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BL4N First Extracted Beam

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Abstract: In this note we summarize the results of measurements we accomplished for the BL4N first extracted beam during 2022 cyclotron beam development activties.

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1 Introduction

By the summer 2022, the BL4N front-end was ready for the proton beam extraction test as all the relevant hardware had been installed, aligned and commissioned with no beam. These include the extraction probe, the beamline components (namely the combination magnet, steerer YCB0, quadrupole magnets Q1 and Q2, wire scanner WS2, a tuning beam dump, and a vacuum pump etc., about 4 m long in total). See Fig. 1. As well, the EPICS controls were developed and commissioned. All these allowed us to proceed with beam extraction tests. The maximum permitted beam intensity down to the beamline was 20 nA ($\sim$1 W), constrained by the facility safety requirement.

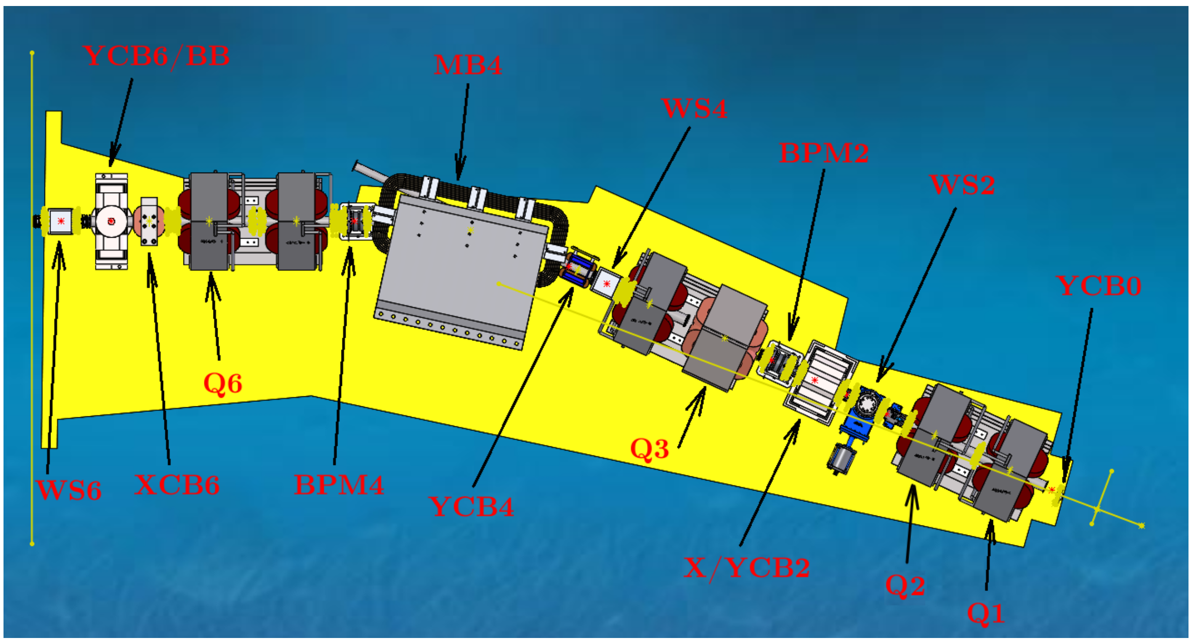

Figure 1: *Diagram showing the layout of BL4N vault section. The beam extraction tests and measurements during 2022 took place only in the front-end of the beamline up to the diagnostic element (wire scanner) WS2 followed by a temporary dump for beam tuning, while the downstream devices were not installed yet.*

2 460 MeV Beam Measurements

2.1 Extraction Probe Parameters

We simply set the Ex4 probe's R, L & Z coordinates to the theoretical values for the energy of 460 MeV, with minor tweak to the L-coordinate, to extract beam down to the beamline and display profiles on the wire scanner WS2. These were R=112.51″, L=3.78″ and Z=1.71″

(See Fig. 2), while the magnets' excitations were set to CM=+43 A, YCB0=0 A, Q1=0 A and Q2=0 A. The stripper foil used in the measurements was a C-type of carbon foil of 1.65 g/cm^2 thick.

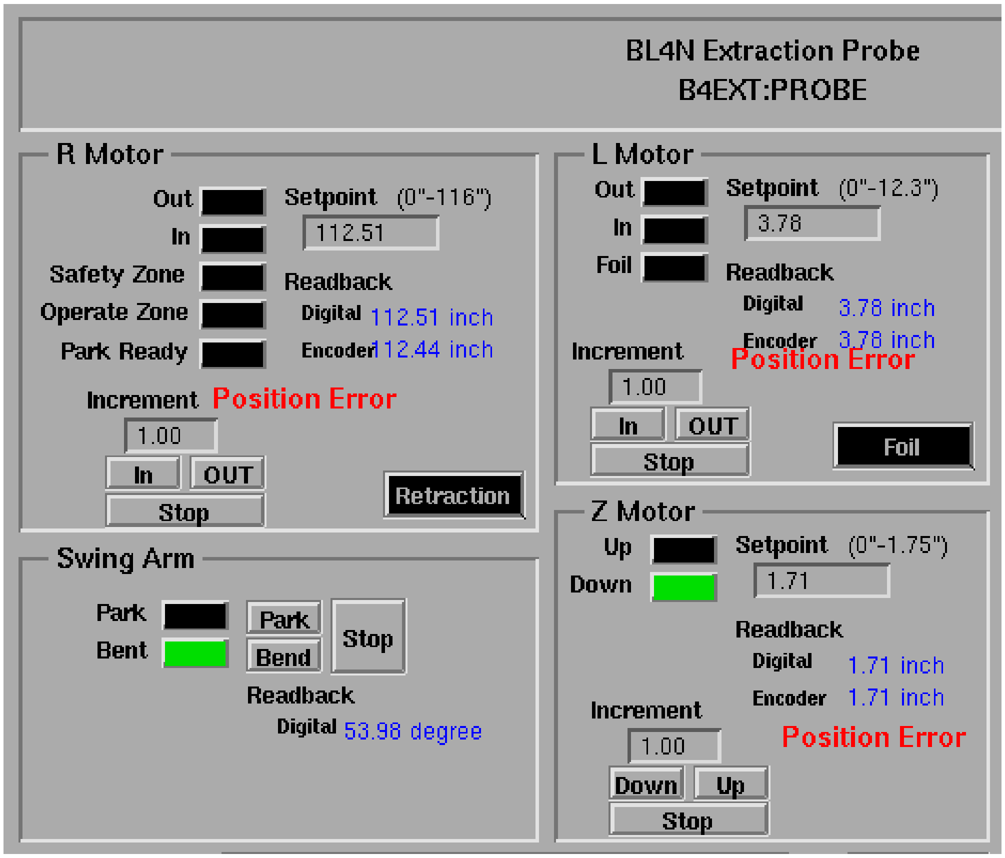

Figure 2: *Theoretical settings for the extraction probe's (R, L, Z) coordinates, calculated for 460 MeV. These worked out right away to extract protons down to the beamline and display profiles on the wire scanner WS2. Under these settings, the Ex4 probe took all the circulating beam at high energy.*

