UCRL-ID-137044

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December 7, 1999

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

HIFAN 717
LBL-38391

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Abstract

We report on progress in the preparation of the 2 MV Injector at LBNL as the front-end of Elise, and as a multi-purpose experimental facility for Heavy Ion Fusion beam dynamics studies. Recent advances on the performance and understanding of the injector are described, and some of the on-going experimental activities are summarized.

1. Introduction

A 2 MV electrostatic quadrupole (ESQ) injector [1] was constructed at Lawrence Berkeley National Laboratory, and has been in operation for nearly two years. The initial goal of the project was to demonstrate the feasibility of an injector that has the required energy, current, and emittance of a full-scale fusion driver, and that goal was achieved relatively early on in the project.

The original design goal of the injector was 2 MV, 0.25 μC/m, (or equivalently 790 mA of K^+) and a normalized edge emittance of less than 1 π mm-mr. In addition, the beam parameters must be constant over the 1 μs main pulse. The design current and energy were exceeded on the first day of operation, and the normalized edge emittance was subsequently measured to be as low as 0.65 π mm-mr, and is less than 1 π mm-mr over a broad range of operating parameters.

The experimental activities since then have been centered on the preparation of the injector as the front-end of Elise/ILSE, which is the present main focus of the HIF driver research effort in the U.S., and on using the injector as a facility for a variety of experiments requiring an intense

*Work performed under the auspices of the U.S. Department of Energy at LBL under contract DE-AC03-76SF00098 and at LLNL under contract W-7405-ENG-48.

space-charge dominated beam. In this paper, we will summarize the progress made on the performance of the injector as well as on-going experiments using the injector beam.

II. Machine Reliability

Reliability against high voltage breakdown of the insulator column was the key issue we had in mind during the choice of the injector configuration as well as over the entire design and construction phase of the project. The ESQ option [2] was chosen over the more conventional electrostatic Pierce column with multiple axisymmetric apertures (ESAC) primarily because of the inherent advantages in high voltage safety. The ESQ is a low gradient device with large transverse fields to sweep out unwanted secondary electrons. Our injector is a composite of 5 ceramic columns. The first column consists of a brazed structure with 16 alumina rings, each 1-1/2 inches in width, and separated by thin niobium rings, enclosing the alumino silicate source and the 750 keV diode front-end. The subsequent 4 columns consist of similarly brazed structures with 3" alumina rings, each containing a set of 4 electrodes arranged in a quadrupolar configuration. The interdigital structure of the four quadruples was arranged to provide strong focusing and acceleration of the ion beam from 750 keV to 2 MV. The graded configuration of the ceramic column was designed to interrupt the propagation of ion plasma channels along the insulator wall, thereby inhibiting the initiation of breakdowns. In addition, the column is protected from the inside by thick (1 cm) stainless steel and copper shields carefully shaped to block direct lines of sight of secondary electrons and X-rays without introducing high surface fields. Similarly, the electrodes are shaped to minimize surface fields without introducing unwanted higher order multipoles.

The operating experience to date has shown this column to be very robust. We have succeeded in reaching 2.3 MV and 950 mA of K^+ (15% above design) with very little conditioning required.

During the early phase of operation, we experienced some failures of the electronics in the high voltage dome due to the combination of heat generated from the hot source assembly [3] and the high voltage of a 160 kV extraction pulser and an 80 kV DC bias power supply (the current extraction assembly) which float in the 2 MV environment [4]. These initial failures have been overcome largely with proper cooling of the 80 psig SF_6 environment, and optimizations of the components. One major source of machine failures had come from the capacitors of the MARX bank [4]. The initial set of capacitors delivered from our manufacturers did not meet our reliability requirement of 100,000 shots at 100 kV. The manufacturers assumed responsibility and rebuilt a new set which met out specifications, and the MARX bank was reassembled with the new capacitors. Two additional observations of the capacitor failure modes during operation suggested some further design improvements which were also implemented. The MARX bank consists of 38 stages each of which has two capacitors in a parallel LC and RC circuit. It was noted that by far the majority of the capacitor failures take place on the branch in series with the inductor, and at a rate higher than the bench tests would suggest. Furthermore, the capacitor failures were correlated with the triggering of the MARX protection gaps, which, under normal operating conditions, would not fire. Resistors have been incorporated to damp the negative swings of the voltage through the inductor side of the MARX circuit when the protection gaps close. We have not experienced any additional capacitor failures since the installation of the new capacitors and the damping resistors, but further tests will be needed before we can make definitive conclusions regarding the reliability of the improved MARX.

