PERFORMANCE BOUNDARIES IN THE NOVEL MULTI-BEAM LANSCE FRONT END

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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. Unavoidable 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 Fig. 1. The detailed description of the proposed Front End is given in Refs. [2-4].

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 µs [5]. With a pulse duration of 625 µs, the Lujan beam achieves full space charge neutralization. Because the WNR beam consists of short, single bunches separated by long 1.8 µs 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 $7\cdot10^{-11}$ mbar·L/s·cm^{-2}, which is a typical outgassing rate after pumping down a stainless steel beamline for ~33 hours [7], the achieved vacuum pressure is between $1.4\cdot10^{-8}$ Torr and $2.2\cdot10^{-8}$ Torr.

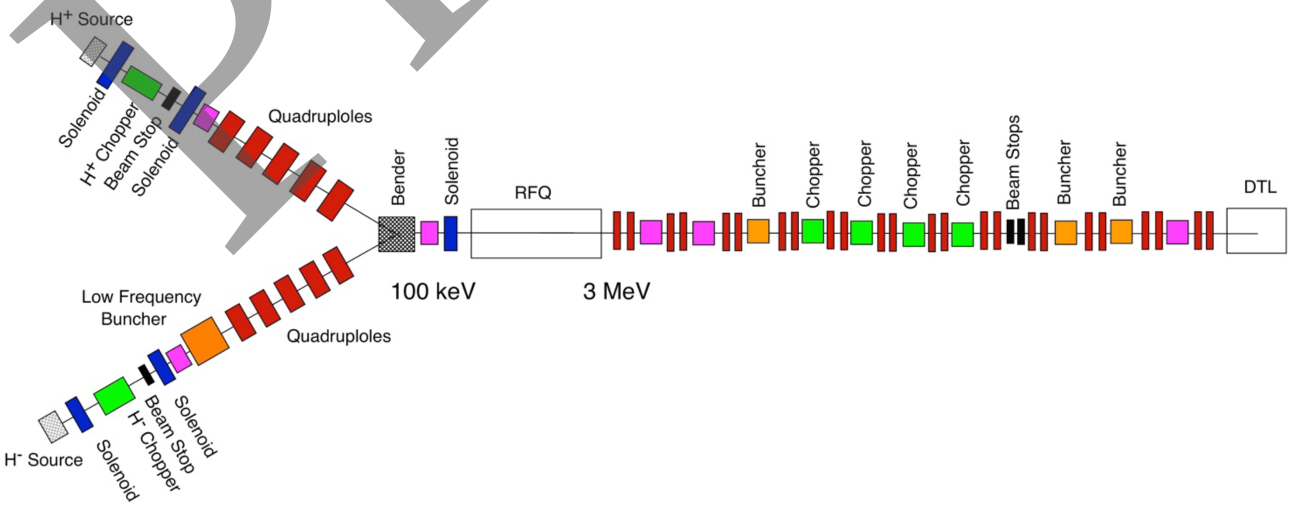

Figure 1: Layout of the proposed LANSCE Front End with distributed beam chopping.

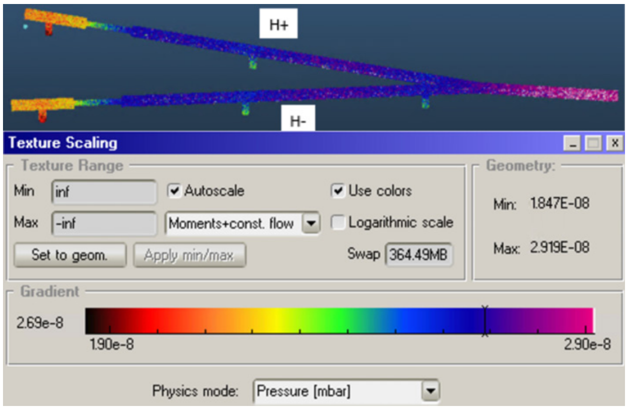

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Figure 2: Vacuum simulation using Molflow program [6].