2.2 Beam Sizes and Fit

We measured beam profiles systematically, and acquired two sets of good data. One was, Q2 remained unchanged at 250 A while Q1 was changed from 0 to 400 A in a step of 50 A. The other was, Q1 remained unchanged at 250 A while Q2 was changed from 0 to 450 A in a step of 50 A. Under each setting, the beam profiles in x and y were measured at WS2.

With the profiles measured, we calculated the beam sizes. We got 40 data of beam size in total, 20 for x and 20 for y. These data were then fitted in the beam envelope calculations with `TRANSOPTR` to find the initial conditions of beam that dumped on the foil. There are only 7 unknown parameters to be determined from the fit: (α_x, β_x, ϵ_x; α_y, β_y, ϵ_y; and $\Delta p/p$), So, the solution to be sought is over-determined. The cyclotron fringe field transfer matrix used in the optics modelling was calculated with `STRIPUBC`.

The fit looks good. See Fig.3 for the comparison between the measured beam sizes and the calculated ones. Should be pointed out that the measured sizes have $\sim \pm 15\%$ uncertainty, related mainly to the difficulty of exactly determining the background noise level for a cut. Table 1 lists the resulting σ-matrix (2rms) of the beam dumped on the foil.

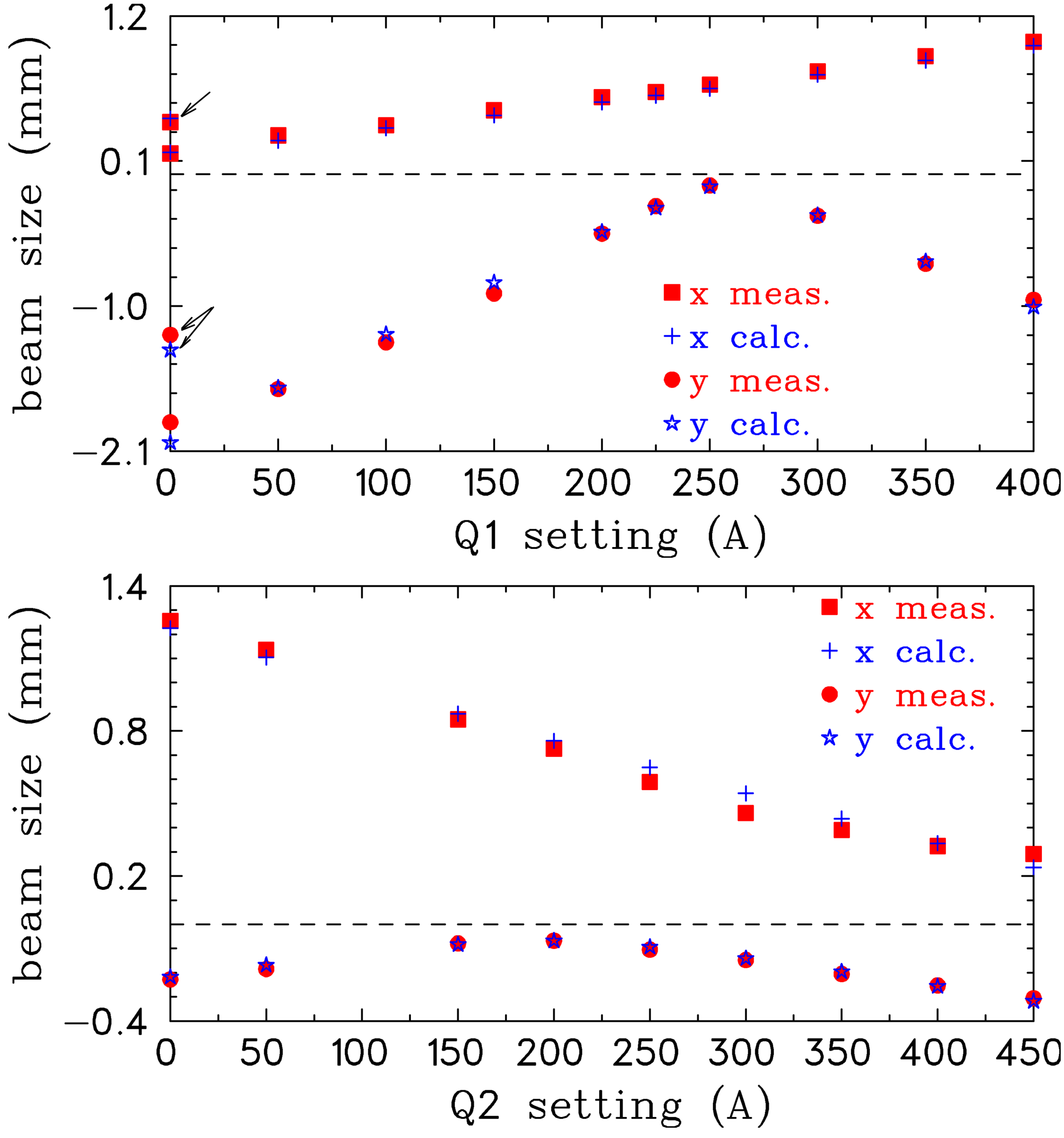

Figure 3: *Comparison of measured beam sizes with the calculated ones, for the quad's settings of Q2=250 A while Q1 was changed from 0 to 400 A (upper) plus Q1=250 A while Q2 was varied from 0 to 450 A (lower). Note that the arrow points in the upper plot are for the setting of Q2=40 A.*

Table 1: Envelope calculation resulting $\sigma-$matrix of 460 MeV beam dumped on the stripper foil

	Diagonal	Off-Diagonals (Normalized Form)				
x (cm)	0.178313					
theta (mrad)	1.39145	0.612479				
y (cm)	0.568835	0.00000	0.00000			
phi (mrad)	0.720134	0.00000	0.00000	-0.632895		
l (cm)	63.2357	0.136939	0.0107176	0.00000	0.00000	
delta (%)	0.066195	-0.834894	-0.0918155	0.00000	0.00000	-0.166998

3 Vertical Beam Tomography

Since the beam vertical plane is dispersionless, the measured beam profiles have no energy spread correlation. So, the quad scanning technique that we used for the profile measurements allows us to reconstruct beam tomography for the vertical phase space. Fig. 4 shows the resulting tomography reconstructed at the exit of stripper foil, along with the statistical values (2rms) of beam size, divergence and emittance which are calculated from the tomography. Notice that these parameters are in good agreement with those obtained from the envelope calculation as shown in Table 1, as the transverse scatter is $\sim$0.22 mrad (2rms, in-plane) for 460 MeV protons passage through 1.65 mg/cm^2 carbon.

