Summary of solenoid field and location studies using the six way probe and load cells

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The $\mathcal{TWIST}$ solenoid has been powered up and some field mapping has begun, using the so-called six way probe. The probe consists of six Hall plates positioned at each end of three mutually orthogonal supports, such that the plates measure the z component of the field at positions nominally ± 20 cm from the common center of the supports in each of the x, y, and z directions in the usual $\mathcal{TWIST}$ coordinate system ($+z$ in the beam direction, $+y$ up, right-handed). It is fixed to a trolley which slides along the rails within the bore of the solenoid. Each Hall device has a precision of about 1 G, which is approximately the field corresponding to a change of one in the least significant bit of the digitization system. Calibration and offset adjustments were done by Doug Evans of the TRIUMF magnets group.

In addition to field mapping, we have been observing the readout of four load cells, which are essentially strain gauges mounted in washer-shaped holders. They were placed on the ends of the longitudinal struts inside the solenoid vacuum chamber, two on the upstream end (where an increase measures force in the $+z$ direction) and two on the downstream end (similarly for $-z$). See Fig. 1 for a schematic of the struts; they are the outer ones (in red, if you're using color) which anchor the middle of the nitrogen shield to each end of the vacuum chamber. The cells nominally put out a voltage signal of 10 mV for 22000 lb (10000 kg force) with a 10 V excitation, so the calibration is about 1 μV per kg force (please excuse the avoidance of Newtons). The support struts are pre-stressed, so a reduction in the force measured by the load cells at one end, equal to the increas in force at the other end, is expected for a purely longitudinal force.

The solenoid has so far been powered to 144 A (1.27 T), in steps of 24 A. Some figures of the changes in the load cell measurements are shown, for ramping down from the indicated current. Initial measurements of the load cell from 96 A to zero (Fig. 2) seemed to indicate an increase in the force due to the magnetic field more from the upstream load cells. For a purely longitudinal force, this would indicate that the coils were closer to the downstream yoke end cap. However, this can't be the entire story, because there is no corresponding decrease in the downstream cells. Nonetheless, the solenoid was then moved by 1.75 mm in the $-z$ direction. The forces on the downstream load cells were then more comparable (Fig. 3: note that the current was 48 A, not 96 A, and that the vertical scale is 20 μV rather than 50 μV per division). On the other hand, they were both positive, which would correspond to a transverse or radial force. Because we believed from inspection of the solenoid during the longitudinal strut repair that the coils were low compared to the yoke and beam axes, and also due to measured off-axis field asymmetries (see following discussion), the solenoid was moved vertically up by 4 mm. The load cell variations from a ramp to zero following this move are shown in Fig. 4. Here there is clearly a greater magnetic force on the downstream load cells, while the upstream load cell changes are not even monotonic.

Figure 5 shows the fields measured at 48 A with the solenoid in its original position. The top graph refers to the two Hall plates on the z axis (defined by the centers of the openings in the upstream and downstream yoke end caps), with respect to the z value at the position of the Hall plate (corrected for the 20 cm distance to the center of the six way device). The middle shows the off-axis fields, but since it is difficult to see the differences, the bottom graph shows the differences $B(x = +20) - B(x = -20)$ as Δx and $B(y = +20) - B(y = -20)$ as Δy.

Figure 6 is a similar result following a move of the solenoid by 1.75 mm in the $-z$ direction. The probe at $z = +20$ had failed, so the top figure includes a broader scan with the other on-axis probe. The increase at $z > 60$ cm was considered to have been due to the effects of the hole in the yoke being on a different axis than the solenoid. To check the vertical alignment (the easy way, assuming that the radial field distribution within the solenoid is not affected by the yoke position but mostly by the coil position), the trolley for the probes was moved down by about 6 mm; the resulting field maps are shown in Fig. 7. The bottom graph is certainly different, and the Δy values are more uniform and consistent with zero. Finally, Fig. 8 shows the field map, again at 48 A, following the raising of the solenoid within the yoke by 4 mm and a realignment of the trolley with the axis of the yoke. It is better than before the vertical move, but there is still a nonuniformity and an apparent difference from zero in the middle of the solenoid.

At 48 A the differences from zero of Δx and Δy are comparable to the precision of one or two gauss. While paying careful attention to the load cell readings, the solenoid was ramped up to 96 A and then to 144 A, which is almost 60% of the nominal operating current. The corrsponding field maps are shown in Figs. 9 and 10. Note that the difference in the lobes near ± 45 cm in the top graph (see text inset in graph) are within the 1 G precision of the probe. On the bottom graph, the differences Δx and Δy from zero are now much clearer, about 8 G in 12.7 kG near the middle of the solenoid for 144 A. The values of Δx and Δy can be compared to the those used by the $\mathcal{TWIST}$ GEANT simulation from the two-dimensional (radially symmetric) field map. The values for $z = 0$ are shown in Fig. 11. If the fields are scaled (ignoring the saturation effects of the yoke), the 8 G difference is difficult to understand. However, Michael Barnes is in the process of calculating fields and forces in order to use the differences to estimate the coil misalignment.

In summary, there is still evidence from both the load cells and the field surveys that the solenoid axis is too low (displaced in the $-y$ direction) and also displaced to the $-x$ side. From the load cells, the move of -1.75 mm in z was perhaps too much, and today (October 10, 2001) it was moved by $+0.75$ mm in z.

