

PERFORMANCE BOUNDARIES IN THE NOVEL MULTI-BEAM LANSCE FRONT END

Y. Batygin, H. Salazar, T. Tajima, Los Alamos National Laboratory, Los Alamos, United States

Abstract

The proposed 100 MeV injector is designed to renovate LANSCE accelerator facility by replacing the 750-keV Cockcroft-Walton injectors, supporting its unique function of delivering multiple, simultaneous beam flavors to several targets. Accelerating multiple beam types in a single RFQ at LANSCE restricts the ability to tune acceleration optimally and focusing due to inherent differences in beam properties (current, charge per bunch, emittance). Strong beam space charge forces induce coupling between degrees of freedom, leading to an unavoidable mismatch in the Front End that necessitates careful six-dimensional matching with accelerator structures. Inescapable transients of beam chopping in Low Energy Beam Transport result in the development of satellite bunches after the 3-MeV RFQ accelerator and force the removal of these using a sophisticated chopper system after the RFQ. The paper addresses critical challenges within the proposed Front End and advances solutions for their mitigation.

INTRODUCTION

LANSCE linear accelerator consists of a 201.25 MHz Drift Tube Linac (DTL) accelerating particles from 0.75 MeV to 100 MeV and an 805 MHz Coupled-Coupled Linac (CCL), accelerating particles from 100 MeV to 800 MeV [1]. This facility employs multi-pass, high-duty-cycle operation to deliver varied particle beams simultaneously to multiple experimental stations. A 100 MeV proton beam is delivered to the Isotope Production Facility (IPF), while 800 MeV H^- beams are distributed to four experimental areas: the Lujan Neutron Scattering Center, the Weapons Neutron Research facility (WNR), the Proton Radiography facility (pRad), and the Ultra-Cold Neutron facility (UCN).

Time structures of the beam are presented in [2]. To mitigate long-term operational risks and achieve future performance goals for laboratory missions, a novel Front End featuring a high-brightness RFQ-based injector was developed, see Figure 1. The detailed description of the proposed Front End is given in Refs. [2, 3, 4].

SUPPRESSION OF SPACE CHARGE NEUTRALIZATION IN LEBT

The novel Front End differs primarily from the existing one by featuring space charge-dominated beam dynamics within the Low Energy Beam Transport (LEBT). A key challenge in this new injector design is managing the distinct space charge neutralization of the low-energy beams. The estimated time for a 100 keV beam to ionize the residual gas at the given pressure of 10^{-6} Torr is $56 \mu s$ [5]. With a pulse duration of $625 \mu s$, the Lujan beam achieves full space charge neutralization. Because the WNR beam consists of short, single bunches separated by long $1.8 \mu s$ intervals, it will not undergo space charge neutralization. To minimize beam dynamics variations in the LEBT across different beam types, space charge neutralization must be eliminated. Maintaining a deep vacuum of at least 10^{-8} Torr achieves this.

Figure 2 illustrates a simulation of deep vacuum conditions in LEBT using the Molflow code [6]. Pumping is performed at the six pump-out ports with a 1000 L/s pump on each port. Within a beamline of diameter 8 cm, and an outgassing rate of $7 \cdot 10^{-11}$ mbar-L/s-cm², which is a typical outgassing rate after pumping down a stainless steel beamline for ~ 33 hours [7], the achieved vacuum pressure is between $1.4 \cdot 10^{-8}$ Torr and $2.2 \cdot 10^{-8}$ Torr.