Figure 5 and Fig. 6 show the measured profiles (smoothed) under various excitations of Q1 and Q2, along with the MENT reconstructed ones. It's seen that each of them is well reproduced.

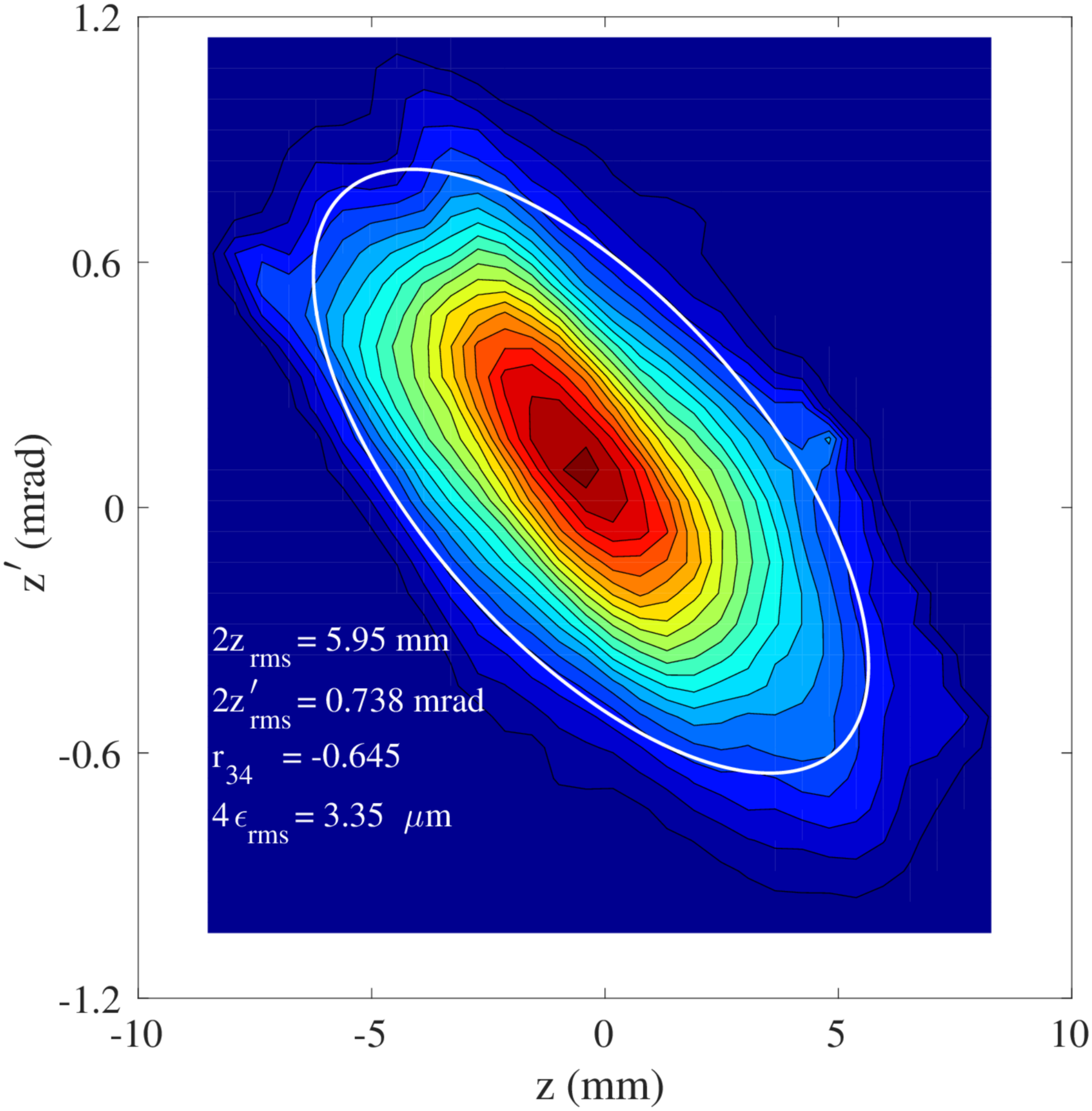

Figure 4: *Vertical tomography of 460 MeV proton beam, reconstructed at the exit of stripper foil.*

