Some Results from M13 Tests and Tuning

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1 Introduction

The precision of the results of the $\mathcal{TWIST}$ experimental program depend partly on the control and measurement of beam parameters such as position, size and divergence (or emittance), momentum spread, *etc.* The M13 beam line has been chosen for $\mathcal{TWIST}$ partly because its characteristics match the demands of the measurements, and also because it is in principle a simple beam to understand to the extent that will be required during data analysis. Much effort has been spent by different individuals and groups to determine M13 beam parameters since installation over twenty years ago, but with the stringent $\mathcal{TWIST}$ requirements, the opportunity to repeat and extend the measurements was taken prior to installation of the solenoid, during high intensity beam time in the fall of 2000.

There was a set of tasks, summarized in a previous note [1], but as usual these tasks were modified based on the experience obtained. Some of the results are reported elsewhere [2, 3]. This document contains results of measurements of production target and beam alignment tests, production target differences, preferred beam element settings, beam tuning, profiles and emittances. It also lists some concerns arising from our experiences which may lead to further beam studies and suggestions for modifications of the beam line and its operation.

For reference, a diagram of the M13 beam elements is shown in Fig. 1. Recall that it consists of seven quadrupoles, Q1-Q7, and two bending dipoles, B1 and B2. Q1, Q4, and Q7 are vertically focussing, while Q2, Q3, Q5, and Q6 are horizontally focussing. The beam line is designed so that Q1 and Q2 focus the beam from the 1AT1 production target through B1 to a dispersed (momentum-dependent) focus at F1, where independently controlled plates allow particles with a selected range of horizontal positions to pass. This momentum selection device is called the F1 horizontal slit (F1HS). There is also a wheel device containing a selection of absorbers and fixed vertical slits near F1. Q3-Q5 form a triplet to focus the image from F1 to a second dispersed focus at F2, where there is also a horizontal slit (F2HS). From here, the beam is guided by B2, Q6, and Q7, to what is supposed to be an achromatic (momentum independent) focus at F3, a meter or so beyond Q7. To limit the beam divergence from the production target, a rectangular aperture is defined by 4 plates between Q2 and B1. The horizontally moving plates, called F0HS even though there is no focus here, can be controlled independently, while the vertically moving plates move in and out symmetrically, and are therefore called F0 vertical jaws (F0VJ) rather than slits.

During this beam period, bending magnet fields were set and monitored by NMR, but quadrupoles were set and monitored only by the readings of the (essentially obsolete) channel control system (TICS). Monitoring of quadrupole currents by a $\mathcal{TWIST}$-specific system, using new current transformers, should be in place by the next running period. An instability in the B2 current was noted from the NMR signal early in the run. It was eventually traced to ground loops in the DAC control and ADC readback signals between the power supply and the CAMAC secondary channel control hardware. An isolation transformer cured the problem. Transformers for all beam elements will also be installed soon.

An apparatus for $\mu\mathcal{SR}$ measurements was installed and operational October 19, and was used until the end of October. Most of the $\mu\mathcal{SR}$ results are described elsewhere [3]. During most of this period, a 12 mm Be target (enclosed in a stainless steel capsule through which cooling water flowed) was in use on the MK2 1AT1 production target ladder.

The vertical position of the targets on the MK2 ladder was aligned according to the request of the CHAOS group in M11. They had found during their M13 run in summer 2000 that an alignment lower than nominal by 1 mm resulted in less quadrupole steering and a more horizontal beam path in their apparatus in M13, and the MK1 1AT1 production target had been lowered by $\sim$1 mm as a result. However, upon their return to M11, they found that this alignment was not optimal for their apparatus on M11 and thus the MK2 ladder was not lowered before its installation, complete with two 10 mm graphite targets as well as 12 mm Be targets, prior to the beginning of our measurements on M13.

Just prior to the end of the $\mu\mathcal{SR}$ beam time, on October 31, the graphite target was moved into beam position, and a few $\mu\mathcal{SR}$ runs were possible with it at reduced rates. On November 1, the $\mu\mathcal{SR}$ apparatus was removed and two x-y wire chambers were installed with scintillators for detection of muons and positrons, and operation began first with the Be target, and from November 9, with the graphite production target. The apparatus is shown schematically in Fig. 2. The thickness of the muon scintillator (M) was 0.5 mm, and it extended beyond the 5 cm size of the first wire chamber (C64, with 64 wires in each of the x and y planes, and wire separation of 0.76 mm). The second chamber (C96, similar to C64 but with 96 wires) was approximately 7 cm square. The purpose of the absorber was to stop muons so that the positron counter P could be used as an anticoincidence in muon definition, especially during cloud muon measurements above 30 MeV/c. Different versions of this setup were used until the end of the beam time, December 5, 2000. Alignment of the wire chambers with respect to the line surveyed to the floor (for x) and a benchmark for the M13 beam height (for y) allowed us to survey the x-y positions of the chambers to better than 1 mm. This was repeated several times during the beam period. In our coordinate system, +y is vertical (up) and +z is the nominal beam direction, so that +x is horizontal to the left of the beam. For most of the results reported here, the separation between the two chambers (C64 and C96) was 300 mm.

During the beam tuning period when the wire chambers were installed, several problems were encountered which made systematic comparisons of some quantities difficult, and some of the data taken, especially early in the period, are of little value. For example, there is some evidence that the graphite target horizontal alignment was not as indicated in the target ladder surveys (optical position measurement with the ladder removed from the target shield and placed in a hot cell). In addition, due to cyclotron problems with the beam inflector, BL1A was not properly tuned until the last days of beam time. Due to nonexistent primary beam diagnostics on the MK2 target ladder, it was replaced on November 21 with the MK1 ladder (still 1 mm low from the CHAOS M13 alignment), which did not have a usable graphite target mounted. Upon inspection of the MK2 ladder in the hot cell after removal from 1AT1, the graphite target was found to be split and broken on a plane perpendicular to the beam, and about half of it had fallen off the support. It is not known with certainty when this happened, even though we were periodically monitoring surface muon intensity, due to at least two separate problems which may have contributed to unexpected muon rate variations. First, a fault in the beam blocker removal system resulted in a partially inserted blocker for a short period. Second, the beam may not have been steered properly or consistently onto the graphite target due to target ladder misalignment, evidence for which was obtained by monitoring M13 rates during a horizontal scan of the proton beam across the target. However, it is reasonably certain that both graphite pieces were exposed to some beam, as both showed discolorations from proton beam heating. Two surface muon edge scans performed on November 13 and November 20 showed significantly different normalized rates [3]; it may be that the target fell apart between the two measurements. Rate measurements for surface muons under nominally identical conditions, taken less than four hours apart on November 20 prior to the second edge scan, showed a decrease in the muon rate by 13%.

