DESIGN OF A DUOPLASMATRON EXTRACTION GEOMETRY AND LEBT FOR THE LANSCE H^+ RFQ PROJECT *

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Abstract

The 750-keV H^+ Cockcroft-Walton at LANSCE will be replaced with a 4-rod RFQ with injection energy of 35 keV. The existing duoplasmatron source extraction optics need to be modified to produce up to 35 mA of H^+ current with an emittance <0.02 pi-cm-mrad (rms,norm) for injection into the RFQ. In addition to source modifications we need a new LEBT for transport and matching into the RFQ. The LEBT uses 2 magnetic solenoids with enough drift space between them to accommodate diagnostics and a beam deflector. The LEBT is designed to work over a range of space-charge neutralized currents and emittances. The LEBT is optimized in the sense that it minimizes the beam size in both solenoids for a point design of a given neutralized current and emittance. Special attention has been given to estimating emittance growth due to solenoid aberrations. Examples of source-to-RFQ matching and emittance growth (due to both non-linear space charge and solenoid aberrations) are presented over a range of currents and emittances about the design point. A preliminary mechanical layout drawing will also be presented.

INTRODUCTION

The LANSCE accelerator presently has 2 CWs for H^+ and H^- operation. The plan is to replace the H^+ CW with a 750-keV 4-rod RFQ being designed by IAP (Frankfurt) and Kress GmbH (with LANL input) and fabricated by Kress. The input energy of the RFQ is 35 keV at a maximum beam current of 35 mA. The design emittance for the RFQ input beam is 0.02 π-cm-mrad, rms-normalized. Presently the LANSCE users of H^+ require about 18 mA of extracted beam. The current H^+ duoplasmatron source is very reliable and has been used for decades at LANSCE. We will use the existing duoplasmatron source with a newly designed extraction system and LEBT for beam injection into the RFQ. For the LEBT a magnetic focusing system was chosen. Careful attention has been paid to the solenoid design so that emittance growth due to non-linear focusing terms is made negligible.

SOURCE EXTRACTION DESIGN

Figure 1 shows the extraction geometry for the 35 keV source. The source design was done using the finite element code TRAK [1]. The relevant parameters are: Pierce, extractor, electron suppressor and ground electrode apertures equal 5 mm, 6 mm, 8 mm and 16 mm, respectively. The gap between the Pierce aperture and the extractor is 12 mm. The Pierce and electron suppressor electrodes are held at 35 kV and -2 kV. The extractor voltage is varied to minimize the emittance for each extracted beam current, mainly determined by the source plasma density and T_e (proportional to source arc current). In Fig. 1 the extractor gap voltage (ΔV) is 22.6 kV and the extracted current is 18 mA. The maximum electric field is 3.44 kV/cm. For 35 mA of extracted current the extractor gap voltage is 35 kV and the maximum electric field is 5.3 kV/cm which is still below our goal of Epeak < 7 kV/cm. A cutaway view of the source design is shown in Fig. 2.

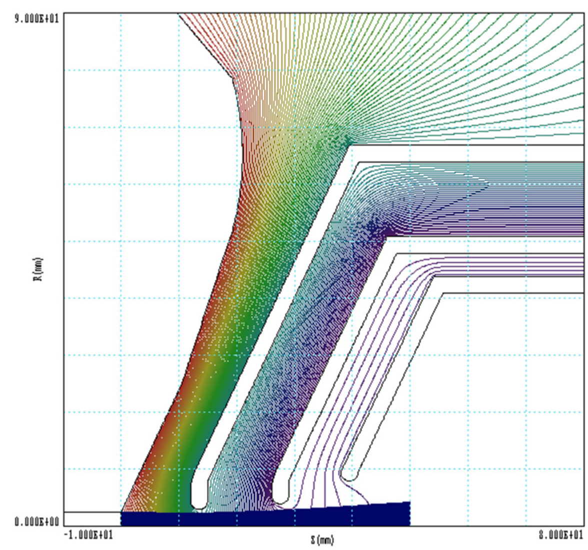

Figure 1: Electrode geometry and beam extraction for a 35 keV, 18 mA H^+ beam. Grid spacing is 10 mm/div.

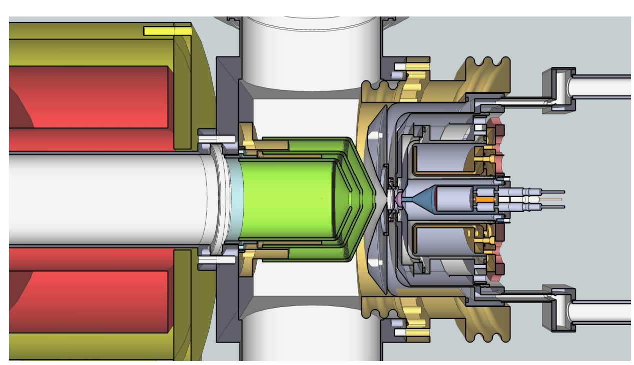

Figure 2: Duoplasmatron source is on the right. Extraction electrodes are in the center and the 1st LEBT solenoid is on the left. Pumps are above and below electrodes.