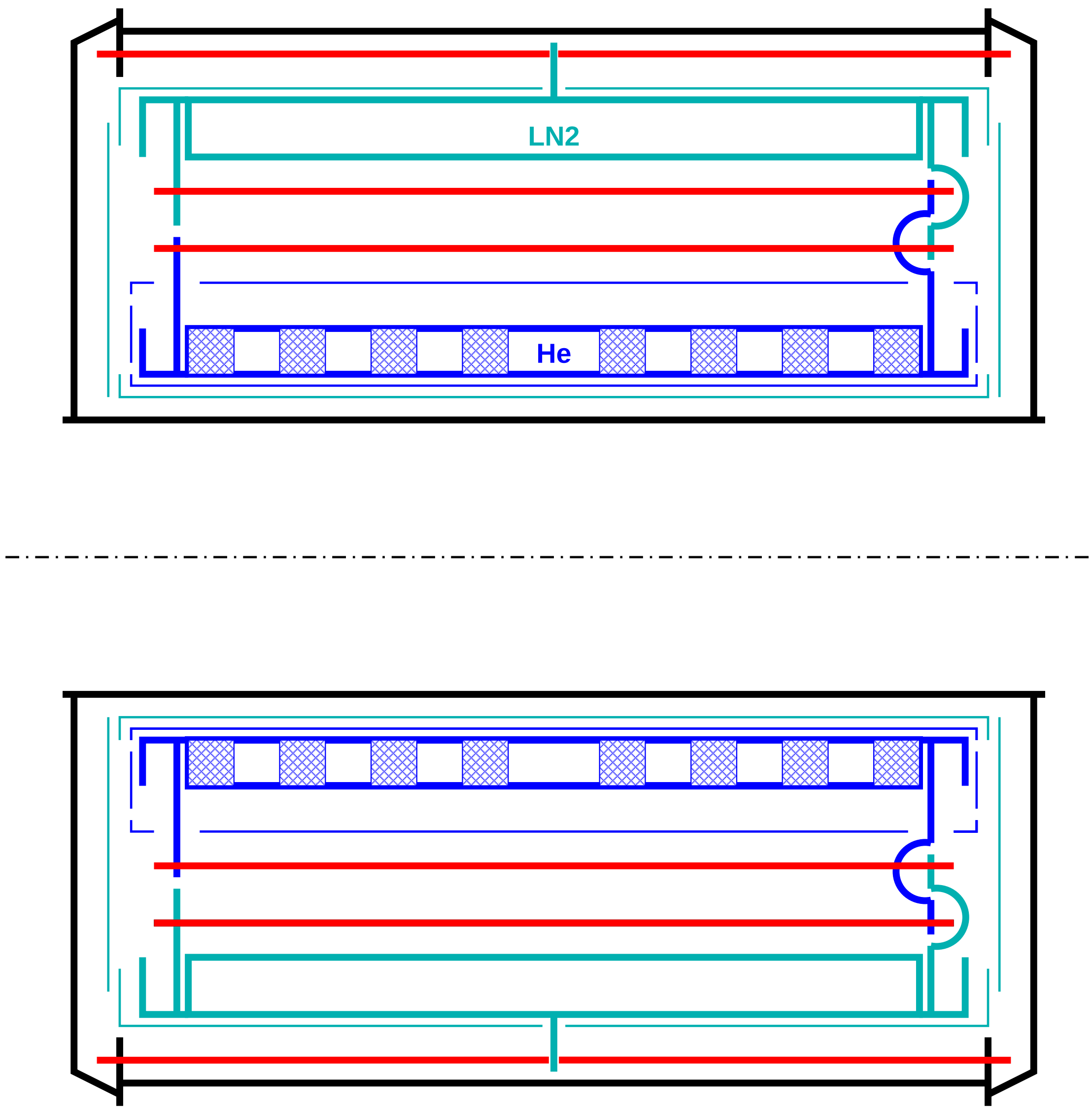
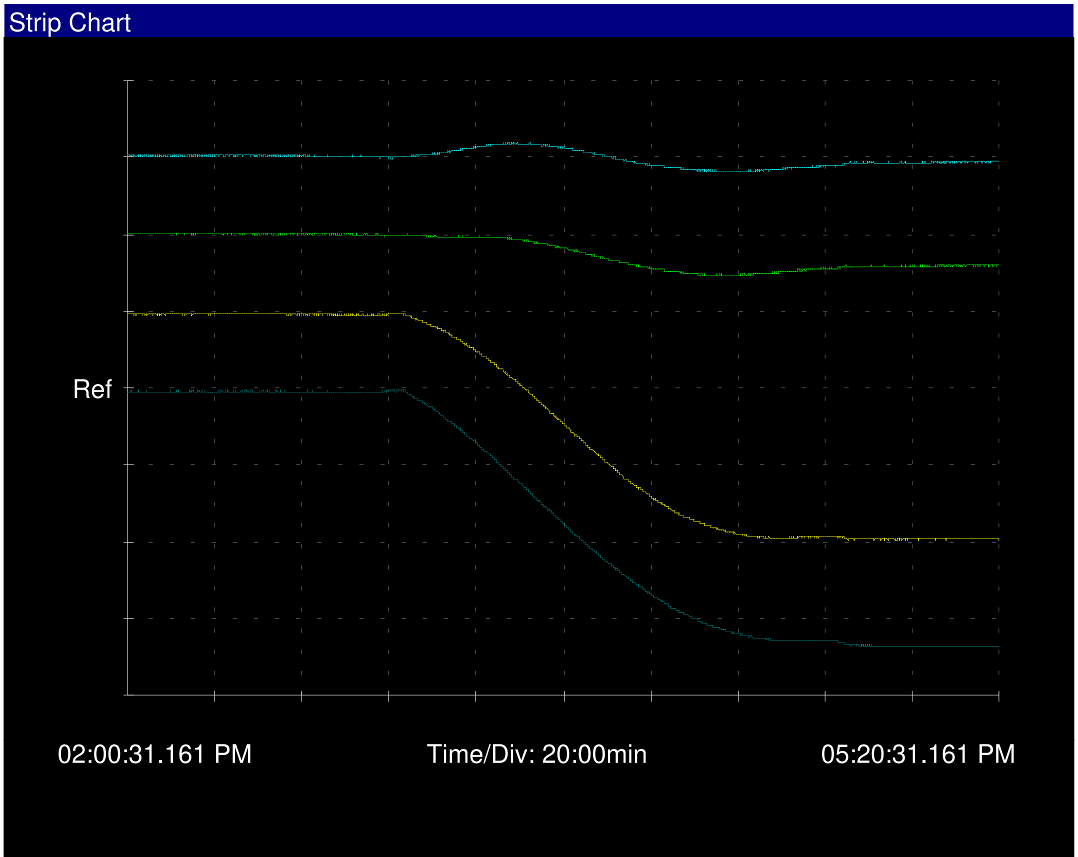


Figure 1: Schematic of support structure of solenoid in its vacuum vessel.



