TRIUMF Beam Physics Note
TRI-BN-15-15
Mar.15, 2015

Beam Rastering, M19 Scan and Beam Tomography in BL2A

Y.-N. Rao

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Abstract: This note summarizes the results of simulation performed to investigate the rastering beam's profiles measured with wire scan monitor M19 in BL2A, with goal to answer such a question: how can we work out the beam tomography when the beam is rastering?

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1 Simulation Parameters

- Beam rastering frequency is between 10 and 400 Hz. Pulser's repetition rate is 1 kHz. Beam bunch's repetition rate is 23.055 MHz.
- Beam rastering radius is 6 mm. Beam static spot size is 3.5 mm (2rms).
- M19 travels vertically across the rastering beam in an uniform speed. Currently, the actual moving speed is about 2 inch/sec (see S.Kellog's message below). In the simulations we can slow it down for example by a factor of 10.
- During travel of M19, data sampling constantly occurs at the rising edge of the pulser signal where the beam is turned on (See B. Rawnsley's memo below), and sampling rate is just identical to the pulser's repetition rate of 1 kHz.

Subject: Re: 2AM19
From: Scott Kellogg <kellogg@triumf.ca>
Date: 07/10/2014 09:32 AM
To: Yi-Nong Rao <raoyn@triumf.ca>
CC: Victor Verzilov <verzilov@triumf.ca>, "'Scott Kajioka'" <skajioka@triumf.ca>

On 7/9/2014 3:00 PM, Yi-Nong Rao wrote:

> Hi Scott,
>
> A quick question for you:
>
> How many seconds does it take for the M19 to travel from one end to the other? Is it traveling in a uniform speed?
>
> Thanks,
> Yi-Nong

Hi Yi-Nong,

With help from Main Ops, we ran the 2A3M19 wire scanner both in and out while stripping the data.

Running the monitor "up" or out of the beam - time was 2.743 seconds

Running the monitor "down" or into the beam - time was 2.043 seconds

The distance between the beam resting position (either top or bottom) and the scanning wires center is 2.50 inches. The distance between in and out positions is 5.00 inches.

The speed should be fairly uniform by the time the wires are passing through the beam. The air cylinder has to overcome frictions of different parts and inertia of all the parts, , but this should take place fairly quickly. There is also the spring rate of the bellows to consider, time for the air to pass through lines and valve and fill the cylinder, etc.

Let me know if you need more information.

Scott
ext. 6248

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Mechanical Technologist

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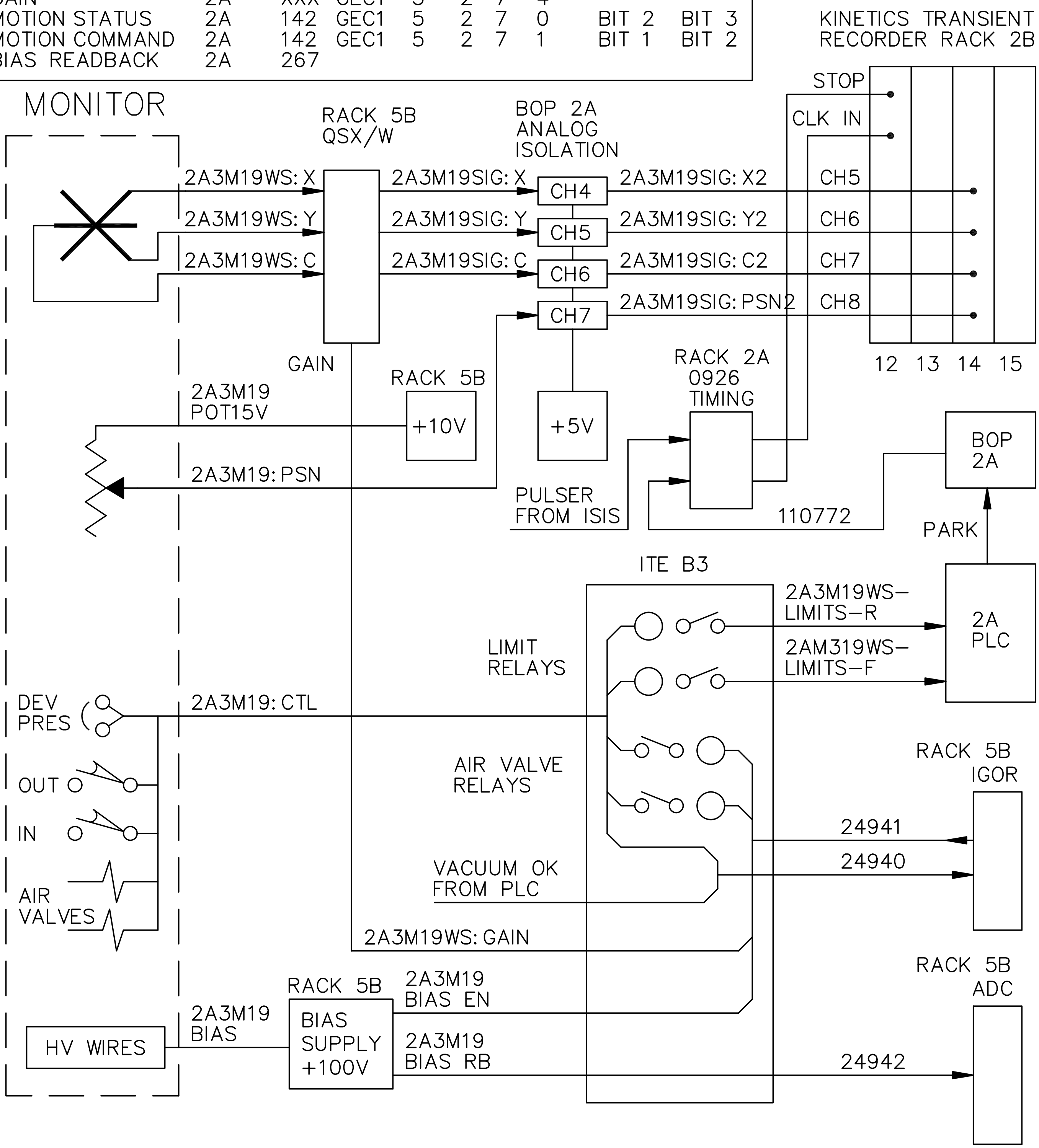
Fax: 604-222-1074

- the pulser frequency is derived from the machine RF as follows:
  - 23.055 MHz / (2^{12} * 5) = 1.125732 kHz.
- the scanner wires and position pot are sampled simultaneously.
- one set of samples is recorded after a fixed time delay from the rising edge of the pulser signal (beam turn on).
- the air bleed valves are adjusted so that a scan takes about 0.5 s end to end
- so a scan consists of ~ 1 kHz * 0.5 s = ~500 sample sets.
- the sample recording occurs in real time hardware, a Kinetics 4022 Transient Recorder CAMAC module paired with a 4050 Memory module.
- I believe that we programmed the 4022 module to raise a LAM (look at me) after 512 samples have been recorded following the wire scanner leaving the In or Out limit switch.
- when the wire scanner program sees the LAM it reads out the stored samples at its leisure and then displays them.
- the normal QSX/W current amplifier modules have a very fast response, 1 ms or faster depending on the gain range.
- the M19 wire scanner signal had a lot of noise due to vibration, at times equivalent to 10 uA of beam.
- the QSX/W modules were modified to give a slow response and gave much cleaner signals, albeit with some hysteresis due to time lag.
- let's assume that response of the amplifier is now slow compared to the 400 Hz beam rotation so that the wire sees a true time average of the beam density.
- then I think one would expect to see saddle shaped X, Y and C profiles as, on average, the beam would be seen to spend more of its time at the ends of travel.
- from the width and depth of the saddle shape one could calculate the radius of the rotation circle and perhaps even infer that the centre of the circle does not have too much beam in it.
- if the response of the amplifier is not too slow, one might see some modulation of the saddle shape, about 400 Hz * 0.5 s = 200 bumps across the full scan.
- they might alias with the ~1 kHz sampling frequency a little.
- as to your tomographic interpretation of the profiles, it might still work if you first give the algorithm some new assumptions about the beam motion, but I am guessing here.

REMCON	SYSTEM	TW#	SYS	B	C	N	A	IN	OUT
DIGITIZER	2A	XXX	GEC1	5	2	X	XXX		
GAIN	2A	XXX	GEC1	5	2	7	4		
MOTION STATUS	2A	142	GEC1	5	2	7	0	BIT 2	BIT 3
MOTION COMMAND	2A	142	GEC1	5	2	7	1	BIT 1	BIT 2
BIAS READBACK	2A	267							

LOCATION
2A ELECTRICAL ROOM



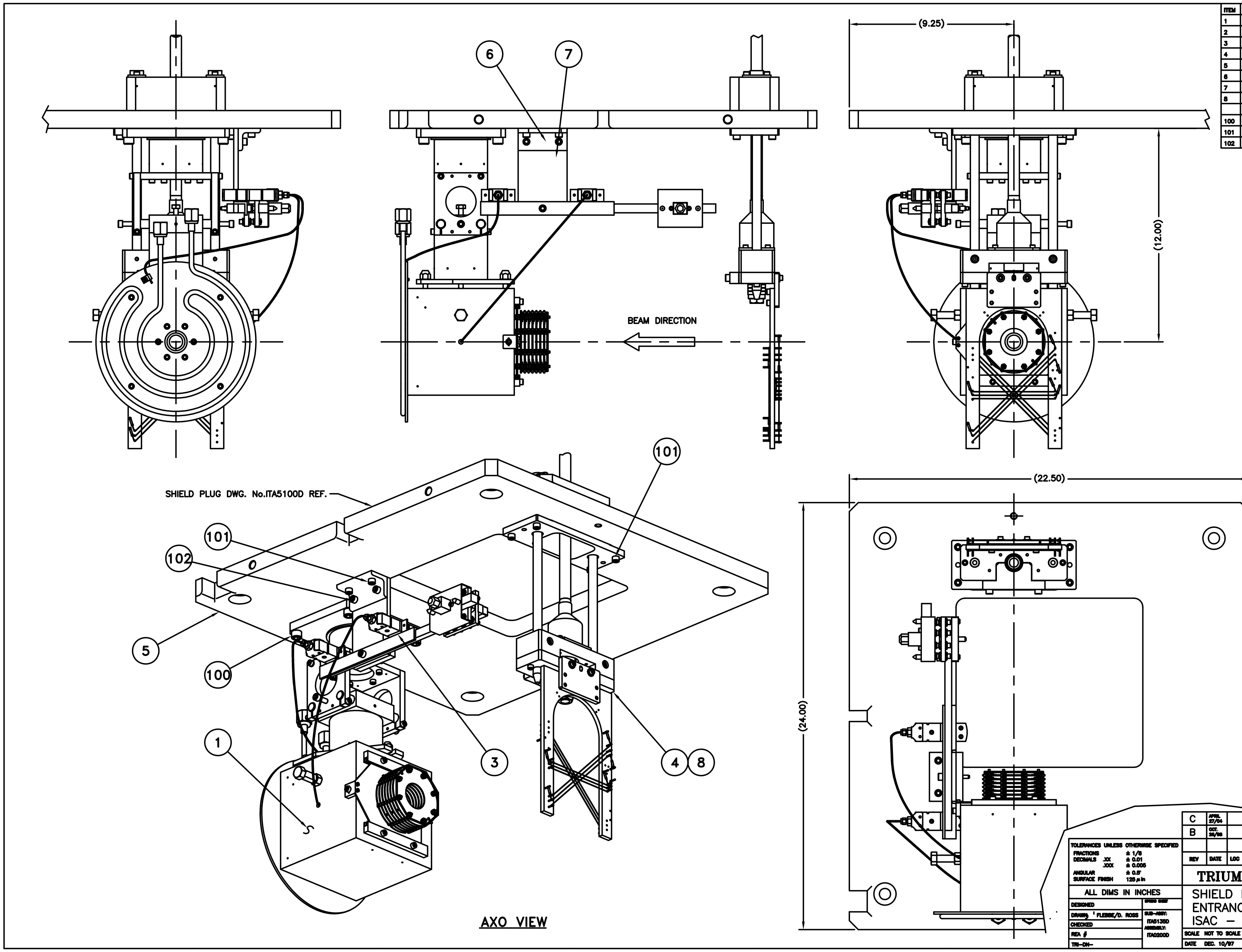
Drawn	DS/TT	Approved	
Designed	WR/DS	Date	Feb. 27, 2002
Checked		Scale	

2A3M19WS
WIRE SCANNER MONITOR

TRIUMF

Dwg. no. A–21921

Rev 3



ITEM	REF No./DESCRIPTION	MATERIAL	QUAN
1	ITA0270C – COLLIMATOR ASSEMBLY	TRIUMF	1
2			
3	ITA5144D – ELECTRICAL CONNETOR MOUNT ASSEMBLY	TRIUMF	1
4	ITA5150D – PROFILE MONITOR GUIDE ASSEMBLY	TRIUMF	1
5	ITA0269D – ALIGNMENT PLATE	TRIUMF	1
6	ITA0992B – ANGLE DETAIL	TRIUMF	1
7	ITA0993A – PLATE DETAIL	TRIUMF	1
8	ITA1231C – WIRE SCANNER HEAD LAYOUT	TRIUMF	1
100	SOC. HEAD CAP SCREW 3/8–16UNC–1.25	SST	4
101	SOC. HEAD CAP SCREW 1/4–20UNC–1.00	SST	6
102	SOC. HEAD CAP SCREW 1/4–20UNC–0.75	SST	2

REV	DATE	LOC	REVISION DESCRIPTION	BY	APP'D
C	APRIL 27/04		DRAWING RE–DRAWN, ISOMETRIC VIEWS ADDED. ITEM 4 WAS ITA0338C. SEE EC0653	DJR	
B	OCT. 26/98		PHOTO IMAGE L:\CADGRAPH\ITA0259D.TIF ADDED ITEMS 4–8 ADDED	DJR	

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/8
DECIMALS .XX ± 0.01
.XXX ± 0.005
ANGULAR ± 0.5°
SURFACE FINISH 125 μin

ALL DIMS IN INCHES

DESIGNED
DRAWN ' FLEBBE/D. ROSS
CHECKED
REA #
TRI–DN–

SPREAD SHEET
SUB–ASSY: ITA5135D
ASSEMBLY: ITA0200D

TRIUMF
4004 WESBROOK MALL
VANCOUVER, BRITISH COLUMBIA
CANADA V6T–2A3
CANADA'S NATIONAL MESON FACILITY

SHIELD LOWER PLATE SUB–ASSEMBLY
ENTRANCE MODULE – WEST
ISAC – TARGET STATION

SCALE NOT TO SCALE
DATE DEC. 10/97
THIRD–ANGLE PROJECTION
DWG NO. ITA0259D
REV C

2 Simulation Results

2.1 Current Working Mode

- Under current working mode, the M19 scan traces out a lot of spikes in each of the 3 projections, shown in Fig.1. This is arising from the beam rastering. Look at a series of snapshots shown in Fig. 2 through Fig. 10.

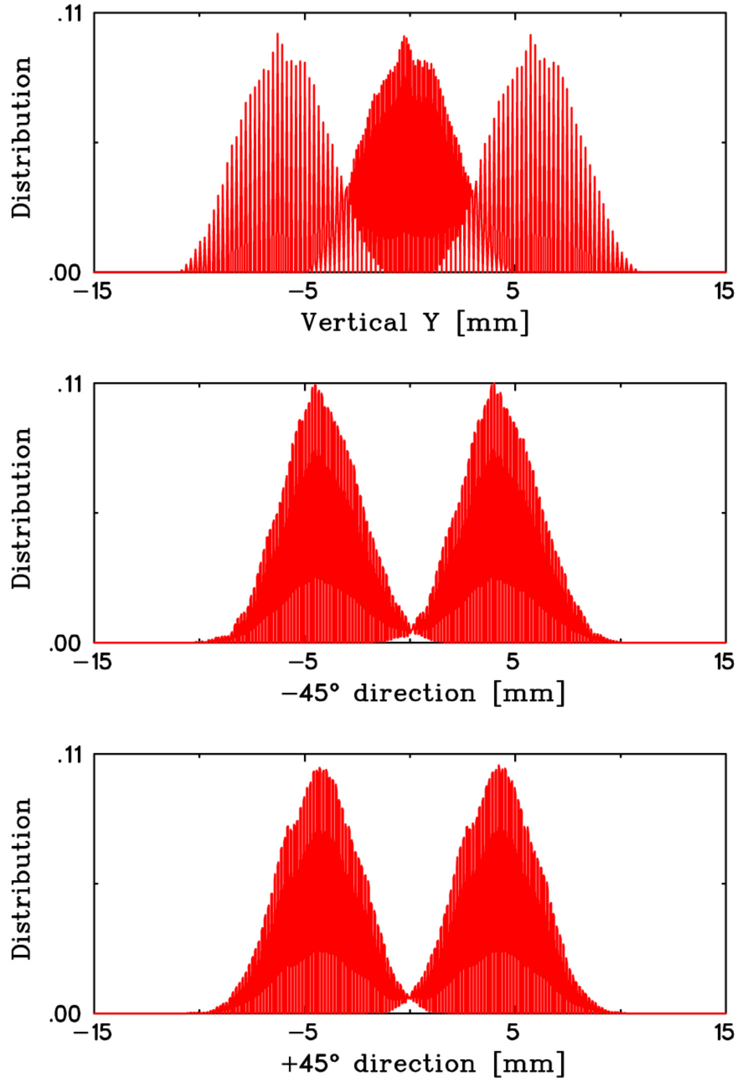


Figure 1: *M19 profiles simulated with a rastering frequency of 250 Hz, synchronized with the pulser's repetition rate of 1 kHz. As a result of the rastering, a lot of spikes show in each of the 3 projections.*

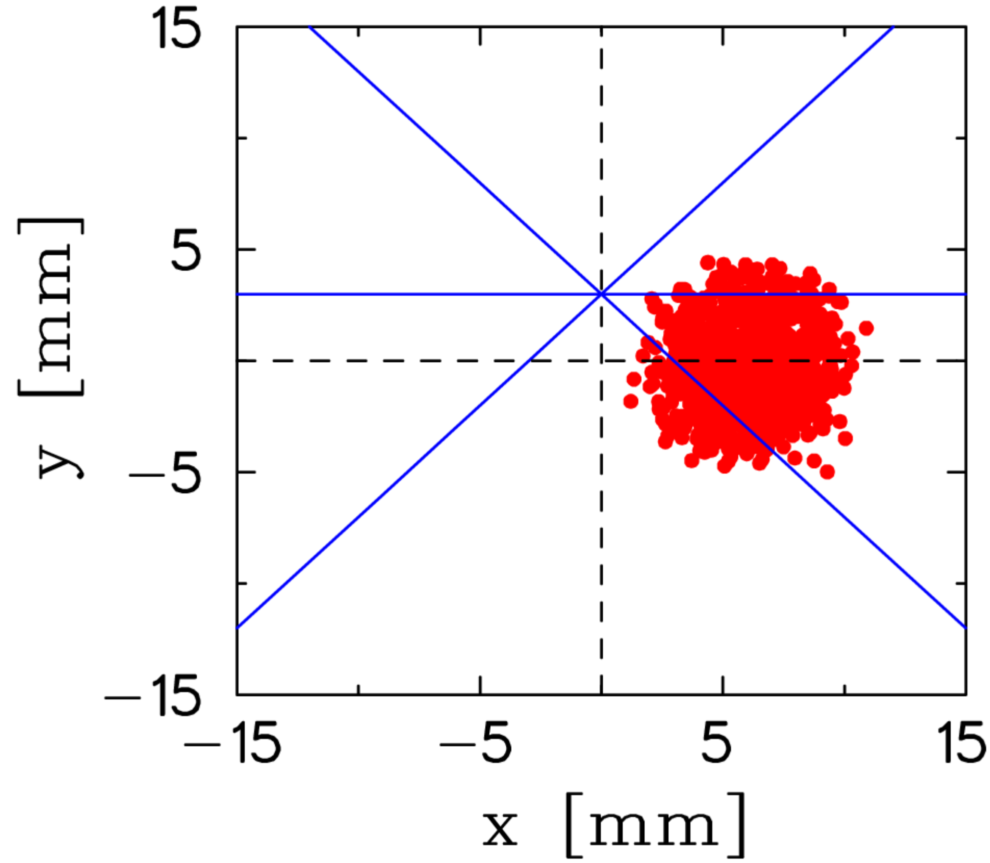


Figure 2: *Snapshot taken at the 1st pulse. The 3 blue lines represent the 3 wires which are jogging in an uniform speed from up to down. Notice that the* 45° *wire is missing the beam.*