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The TRAK code was 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 optic aberrations in the first few centimeters downstream of the source aperture. Presently at LANSCE, with ≈15 mA of H^+ current at 750 keV the measured beam emittance is ≈ 0.004 π-cm-mrad, rms-normalized (Fig. 3). The second beam seen in the figure is H_2^+. The measured ratio $\varepsilon_{total}/\varepsilon_{rms} = 5.6$ is indicative of a waterbag distribution ($\varepsilon_{total}/\varepsilon_{rms} = 6.0$). For our LEBT design with 35 mA of extracted current we assume an emittance of 0.0075 π-cm-mrad.

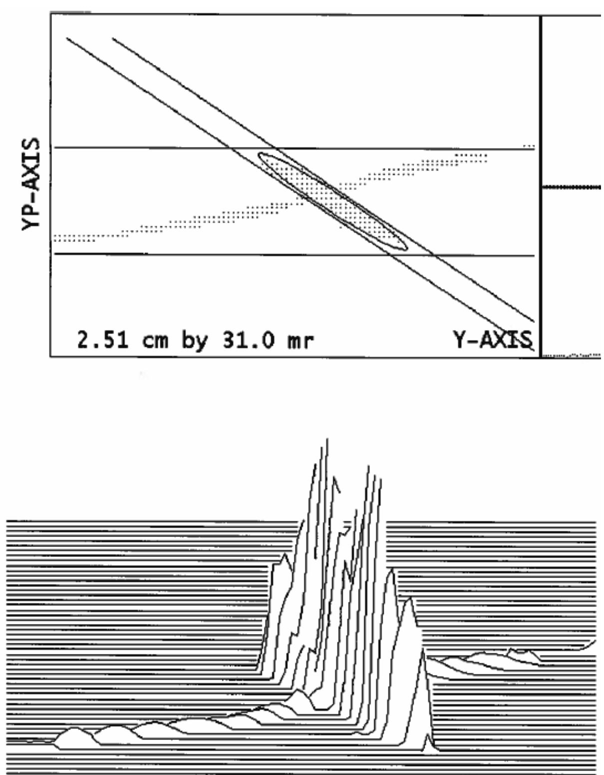

Figure 3: Measured H^+ transverse phase space at 750 keV for the LANSCE duoplasmatron source. H_2^+ beam is also observed.

LEBT DESIGN

A TRACE2D envelope simulation of the $4\varepsilon_{rms}$ beam is shown in Fig. 4.

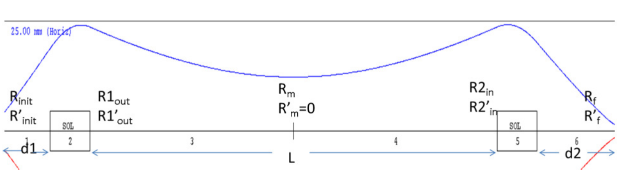

Figure 4: TRACE 2D envelope simulation with LEBT design variables defined. The source aperture is 50 mm upstream of the simulation starting point on the left.

A magnetic LEBT was selected instead of an electrostatic design so as to have a high degree of space charge neutralization via ionization of the background neutral gas. With less effective current, emittance growth due to the nonlinear space-charge force is reduced to a tolerable level. In addition, for the same focal length magnetostatic lenses have smaller aberrations than electrostatic lenses [2]. An electrostatic deflector (for beam gating), emittance diagnostic, steering magnet and valve (not shown) will be located in the drift between the 2 solenoids. Our design is an optimized point design [3] in the following sense: for a given drift distance L between solenoids, a beam waist at the center ($R'_m=0$), a given effective (partially neutralized) beam current, and a given beam emittance, there is one value for the beam size at the waist (R_m) that minimizes the beam size ($R1_{out} = R2_{in}$) in both solenoids. This is desirable to minimize emittance growth due to nonlinear solenoid focusing. Once the beam size at the waist, R_m, is determined then $R1_{out}$, $R1'_{out}$, $R2_{in}$ and $R2'_{in}$ are determined. With that information the beam is matched backwards to the source with d1 and the strength of the 1st solenoid (B1) as matching variables. Similarly, the beam is matched to the RFQ input with d2 and B2 as matching variables. If the beam current or emittance are different from the optimized point design parameters, the beam can still be matched to the RFQ using different solenoid strengths but the symmetry of the design is broken. The beam size in the solenoids will grow if either the emittance or current is larger than the point design. Table 1 gives the LEBT parameters.