III. Beam Pulse Uniformity from Head to Tail

Uniformity of beam pulse from head to tail is important for several reasons. First, fusion driver requires delivering an <u>entire</u> pulse with prescribed energy and current waveforms to the target, and it is essential to have control over the entire pulse all the way through the accelerator, beginning from the injector. The final momentum tolerance is of the order of $\Delta p/p \sim \pm 0.1\%$, and it will be desirable to maintain that level of accuracy throughout the accelerator, from injector to final focus. Finally, from the point of view of steering at injector exit, it is essential that the beam has minimal transverse displacement variations from head to tail, commonly known as "corkscrew", which results when a beam with head-to-tail energy variation traverses a misaligned focusing system.

The ESQ injector was designed with these considerations in mind. The MARX generator was designed to have a 4μs flat-top to accommodate the entire μs pulse and the necessary transit time through the ESQ structure. The LC/RC circuit described earlier was designed to achieve this flat-top and the MARX performance agrees perfectly with design. In addition, the MARX system was designed to be stiff (5kΩ) in order to minimize the effect of beam loading. Similarly, the current extraction pulser was designed to have a tunable inductance to achieve fine adjustments of the voltage flat-top.

When the machine was first turned on, the variations of the beam parameters (voltage, current, beam envelope, beam centroid) were in the <10% level. The beam centroid variation over the entire pulse could be as much as 5 mm in some cases. To deliver the entire pulse into the Elise channel (2.3 cm radius), some further refinements seemed necessary.

As a prerequisite to head-to-tail control, we need a very sensitive energy spectrometer. An existing energy spectrometer at LBNL has the required resolution, but has a dynamic range of 1 MV at the maximum. To measure our 2 MV beam, we modified the electrostatic energy spectrometer system by inserting a 2 cm "gas-stripper" in front of the energy analyzer. The K^+ ions traversing the stripper were stripped to higher charge states. To measure the energy of a doubly charged ion, for example, the required dipole voltage in the energy analyzer is halved. We have measured charge states of up to +4 . Hence, for the same maximum dipole voltage, the range of measurable ion energy is increased by a factor of 4. We have performed self-consistency checks of the beam energy, using the different charge states, and the resultant energy profiles were consistent.

This energy diagnostic allows us to measure energies to less than 0.1% resolution. With the aid of this diagnostic, fine tuning of the pulser and MARX has led to a measured energy flatness of ± 0.15% over the main body of the pulse (>1 μs) [Figure 1].

With the flat energy profile, the variations of the current, beam radius, and beam centroid from head-to-tail are also reduced significantly. The beam centroid variation is now less than 1 mm over the entire pulse [Figure 2].

IV. ESQ Beam Dynamics

Beam dynamics of the intense space-charge-dominated ion beam is another critical issue for the injector operation. Quantitative prediction of beam performance requires a thorough understanding of the 3-dimensional effects from the interdigital quadrupole geometry, and from a 3rd order beam aberration resulting from the kinematics of a low energy beam traversing a strong quadrupole field. The kinetic energy, and therefore, the betatron motion of the beam, vary according to the proximity of individual ions to the positive or negative electrodes in the transverse plane. This "energy effect" can lead to a distortion of the phase space and deleterious increase of emittance if uncontrolled. Extensive theoretical studies, in conjunction with 3-D particle-in-cell simulations with the LLNL code WARP3D [5] have provided detailed and quantitative predictions of beam behavior through these structures, and an earlier small scale experiment [6] with a 100 keV beam from SBTE confirmed code predictions to high levels of detail. WARP3D was subsequently deployed as our "design tool" for the specification of the 2 MV injector operating parameters.

When the injector was turned on, we indeed measured the low emittance predicted by the code, but there was a systematic discrepancy of the envelope parameters (beam radii and convergence angle) between theory and experiment which was not present in the SBTE experiment. Extensive checks through the experimental set-up and the code led eventually to the finding of a subtlety in the simulation procedure as the main culprit. Earlier calculations were performed with two codes, the axisymmetric source code EGUN for current extraction, and the 3D code WARP3D for beam transport through the ESQ structure. Although the matching of these codes was done with considerable care, very small mismatches in the particle and field distributions in this procedure lead to major distortions of the gross beam behavior at injector exit. Subsequent upgrades of WARP3D by incorporating the current extraction features remove the need for the matching of codes, and the new version of WARP3D agrees well with the measured beam envelope over a wide-range of parameters [7].