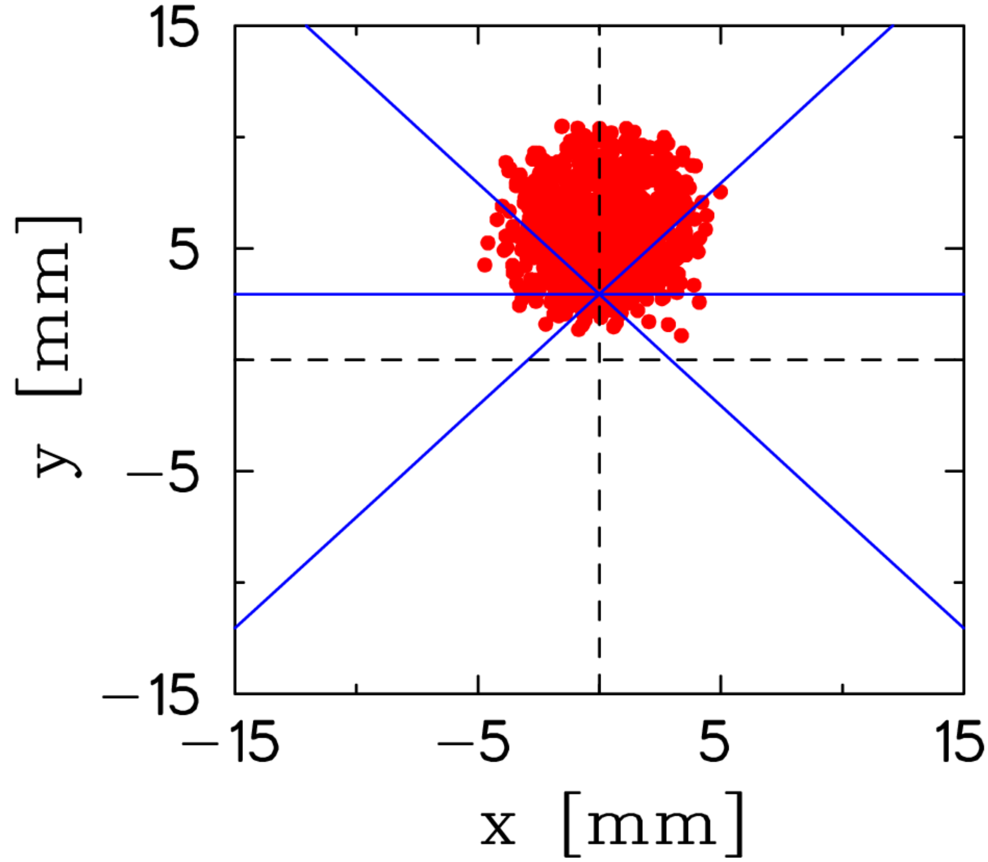


Figure 3: *Snapshot taken at the 2nd pulse.*

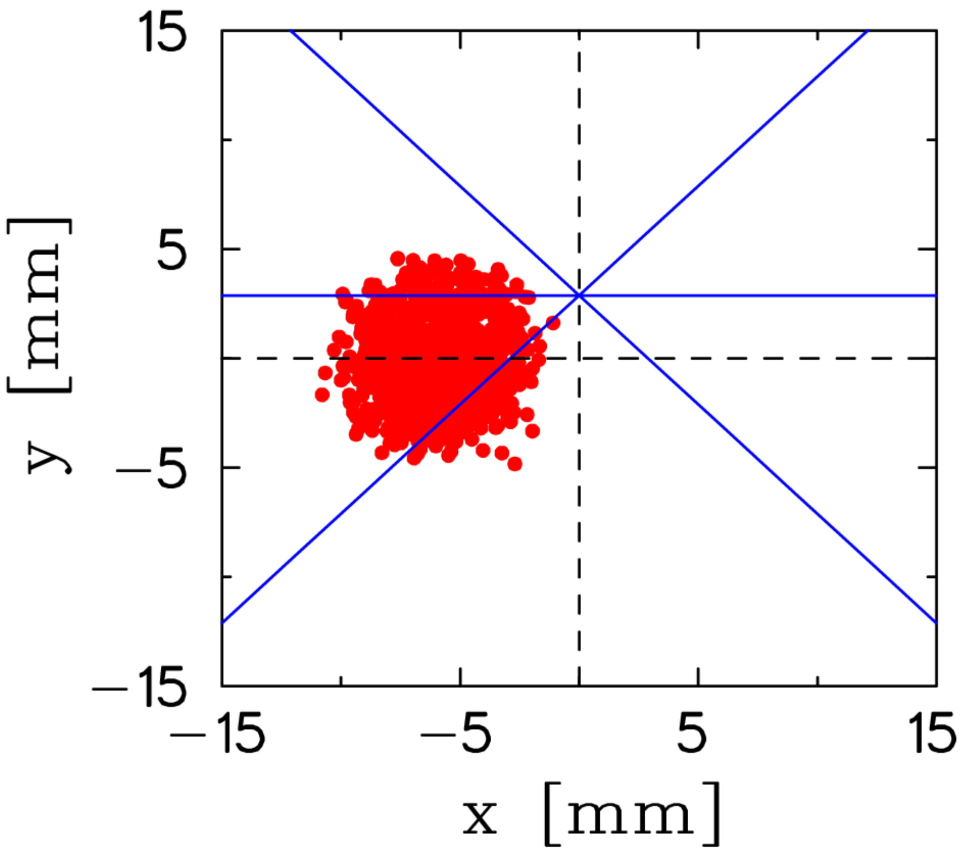


Figure 4: *Snapshot taken at the 3rd pulse. Notice that the* $-45°$ *wire is missing the beam.*

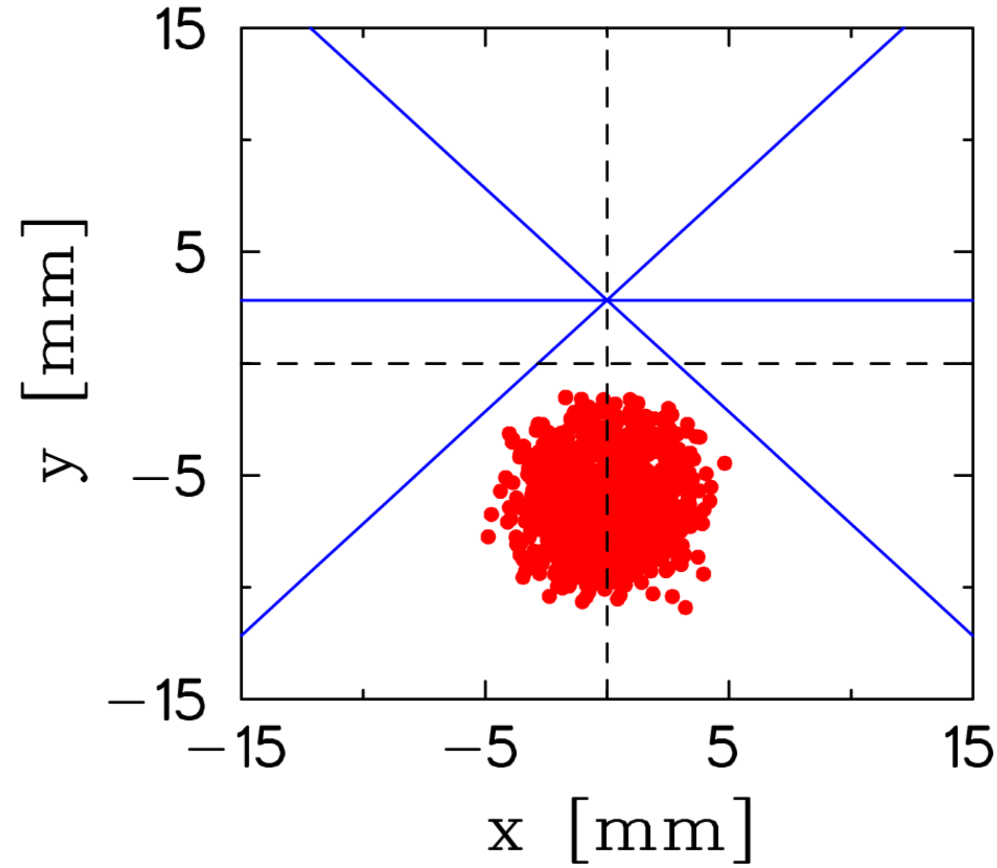


Figure 5: *Snapshot taken at the 4th pulse. Notice that all 3 wires are missing the beam.*

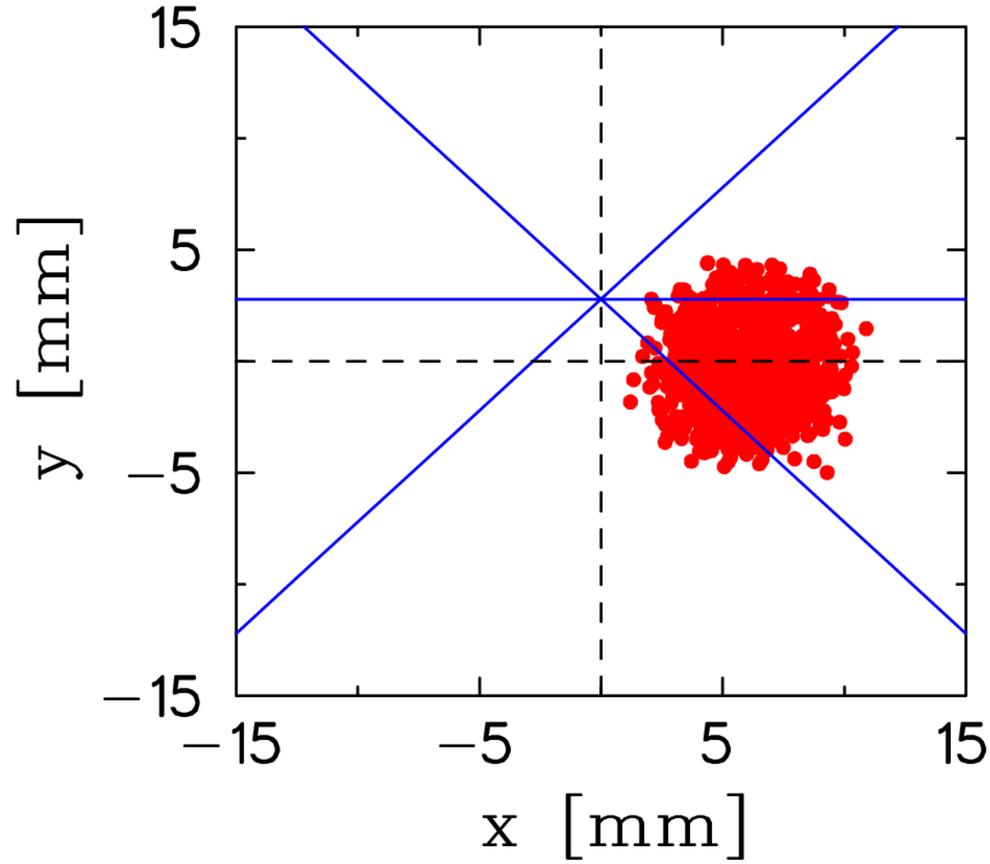


Figure 6: *Snapshot taken at the 5th pulse. Again, the* 45° *wire is missing the beam.*

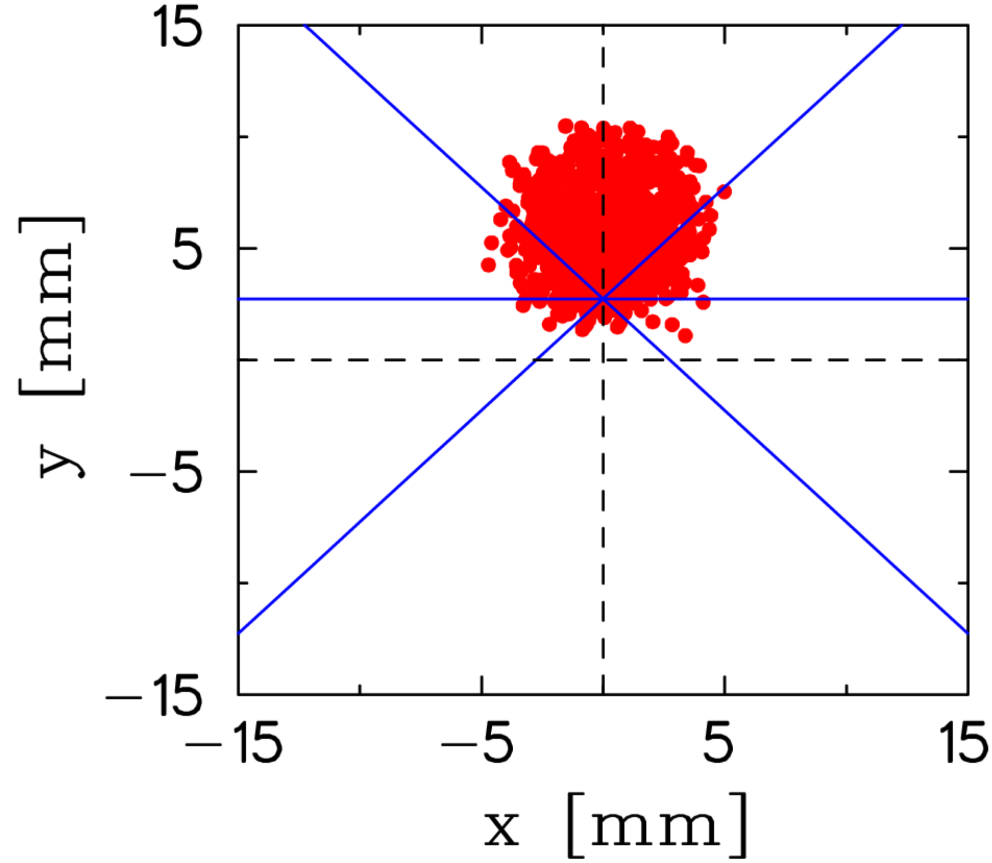


Figure 7: *Snapshot taken at the 6th pulse.*

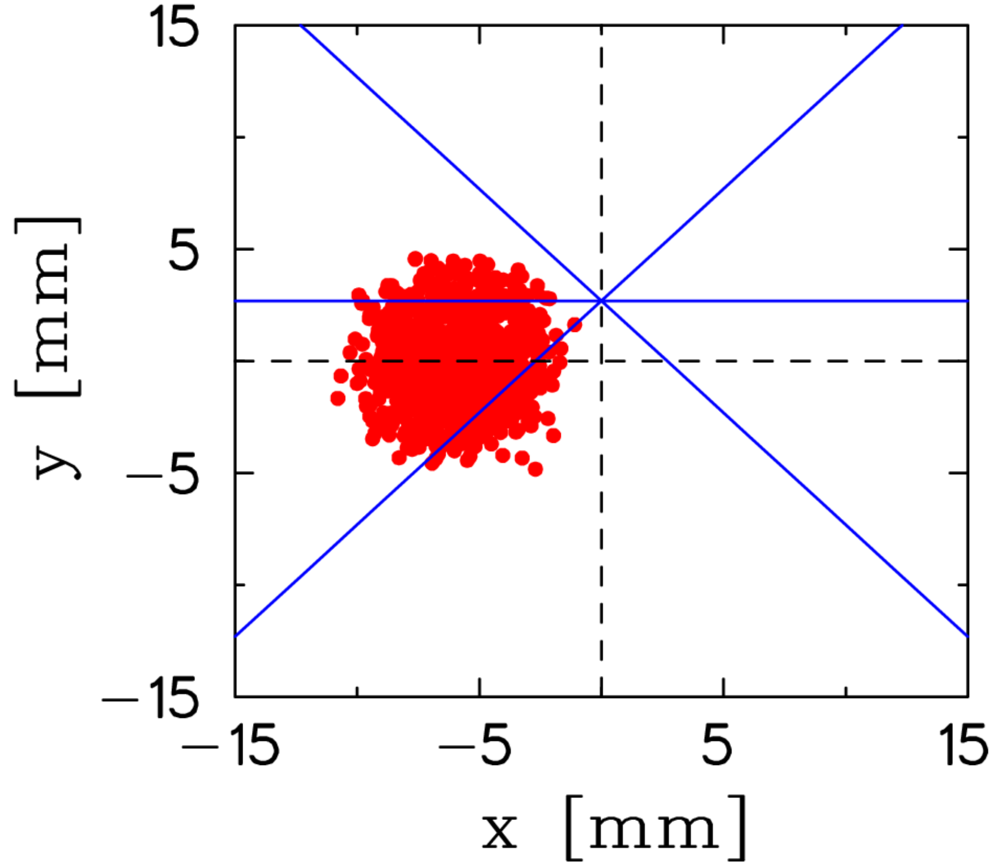


Figure 8: *Snapshot taken at the 7th pulse. Again, the* -45° *wire is missing the beam.*

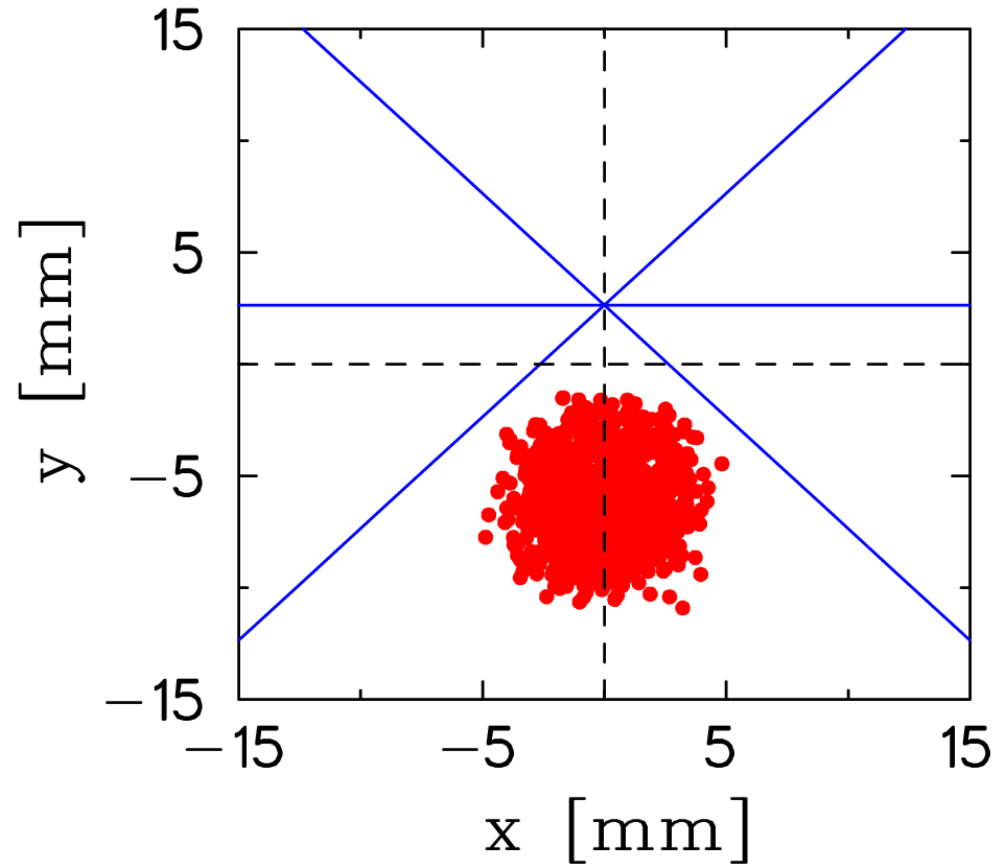


Figure 9: *Snapshot taken at the 8th pulse. Again, all 3 wires are missing the beam.*