Table 1: LEBT Parameters

ε initial rms- normalized	0.0075 π cm-mrad
Source to d1	50 mm
d1	204 mm
L	1800 mm
d2	346 mm
Solenoids effective length	176 mm
R max in solenoids	24.5 mm
R waist between solenoids	11 mm
R final	1.38 mm
R' final	- 31.4 mrad
B1 max	2758 Gauss
B2 max	2536 Gauss

SOLENOID DESIGN

An important aspect of the LEBT design is to minimize emittance growth. If the beam size in the solenoids is not small compared to the solenoid aperture then there will be emittance growth due to non-linear effects. To second order the deflection of an ion after traversing a solenoid is,

$$\Delta r' = - e^2 / (4\,(m\,\gamma\,v_z)^2) \times \int [\, Bz^2(0,z)\, r - \tfrac{1}{2}\, r^3\, Bz(0,z)\, \partial^2/\partial z^2\, (Bz(0,z)) \,]\, dz .$$

The first term in brackets is the usual linear focusing. The second term in brackets is non-linear. Smaller beams have less aberration because of the r^3 dependence.

Longer solenoids that result in the same deflection as shorter solenoids will also have less aberration. This comes from the $\partial^2/\partial z^2$ (Bz(0,z)) factor which makes less of a contribution to the line integral if the magnetic field profile is flat and sharp (long solenoids) as opposed to peaked and rounded (short solenoids). The integrated second derivative term is <0 so the overall effect of the second term is >0 and thus larger radii particles are over focused. It is more practical to make a solenoid longer than it is to make the aperture larger. After iterating on solenoid designs and particle simulations, we settled on an iron yoke design with the following specifications: solenoid physical length = 250 mm, effective length = 176.3 mm, aperture = 54 mm, and coil current density ≈ 4.1 Amps/mm^2. A solenoid of these dimensions causes a small but acceptable amount of emittance growth.

PARTICLE SIMULATIONS

To simulate the effects of both solenoid aberrations and nonlinear space charge on emittance growth in the LEBT we use the particle tracking code BEAMPATH [4]. Figure 5 shows particle tracks through the LEBT for a waterbag distribution. This distribution was selected based on the emittance measurement results previously discussed. Based upon measurement and calculations we expect the level of space charge neutralization to be ~ 90%. Therefore, the effective beam current is 3.5 mA. Qualitatively the beam is mostly laminar though some ray crossing is observed.

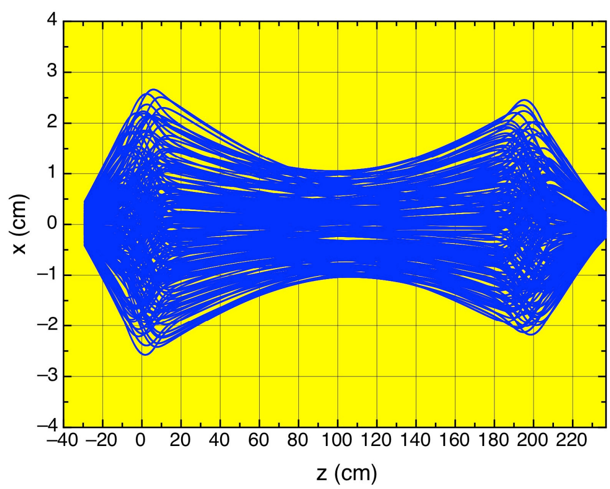

Figure 5: BEAMPATH simulation of matched beam in the LEBT. A waterbag distribution is assumed.

Figure 6 shows the emittance growth along the LEBT, again starting with a waterbag distribution and an effective current of 3.5 mA. The dashed line is the emittance growth with nonlinear space charge included but with the nonlinear solenoid focusing term turned off. The solid line includes the solenoid nonlinear focusing. The emittance growth due to solenoid aberrations is relatively small for the reasons given above. The simulated normalized rms emittance at the RFQ match point is comfortably below our requirement of 0.02 π cm-mrad.

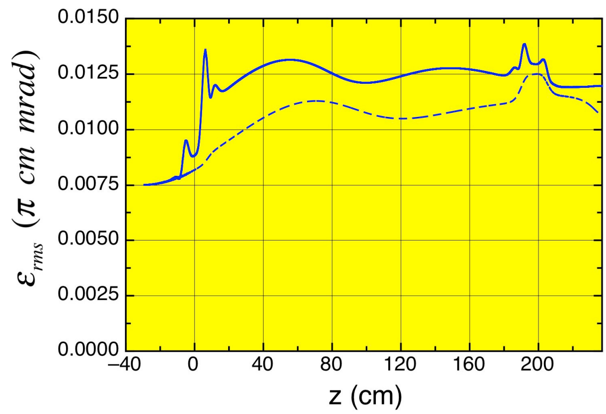

Figure 6: Emittance growth along the LEBT with (solid line) and without (dashed line) nonlinear solenoid focusing included.

SUMMARY

A new 35-keV extraction system for the H^+ duoplasmatron source and an optimized point design of a LEBT for matching into the H^+ RFQ has been presented. The physics design of the extraction system has been incorporated into a solid model. The LEBT design is optimized to minimize the beam size in the solenoids for the expected emittance, neutralized beam current, and desired drift space between the solenoids. Careful attention has been given to the solenoid design so that emittance growth due to nonlinear focusing is at an acceptable level. The physics design of the source extraction system and LEBT is complete and mechanical design will start this coming year.

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