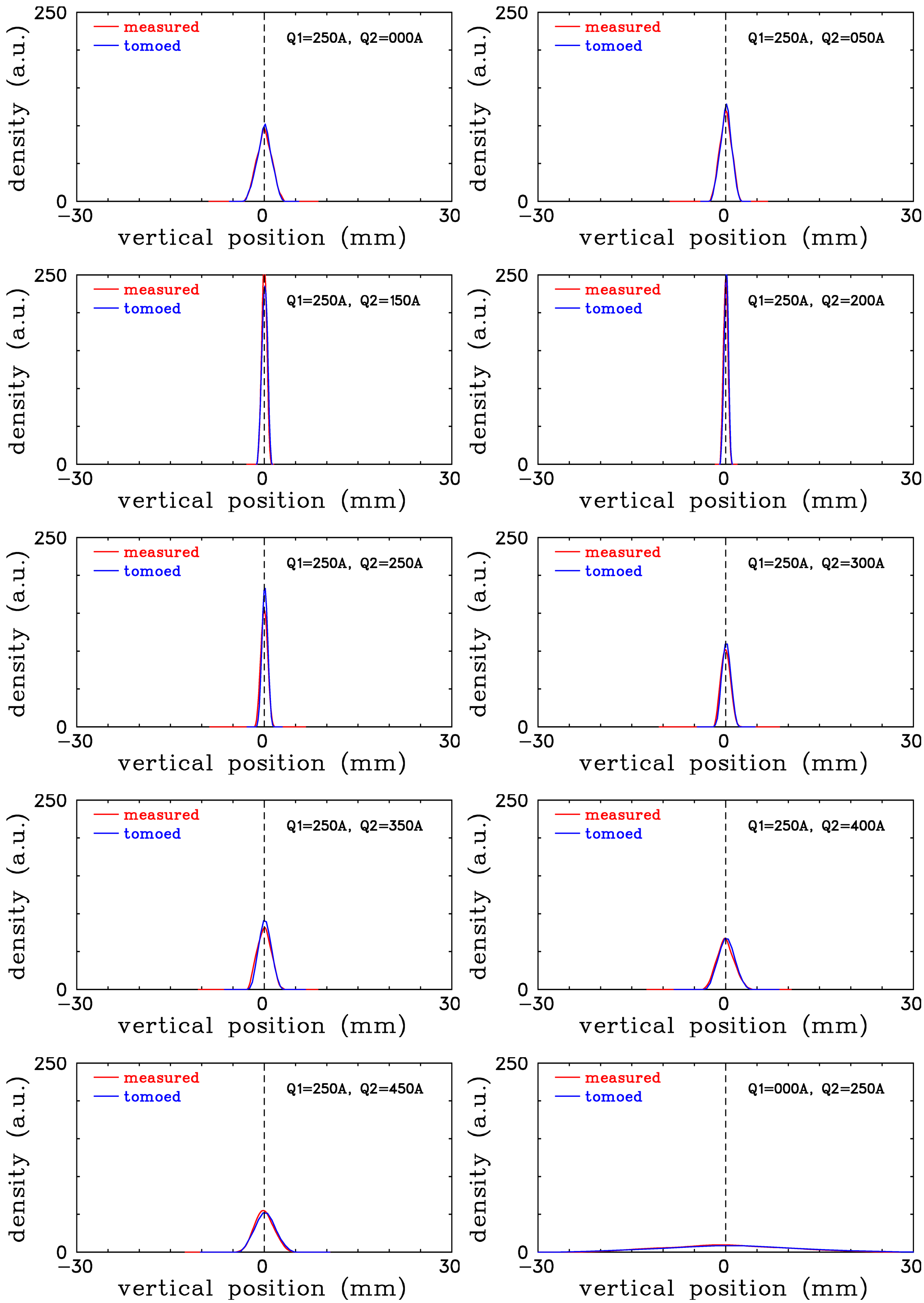

Figure 5: Vertical profiles of 460 MeV beam, measured and reconstructed at the monitor WS2 under various excitations of the quads Q1 and Q2.

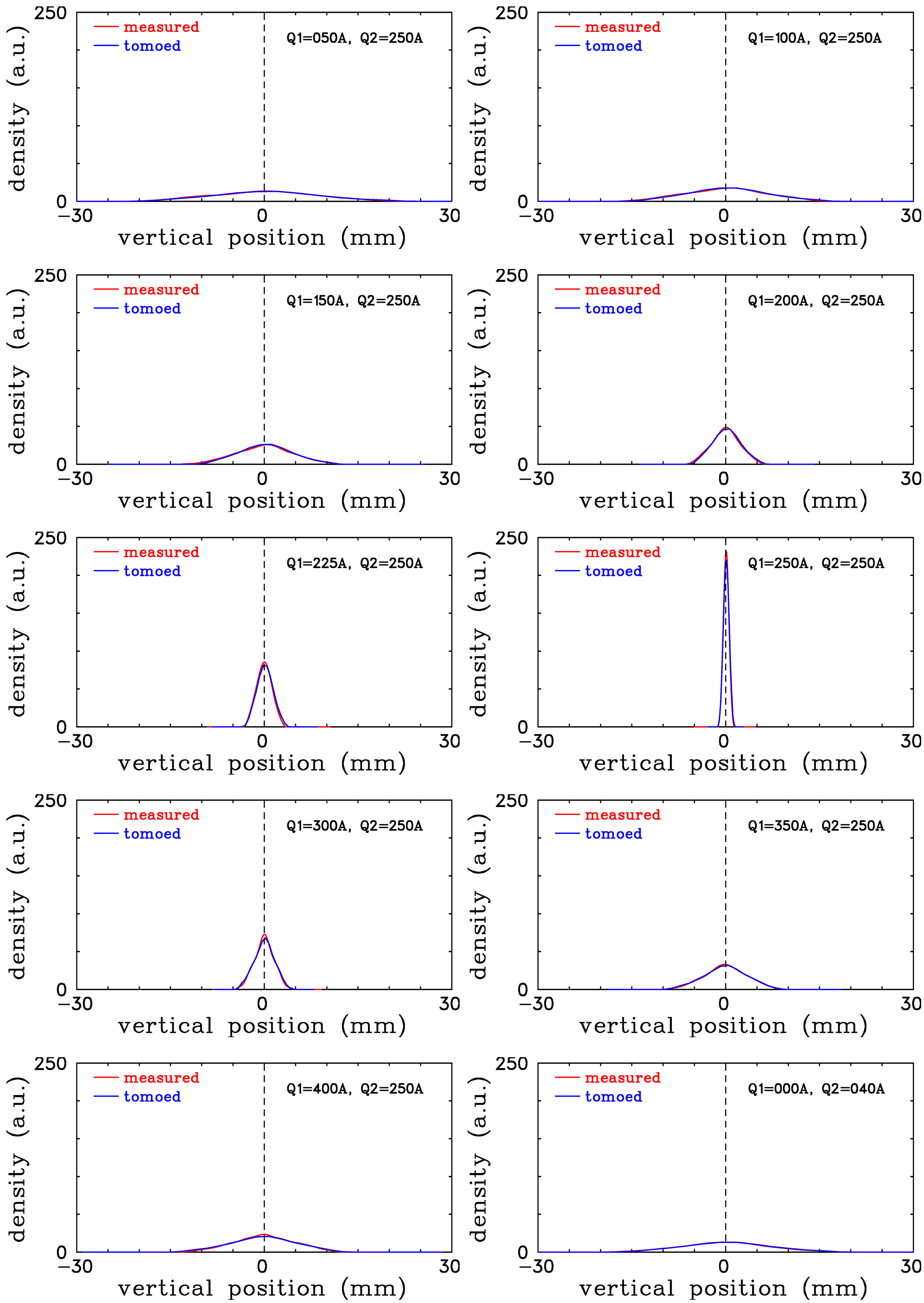

Figure 6: Vertical profiles of 460 MeV beam, measured and reconstructed at the monitor WS2 under various excitations of the quads Q1 and Q2.

