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Design of low energy beam transport for new LANSCE H^+ injector

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ABSTRACT

The present LANSCE injector utilizes two 750-keV Cockcroft–Walton (CW) based injectors for simultaneous injection of H^+ and H^- beams into 800-MeV accelerator. To reduce long-term operational risks, the new project to replace the existing H^+ CW injector with a Radio-Frequency Quadrupole (RFQ) accelerator is underway [1]. The new injector requires a Low-Energy Beam Transport (LEBT). An ion source and 2-solenoid magnetic LEBT have been designed and optimized to transport beams over a wide range of space-charge neutralization and transverse emittance, while allowing sufficient space for diagnostics and a beam deflector. The design layout minimizes the beam size in the LEBT and potential emittance growth due to solenoid aberrations and nonlinear space-charge forces. This paper describes the details of the LEBT design activity.

1. Design issues of the low-energy beam transport

A low-energy beam transport (LEBT) line is required to connect the particle source with the subsequent accelerating section of the RFQ. The LEBT performs the following functions:

- extraction and low-energy acceleration of the beam
- match beam out of the ion source to the transport channel
- match the beam into the subsequent RF accelerating structure
- provide beam diagnostics and test facilities
- provide fast switching (chopping) before the RFQ to introduce a time structure to the beam

A critical issue for the LEBT design is minimization of beam emittance growth. The main sources of emittance growth and beam halo formation in the LEBT are:

- irregularities in the plasma meniscus extraction surface
- aberrations due to ion-source extraction optics
- optical aberrations of the focusing elements of the LEBT
- non-linearity of the electric field created by the beam space charge
- beam fluctuations due to ion-source instability or power regulation

Typical LEBT designs are based on electrostatic or magnetostatic focusing. Advantages and disadvantages of both schemes can be summarized as follows [2]:

Magnetostaic LEBTs usually contain 2 or 3 solenoids, beam diagnostics, and chopper elements. The major attractive feature of magnetic focusing is based on the fact that the beam might be fully neutralized by residual gas present in the line. The magnetic field of the solenoids does not affect the cloud of ion-electron plasma resulting from beam ionization of the residual gas. Therefore, emittance growth due to nonlinear space-charge forces can be minimized or eliminated completely in a magnetostatic LEBT. The gas in the LEBT comes mainly from the ion source, however, better neutralization can be achieved by adding to the H_2 gas in the LEBT heavier gases such as Kr of Xe. Experimental results indicate significantly improved beam neutralization and less deterioration of emittance of transported beam in a heavy gas [3].

One disadvantage of using space charge neutralization to reduce space-charge induced emittance growth is that it takes some time to develop (from several μs to several tens of μs). During this time, the beam is significantly mismatched with the structure, and, in most cases, is lost. This phenomenon might be controlled by chopping of the beam at the end of the LEBT to prevent the mismatched part of the beam pulse to be injected into the subsequent RF accelerator. Choppers are also required to create a certain beam timing structure, especially in the case of subsequent injection of the beam pulse into a ring.

In an electrostatic LEBT, the focusing is provided by Einzel lenses. Focusing of low-energy ions using an electric field is more effective than using a magnetic field. However, in an electrostatic LEBT, the beam is fully un-neutralized resulting in strong beam filamentation in phase space and, eventually, in significant emittance growth. Although electrostatic LEBTs can be very compact, they are sensitive to beam losses which might result in high-voltage breakdowns and

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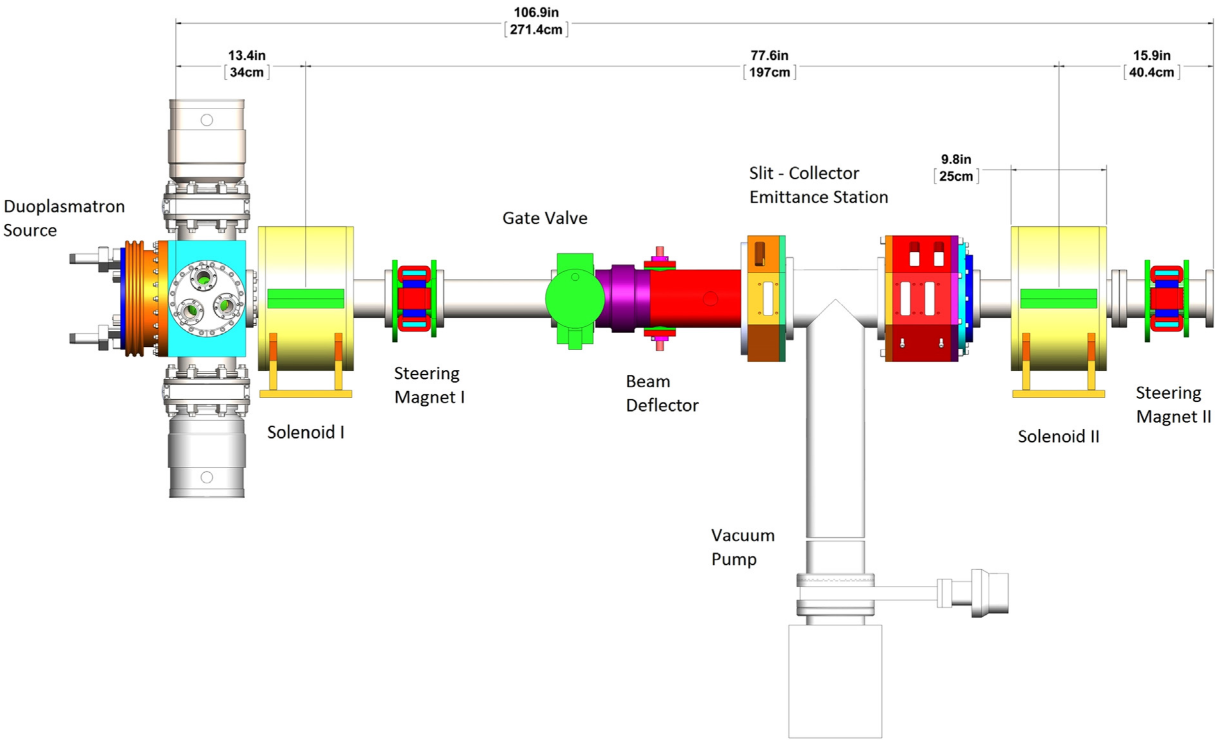

