Fermilab

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TO: LOCAL MAGNET WATCHERS

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SUBJECT: SUMMARY OF FIELD ANGLE PROBE MEASUREMENTS ON 4-CM-APERTURE, 17 M LONG DIPOLE MAGNETS

This note summarizes the axial Field Angle Probe (FAP) measurements made on 4-cm-aperture, 17-m-long SSC dipole magnets DD0001 through DC0306. The FAP device is in use only at FNAL and consequently FAP data is available only for magnets that have been cryostatted or tested at FNAL.

Device

The FAP probe consists of a small permanent magnet mounted to a frame having an attached electrolytic bubble level sensor. The permanent magnet aligns itself with the field, and the angle of the frame (which rotates freely on jeweled gimbals) with respect to vertical is reported by the level sensor. A complete description of the probe can be found in reference 1. A sketch of the probe is shown in figure 1. The small size of the probe makes it ideal for spotting large local deviations in the rotation angle that might not be noticed if a large region were being averaged.

The data summarized have been taken over a period of ~5 years, and during this time this measurement system has undergone several improvements in hardware, software and measurement technique. To the extent that these developments influence the comparison of data, they will be specified in the discussion section.

Measurement Procedure:

Measurements are usually made before or after the cold mass is put into the cryostat at the Industrial Center Building (ICB) or before or after testing at the Magnet Test Facility (MTF). The FAP measurements are made warm (the FAP is too large to fit into the warm bore tube - measurements are made with the latter removed) at 10 Amps current in measurements earlier than DD0028 and 9 Amps current in more recent measurements. The lower current is a limitation of a recently acquired power supply, but it has been verified using the reference magnet (see below) that equally sensitive results are obtained at this current. The probe is positioned using a set of interconnecting aluminum rods

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* Also MD-TA-203

which connect to it, and data points are taken every 3" along the magnet using the rule marks on the rods. These data points constitute a sweep and are stored in a file. Two sweeps are made, one with the probe pointing toward the lead end, and one with the probe pointing toward the return. These files are later averaged (to remove the zero offset from the probe calibration and provide a verification of the reproducibility of the data) to determine the orientation of the dipole with respect to vertical. Note that the FAP position coordinate uses the location of the center post in the cryostat as its 'zero' with the lead end of the magnet being positive (this location may be slightly different than the mole center coordinate which uses the "magnetic center" of the magnet). When viewing the magnet from the cryogenic lead end, the rotation angle is defined positive for counter-clockwise rotations from the vertical. The probe is typically calibrated before and after each set of sweeps (using a reference magnet whose field angle with respect to vertical can be precisely adjusted over the entire active range of the FAP) to determine the probe output at a given angle. The calibration is then applied to the data of the given measurement to determine field angle.

Data

There exists two specifications for field angle orientation[2]: 1) that the average dipole field angle must be vertical to within 1 mrad, and 2) that local dipole angle, Φ, variation must satisfy $\int \Phi \, dz$ (integrated beginning at one end to any position z along the magnet's length) less than 10 mrad-m.

Determination of the average angle with respect to vertical always depends on how the magnet is mounted for the FAP measurement. Consequently, if the average field angle is accurately determined relative to external fiducials, specification 1) can always be achieved when the magnet is mounted in the tunnel. Since the measurements we are reporting have not necessarily been made with the magnet fiducials surveyed (i.e. their orientation with respect to vertical is not known for most of the measurements), offsets in the field angle with respect to vertical are introduced depending on how the magnet is mounted for measurement. The measurement data of this note include plots of the two individual measurement sweeps (to provide information on reproducibility), and a plot of the dipole angle with respect to vertical (the data of which may contain such an offset from mounting). The dashed line on the dipole angle plot indicates the average dipole angle, which ideally would be zero if the magnet was perfectly aligned. The average is calculated as:

$$\Phi_{ave} = \frac{\sum_{i=1}^{n} \Phi_i}{n}$$

The maximum angle relative to this average as well as the standard deviation have been tabulated to offer comparison of the scatter in field angle for a given magnet (see Summary Table).

The value which must satisfy specification 2) is determined by calculating

$$\int_{LE=0}^{z} (\Phi(z) - \Phi_{ave})\, dz$$

at each z position using the trapezoid rule. Note that LE=0 indicates that the integration is started from the lead end of the magnet and that the integral is calculated relative to the average field angle - i.e. it assumes that the average field angle will be perfectly aligned to vertical. The integration results are also included in the Summary Table and in the plots.

Note that the field angle and integral angle data are examined from -8.15 to +8.15 meters in order to avoid including the effects of the ends (the coil straight section length unaffected by the ends is ~16.3 meters as determined from Hall probe measurements).

Discussion

1) The FAP measurement data files are stored in the FNAL MDTF00::USR$ROOT1:[FAP] account.

2) As can be seen from the sample plot of probe calibration vs. reference magnet angle (figure 2), the FAP has a region of roughly ±9 mrad in which the probe is properly sensitive after which it begins to approach a "saturation" value. In fact, the amplifier limits the probe range for measured angle (which may also include an offset from vertical due to the mounting of the magnet) to ~±10 mrad, and if a position in the magnet has a measured twist larger than this, a saturated value will result. A saturated value may be a 'real' effect if the dipole angle plus offset is large, or these may be caused by errors in operation (e.g. the probe being upside-down or way off the proper orientation). These conditions may be evident if one of the two individual measurement sweeps shows a few points having a saturated value where the other sweep (and previous sweeps) do not. The data presented have been screened so as to eliminate such 'bad' points in obvious cases where they are known to occur , but such points have not been eliminated from the data where their large number compromise the value of the measurement. Also, by using data from the straight sections (as described above), most saturated data caused by end effects are removed (these may be seen in the individual sweep data, however). In cases where there are reproducible saturated data in the straight section near the end, therefore, the data are indicating an actual large field angle (e.g. in DD0010).

Some of the data included in this note show large regions of saturation, sometimes actual (e.g. see the measurements for magnets DD000Z and DD0012), sometimes due to operator error (e.g. compare the measurements for magnet DC0306, the last of which has such errors), and should be regarded accordingly.

3) The bubble level sensor output is brought out via #51 copper wire leads (see figure 1). Although the jeweled gimbals allow the frame to rotate and align the probe magnet to the field, it was found that if the probe frame is not aligned to within ±5 degrees, the #51 copper wires transfer a torque which causes error in the data. Thus it is

essential during each data point that the probe be aligned to within ±5 degrees. The operators are expected to maintain this alignment which can be made by eye. In cases where this alignment is not maintained, incorrect or saturated values (as described above) may result.

4) If the positioning of the probe is not the same for each of the two measurement sweeps, the average of the sweeps which determines the dipole angle at that point will have an error. Measurements before January 1988 did not include starting the probe at the same position for both individual measurement sweeps and such measurements may have individual sweeps which differ in probe position by as much as 1.5". After this date the probe positioning is typically better than .5" (subject to operator error or error in determination of the distance from the positioning fiducials to the magnet center).

Also, among the multiple measurements on a given magnet, systematic shifts in coordinate system (e.g. if a different operator is systematically aligning the positioning marks differently) may add a source of variations among the measurements.

5) The magnet inside the FAP tends to oscillate as it settles in to its final alignment with the dipole field. The original system design helped eliminate some large oscillations by means of weights and counterweights. Still, in measurements before February 1990, operators had to wait for the oscillations to die away before taking a data point. After February 1990, the FAP system was upgraded so that the eventual alignment of the FAP magnet in the dipole field could be determined from the oscillations themselves, thereby making the measurement much faster and reducing concerns about friction. This upgrade, besides reducing the waiting time by a factor of ~5, includes prompts to the users for position and automatically records in a data base. Operator error during data acquisition and during data transfer to computer (which used to be done by hand!) is consequently minimized. This new system was tested extensively and was shown to be as accurate with fewer operator errors.

6) It was observed that measurement 870912 on magnet DD000Z had large differences in the individual sweeps. The cause of this was determined to be degradation in a joint which caused parasitic oscillations in the probe electronics, and this was repaired before the subsequent measurement.

7) If the probe offset changes during a measurement (e.g. if the probe is dropped), the measurement sweep which includes the offset will cause the calculated dipole angle to be in error. Since this was realized in January, 1988, calibrations have been performed before <u>and</u> after each pair of measurement sweeps. This assures that the calibration and offset have not been changed during the measurement procedure. If there is an offset which does not change, there will be no effect on the measurement. An example of this is the measurements on magnet DD0016 (and the first of DD0017) in which there was an offset in <u>both</u> individual sweeps (due to a problem with a counterweight). Though the individual sweeps were affected, the dipole angle (as determined by the average) was not.

8) The reproducibility of the FAP has been tested at various times (e.g. when the upgrade in 5 was implemented) and has always been found to be very good when the measurements are executed properly (especially after magnet DD0010 when the upgrades in 4 and 5 were implemented). For magnets in this note having more than one measurement, one can compare the differences between the various dipole angle results directly. The three measurements for DD0027 are a case in point. The magnet 'signature' is very distinct in each measurement, though there are some small local discrepancies, perhaps arising from the error sources mentioned particularly in 3 and 4 above, which will be characterized by σ_ε as discussed below. Note that small local changes do seem to actually occur (e.g. one can compare the individual sweeps near the center on the measurements of magnet DC0202).

Since there are two sweeps for each measurement, one way in which the reproducibility can be judged is by determining at each position the difference between the individual sweep data and the dipole angle as determined by their average. That is we calculate at each position

$$\sqrt{\frac{(v_R - v_a)^2 + (-v_L - v_a)^2}{2}} = \frac{|v_R + v_L|}{2}$$

(where v_R signifies the data taken during the 'return' sweep, v_L signifies the data taken during the 'lead' sweep, and v_a is the average of these measurements given by $\frac{v_R - v_L}{2}$)

This is just the offset at each position plus any error that may be present in either sweep measurement. If we measure this quantity at each sweep position, then over the length of the magnet, an average 'offset' with a standard deviation, σ, results. Since any real offset is expected to remain constant during the measurement (as mentioned in 7 above) this will not have an influence on the average dipole angle determined. This also means that the deviation in offset, σ, is caused by the variability in measurement, and thus it provides an estimate of uncertainty for any given point in the measurement. This estimate of uncertainty in the Φ_i will be designated σ_ε and has been included in the summary table for each measurement. For measurements in which no large (e.g. saturation) errors occur a typical values is

$$\sigma_\varepsilon = \sim .4 \text{ mrad}$$

Furthermore, since Φ_{Ave} is defined as

$$\Phi_{ave} = \frac{\sum_{i=1}^{n} \Phi_i}{n}$$

where $\Phi_i = \phi_i + \varepsilon_i$ (ϕ_i is the actual dipole angle at each point and ε_i is the error in the dipole angle at a given point), $\Phi_{Ave} = \phi_{Ave} + \varepsilon_{Ave}$. Since we do not know the true offset we cannot determine ε_{Ave}. But since we do know σ_ε (which, as mentioned above, is the standard deviation of ε_{Ave}), we know how much ε_{Ave} might change and thus know how much Φ_{Ave} might change. The uncertainty in ε_{Ave} is given by

$$\frac{\sigma_\varepsilon}{\sqrt{n}}$$

where n is approximately 200 for each measurement. Thus a typical reproducibility for the average of each measurement (based on the errors at each sweep position) is

$$\frac{.4}{\sqrt{200}} = \sim.03 \text{ mrad.}$$

A rough value for the reproducibility in the extremum value of the integral field based on measurement uncertainties can be estimated as follows. If we assume that for multiple measurements of the same magnet, the dipole angle of a given measurement shows no regions of large variation with respect to the others, then the differences in extrema of the integrals are caused by the small relative variations in that portion of the magnet which is above (below) average. Since there are no large local variations, this portion is approximately half of the length of the magnet. If we multiply the average uncertainty (~.03 mrad) by half the magnet's length (~8 meters) a rough reproducibility estimate in the extremum of $\int \Phi \, dz$ is given as .25 mrad-meters. This seems to be about right when the above assumption is true. Going back to DD0027 as an example, the first two measurements show a difference in extremum of the integral of less than .2 mrad-m. The extremum of the third measurement differs by almost 3 mrad-m but has a region from +3 to +5 meters whose measured value has changed (perhaps as a result of the cold test?). Typically, in the data summarized here, the overall variation in the measured extremum of $\int \Phi \, dz$, which can include real changes in the magnet field angle as well as the errors occurring locally within a measurement, is seen to be 1-2 mrad-meters for a given magnet.

9) Note that many of the BNL "DD-series" magnets (which were all collared with 1-meter length presses) exceed the 10 mrad-meter specification, whereas none of the "DC300-series" magnets (built at FNAL using a full length collaring press) excede this specification.

Acknowledgements

We wish to acknowledge the contributions of M. Bleadon, A. Desportes, Ed E. Schmidt, and D. Sorenson.

References:

1) M. Kuchnir and Ed. E. Schmidt, Measurements of Magnetic Field Alignment, IEEE Trans. Magn. 24, 950 (1988), also TM1493, November 6, 1987 Fermilab, also SSC-N-435.

2) 15 Meter Collider Dipole Magnet Prime Item Developement Specification, Revision 1, p. 14, October 25, 1990.