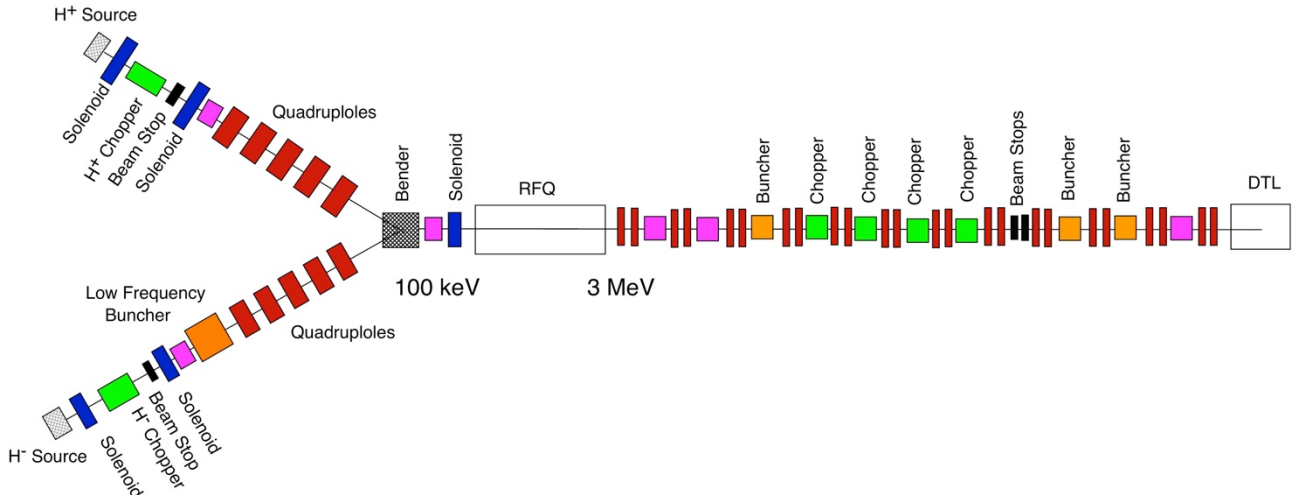


Figure 1: Layout of the proposed LANSCE Front End with distributed beam chopping.

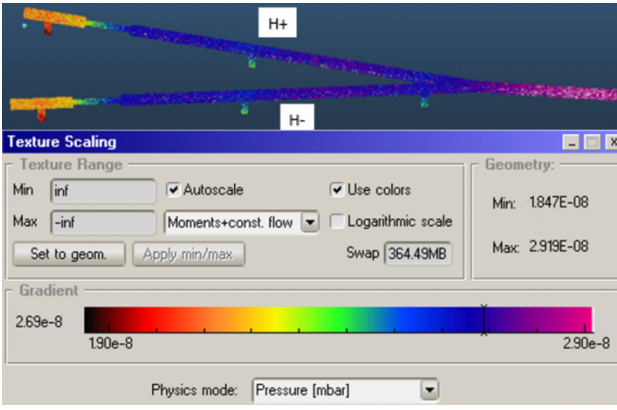


Figure 2: Vacuum simulation using Molflow program [6].

The necessity to remove beam space charge neutralization in LEBT results in (i) space charge induced beam emittance growth, which limits beam intensity in accelerator; (ii) unavoidable mismatch of the different H^- beam components due to difference in beam emittance, charge per bunch, and beam current; (iii) reduction of flexibility of beam manipulations with respect to present LANSCE operational setup.

BEAM CHOPPING IN LEBT

LANSCE operations require creating and injecting high-intensity WNR bunches, which consist of a pulse sequence operating at a 0.56 MHz repetition rate. Each WNR bunch is initially separated from the continuous (DC) beam using a short chopper pulse of ~ 25 ns. The chopped beam pulse passes through the Low Frequency Buncher (LFB), where it undergoes longitudinal momentum modulation. Subsequently, the WNR bunch experiences a longitudinal phase-space rotation within the drift space, and, following compression, it is captured into the RFQ. Details of the formation of a highly charged short pulse chopped beam are discussed in Ref. [4].

To calculate beam dynamics in LEBT, the model of chopper dynamics was developed in the particle-in-cell code BEAMPATH [8]. The chopper pulse is a traveling wave pulse of vertical field $E_y(\xi)$ propagating within the

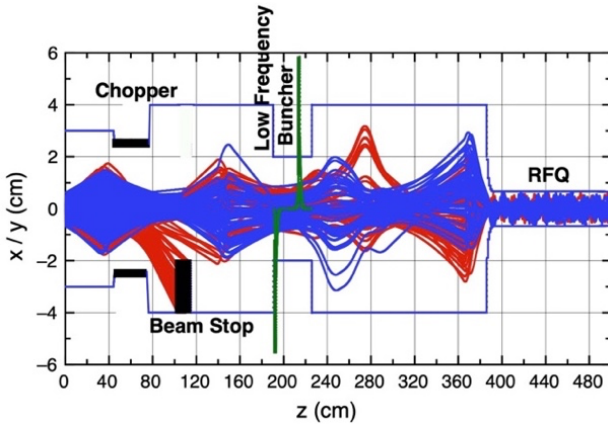


Figure 3: LEBT dynamics of 25 ns chopped H^- WNR beam pulse with subsequent bunching by the 10.0625 MHz Low Frequency Buncher: (red) vertical, (blue) horizontal.

