OPERATION OF LANSCE LINEAR ACCELERATOR WITH DOUBLE PULSE RATE AND LOW BEAM LOSSES*

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Abstract

In 2014 the LANSCE accelerator facility returned to 120 Hz pulse rate operation after a long period of operation at a 60 Hz pulse rate. Increased capabilities required careful tuning of all components of the linear accelerator. Transformation to the double pulse rate resulted in re-evaluation of tuning procedures in order to meet new challenges in beam operation. This paper summarizes experimental activity on sustaining high productivity of the accelerator facility while keeping beam losses along accelerator low.

LANSCE ACCELERATOR FACILITY

The LANSCE Accelerator facility has been in operation for more than 40 years. Currently it operates with four 800 MeV H^- beams and one 100 MeV proton beam (see 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 performs acceleration up to the energy of 100 MeV. After the DTL, the Transition Region (TR) beamline directs 100 MeV proton beam to the Isotope Production Facility (IPF), while 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 structure of a low-energy chopper, are distributed in the Switch Yard to four experimental areas. The most powerful H^- beam, average current 100 μA, is accumulated in the Proton Storage Ring (PSR) and is extracted to the Lujan Neutron Scattering Center facility for production of moderated neutrons with meV-keV energy. Another H^- beam, as a sequence of short pulses, is delivered to the Weapon Neutron Research (WNR) facility to create un-moderated neutrons in the keV- MeV energy range. The third H^- beam is shared between the Proton Radiography Facility (pRad) and the Ultra-Cold Neutron (UCN) facility.

Between 2006 – 2014, the LANSCE accelerator was in operation at 60 Hz pulse rate to prevent excessive cathode emission and ceramic cracking in 201.25 MHz amplifiers feeding the DTL. The LANSCE Risk Mitigation Project [1] was initiated to replace three out of four 201.25 MHz amplifiers with newly developed RF power systems based on TH628L Diacrodes [2]. The first RF power system was replaced in 2014 enabling restoration of 120 Hz operation. The replacement of 201.25 MHz RF system will be completed in 2016. In addition, a new low-level RF control system was installed, and end-of-life CCL klystrons were replaced to insure further stable beam operation.

*Work supported by US DOE under contract DE-AC52-06NA25396
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Table 1: Beam Parameters at 120 Hz LANSCE Accelerator (number in brackets are given for previous 60 Hz operation)

Area	Rep. Rate (Hz)	Pulse Length (μs)	Current / bunch (mA)	Average current (μA)	Average power
Lujan	20 (20)	625	10	100	80
IPF	100(40)	625	4(10)	230	23
WNR	100(40)	625	25(25)	4.5 (1.8)	3.6 (1.4)
pRad	1	625	10	<1	<1
UCN	20 (20)	625	10	10	8

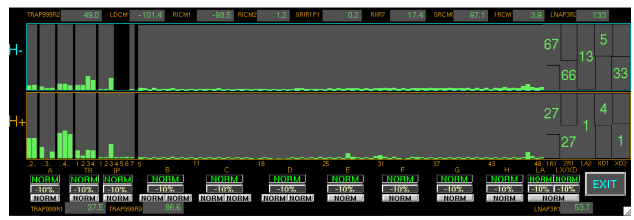

Figure 1: EPICS display of beam spill along the linear accelerator.

BEAM LOSSES IN ACCELERATOR

Minimization of beam losses is one of the main criteria of successful operation of the accelerator facility. 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. While these beams kept their power at the same level after doubling of pulse rate, beam power for the Weapon Neutron Research increased 2.5 times. Doubling the pulse rate required more careful tuning of the beam along the accelerator facility, and more stable operation of all accelerator components.

The main sources of beam losses in linac are mismatch of the beam with the accelerator structure, 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 linear accelerator is equipped with scintillators, while high-energy part includes also ion-chamber detectors. The main control of beam losses is provided by Activation Protection (AP) detectors (see

ISBN 978-3-95450-147-2

Fig.1), 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 LANSCE linac is equipped with 107 APs. Table 2 compares the integral beam losses in the accelerator facility for the last several years. As seen, the last operational period is characterized by significantly smaller losses. Typical averaged rate of beam losses along accelerator is around 0.1 – 0.2 W/m. Another criterion is relative beam losses in Proton Storage Ring, which are also significantly smaller than average in previous years (see Fig. 2). Improvement of beam losses in the last operational period is related to more careful tuning of the beam in each section of the accelerator facility. Table 3 lists the tuning procedures utilized in the accelerator. Improvement of beam matching in each particular point resulted in overall decrease of beam losses in the linear accelerator.