FAP Measurements Summary Table

Magnet	File Date	Φ Extremum (mrad)	Φ standard deviation (mrad)	Est. uncert. of Φ_i(1) (mrad)	$\int \Phi\, dz$ Extremum (mrad - m)	Description
DD0001	870120	8.72	2.72	0.44	9.16	Meas. aft cold test at MTF
DD0002	861112	6.36	2.40	0.94	6.71	Meas. at ICB
DD000X	870413	-9.57	3.52	0.51	10.34	Meas. out of cryostat at ICB
DD000X	870421	-8.97	3.78	0.73	11.49	Meas. out of cryostat at ICB
DD000X	870513	-10.14	3.94	0.65	11.61	Meas. in cryostat at ICB
DD000X	880319	-8.45	3.48	0.59	10.40	Meas. aft cold test at MTF
DD000Z	870912	8.52	4.77	1.66	-26.25	Meas. bfr cold test at MTF
DD000Z	871003	10.26	6.17	0.61	-34.74	Meas. in cryostat
DD0010	871212	11.22	4.52	0.85	21.38	Meas. in cryostat at MTF
DD0010	880602	10.40	3.72	0.28	15.10	Meas. aft cold test at MTF
DDA010	890314	-6.31	2.32	0.34	-12.19	Meas. out of cryostat at ICB
DDA010	890408	-6.69	2.35	0.33	-12.16	Meas. in cryostat at ICB
DD0011	880531	-10.06	4.12	0.79	-25.49	Meas. out of cryostat at ICB
DD0011	880625	9.57	3.94	0.35	-23.96	Meas. bfr cold test at MTF
DD0012	880122	-11.61	4.13	0.66	14.11	Meas. out of cryostat at ICB
DD0012	880203	-10.33	4.48	0.41	14.23	Meas. bfr cold test at MTF
DD0012	880211	-10.12	4.43	0.31	12.48	Meas. bfr cold test at MTF
DD0013	880708	-8.30	2.96	0.32	12.01	Meas. out of cryostat at ICB
DD0013	880909	-8.50	2.85	0.34	11.94	Meas. bfr cold test at MTF
DD0014	880302	-10.21	3.06	0.43	-10.97	Meas. out of cryostat at ICB
DD0014	880527	-7.89	2.66	1.00	-10.34	Meas. bfr cold test at MTF
DD0015	880910	-6.20	2.79	0.27	-16.97	Meas. out of cryostat at ICB
DD0015	880928	-5.84	2.69	0.26	-16.44	Meas. bfr cold test at MTF
DD0016	881230	5.53	2.05	0.28	-3.84	Meas. out of cryostat at ICB
DD0016	890119	-5.28	2.09	0.36	-4.09	Meas. bfr cold test at MTF
DD0017	890117	8.00	2.05	0.45	8.03	Meas. out of cryostat at ICB
DD0017	890203	7.56	2.26	0.46	9.55	Meas. bfr cold test at MTF
DD0017	890927	9.19	2.22	0.56	8.64	Meas. aft cold test at MTF
DD0018	890302	-8.87	2.89	0.73	16.44	Meas. out of cryostat at ICB
DD0018	890721	-11.43	3.24	0.43	17.62	Meas aft test at MTF
DD0019	890812	-5.22	2.16	0.56	8.63	Meas. out of cryostat at ICB
DD0019	890828	5.22	2.01	0.37	7.99	Meas. bfr test at MTF
DD0019	900209	4.88	1.84	0.35	7.06	Meas. bfr removal at MTF
DD0026	890911	-7.04	2.41	0.27	14.26	Meas. out of cryostat at ICB
DD0026	891010	-6.51	2.43	0.38	15.01	Meas. bfr test at MTF
DD0027	900208	-6.74	2.43	0.72	14.69	Meas. at ICB
DD0027	900314	-7.10	2.51	0.29	14.55	Meas. bfr cold test at MTF
DD0027	901011	-6.30	2.18	0.31	11.82	Meas. aft cold test at MTF

(continued)

FAP Measurements Summary (continued)

DD0028	900423	-8.14	3.14	0.34	12.68	Meas. out of cryostat at ICB
DD0028	900730	-7.71	3.33	0.59	14.09	Meas. at ICB
DD0028	900928	8.74	3.22	0.34	12.14	Meas. bfr cold test at MTF
DD0028	901205	-6.33	2.87	0.45	11.17	Meas. aft cold test at MTF
DC0202	901102	8.31	2.16	0.34	-8.95	Meas. out of cryostat at ICB
DC0202	901210	7.13	2.26	0.29	-9.88	Meas. in cryostat at ICB
DC0301	901004	-4.81	1.21	0.39	-2.24	Meas. at ICB
DC0304	910221	4.32	1.35	0.37	-5.74	Meas. at ICB
DC0304	910311	-3.44	1.11	0.44	-3.68	Meas. bfr cold test at MTF
DC0304	910424	-3.26	1.08	0.29	-4.34	Meas. aft cold test at MTF
DC0306	910410	4.34	1.40	0.43	-4.79	Meas. at ICB
DC0306	910423	5.78	1.66	0.49	-5.22	Meas. bfr cold test at MTF
DC0306	910627	4.29	1.65	1.33	-6.14	Meas. aft cold test at MTF

Notes:

1) The estimated uncertainty of Φ_i is defined in 8) of the Discussion section in the text.

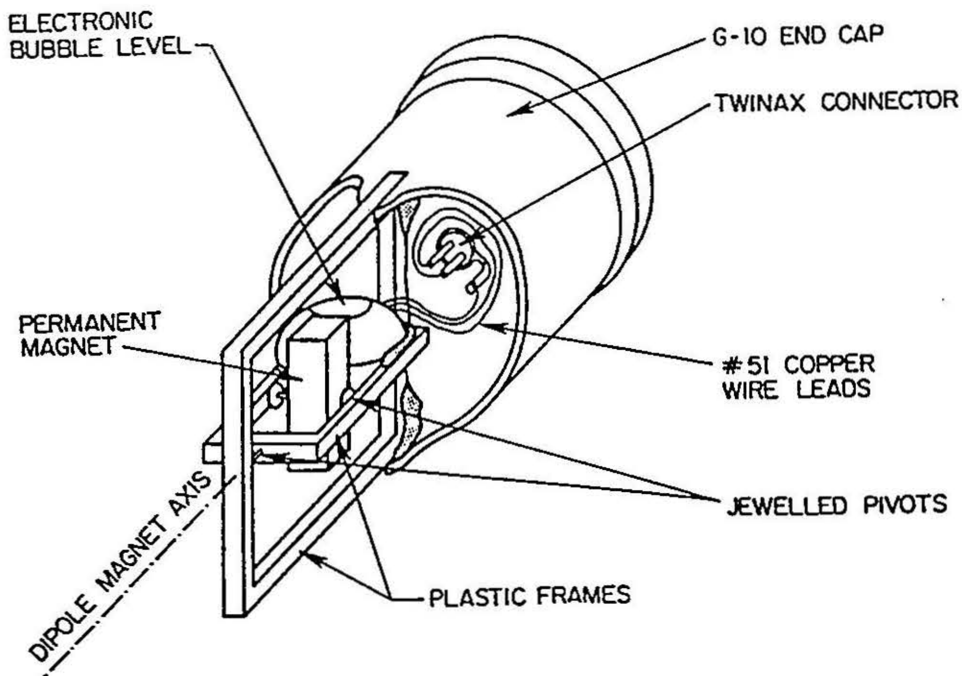
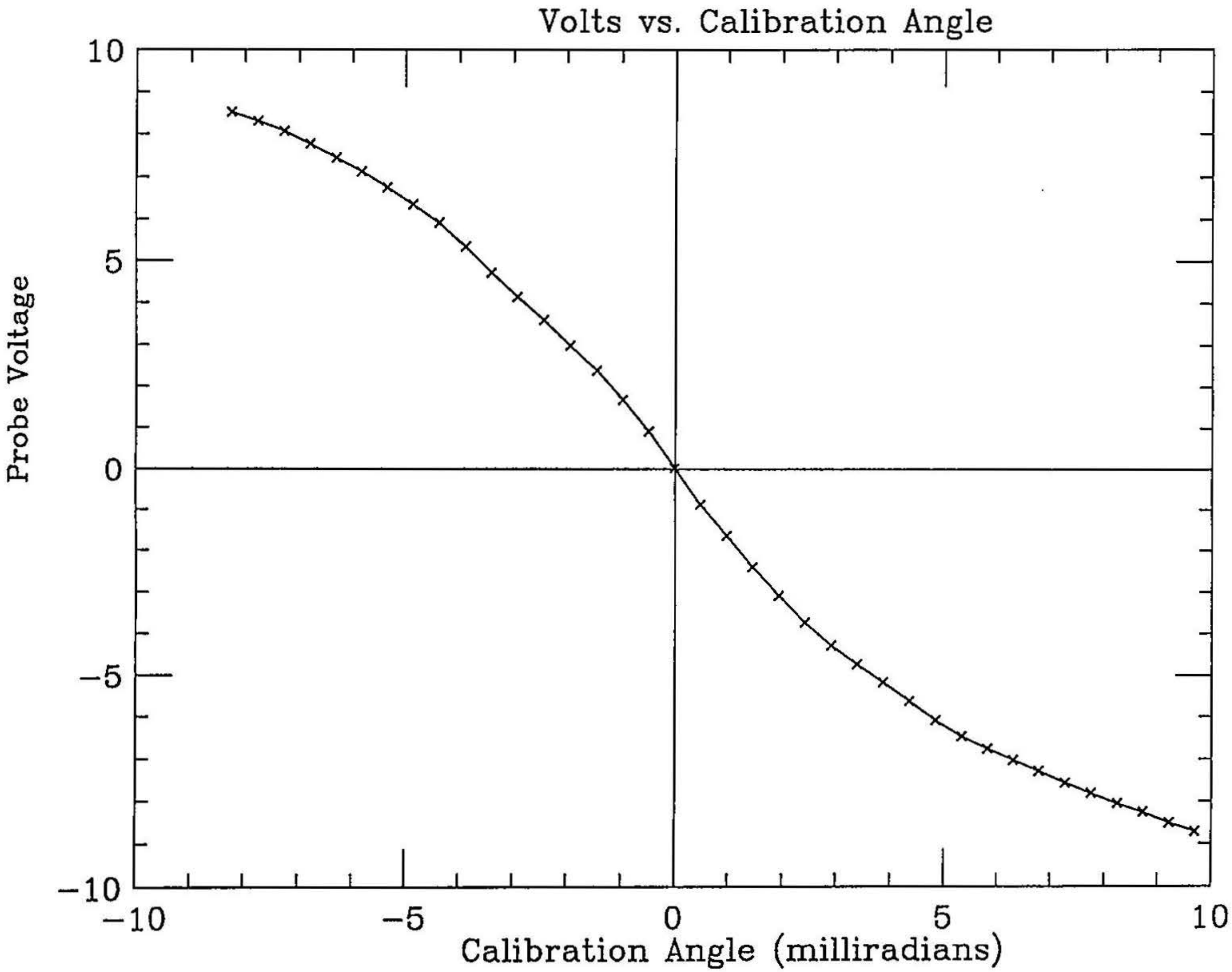


Fig. 1. Probe schematic



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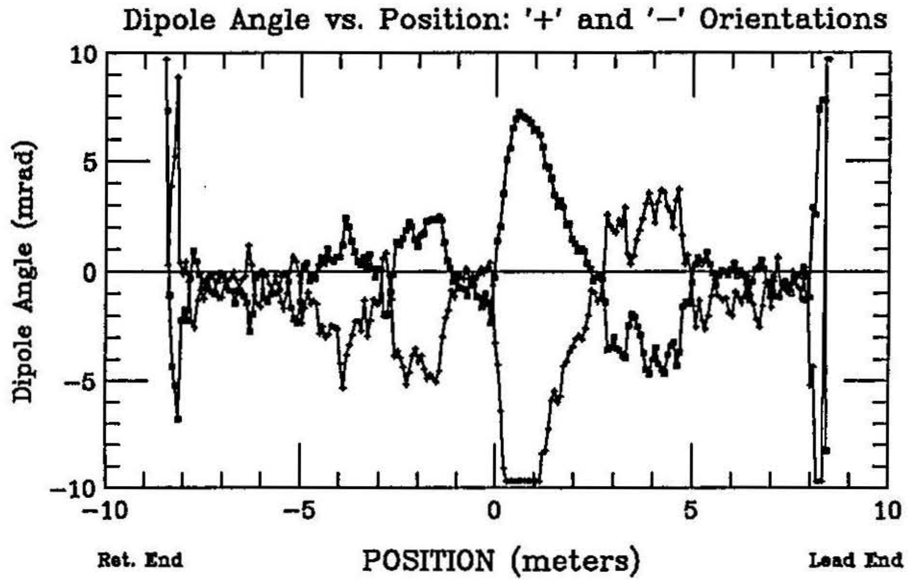
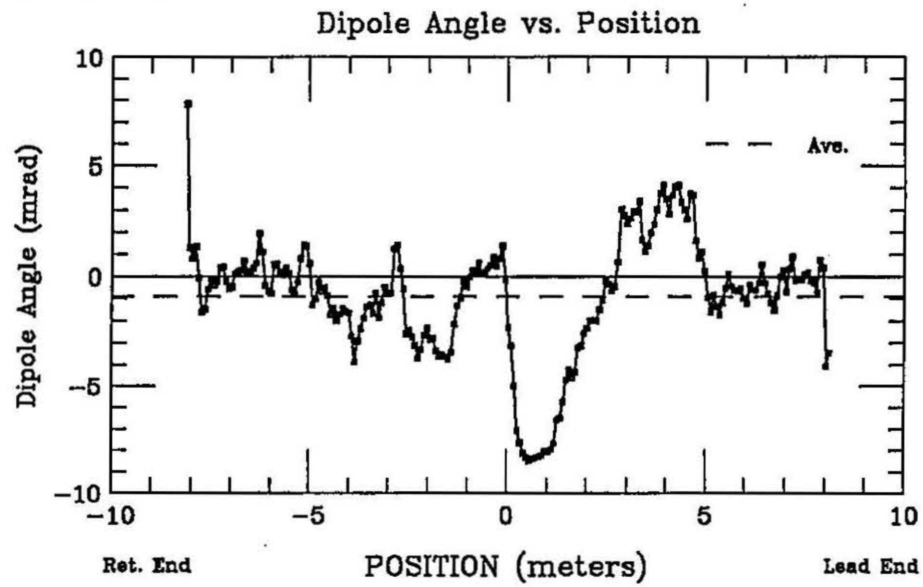
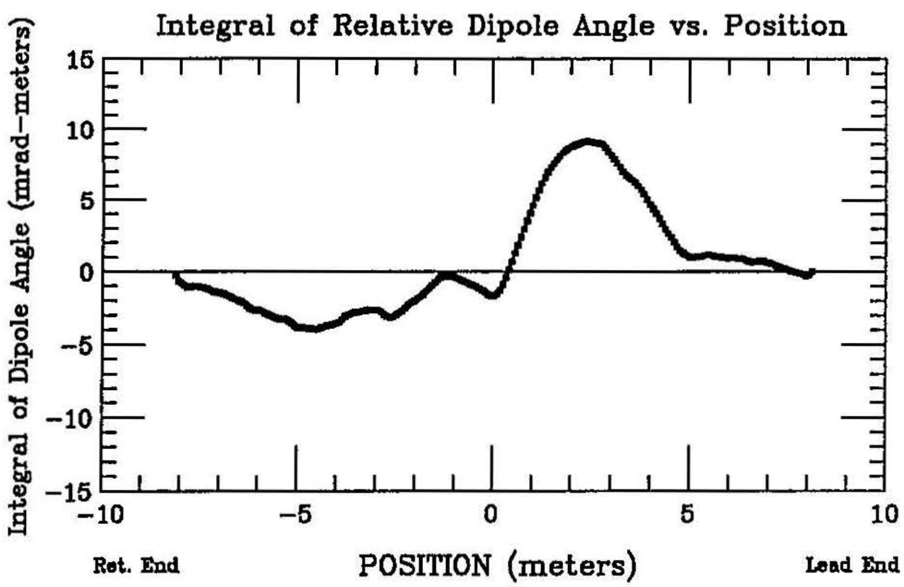
DC0304 calibration measurement