While the phase-space measurement at the end of the injector is now well understood in terms of the code predictions, recent quantitative measurements of the beam profile have revealed new features which await more detailed code analysis. Beam density profile measurements (projections in the vertical plane) show unambiguous signs of beam hollowing, rippling and halos [Figure 3]. While WARP3D also shows qualitative hollowing features, present calculations do not have the resolution to identify rippling and/or halos. The ion beam exiting the injector has been transported through three quadrupoles in the matching section (to be described later), and preliminary beam profile measurements indicate major changes from the hollow beam profile at injector exit to a more Gaussian like structure in mid matching section. These observations are preliminary and will require much more experimental and theoretical work for a thorough understanding. The issue, if real, may have important implications, since density nonuniformities can lead eventually to emittance growth. Understanding the origin of the observed nonuniformities and how to minimize them is clearly desirable.

V. Experiments at the 2 MV Injector Facility

The 2 MV injector is evolving into an experimental facility where a number of experiments have been and are being performed, and several more are being planned and considered. The following is a partial list:

(1) The 6-quad matching section. In the ILSE scenario, a 4-beam injector produces 4 independent ion beams, each of which will have to be focused and steered into 4 small (2.3 cm radius) electrostatic channels in close proximity. This requires a reduction of ion beam size and steering of the beam. The matching section performs the dual function of focusing and steering. While the Elise project itself does not involve a 4-beam injector, the matching section is needed to focus a beam which is approximately 4 cm in radius at injector exit to 1 cm in radius at Elise entrance, increasing the current density by an order of magnitude. In addition, the physics of beam bending with displaced quadrupoles, which has been studied thus far with simulations only require experimental verification. The matching section is therefore a part of the Elise project as well as a focusing and bending experiment in its own right. Construction of the matching section components is now complete, and the transport of ion beams through the system is being studied in stages. Displacement of a single quad by 1.5 cm in a 3-quad experiment led to the bending of the ion beam by nearly 2 cm, in very good agreement with simulation predictions. The preliminary beam profile measurements have been alluded to earlier and investigations, experimental as well as theoretical, should continue.

(2) Ion-atom interactions. The energy analyzer with 'gas-stripper', discussed earlier, is an ideal set-up for measuring ion-atom scattering processes. The gas stripper has been filled with Helium, N_2, and Ar at various pressures. From near vacuum to above a torr, we have measured the scattering of the ion beam (by a moveable slit cup in front of the energy analyzer), energy loss, current enhancement, and charge state distribution. While the acquisition of these basic data is an activity of interest in its own right, (particularly in the energy regime of the present injector, where the projectile velocity is comparable to electron orbital velocities), we have collected this data primarily as a prerequisite for the adiabatic focusing experiment.

(3) The adiabatic focusing experiment explores the possibility of using a tapered Z-pinch for final focusing in a fusion reactor. The potential advantage of such a focusing scheme is that it relaxes the requirements of emittance, energy spread, charge state and current-dependent focusing

of the driver. In addition, the reactor associated with this scheme requires only small port holes. We have incorporated a tapered Z-pinch (30 cm in length, with variable diameter from 2 cm at one end to 0.5 cm at the other) in our diagnostic chamber, and the first experiment has yielded current density enhancement by a factor of 20 when an external current of a few kA is applied. Details of this experiment are described in another paper in these Proceedings [7].

(4) Development of a high charge state ion source, supported by an SBIR, and reported by S. Eylon and E. Henestroza [8] is conducted with the same experimental set-up as in (2). They have found that under the right conditions of gas species, pressure, and beam energy, it is possible to generate copious amounts of charge state +2 ions without significant degradation of emittance due to scattering and/or space charge effects.

(5) Elise component tests with beam. A major thrust of the LBNL HIF effort is in the development of Elise components. In conjunction with multiple high voltage breakdown test of components on the bench, experiments are being planned to test quadrupole breakdown in the presence of a beam. Similarly, further acceleration, ear correction tests with Elise components are possible, and acquiring experience with beam for a few 'real-size' components before large-scale production is clearly advantageous .

(6) Magnetic Transport. Various experiments with permanent magnets and or pulsed quadrupoles are being planned and/or considered.

(7) Ion source development. The possibility of using the injector for alternative ion source development has also been considered. While the source end of the injector has much less flexibility than the exit end for experimentation, and much more caution has to be exercised to protect the diode from possible contamination and damage, nevertheless, the injector source was designed to accommodate modifications. The 2 MV injector, deployed in parallel with separate off-line source development efforts may lead to significant advances in ion sources for HIF.