PERFORMANCE OF MAJOR LINAC COMPONENTS

Ion Sources and Low Energy Beam Transport

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 H^+ beam injector includes a duoplasmatron proton source mounted at 750 keV Cockroft-Walton accelerating column, and low-energy beam transport. Presently the source delivers a proton beam current of 5 mA at 100 Hz x 625 μsec pulse length. Typical value of rms normalized proton beam emittance is ε_{rms} = 0.004 π cm mrad. The H^- beam injector includes a cesiated, multicusp - field, surface - production ion source with beam current 15 mA at 120 Hz x 625 μsec pulse length with typical rms normalized beam emittance of ε_{rms} = 0.02 π cm mrad and two-stage low-energy beam transport.

Both beams are transported in 750 keV beamlines and merged before injection into Drift Tube Linac. Space charge neutralization plays an important role in beam dynamics. Typical spectra of residual gas in the 750 keV transport channel indicate that main components are H_2 (48%), H_2O (38%) and N_2 (9%), while residual gas pressure is 10^{-6} Torr. Measurements [3] show that space charge neutralization of H^- beam along beamline varies between 50%-100%, while neutralization of H^+ beam does not exceed 20%. Knowledge of effective beam current under space charge neutralization allows precise beam tuning in the structure. Typical beam losses in each beamline are within 0.5 mA peak current.

Both beams experience emittance growth due to RF bunching. Relative increase of proton beam emittance is around 1.9, and that of H^- beam is 1.2. Space charge induced beam emittance growth in transport beamlines is insignificant. Additionally, the 36 ns pulse length H^- beam experiences 30% emittance growth due to chopping.

Table 2: Integral Beam Losses in Accelerator

Year	Pulse Rate (Hz)	Summed Losses in CCL (AP reading)	Relative PSR beam losses (%)
2015	120	135	0.13
2014	60	211	0.24
2013	60	190	0.23
2012	60	183	0.26
2011	60	167	0.24

Table 3: Tuning Procedures Used in Accelerator Facility

Energy (MeV)	Transverse (matching, steering)	Longitudinal (RF set points)
0 - 0.75	Emittance Scans	
0.75 - 100	Emittance Scans, Wire Scans, Harps, BPMs	Phase Scans
100 - 800	Wire Scans	Phase Scans, Delta-t
800	Wire Scans, BPMs, Phosphor Screens	Wire Scan at High Dispersion Point

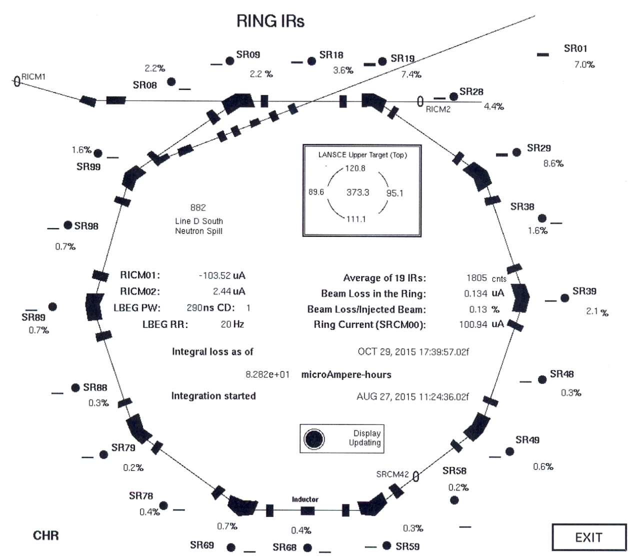

Figure 2: Beam losses in Proton Storage Ring.