It turned out that the target ladder change was important for beam tuning, as it was determined that the MK1 target ladder vertical alignment was better for our M13 tests, in agreement with the conclusion reached by the CHAOS group. Unless otherwise indicated, the results reported here were obtained with the Be production target. The problems and inconsistencies encountered while using the graphite target made those results much less reliable.

2 Pion tuning

By adjusting the beam momentum up to about 120 MeV/c, multiple scattering is reduced to the extent that two wire chambers, as shown in Fig. 2, could be used to determine beam divergence as well as position. The muon counter (M) and the absorber (abs) were removed, and a beam trigger was determined by P·E1·E2. Since the beam is dominated by pions at this momentum, no particle identification is necessary.

Alignment problems, in the form of quadrupole steering and non-zero average beam divergence in both x and y were encountered at an early stage. In order to try to assess the source of beam misalignment (asymmetric quadrupoles *vs* misaligned target or beam elements), the quadrupoles were turned off and the horizontal slits F1HS and F2HS closed to 5 mm width. Scans of rates *vs* position of F2HS for different positions of F1HS were used to check relative slit alignment, to find the path of the beam between B1 and B2. One of the set of maximum values was chosen such that the sum of the absolute distances of the slits from the nominal zero position was a minimum; these distances were $\pm$ 0.7 mm, *i.e.*, nearly zero, evidence that target, dipoles and final focus were in reasonable alignment. The beam emittance obtained under this condition, after adjusting B2 to 3826 G to center the beam in x, is summarized in Fig. 3. Note that the beam is approximately on axis and simultaneously parallel to the axis, indicating alignment of dipoles and production target consistent with the nominal beam center line. This and some of the following figures show a few zero channels corresponding to dead wires.

Q6 and Q7 were then turned on, separately and one at a time, to check for steering effects. They were not turned on to full (120 MeV/c) values since the beam would then not be within the wire chamber sensitive region. F2HS was then opened from 5 mm to 50 mm, and the procedure was followed for Q3-Q5 separately. The results are summarized in

Table 1. It shows strong horizontal steering effects from Q6 and Q7, with smaller effects in other cases. The beam emittance for Q7 only is summarized by Fig. 4, which should be compared to Fig. 3.

When all quads are set to nominal values, B2 required adjustment to 3861 G in order to center the beam on the first chamber. This value is 0.9% higher than that with quadrupoles off. The tune that was established via the methods described in [2] is summarized in Table 2, for settings of F0HS of 40 mm and F0VJ of 25 mm. The momentum slit F1HS was set to 10 mm, while F2HS remained open (140 mm). The rate was about 1.7×10^5 s^{-1}. Emittance measurements are shown in Fig. 5; the beams are mostly within ellipses of areas $\pi \cdot (10$ mm$) \cdot (10$ mr$)$ in x and $\pi \cdot (7$ mm$) \cdot (15$ mr$)$ in y.

3 Surface muon tuning

The strategies used for tuning M13 for muons are described in detail in [2]. Only a few examples of the results are given here.

Tuning Q2 was best accomplished by a scan of the F1HS position (with narrow width) for various values of Q2, which provides the horizontal dispersed focus at F1. The best setting is indicated by the steepest gradient in the rate as the slit is moved to higher momentum, beyond the momentum of surface muons. A contour plot is shown in Fig. 6, and the optimum value for Q2 is clearly visible.

The surface muon edge was scanned several times to provide a precise momentum calibration and to measure the momentum resolution. Two scans using the graphite target are reported in [3]. A scan done on December 5 of the positron rate near 52.83 MeV/c (the maximum for a surface positron from muon decay at rest in the production target) provides a second momentum calibration, although not as precise. The B1 NMR measurement at this endpoint is 1552.0 ± 1.5 G, and is consistent to within the 0.1% uncertainty with proportionality to the surface muon edge at 29.79 MeV/c of 876 G determined in a scan on the same day. Both were obtained with the Be target; production target alignment differences may account for the slight difference of this surface muon edge NMR value, compared with [3].

Table 4 summarizes muon rates for different F0 slit and jaw settings, for values which are close to what we expect to use with $\mathcal{TWIST}$. The muon beam size (FWHM) was approximately 24 mm in x and 11 mm in y, with no significant dependence on the F0 settings. However, the beam distributions showed tails to a significantly greater degree than for the pion beam, especially to negative values of x. For comparison, Fig. 5 shows the pion beam sizes (FWHM) to be about 16 mm in x and 13 mm in y. Attempts to reduce the x size of the beam were not successful. One explanation may be that the surface muon source is the stainless steel water jacket, which is larger by a few mm than the beryllium pion source.

Two rate measurements were taken on November 8 and November 9, before and after, respectively, the change of production target from Be to graphite. Although it was early in the beam period, before a reliable tune had been established, conditions were otherwise similar. The surface muon rate, normalized to primary beam intensity, was 33% higher with the graphite target.

The surface muon beam profile in the x direction was confirmed to be non-uniform, with a peak at low values of x, as had been observed in previous surface muon studies on M13 by Dave Gill *et al.* This shape was observed for several of the runs of the surface muon edge scan of December 5. In Fig. 7, the x profile along with the y profile, RF time of flight, and muon energy loss in the thin scintillator (M) are displayed with different runs at different momenta superimposed. They are normalized to the muon rate to show the behavior of the distributions as the momentum changes. Widths of slits and jaws were 80 mm for F0HS, 25 mm for F0VJ, and 10 mm for F1HS, with F2HS open to 140 mm. In Fig. 8, the individual normalized x distributions are shown for clarity. What is surprising is that the muons at low values of x disappear at lower channel momentum settings. This may indicate a dependence of mean channel momentum on x position at the muon source.