	Channel Name	Units/Div	Reference	Marker:	Marker:	
1	<105>	50.00 uVdc	641.1555 uVdc	Off	Off	
2	<106>	50.00 uVdc	565.5955 uVdc	Off	Off	
3	<107>	50.00 uVdc	1.388910 mVdc	Off	Off	
4	<108>	50.00 uVdc	865.0000 uVdc	Off	Off	

Time/Div 20:00min	y2:(Off)	t2:(Off)
	y1:(Off)	t1:(Off)
	Delta y	Delta t

Figure 2: Load cell voltages during field ramp down from 96 A to zero, for solenoid in its original nominal position. The top two traces are the downstream cells, the bottom two are the upstream cells.

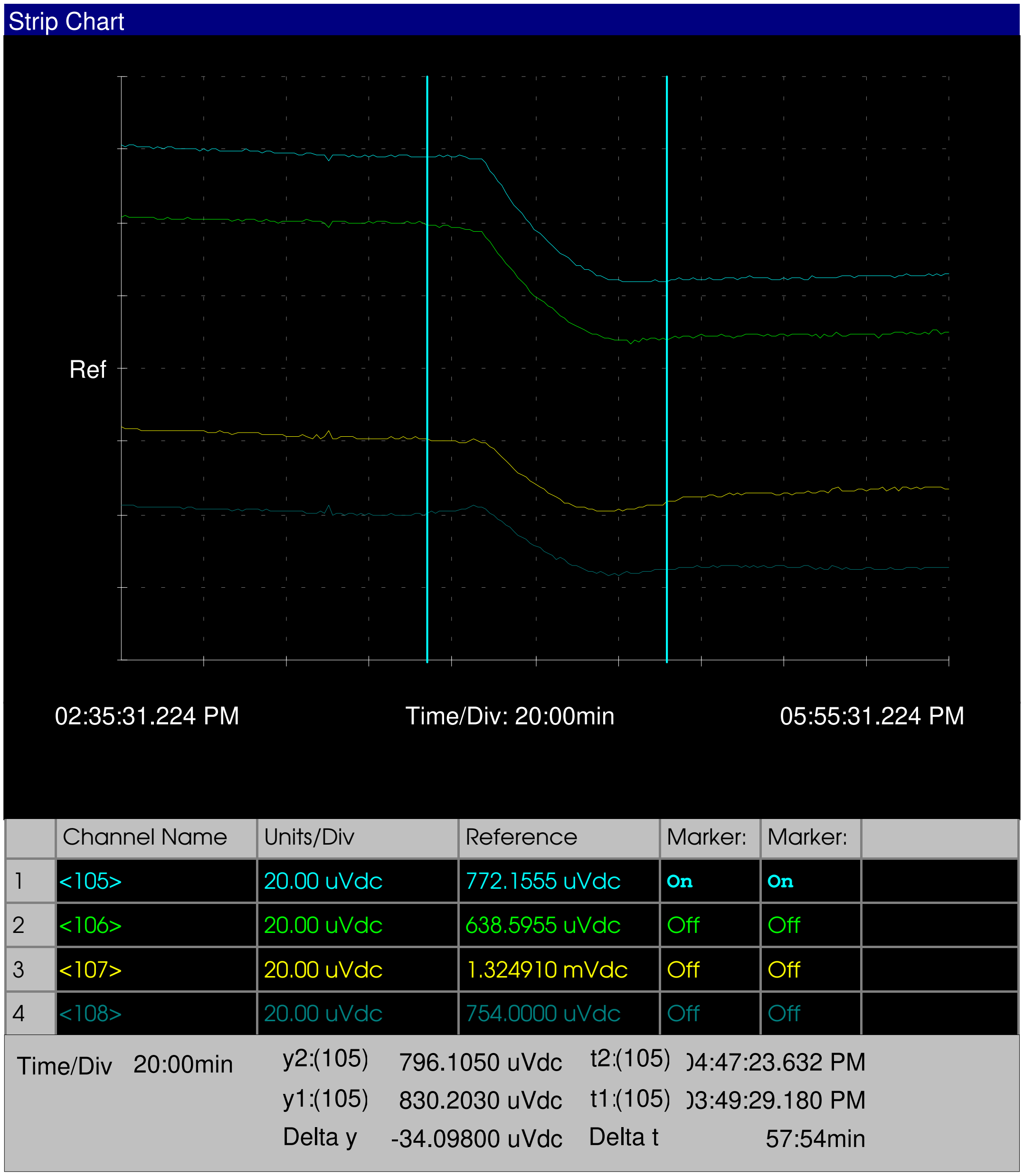


Figure 3: Load cell voltages during field ramp down from 48 A to zero, for solenoid in adjusted position (1.75 mm toward $-z$ (upstream). The top two traces are the downstream cells, the bottom two are the upstream cells.