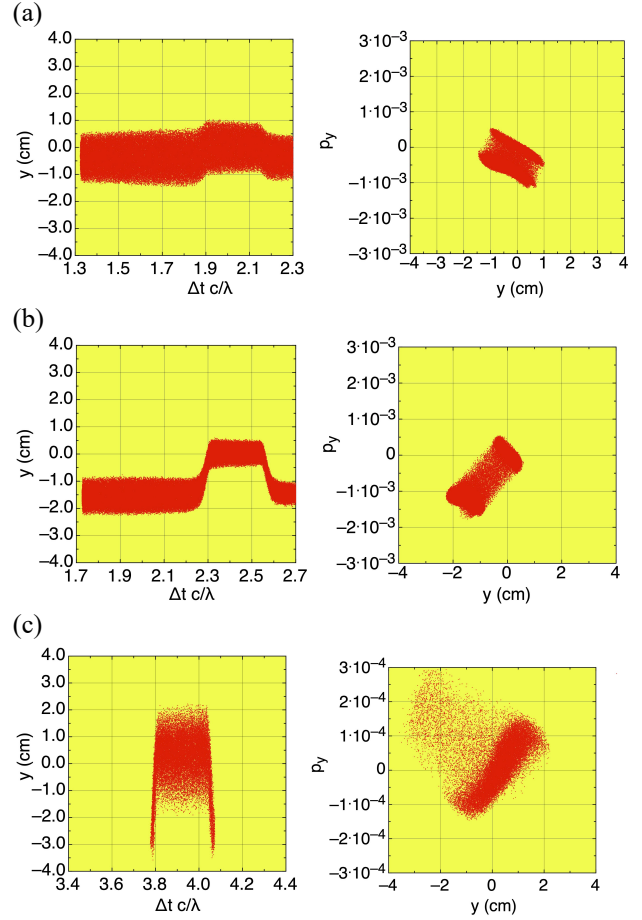


Figure 4: (Left) vertical beam profile and (right) vertical beam emittance in LEBT chopper: (a) inside chopper, (b) after chopper, (c) after chopper beam stop.

chopper length L with velocity β_{ch} having the following dependence of vertical field:

$$E_y(\xi) = E_o \left[1 - \frac{1}{1 + \alpha \left(\frac{\xi - \xi_{front}}{\xi_{front}} \right)^n} \right], \quad 0 < \xi < \xi_{front}, \quad (1)$$

$$E_y(\xi) = 0, \quad \xi_{front} < \xi < \xi_{front} + \xi_{top}, \quad (2)$$

$$E_y(\xi) = E_o \left[1 - \frac{1}{1 + \alpha \left(\frac{\xi - \xi_{front} - \xi_{top}}{\xi_{front}} \right)^n} \right], \quad \xi > \xi_{front} + \xi_{top} \quad (3)$$

where traveling-wave variable ξ is

$$\xi = (z - z_o) - \beta_{ch} c(t - t_o), \quad (4)$$

z_o is a position of simulated chopper pulse at the time t_o , and $\xi_{front} = (\beta_{ch} c) t_{front}$, $\xi_{top} = (\beta_{ch} c) t_{top}$ are values that determine pulse front and top. Parameters α , n define the

shape of the modeled chopper pulse. A good approximation of pulse profile is achieved with $\alpha = 32$ and $n = 4$.

Effective rising/falling time includes the transient time of chopper/beam interaction (e.g., stray capacitance, fringing fields, beam size) and that of the pulse generator

$$t_{front} = \sqrt{t_{trans}^2 + t_{gen}^2 + \dots} \quad (5)$$

Figure 3 and Figure 4 illustrate the process of chopping the WNR bunch in the LEBT with selected chopper parameters $E_o = 0.5$ kV/cm, $L = 35$ cm, $t_{front} = 10$ ns, $t_{top} = 20$ ns, $\beta_{ch} = 0.0146$. Chopping of the WNR beam in LEBT results in noticeable beam emittance growth ~ 2.4 . Parameters of all beams in front of RFQ are presented in Table 1. The values of beam emittance growth along Front End are summarised in Ref. [9]. Based on attained beam physics constraints, the LEBT design was developed to minimize the mismatch of multiple beams in the LEBT to provide successful capture and acceleration in the novel RFQ.

Table 1: Twiss Parameters, Normalized Transverse RMS Beam Emittance (π mm mrad) and Charge per Bunch at RFQ Injection

Beam (Facility)	a_x	β_x (cm)	a_y	β_y (cm)	ε_{rms}	Q/b (pC)
H ⁻ (Lujan/ pRad/UCN)	1.22	5.10	1.34	5.28	0.26	60
H ⁻ (WNR)	1.48	4.40	2.29	5.54	0.47	125
H ⁺ (IPF)	1.49	3.60	1.94	4.61	0.12	20

BEAM CHOPPING IN MEBT

Unavoidable beam-chopping transients from finite-aperture limitations in the Low-Energy Beam Transport chopper result in the creation of a longitudinal WNR bunch size larger than the longitudinal RF bucket of 201.25 MHz RFQ. This leads to the formation of satellite WNR bunches after the 3-MeV RFQ accelerator [9], which necessitate removal via a specialized downstream chopper.