4 Test of fiber light guide muon counter

The arrangement of Fig. 2 was convenient for testing the fiber light guide scintillator (FLGS) prototype built for $\mathcal{TWIST}$ and previously tested by M. Quraan, J.-M. Poutissou and J.A. Macdonald [4]. It was inserted between C64 and the M scintillator. In this way, using M as a trigger counter, an event which also had one and only one x-y pair in C64 defined a particle passing through the FLGS at a known position, with position resolution determined by scattering and any angular divergence of the beam.

The FLGS is read out by two phototubes, one at each end of a fiber of wave shifting material which encircles the scintillator. Two runs were taken, one with a voltage of 1750 and one with a voltage of 1850 on each phototube. Contour plots of the efficiencies at each voltage are shown in Fig. 9 for surface muons as defined by the appropriate pulse height in the M scintillator. A signal above the pedestal in the ADC from both fiber light guide phototubes was required. Similar plots are shown in Fig. 10 for beam positrons, identified by low pulse heights in the M counter.

The efficiencies measured for muons are reasonably uniform over the surface. They are above 90% for both 1750 and 1850 V, and can be seen to be slightly better at the higher setting. For positrons, the values as expected are much lower, typically 30%. Regions on the periphery and on the right side where the fiber runs toward the phototubes show higher efficiency, which must be due to positrons passing directly through the fiber light guide. Due to the way that events are triggered with the M counter, which biases the selection of beam positrons toward those which deposit more energy in M, this may not be quantitatively reliable.

References

[1] G. Marshall, M13 muon beam development for $\mathcal{TWIST}$, $\mathcal{TWIST}$ beams study group note, July 2000. (http://stoney.phys.ualberta.ca/ e614/Projects/E614-S2/00016/)

[2] J. Doornbos, The tuning of M13 for $\mathcal{TWIST}$, theory and some results, $\mathcal{TWIST}$ Technical Note TN-51, December 2000. (http://stoney.phys.ualberta.ca/ e614/Projects/-E614TN/00051/)

[3] R. MacDonald, Summary of $\mu\mathcal{SR}$ beam studies at M13, report to January 2001 $\mathcal{TWIST}$ collaboration meeting. (http://stoney.phys.ualberta.ca/ e614/Projects/-E614MEETINGS/00067/)

[4] M. Quraan *et al.*, Muon trigger scintillator, $\mathcal{TWIST}$ Technical Note TN-26, January 1999. (http://stoney.phys.ualberta.ca/ e614/Projects/E614TN/00026/)

Quad	% of nominal	x (mm, mean)	y	dx (mr, mean)	dy
F1HS = 5 mm, F2HS = 5 mm					
-		-0.7	+0.4	+0.8	+0.8
Q7	50%	+5.4	+1.0	+5.3	+1.4
Q6	50%	-7.8	-1.8	-3.2	-0.8
F1HS = 5 mm, F2HS = 50 mm					
-		+0.8	+0.3	+0.3	+0.3
Q5	20%	-3.2	+0.6	-0.7	+0.7
Q4	10%	+1.2	-0.1	+0.3	+1.0
Q3	20%	+0.9	+0.8	-0.1	-0.9

Table 1: Summary of beam steering for individual quadrupoles energized separately to a percentage of nominal current.

Element	Set Point (DAC)	Current (A)	Field (G)
B1	10690	164.	3540.6
B2	11999	135.	3860.7
Q1	2587	633.	
Q2	31513	239.	
Q3	2820	513.	
Q4	3113	374.	
Q5	2930	511.	
Q6	1680	206.	
Q7	1760	209.	

Table 2: M13 beam line settings for approximately 120 MeV/c pions, determined in beam tests of November and December 2000. Currents are estimates from the channel control system only, and are neither precise nor reproducible. Fields are NMR values for B1 and B2.

Element	Set Point (DAC)	Current (A)	Field (G)
B1	2631	40.	876.0
B2	3049	34.	956.3
Q1	639	156.	1040.9
Q2	7795	59.	900.4
Q3	697	127.	1376.5
Q4	769	93.	1419.5
Q5	786	123.	1340.3
Q6	420	53.	800.8
Q7	540	63.	959.4

Table 3: M13 beam line settings for 29.79 MeV/c, the edge of the surface muon momentum distribution, determined in beam tests of November and December 2000. Currents are estimates from the channel control system only, and are neither precise nor reproducible. Fields are NMR values for B1 and B2, and estimated pole tip fields derived from the currents and the activation specifications for all quadrupoles. Note that these are not final $\mathcal{TWIST}$ settings, but still require modifications for transport into the solenoidal field, for specific slit and jaw settings, and following any changes or upgrades to M13 beam elements and monitoring.

F0HS width (mm)	F0VJ width (mm)	μ^+ rate $\times 10^{+3}$ s^{-1}	e$^+$ rate $\times 10^{+3}$ s^{-1}
80	25	18.6	107.
40	25	9.0	52.
40	15	5.0	30.

Table 4: Muon and positron rates for different settings of F0 slit and jaw, for 29.4 MeV/c (B1 set to 864.3 G). F1HS was 10 mm, and the proton beam current was 140 μA on a 1.2 mm Be target in a stainless steel water jacket.