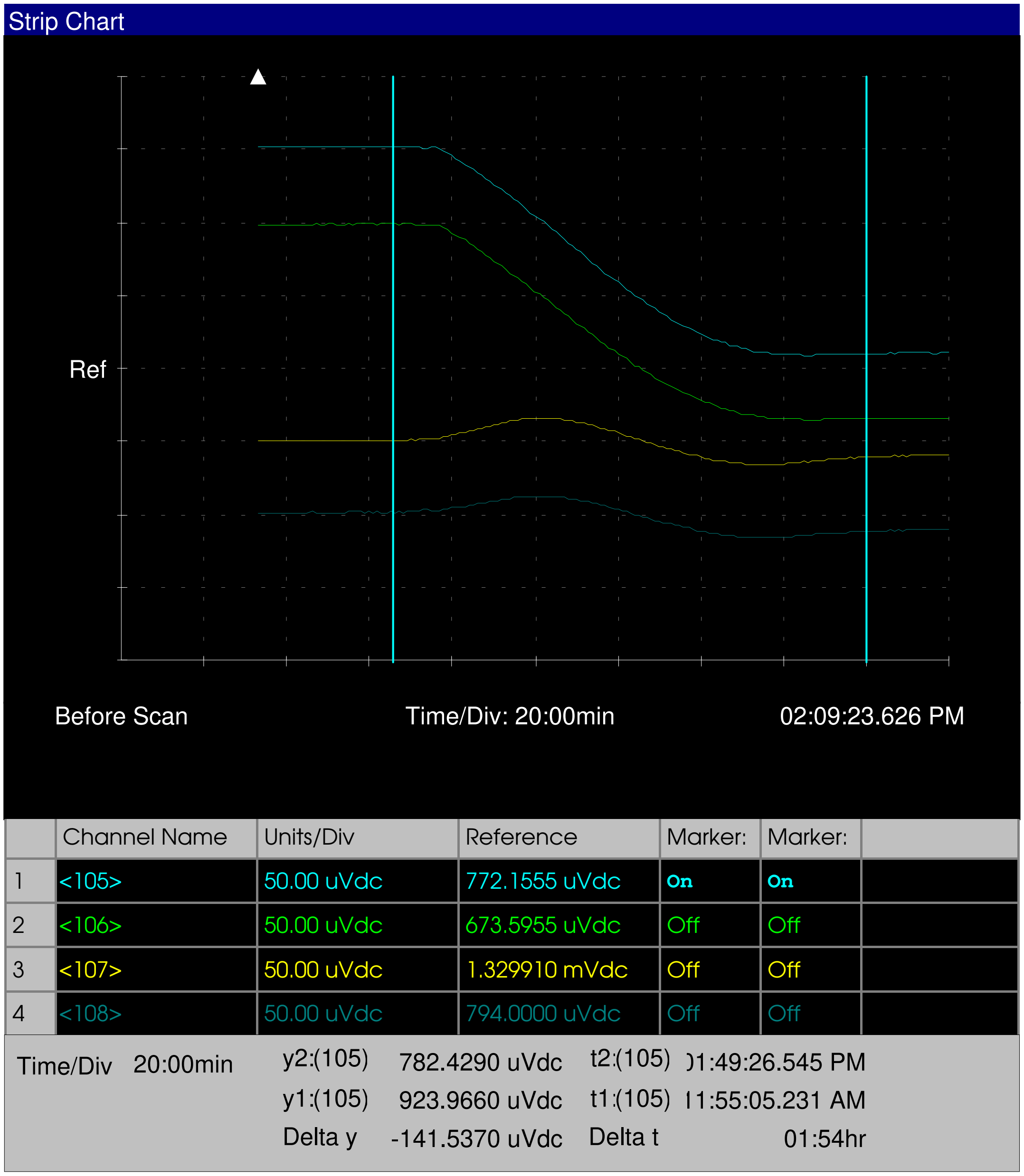


Figure 4: Load cell voltages during field ramp down from 96 A to zero, for solenoid in adjusted position (1.75 mm toward $-z$ (upstream), 4 mm toward $+y$ (up). The top two traces are the downstream cells, the bottom two are the upstream cells.

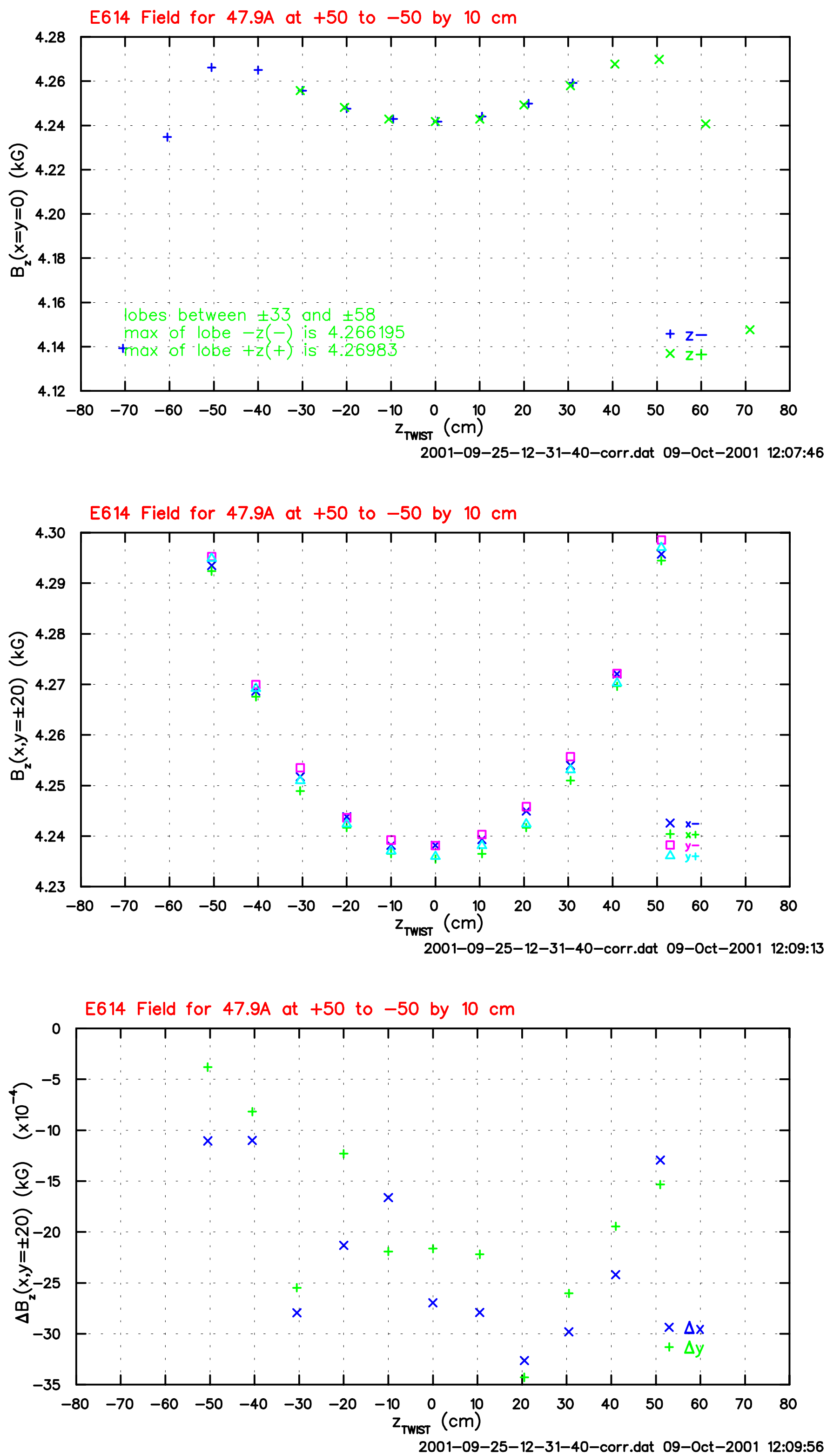


Figure 5: Original solenoid location, 48 A.