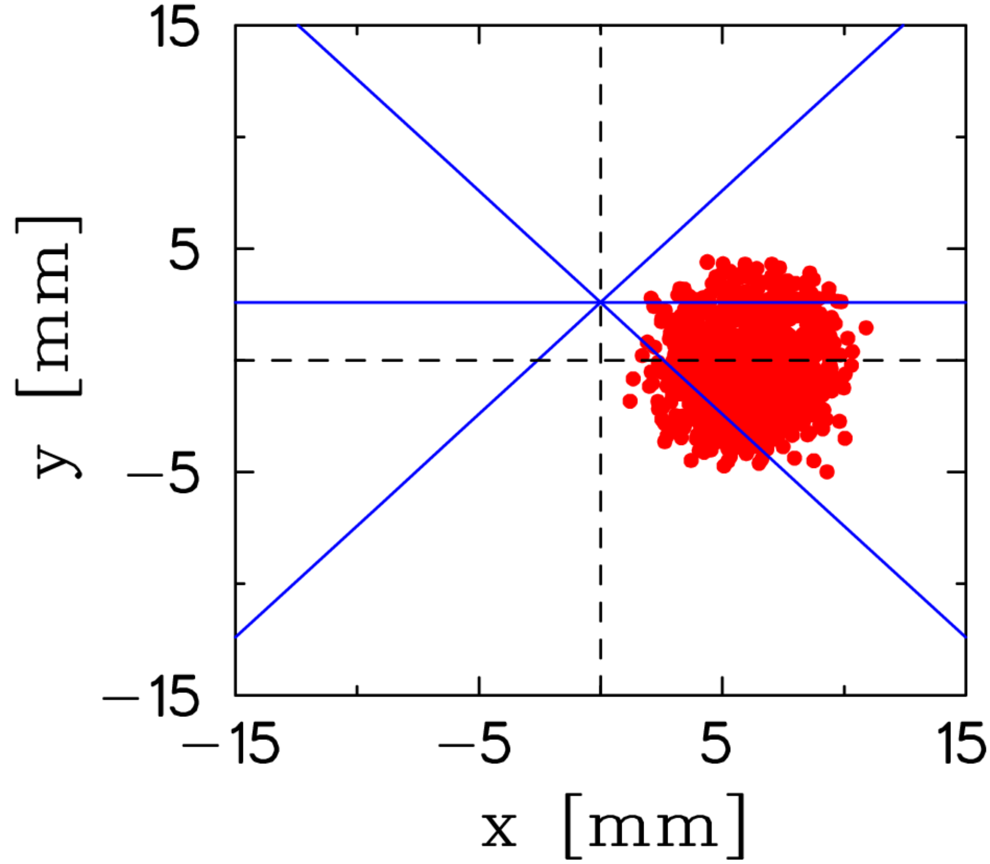


Figure 10: *Snapshot taken at the 9th pulse.*

2.2 Measurement

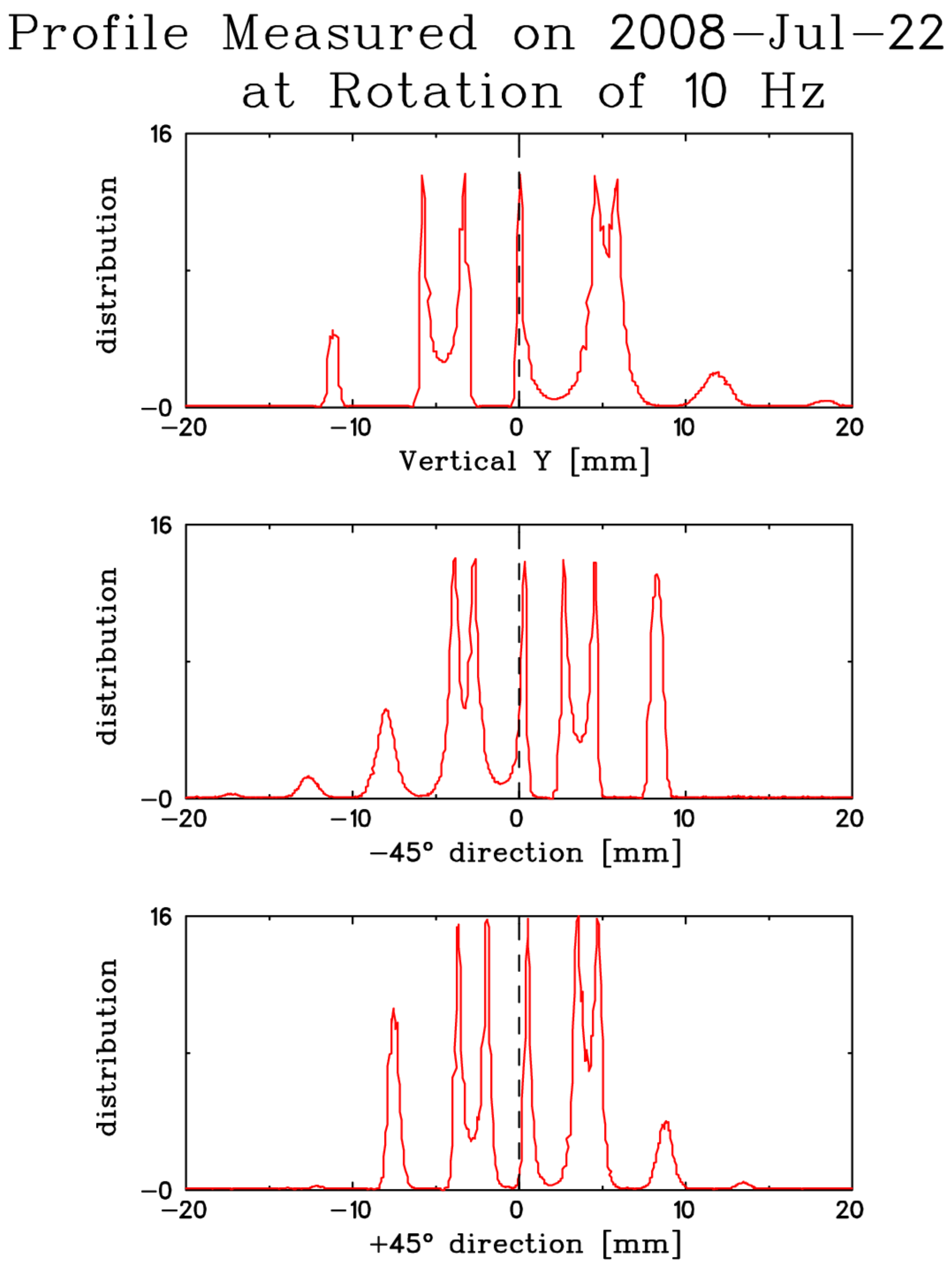


Figure 11: *M19 profiles measured at a rastering frequency of 10 Hz on 2008-Jul-22 when we were running the ANAC AC magnet in BL2A. Look at Fig.12 for the control's XT-page on that day.*

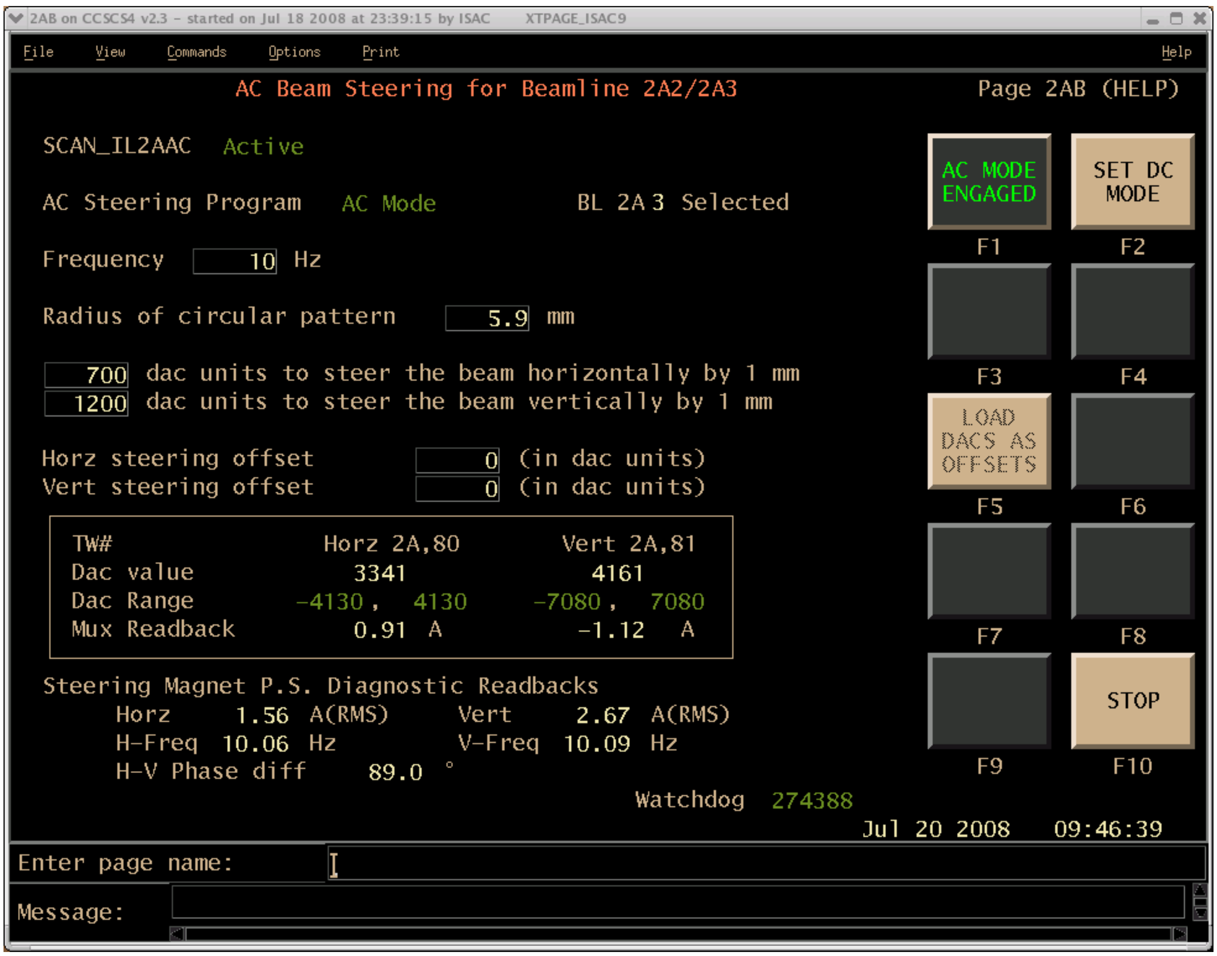


Figure 12: *The XT-page of Jul 20, 2008 showing the rastering frequency of 10 Hz.*

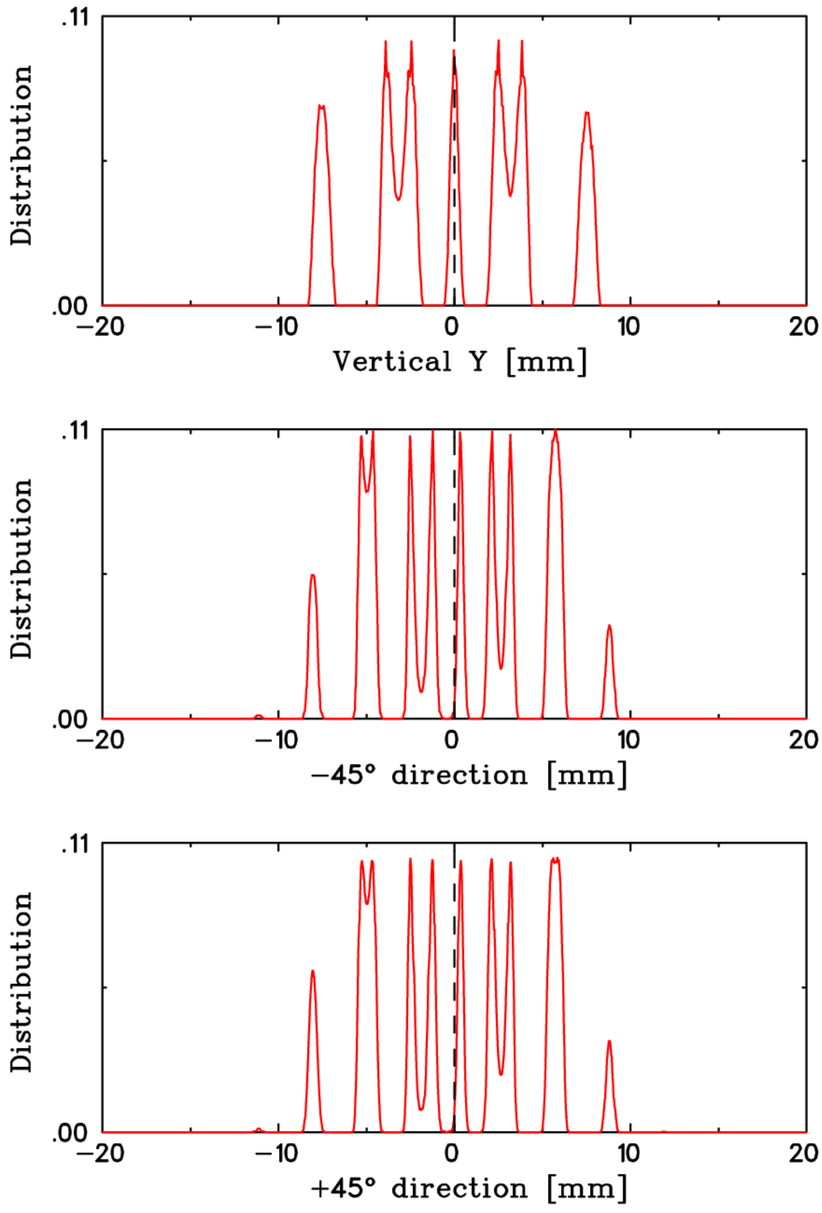


Figure 13: *Profiles simulated for the rastering frequency of 10 Hz. This picture looks very similar to the above measured result in terms of the spikes.*

- Each of the spikes is resulted from the beam at different positions. This violates the tomography fundamental that the wires must see the same beam. Under such a circumstance, the MENT tomography produces nonsense.

2.3 Desired Working Mode

- In order to have the MENT tomography work for the beam in rastering, we have to let the wires see the beam at the same positions. This suggests two conditions: one is that the beam rastering frequency must be synchronized with the pulser's repetition rate, IOW, ratio of the latter to the former must be an integer N; the other one is that the monitor movement must be slow enough over a period of N beam pulses (ideally, the wires should stall for a duration of N pulses before jogging for the next step) so that we can take a time average of the wire's positions to represent the beam projections. The simulation results are shown in the following.

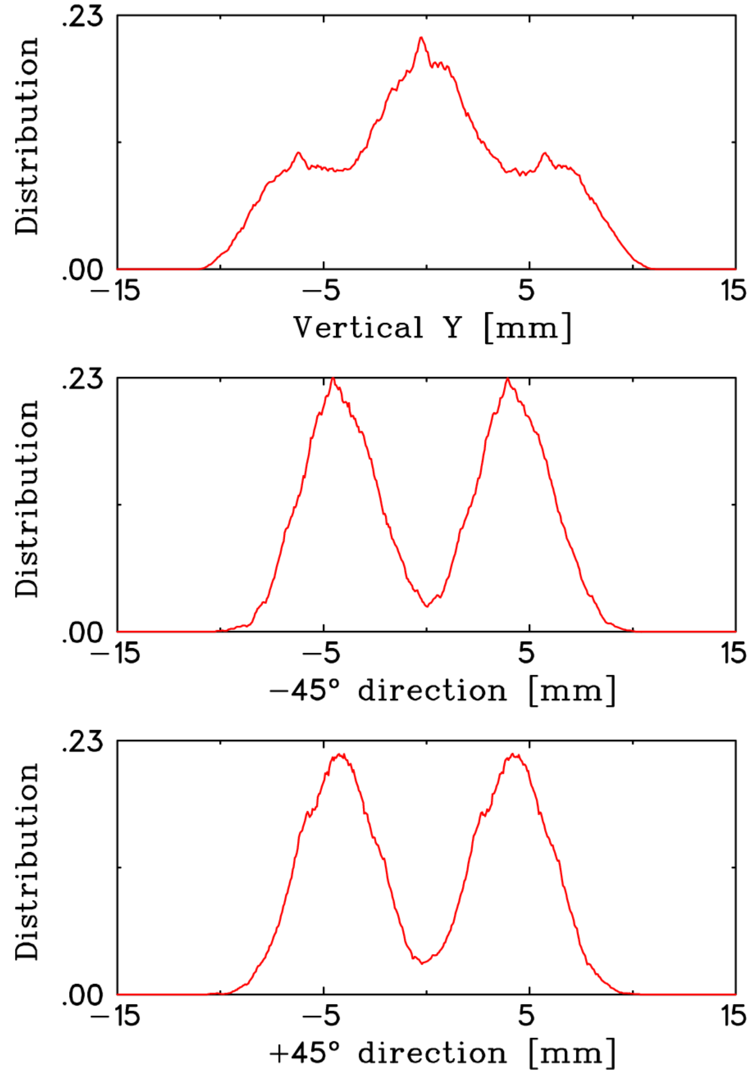


Figure 14: *Profiles simulated for a rastering frequency of 250 Hz, where the wire's positions and beam densities have been averaged over samples taken for 4 consecutive pulses. This way gives smooth projections without spikes.*

- Given with the smoothed profiles/projections, the tomography works out as is shown in Fig. 15.

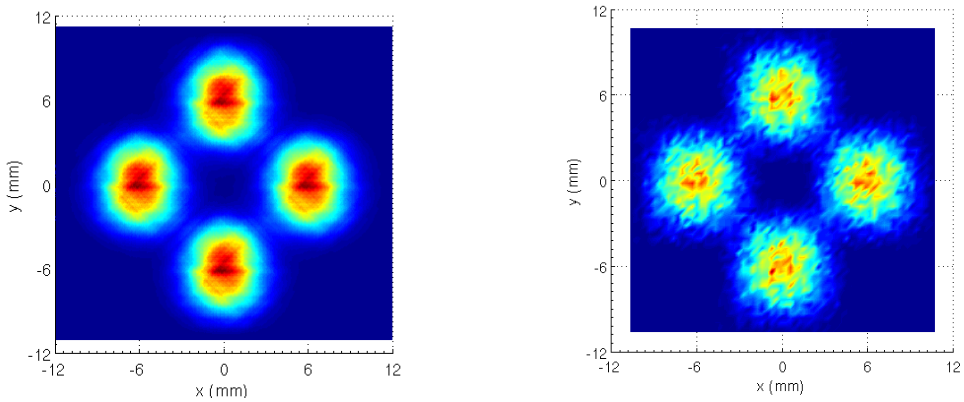


Figure 15: *Comparison of the reconstructed tomography (Left) with the original contour (Right). Clearly, the reconstruction result agrees very well. This is obtained from a given phase angle of rastering. Note that in this simulation the M19 has 3 wires as it is now.*

- But, if the phase angle of rastering differs, as shown in Fig.16 and Fig.17, then the reconstruction result becomes distorted.