4 480 MeV Beam Measurements

4.1 Extraction Probe Parameters

For 480 MeV, we simply set the Ex4 probe's R, L & Z coordinates to the theoretical values to extract beam down to the beamline and display profiles on the wire scanner WS2. These were R=108.38″, L=5.21″ and Z=1.70″ (Fig. 7), while the magnets' excitations were set to CM=+26.0 A, YCB0=0 A, Q1=0 A and Q2=0 A. The stripper foil used was the same one as for the 460 MeV measurements, that is, a C-type of carbon foil of 1.65 g/cm^2 thick.

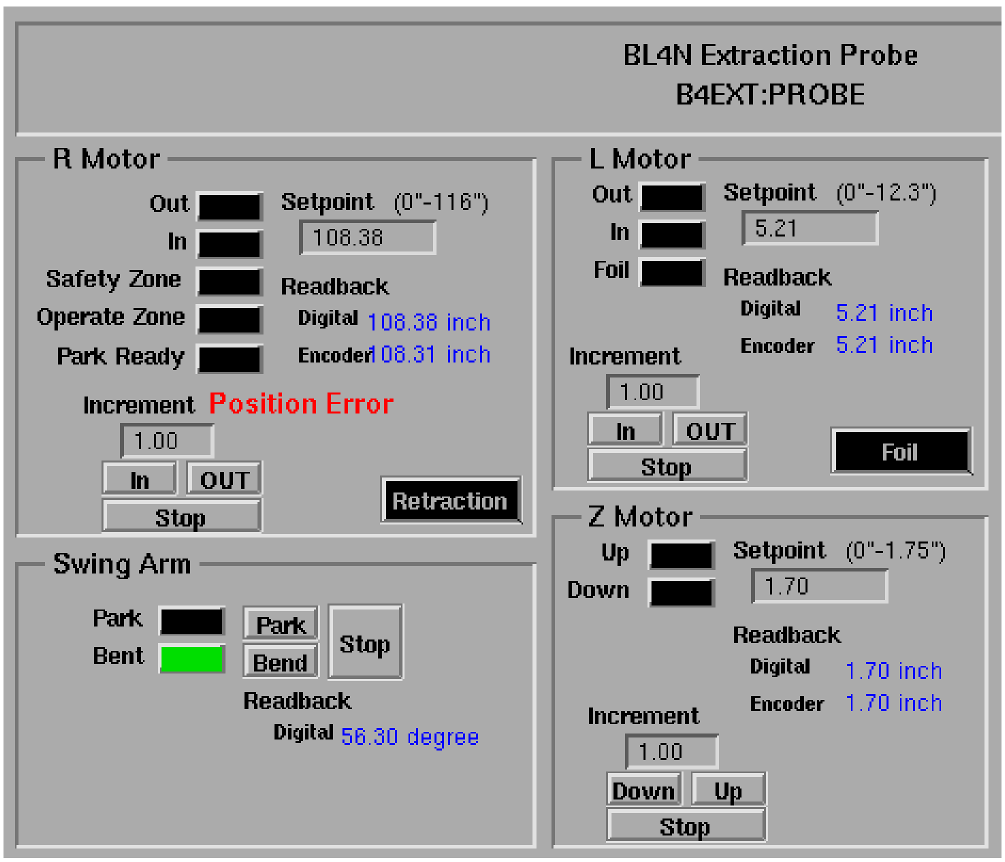

Figure 7: *Theoretical settings for the extraction probe's (R, L, Z) coordinates, calculated for 480 MeV. These worked out right away to extract protons down to the beamline and display profiles on the wire scanner WS2. Under these settings, the Ex4 probe shadowed Ex1 probe with beam split ratio of 1:1 at 480 MeV.*

4.2 Beam Sizes and Fit

Similar to the 460 MeV measurements, we scanned Q1 and Q2 respectively to measure the beam profiles of 480 MeV but took denser data points around the narrowest profile in the vertical plane. And then we calculated the beam sizes. We got 132 data of beam size in total, 66 for x and 66 for y. These data were then fitted in the beam envelope calculations with `TRANSOPTR` to find the initial conditions of the beam that dumped on the foil. The fit looks good too. Fig.8 compares the measured beam sizes and the calculated ones. Likewise, these measured sizes have $\sim \pm 15\%$ uncertainty. Table 2 lists the resulting σ-matrix (2rms) of the beam dumped on the foil.

Table 2: Envelope calculation resulting $\sigma-$matrix of 480 MeV beam dumped on the stripper foil

	Diagonal	Off-Diagonals (Normalized Form)				
x (cm)	0.175183					
theta (mrad)	0.658524	0.683245				
y (cm)	0.363097	0.00000	0.00000			
phi (mrad)	0.565912	0.00000	0.00000	-0.533347		
l (cm)	64.8001	0.0559507	0.0120271	0.00000	0.00000	
delta (%)	0.062534	-0.838155	-0.206065	0.00000	0.00000	-0.679999