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

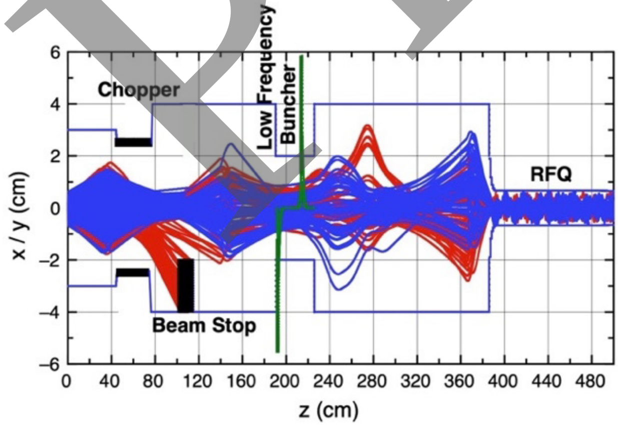

Figure 3: LEBT dynamics of 25 ns chopped H$^-$ WNR beam pulse with subsequent bunching by the 10.0625 MHz Low Frequency Buncher: (red) vertical, (blue) horizontal.

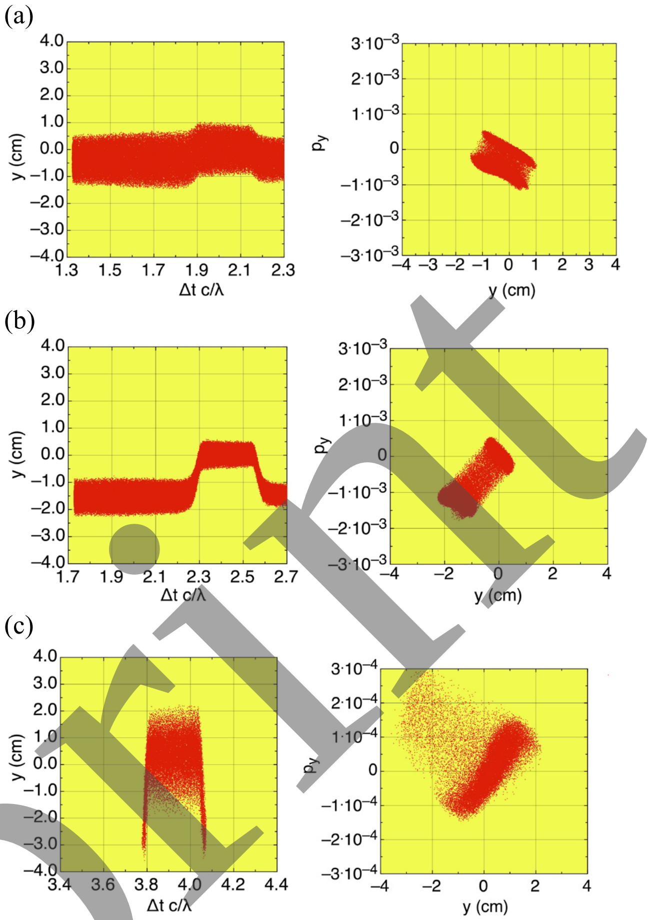

Figure 4: (Left) vertical beam profile and (right) vertical beam emittance in LEBT chopper: (a) inside chopper, (b) after chopper, (c) after chopper beam stop.

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

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

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

where traveling-wave variable ξ is

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

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. A good approximation of the chopper pulse 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

$$t_{front} = \sqrt{t_{trans}^2 + t_{gen}^2 + ..} \quad . \tag{5}$$

Figures 3 and 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 LEBT are presented 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.

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 (see Fig. 5 and Fig. 6).