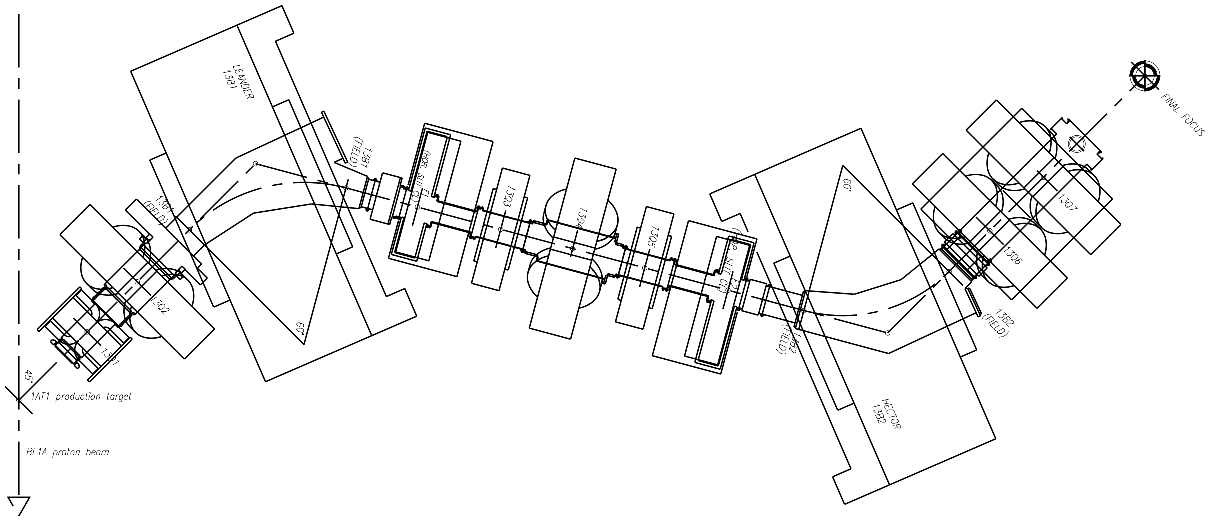

Figure 1: Diagram of elements of M13.

Figure 2: Arrangement of chambers (C64 and C96) and scintillators (M, P, E1, and E2), showing end of beam pipe and an absorber (abs).

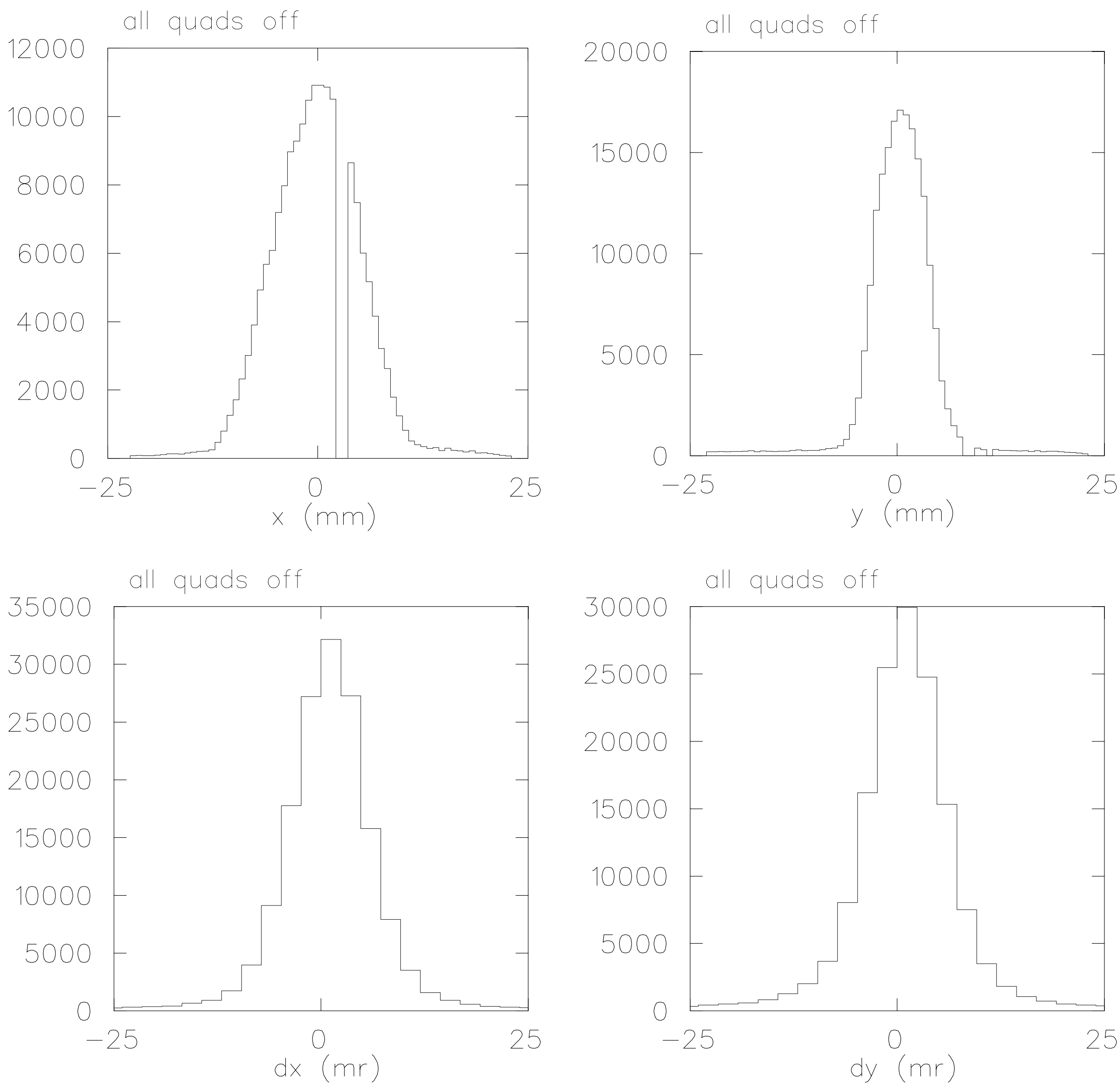

Figure 3: Beam position and divergence distributions for 120 MeV/c pions, with no quadrupoles turned on.

