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CRITICAL DESIGN ISSUES OF THE NOVEL MULTI-BEAM LANSCE FRONT END

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Abstract

The proposed novel 100 MeV injector for the modernization of the LANSCE Accelerator Facility aims to replace the existing injector based on 750-keV Cockcroft-Walton columns. The specific feature of the LANSCE accelerator is the simultaneous delivery of beams with multiple beam flavors to several targets. The acceleration of various beams in a single RFQ provides less flexibility for optimizing acceleration and focusing parameters compared to the existing LANSCE setup, due to differences in beam current, charge per bunch, and beam emittances. An important issue in the low-energy beam transport of the injector is the different degrees of space charge neutralization of the multi-component beam. Coupling between degrees of freedom in the presence of strong space charge forces of the beams results in unavoidable beam mismatch in the Front End and requires careful six-dimensional matching of beams with accelerator structures. The paper discusses key issues in the proposed Front End and proposes ways to mitigate them.

INTRODUCTION

LANSCE linear accelerator [1] 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 [2]. This accelerator facility simultaneously delivers various beams to multiple targets. 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). To reduce long-term operational risks and to realize future beam performance goals in support of the laboratory missions, we developed a novel Front End including a high-brightness Radio-Frequency Quadrupole (RFQ) based injector [1, 3, 4].

LOW ENERGY BEAM TRANSPORT

The conceptual layout for the new RFQ-based system contains a 100-keV injector with a 3-MeV RFQ (see Fig. 1). Planned low-energy injector includes two independent transports merging H^+ and H^- beams at the entrance of the RFQ. Beamlines are aimed at performing beam matching with subsequent simultaneous acceleration of H^+/ H^- beams with multiple beam flavors in a single RFQ. Multi-beam structure is achieved with beam chopping and bunching in LEBT.

Because H^- beam leg accommodates 2 different types of beams (LBEG/UCN/pRad and WNR), the transverse matching assumes adjustment of eight Twiss parameters to the RFQ. From the operation experience of exiting the LANSCE facility, it follows that matching of multiple beams requires empirical adjustment of Low Energy Beam Transport (LEBT) elements, since different H^- beams have different emittances and charge per bunch. It is required to have a sufficiently large number of independently controlled focusing elements in LEBT. Figure 1 illustrates the LEBT design with 2 solenoids and 5 quadrupoles per leg, with an additional solenoid in the common LEBT beamline. The 3-MeV Medium Energy Beam Transport contains several choppers and rebunchers to match beams to the novel DTL. After RFQ and MEBT, beams are accelerated in the Drift Tube Linac from 3 MeV up to 100 MeV.

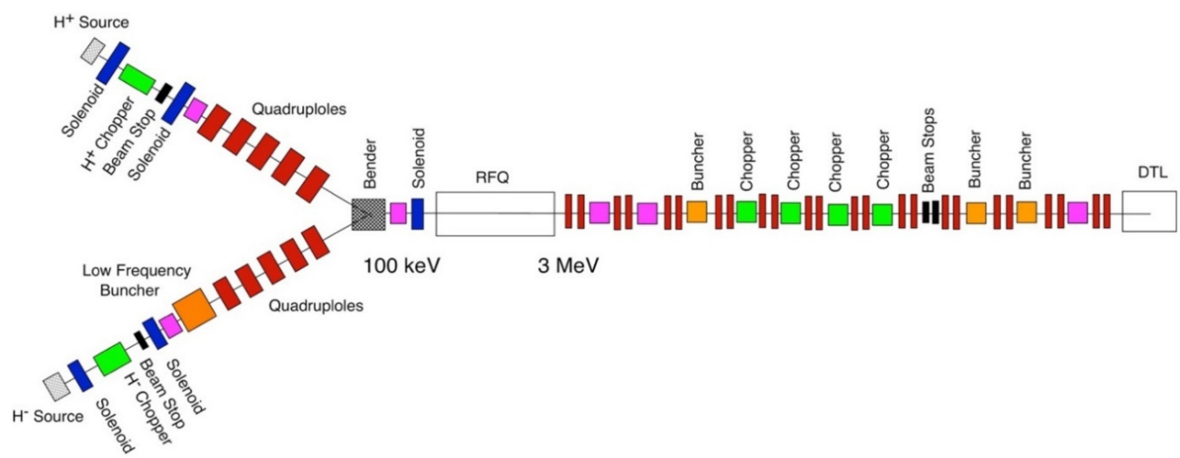

Figure 1: Layout of the proposed LANSCE Front End with distributed beam chopping.