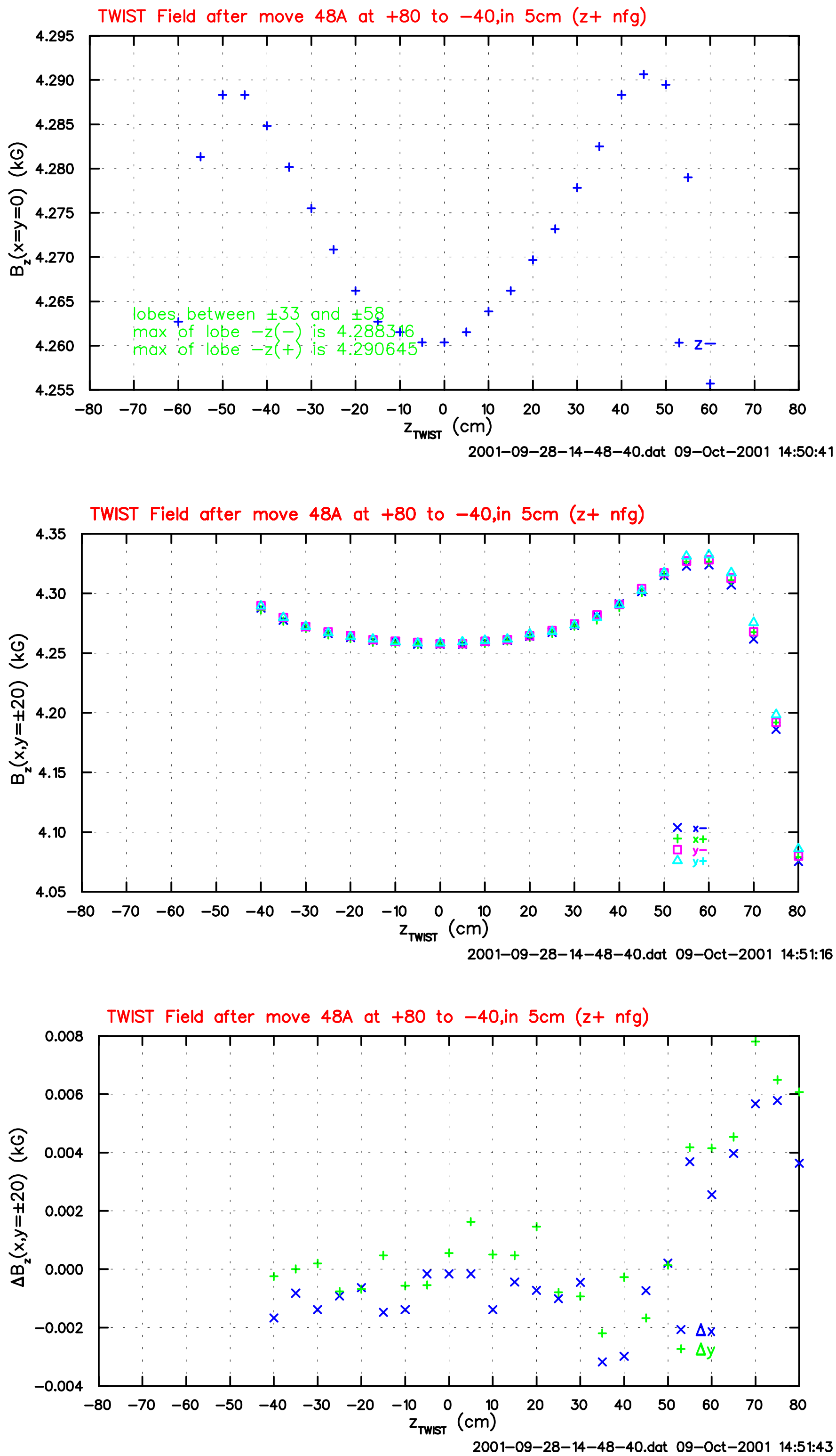


Figure 6: As previous figure, but solenoid moved in $-z$ direction by 1.75 mm.