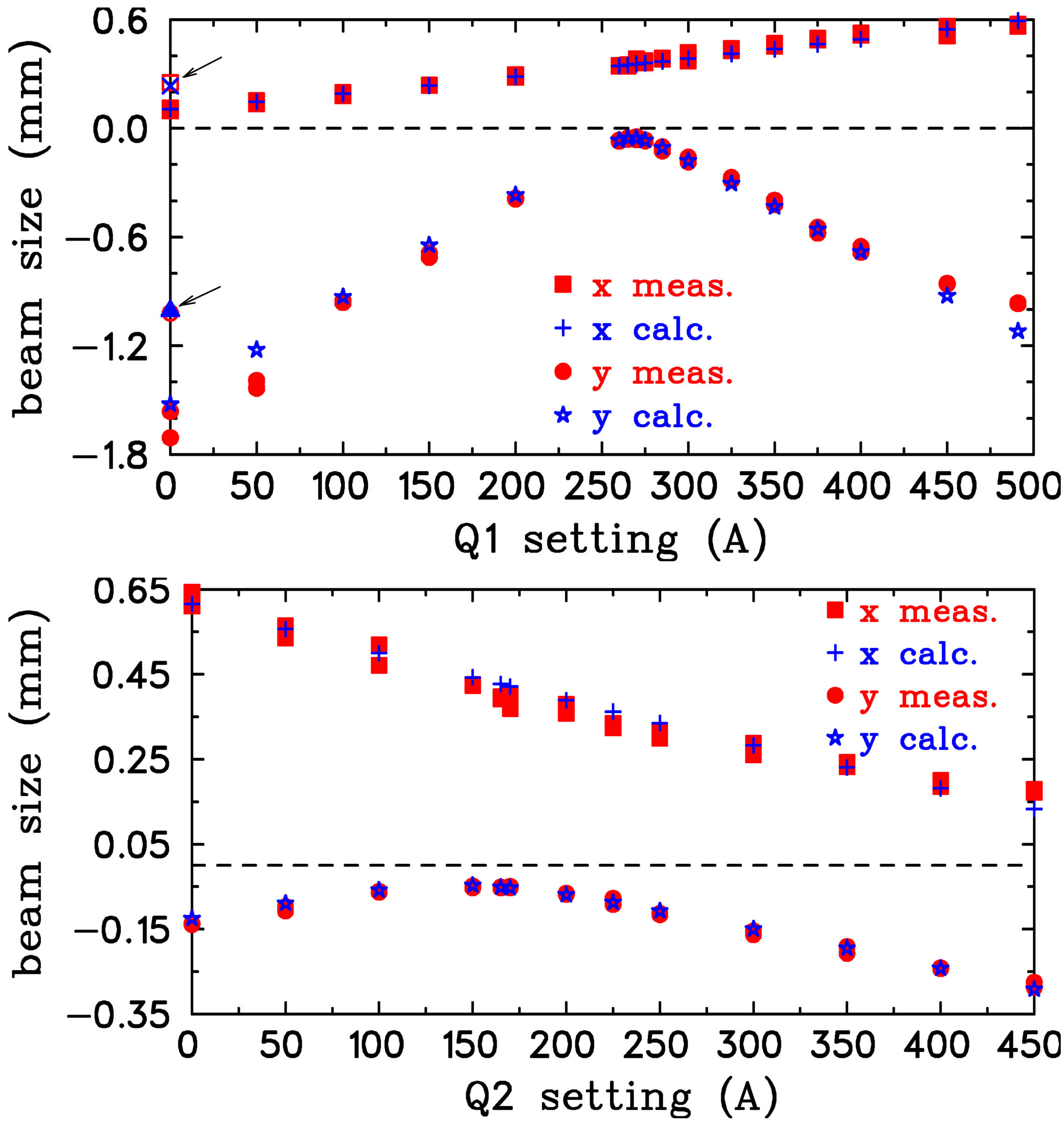

Figure 8: *Comparison of measured beam sizes with the calculated ones, for the quad's settings of Q2=250 A while Q1 was scanned from 0 to 491 A (upper) plus Q1=250 A while Q2 was varied from 0 to 450 A (lower). Note that the arrow points in the upper plot are for the setting of Q2=40 A.*

5 Vertical Beam Tomography

Similarly, the vertical beam tomography is reconstructed at the exit of stripper foil. The result is shown in Fig. 9, along with the statistical values (2rms) of beam size, divergence and emittance that are calculated from the tomography. Notice that these parameters are in good agreement with those obtained from the envelope calculation as shown in Table 2, as the transverse scatter is ~0.21 mrad (2rms, in-plane) for 480 MeV protons passage through 1.65 mg/cm^2 carbon.

Figure 10 to Fig. 12 show the measured profiles (smoothed) under various excitations of Q1 and Q2, along with the MENT reconstructed ones. It's seen that each of them is well reproduced.

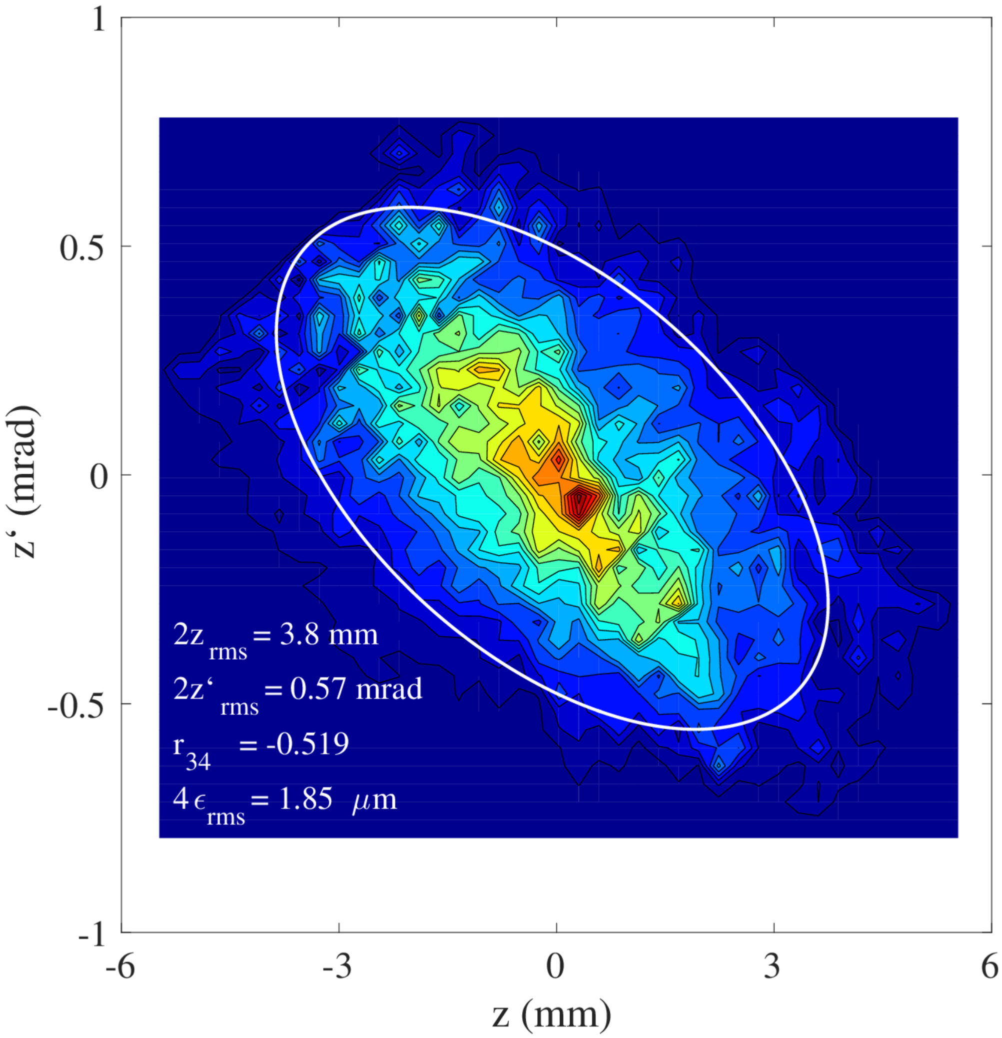

Figure 9: *Vertical tomography of 480 MeV proton beam, reconstructed at the exit of stripper foil.*

