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Beam Tomography and Emittance Measurements in ISIS

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Abstract: In this note we summarize the results of measurements that we took on 2020-Jun-30 beam development shift about the beam tomography and emittance in the ISIS front end.

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1 Tomography

We dedicated a beam development shift on 2020-Jun-30 to measuring the ISIS beam phase space density distribution, using both the Maximum Entropy technique and the emittance scanner directly. These results might help with the re-design of the ∼21 m long horizontal section which has been planned for a refurbishment, because knowledge of the phase space density distribution in details is useful to understand subsequent evolution of the beam.

We began with the production tune of ISIS for the measurements, where the quad's settings were:

$$\begin{aligned}
&\mathrm{D106} = 2.02\ \mathrm{kV}, \mathrm{F107} = 4.36\ \mathrm{kV}, \mathrm{D111} = 4.98\ \mathrm{kV}, \mathrm{F112} = 4.92\,\mathrm{kV},\\
&\mathrm{D113} = 0.21\ \mathrm{kV}, \mathrm{F116} = 6.08\ \mathrm{kV}, \mathrm{D117} = 5.74\ \mathrm{kV}, \mathrm{F216} = 0.00\,\mathrm{kV},\\
&\mathrm{F215} = 2.26\ \mathrm{kV}, \mathrm{D217} = 3.49\ \mathrm{kV}, \mathrm{Q223} = 3.05\ \mathrm{kV}, \mathrm{Q236} = 3.00\,\mathrm{kV}.
\end{aligned}$$

This tune is shown in Fig. 1, where the + signs mark the beam sizes (2rms) measured at the

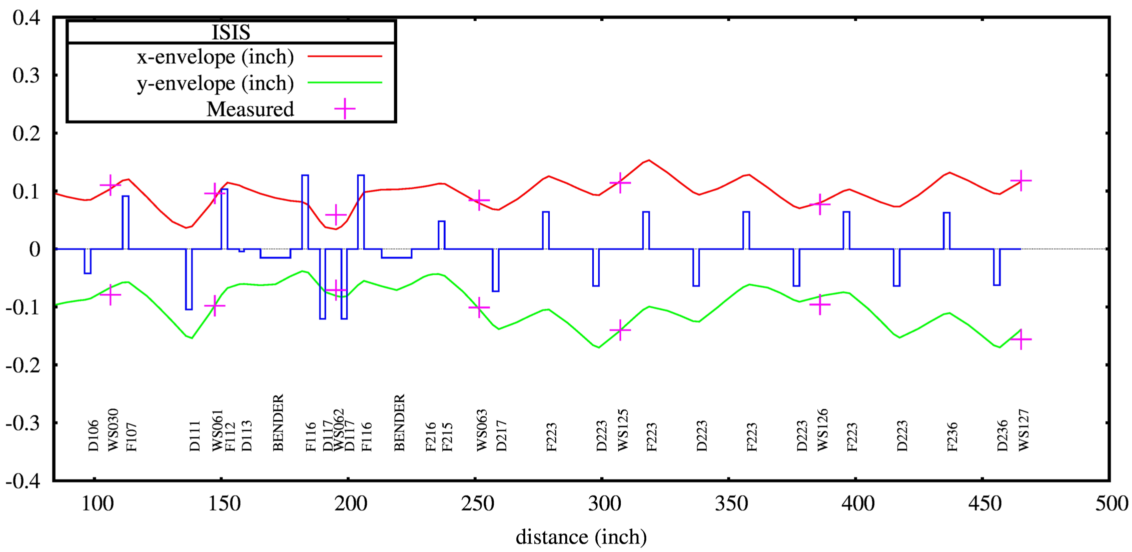

Figure 1: The production tune of ISIS, measured with wire scanners up to WS127 and calculated (in red and green lines) to match the measured sizes (in + sign). Note that x is vertical while y is horizontal.

wire scanners, while the red and green lines are the x (vertical) and y (horizontal) envelopes obtained from optics calculation by fitting an initial beam to match the measured beam sizes. **Should be pointed out that the measured sizes here are calculated statistically from the measured beam profiles, in which the shoulders/tails have been cut off, meaning that only the beam core is taken into account**. There are 14 known values of beam size in total (7 in x and 7 in y), while only 6 unknown parameters to be determined for the initial beam, i.e. $\alpha_{x,y}$, $\beta_{x,y}$ and $\epsilon_{x,y}$. So the solution to be sought is over-determined. The beam current is 430 μA DC of zero energy spread. The fit works out well under full space charge force, giving rise to an initial beam of

$$\begin{aligned}
\alpha_x = 0.73,\quad \beta_x = 51.5\,\mathrm{inch} = 1.308\,\mathrm{m},\quad \epsilon_x = 0.18\,\mathrm{inch\,mrad} = 4.572\,\mu\mathrm{m};\\
\alpha_y = 0.60,\quad \beta_y = 52.2\,\mathrm{inch} = 1.326\,\mathrm{m},\quad \epsilon_y = 0.18\,\mathrm{inch\,mrad} = 4.572\,\mu\mathrm{m},
\end{aligned}$$

which appears nearly round in the real plane.