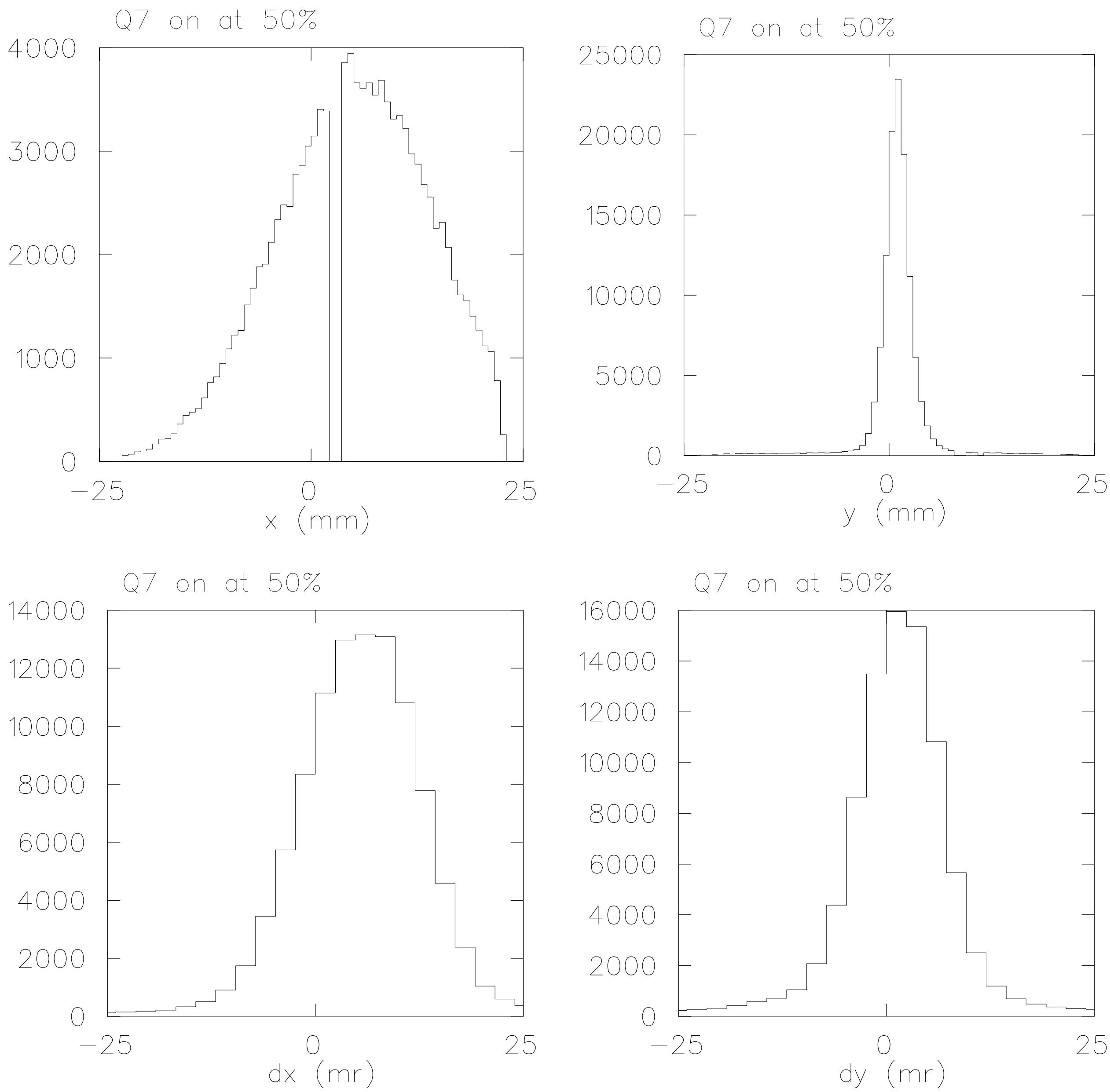

Figure 4: Beam position and divergence distributions for 120 MeV/c pions, with Q7 only turned on at 50% of nominal current. Note the shifts compared to Fig. 3, especially in x and dx.