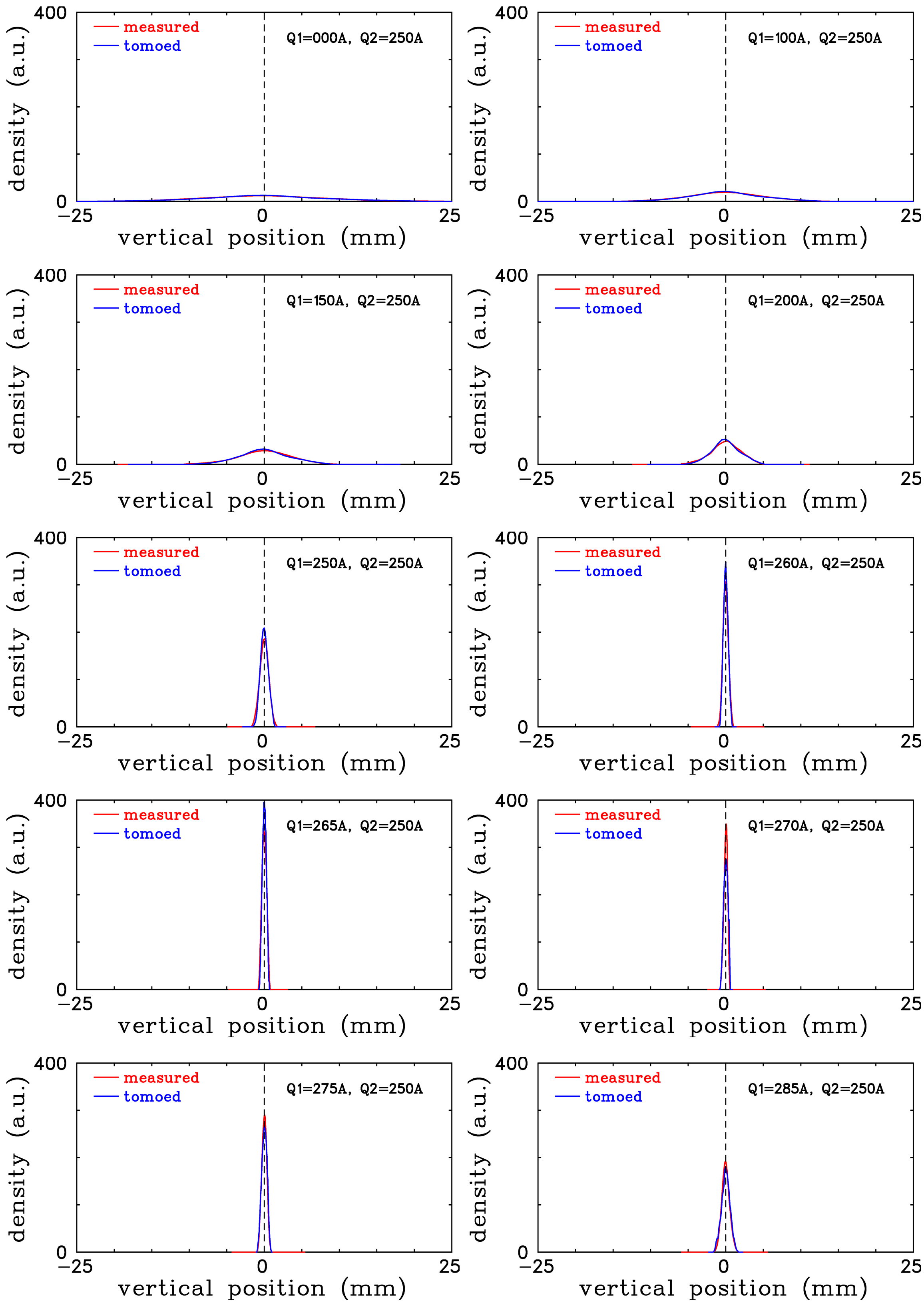

Figure 10: Vertical profiles of 480 MeV beam, measured and reconstructed at the monitor WS2 under various excitations of the quads Q1 and Q2.