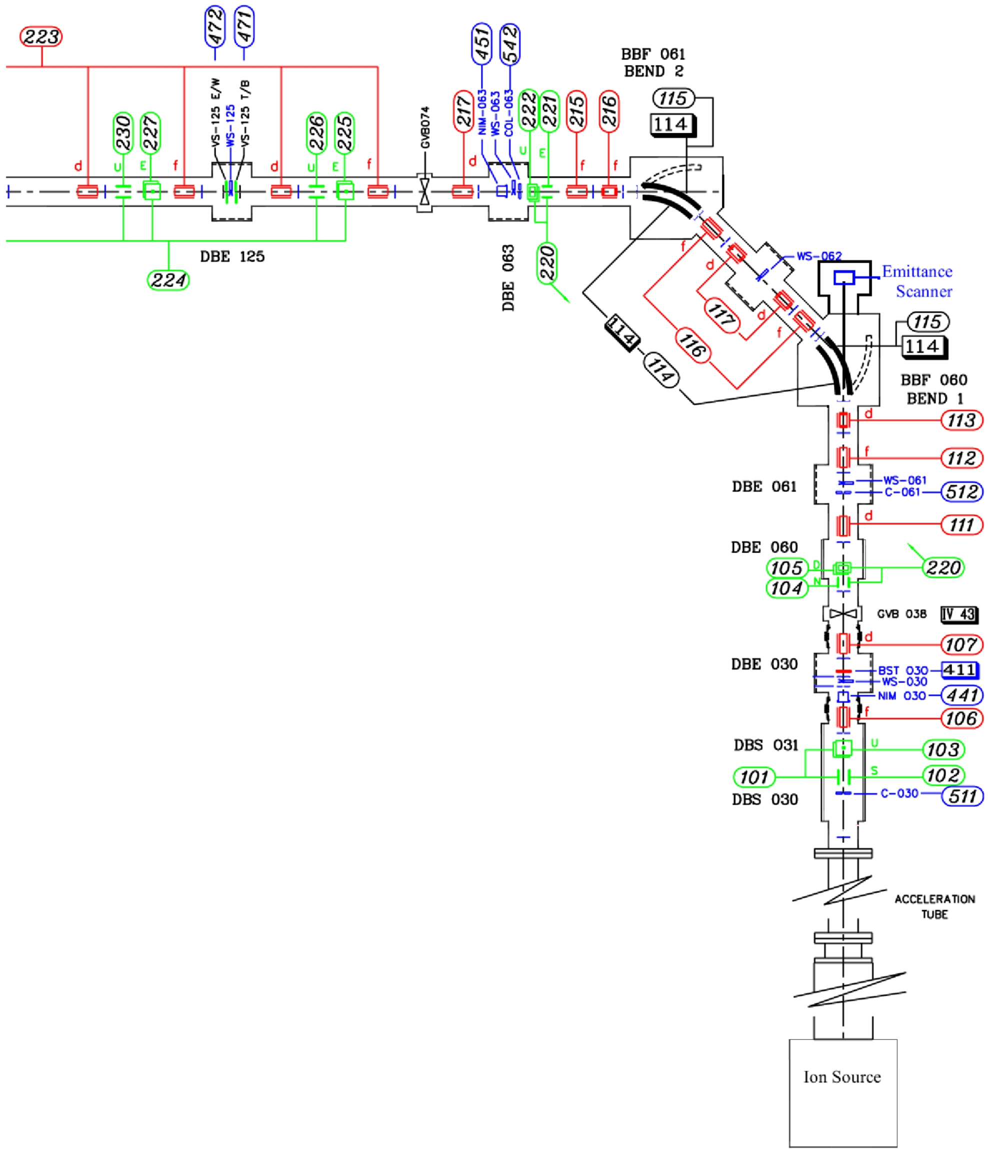

Figure 2: Diagram of ISIS front end, where the measurements were performed.

Ideally, we would prefer to perform the tomography measurements in the front-end straight section, namely, from the quad D111 to the profile monitor WS061 (see Fig. 2), as this section is closest to the emittance scanner which is $\sim 53.39''$ straight downstream of Q111, involving minimum number of quads in between (namely D111, F112 and D113), and would therefore allow to minimize uncertainties which might exist for instance in effective lengths of the quads. Unfortunately, this section is not a good choice, because it can't create a large enough rotation of the phase space to allow for a tomographic reconstruction of reduced distortion. The beam size in either plane at WS061 vs. the setting of Q111 within $\pm 10\,\mathrm{kV}$ can hardly reach a minimum value before the beam becomes too large in another plane and consequently gets lost on the collimator C061 (see Fig. 3).

