

## TITLE:

APPLICATION OF A TRANSVERSE PHASE-SPACE  
MEASUREMENT TECHNIQUE FOR HIGH-BRIGHTNESS, H<sup>-</sup>  
BEAMS TO THE GTA H-BEAM

## AUTHOR(S):

Kenneth F. Johnson	AOT-4
Roger C. Connolly	AOT-10
Ralph C. Garcia	AOT-3
Daniel P. Rusthoi	AOT-2
Oscar R. Sander	AOT-3
Darryl P. Sandoval	AOT-3
Michael A. Shinas	AOT-2
Malcolm Smith	AOT-3
Vincent W. Yuan	AOT-1

## SUBMITTED TO:

1995 Particle Accelerator Conference and International Conference on  
High-Energy Accelerators  
Hyatt Regency Hotel, Dallas , TX  
May 1-5, 1995

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# APPLICATION OF A TRANSVERSE PHASE-SPACE MEASUREMENT TECHNIQUE FOR HIGH-BRIGHTNESS, $H^-$ BEAMS TO THE GTA $H^-$ BEAM\*

K. F. Johnson, R.C. Connolly,\* R.C. Garcia, D.P. Rusthoi, O. R. Sander, D.P. Sandoval, M.A. Shinas, M. Smith, and V.W. Yuan, Los Alamos National Laboratory, Los Alamos, NM 87544 USA

The Ground Test Accelerator (GTA) [1] had the objective of producing a high-brightness, high-current  $H^-$  beam. The major components were a 35 keV injector, a Radio Frequency Quadrupole (RFQ), an intertank matching section (IMS), and a drift tube linac (DTL), consisting of 10 modules. A technique for measuring the transverse phase-space of high-power density beams has been developed and tested [2]. This diagnostic has been applied to the GTA  $H^-$  beam. Experimental results are compared to the slit and collector technique for transverse phase-space measurements and to simulations.

## I. INTRODUCTION

In the commissioning of an accelerator, measurements of the beam's phase-space distributions are made to evaluate the accelerator's performance and to determine the accelerator's operating parameters. A common method of measuring transverse phase-space distributions in charged-particle beams is to intercept the beam with slits, pinhole plates, or wire grids, and to determine the beam distribution after a drift with a parallel-channel collector or fluorescent screen. For high-brightness beams, these measurements should be made near the last optical element to eliminate the space-charge corrections during data analysis. However, the power densities of beams are often too high to allow beam masks, such as slits, to survive the full intensity of the beam.

This paper describes results from a phase-space measurement technique which is applicable to high-brightness  $H^-$  beams. It utilizes conventional beam diagnostics combined with the laser induced neutralization diagnostic approach (LINDA) [2]. A small portion of the beam is separated from the full beam by means of photoneutralization with a laser that is upstream from a sweep magnet. Phase-space measurements are made on only the neutralized beam. Because the measured portion of the beam drifts without space charge, the phase-space distribution of the beam at the neutralization point can be inferred accurately from a measurement taken downstream.

\*Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

\*Industrial partner, Grumman Corporate Research Center

## II. MEASUREMENT

The LINDA technique as applied to GTA is shown schematically in Fig. 1. A short laser pulse of the appropriate wavelength to neutralize the ions, was passed through the ion beam upstream of a bending magnet. The small fraction of the full beam that was neutralized ( $H^0$  beam) passed through the magnet into the detector (i.e. the slit and collector system). The remaining  $H^-$  beam was swept into a beam dump.

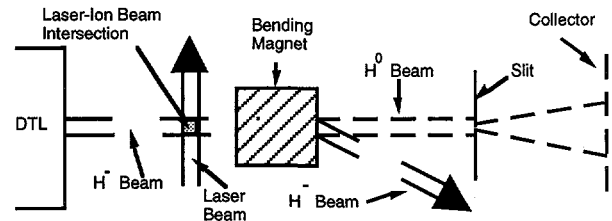


Figure 1: Schematic view of the LINDA technique for measurements of transverse phase-space.

The technique was developed and tested [2] on the Accelerator Test Stand (ATS) [3]. Reference 2 discusses the principles of the neutralization process, the laser characteristics, the geometry of the measurement, the electronics, the data acquisition, and the data analysis for extracting transverse phase-space distributions (e.g. emittances and the Courant-Snyder (CS) parameters).

The measurements of the GTA  $H^-$  beam differed from those of the ATS  $H^-$  beam primarily in three areas. First, the geometry was improved. The bending magnet was located upstream of the slits instead of its ATS location between the slit and collector. This made interpretation of space charge effects clearer. Second, the ATS measurements were restricted to the horizontal plane. This restriction was removed for the GTA measurements where data were obtained for the horizontal (x) and vertical (y) planes. Third, the bending magnet was an electromagnetic dipole rather than a permanent magnetic dipole as in the ATS measurements. To switch from measurements of the  $H^0$  beam to measurements of the  $H^-$  beam the dipole was turned off. The effects of the residual field of the dipole on emittance measurements was negligible.