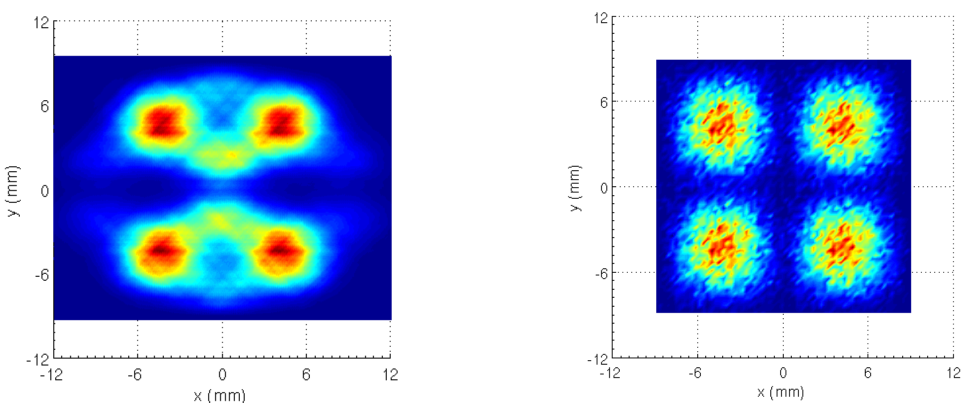


Figure 16: *For a phase angle of rastering that is different than in the Fig.15, the reconstruction result (Left) becomes distorted compared with the original one (Right).*

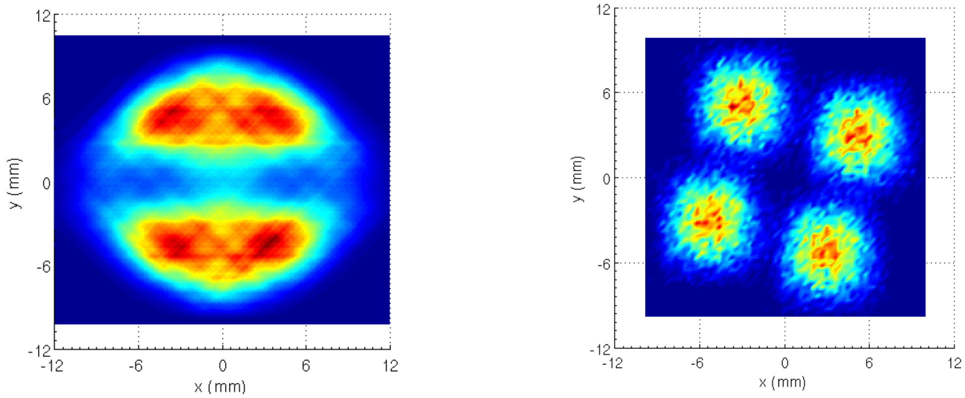


Figure 17: *For another phase, even bigger distortion (Left) occurs. Such a result would be misleading as it looks as if the beam was in a nonuniform rastering.*

- It turns out that the distortion is arisen from the fact that there are only 3 projections being fed for the reconstruction. This is inadequate. If we add up 2 more projections, for instance, in 22.5° and −67.5° directions respectively, then we can achieve a much better reconstruction result, regardless of the phase angle of rastering. See Fig.18 as an example.

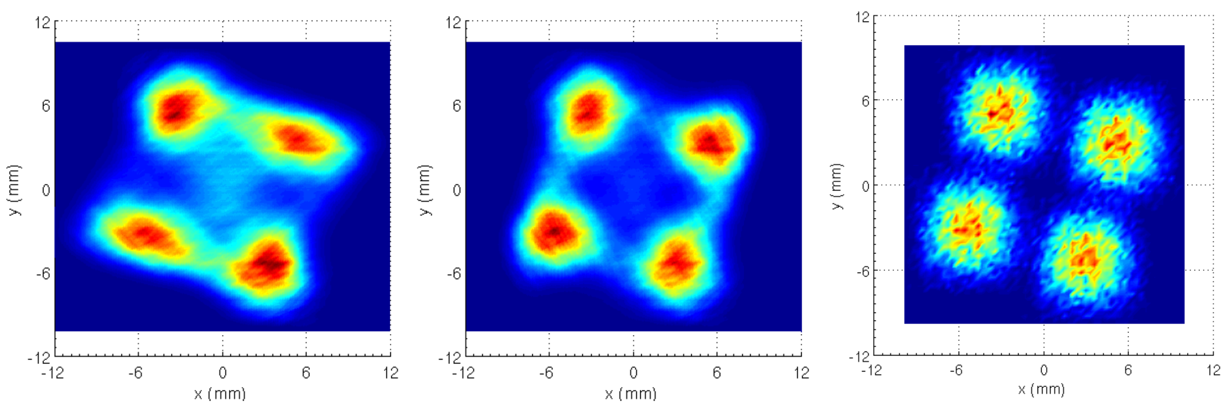


Figure 18: *Reconstruction result using 4 projections(Left) and 5 projections (Middle) respectively. Clearly, the 5-projection case gives better result.*

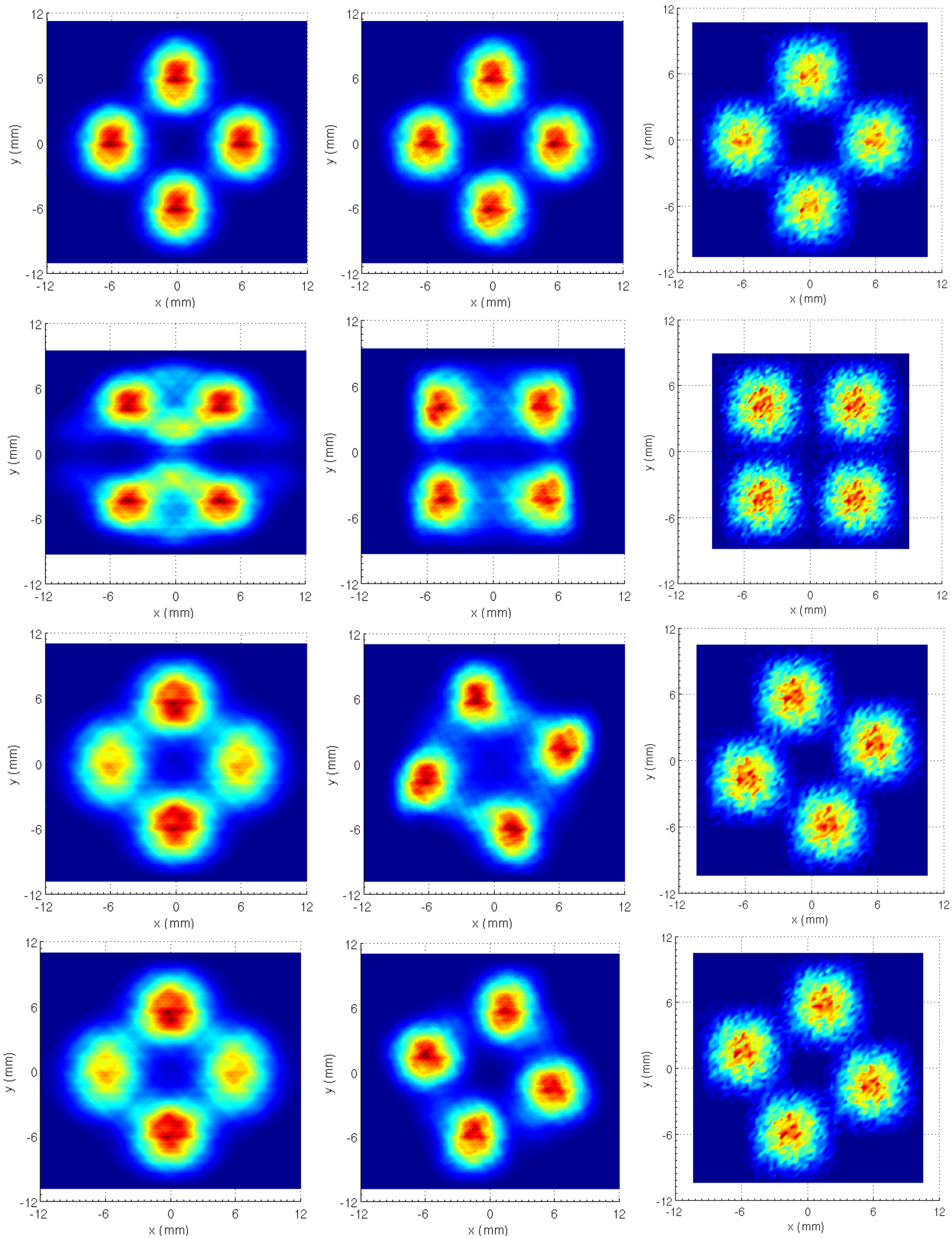


Figure 19: *Rastering of 250 Hz with various initial phases from top to bottom. The left is the reconstruction result from 3 projections; the middle is reconstructed from 5 projections; the right is the original.*

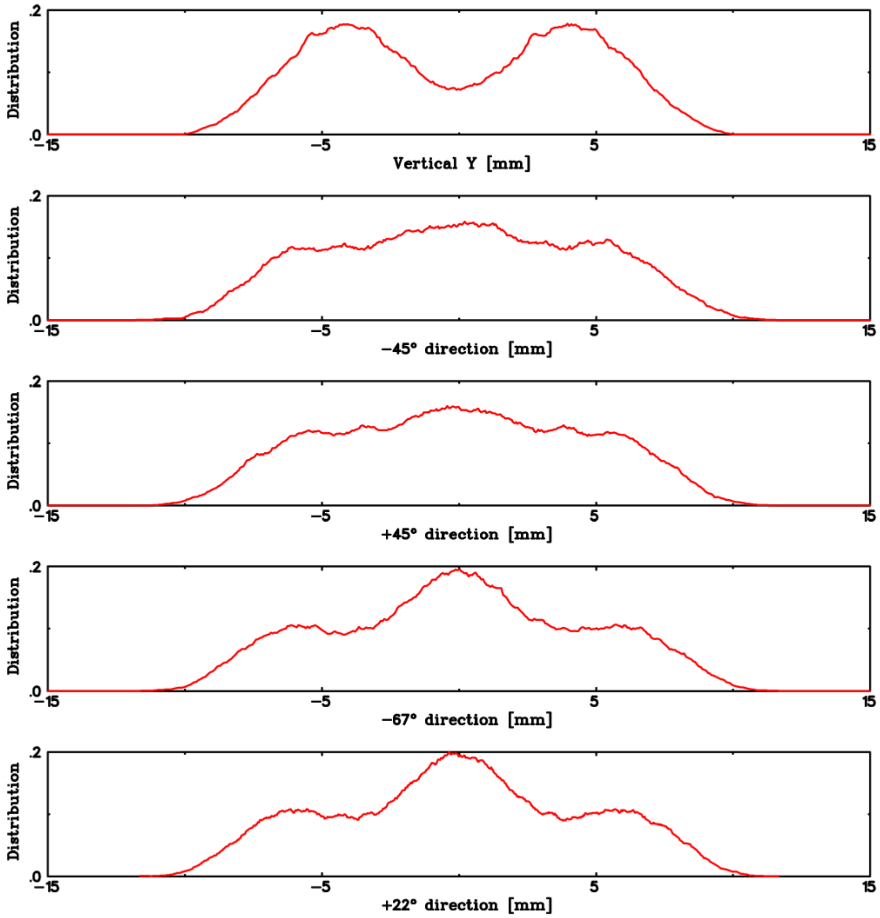


Figure 20: *Profiles simulated with 2 more wires added up to the existing 3 wires to create 5 projections for each scan. All other parameters remain exactly the same as in the Fig.15*

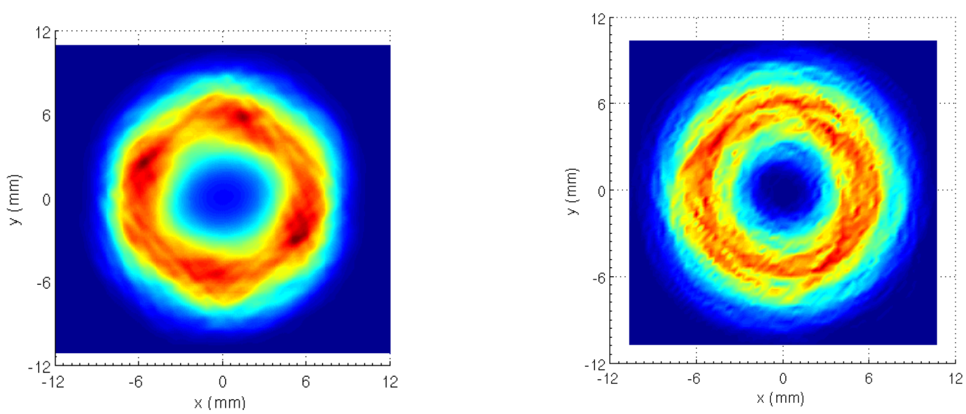


Figure 21: *Result of simulation performed under ∼100% duty factor: the reconstructed (Left) and the original (Right). Note that a data sampling rate of 250 kHz instead of 1 kHz is assumed in this simulation; this appears to be fast enough to reveal the duty factor of beam. The other parameters remain the same as in the Fig.18 with 5 projections.*

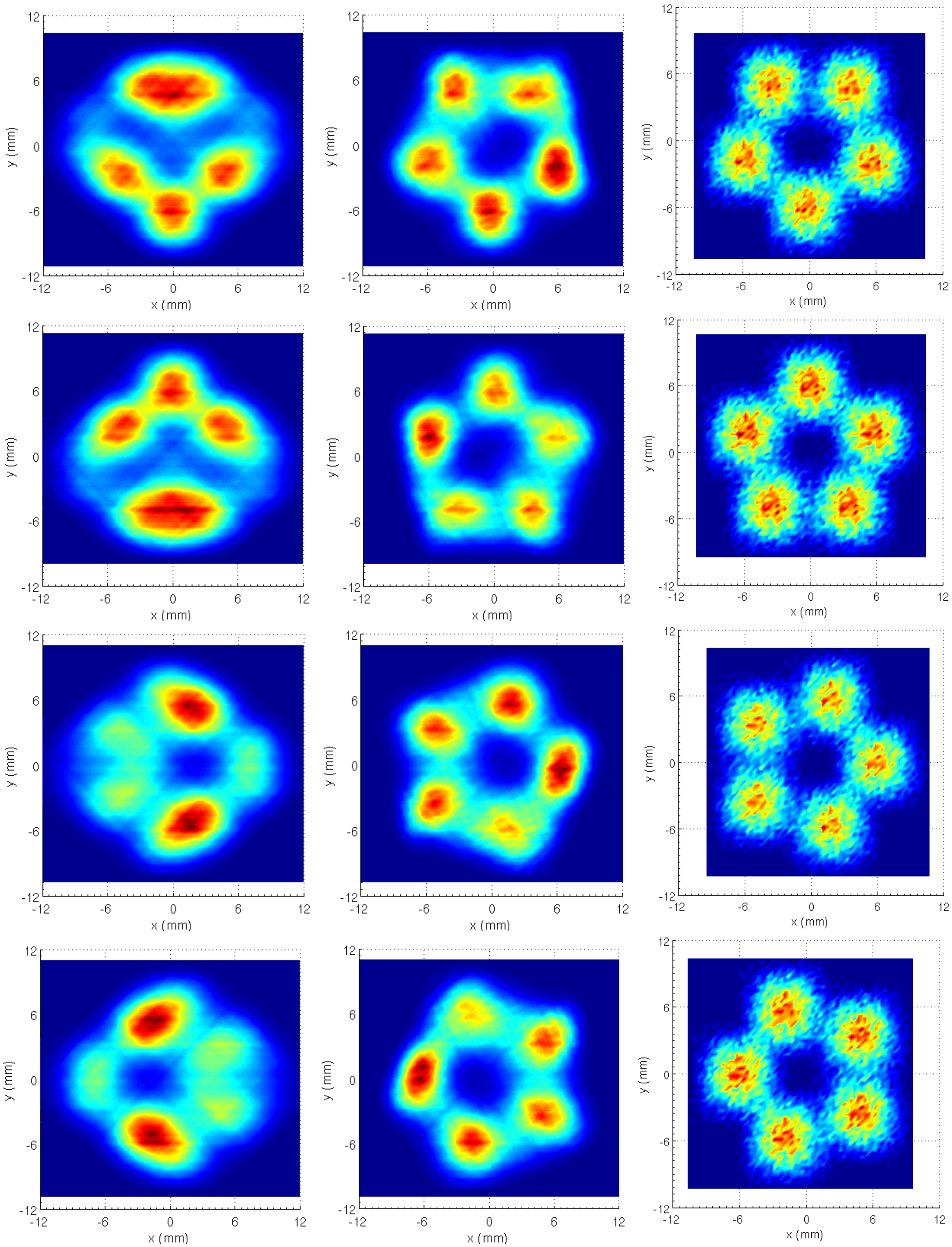


Figure 22: *Rastering of 200 Hz with various initial phases from top to bottom. The left is the reconstruction result with 3 projections; the middle is reconstructed from 5 projections; the right is the original. With the 3 projections, the top one has a minimized distortion, achieved by properly choosing the initial phase; the distortion is still quite evident, though.*