Drift Tube Linac and Transition Region

The Drift Tube Linac consists of 4 tanks with energies 5 MeV, 41 MeV, 73 MeV, and 100 MeV, respectively. Originally designed for operation with synchronous phase of -26°, the linac was historically retuned for -32°, -23°, -22°, -32° synchronous phase setup with field amplitude of 98%, 96%, 94%, 98% of nominal values to minimize beam spill. Both H^- and proton beams are captured with efficiency 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 DTL are

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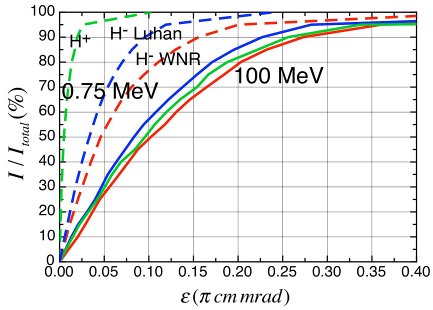

Figure 3: The distribution of the current in the phase space of the different beams in LEBT (0.75 MeV dotted lines) and after DTL (100 MeV, solid lines): (green) H$^+$, (blue) H$^-$ Lujan, (red) H$^-$ WNR.

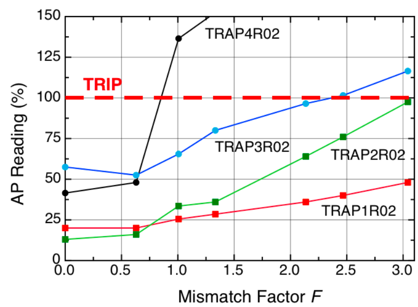

Figure 4: Effect of beam mismatch at the entrance of DTL on beam loss in Transition Region.

determined by un-captured particles and by expansion of phase space volume occupied by the beam. Figure 3 illustrates expansion of beam emittance of H$^-$ and H$^+$ beam in the accelerator. While beam distributions and beam currents are significantly different at the entrance of DTL, distribution of all beams at the end of DTL tend to be the same. Beam emittance growth is a weak function of beam current and is most likely to be determined by misalignments of focusing and accelerating elements along the channel.

An important factor affecting beam losses is beam matching at the entrance of the linac. Figure 4 illustrates the dependence of beam losses in the Transition Region versus mismatch parameter [4] of the beam at the entrance of the DTL. While significant losses are observed at the level of mismatch factor $F \approx 1$, the single beam trip might happen at smaller value of mismatch factor $F \approx 0.6$.

Coupled Cavity Linac

In Coupled Cavity Linac, H$^-$ beam experiences additional emittance growth, and normalized rms beam emittance at the end of linac is around 0.07 π cm mrad. Figure 5 displays a typical distribution of beam spill in the CCL, which is characterized by increasing function of beam energy. This dependence is opposite to previously observed decreasing function of beam spill with energy for proton beam. A dedicated study [5] showed that H$^-$

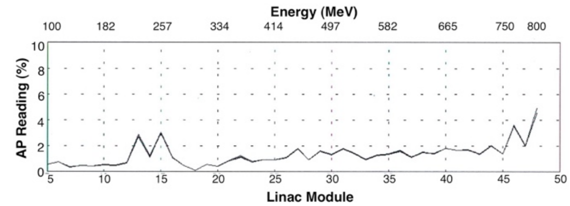

Figure 5: H$^-$ beam spill in Coupled Cavity Linac.

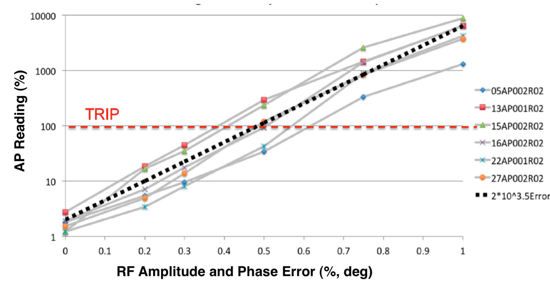

Figure 6: Effect of Drift Tube Linac cavity field error on maximum beam losses at various locations of Coupled Cavity Linac.

beam stripping on residual gas and intra-beam stripping play a significant role on beam loss at high energy. Another study [6] indicated strong dependence of H$^-$ beam losses on stability of RF amplitude and phase in the DTL linac (see Figure 6). Maximum beam spill excited by DTL RF systems is estimated as $10^{n\,err}$ 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 degree. Results of the study imply new standards on stability of RF parameters provided by the DTL Low Level RF control systems, which are established at the level of 0.1% in RF amplitude and 0.1° in RF phase.

SUMMARY

The LANSCE Accelerator facility successfully transformed operation from 60 Hz to 120 Hz. Careful tuning of all components resulted in significant decrease of integral beam losses in the accelerator. New quantitative criteria for minimizing of beam losses are established for the DTL Low Level RF control system of DTL, and initial beam matching at the entrance of DTL.

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