The GTA measurements were made at the exit of the first GTA Drift Tube linac (DTL) module [4] (output beam energy 3.2 MeV). Transverse phase-space measurements were made with the full  $H^-$  beam and with the laser-

neutralized beam ( $H^0$  beam). In both cases, the same slit and parallel-channel collector were used and their location with respect to the DTL exit remained fixed. For these set of measurements the average beam current was  $\approx 32$  mA. The laser neutralization point (see Fig. 1), was  $\approx 32$  cm upstream of the transverse emittance gear slit. Lastly, data from the two techniques were taken close in time to avoid ambiguities due to changing beam conditions.

### III. EXPERIMENTAL RESULTS

The objective of these measurements of the GTA DTL output phase-space distributions was to obtain a more complete data set than was obtained in the ATS experiment. A more complete data set, in term, allows for a more detailed comparison of the LINDA technique and the conventional slit and collector technique. Also a more complete measurement contributes to the understanding of space charge effects in the measurement of the transverse phase-space distributions (emittances).

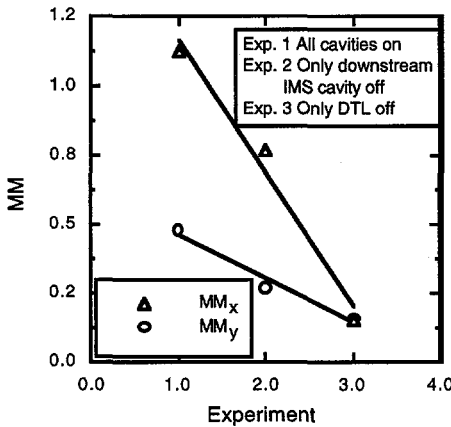


Figure 2: The dependence of the MM (between the two techniques) on the degree of bunching. The lines are meant to guide the eye.

With the accelerator's operating parameters set at their nominal values, repeated emittance measurements were made in the x and y planes with LINDA and the slit and collector techniques. This allowed for reproducibility checks for each technique and for a comparison between techniques. Different criteria were applied in the comparison of the slit and collector (LINDA "off"), technique, which measured the full  $H^-$  beam, and the LINDA technique (LINDA "on"), which measured the  $H^0$  beam. The reproducibility of the data was good for each method based on a comparison of the rms normalized emittances,  $\epsilon_x$  and  $\epsilon_y$ .  $\epsilon_x$  and  $\epsilon_y$  were determined from a beam fraction of 86.5% which corresponds to  $4\sigma$  if the beam is Gaussian. A beam fraction of 100% includes all of the beam above a 1% background threshold. For LINDA

"off",  $\epsilon_x = 0.0186 \pm 0.0013 \pi$  cm mrad and  $\epsilon_y = 0.0151 \pm 0.0011 \pi$  cm mrad. For LINDA "on",  $\epsilon_x = 0.0158 \pm 0.0011 \pi$  cm mrad and  $\epsilon_y = 0.0151 \pm 0.0011 \pi$  cm mrad. These data show a 23% emittance growth in the x-plane over the  $\approx 32$  cm drift space between the neutralization point and the emittance slit. There was no observed emittance growth in the y-plane.

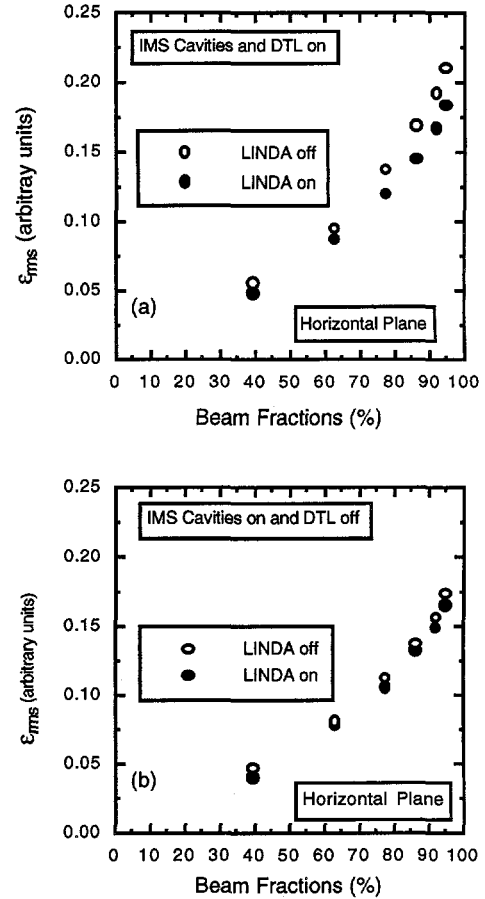


Figure 3:  $\epsilon_{rms}$  versus the beam fraction used in the calculation of  $\epsilon_{rms}$  for the LINDA "on" and "off" techniques. (a) All cavities on at nominal settings. (b) The same as (a) with the DTL off.