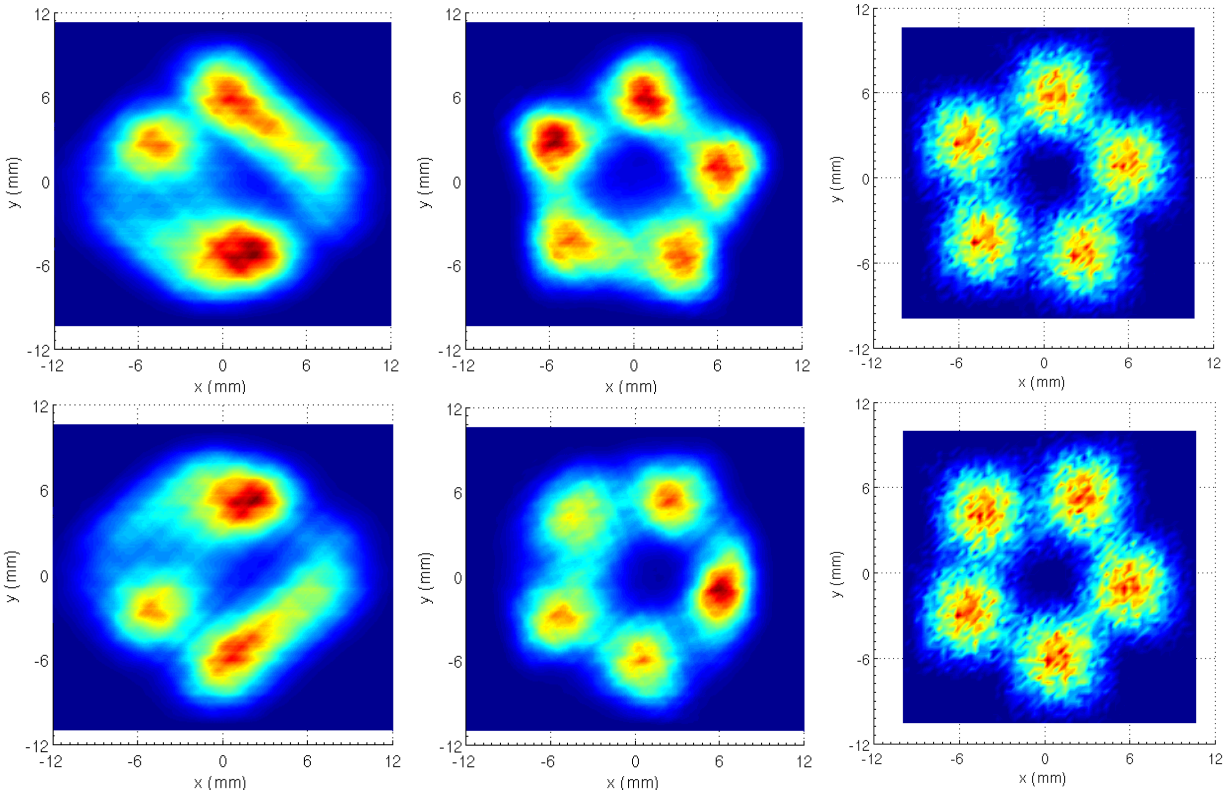


Figure 23: *Continued Fig.22.*

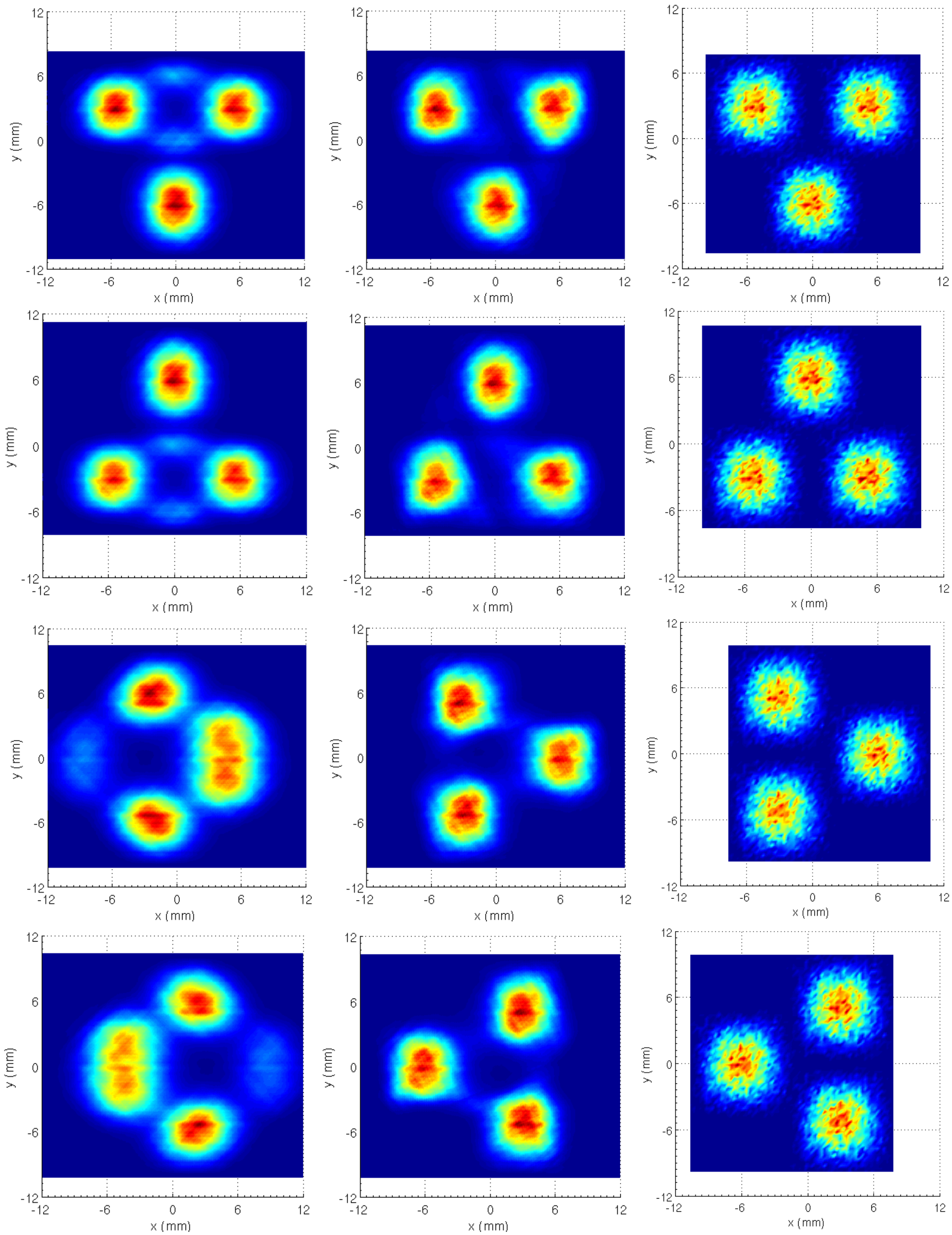


Figure 24: *Rastering of 333.3 Hz with various initial phases from top to bottom. The left is the reconstruction result with 3 projections; the middle is reconstructed from 5 projections; the right is the original.*

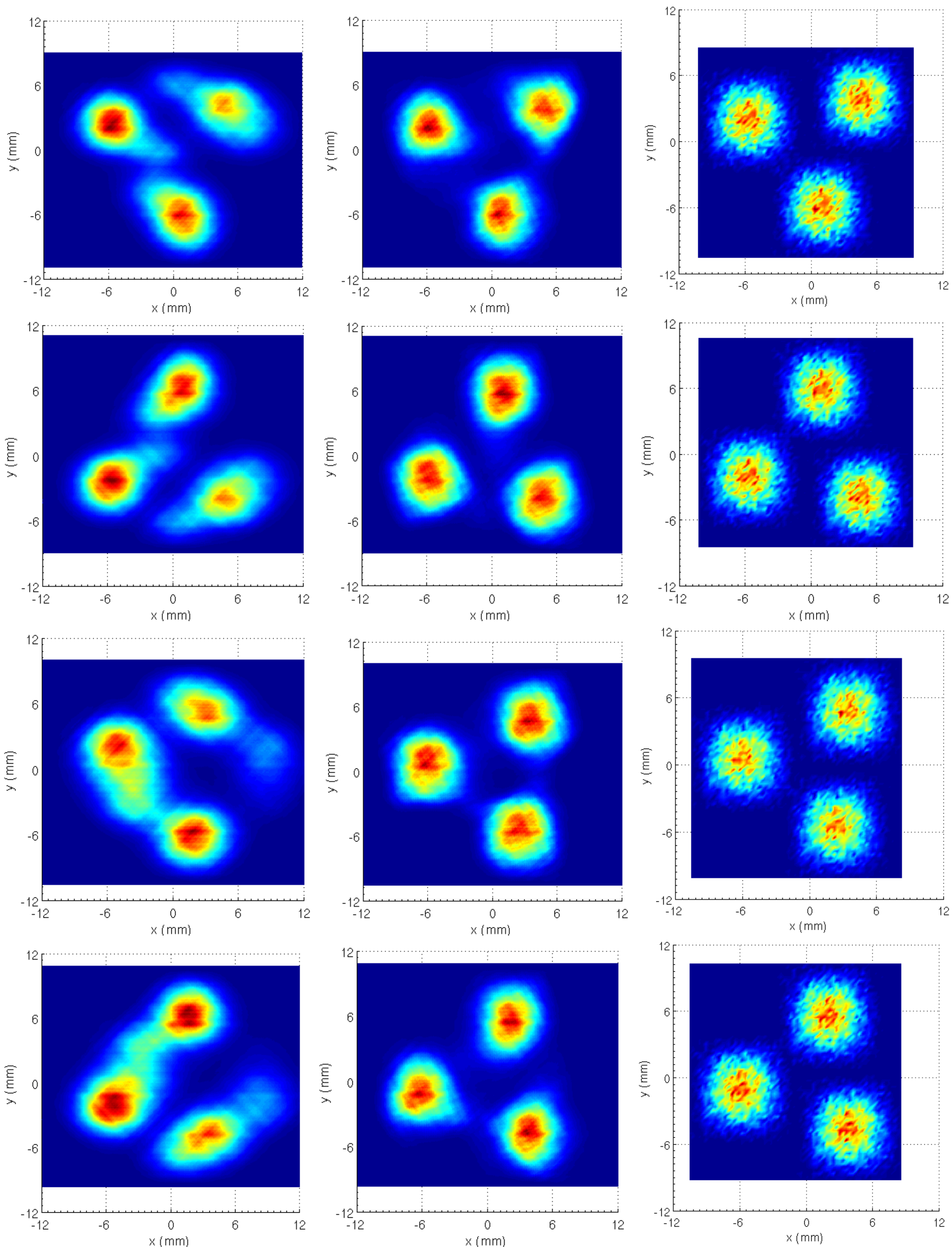


Figure 25: *Continued Fig.24.*

3 Conclusions

We can expect to work out tomography for the beam in rastering **under the following conditions: (1) the beam rastering frequency must be synchronized with the pulser's repetition rate, that is, the ratio of the latter to the former must be an integer N; (2) the control's software `BLWS` for the wire scanner has to be modified to take a time average of the wire's positions for the data samples taken over a period per N pulses, and then output the average values to represent the beam profiles; (3) depending on the rastering frequency, the initial phase angle of rastering must be a certain particular value in order to minimize distortions in the reconstruction result.** Ideally, it's best to add up another 2 wires (e.g. in $22.5°$ and $-67.5°$ directions) to the existing 3-wire configuration of M19 so that each scan can trace out 5 projections, which allows to produce an unambiguous reconstruction of the tomography.

The tomography will enable a direct measurement of the rastering radius which is an important parameter for the ISAC target.

BL2A Beam Rastering Test Results of 2015-May-20: M19 Scans and Tomography

Y.-N. Rao

May 22, 2015

1 Horizontal Rastering

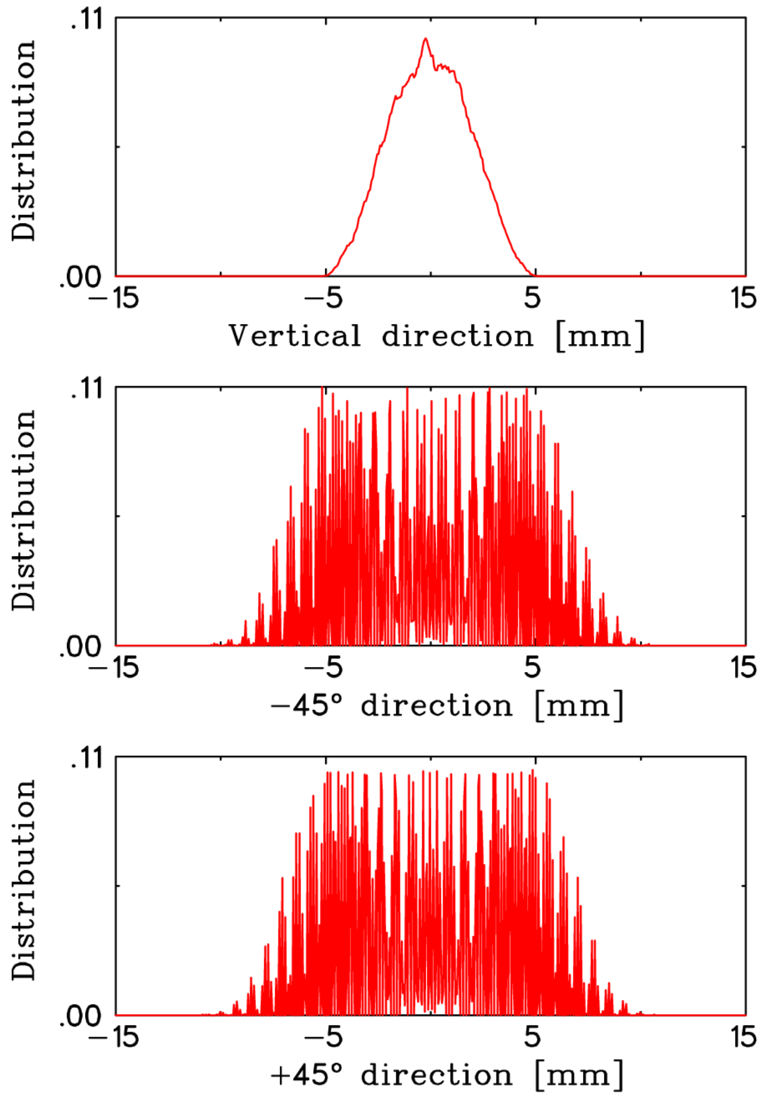


Figure 1: *M19 scan profiles, simulated for a horizontal rastering of 400 Hz (while the vertical rastering was turned off).*

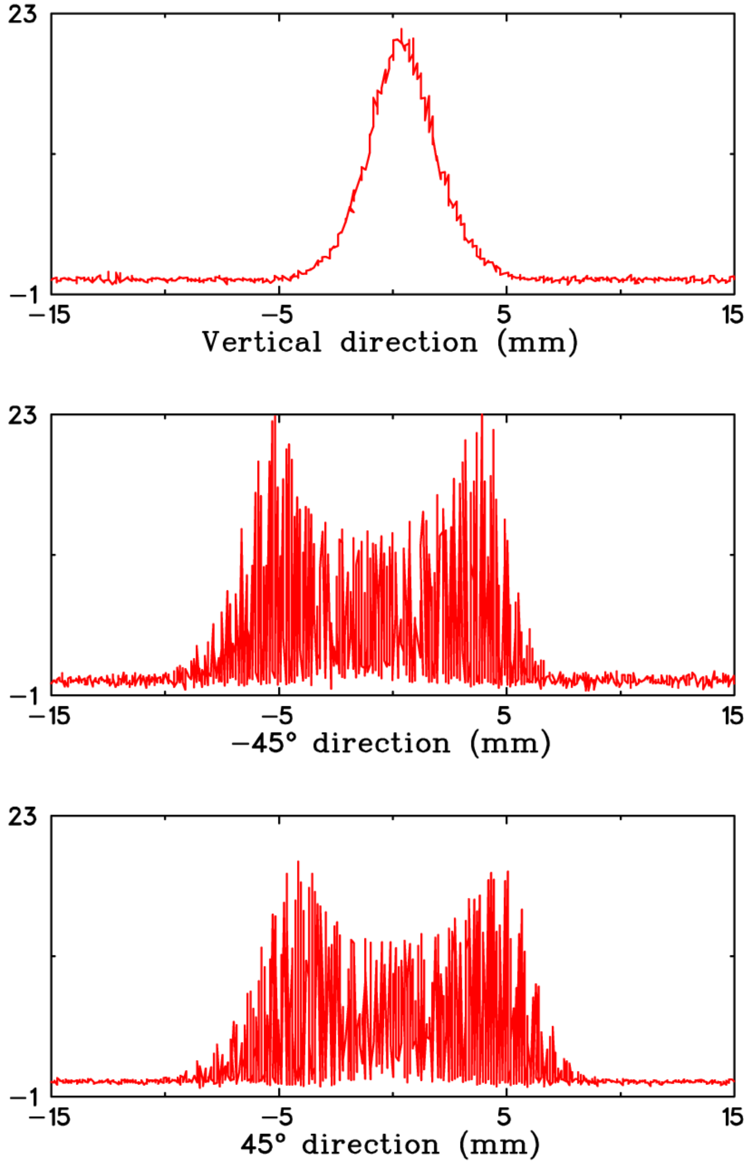


Figure 2: *M19 scan profiles, experimentally measured for the horizontal rastering of 400 Hz (while the vertical one was turned off).*

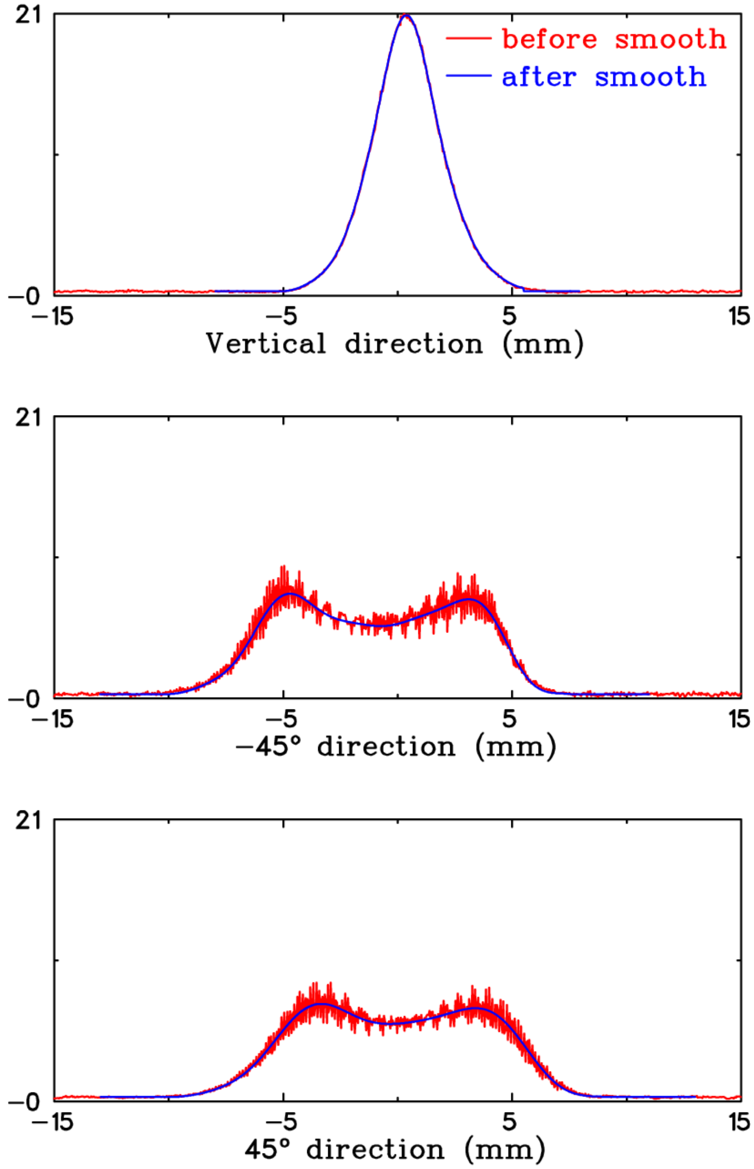


Figure 3: *M19 profiles, averaged over multiple scans that were taken inward and then smoothed out. The smoothing was performed by applying a low pass filter to eliminate the high harmonics. The same in the following.*

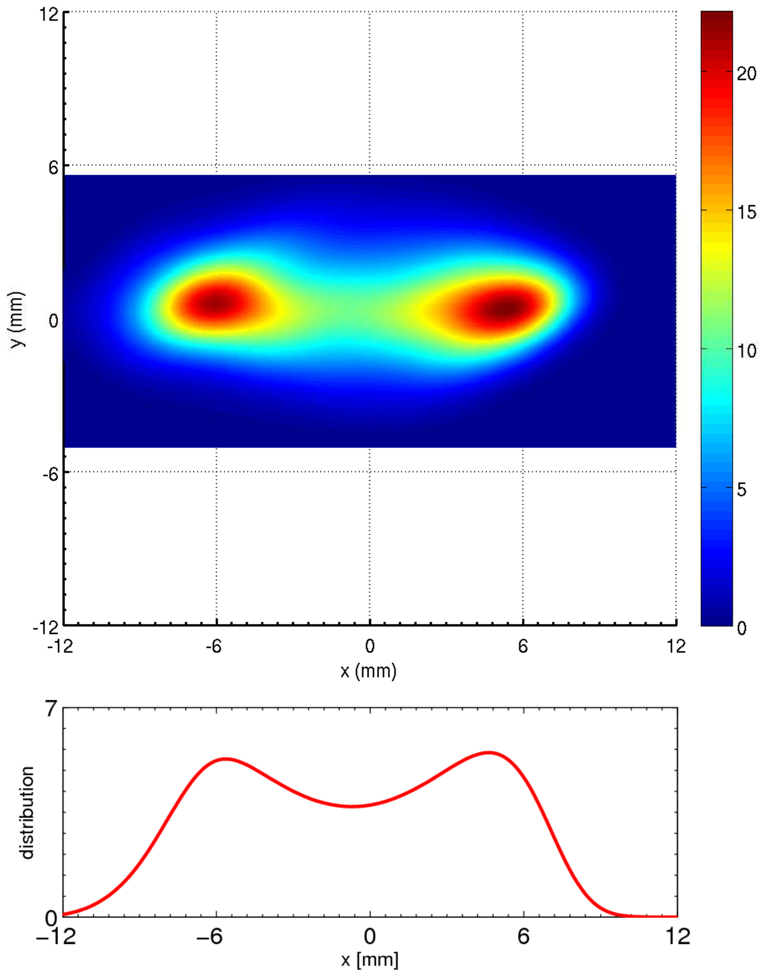


Figure 4: *Beam tomography (Top) resulted from the smoothed inward scan profiles and the horizontal profile (Bottom) reconstructed.*

