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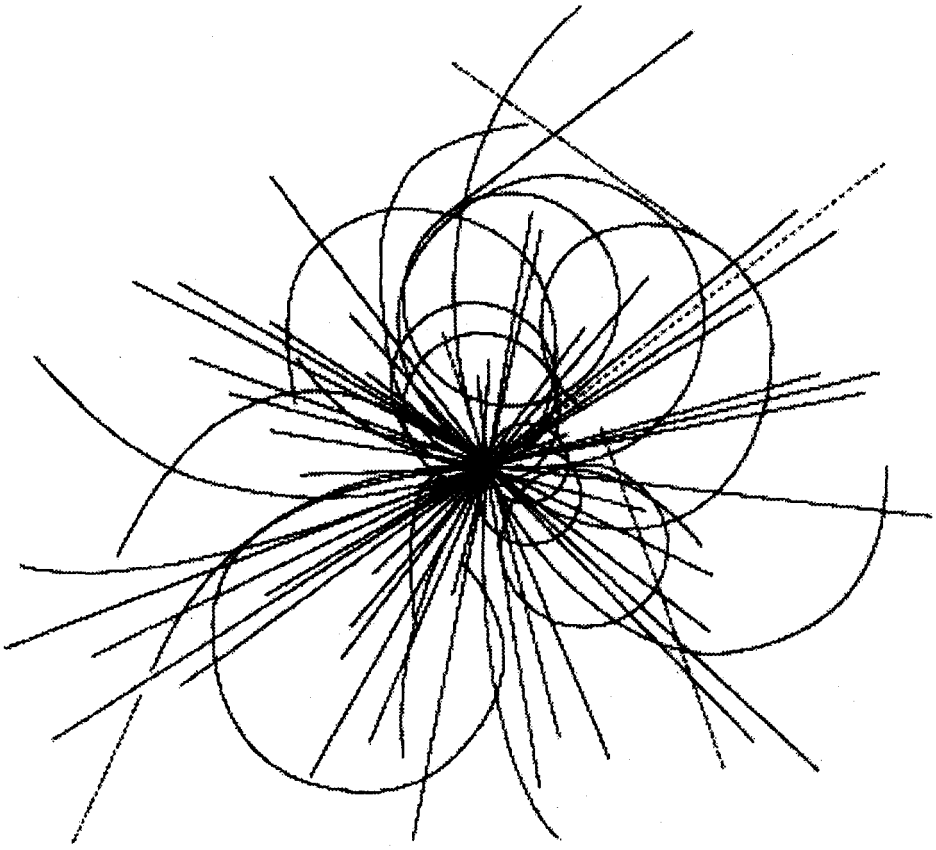

Superconducting Super Collider Laboratory

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Performance of the SSC H^- RF Volume Ion Source and Linac Injector*

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The Superconducting Super Collider (SSC) ion source is required to provide a 30-mA H^- beam at 35 keV with a normalized rms emittance ($\varepsilon_{n\text{-}rms}$) of less than 0.18 π mm-mrad. An rf-driven volume source was chosen for the commissioning of the SSC linear accelerator (Linac). The divergent ion source output beam is matched into the Radio Frequency Quadrupole accelerator (RFQ) by an electrostatic Low Energy Beam Transport (LEBT). The SSC Linac Injector (consisting of ion source, LEBT, and RFQ) 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 ($\varepsilon_{t\text{-}n\text{-}rms}$) of less than 0.2 π mm-mrad and longitudinal normalized rms emittance (ε_l) of less than $0.82*10^{-6}$ eV-s. The performance of our rf volume source and initial experimental results from the SSC Injector are discussed.

I. Introduction

Volume-produced, low-temperature (< 2 eV) H^- ions can be directly extracted from a multicusp plasma source to form a low-emittance and high-brightness beam. A pulsed rf-driven (2 MHz) volume H^- source was developed for the Superconducting Super Collider (SSC) by Lawrence Berkeley Laboratory (LBL) [1]. Presently, we are operating two rf volume sources. An R&D source has been under study on a test stand since May 1992, and an Injector source has been providing beam for the SSC linear

accelerator (Linac) Injector since April 1993. In this paper, the performance of the SSC rf ion sources and Injector will be discussed.

