Performance of SSC LINAC Injector*

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Abstract

The Superconducting Super Collider (SSC) LINAC Injector consists of an Ion Source, Low Energy Beam Transport (LEBT) and Radio Frequency Quadrupole accelerator (RFQ). The LINAC Injector is required to provide 25 mA of H⁻ beam (pulse width of 9.6- 48 μs at 10 Hz repetition rate) at 2.5 MeV with transverse normalized rms emittance ($\varepsilon_{t-n-rms}$) of less than 0.2 π mm-mrad and longitudinal normalized rms emittance (ε_l) of less than $0.82*10^{-6}$ eV-s. An RF-driven volume source was chosen for the initial commissioning of the SSC LINAC Injector. The RF volume source generates beams with $\varepsilon_{t-n-rms}$ as low as 0.06 π mm-mrad while meeting all other SSC ion source operating requirements (30 mA at 35 keV). The highly converging input beam required by the SSC RFQ is provided by a dual einzel lens. The initial experimental results from commissioning of the SSC LINAC Injector and experimental results pertinent to the performance of the SSC ion source and LEBT will be discussed.

I. INTRODUCTION

Figure 1 is a functional diagram of the SSC LINAC Injector (Injector) showing the H⁻ Ion Source, LEBT, and RFQ. Figure 2 shows the Injector at its temporary location at our R&D laboratory in Waxahachie, Texas. The Injector is scheduled to be moved to its permanent tunnel location later this year. First beam was successfully accelerated through the Injector on April 8th, 1993. With 30 mA from the 35 keV ion source, the Injector output current was 18 mA. After a brief description of the Injector subsystems, details of experimental results from the Injector output beam characterization will be presented.

II. INJECTOR SUBSYSTEMS

A. SSC H⁻ RF Volume Source

Multicusp plasma sources provide volume production of low energy (<2 eV) H⁻ ions leading to low emittance, high brightness beams. An RF driven volume H⁻ source, based on RF induction discharge, was developed for SSC by LBL [1] . A schematic of the SSC RF volume ion source is shown in Figure 3. The plasma is confined by the longitudinal line-cusp field produced by samarium-cobalt magnets that surround the source chamber and back flange. A pair of water-cooled permanent magnet filter rods placed near the plasma electrode creates a narrow region of transverse magnetic field which
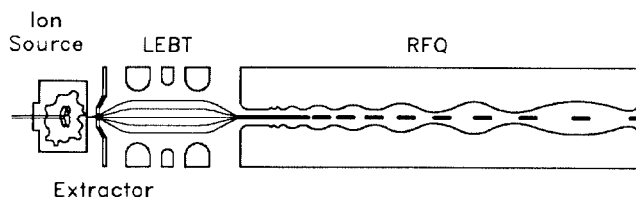
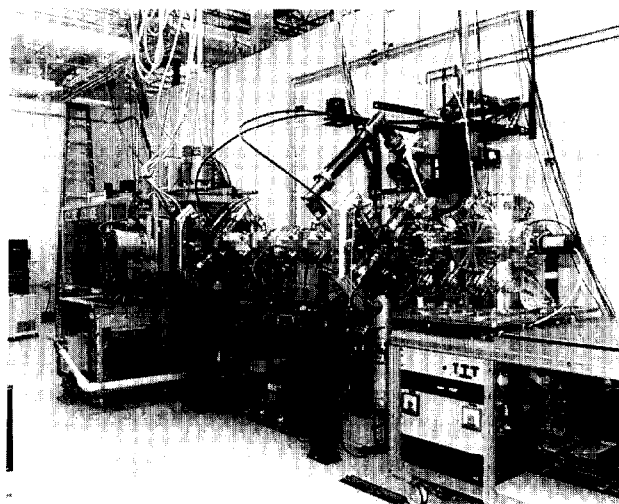Figure 1. Functional diagram of SSC LINAC Injector

Figure 2. SSC LINAC Injector

divides the source chamber into discharge and extraction regions. The 2 MHz RF power, with electrons supplied by a hairpin tungsten filament plasma starter, excites and ionizes the hydrogen gas molecules in the discharge region. The RF power is inductively coupled to the mixture via a two turn ceramic coated copper antenna. The magnetic field of the filter rods prevent the energetic plasma electrons from entering the extraction region. Cold electrons, the positive and negative ions, and the vibrationally excited hydrogen molecules can drift across this magnetic field forming a plasma in the extraction region with a low electron temperature . The cold plasma enhances the formation of H⁻ ions by dissociative attachment [2].