Fig. 2

DD0001 File 870120







Angle Extrema = 8.72 mrad
(Relative to Average)

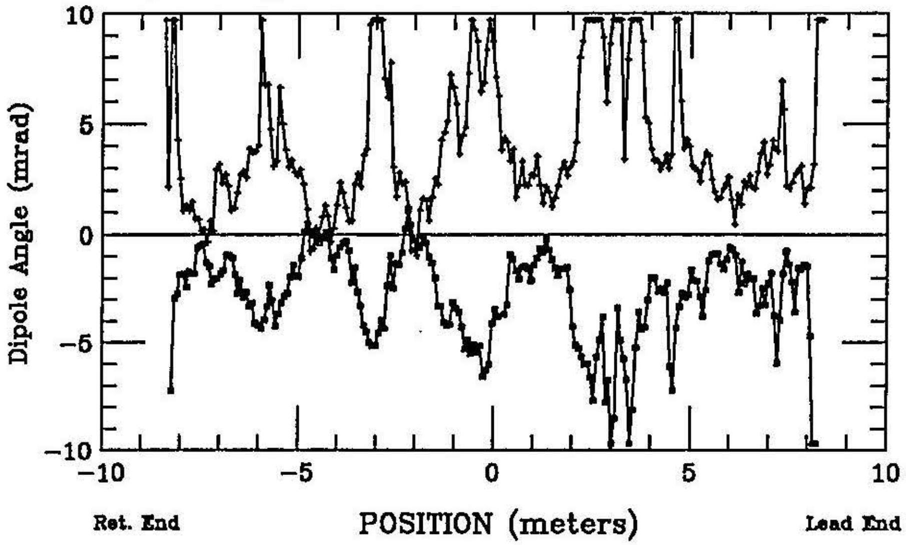
Angle S. Dev. = 2.72 mrad

Integral Extrema = 9.16 mrad−m

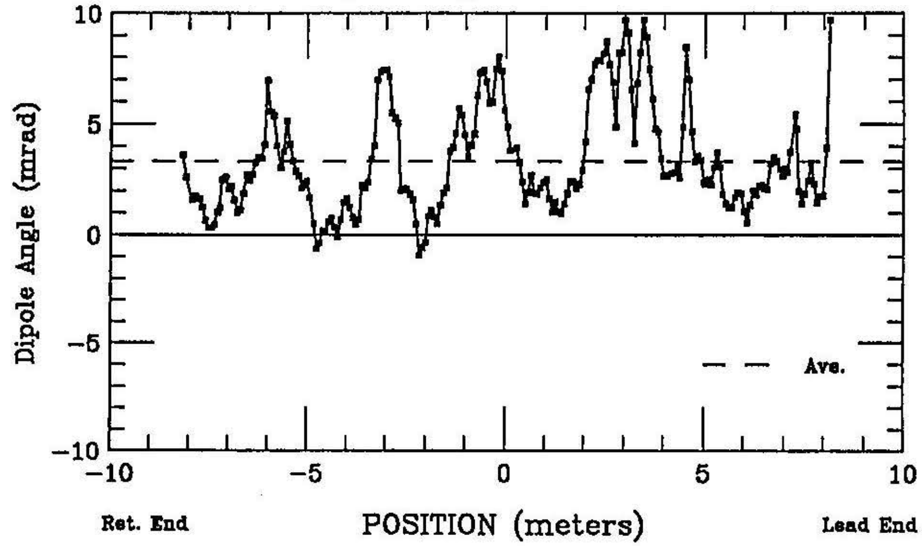
Measurement after Test at MTF

DD0002 File 861112

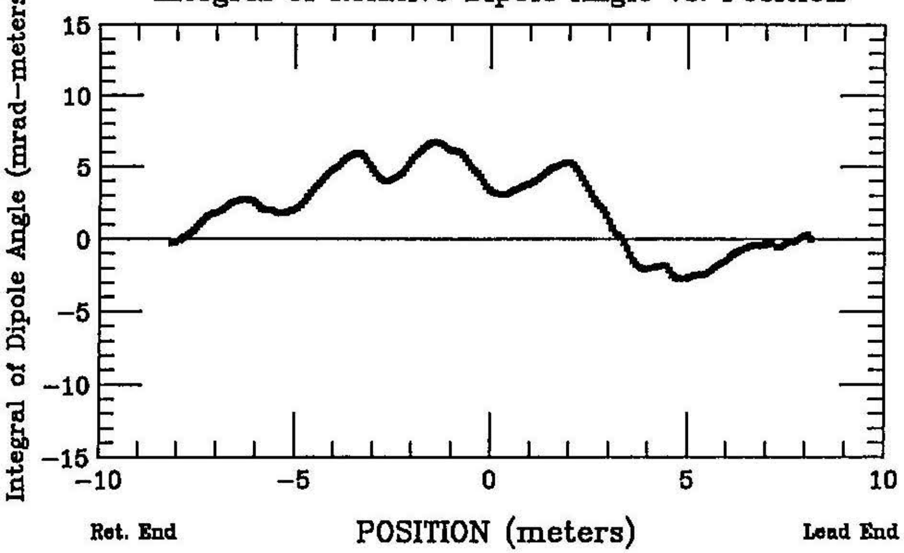
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



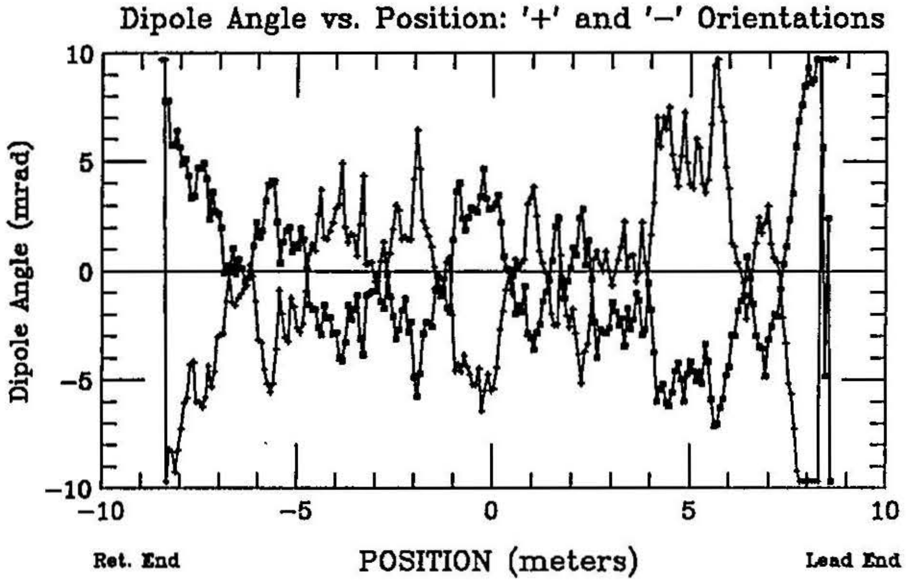
Angle Extrema = 6.36 mrad
(Relative to Average)

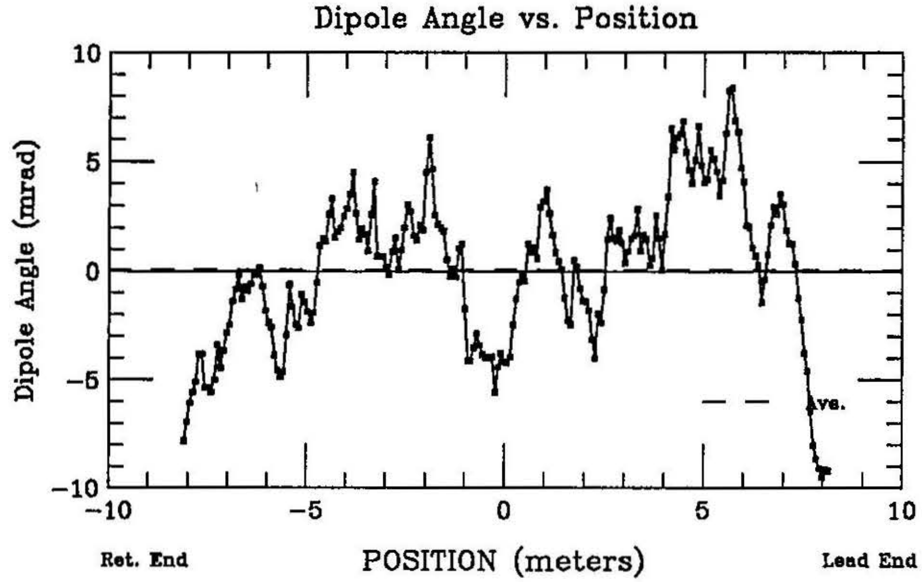
Angle S. Dev. = 2.40 mrad

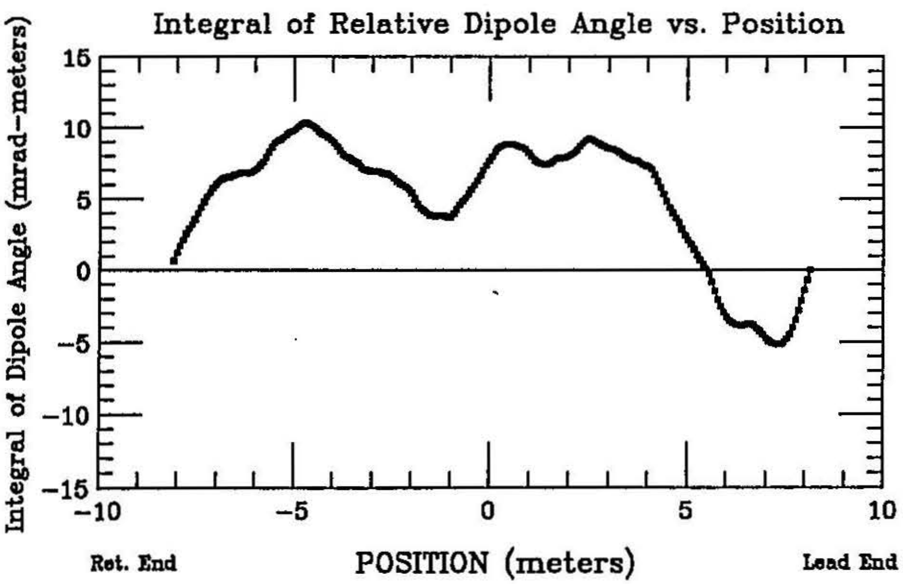
Integral Extrema = 6.71 mrad−m

Measurement at ICB

DD000X File 870413







Angle Extrema = −9.57 mrad
(Relative to Average)