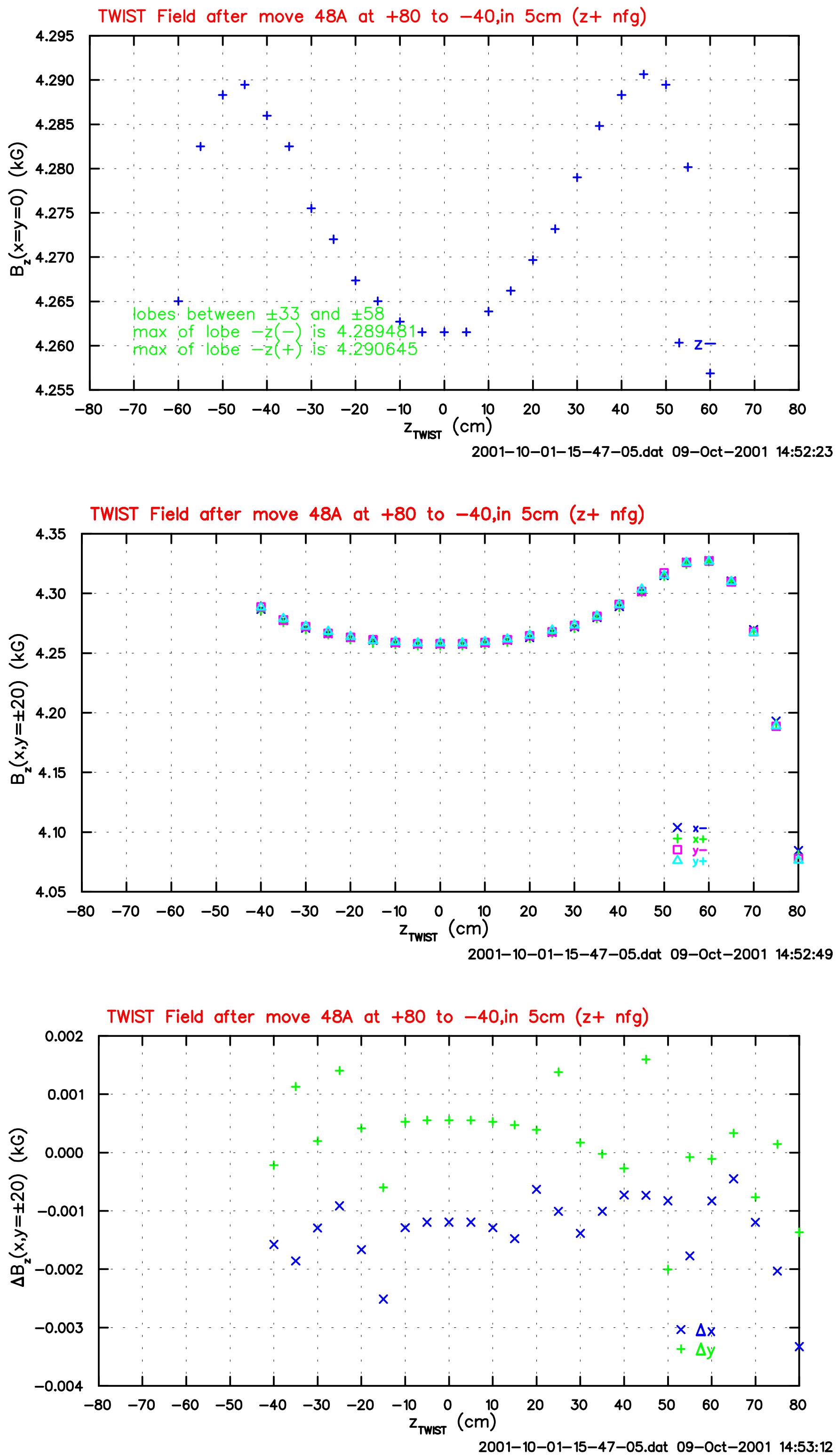
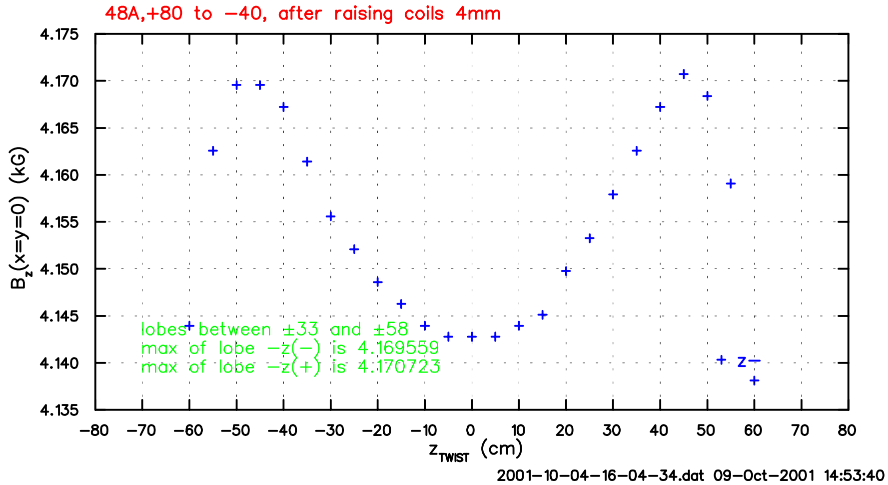
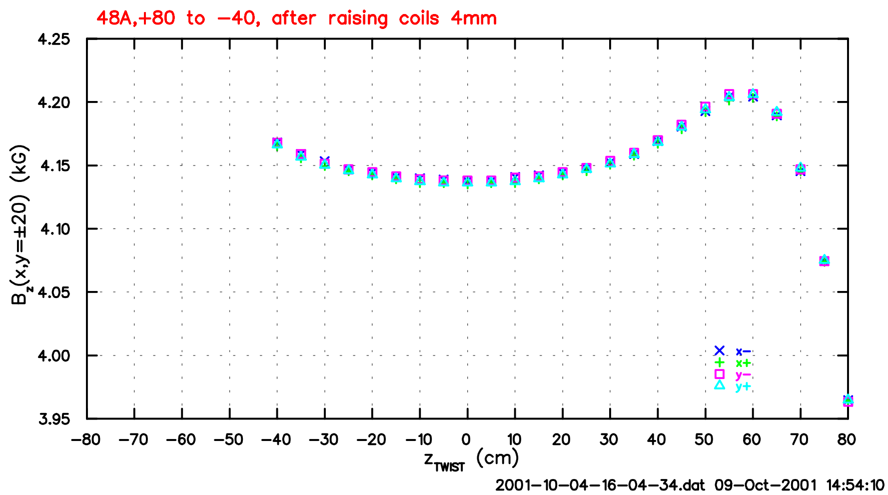


Figure 7: As previous figure, but probe trolley moved toward $-y$ by 6 mm.





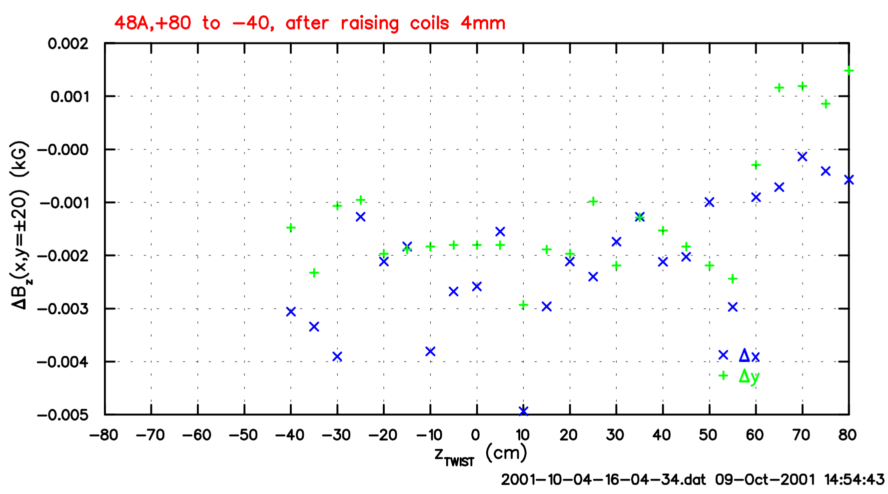


Figure 8: As previous figure, but solenoid moved in $+y$ direction by 4 mm, and trolley realigned with yoke axis.