We have extracted H⁻ beam currents as high as 40 mA at 35 kV. The volume source has a high extracted electron to H⁻ ratio (30:1). These unwanted electrons are separated from the H⁻ beam by a 4 cm long magnetic spectrometer at the extractor electrode exit (Figure 3). The spectrometer's magnets are
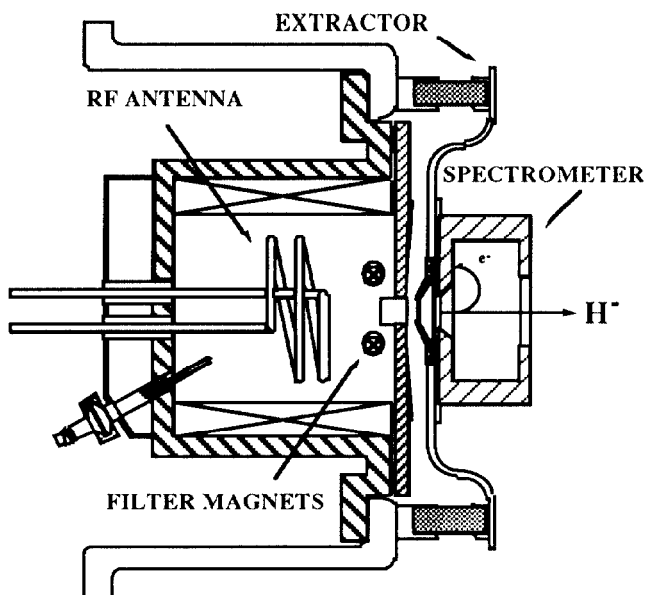
Figure 3. SSC H⁻ RF Volume Source

housed inside a soft iron envelope to prevent fringe field from penetrating the extraction gap and the volume source. Figure 4 is a close up of the RF volume source as part of the Injector assembly (the LEBT vacuum shell and portions of the RFQ are also shown).
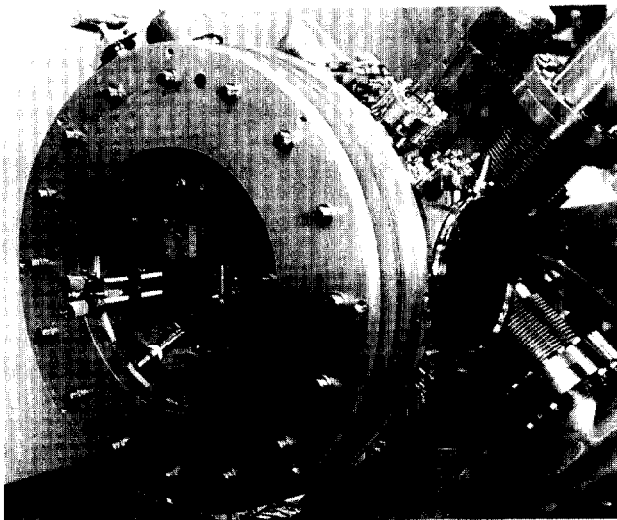

Figure 4. RF volume source as part of the Injector assembly.

Emittance measurements, at an axial position corresponding to the LEBT entrance (~ 5 cm downstream of extractor electrode), yield $\varepsilon_{t-n-rms}$ (rms normalized emittance extrapolated to 100% of the assumed Gaussian beam [3]) of 0.10 - 0.15 π mm-mrad. Smaller emittance [4], $\varepsilon_{t-n-rms}$ = 0.06 π mm-mrad, has been measured in the presence of Xe neutralizing gas which minimizes space charge effects. The actual H⁻ beam emittance out of the ion source is believed to

be closer to 0.06 π mm-mrad. Figure 5 shows a typical horizontal phase-space emittance contour plot of beam out of the volume source. The beam is highly diverging and is about 0.8 cm in radius.
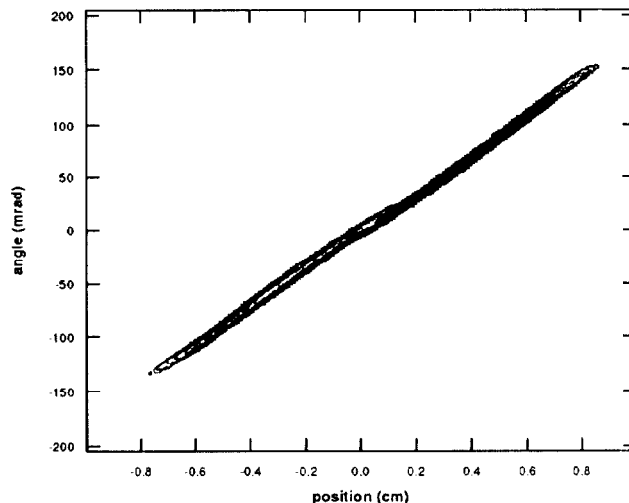