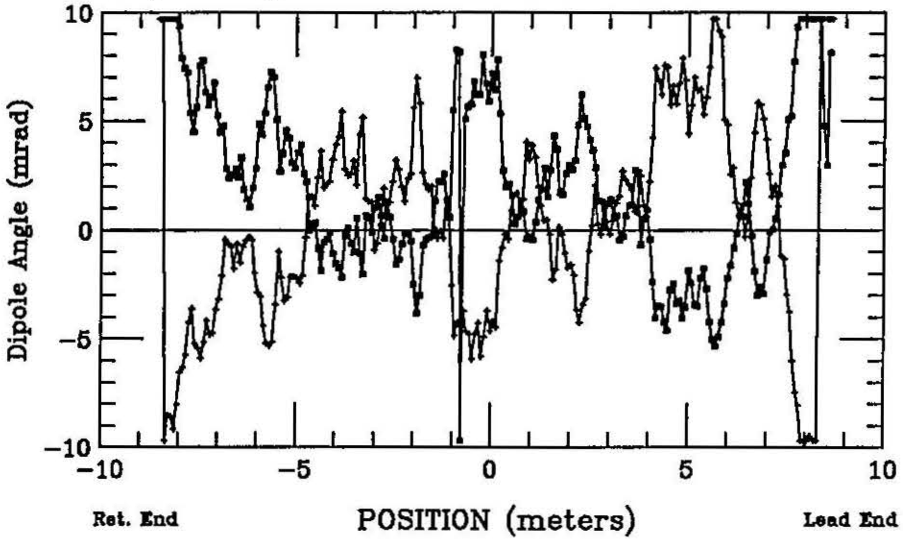
Angle S. Dev. = 3.52 mrad

Integral Extrema = 10.34 mrad−m

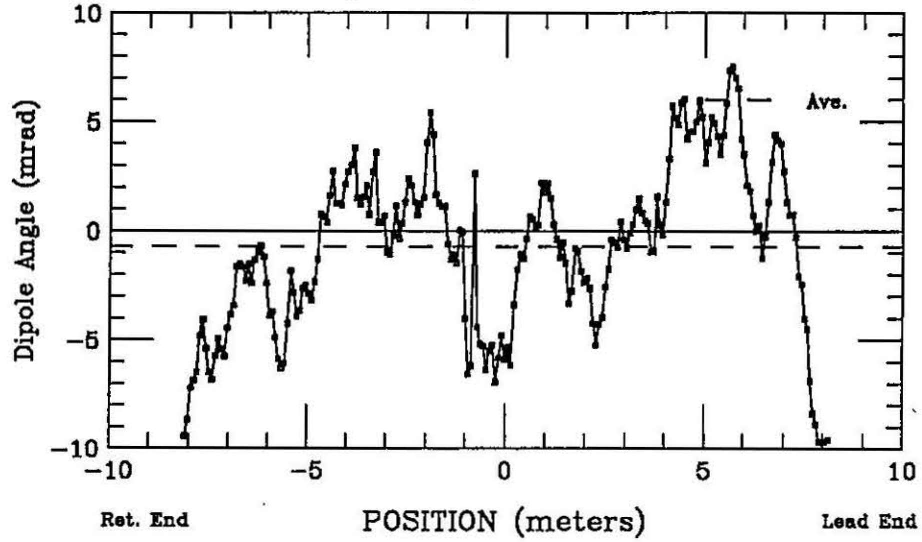
Measurement at ICB

DD000X File 870421

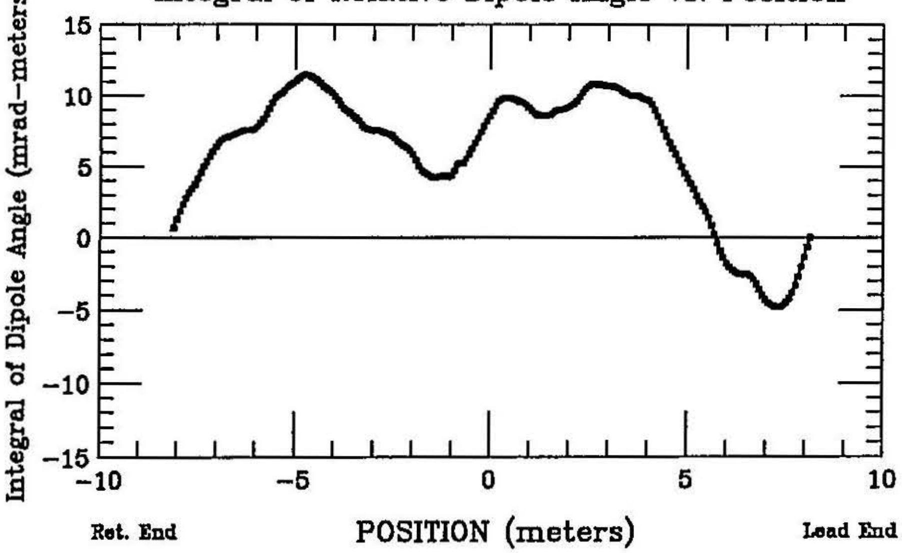
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



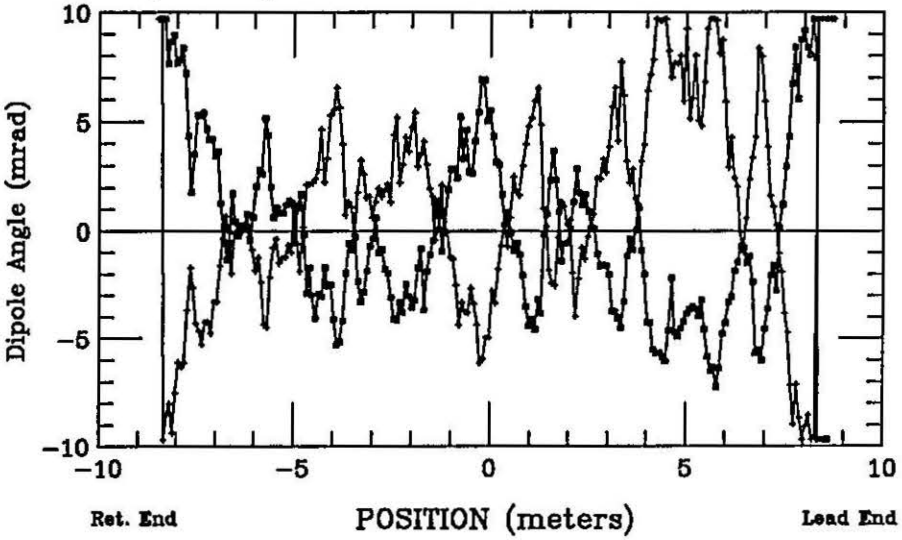
Angle Extrema = −8.97 mrad
(Relative to Average)

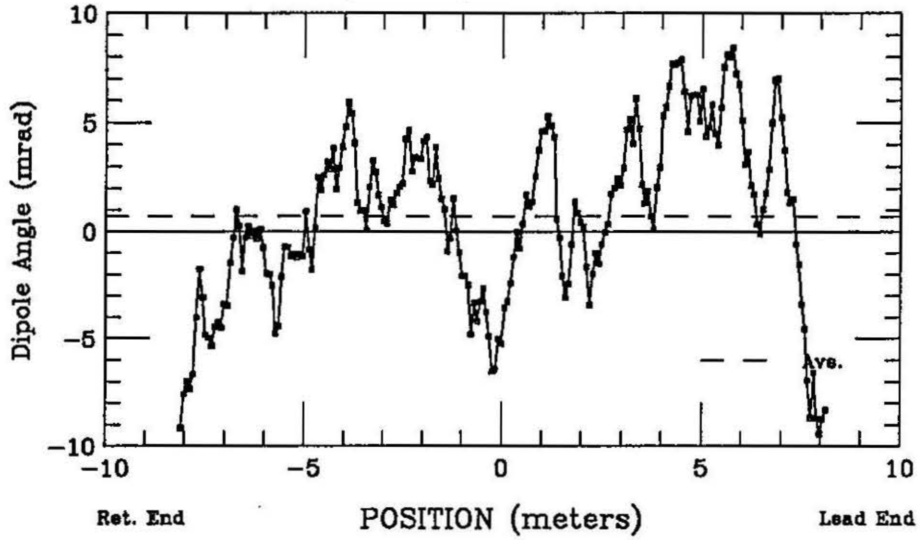
Angle S. Dev. = 3.78 mrad

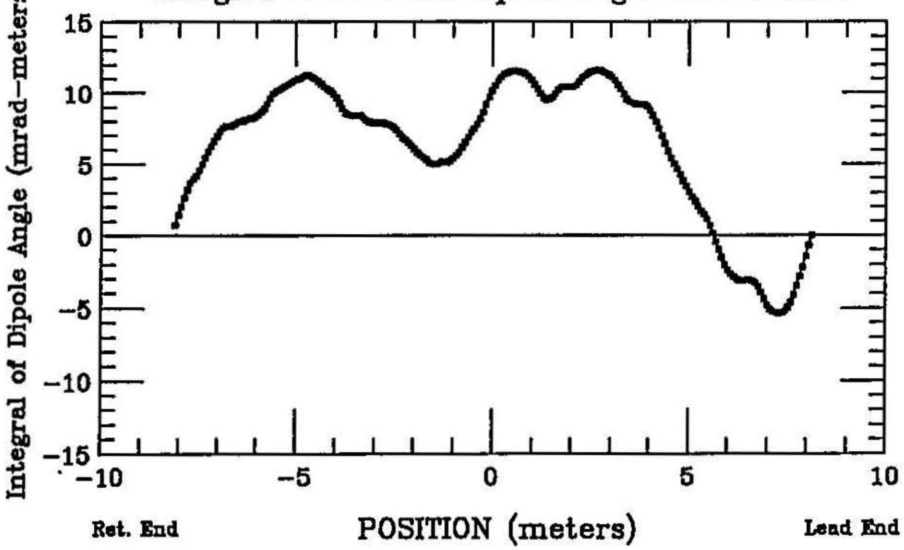
Integral Extrema = 11.49 mrad−m

Measurement out of Cryostat at ICB

DD000X File 870513







Angle Extrema = −10.14 mrad
(Relative to Average)

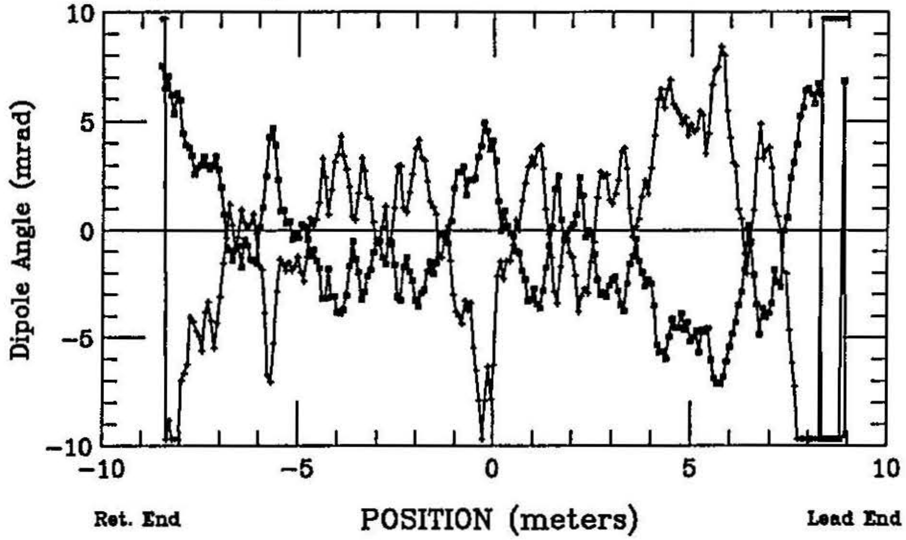
Angle S. Dev. = 3.94 mrad

Integral Extrema = 11.61 mrad−m

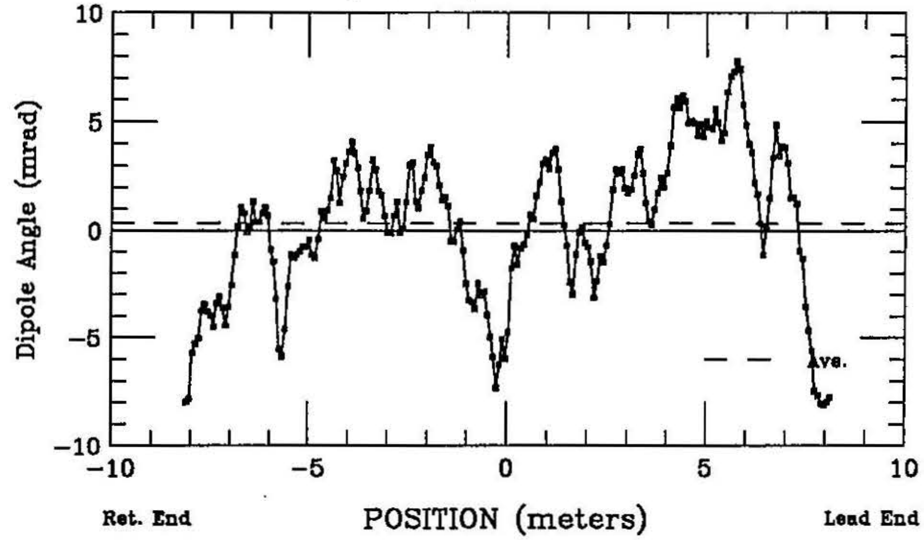
Measurement in Cryostat at MTF

DD000X File 880319

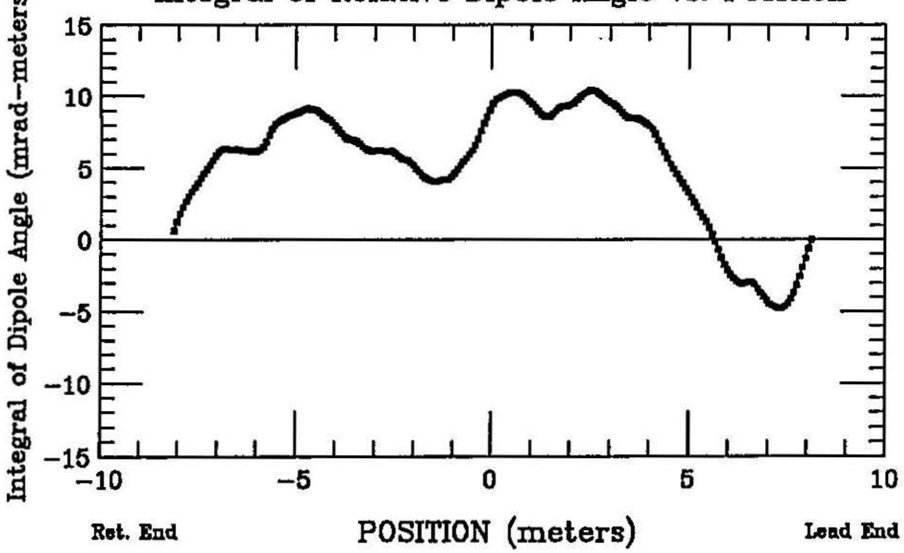
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



Angle Extrema = −8.45 mrad
(Relative to Average)