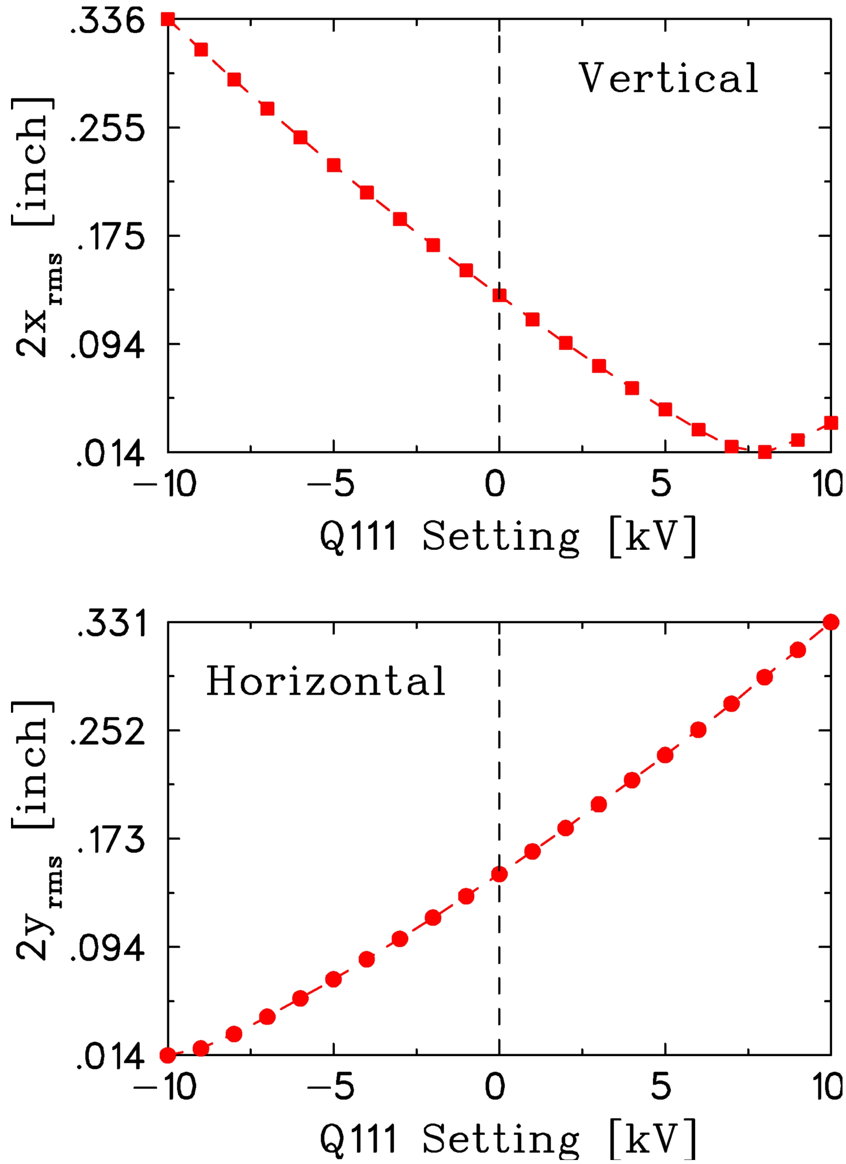

Figure 3: The beam size (2rms) at WS061 vs. the voltage setting of Q111, calculated with the production tune as shown in the Fig. 1. This indicates that the beam size in either plane can hardly reach a minimum value before the beam becomes too large in another plane and consequently gets lost on the collimator C061.

Therefore we decided to move downstream to use a combination of F215 and WS063. Without changing anything else to the production tune except that the D106's setting was raised to 3.82 kV from 2.02 kV, the beam profile and beam size were measured with WS063 as a function of Q215's setting. See Fig. 4. It shows a large enough variation and covers a minimum value in each plane in a scan range between −1.0 kV and +10 kV, within which there was no beam getting lost on the collimator C063.

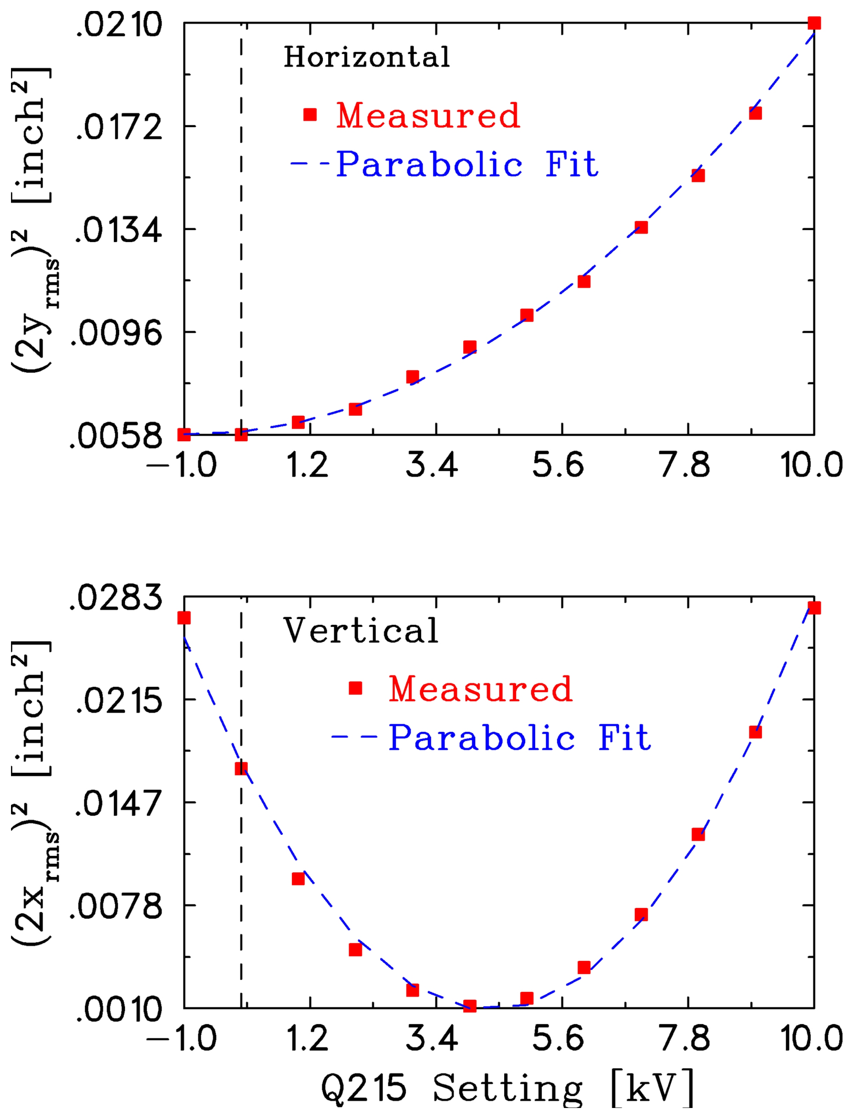

Figure 4: The beam size (2rms) measured at WS063 vs. the voltage setting of Q215. It reaches a minimum value in each plane in a scan range between −1 kV and +10 kV, within which there was no beam lost at the collimator C063.

The beam tomography was reconstructed at the entry of Q215. This is shown in Fig. 5, along with the statistical values (2rms) of beam size, divergence and emittance which are calculated from the tomography (Similarly hereinafter). The filamentation is apparent in the vertical plane.

Fig. 6−Fig. 8 show the originally measured profiles under various voltage settings of Q215, along with the MENT reconstructed ones. It's seen that each of them is well reproduced.