VI. Conclusion

In preparation of the 2 MV injector as a user facility, we have made substantial progress in machine reliability and control of the head-to-tail variations of the beam. The injector column has been shown to withhold 2.3 MV at 950 mA of K^+ (15% above design goals), and energy flatness of $\pm 0.15\%$ over the entire pulse has been demonstrated. A previously reported discrepancy between experiments and 3-D simulations in transverse phase-space at injector exit is now removed, and the new version of WARP3D predicts beam envelopes in very good agreement with experiments. Detailed structures in beam density profile have been measured at injector exit, and their evolution through a newly completed matching section is being studied. The injector facility is now being used for a number of beam dynamics experiments.

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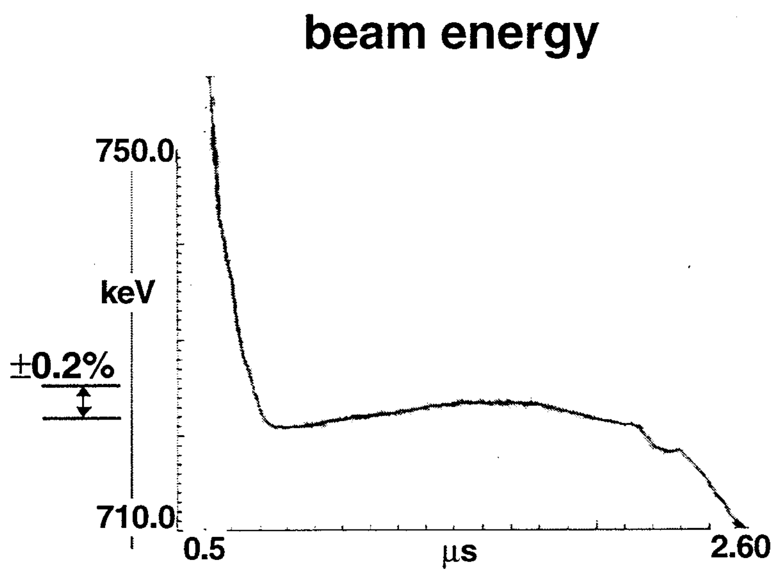
Figure Captions

Figure 1(a) Energy measurement shows variations of $\pm 0.15\%$ over the 1 μs main pulse The high energy beam front is due to space charge effects

Figure 1(b) MARX and extraction pulser waveforms

Figure 2 Variations of beam radius, beam centroid, and emittance from beam head to tail