II. SSC Volume Sources

A schematic of the SSC Injector rf volume ion source is shown in Figure 1. The source chamber is made of a 10-cm-long by 10-cm-diameter copper cylinder with a back plate at one end and a plasma electrode at the other end. The plasma is confined by the longitudinal line-cusp field produced by rows of water-cooled, 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 that divides the source chamber into the discharge and the extraction regions.

In the discharge region, pulsed rf power is inductively coupled to a mixture of hydrogen gas and electrons (supplied by a hairpin tungsten filament) to ionize and excite the hydrogen gas molecules. Rf power coupling is accomplished via a two-turn, ceramic-coated copper antenna connected through an isolation transformer to a matching network that matches the impedance of the rf amplifier to the plasma. The magnetic field of the filter rods prevents the energetic plasma electrons from entering the extraction region. Cold electrons, positive and negative ions, and vibrationally excited hydrogen molecules drift across this magnetic field into the extraction region and form a low-temperature plasma. This cold plasma enhances the formation of H^- ions by dissociative attachment [2].

The rf volume source is operated in the pressure range of 15–25 mtorr at 30–50 kW of pulsed rf power (up to 1-ms pulse width). Beam is extracted through 35 kV across a single extraction gap. Unavoidably, a high-current electron beam is also extracted. At high powers, the electron-to-H^- ratio can be as high as 50:1, but we have achieved a ratio as low as 25:1 under nominal operating conditions. These electrons are separated from the H^- beam by a set of spectrometer magnets placed immediately downstream of the

extractor electrode. The separator magnets are housed inside a soft iron envelope (11 and 5 cm long for the R&D and Injector sources, respectively) to prevent fringe fields from penetrating the extraction gap and source. Figure 2 shows a typical H^- beam current (upper waveform, 30 mA) and electron current (lower waveform, 800 mA).

III. RF Volume Source Output Beam Characterization

To characterize the SSC rf volume source, we have measured the extracted H^- beam transverse emittance using a slit-and-collector diagnostic system [3]. These emittance measurements, at an axial position corresponding to the LEBT entrance (5 cm downstream of the extractor electrode for the Injector source and 12 cm for the R&D source), yield $\varepsilon_{t\text{-}n\text{-}rms}$ (rms normalized transverse emittance extrapolated to 100% of the assumed Gaussian beam [4]) of 0.11–0.18 π mm-mrad. Figure 3 shows a typical (30 mA @35 keV) Injector volume source output beam horizontal phase-space emittance contour plot. The beam is highly divergent with total envelope divergence angle ($\Delta\theta$) of 280 mrad, a diameter (D) of 1.6 cm, and $\varepsilon_{x\text{-}n\text{-}rms} = 0.16\ \pi$ mm-mrad. The output beam characteristics of the Injector and the R&D sources are summarized in Table I.

For our extractor optics geometry, a measured normalized rms emittance of 0.11 π mm-mrad suggests an H^- ion temperature of 5 eV [5], which is much higher than the expected 2 eV. With an ion temperature of 2 eV, one would expect a normalized rms emittance of 0.07 π mm-mrad. In our R&D set-up, with Xe neutralizing gas added to the drift region downstream of the extractor electrode to minimize space-charge effects, we have measured a much smaller emittance, $\varepsilon_{y\text{-}n\text{-}rms} = 0.07\ \pi$ mm-mrad ($\Delta\theta$ = 100 mrad, D = 1.1 cm) [6]. This result is consistent with the theory concerning space-charge induced emittance growth of the drifting beam at low energies. Thus, the actual H^- beam emittance out of our ion source is believed to be close to 0.07 π mm-mrad.

IV. Injector Output Beam Characterization

During Injector operation [7], when no neutralizing gas is present [8], the large and divergent ion beam from the Injector source is matched into the RFQ by an electrostatic LEBT. For initial commissioning of the Injector, we are using an existing dual einzel lens LEBT that is not optimized for the volume source. The SSC RFQ is a four-vane structure designed and built for the SSC by Los Alamos National Laboratory [9]. Figure 4 shows the Injector at its temporary location in our R&D laboratory at Waxahachie, Texas.