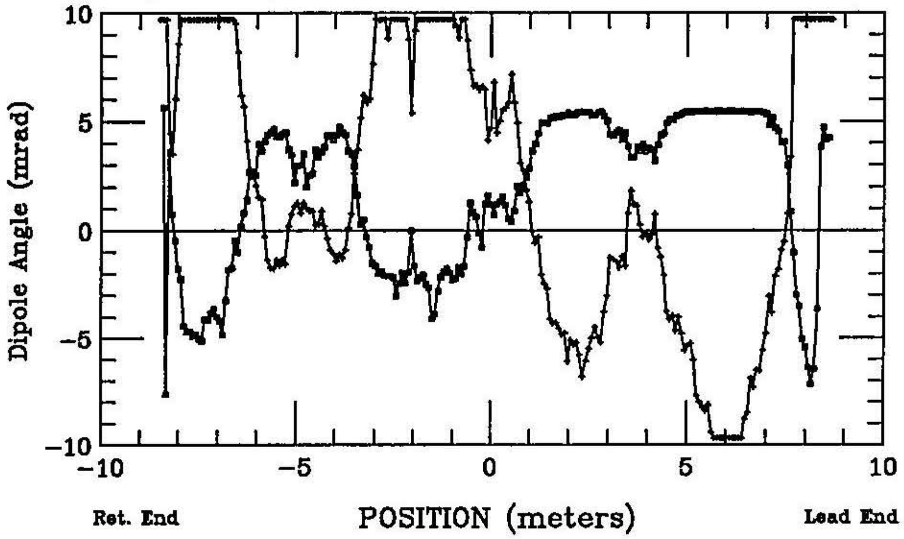
Angle S. Dev. = 3.48 mrad

Integral Extrema = 10.40 mrad−m

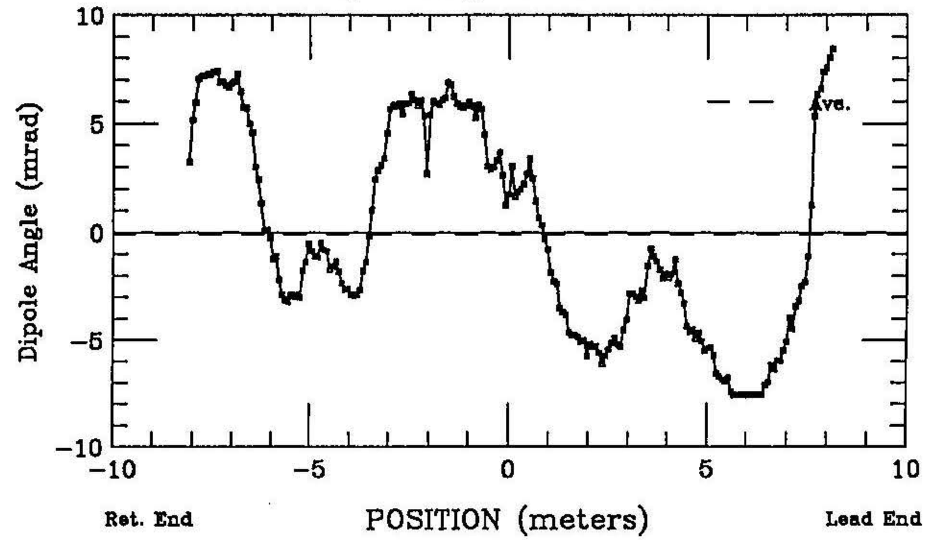
Measurement after Test at MTF

DD000Z File 870912

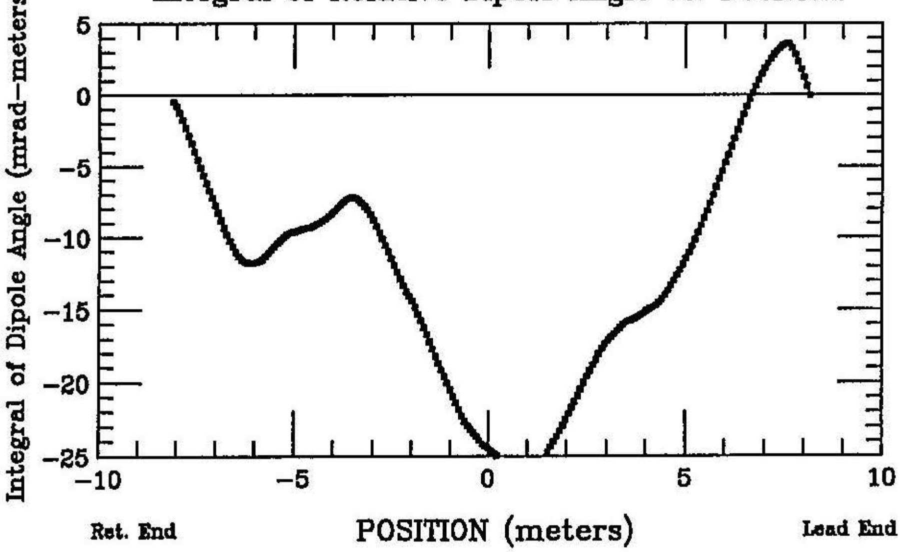
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



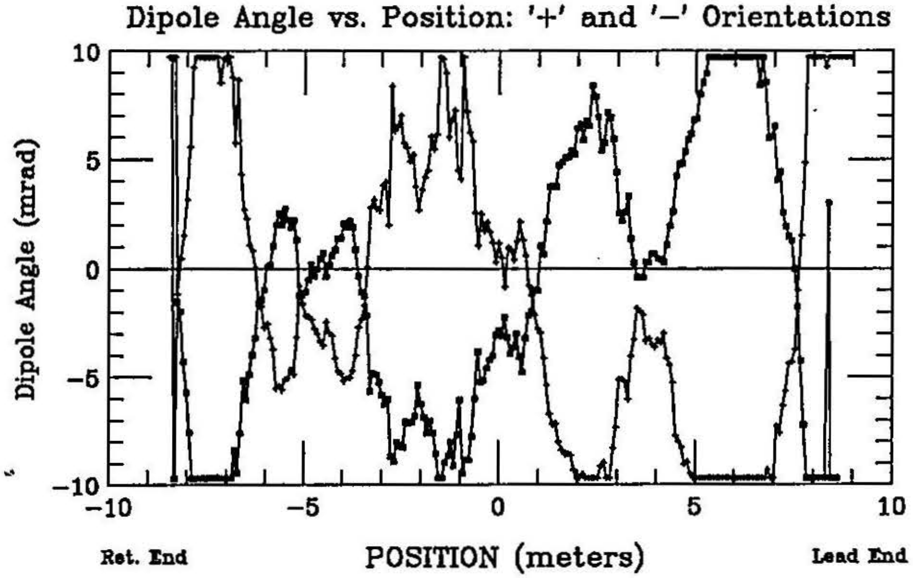
Angle Extrema = 8.52 mrad
(Relative to Average)

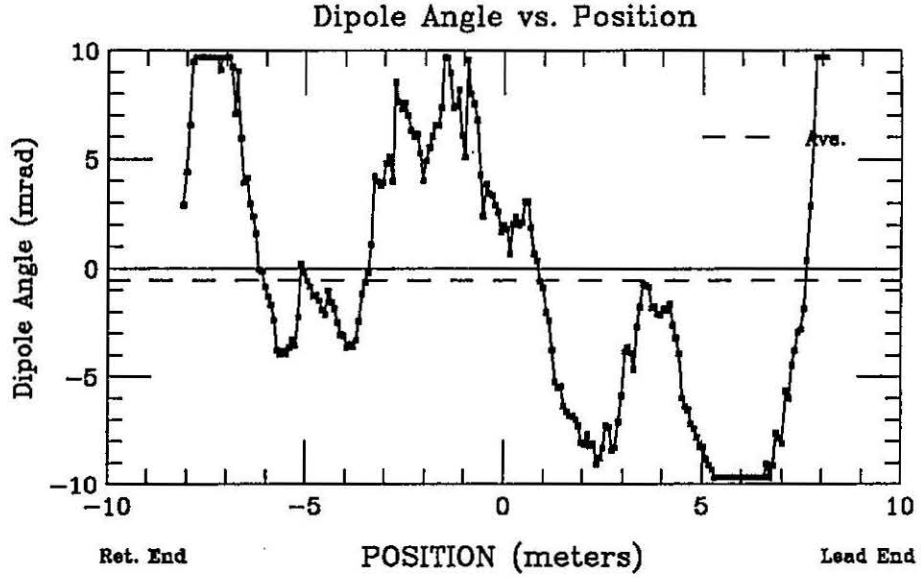
Angle S. Dev. = 4.77 mrad

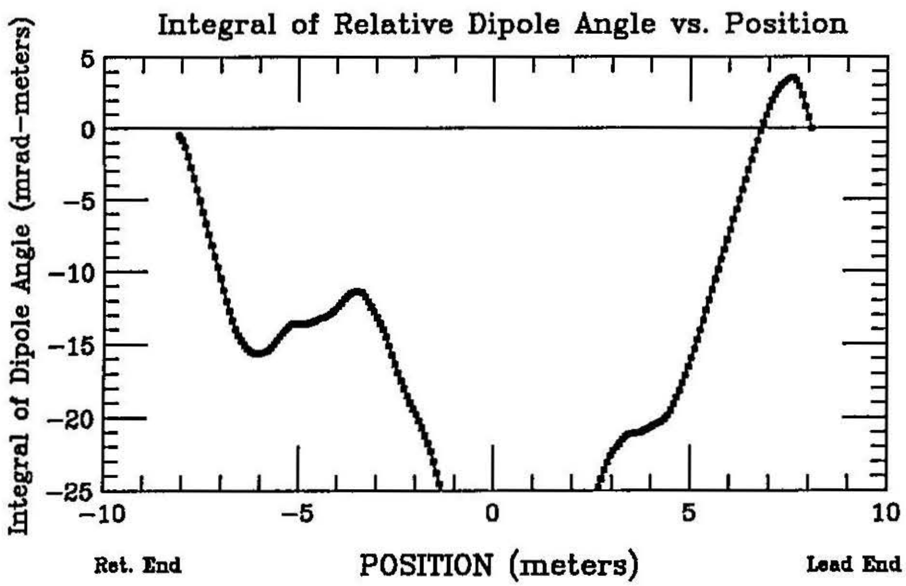
Integral Extrema = −26.25 mrad−m

Measurement before Test at MTF

DD000Z File 871003







Angle Extrema = 10.26 mrad
(Relative to Average)

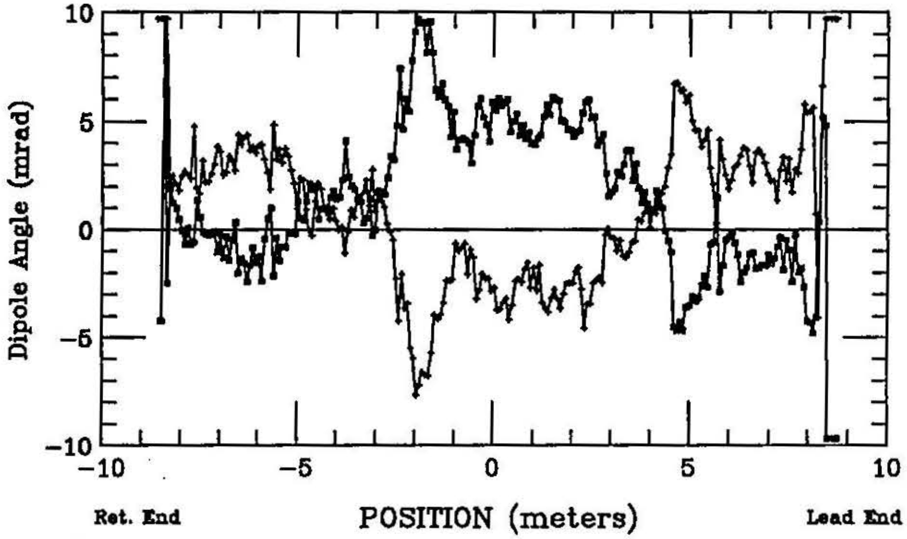
Angle S. Dev. = 6.17 mrad

Integral Extrema = −34.74 mrad−m

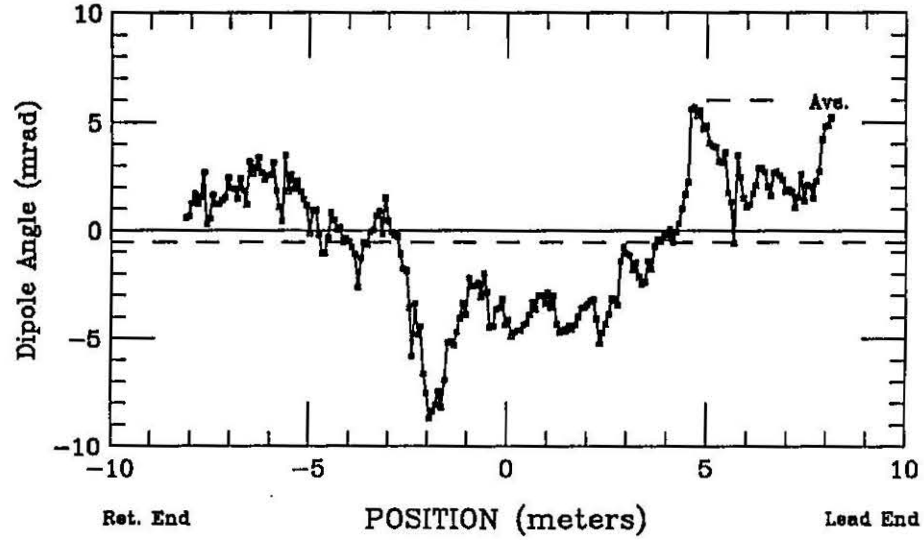
Measurement in Cryostat

DD0028 File 900423

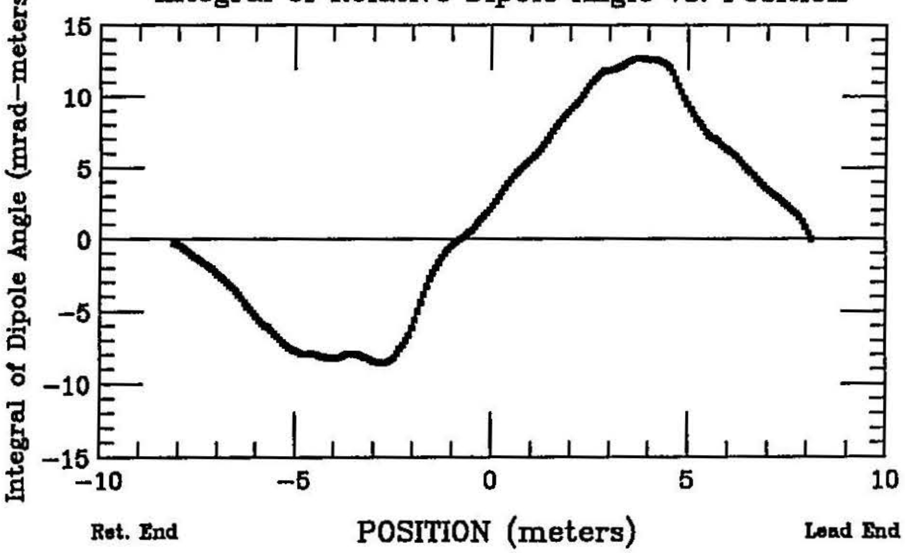
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