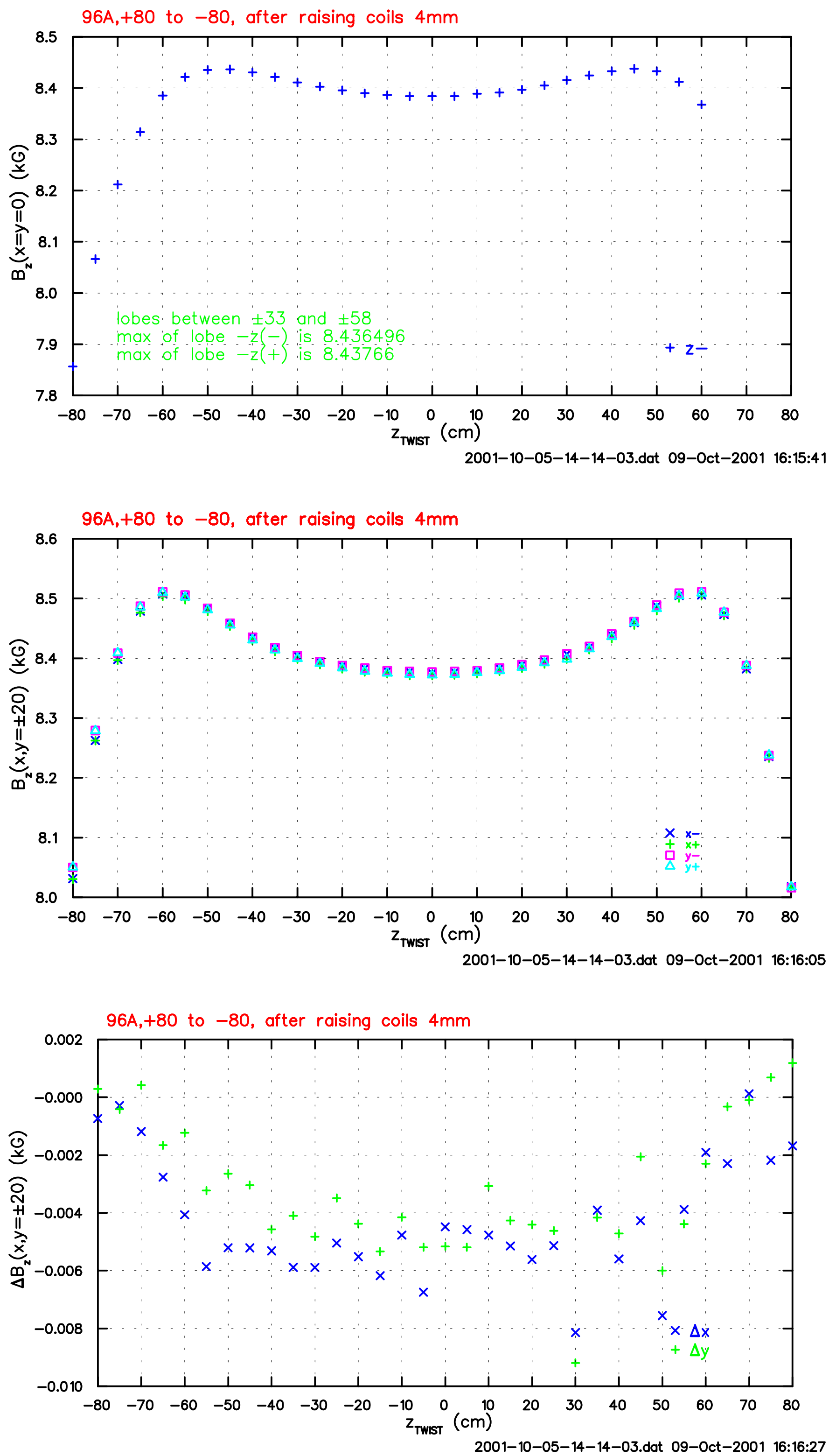


Figure 9: As previous figure, but at 96 A.