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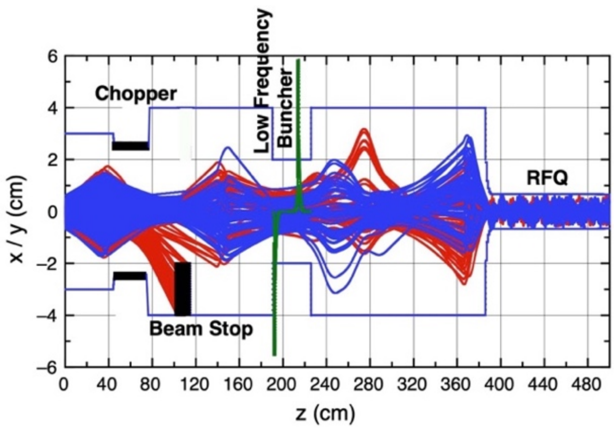

Figure 2: LEBT dynamics of 25 ns chopped H- WNR beam pulse with subsequent bunching by the 10.0625 MHz Low Frequency Buncher: (red) vertical, (blue) horizontal.

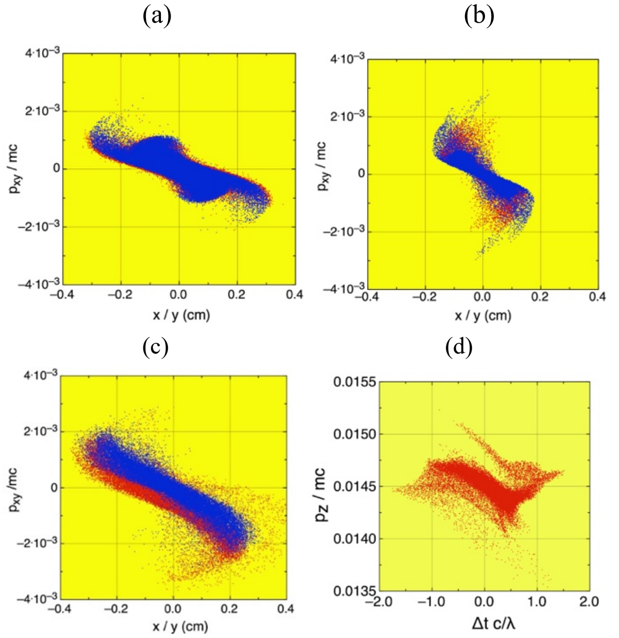

Figure 3: (a-c) transverse beam emittances at the injection to RFQ: (a) H- Lujan/UCN/pRad (b) H+ IPF, (c) H- WNR, (d) longitudinal emittance of H- WNR beam at the injection to RFQ.

The main difference between the novel Front End and the existing one is the space charge-dominated beam dynamics in LEBT. An important issue in the proposed injector is the different space charge neutralization of the low-energy beams. The time required for the ionization of residual gas by the incoming 100 keV beam under the pressure of residual gas $3\cdot10^{-6}$ Torr is estimated as $\tau_N = 56$ µs. Since the Lujan beam pulses are 625 µs long, such a beam would be fully space charge neutralized, which was observed experimentally in LANSCE 80-keV H- Test Stand [5]. However, the WNR beam, as a combination of short single bunches, separated by long time intervals of 1.8 µs, will not be space charge neutralized. To avoid significant differences in LEBT beam dynamics for various beams, the space charge neutralization must be removed in LEBT. It can be achieved with a deep vacuum of at least 10^{-8} Torr.

BEAM INTENSITY LIMITATION IN LEBT

The significance of space charge on beam dynamics is measured as a ratio of depressed betatron tune, μ, to an undepressed betatron tune, μ_o:

$$\frac{\mu}{\mu_o} = \sqrt{1 - \frac{2I}{I_c(\beta\gamma)^3\mu_o^2}\left(\frac{S}{R}\right)^2}\ , \quad (1)$$

where I is the beam current, S is the focusing period, R is the average beam radius, and $I_c = 4\pi\varepsilon_o mc^3/q$ is the characteristic beam current. Beam emittance growth due to space charge in transport systems is estimated as [6]:

$$\frac{\varepsilon_f}{\varepsilon_i} = \sqrt{1 + \left(\frac{\mu_o^2}{\mu^2} - 1\right)\frac{\Delta W}{W}}\ , \quad (2)$$

where $\Delta W / W \sim 0.02$ -0.15 is the "free energy" factor. For analysis, it is convenient to introduce dimensionless beam brightness $b = (\mu_o / \mu)^2 - 1$, which can be written as:

$$b = \frac{2}{\beta\gamma}\frac{I}{I_c}\left(\frac{R}{\varepsilon}\right)^2, \quad (3)$$

where ε is the transverse normalized beam emittance. To prevent significant emittance growth, the ratio of depressed to undepressed betatron tune should not be smaller than 0.4 [7], which corresponds to the maximal value of dimensionless beam brightness $b_{\max}$ =5.25 limiting beam current in a transport with given beam radius and emittance.