Figure 5. A typical ion source horizontal phase-space emittance contour plot

B. LEBTs

The divergent ion source beam is matched into the RFQ by the LEBT. The LEBT housing also contains source diagnostics and provides the differential pumping between the source and the RFQ. The SSC RFQ requires a highly convergent input beam. The Twiss parameters for the design input beam are $\alpha_{x,y}$ =1.26 and $\beta_{x,y}$ =0.018 mm/mrad (140 mrad convergence and ~ 4 mm in diameter).

A gas neutralized LEBT is not an option for SSC since the neutralization time (~50 μs) is longer than the SSC pulse length. Thus, electrostatic LEBTs were the only viable option. The 30 mA operating current is low enough that several electrostatic focusing concepts can be considered. The einzel lens and helical electrostatic quadrupole (HESQ) lens are the leading candidates for the SSC LINAC and their characteristics are being evaluated at the SSCL. The University of Maryland is investigating a straight electrostatic quadrupole (ESQ) LEBT concept [5] on our behalf and LBL is investigating a very compact single ring lens concept [6].

The einzel lens is probably the most mature technology for this application. Unfortunately this LEBT requires voltages similar to the source voltage which results in nonlinear aberrations. For the initial commissioning of the Injector, we are using an existing dual einzel lens LEBT optimized to meet the SSC magnetron ion source requirements. This choice was not the most desirable one but, in the interest of meeting our schedule, it was the logical choice.

The 30 mA output beam of the volume source and einzel LEBT configuration was characterized at 35 keV. Figure 6 shows a typical horizontal beam phase-space emittance contour plot out of the einzel lens at an axial location corresponding to the RFQ entrance. Nonlinear aberrations are quite pronounced. However, the shape of the vertical and horizontal phase-space
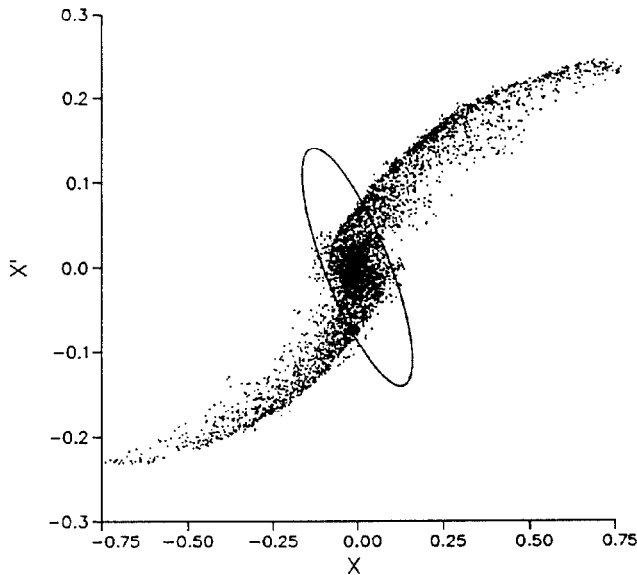
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Figure 6. LEBT Phase-space horizontal emittance contour plot

emittance contour plots are similar. The measured $\varepsilon_{t-n-rms}$ ranges between 0.38 π mm-mrad in the vertical plane to 0.79 π mm-mrad in the horizontal plane. This is 3- 5 times the ion source emittance. However, most of this LEBT induced effective emittance growth is due to the large, low particle-density, phase-space wings. As shown in Figure 6, the converging core of this beam, which contains the majority of particles, fits within the nominal acceptance space of the RFQ. Computer simulations [7] have indicated a 40-65% transmission of this beam through the RFQ. A 50% transmission, will provide a more than adequate Injector beam (15 mA) to commission the following stages of the SSC LINAC. Figure 7 is a close up of the einzel lens housing assembly as installed in the Injector. The ion source extractor and magnetic spectrometer are also shown in this figure.
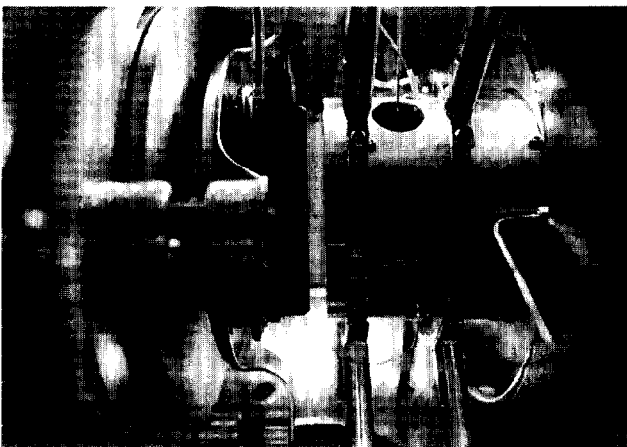

