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IMPROVED MODEL

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# Characterizing Proton Beam of 6.7 MeV LEDA RFQ by Fitting HEBT Wire-Scanner Profiles to Improved Model\*

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## Abstract

Quadrupole scans in the HEBT of the 6.7 MeV LEDA RFQ were analyzed to characterize the transverse phase space at the RFQ exit. In previous work, the profiles measured by the wire scanner were fit to various models (HEBT simulations from the RFQ exit to the wire scanner) in an effort to determine the transverse Courant-Snyder parameters ( $\alpha$ ,  $\beta$ , and  $\epsilon$ ) at the RFQ exit. Unfortunately, at the larger quadrupole settings, the measured profiles showed features that were not present in the simulations. This made good fits impossible. Here we describe our latest analysis, which resulted in very good fits by using an improved model for the beam at the RFQ exit. The model beam was generated by the RFQ simulation code TOUTATIS. In the fitting code, this beam was distorted by linear transformations that changed the Courant-Snyder parameters to whatever values were required by the nonlinear optimizer while preserving the high-order features of the phase-space distribution. This present success indicates that there has not been any missing physics in the codes, which gives us increased confidence in our accelerator designs. In addition, we have learned that details in the RFQ beam can make a significant difference in observed behavior downstream of the RFQ.

## 1 INTRODUCTION

### 1.1 Quadrupole scans

During commissioning of the 6.7 MeV LEDA RFQ, we used a four-quadrupole high energy beam transport (HEBT) to transport the beam from the RFQ exit to the beam stop. Quadrupole scans in the HEBT were used to characterize the transverse phase space at the RFQ exit. In this procedure, only the two quadrupoles immediately downstream of the RFQ exit were used. Quadrupole Q1 focuses in the  $y$  direction and Q2 focuses in  $x$ . For characterizing the beam in the  $x$  direction, Q2 was varied and the beam was observed at the wire scanner, which was about 2.5 m downstream, just before the beam stop. The strength of Q1 was fixed at a value that ensured that the beam was contained in the  $x$  direction for all values of Q2. For characterizing the  $y$  direction, Q1 was varied while Q2 was fixed.

For both the  $x$  and  $y$  scans, as the quadrupole strength

is increased from its minimum to its maximum value (we used about 10 settings in both cases), the beam size at the wire scanner goes through a minimum. At the minimum, the beam has a waist at the wire-scanner position. For larger quadrupole strengths, this waist occurs somewhere between the RFQ and the wire scanner. In this experiment, the wire-scanner profiles (beam intensities as functions of  $x$  or  $y$ ) were recorded for each quadrupole setting.

### 1.2 Fitting to Model of HEBT

To determine the phase-space properties of the beam at the RFQ exit, we have to fit our data to some model that describes the behavior of the beam in the HEBT under quad-scan conditions. A model consists of two parts: a representation of the beam at the RFQ exit and a means of computing the beam at the wire-scanner position, given this starting beam. The problem is to find a beam that best fits our data. For computing the evolution of the beam in the HEBT, we used various simulation codes. We used input beams generated by the codes parameterized by the Courant-Snyder parameters  $\alpha$ ,  $\beta$ , and  $\epsilon$  in the three directions. In our first experimental fits, we used the TRACE 3-D and the LINAC codes to determine the values of  $\alpha$ ,  $\beta$ , and  $\epsilon$  that best fit the rms beam sizes seen at the wire scanner for all values of the quadrupole gradient.

## 2 PREVIOUS RESULTS

### 2.1 Fit to LINAC rms sizes

Using the LINAC code as our model, we could find a set of  $\alpha$ ,  $\beta$ , and  $\epsilon$  values that produced a good fit to the rms beam size as a function of quadrupole gradient. However, for the larger quadrupole gradients, for the situation in which the beam waist is upstream of the wire scanner, the simulated and the measured beam profiles look quite different. The measured profiles had triangular tails (or shoulders) that did not appear in any of the simulations. The agreement is especially poor in the  $x$  direction. Because of this inability to reproduce this observed behavior, we did not believe our model of the beam behavior in the HEBT could not be trusted to determine the Courant-Snyder parameters of the RFQ beam.

The input beam in the LINAC simulation was a uniform-in-4-D distribution.