Figure 3 Density profile at injector exit shows hollowing, rippling, and haloes. The hallowing feature is reproduced qualitatively in WARP3D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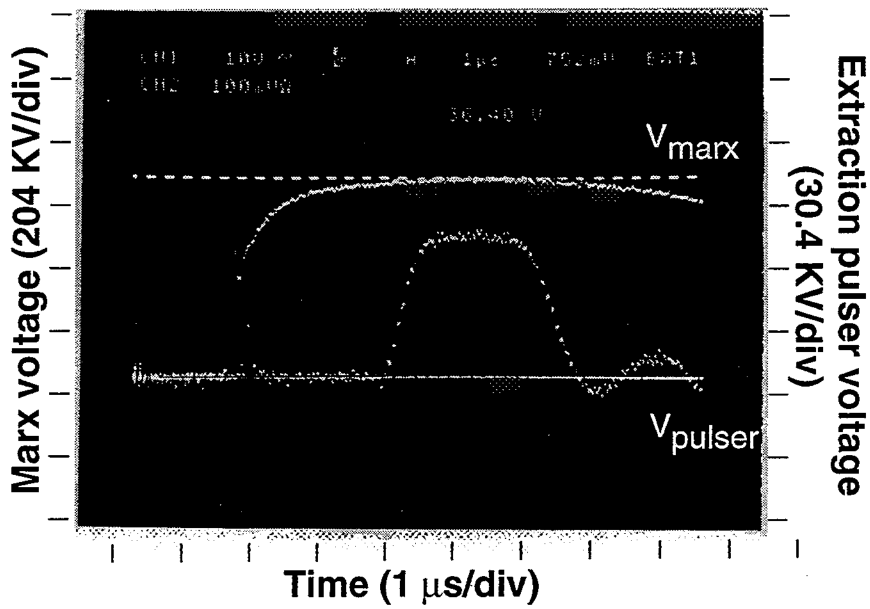
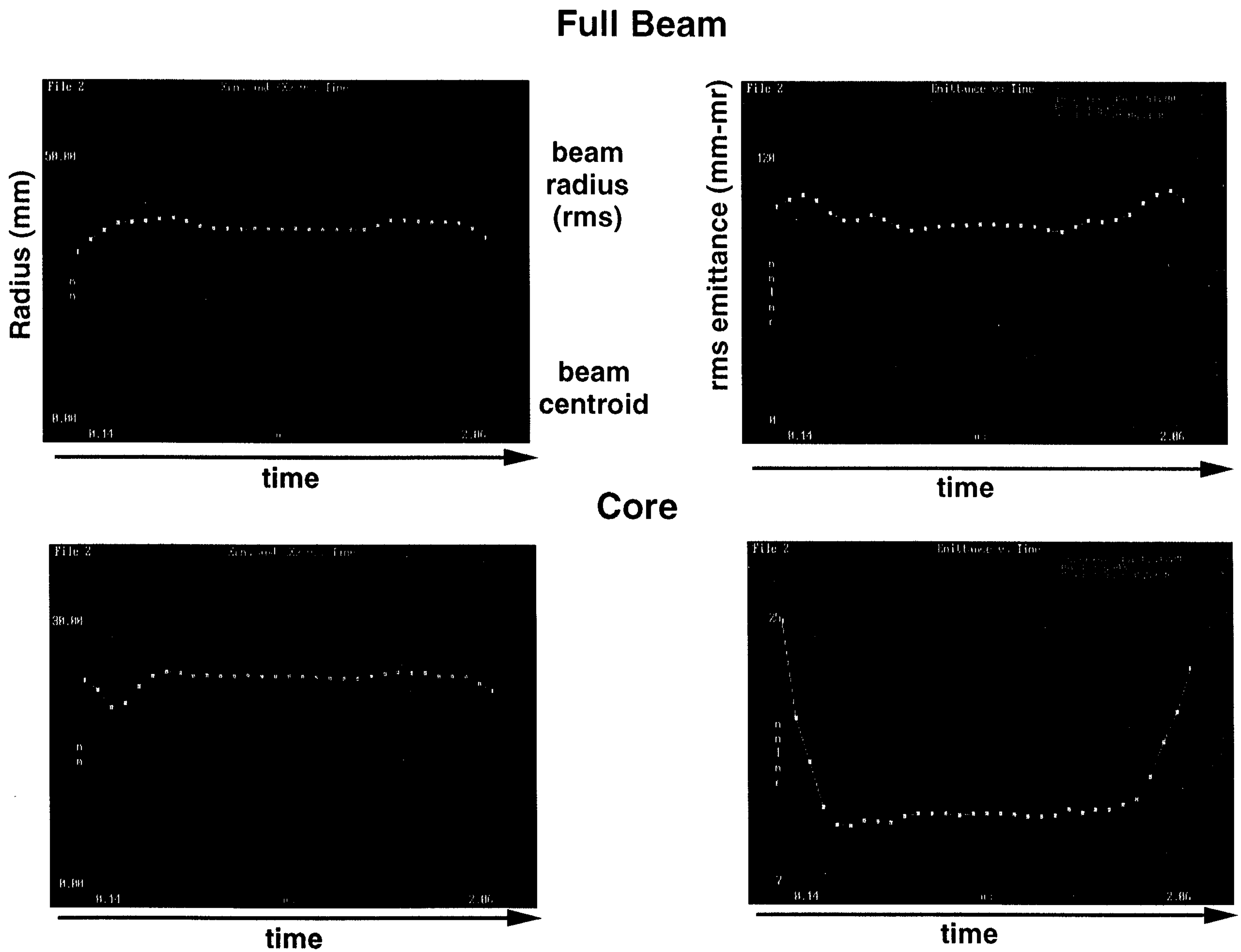
750.0
keV
±0.2%
710.0
0.5
μs
2.60

Author: Yu
Figure 1(b)