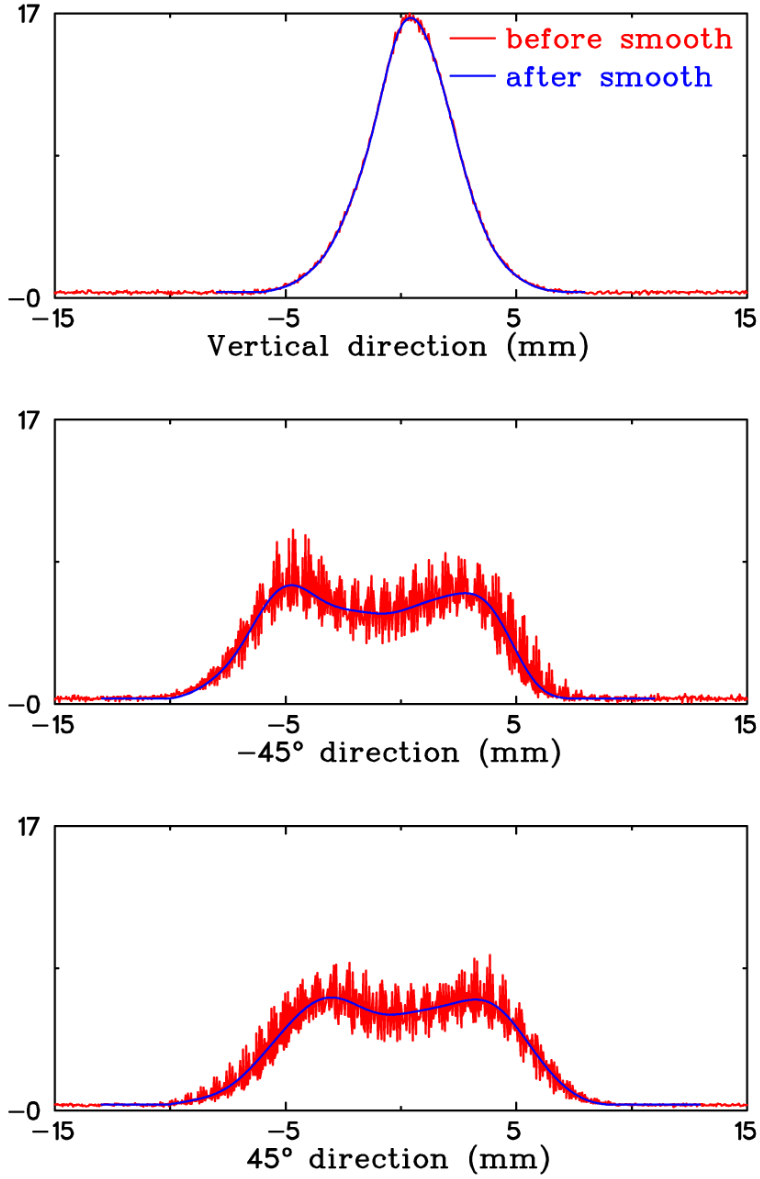


Figure 5: *M19 profiles, averaged over multiple scans that were taken outward and then smoothed out by using a low-pass filter.*

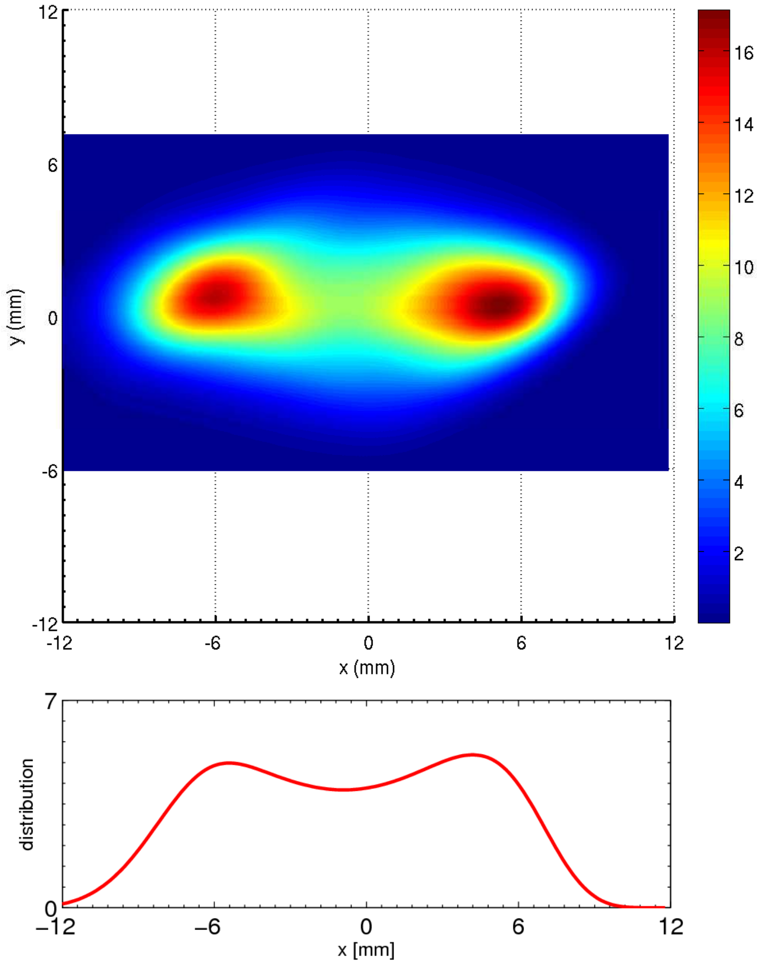


Figure 6: *Beam tomography (Top) resulted from the smoothed outward scan profiles and the horizontal profile (Bottom) reconstructed.*

```
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In[4]:= A = 3; DensityPlot[NIntegrate[f[x, y, t], {t, -π, π}],
   {x, -A - 5, A + 5}, {y, -5, 5}, PlotRange → All, ColorFunction → "Rainbow",
   AspectRatio → Automatic, MaxRecursion → 15, ImageSize → Large]
```

Out[4]=

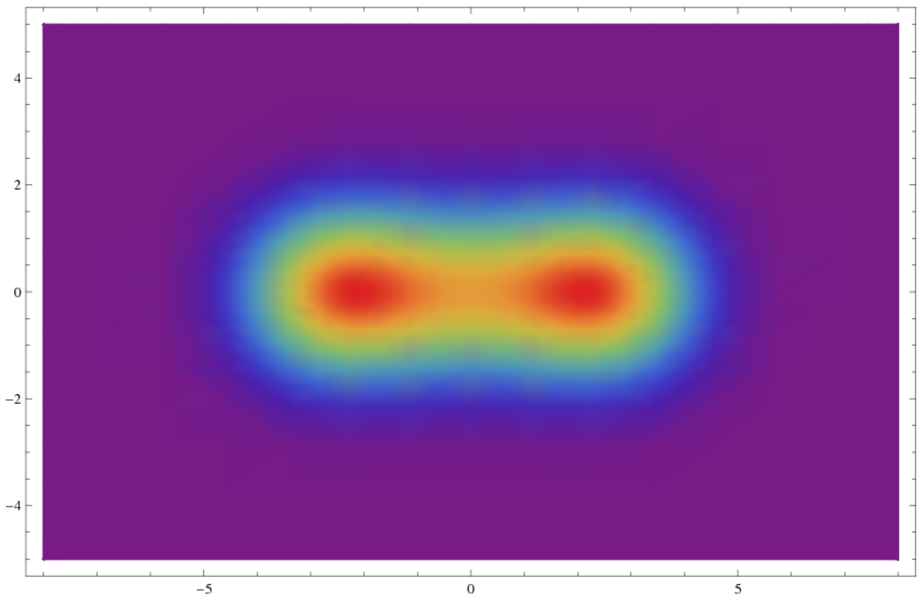

Figure 7: *Beam density contour, computed with an analytical model for rastering of a gaussian beam. This picture backs up the above tomography as shown in the Fig.4 and Fig.6: the beam density arrives at a maximum at turnaround points.*

2 Vertical Rastering

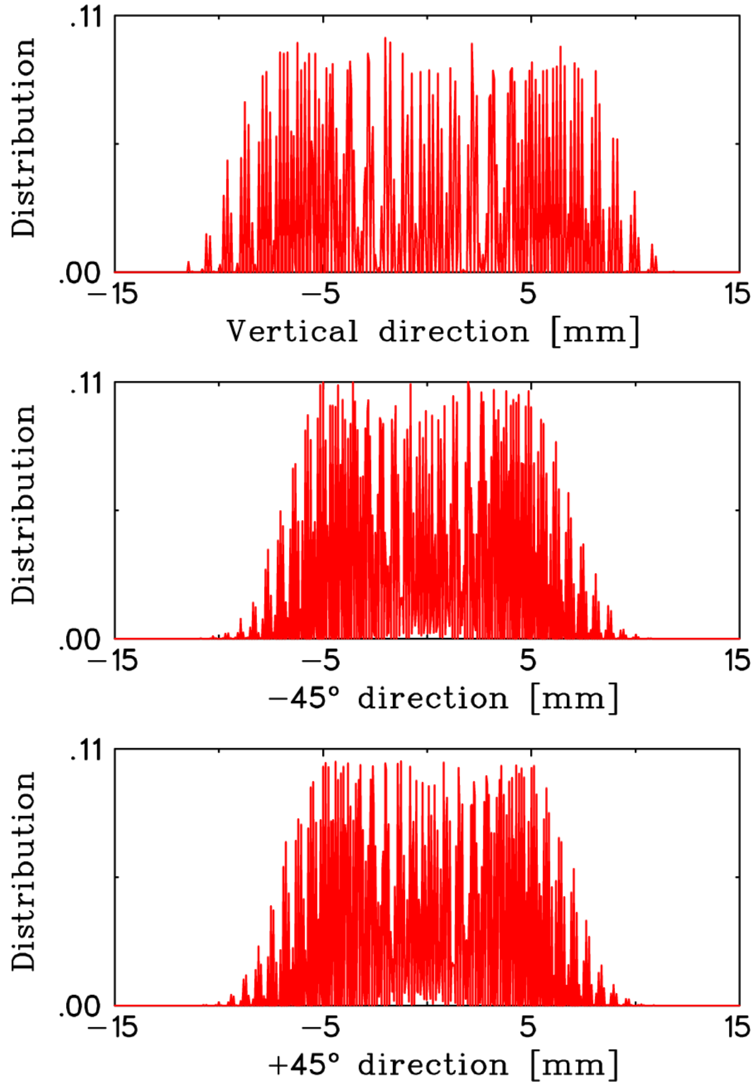

Figure 8: *M19 scan profiles, simulated for a vertical rastering of 400 Hz (while the horizontal rastering was turned off).*

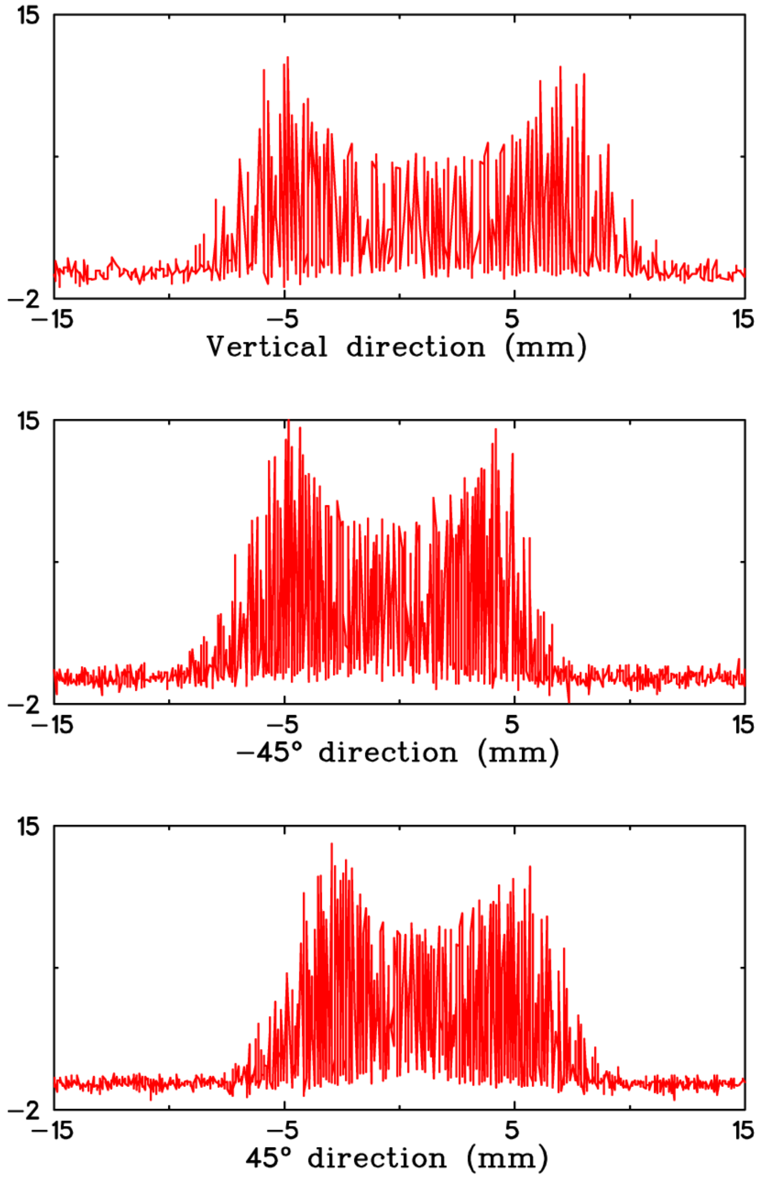

Figure 9: *M19 scan profiles, experimentally measured for the vertical rastering of 400 Hz (while the horizontal one was turned off).*

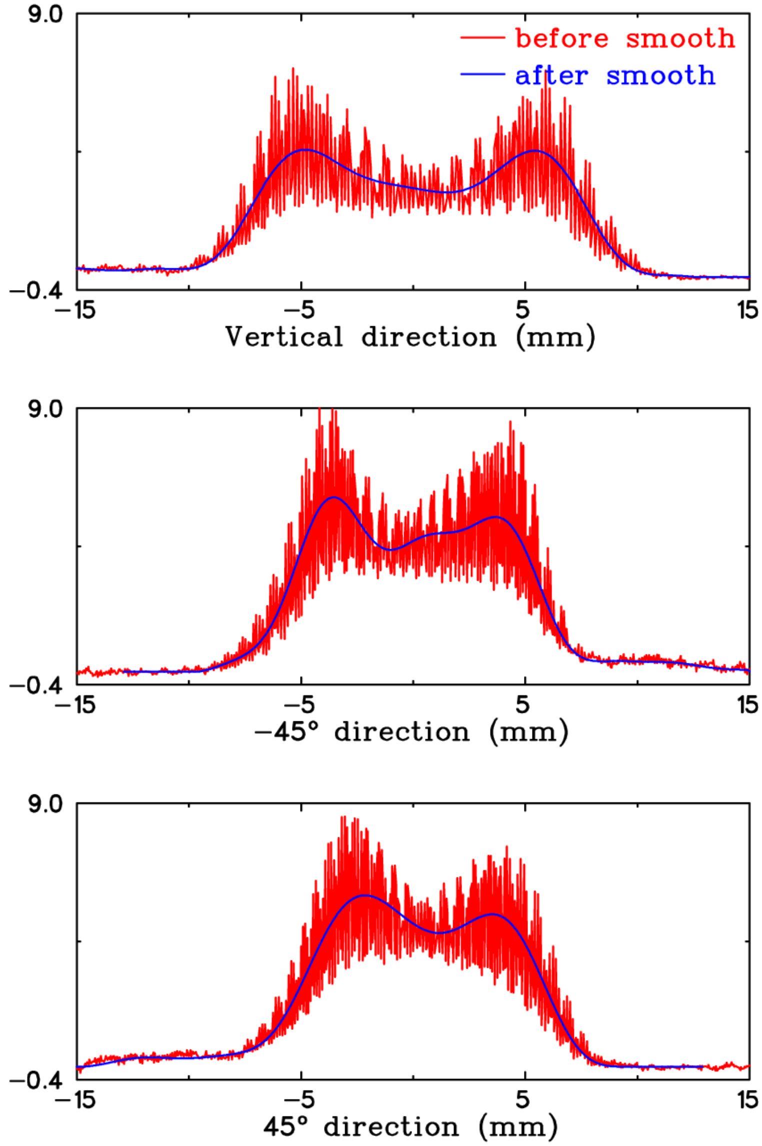

Figure 10: *M19 profiles, averaged over multiple scans that were taken inward and then smoothed out.*

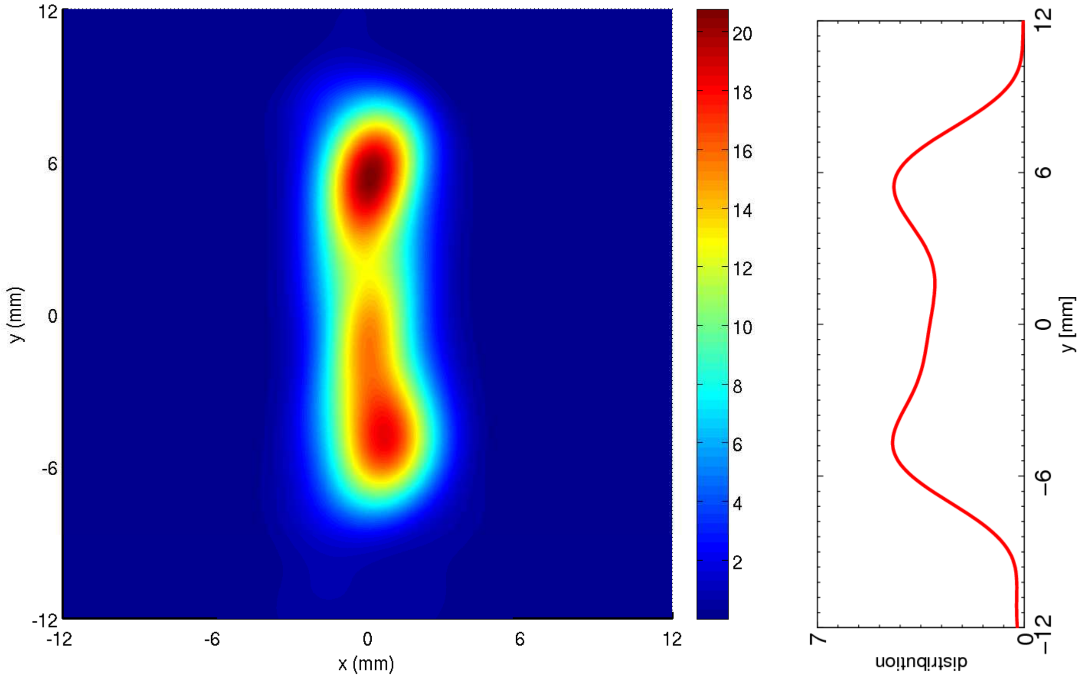

Figure 11: *Beam tomography (Left) resulted from the smoothed inward scan profiles and the vertical profile (Right) reconstructed.*