Figure 5 shows a typical einzel lens output beam horizontal phase-space emittance contour plot at an axial location corresponding to the RFQ entrance. Nonlinear aberrations are quite pronounced. However, the shape of the vertical and horizontal phase-space emittance contour plots are similar. The measured $\varepsilon_{t\text{-}n\text{-}rms}$ ranges from 0.38 π mm-mrad in the vertical plane to 0.79 π mm-mrad in the horizontal plane. This is several times the LEBT input 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 5, the converging core of this beam, which contains the majority of particles, fits within the nominal acceptance space of the RFQ. Computer simulations [10] have indicated up to 65% transmission of this beam through the RFQ. The highest Injector output beam current achieved to date is 20 mA (for 30 mA input).

An absorber-collector experiment [7] has shown 100% accelerated output beam at the nominal RFQ design field value. A Rutherford scattering experiment [11] has confirmed the results of the absorber-collector experiment and has measured the Injector output beam energy to be 2.5 MeV, within 50-keV accuracy. The results from a bunch shape monitor were in good agreement with theory and indicated a well-bunched beam with an rms micro-bunch length of 10 deg, 15 cm downstream of the RFQ [12]. The transverse emittance of the Injector output beam was measured by a slit-and-collector diagnostic system. A typical Injector output beam vertical phase-space emittance contour plot is shown

in Figure 6. These measurements have yielded transverse emittance measurements of $\varepsilon_{x\text{-}n\text{-}rms} = 0.2$ and $\varepsilon_{y\text{-}n\text{-}rms} = 0.19\ \pi$ mm-mrad, 21.6 cm downstream of the Injector (output current of 20 mA; 67% transmission).

V. Ion Source Extractor Optics Optimization

The ion source beam undergoes severe aberrations within the LEBT (see Figure 5). To minimize these aberrations and the resultant emittance growth, one is required to keep the beam small and within the linear region of the electrostatic field. Improving the single-gap extractor optics by means of shaping the electrodes could lead to reduced output beam size, total divergence, and possibly emittance. Different-shaped plasma apertures with inclination angles α (the angle between the beam and the electrode) of 30, 45, 55, and 67.5 deg were tried on the R&D ion source. The emittance, total envelope divergence, and beam diameter in each case were measured; the results are tabulated in Table II, along with the values from the unshaped ($\alpha = 90$ deg) electrode. It is clear that shaped electrodes can significantly improve the output beam quality. For the extraction geometry used in this experiment (extractor gap = 9 mm, plasma aperture diameter = 6.3 mm, extractor aperture diameter = 6.0 mm) a plasma electrode with $\alpha = 45$ deg resulted in the best beam. Being more compact, this beam will be more constrained to the linear field region at the entrance of the LEBT.

VI. Future Work

We have achieved the SSC beam requirements with the rf-driven volume source. Work is continuing to further optimize the extractor optics and to reduce the electron-to-H^- current ratio. The Injector output measurements thus far have shown that we have met all the Injector output requirements except the required output beam current. We are confident

that we can achieve the required 25-mA Injector output beam current by optimizing the extractor optics for the Injector ion source and designing a new LEBT based on the volume source output beam characteristics. However, the present 20-mA Injector output beam is more than adequate to commission the downstream components of the SSC Linac. We will continue the Injector output beam studies in an attempt to further optimize the output beam characteristics in the next few months.

VII. Acknowledgements

The authors thank K. N. Leung of LBL, and G. Arbique, F. Guy, J. Hurd, and D. Raparia of SSCL for many discussions. We also thank P. Datte, M. Haworth, J. Lenz, and S. Volz of SSCL for their assistance in running the ion source and the Injector.

VIII. References

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[7] K. Saadatmand et al., to be published in *PAC93 Proceedings*.

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[11] Gary Arbique, private communications.

[12] J. W. Hurd et al., to be published in *PAC93 Proceedings*.

Table I. Output beam characteristics of the Injector and the R&D sources.