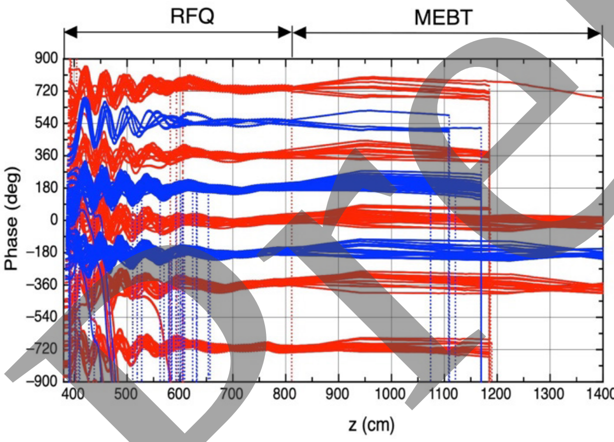

Figure 5: Phase trajectories of simultaneous acceleration and MEBT transport and chopping of (red) H^+ IPF beam and (blue) H^- WNR beam.

Medium Energy Beam Transport (MEBT) is designed as a beamline 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_oT = 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.

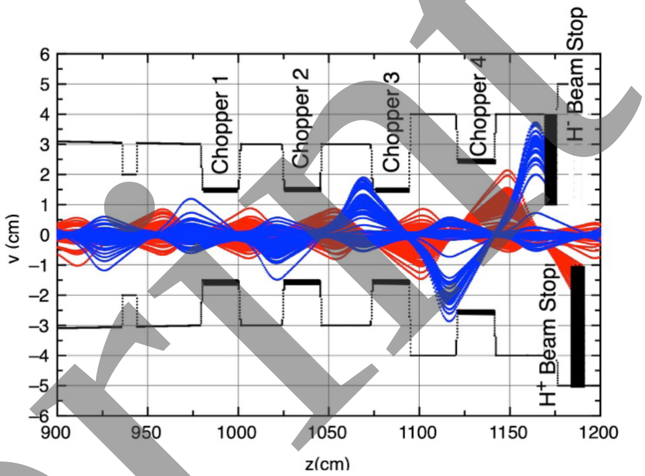

Figure 6: 3-MeV Medium Energy Beam Transport chopping of (red) H^+ IPF proton beam and (blue) H^- WNR beam.

ACKNOWLEDGEMENT

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REFERENCES

[1] K. W. Jones and P. W. Lisowski, “LANSCE High Power Operation and Maintenance Experience”, in *Proc. 6th Int. Top. Meeting Nucl. Appl. Accel. Technol. (AccApp’03)*, p. 372, San Antonio, TX, USA, Jun. 2003.

[2] Y. K. Batygin, D. Gorelov, S. S. Kurennoy, J. W. Lewellen, N. A. Moody, and L. Rybarcyk, “Advancement of LANSCE Front End Accelerator Facility”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1894-1896. `doi:10.18429/JACoW-IPAC2021-TUPAB205`

[3] Y. K. Batygin *et al.*, “Novel Multi-Beam Front End for LANSCE Acceleration Facility”, *J. Phys.: Conf. Ser*, vol. 2687, p. 052006, 2024. `doi:10.1088/1742-6596/2687/5/052006`

[4] Y. Batygin, “Low energy multi-beam dynamics in novel LANSCE front end”, in *Proc. LINAC'24*, Chicago, IL, USA, Aug. 2024, pp. 40-43. `doi:10.18429/JACoW-LINAC2024-MOAA010`

[5] Y. K. Batygin, I. N. Draganic, C. M. Fortgang, and G. Rouleau, “Space Charge Neutralization of Low Energy H-Beam”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper TUPWA066, pp. 1856-1858.

[6] Molflow code, `https://molflow.docs.cern.ch`

[7] H. F. Dylla, D. M. Manos and P. H. LaMarche, “Correlation of outgassing of stainless steel and aluminum with various surface treatments,” *J. Vac. Sci. Technol. A* 11, vol. 11, no. 5, pp. 2623-2636, Sep, 1993. doi:10.1116/1.578617

[8] Y. K. Batygin, “Particle-in-cell code BEAMPATH for beam dynamics simulations in linear accelerators and beamlines”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 539, no. 3, pp. 455-489, Mar, 2005. doi:10.1016/j.nima.2004.10.029

[9] Y. Batygin, “Critical design issues of the novel multi-beam LANSCE front end”, in *Proc. NAPAC'25*, Sacramento, CA, USA, Aug. 2025, pp. 985-989. doi:10.18429/JACoW-NAPAC2025-THP020