Figure 7. Einzel lens housing assembly

C. RFQ

The SSC RFQ is a four vane structure designed and built for SSC by LANL [8]. The design parameters of the SSC RFQ are given in Table I. The SSC RFQ has two unique features. First, the design included the effects of higher multipoles by using an 8-term electric field potential to optimize transmission. Second, the intervane voltage is ramped along the length of the RFQ to minimize the beam losses and structure length .
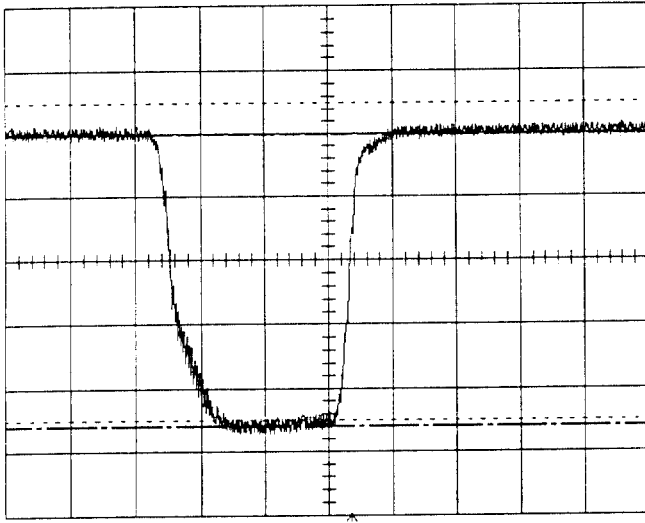
Table I
RFQ Design Parameters

Frequency	428 MHz
Injection Energy	35 keV
Output Energy	2.5 MeV
Injection current	30 mA
Output current	28 mA
RFQ length	218 cm
Input aperture radius	0.198 cm
Final aperture radius	0.240 cm
Final modulation factor	1.93
Intervane voltage	54.82 to 88.5 kV
Peak surface field	36 MV/m (1.8 K)
Cavity peak rf power	<300 kW
Input $\varepsilon_{t-n-rms}$	<0.2 π mm-mrad
Output $\varepsilon_{t-n-rms}$	<0.2 π mm-mrad
Output ε_l	<0.82*10⁻⁶ eV-s.
Output beam radius (rms)	0.75 mm

III. INJECTOR OUTPUT BEAM CHARACTERIZATION

A set of toroids and Faraday cups (FC) placed in various axial locations along the Injector are used to measure the output beam current and beam transmission through the RFQ. A Faraday cup can be inserted between the ion source and the LEBT to measure the ion source beam current and to block the beam from the rest of the Injector. A non-intecepting toroid in the LEBT measures the RFQ input beam current. At the RFQ output, the Injector current is measured by a toroid and a downstream FC. The Injector output beam current, as measured by the RFQ output FC is shown in Figure 8. The measured output beam shape is an exact duplicate of the measured ion source output beam current (Figure 9). The highest Injector output beam current achieved to date is 20 mA (for 30 mA input), this translates to a 66% transmission through the SSC RFQ.
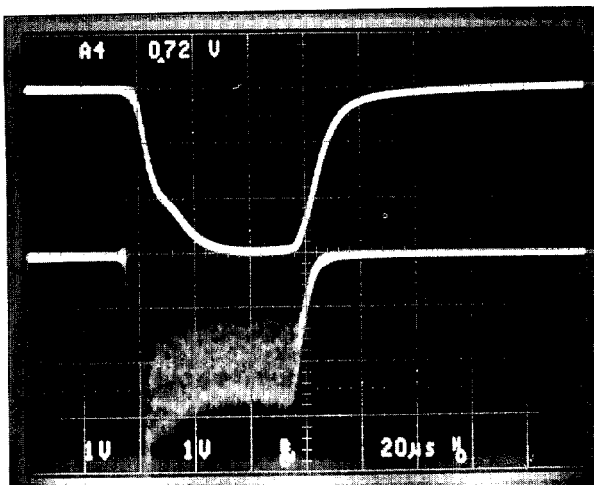
An absorber-collector experiment has bracketed the output beam energy to a value between 2.1 MeV and 3.3 Mev. In this experiment a 2.1 MeV range-thick foil, placed upstream of the output F.C., allowed the whole Injector output beam to be collected while a 3.3 MeV range-thick foil stopped the entire beam. This experiment also indicated a 100% accelerated beam at the nominal RFQ design field.