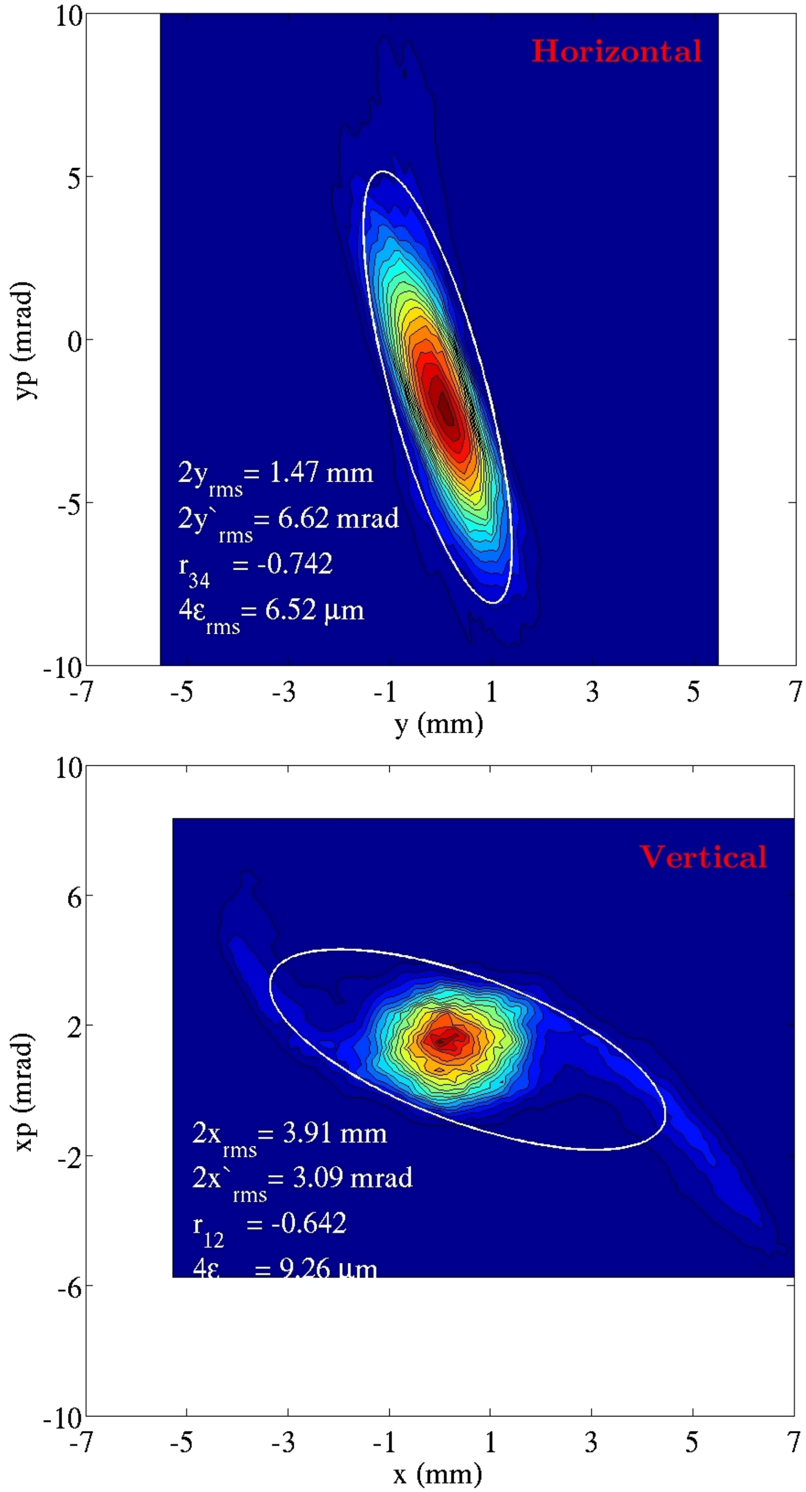

Figure 5: The horizontal (upper) and vertical (lower) beam tomography reconstructed at the entry of Q215. Also shown in white is the statistical values (2rms) of beam size, divergence and emittance (similarly hereinafter).