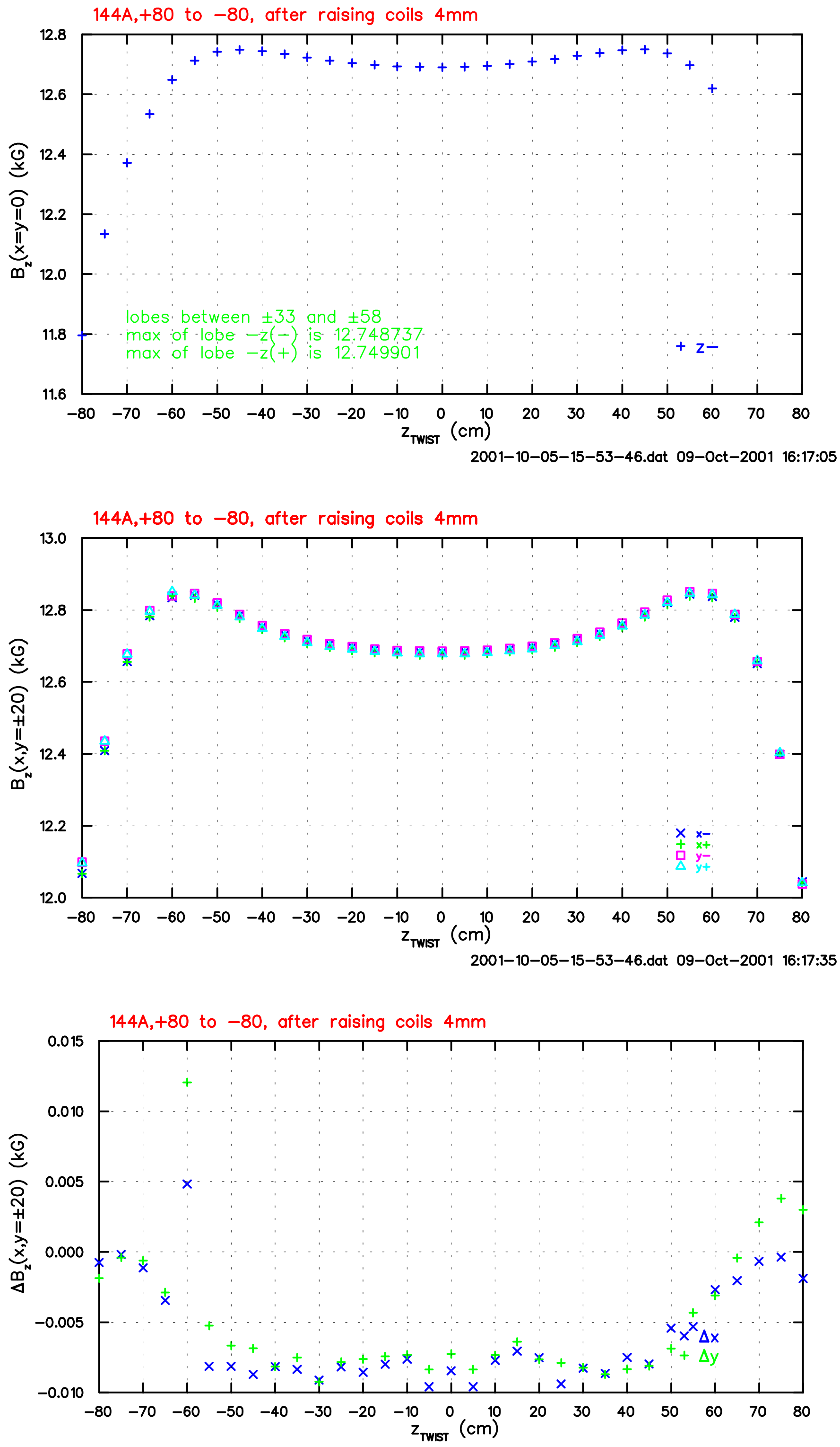


Figure 10: As previous figure, but at 144 A.

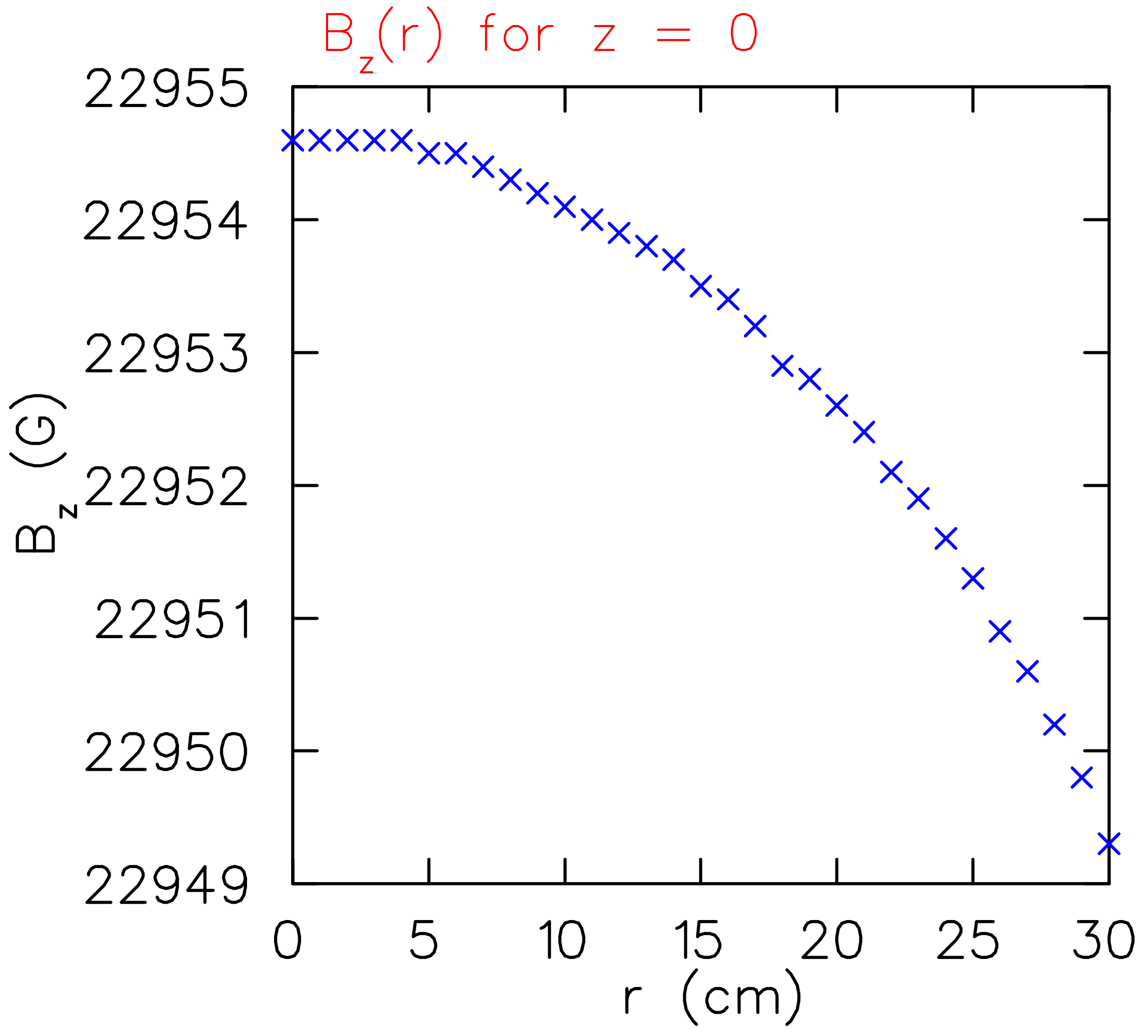


Figure 11: Dependence on r of the z component of the field calculated for the $\mathcal{TWIST}$ solenoid, for $z = 0$.