Figure 10. An Injector output beam horizontal phase-space emittance contour plot

Figure 8. Injector output current time profile

A slit & collector diagnostic [9] system has been used to measure the Injector beam emittance 21.6 cm downstream of the RFQ. Typical horizontal and vertical phase-space emittance contour plots of the Injector output beam are shown in figures 10 and 11, respectively. The elliptical contours are well defined and the measured emittance in the transverse planes are $\varepsilon_{x\text{-n-rms}} = \varepsilon_{y\text{-n-rms}} = 0.25 \pi$ mm-mrad. These values are 25% larger than the SSC LINAC Injector goal. However, the large emittance is believed to be due to the use of the non-optimized LEBT. We expect to improve the Injector output beam current and transverse emittance once the Injector is fully optimized and tuned.

A bunch shape monitor diagnostic built by INR [10] was used to determine the micro-bunch longitudinal phase profile. The beam hits a thin wire at a 10 kV potential and secondary electrons are emitted proportional to the beam intensity. The electron beam is collimated and "time stamped" with an rf deflector. The deflector phase (w.r.t. the output beam phase) is scanned, measuring the intensity of the electron beam at different times during the micro-pulse to produce an intensity versus phase profile. The first measurements of the SSCL bunch shape monitor are in good agreement with theory. Figure 12 shows a comparison of measured results with the theoretical model at nominal RF power, 15 cm downstream of
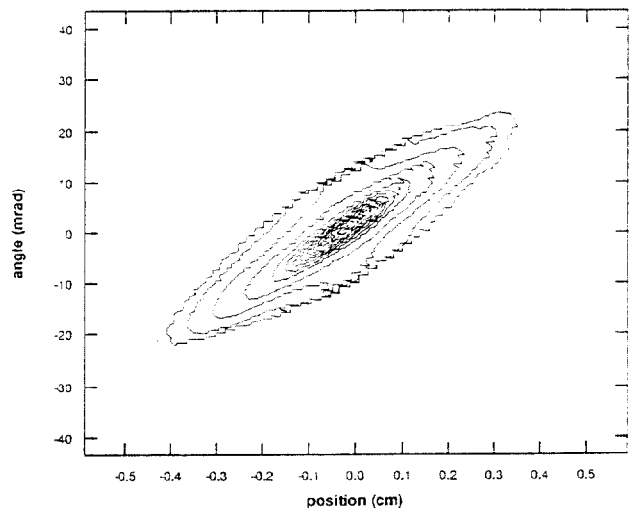
Figure 9. Ion source output current time profile

Figure 11. An Injector output beam vertical phase-space emittance contour plot

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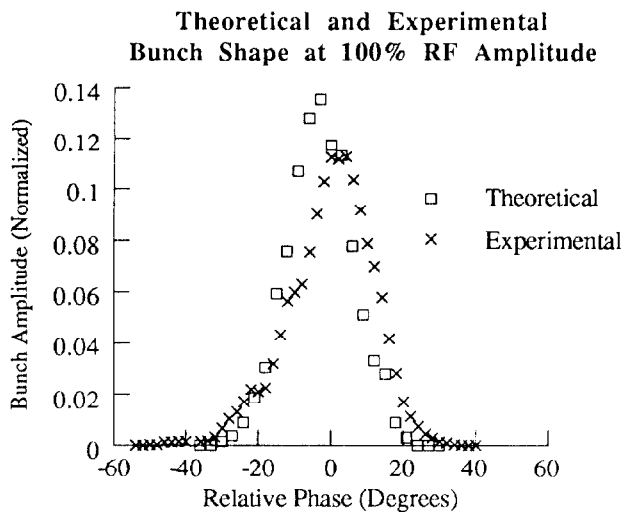**Theoretical and Experimental Bunch Shape at 100% RF Amplitude**

Figure 12. Theoretical bunch shape predicted by PARMTEQ simulation and experimental data as measured by the bunch shape monitor for nominal vane voltage. The intensity is normalized for a unit area.

the RFQ. The measurements indicate a well bunched beam with an rms micro-bunch length of 10 degrees.

IV. FUTURE WORK

In the near future, we are planning to measure the output beam energy more precisely using a magnetic spectrometer and Rutherford scattering diagnostics. We will continue the Injector output beam studies in an attempt to optimize the output beam characteristics in the next few months.

V. ACKNOWLEDGEMENTS

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