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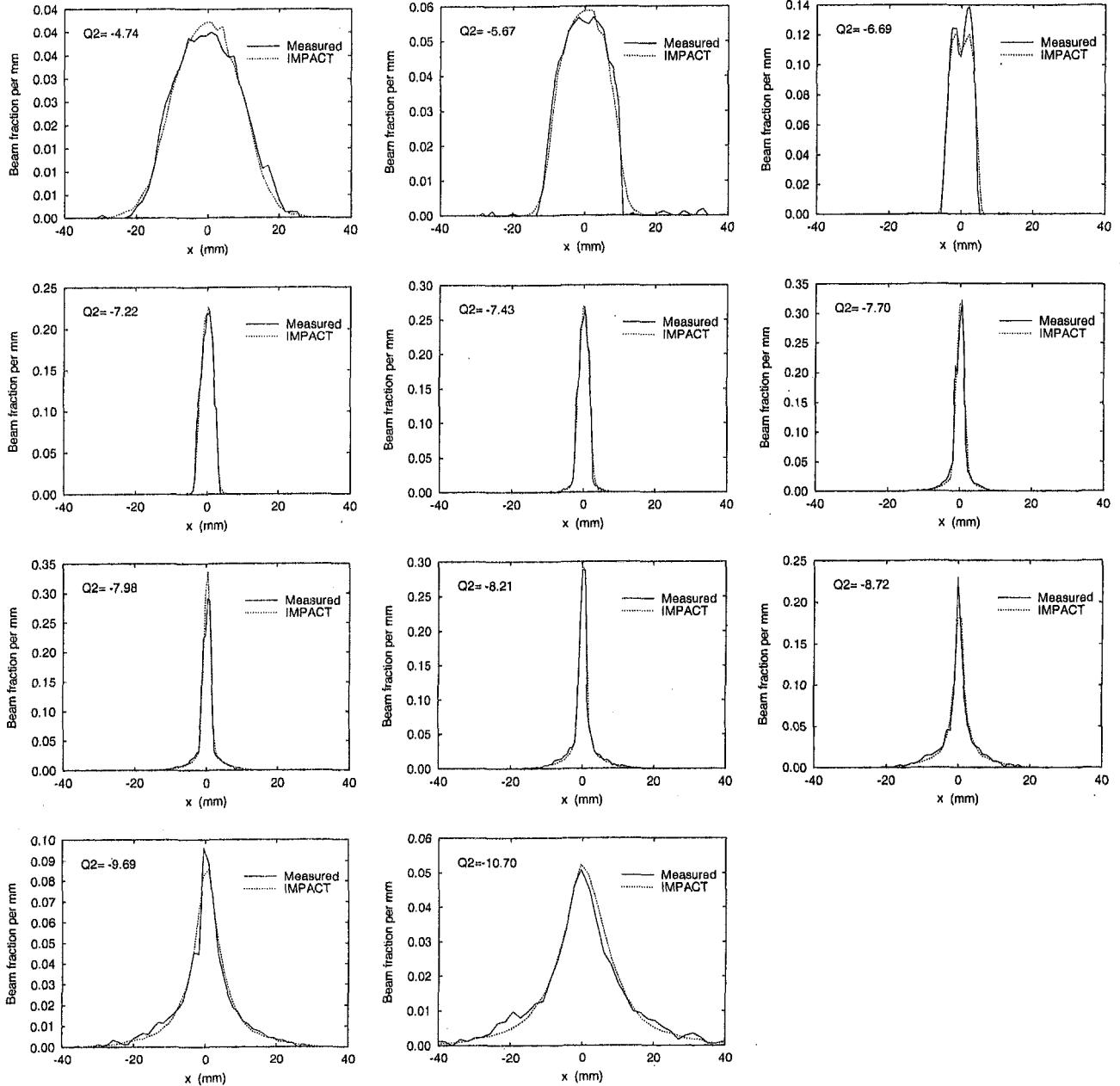


Figure 1: Comparison of measured profiles in the  $x$  direction with IMPACT simulations for various values of  $Q2$ . The initial beam for all these simulations was an RFQ exit beam generated by TOUTATIS and distorted by a linear transformation to have Courant-Snyder parameters corresponding to those determined by fitting rms widths to LINAC simulations.

Table I shows the Courant-Snyder parameters determined by the LINAC fit to the rms beam sizes at the wire scanner. Also shown is the prediction from the PARMTEQM code and the prediction from the TOUTATIS code (see below).