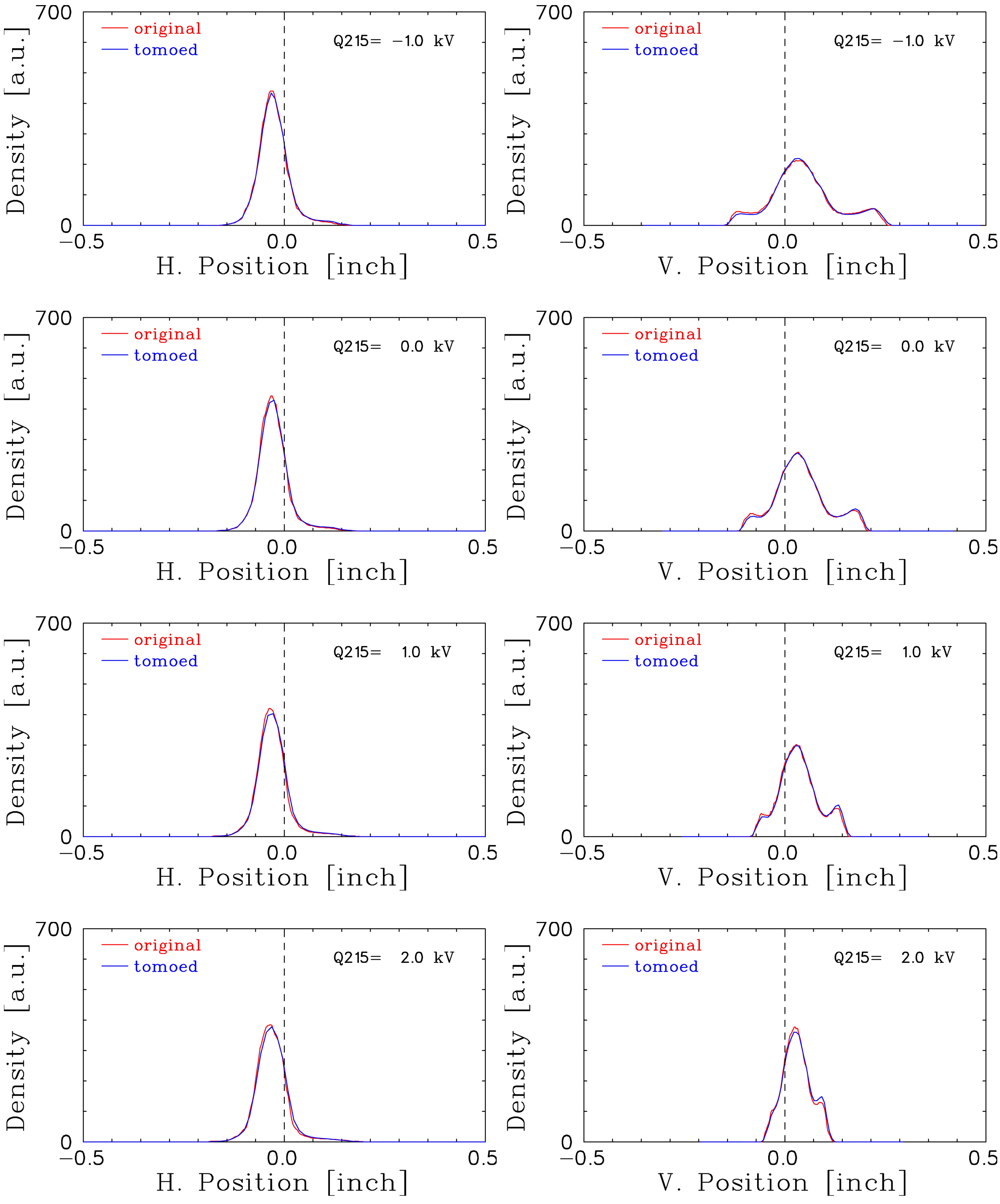

Figure 6: Horizontal (left) and vertical (right) beam profiles, measured and reconstructed, at the monitor WS063 under various voltage settings of the quad Q215.

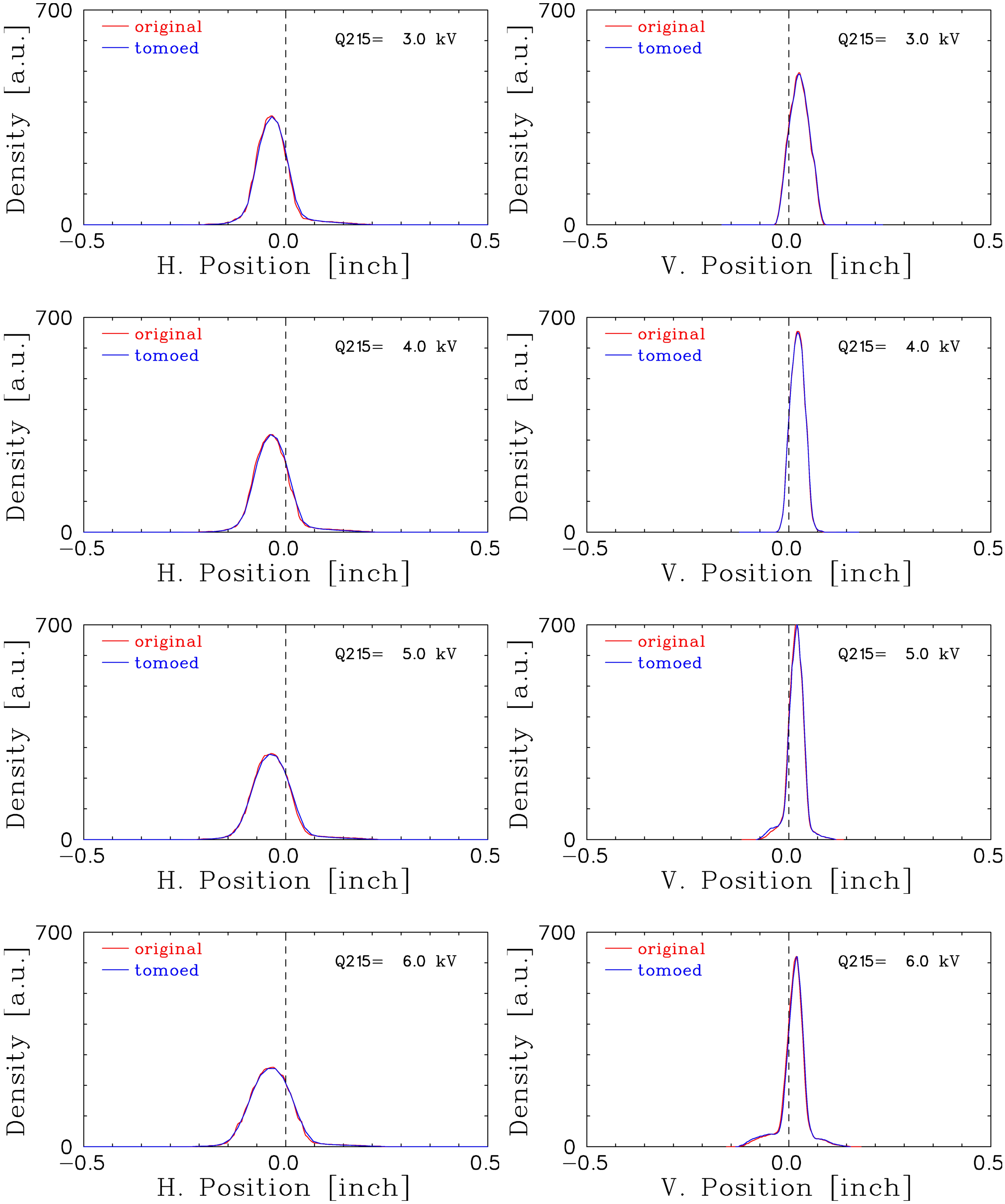

Figure 7: Horizontal (left) and vertical (right) beam profiles, measured and reconstructed, at the monitor WS063 under various voltage settings of the quad Q215.