	Injector source		R&D source	
	x	y	x	y
ε (π mm-mrad)	0.16	0.16	0.17	0.12
$\Delta\theta$ (mrad)	280	230	250	200
D (cm)	1.6	1.3	2.4	2.1

Table II. Emittance, total envelope divergence, and beam diameter for various-shaped plasma apertures.

	x			y		
α (deg)	ε (π mm-mrad)	$\Delta\theta$ (mrad)	D (cm)	ε (π mm-mrad)	$\Delta\theta$ (mrad)	D (cm)
90	0.17	247	2.5	0.12	210	2.1
67.5	0.12	208	2.0	0.11	220	2.1
55	0.12	200	1.8	0.10	192	1.6
45	0.12	200	1.9	0.09	187	1.5
30	0.10	250	2.2	0.12	250	2.1

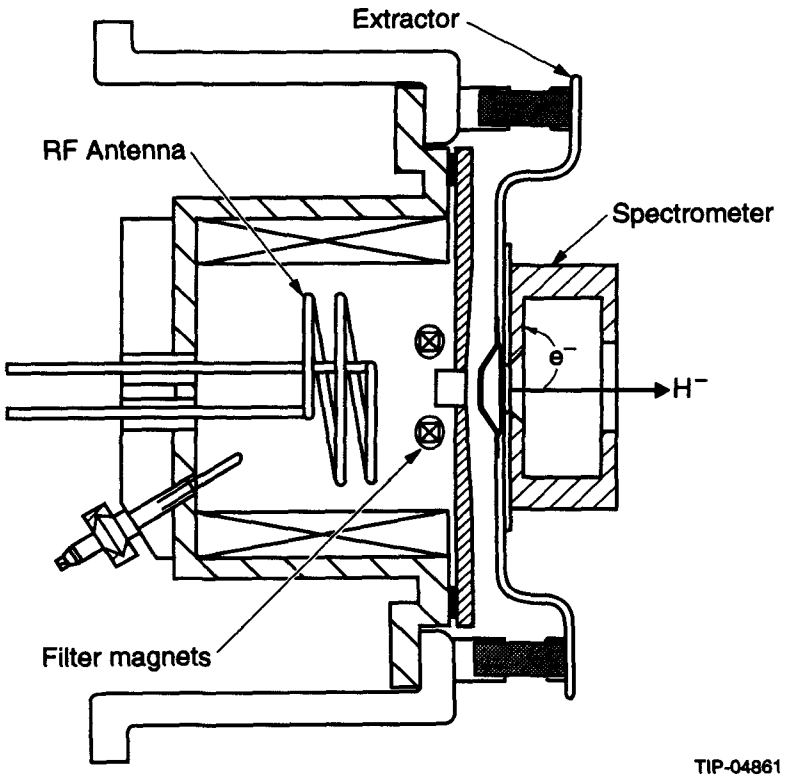

Figure 1. Schematic of the SSC Injector rf volume ion source.

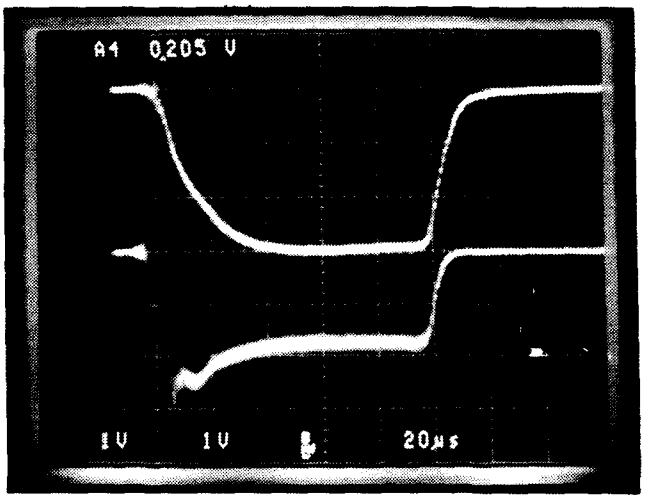

Figure 2. Typical H^- beam current (upper waveform, 30 mA) and electron current (800 mA).