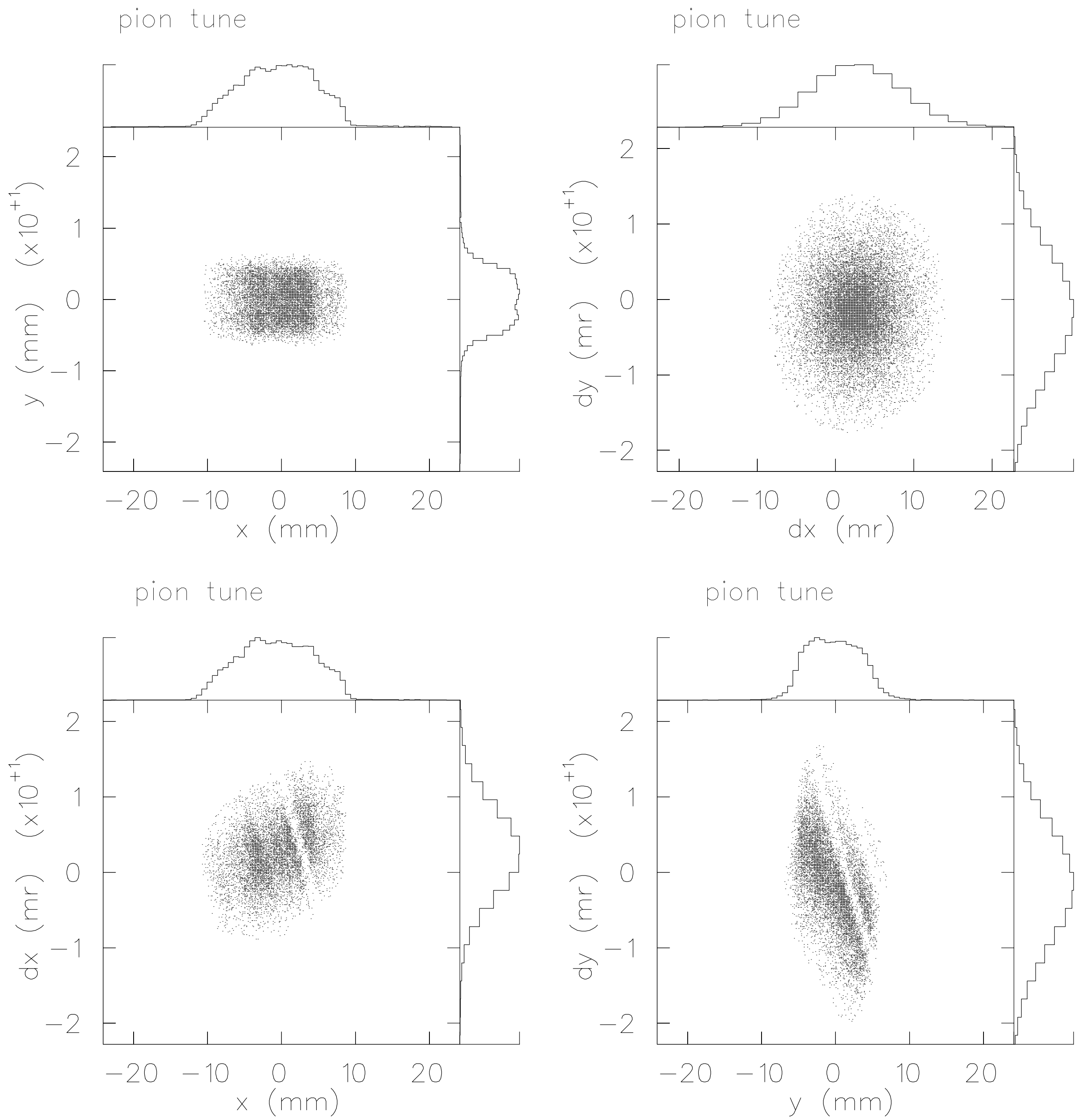

Figure 5: Beam emittance plots following tuning for 120 MeV/c pions.

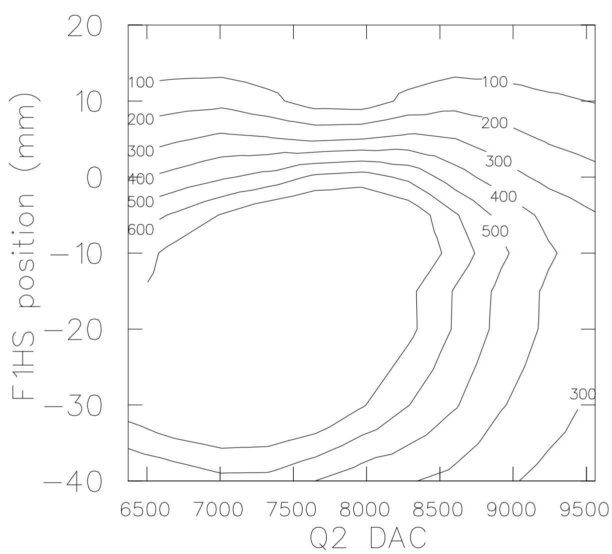

Figure 6: Muon rate contours for a grid of settings of F1HS position and Q2 DAC. The close contour lines indicate a steep gradient at the surface muon edge, a requirement for a dispersed focus at F1.

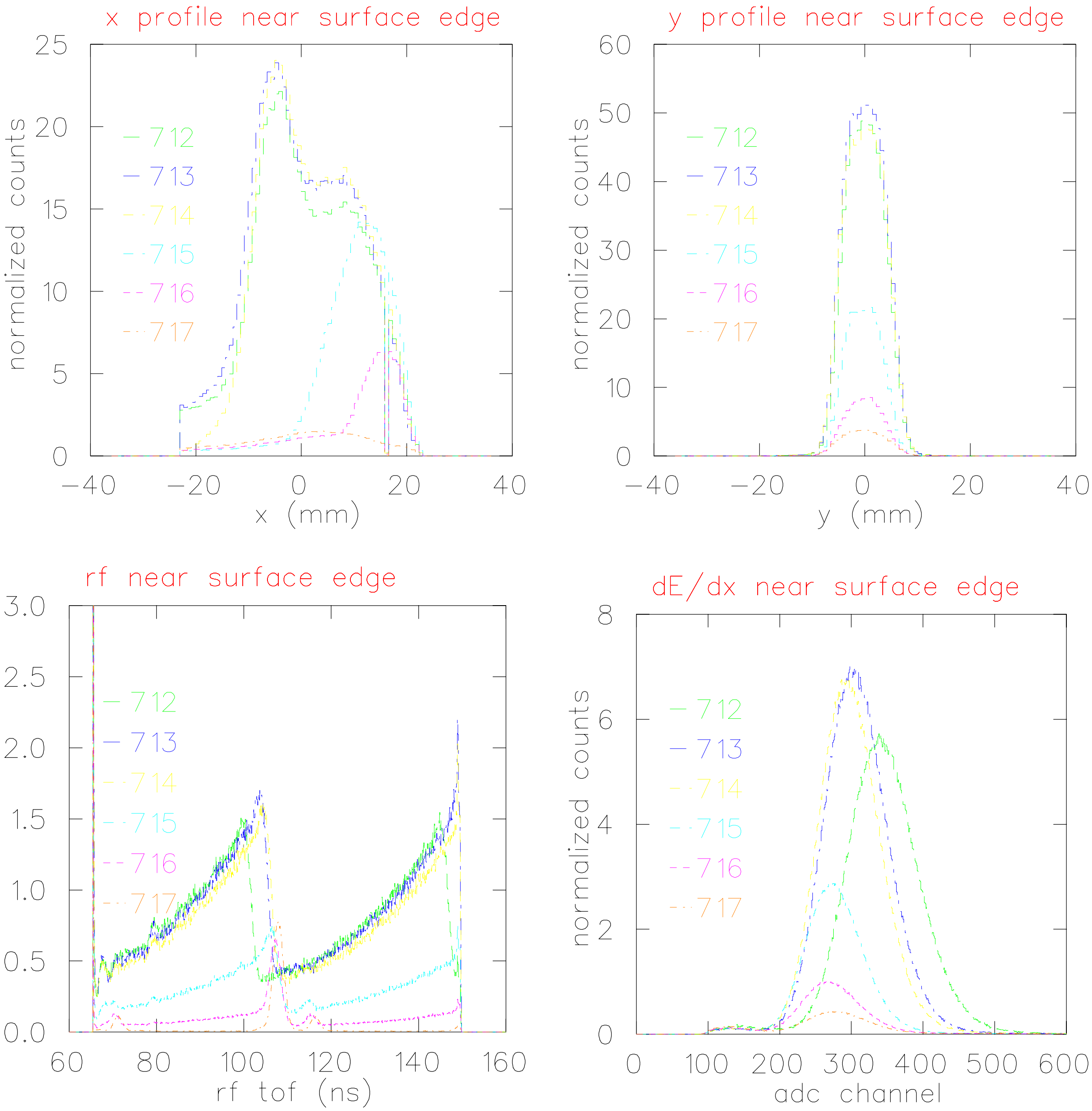

Figure 7: Beam profiles in x and y, with time of flight and muon energy loss distributions, for beam momenta near the surface muon edge. The legend indicates a sequential run number, for B1 NMR values of 835.0, 864.3, 870.5, 878.8, 883.0, and 889.2 gauss respectively.