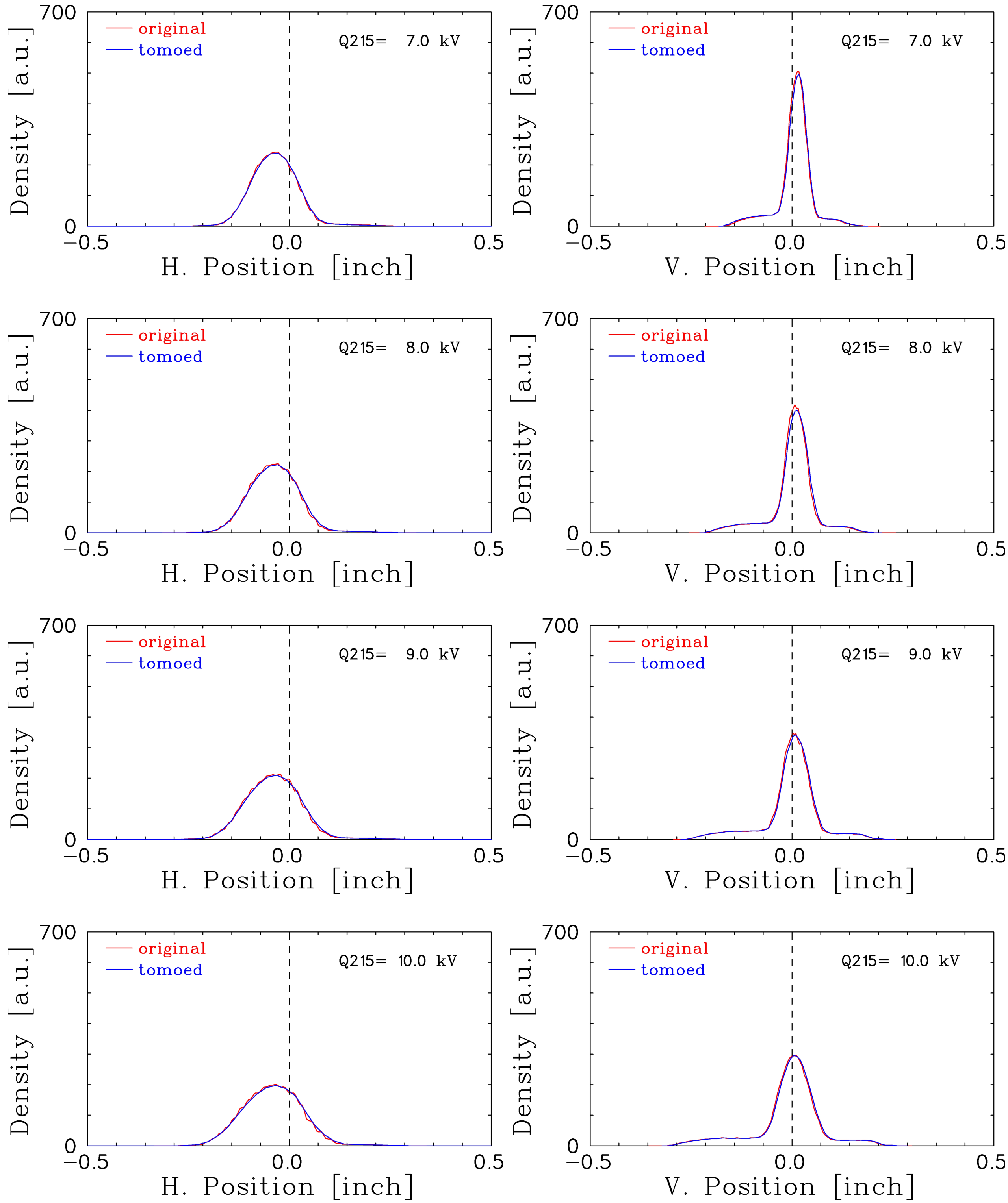

Figure 8: Horizontal (left) and vertical (right) beam profiles, measured and reconstructed, at the monitor WS063 under various voltage settings of the quad Q215.

2 Emittance Scanner's Measurement

Fig. 9 shows the phase plots directly measured at the emittance rig under the production tune.