Marx & gate voltage

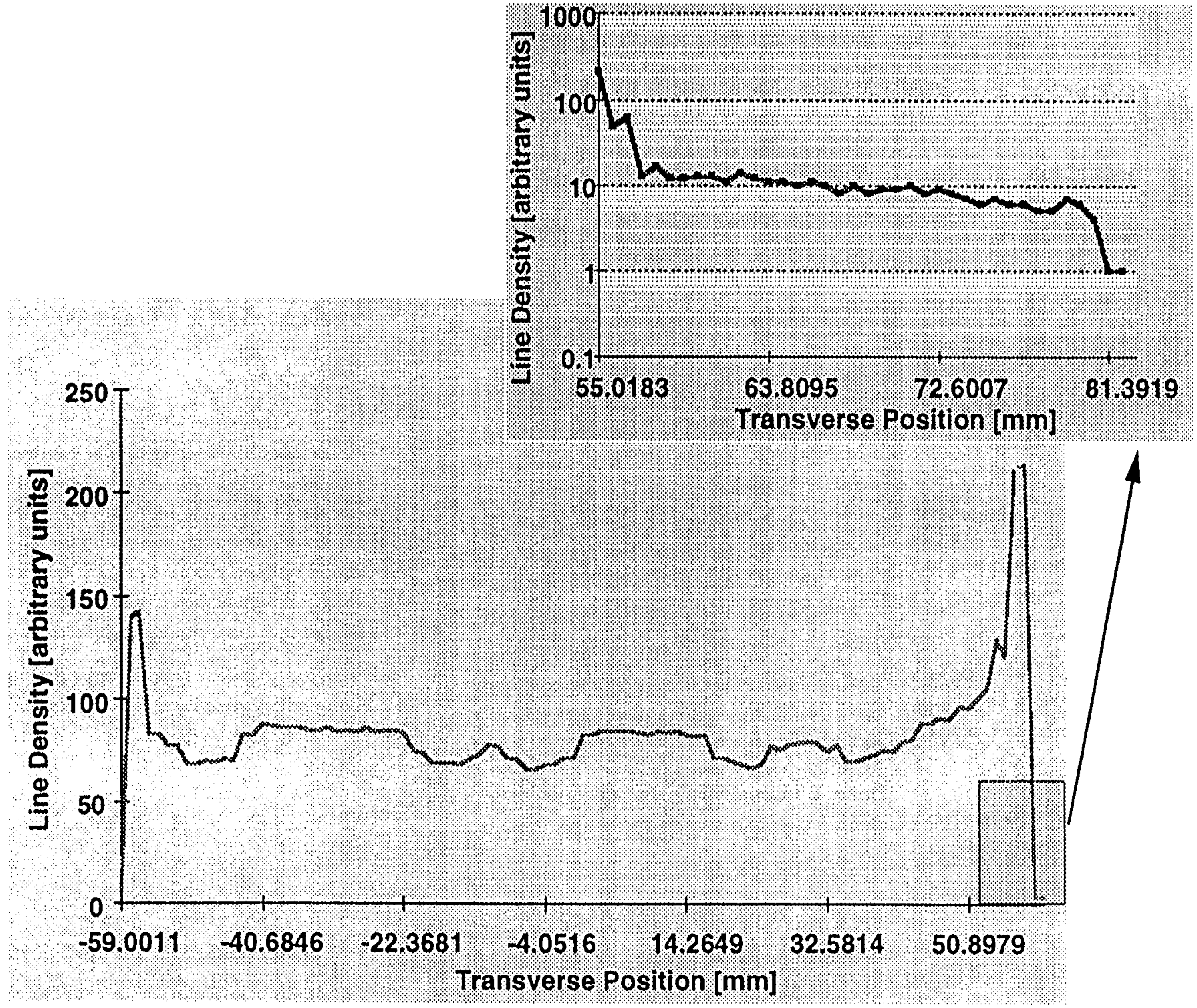


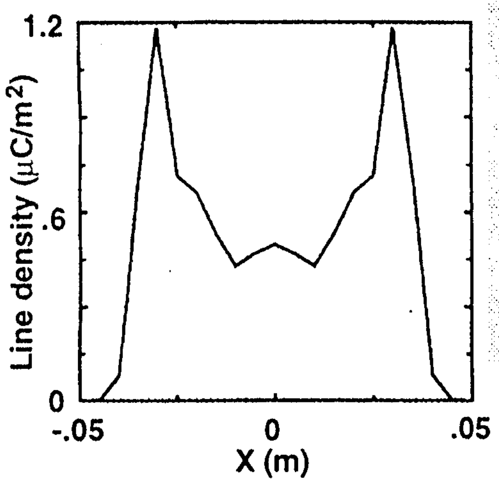
Author: S. Yu
Figure 2



Author: S. Yu
Figure 3

Beam density profile shows hollowing, rippling, and halos





WARP 3D Simulation

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