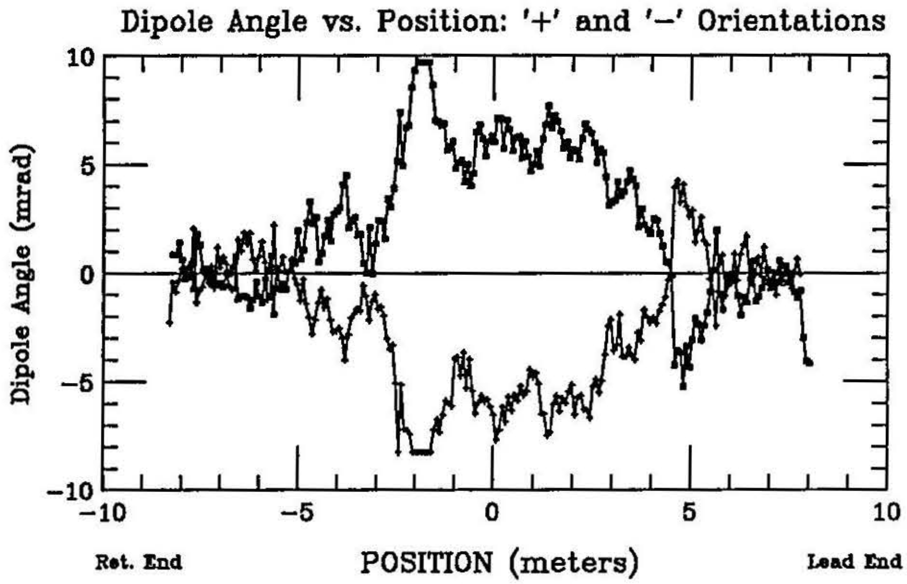
Angle Extrema = −8.14 mrad
(Relative to Average)

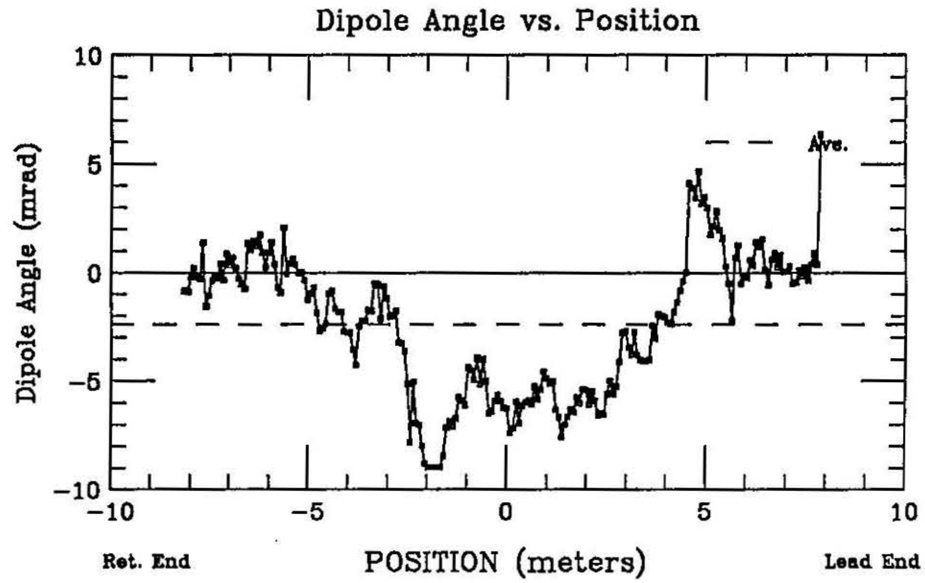
Angle S. Dev. = 3.14 mrad

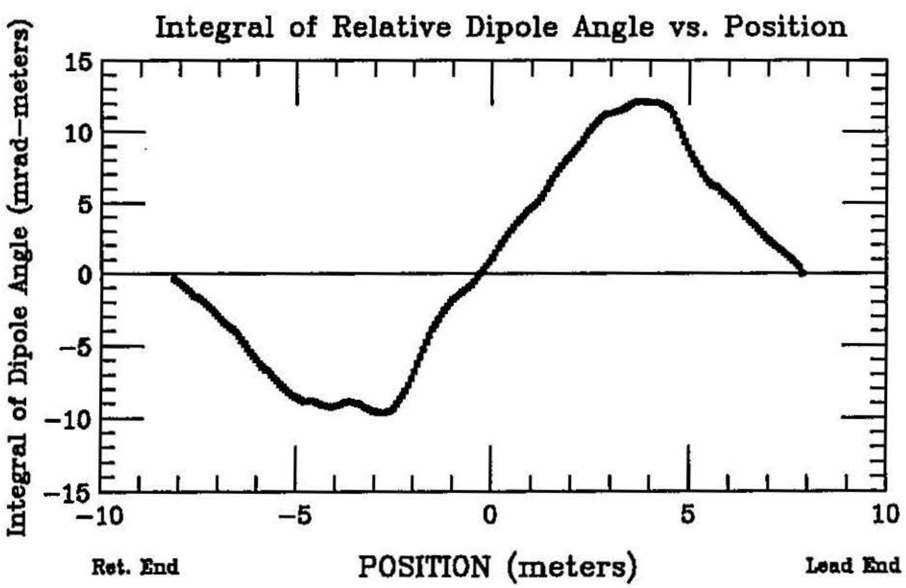
Integral Extrema = 12.68 mrad−m

Measurement out of Cryostat at ICB

DD0028 File 900928







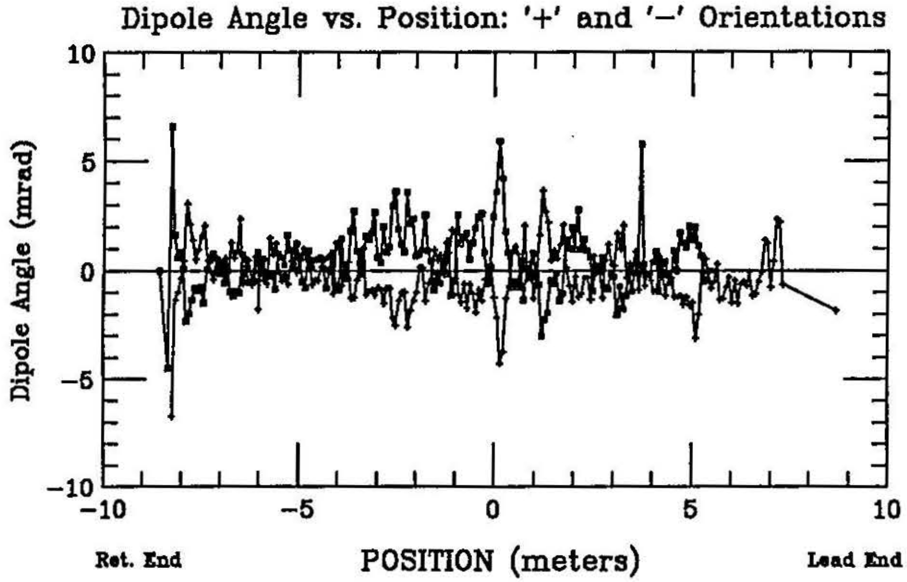
Angle Extrema = 8.74 mrad
(Relative to Average)

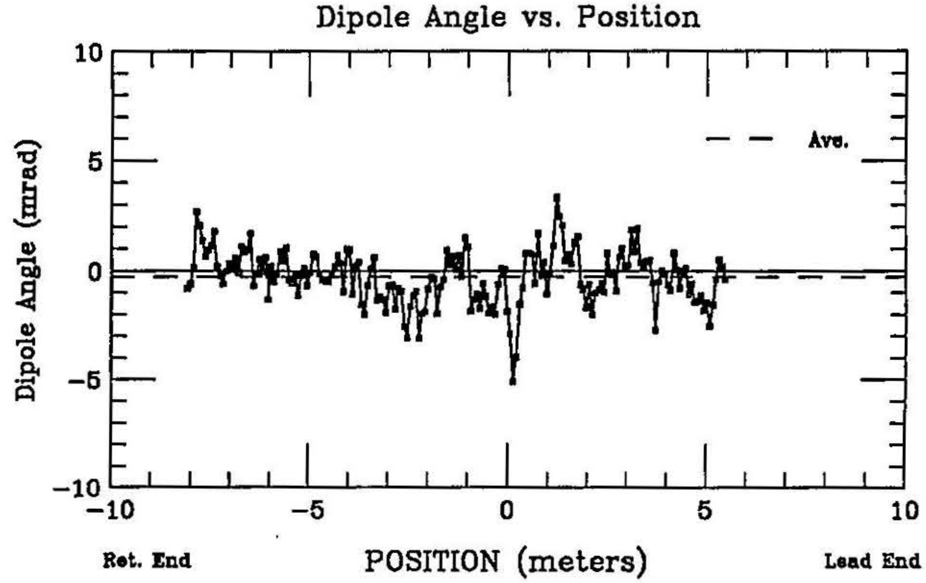
Angle S. Dev. = 3.22 mrad

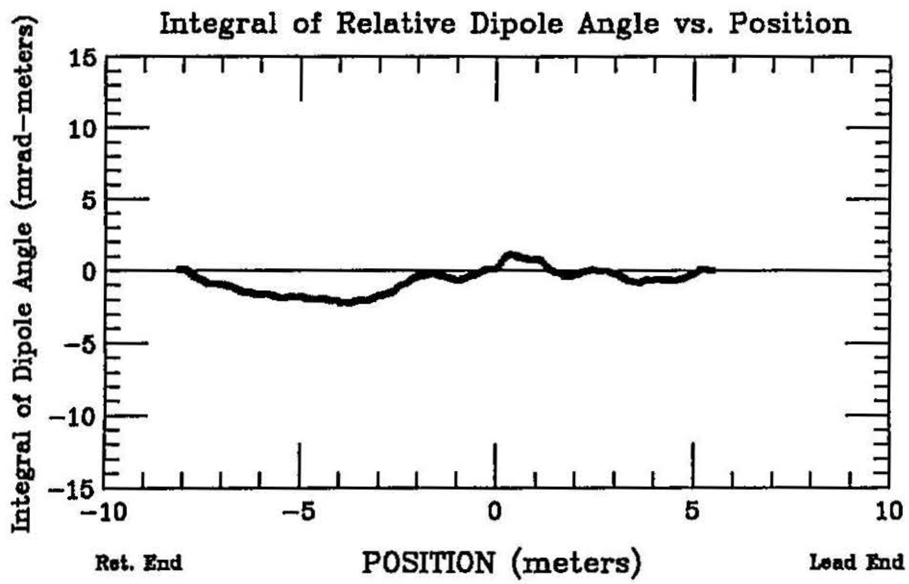
Integral Extrema = 12.14 mrad−m

Measurement at MTF before TC#1

DC0301 File 901004







Angle Extrema = –4.81 mrad
(Relative to Average)

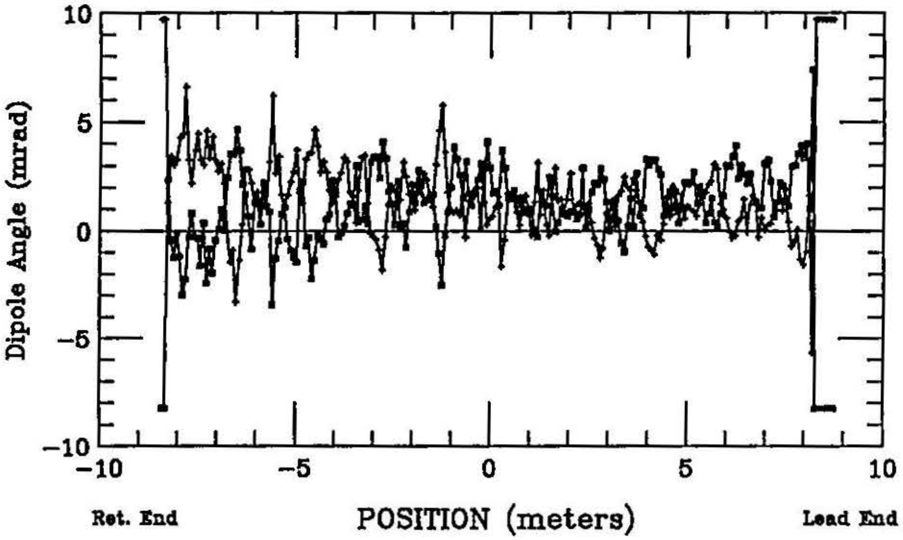
Angle S. Dev. = 1.21 mrad

Integral Extrema = –2.24 mrad–m

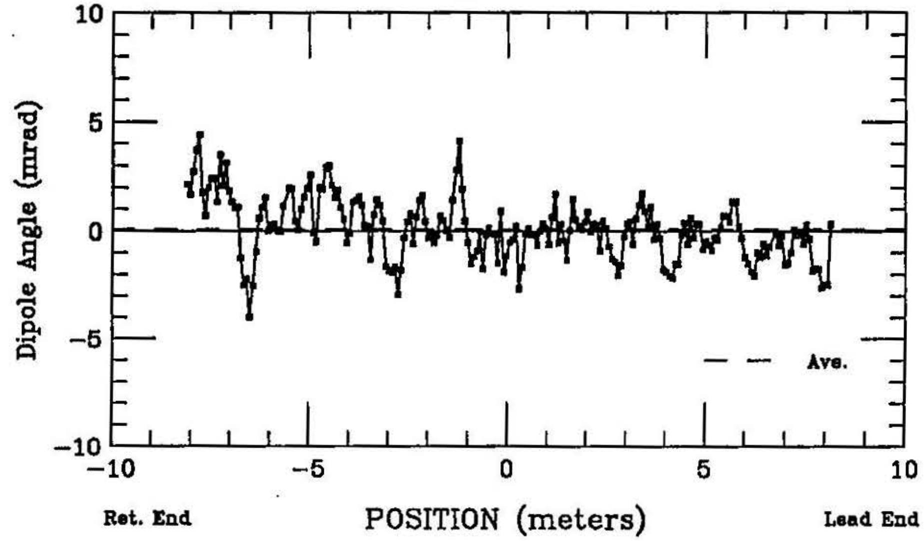
Measurement at ICB

DC0306 File 910410

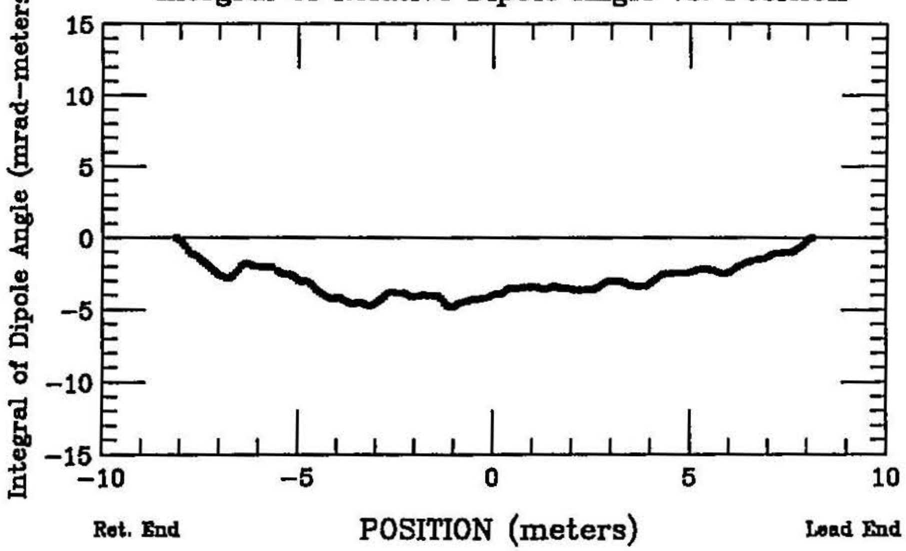
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