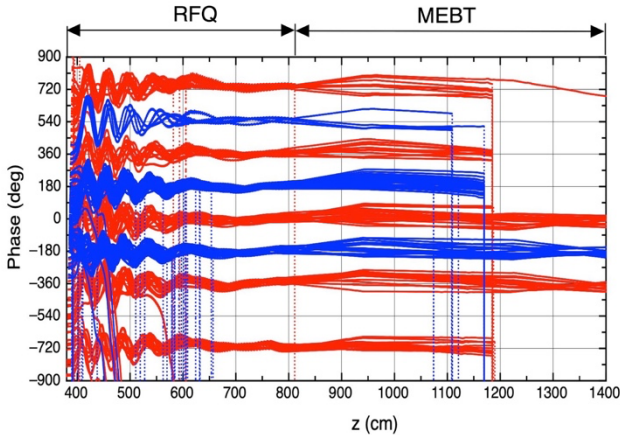


Figure 5: Phase trajectories of simultaneous acceleration and MEBT transport and chopping of (red) H⁺ IPF beam and (blue) H⁻ WNR beam.

Figure 5 illustrates simultaneous formation of H⁻ WNR bunches (in blue) and H⁺ bunches (in red) in RFQ and in the 3 MeV Medium Energy Beam Transport (MEBT). The H⁺ beam is injected as a continuous beam with pulse length of 625 μ s, which results in appearance of train of the bunches after RFQ. The injected WNR H⁻ beam pulse has a length about $2.7 \beta\lambda$, which results in appearance of at least three H⁻ bunches. Experimental requirements assume delivering only single WNR H⁻ bunches with repetition rate of $201.25/360 = 0.559$ MHz, which corresponds to time interval between WNR bunches of $\sim 1.788 \mu$ s.

Medium Energy Beam Transport is designed as a beam-line that matches all beam components to the Drift Tube Linac with additional chopping for the WNR beam. Since the proton IPF beam is accelerated at the same RF pulse as the WNR H⁻ beam, the chopper also cuts a fraction of H⁺ beam. Because the time interval between 201.25 MHz bunches is ~ 5 ns, the chopper has a tight requirement for short rising/falling times. Figure 6 illustrates the process of coincident chopping of H⁺ and H⁻ beams in the designed MEBT using a sequence of four choppers with parameters $E_o = 2.75$ kV/cm, $L = 20$ cm, $t_{front} = 1$ ns, $t_{top} = 6$ ns, $\beta_{ch} = 0.08$.

The additional function of MEBT is a longitudinal matching of proton and H⁻ beams between RFQ and Drift Tube Linac. It is achieved with the placement of three RF cavities along MEBT with field gradients $E_o T = 23$ kV/cm, 21 kV/cm, 1.8 kV/cm at locations $z = 935$ cm, 1220 cm, 1268 cm, respectively. Performed simulation confirms effectiveness of 3-MeV multi-beam transport with simultaneous chopping of H⁻ and H⁺ beams.

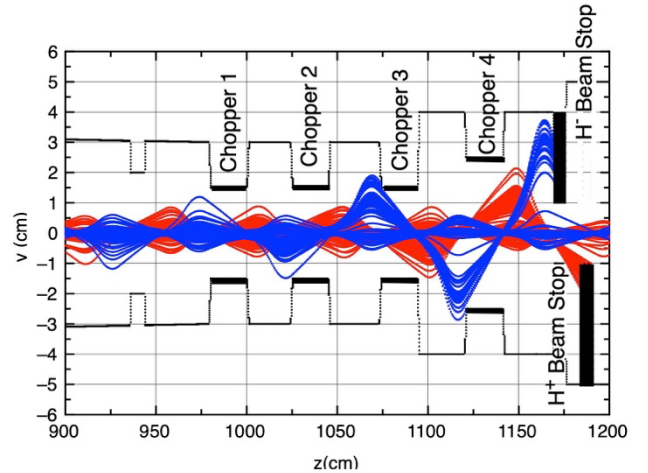


Figure 6: 3-MeV Medium Energy Beam Transport chopping of (red) H⁺ IPF proton beam and (blue) H⁻ WNR beam.

ACKNOWLEDGEMENT

The research presented in this paper was supported by the Laboratory Directed Research and Development program of Los Alamos National Laboratory under project number 20240177ER.

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