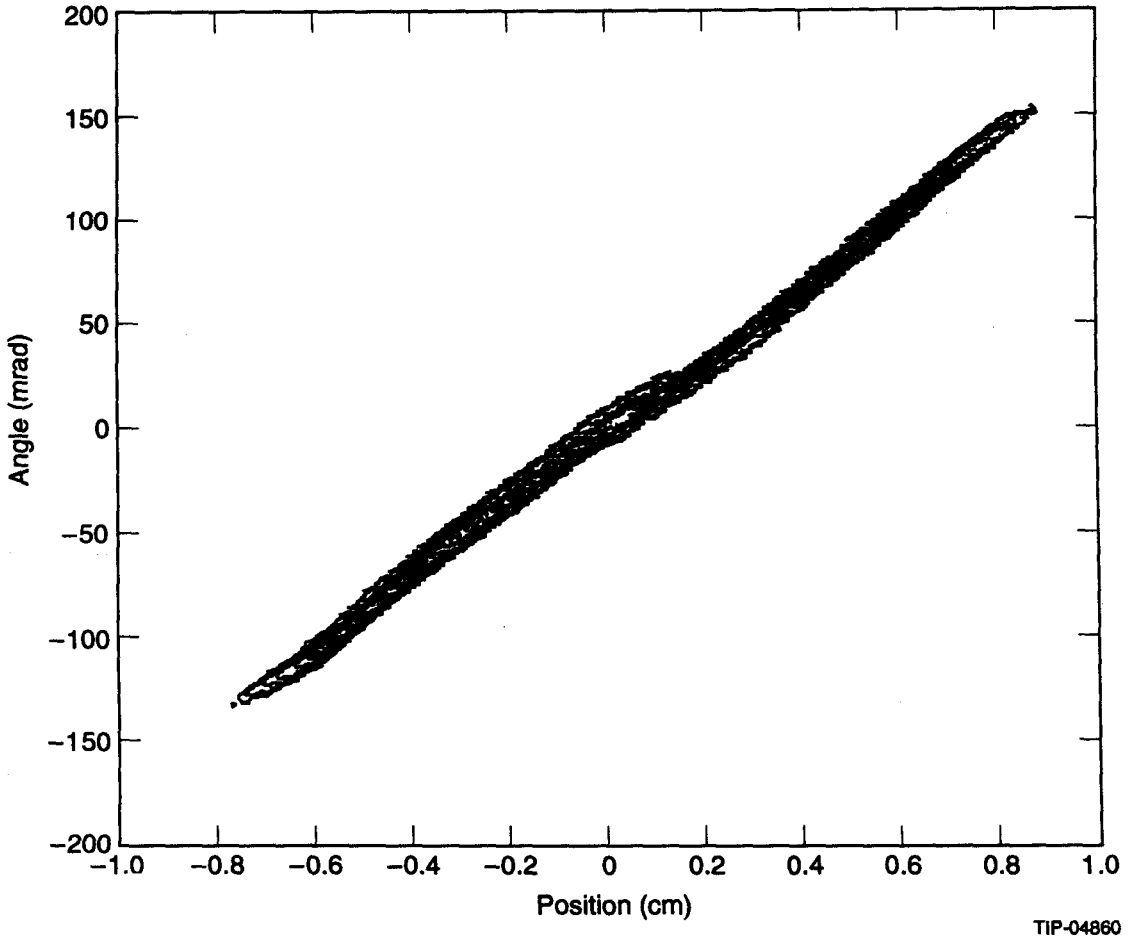

Figure 3. Typical (30 mA @ 35 keV) injector volume source output beam horizontal phase-space emittance contour plot.