The value of the beam radius in LEBT is determined by the requirement to provide sufficiently long beam drift before beam waists for the placement of the chopper, Low Frequency Buncher, and merging area of the H+/ H- beams. For space charge dominant beam drift, the maximal beam current that can be transported through the drift space of length L_d is $I_{\lim} = 1.17 I_c (\beta\gamma)^3 (R/L_d)^2$ [6], where R is the beam size at the beginning and at the end of the drift space. From that expression, the beam radius is:

$$R = L_d\sqrt{0.85\frac{I_{\lim}}{I_c(\beta\gamma)^3}}\ . \quad (4)$$

Combining equations (3) and (4), the limited beam current to avoid significant emittance growth is:

$$I_{\lim} = \frac{I_c}{1.3}\sqrt{b_{\max}}(\beta\gamma)^2\frac{\varepsilon}{L_d}\ . \quad (5)$$

Assuming L_d =0.9 m, ε = 10^{-6} m, the value of maximal beam current to avoid significant emittance growth is $I_{\lim}$ = 13 mA, which is 30% larger than that in the present operation of the LANSCE facility. The further increase of beam current is restricted by the H- intra-beam stripping effect in the high-energy part of the machine, which increases beam loss as the square of the bunch population [8].

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Table 1: Normalized Transverse RMS Beam Emittance (π mm mrad) and Charge per Bunch in the Proposed LANSCE Front End

Beam (Facility)	Source	100 keV	3 MeV	Q/b (pC)
H^-(Lujan/ pRad/UCN)	0.2	0/26	0.45	60
H^- (WNR)	0.2	0.47	0.68	125
H^+ (IPF)	0.03	0.12	0.17	20

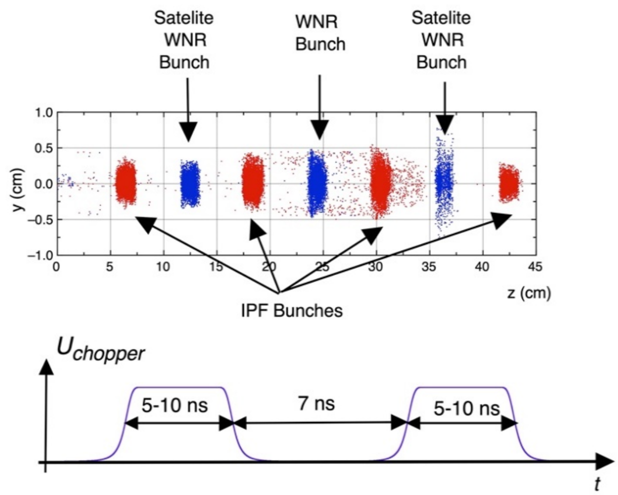

Figure 4: Time structure of H^- WNR and H^+ IPF bunches after RFQ, and required MEBT chopper time pattern.

The offered Front End scheme (see Fig. 1) is designed to minimize emittance growth and beam mismatch in front of the RFQ. Figure 2, Fig. 3, and Table 1 illustrate beam dynamics and beam emittance growth in LEBT.

BEAM CHOPPING AND BUNCHING

Operation of the LANSCE facility requires the creation and injection of highly charged WNR bunches in the RFQ. WNR beam is a sequence of single bunches, followed by a frequency of 0.56 MHz. Each WNR bunch is first cut from the DC beam with a short chopper pulse. The chopped beam pulse goes through the Low Frequency Buncher and receives modulation in longitudinal momentum. Then, in drift space, the WNR bunch rotates in longitudinal phase space and, after compression, is accommodated in the 201.25 MHz RF bucket of the RFQ.

Analysis shows that the maximal drift space from the Low Frequency Buncher to the point of longitudinal beam waist is:

$$L_{WNR} = 0.765 \frac{R_{LFB}}{\sqrt{K_z}}, \quad (6)$$

where R_{LFB} is the longitudinal bunch radius in Low Frequency Buncher, K_z is the longitudinal space charge parameter:

$$K_z = \frac{Qc}{I_c R(\beta\gamma^2)^2}, \quad (7)$$

and Q is the charge accumulated in the WNR bunch.

Analysis of chopper systems was done in Ref. [9]. The longitudinal bunch size, $2R_{LFB} = \beta c \tau_{WNR}$, is determined by the chopping pulse τ_{WNR}, which is affected by the power supply rise time and edge field of the chopper [10]. The transient time in a traveling wave chopper with an aperture a = 5 cm is $\tau_t \approx a/(\beta c)$ = 11.4 ns. Selecting the chopper pulse as τ_{WNR} = 25 ns, the value of the beam size in the chopper is R_{LFB} = 5.5 cm. After the chopper, the longitudinal beam size is increased up to R_{LFB} = 7 cm in a drift space between the chopper and the Low Frequency Buncher. The charge accumulated in a single chopped WNR pulse is $Q = I\tau_{WNR}$ = 13 mA x 25 ns = 325 pC. Assuming a transverse beam size in LEBT as R =1.5 cm, the value of $K_z = 9.75 \cdot 10^{-4}$, and the optimal beam drift is L_{WNR} = 1.7 m. After the Low Frequency Buncher, the longitudinal beam radius is compressed as $R_w = R_{LFB}/2.35$ =2.98 cm (see Fig. 3d). Therefore, at the injection to RFQ, the longitudinal bunch size, 2 R_w = 2.7 $\beta\lambda$, is larger than the longitudinal RF bucket. It results in the appearance of satellite WNR bunches after RFQ (see Fig. 4), which must be removed by the Medium Energy Beam Transport choppers (see Fig. 1).

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