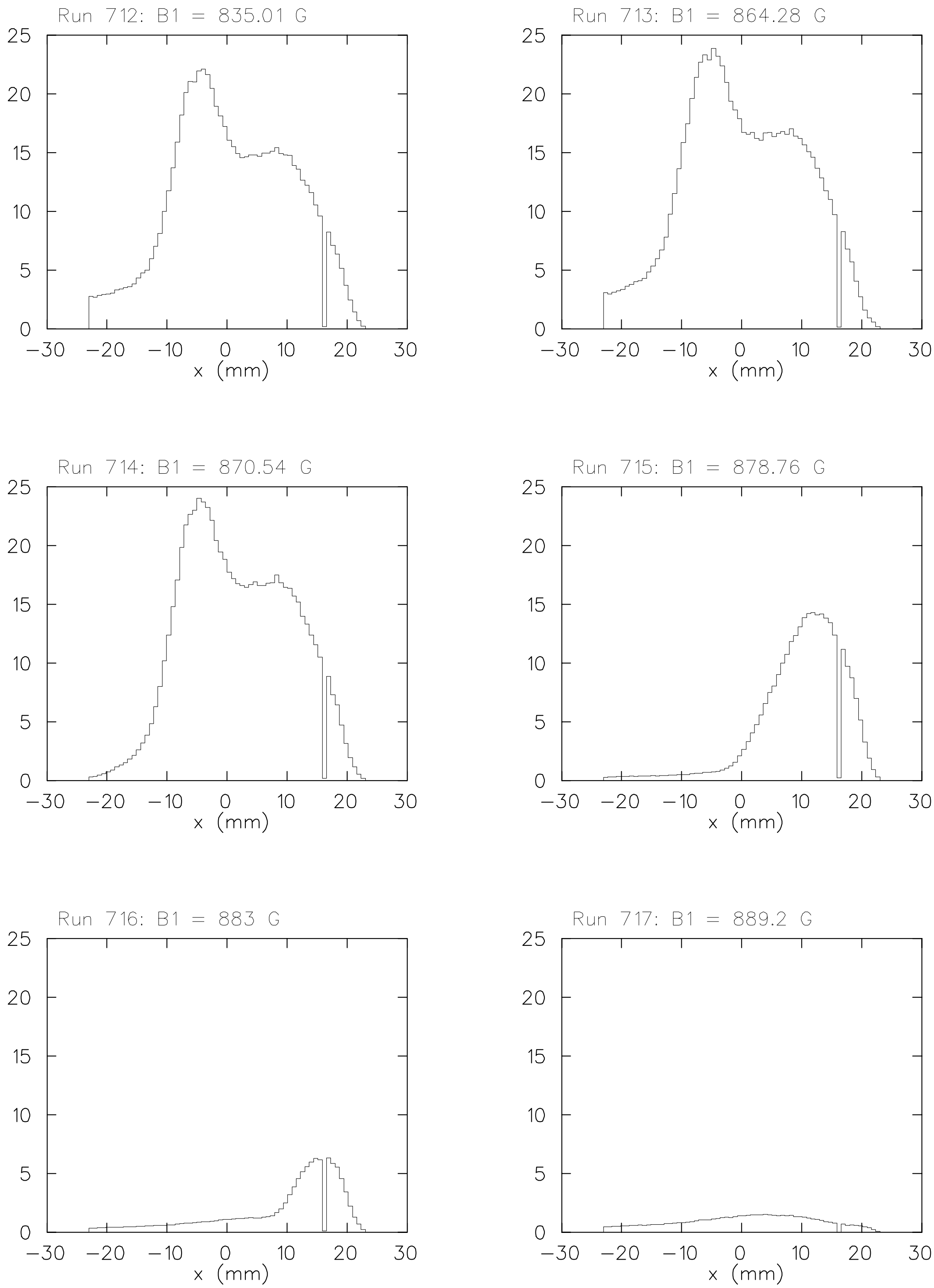

Figure 8: Beam profile in x as in first plot of Fig. 7, normalized to muon rate, for different runs at different momenta near surface muon edge.