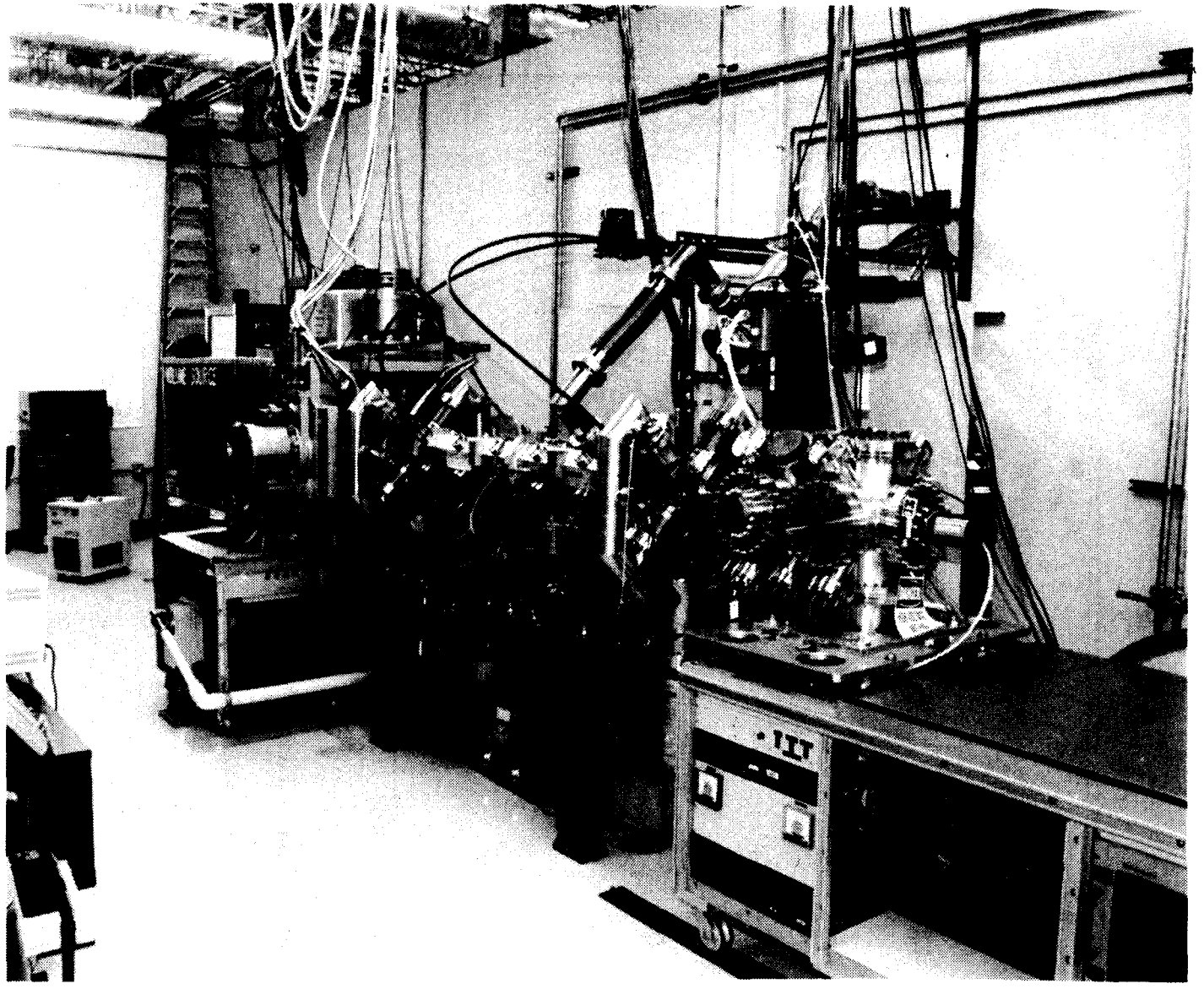

Figure 4. Injector at its temporary location at SSC R&D laboratory in Waxahachie, Texas.