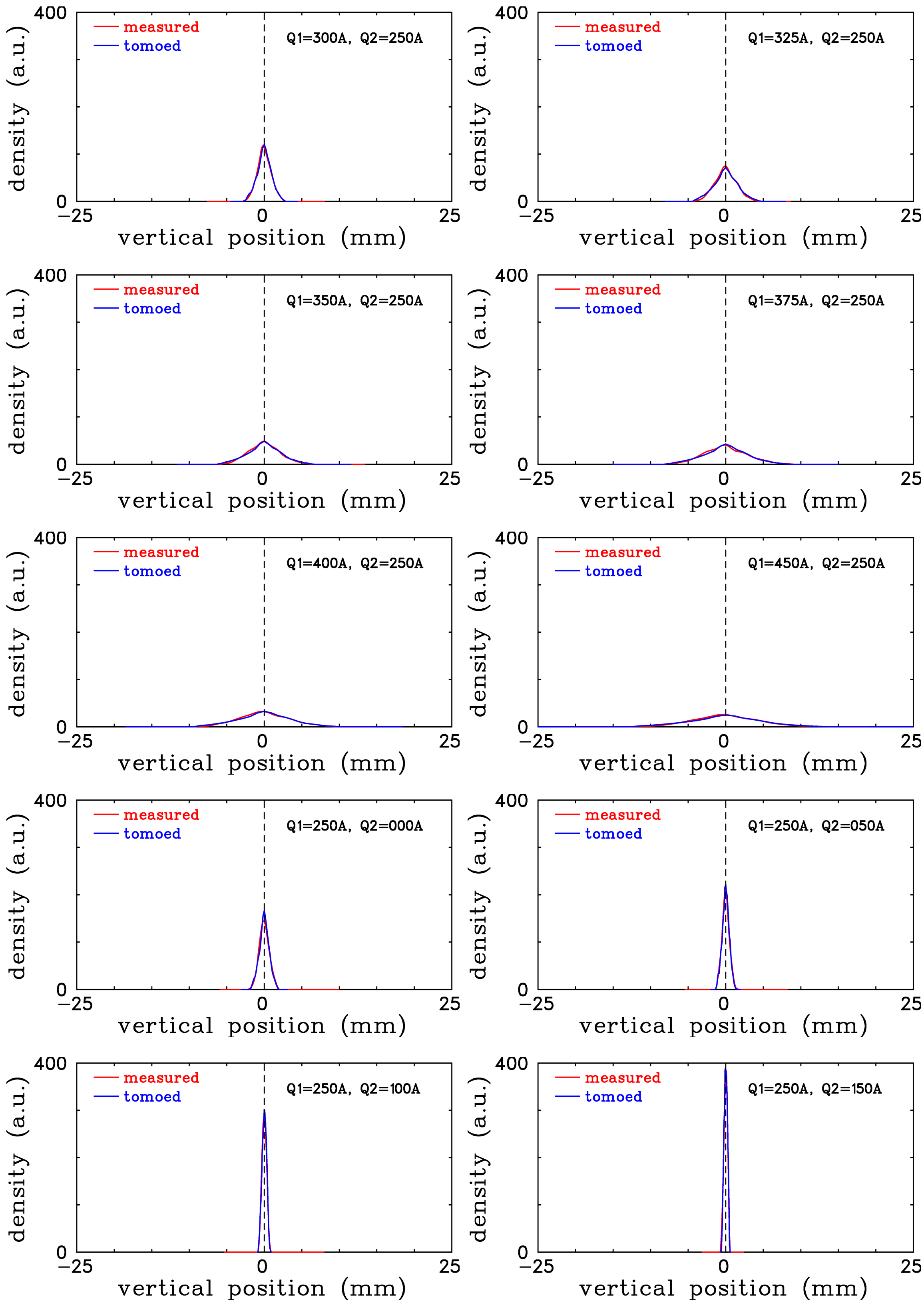

Figure 11: Vertical profiles of 480 MeV beam, measured and reconstructed at the monitor WS2 under various excitations of the quads Q1 and Q2.

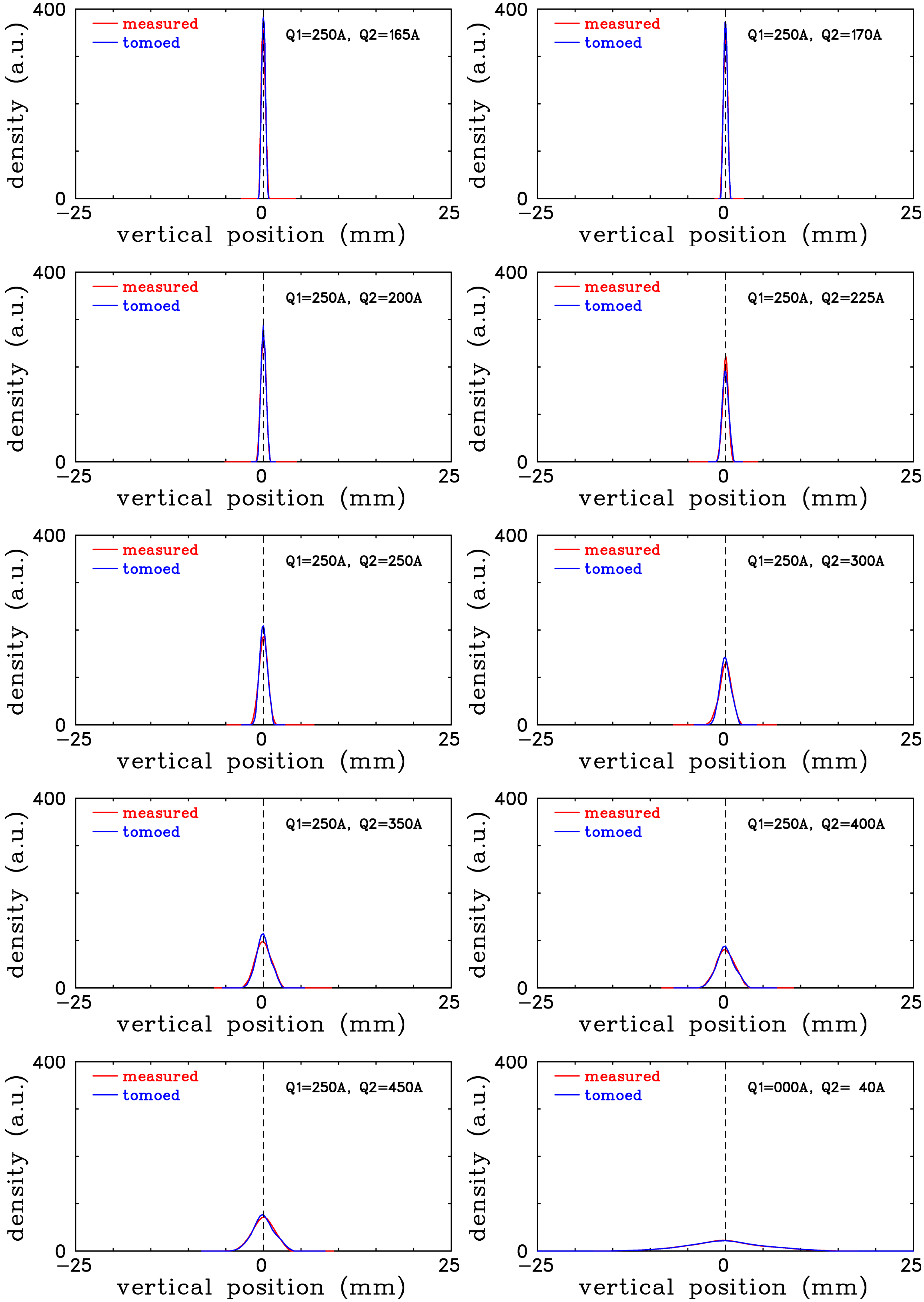

Figure 12: Vertical profiles of 480 MeV beam, measured and reconstructed at the monitor WS2 under various excitations of the quads Q1 and Q2.

6 Summary

We successfully extracted proton beam from cyclotron to the tuning beam dump in the vault section of BL4N. We validated the EX4 probe parameters, and measured beam profiles systematically with the new type of wire scanner. Moreover, we validated the front-end beam optics and characterized the beam property.

7 Acknowledgements

Useful discussions with cyclotron beam development team and L. Zhang's effort in data processing as well as cyclotron operators' help with data collection are greatly appreciated.