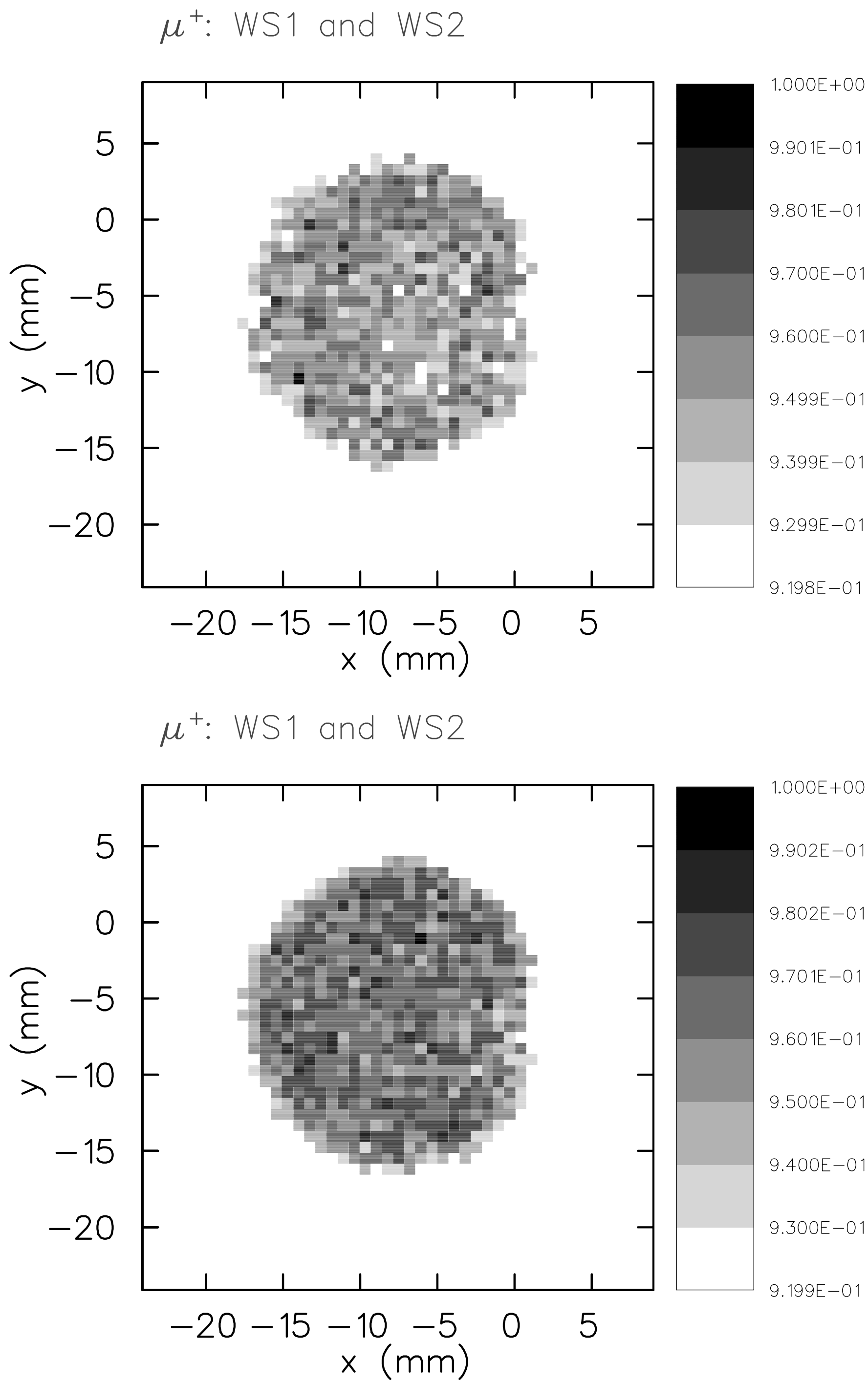

Figure 9: Plots of fiber light guide scintillator efficiency versus position for surface muons, for photomultiplier high voltages of 1750 V (upper) and 1850 V (lower). Note that the range displayed is from 92% to 100% only.

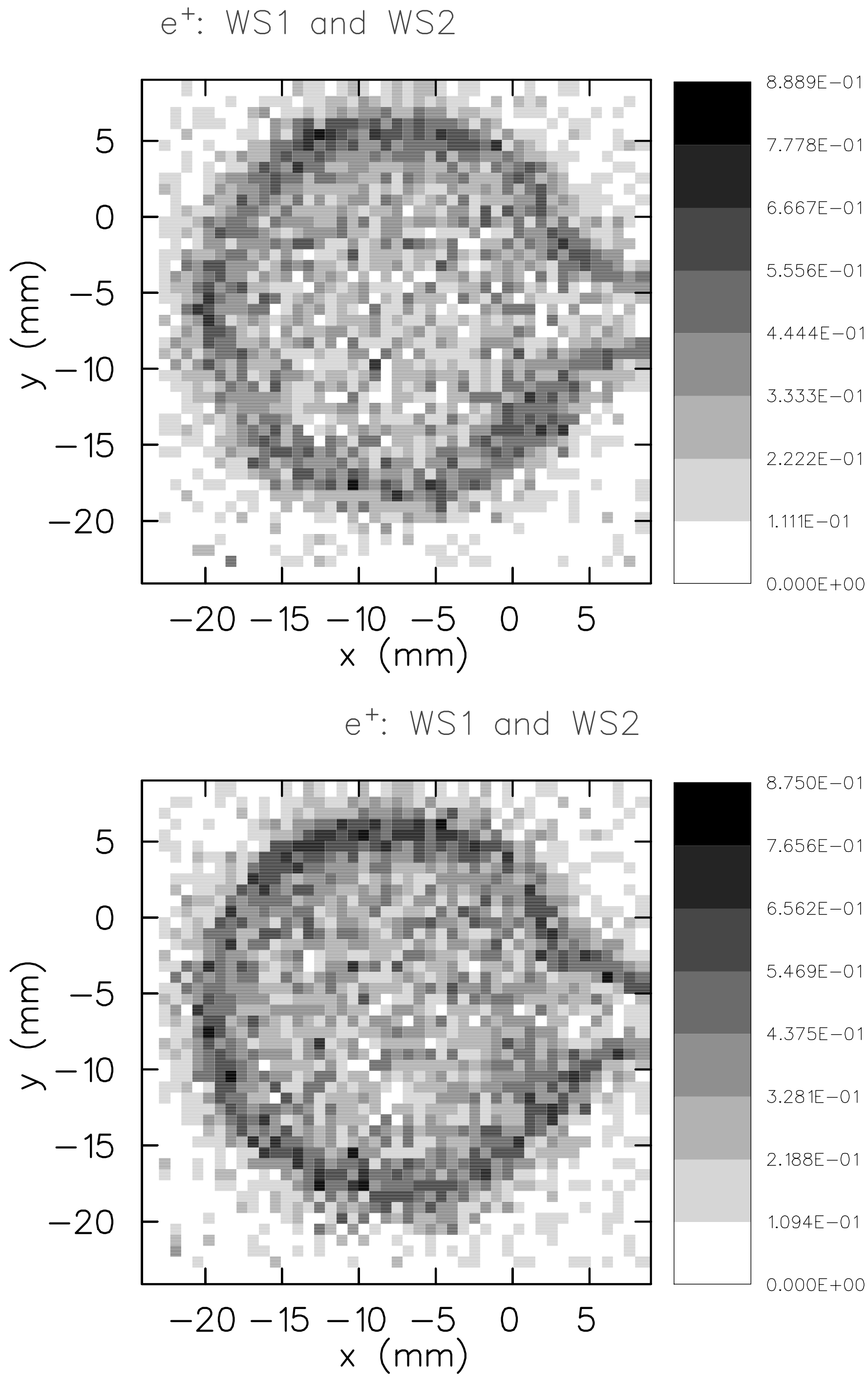

Figure 10: As Fig. 9, except for beam positrons rather than surface muons. In this case, the range is from 0% to almost 90%. The fiber path to the photomultipliers can be seen on the right side.