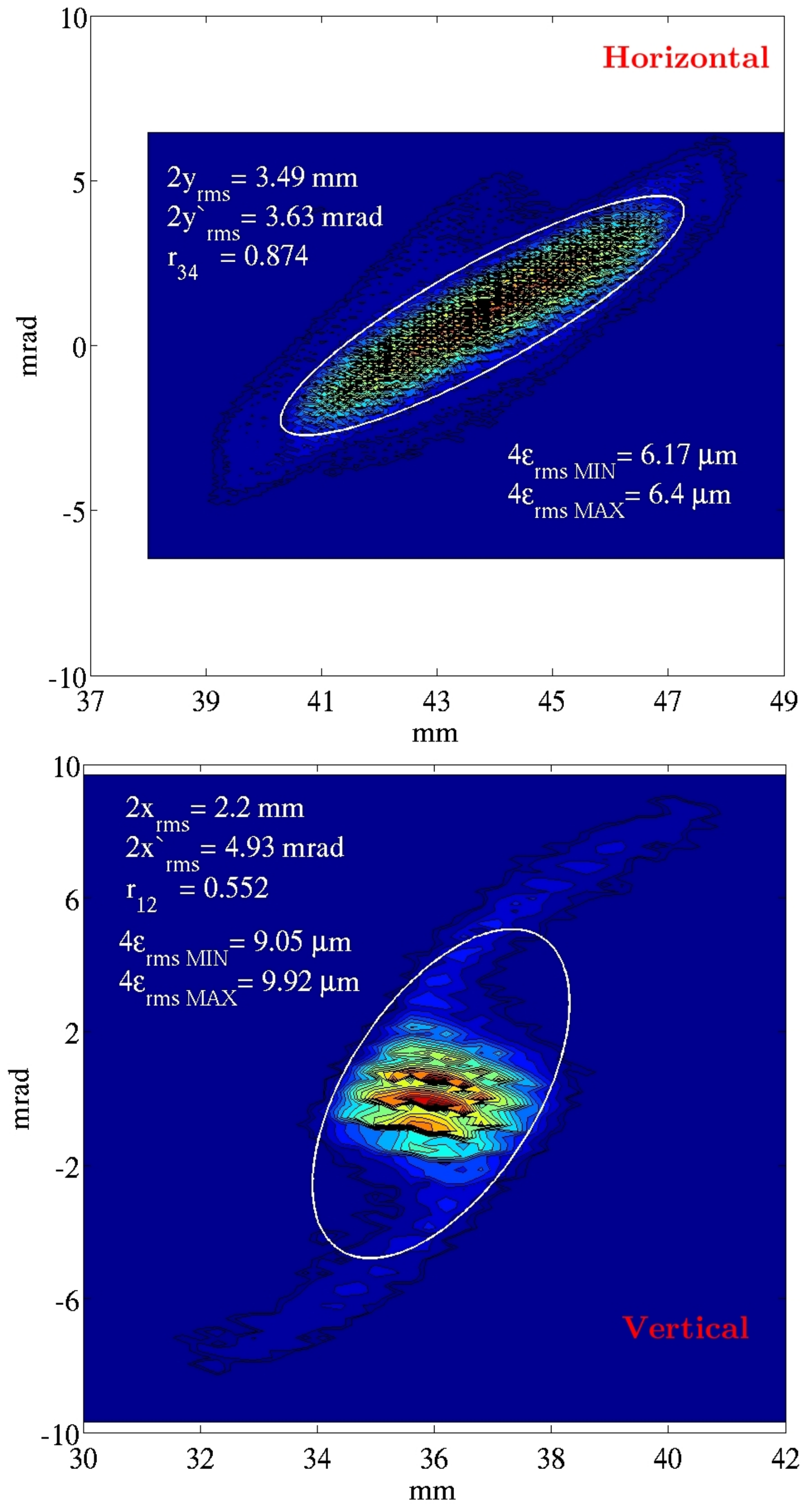

Figure 9: The horizontal (upper) and vertical (lower) phase plots measured at the emittance scanner under the production tune.

3 Comparison

For comparison, the phase space density distributions as MENT reconstructed at Q215 entry and as measured at the emittance scanner are transformed to an identical location i.e. the start of the beamline. The results are shown in Fig. 10 and Fig. 11, obtained by assuming full space charge force and zero space charge force respectively in the beam transport.

