCN)		H^- (WNR)		H^+ (IPF)	
$\frac{\varepsilon_{rms}(100)}{\varepsilon_{rms}(0.75)}$	$\frac{\varepsilon_{tot}(100)}{\varepsilon_{tot}(0.75)}$	$\frac{\varepsilon_{rms}(100)}{\varepsilon_{rms}(0.75)}$	$\frac{\varepsilon_{tot}(100)}{\varepsilon_{tot}(0.75)}$	$\frac{\varepsilon_{rms}(100)}{\varepsilon_{rms}(0.75)}$	$\frac{\varepsilon_{tot}(100)}{\varepsilon_{tot}(0.75)}$
1.86	2.42	1.7	1.89	5.0	6.3

Table 4: Normalized rms Beam Emittance in CCL (π cm mrad)

Energy	100 MeV	800 MeV
H^- (Lujan / pRad /UCN)	0.04	0.065
H^- (WNR)	0.058	0.124

ISOTOPE PRODUCTION FACILITY

After the DTL, the 100-MeV protons enter the transition region (TR) and continue propagation to the IPF beamline. Operation of the TR and IPF beamlines include beam position monitors (BPMs) to measure and control the beam centroid, correction of beam position at the target and control of beam losses using the Activation Protection devices. Typical beam losses in the IPF beamline are characterized by summed AP device readings of 15% - 20%, which is equivalent to 1-μA beam losses, or relative beam losses of 4×10^{-3}.

During the 2015-2016 accelerator run cycle, a series of beam development experiments were undertaken to reduce beam losses. Analysis of beam dynamics, using 100-MeV beam emittance scans, indicated that beam envelopes had excessive variation, which was corrected by quadupole setup. Additional improvement of beam quality was achieved by beam steering in the IPF beamline. A combination of the steering and bending magnets were adjusted to center the beam through the sequence of quadrupoles. As a result of improved beam matching and steering, the beam losses were reduced and reached 5×10^{-4}.

COUPLED CAVITY LINAC

In the Coupled Cavity Linac (CCL), the H^- beam experiences additional emittance growth, and normalized rms beam emittance at the end of linac is 1.5-2 larger than that at the beginning of the CCL (see Table 4). A dominant factor of beam emittance growth in this high energy part of the linac is diffusion of the beam distribution due to misalignments of the accelerator lattice.

Figure 6 displays a typical distribution of beam spill in the CCL as a function of increasing beam energy. This

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dependence is opposite to that previously observed; previously decreasing beam spill as a function of beam energy was observed for the proton beam. A dedicated study [6] showed that H$^-$ beam stripping on residual gas and intra-beam stripping play a significant role in beam losses at high energy. Another study [7] indicated a strong dependence of H$^-$ beam losses on the stability of RF amplitude and phase in the DTL linac. Maximum beam spill excited by DTL RF systems is estimated as:

$$Max\ Beam\ Spill \sim 10^{n*err}, \quad (5)$$

where $n \sim 3$ - 4, and err is equal to the relative error in RF amplitude in percent, and/or RF error of RF phase in degrees. This study was extended for beam losses generated by RF instabilities in the 805- MHz CCL [8]. Results of the study imply new limits on stability of RF parameters provided by the Low-Level RF control systems, which require ±0.1% in RF amplitude and ±0.1° in RF phase to keep losses at a level that allows hands-on maintenance of the accelerator.

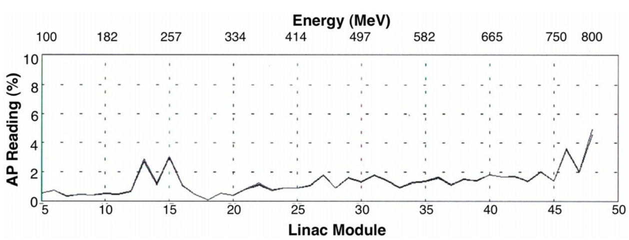

Figure 6: H$^-$ beam spill in Coupled Cavity Linac.

SUMMARY

The LANSCE is a unique accelerator facility that simultaneously delivers beams to five experimental areas. Multi-beam operation requires compromises in beam tuning to meet beam requirements at the different target areas while minimizing beam losses throughout the accelerator, proton storage ring, and beam transport lines. Beam losses and emittance growth are controlled through careful beam matching along the accelerator, ion-source and LEBT adjustments, beam-based alignment, and improved RF phase and amplitude control.

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