## 2.2 Fit to IMPACT profile shapes

In an attempt to improve our fitting procedure, we made two changes: The first change is that we used the IMPACT code as our model. This is a 3-D particle in cell PIC code with nonlinear space charge. The input beam was a truncated Gaussian parameterized by the usual Courant-Snyder parameters. The second change we made was that we used all the profile data, not just the rms widths. For the  $x$  scans, for each of the 11 values of  $Q2$  and for each of the 51  $x$  positions of the wire, the difference between the measured intensity and the simulated intensity at the wire positions

Table I. Unnormalized rms emittances at RFQ exit		
	$\epsilon_x$ (mm·mrad)	$\epsilon_y$ (mm·mrad)
Prediction (PARMTEQM)	2.03	2.04
Prediction (TOUTATIS)	1.75	2.12
Measured (LINAC rms fit)	2.11	2.62

was computed. It is the sum of the squares of these 561 differences that is minimized by varying the values of  $\alpha_x$ ,  $\beta_x$ , and  $\epsilon_x$  of the input beam (beam at RFQ exit). Unfortunately, this improved fitting procedure failed to improve the agreement between the measured and simulated profiles for the larger quadrupole gradients[3].

### 3 IMPROVED INPUT BEAM MODEL

The beams we were using in the fitting procedures described above were uniform or truncated Gaussians in 4-D phase space. We also did IMPACT simulations (no fitting) using collections of particles generated by the RFQ simulation code PARMTEQM, which was used to design this RFQ. In addition, we investigated various distortions of the input phase-space distributions. In no case did our simulations exhibit the shoulders on the profiles that were seen in the measurements for the larger quadrupole gradients.

In this paper we describe our latest, and finally successful, attempt at obtaining a good model for the behavior of our RFQ beam in the HEBT. Our latest improvement consisted of using the beam generated by the TOUTATIS code as the input beam for the simulations in the fitting process. In the fitting code, this beam (collection of particle coordinates) was distorted by a linear transformation that changed the Courant-Snyder parameters to whatever values were required by the nonlinear optimizer. This process generated beams having whatever Courant-Snyder parameters were required while preserving the high-order features of the phase-space distribution that were present in the original TOUTATIS simulation.

### 4 RESULTS FOR IMPROVED MODEL

Our new fitting procedure was to take a TOUTATIS RFQ beam as input to an IMPACT simulation. We started with a beam distorted in such a way as to have the Courant-Snyder parameters correspond to our previous fits using the LINAC code to fit to the rms widths at the wire scanner. The IMPACT fitting procedure varied the Courant-Snyder parameters to best fit to the profile shapes seen at the wire scanner for all eleven values of the quadrupole gradient. We found that the optimizer could not improve the fit for the reason that the initial guess (the LINAC fit to the rms widths) was already a very good fit. The shoulders in the profiles for the larger quadrupole settings were now apparent in our simulations.

Figure 1 shows the beam profiles for the  $x$  quadrupole scan simulated by the IMPACT code using the Courant-Snyder parameters determined by the LINAC fit to the rms beam widths.

### 5 DISCUSSION

In summary, we have seen that using the TOUTATIS beam as an input in our model correctly predicts the previously mysterious shoulders in the wire scanner profiles seen for the larger quadrupole settings. We have also seen that the

previous fits using LINAC, which considered only the rms widths and not the detailed profile shape generated good values for the Courant-Snyder parameters.

Apparently, some details in the TOUTATIS simulation lead to new higher-order features that are different from those in the older PARTEQM simulations and in the uniform-in-4D-phase-space models. It appears that features of the beam seen in the HEBT have their origins in the RFQ or perhaps even upstream of the RFQ. The practical consequence of this is that we have to be careful in preparing beams as high-order features can influence behavior downstream. The good news is that we now know our simulation codes are not missing any physics. They correctly predict what is going on in this situation. Although the quad-scan procedure differs from the ordinary HEBT operation or beam transport in a linac, the physics regime is still similar. We felt it was important that the beam behavior we observed in the experiment be seen in the simulations. We now believe in our characterization of the RFQ beam is probably fairly reliable, but this is of secondary importance (quad scans are probably not a good way to measure beam properties). The fact that the codes correctly predict beam behavior increases our confidence in the design work that was and is being done using our simulation codes.

Of course, there is still a mystery. Exactly what high-order features in the RFQ beam are causing the shoulders in the wire-scanner profiles of the quad-scan experiment? This should be investigated because it may be related to halo generation in linac having its origin upstream of the RFQ exit.

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