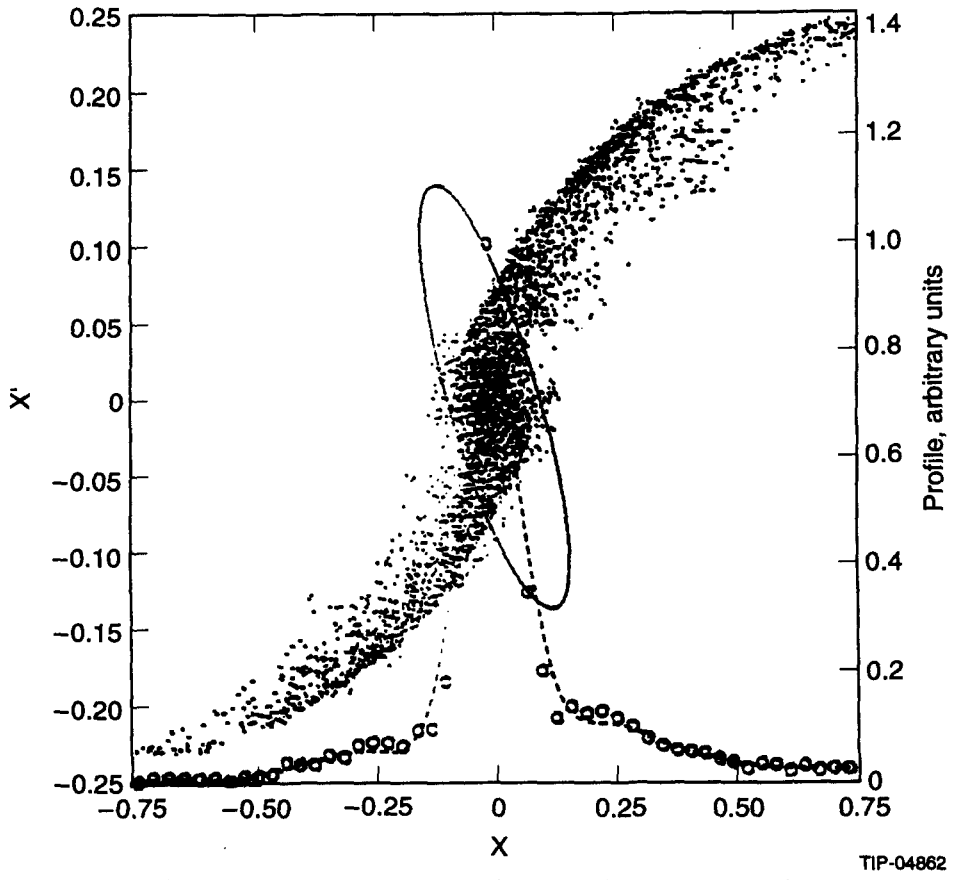

Figure 5. Typical einzel lens output beam horizontal phase-space emittance contour plot.

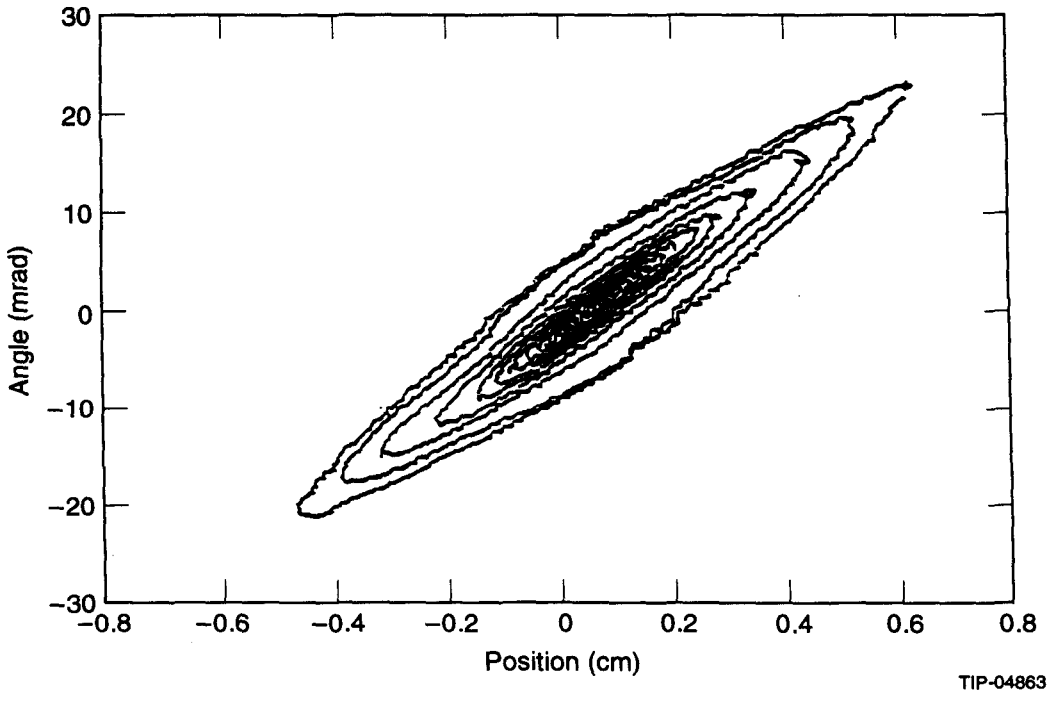

Figure 6. Typical Injector output beam vertical phase-space emittance contour plot.