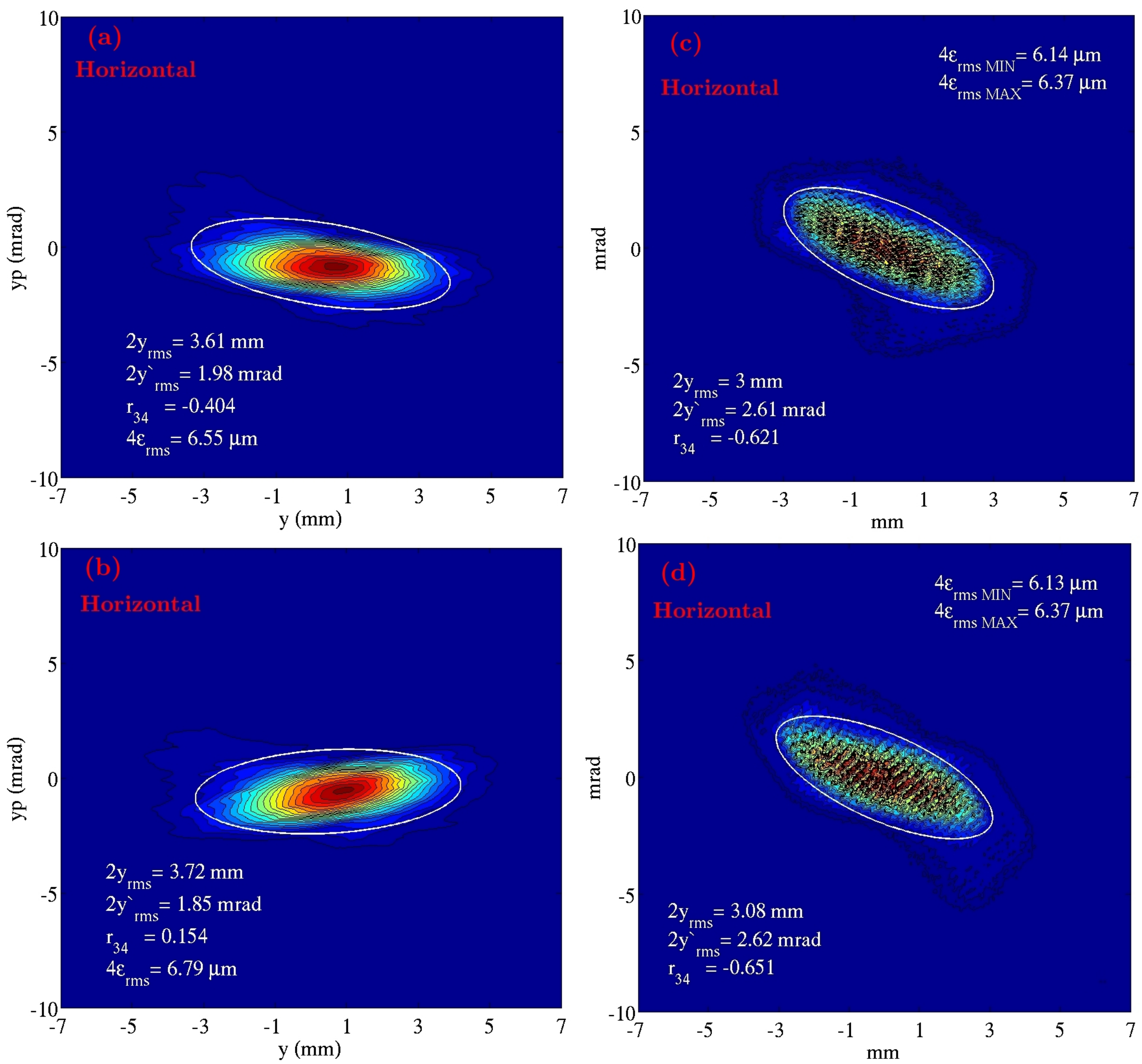

Figure 10: Horizontal phase space density distribution viewed at the start of the beamline: (a) transformed from Q215 assuming full space charge force; (b) transformed from Q215 assuming zero space charge force; (c) transformed from emittance rig assuming full space charge force; and (d) transformed from emittance rig assuming zero space charge force.

From Fig. 10 it looks that (1) in picture (a) the beam gets cut at bottom, while in picture (c) the beam gets cut at top; (2) the full space charge (i.e. zero neutralization) assumption makes more sense as it brings closer agreement between the two pictures.

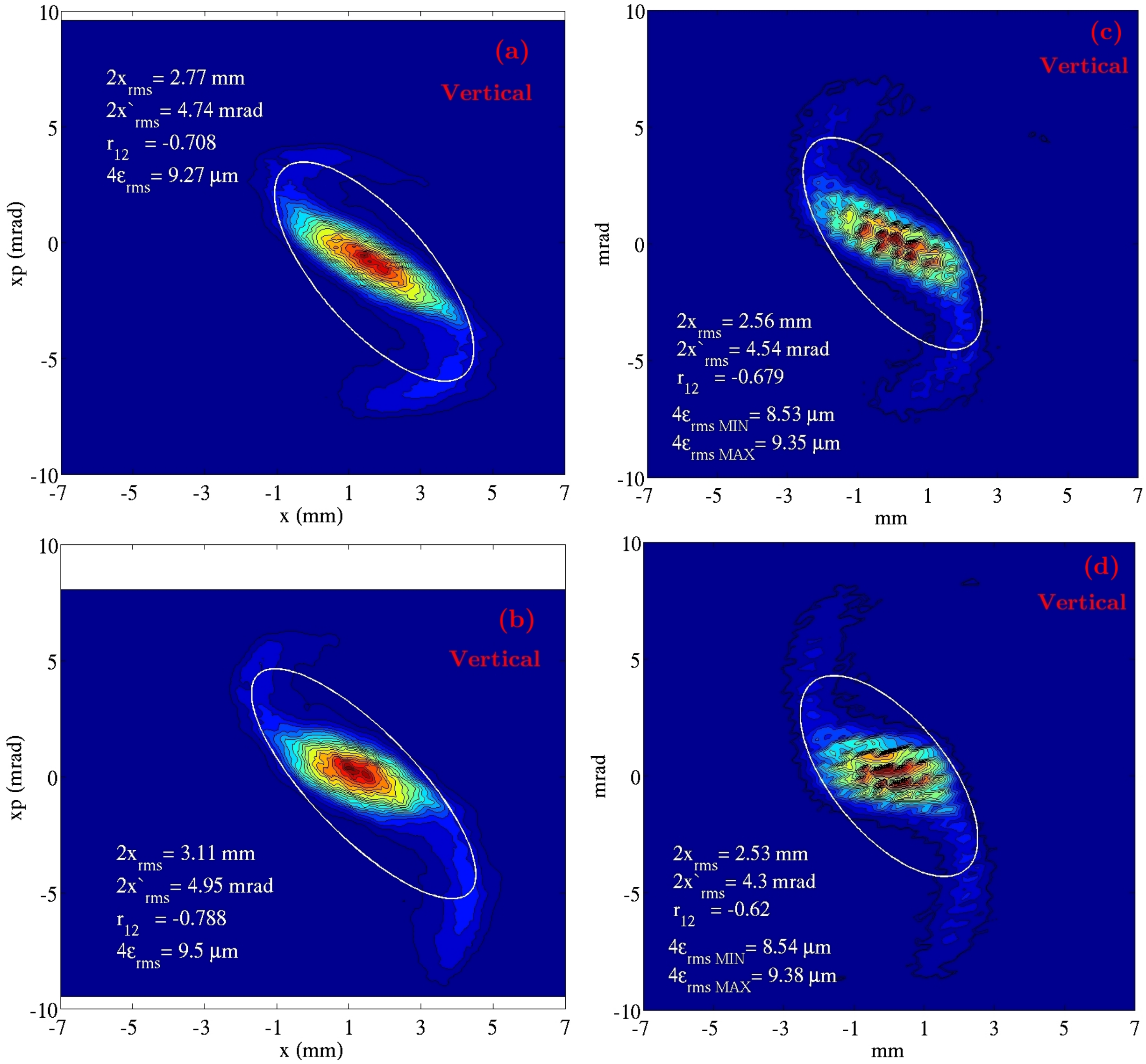

Figure 11: Vertical phase space density distribution viewed at the start of the beamline: (a) transformed from Q215 assuming full space charge force; (b) transformed from Q215 assuming zero space charge force; (c) transformed from emittance rig assuming full space charge force; and (d) transformed from emittance rig assuming zero space charge force.

It's seen from Fig. 11 that both techniques can reveal the s-shape and as well the full space charge assumption makes more sense. The "mismatch factor" and the relative rotation between the two ellipses in (a) and (c) are 22% and 1.4° respectively. This discrepancy can possibly arise from inaccurate measures of the emittance rigs geometric parameters (i.e. plate gap, plate length and orientation) as well as the effective lengths of the quads in between.