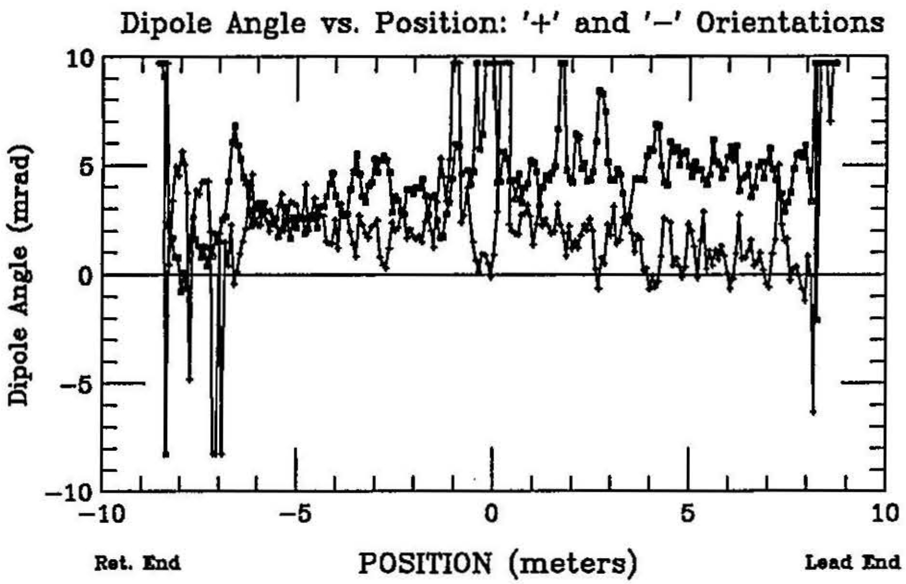
Angle Extrema = 4.34 mrad
(Relative to Average)

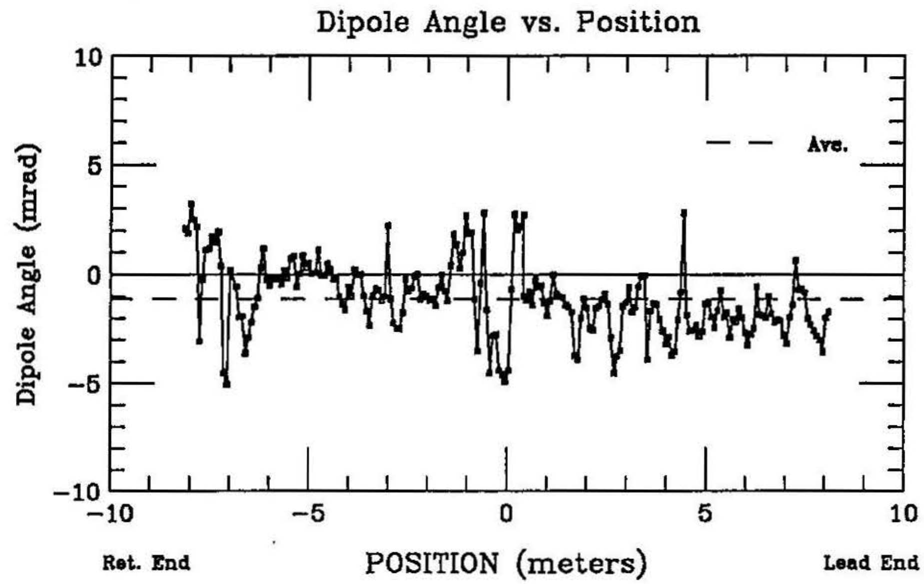
Angle S. Dev. = 1.40 mrad

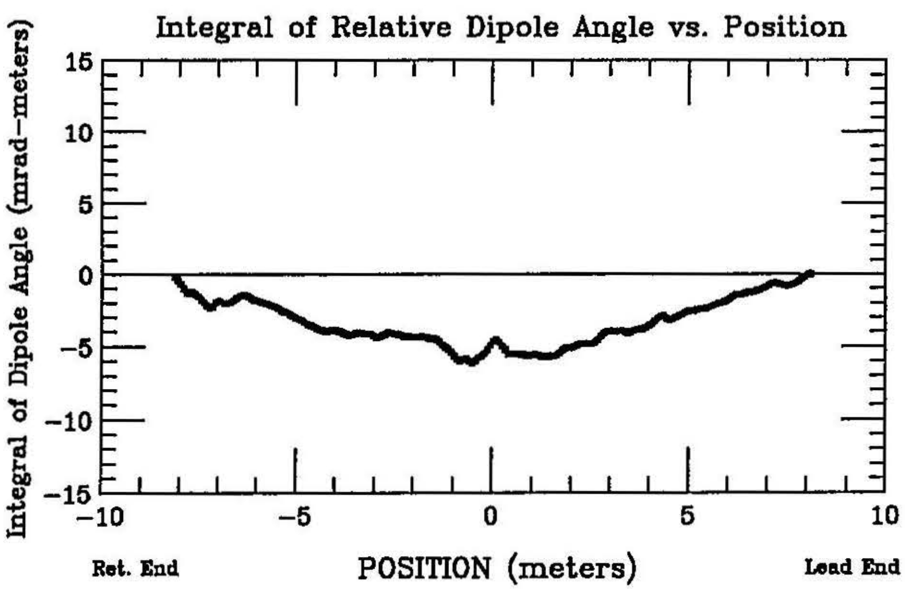
Integral Extrema = −4.79 mrad−m

Measurement at ICB

DC0306 File 910627







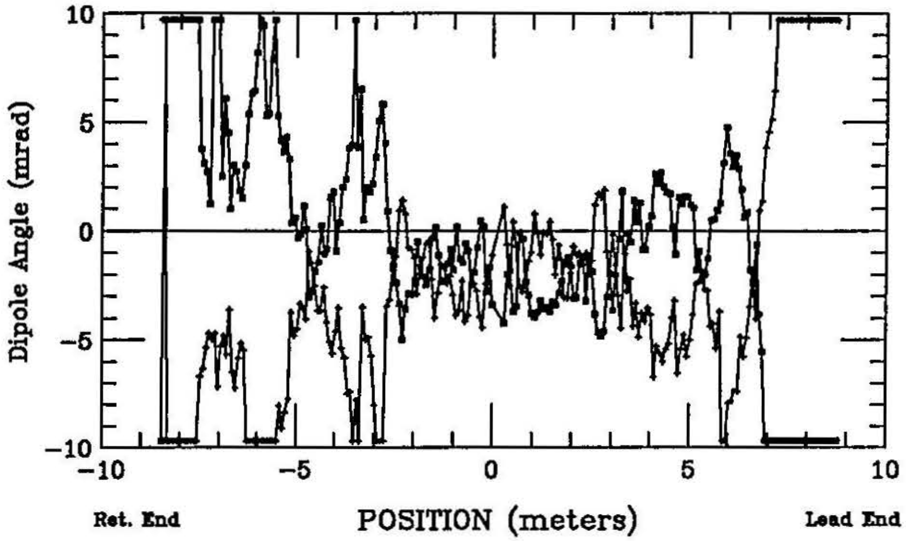
Angle Extrema = 4.29 mrad
(Relative to Average)

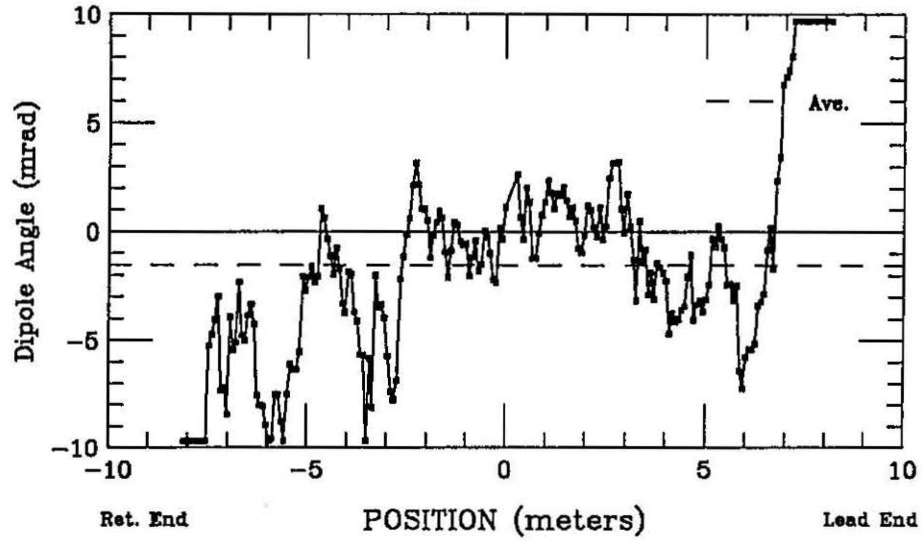
Angle S. Dev. = 1.65 mrad

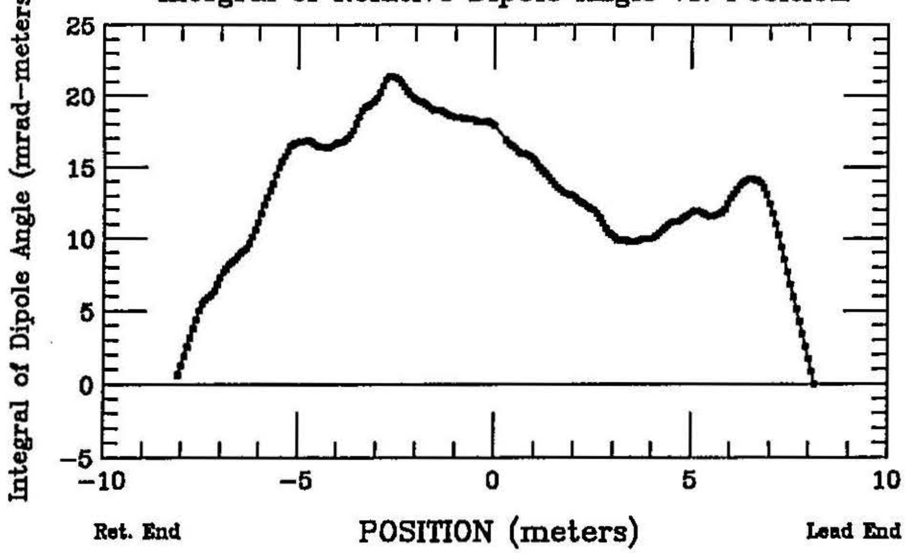
Integral Extrema = −6.14 mrad−m

Measurement at MTF after Cold Testing

DD0010 File 871212







Angle Extrema = 11.22 mrad
(Relative to Average)