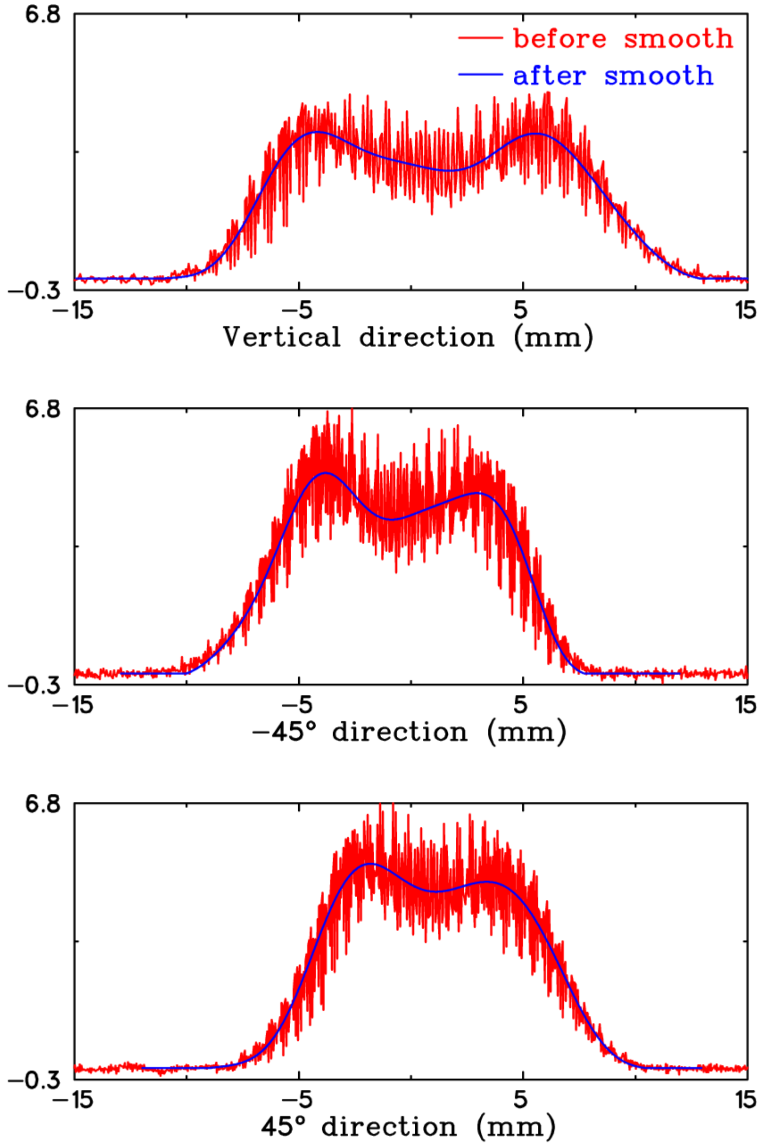

Figure 12: *M19 profiles, averaged over multiple scans that were taken outward and then smoothed out.*

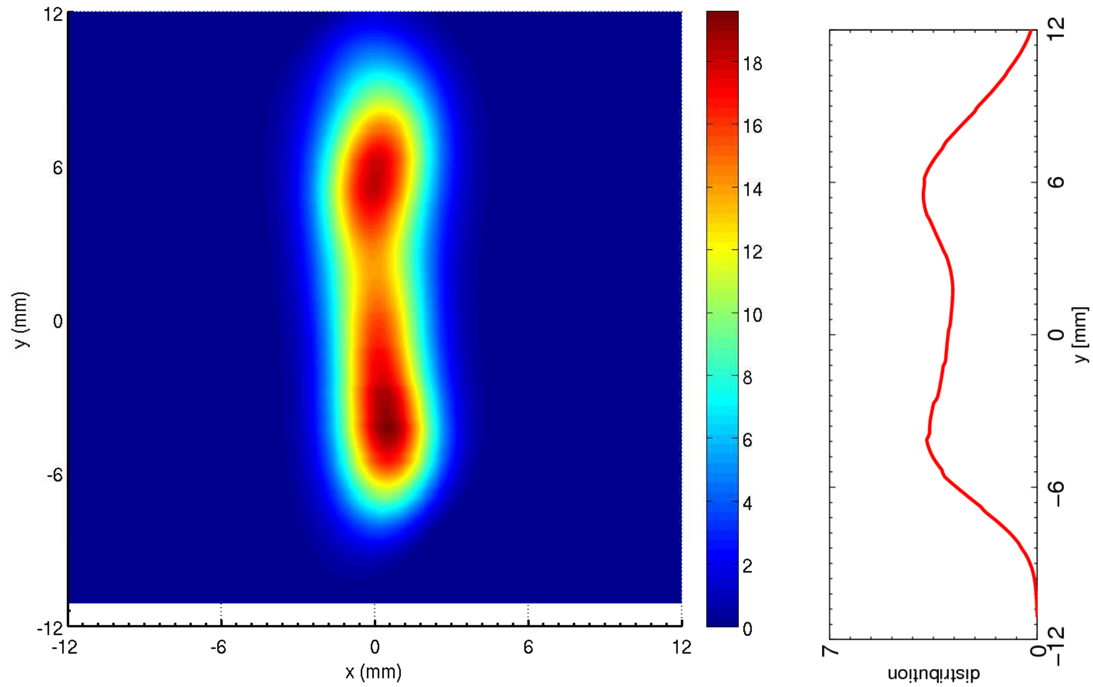

Figure 13: *Beam tomography (Left) resulted from the smoothed outward scan profiles and the vertical profile (Right) reconstructed.*

3 M19 Travel Speed

What's needed to do next is to slow down the travel speed of M19 by a factor of 10, to ∼0.2 inch/sec from the current value of ∼2.0 inch/sec. In this way we shall expect to wash out the spikes caused by the rastering in the profiles, as shown in Fig.13 as an example. This is essential for a proper reconstruction of the beam tomography.

Alternatively, Diagnostics group should devise different approach for the data collection and processing in order to minimize the spikes. For example, implementing a low pass filter into the electronics to eliminate the high harmonics will help.

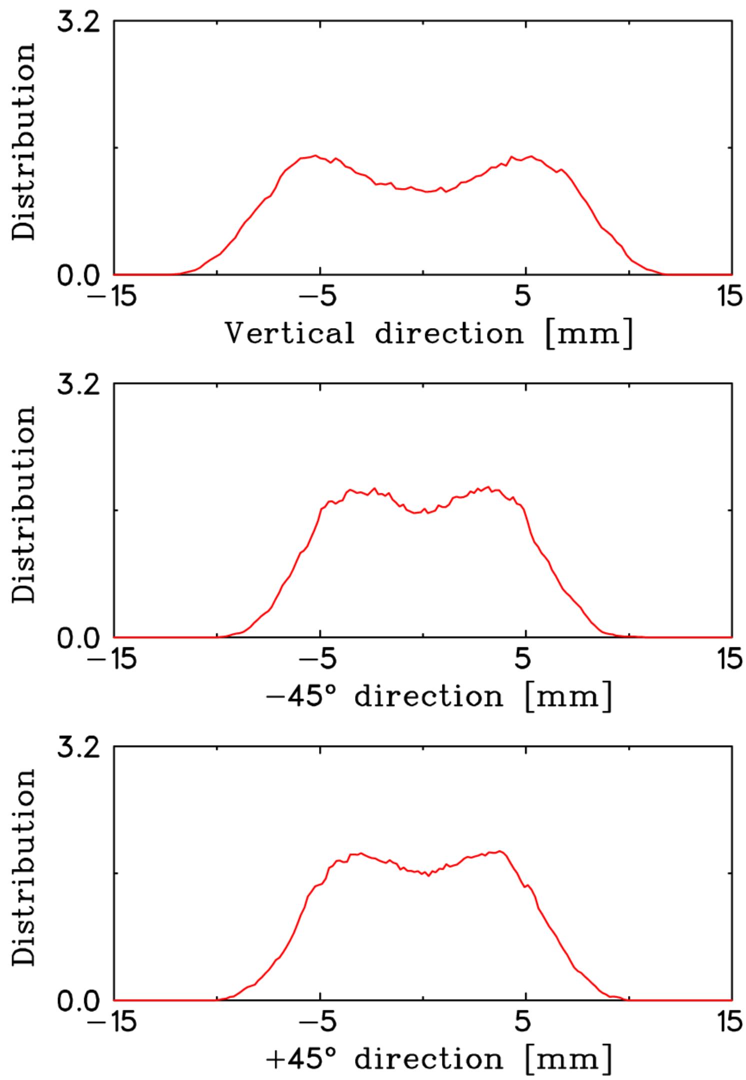

Figure 14: *M19 scan profiles, simulated for a reduced travel speed of 0.2 inch/sec. The other parameters remain the same as in the Fig.7.*

4 Conclusion

The test of beam rastering in single direction (either horizontal or vertical) was successful, and the tomography worked out.

BL2A Beam Rastering Test of 2015-Nov-13

Y.-N. Rao
Nov. 14, 2015

1 Introduction

This summary mainly focuses on M19 profiles, beam tomography and BL2A tune for the rastering test performed on 2015-Nov-13.

2 Increased Sampling Rate

On 2015-Nov-13, 2A3M19 scans were taken with data sampling rate being raised by a factor of 20 from the original 1.125 kHz. As a result, the number of data samples recorded and saved for each scan was increased from 2,048 to 30,000 (limited by the memory available in the hardware Transient Recorder). As an example, Fig.1 shows the beam profiles measured under rastering frequency of 400 Hz and a rastering radius of 3.5 mm at the target.

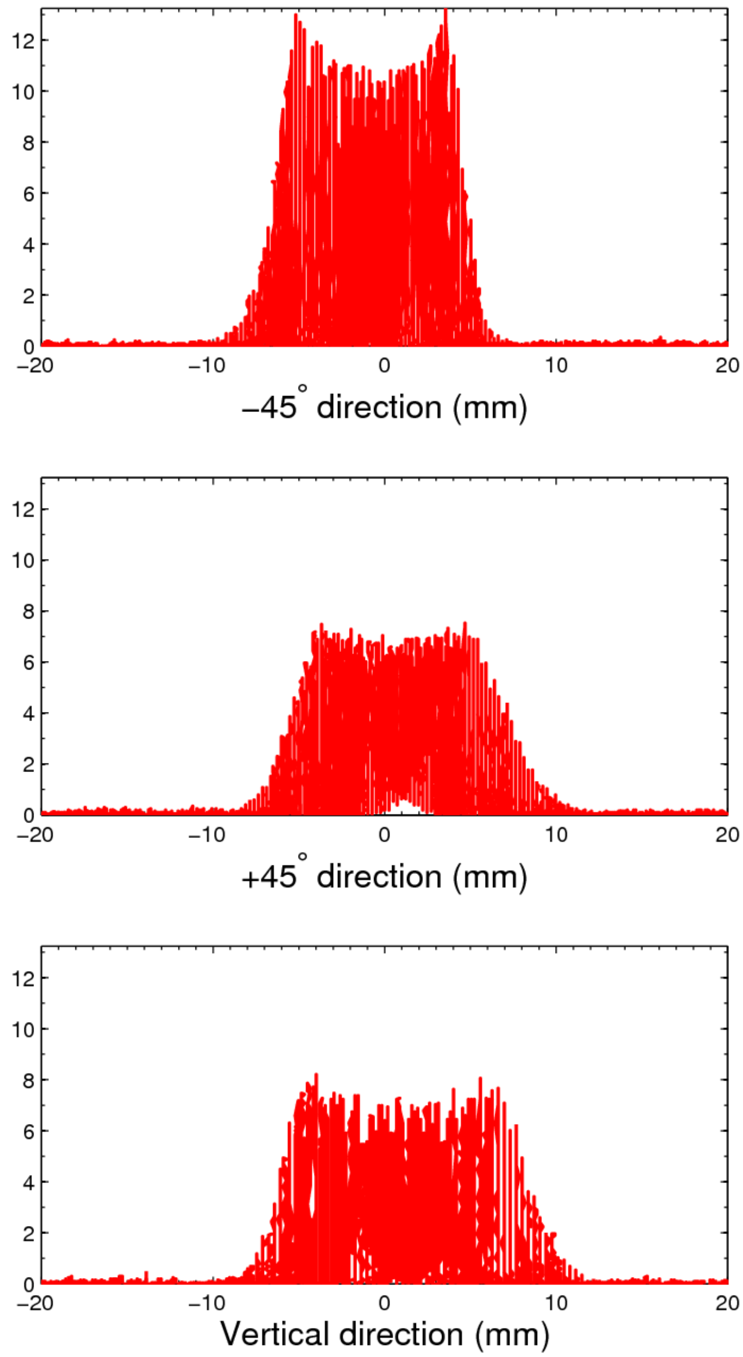

Figure 1: *Beam Profiles of M19 scan, taken with data sampling rate being raised by a factor of 20. In this measurement, the machine duty factor was 90%; the rastering frequency was 400 Hz; the rastering radius was 3.5 mm at target.*

Similar to the measurements [2] shown before, the profiles appear to have a lot of spikes. Fig.2 shows a zoom-in picture of the vertical profile as is shown in the Fig.1. It is well understood [1] that these spikes are caused by the beam rastering.

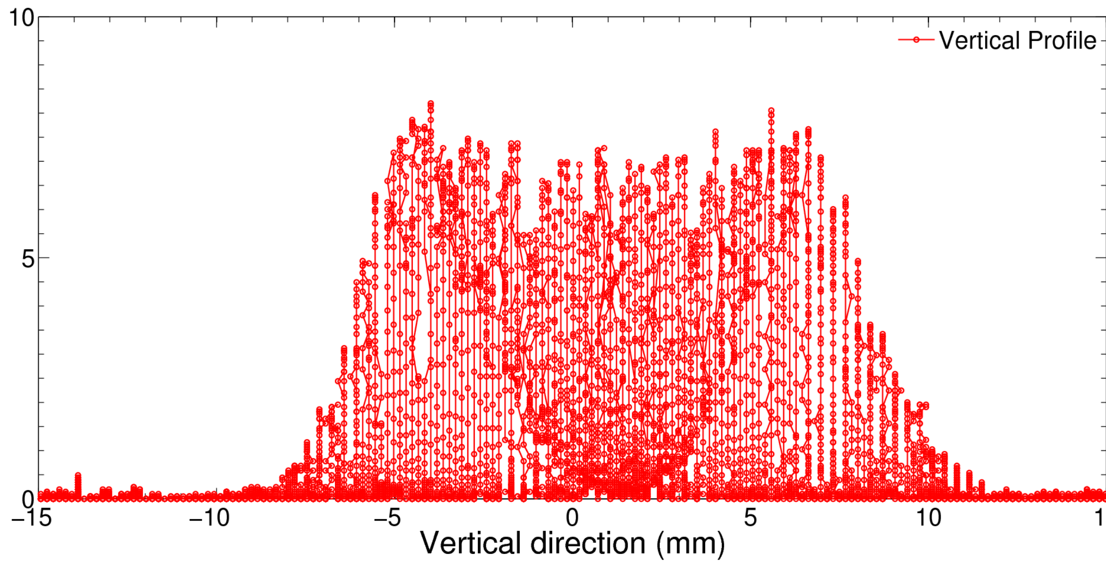

Figure 2: *Zoom-in of the vertical profile as is shown in the Fig.1. Clearly, there are a lot of spikes contained.*

The motivation for raising the sampling rate was hoping to reduce the spikes by means of taking average over the data samples recorded within every pulse of $1/(1.125\,\mathrm{kHz}) \simeq 0.889$ millisecond. But this turns out to be reducing very little. Fig.3 shows the result. Remember that this is for the case of duty factor being as high as 90%; at any duty factor below 10%, high sampling rate almost reduces nothing. This is simply because the width of that window for averaging is too small.

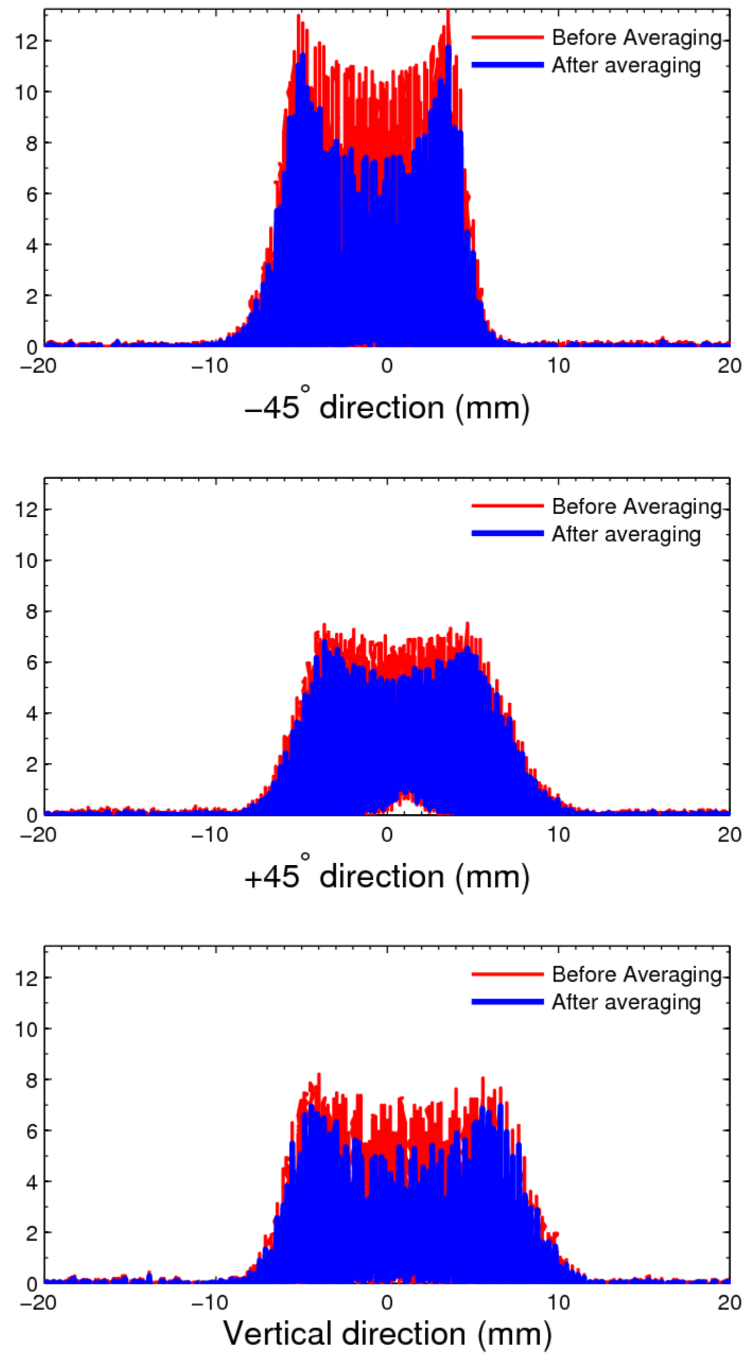

Figure 3: *Comparison of the profiles before and after taking an average for the* $20 \times 90\% = 18$ *data samples recorded within every pulse. Apparently, this averaging reduces the spikes very little.*

In order to eliminate the large spikes, one would have to widen the window for averaging. Fig.4 shows a result of averaging with a moving window of 10 pulses. Apparently, the spikes get largely reduced, and the profiles become significantly smoothed. But still, they are not smooth enough to allow the tomography to work out nicely. To minimize the spikes, one would have to double the window size for averaging. But that would result in profiles of having less than 40 effective data points, which is too less for the tomography. Remember the one-fifth story, that is, the full width of the beam rastering is no more than one-fifth of the full travel distance ($5''$) of the monitor. Thus, at most only one-fifth of the samples taken are useful data whereas the rest 80% are just background zeroes which are not useful.