Another criteria was the mismatch factor MM, which facilitated the comparison of the Courant-Snyder (CS) parameters or beam shape. This criteria was applied in the x-plane where the large emittance growth was observed. For the LINDA "on" (LINDA "off") data the repeatability of measurements was characterized by  $MM_x = 0.06$  (0.07). These data indicate little variation in the emittance shape for either technique. However,  $MM_x$  varied between  $\approx 1.2$  and  $\approx 1.4$  when the two techniques were compared. Although each data set was internally consistent, there was significantly different emittance shapes between data sets.

Using TRACE3D [6], the measured LINDA "off" CS parameters were transported with space charge from the

emittance slit upstream to the laser neutralization point and then transported without space charge downstream to the slit. The resulting CS parameters were compared to the LINDA "on" data giving  $MM_x \approx 0.23$  which, although not as small as 0.06, was substantially better than 1.3. These results suggest that space charge plays a significant role over the drift between the neutralization point and the emittance slit.

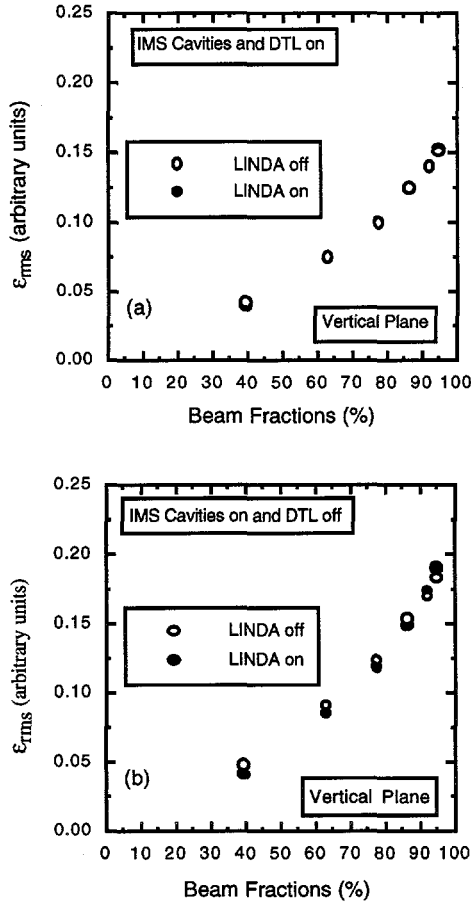


Figure 4:  $\epsilon_{rms}$  versus the beam fraction used in the calculation of  $\epsilon_{rms}$  for the LINDA "on" and "off" techniques. (a) All cavities on at nominal settings. (b) The same as (a) with the DTL off.

To further explore the effects of space charge, a set of measurements was performed where the bunch length was varied. In Experiment 1, the IMS buncher cavities and the DTL were operated at their nominal settings. In Experiment 2, the downstream IMS buncher was turned off, allowing the bunch length to increase. To increase the bunch length further, the IMS cavities were set at their nominal operating settings and the DTL was turned off. The expectation was that space charge effects in the emittance measurements should decrease as the bunch length increases. This was confirmed by the MM between the two techniques (see Fig. 2) where  $MM_x$  and  $MM_y$

decreased as the bunch length was increased. The effect was considerably larger in the x-plane where  $MM_x$  varied by a factor of 10. In the y-plane,  $MM_y$  was considerably less sensitive to the bunch length.

Figures 3 and 4 show the sensitivity of  $\epsilon_{rms}$  on the beam fraction. As the beam fraction increases, more of the halo is included in the determination of  $\epsilon_{rms}$ . Figure 3(a) shows that, when the bunch length is small, the difference in  $\epsilon_{rms}$  for LINDA "on" and "off" depends on the amount of halo included in the emittance determination. The two techniques agree if the determination of  $\epsilon_{rms}$  is restricted to the core of the beam. Figure 3(b) shows that the difference between LINDA "on" and "off" is disappearing as the bunch length grows and space charge effects diminish. This suggests that space charge forces may push some particles into the halo, causing the overall emittance area to grow and the shape to change (Fig. 2), while leaving the core of the bunch largely unchanged [7,8]. Figures 2 and 4 show that, for the y-plane, there is some evidence for a change in the emittance shape but not in area.

#### IV. CONCLUSIONS

The LINDA technique for measuring transverse phase-space distributions works well. The measurements are repeatable. The differences between the LINDA and the slit and collector techniques are qualitatively understood. Further simulations are needed to explain quantitatively the observed behavior. The differences between the x and y planes may be explainable in terms of the transverse beam sizes and orientation in phase space.

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