Fig. 1. Layout of LEBT with ion source and 2 solenoids.

beam trips. Einzel lenses also suffer from larger spherical aberrations, compared to magnetic lenses of the same focal length [4], which results in larger beam emittance growth. Because of the advantages of the magnetostatic LEBT, we have adopted this scheme for our new H^+ injector (see Fig. 1).

2. Ion source and extraction system

The ultimate goal of source and LEBT design is to maximize beam current while minimizing beam emittance. The current LANSCE H^+ duoplasmatron source is very reliable and has been used for decades. We will use the existing duoplasmatron source with a newly-designed extraction system. Presently at LANSCE, with a beam current $I \approx 15$ mA at 750 keV the measured rms-normalized beam emittance is $\varepsilon_{\rm rms} \approx 0.003\pi$-cm-mrad (Fig. 2). The second beam seen in the figure is H_2^+. The measured ratio $\varepsilon_{\rm total}/\varepsilon_{\rm rms} = 5.7$ is indicative of a waterbag distribution where $\varepsilon_{\rm total}/\varepsilon_{\rm rms} = 6.0$ (also true for Gaussian distribution, truncated at some sigma). For our LEBT design with 35 mA of extracted current we assume the rms normalized emittance of $\varepsilon_{\rm rms} = 0.0075\pi$-cm-mrad.

Fig. 3 shows the extraction geometry for the 35-keV source. The source design was done using the finite element code TRAK [5]. The code is used to adjust the electrode shapes to produce a uniform and laminar beam to minimize emittance growth due to nonlinear space charge fields and geometric optical aberrations in the first few centimeters downstream of the source aperture [6]. The relevant electrode parameters are: Pierce, extractor, electron suppressor and ground electrode apertures equal to 5 mm, 6 mm, 8 mm and 16 mm, respectively. The gap between the Pierce electrode aperture and the extractor electrode is 12 mm. The Pierce and electron suppressor electrodes are held at 35 kV and −2 kV, respectively. The extractor voltage is varied to minimize the emittance for each extracted beam current, mainly determined by the source plasma density and electron temperature (proportional to source arc current). In Fig. 4 the extractor gap voltage $\Delta V = 22.6$ kV corresponds to an extracted current of 18 mA. The maximum electric field is 3.44 kV/cm. To extract a beam current of 35 mA requires an extractor gap voltage of 35 kV; the maximum electric field is 5.3 kV/cm, which is still below our goal of $E_{\rm peak} < 7$ kV/cm.

3. LEBT design procedure

The approach outlined here follows Ref. [7]. The technique results in an optimized point design, where the desired matched beam has the minimal beam size possible in both solenoids for a given beam emittance and beam current. Minimizing beam size inside the solenoids results in minimization of solenoid power consumption, beam losses, lens aberrations, and beam emittance growth due to non-linear space-charge forces.

Consider a LEBT comprised of 2 solenoids, separated by a distance L (see Fig. 5). The beam is characterized by an unnormalized emittance $\ni$ and effective current

$$I = I_o(1-\eta), \quad (1)$$

where I_o is the total beam current and η is the space-charge neutralization factor. Initial envelope parameters R_s, R_s' are determined by extraction conditions from the ion source column. Final beam parameters R_f, R_f', are determined by the matching conditions at the front end of the RF accelerator. The purpose of the design is then to find appropriate solenoid parameters, and distances d_1, d_2.

For a fully space-charge compensated beam with negligible effective beam current, $I = 0$, the maximum and minimum values of the beta-function, $\beta_{\max}$, $\beta_{\min}$ in the channel are given by:

$$\beta_{\max} = \frac{L\cos^2(\theta/2)[1-(D/L)(1-((\tan\,\theta/2)/(\theta/2)))]}{\sin\,\mu_o}, \quad (2)$$