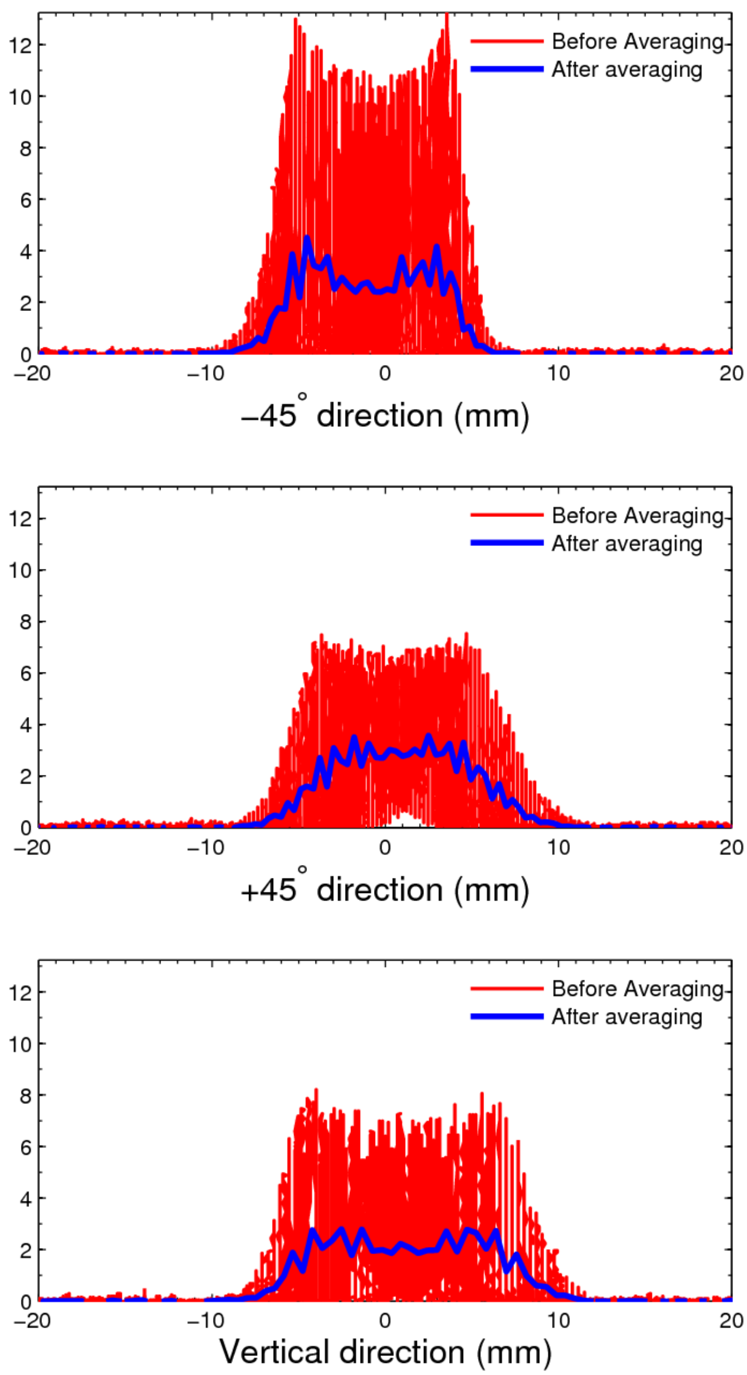

Figure 4: *Comparison of the profiles before and after averaging with a moving window of 10 pulses. Clearly, the spikes get significantly reduced but still some wiggles remain.*

3 Low-Pass Filtering

Low-pass filtering to the data samples appears to be essential to washing out the spikes and wiggles, and eventually to creating well-smoothed profiles with decent resolution for the tomography to work out. With such a filtering technique implemented, the fore-mentioned averaging method is not needed. See Fig.5 for the result.

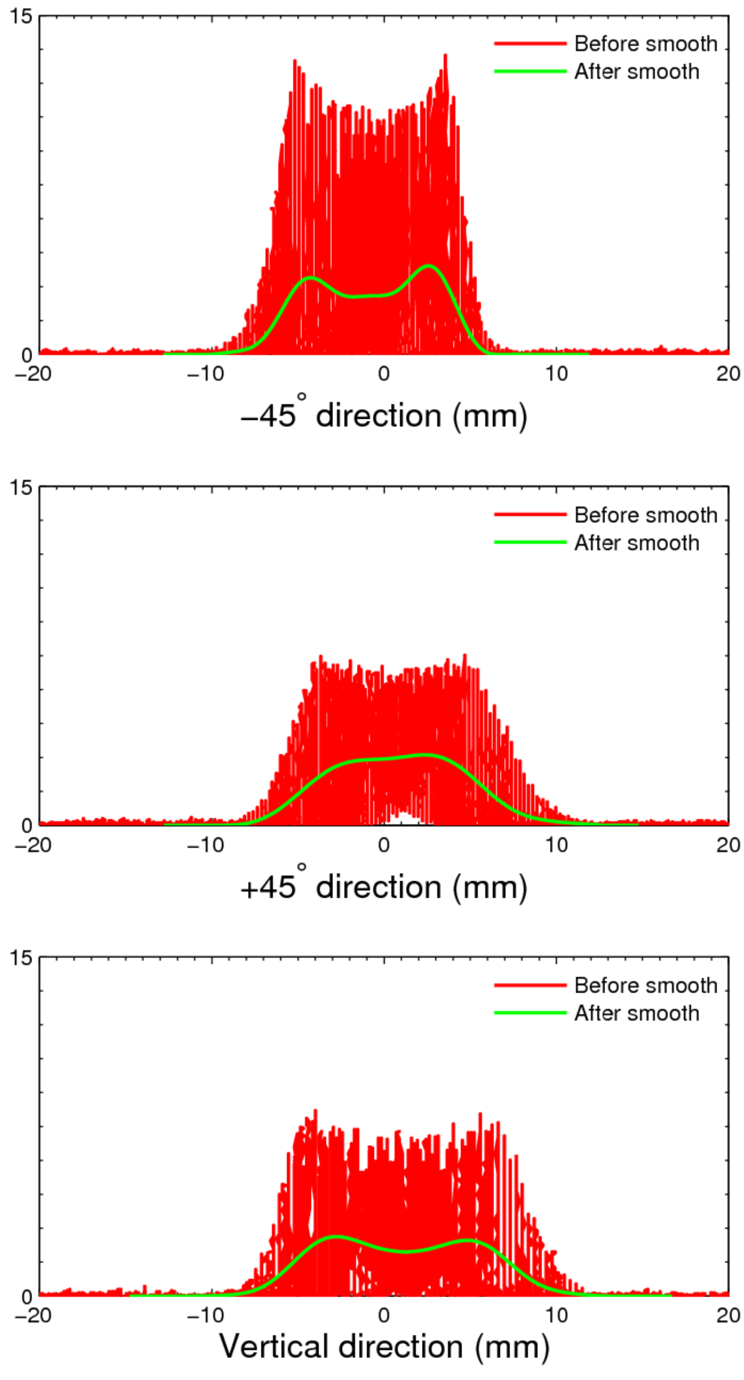

Figure 5: *Profiles before and after being smoothed with a low-pass filter. These smoothed profiles will be good enough for tomographic reconstruction.*

4 Tomography

Fig.6 shows the tomography that is resulted from the filtered profiles as shown in the Fig.5. Similar to what I showed before, the beam seems to be not rastering on an annular or elliptical ring. It is well understood [1] that this is a distorted picture, arisen from the fact that there are merely 3 projections available for the maximum entropy reconstruction, which are inadequate. In order to achieve a minimized distortion in the reconstruction, we will need at least 2 more projections in addition [1].

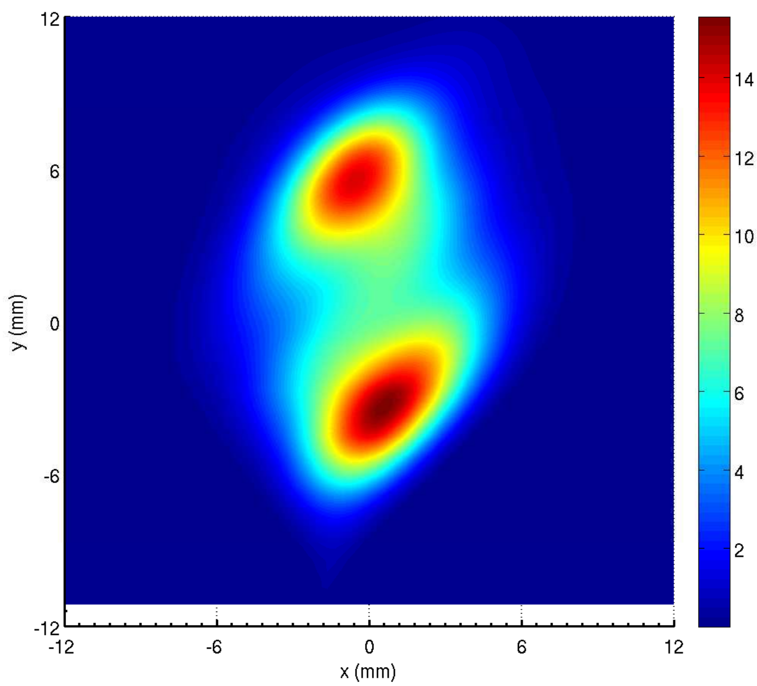

Figure 6: *Tomography reconstructed from the filtered profiles as shown in the Fig.5.*

5 2A Tune For Rastering Test

For the rastering test, we ran up the last quadrupole doublet Q15, Q16 from zero to 181.1, 227.4 A respectively to narrow down the beam spot from 7 mm to ∼3.5 mm (2rms) at M19. This 3.5 mm size was prescribed by the Target/Ion Source group. Fig.7 shows the 3.5 mm instantaneous beam spot at M19.

With these excitations of Q15 and Q16, I first calculated the kick arms (i.e. transfer matrix elements R_{12} and R_{34}) from the centre-lines of H and V raster magnets to the target centre, and then calculated the values of voltage settings for the two raster magnet's power supplies, given a rastering radius desired at the target. Should be pointed out that the calculations

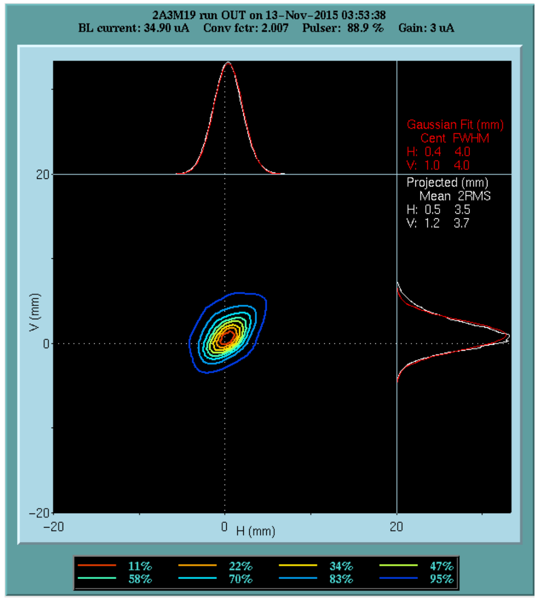

Figure 7: *Instantaneous beam spot of 3.5 mm (2rms) created for the rastering test, by running up the last doublet Q15,Q16.*

for the voltage values were employing the data of BdL obtained from the actual survey for both magnets. Fig.8 shows the calculated results of R_{12}, R_{34}, d_x and d_y (i.e. displacements of reference trajectory in H and V), for a given rastering radius of 3.5 mm at the target. It's seen that the displacements in H and V are not the equal until reaching the target, and the vertical one is always larger than the horizontal one. This means that the rastering beam will display on an elliptical ring instead of on an annular ring at BPM18.5 and M19 both. Also notice that the vertical displacement reaches $\sim \pm 9$ mm at maximum. Does this cause spills down to the line? The answer is unknown for the moment.

Bear in mind that the M19 wire plane is not at the target but at ~1 m upstream of the target. The rastering size measured at M19 is definitely not equal to the one at the target. The instantaneous beam spot size measured at M19 is not necessarily identical to the one at the target either, unless the beam envelope is made parallel onto the target. The current tune of 2A, as is shown in Fig.9, is very much the same in both legs and it has been running steadily and reliably with a large ~7 mm spot at the target for years. But for the purpose of rastering with a small spot, this tune may not be optimized. For instance, we may want to produce a parallel instead of a strongly-focused beam onto the target, also we may want to create equal displacements in both planes so that the rastering will appear on an annular instead of on an elliptical ring at BPM18.5 and M19 both. Such a tune would look like shown in the Fig.9, but we will need dedicated beam development time to demonstrate it.

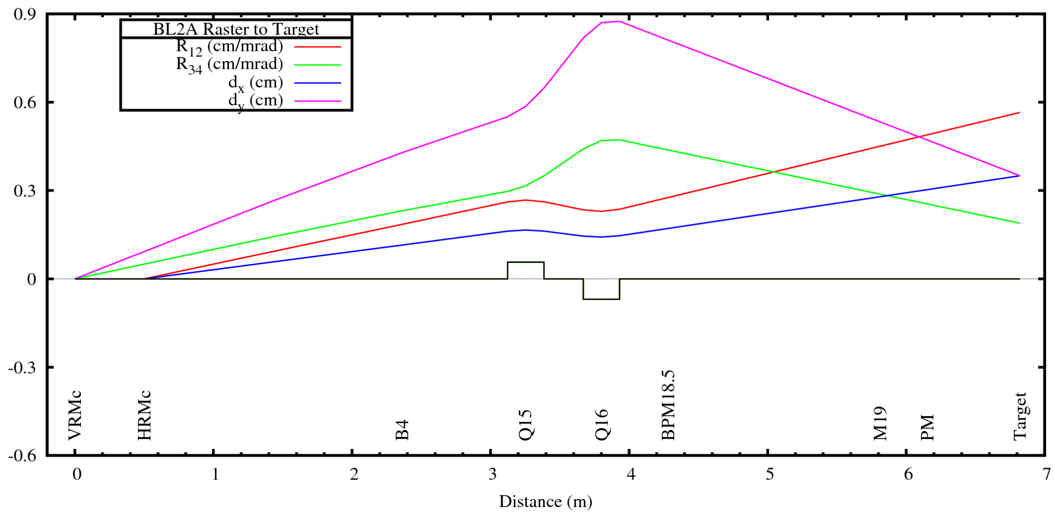

Figure 8: *Displacements of reference trajectory calculated for a rastering radius of 3.5 mm at the target.*

6 Conclusions

In conclusion, raising the data sampling rate helps very little in reducing the spikes in the measured profiles, in particular at low duty factors. In order for the tomography to work out properly and nicely, it's critical that (1) we have a low-pass filter implemented in the electronics to smooth out the the beam profiles, and (2) we add up at least 2 more wires in appropriate orientations to the existing monitor to create 2 more projections for the tomographic reconstruction.

Besides, the 2A tune might need to be revisited and optimized for the purpose of rastering with small beam spot.

References

[1] Y.-N. Rao, *Beam Rastering, M19 Scan and Beam Tomography in BL2A*, Mar. 15, 2015.

[2] Y.-N. Rao, *BL2A Beam Rastering Test Results of 2015-May-20: M19 Scans and Tomography*, May 22,, 2015.

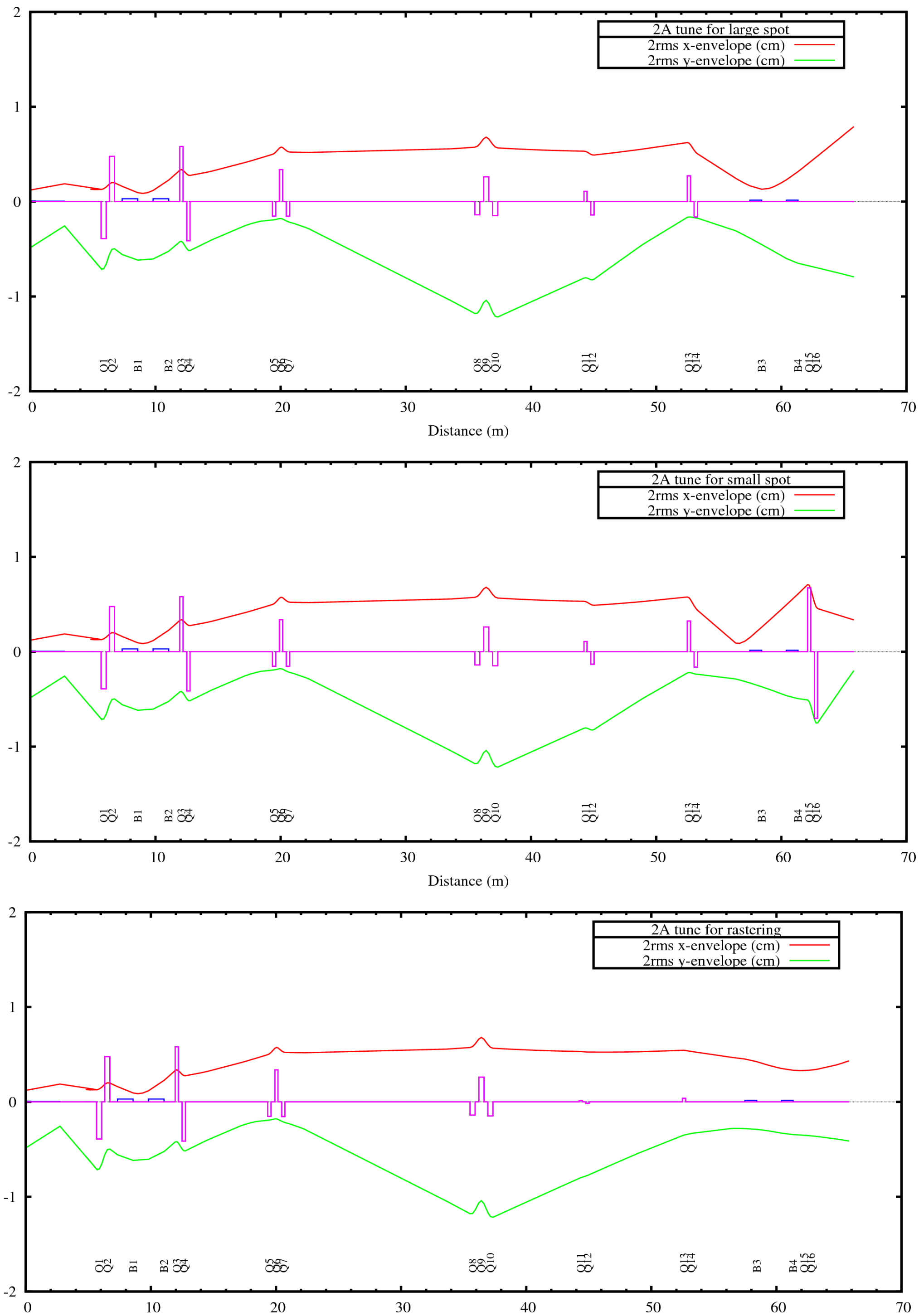

Figure 9: *Top and Middle: the current beam production tune of 2A for large and small spots at target. Bottom: theoretical tune, optimized for beam rastering but to be demonstrated.*