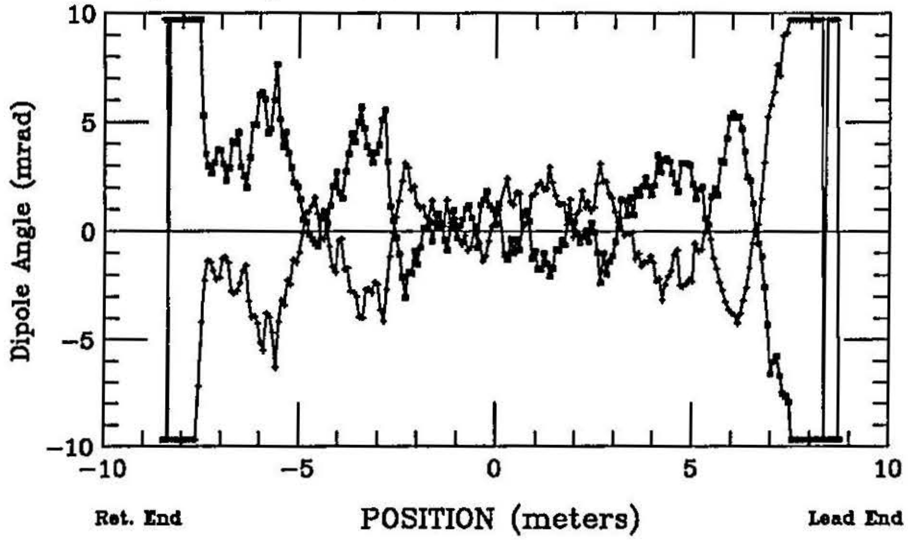
Angle S. Dev. = 4.52 mrad

Integral Extrema = 21.38 mrad−m

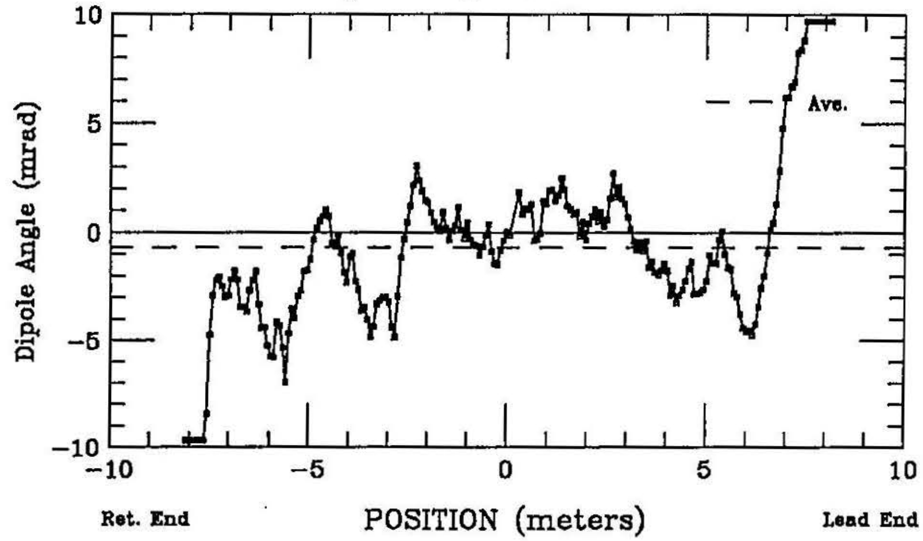
Measurement in Cryostat at MTF

DD0010 File 880602

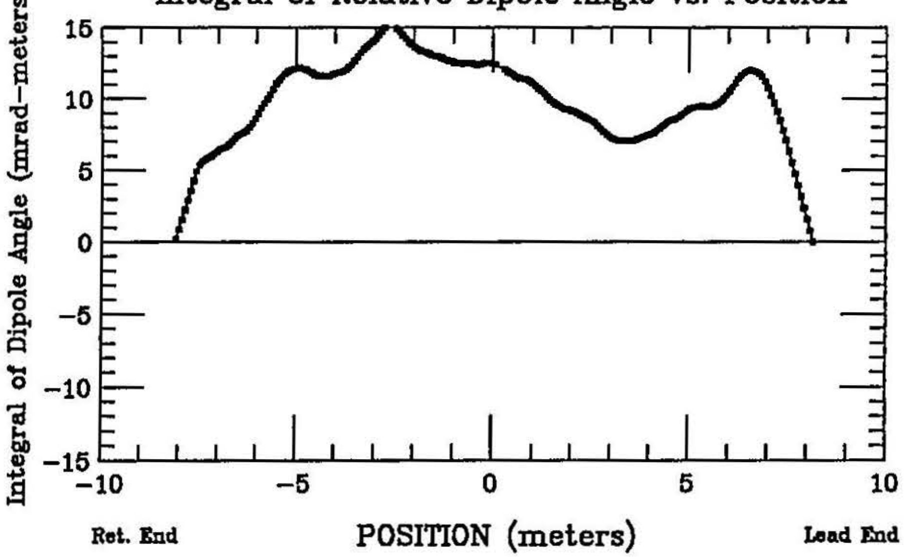
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



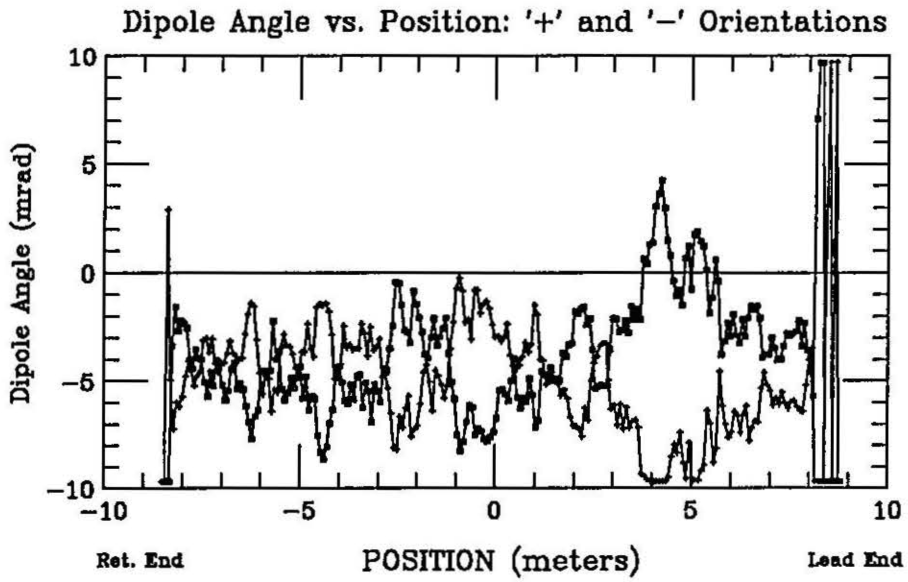
Angle Extrema = 10.40 mrad
(Relative to Average)

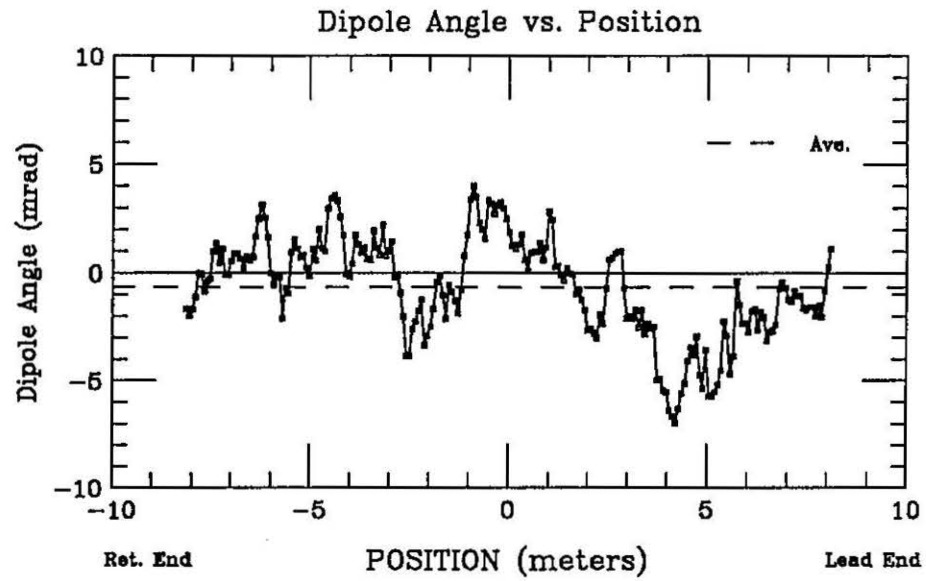
Angle S. Dev. = 3.72 mrad

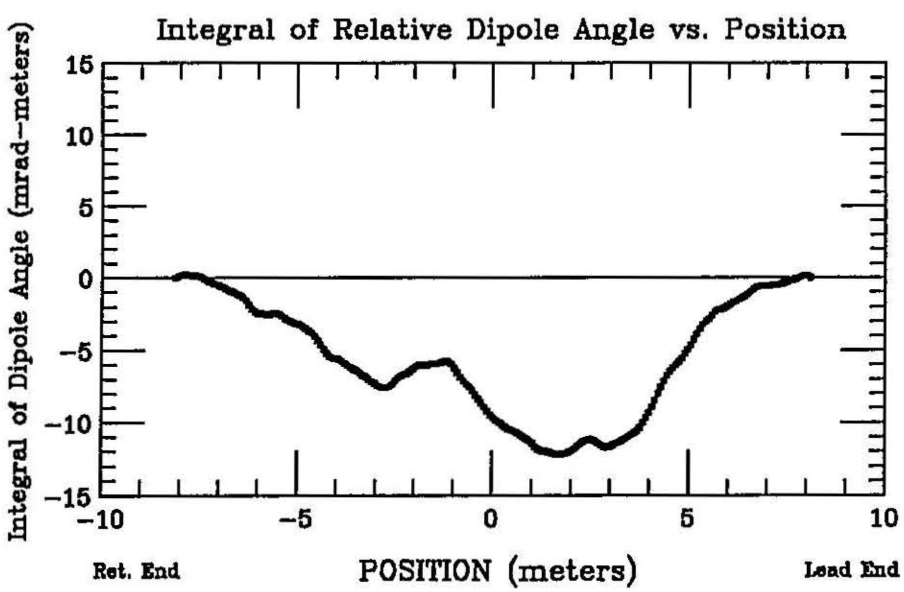
Integral Extrema = 15.10 mrad−m

Measurement after Test at MTF

DDA010 File 890314







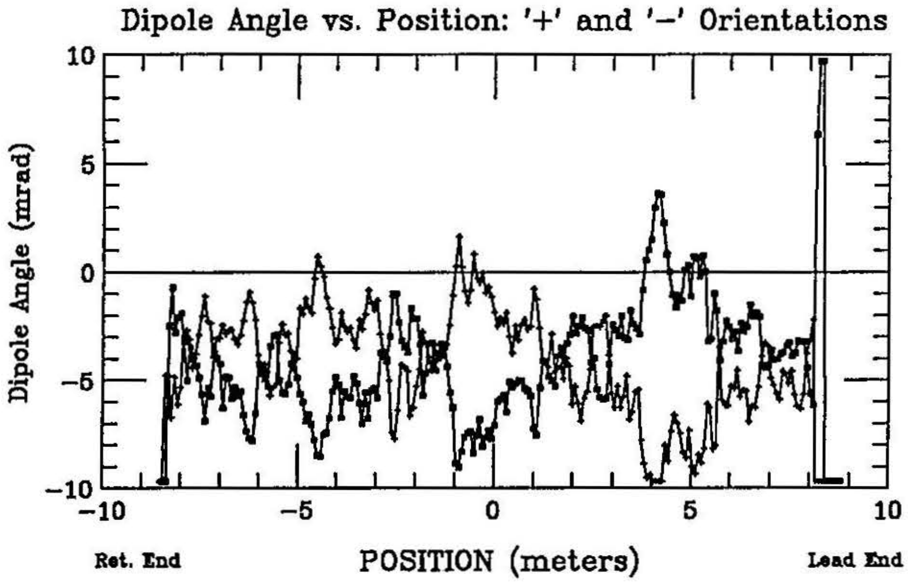
Angle Extrema = −6.31 mrad
(Relative to Average)

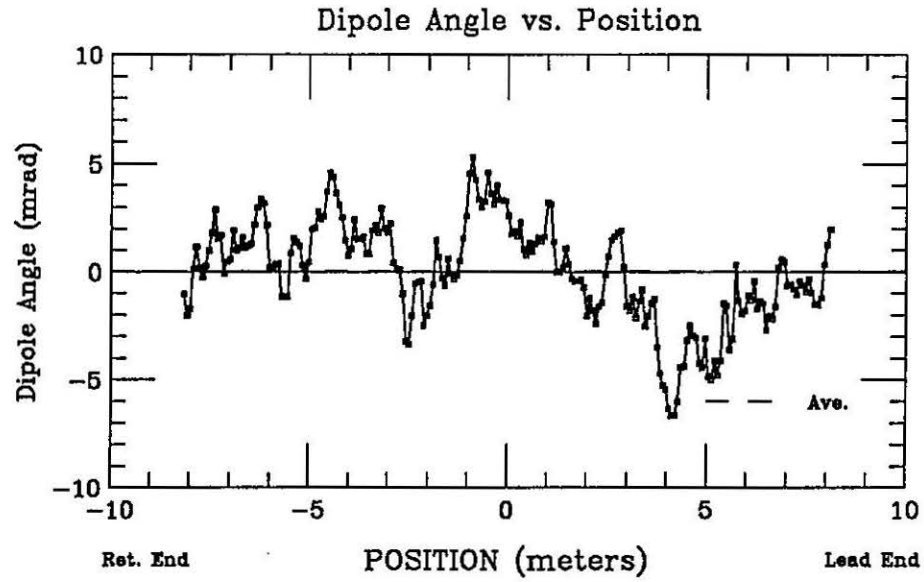
Angle S. Dev. = 2.32 mrad

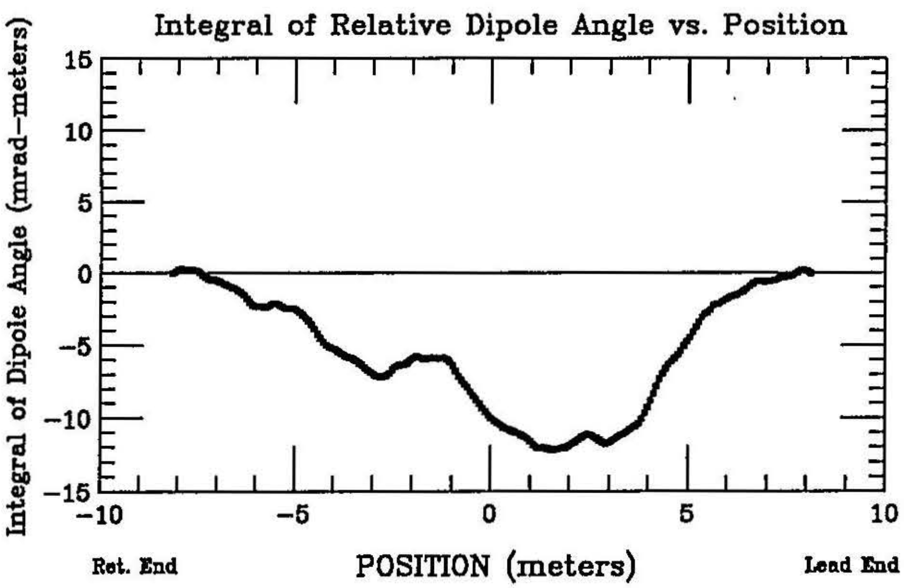
Integral Extrema = −12.19 mrad−m

Measurement out of Cryostat at ICB

DDA010 File 890408







Angle Extrema = −6.69 mrad
(Relative to Average)

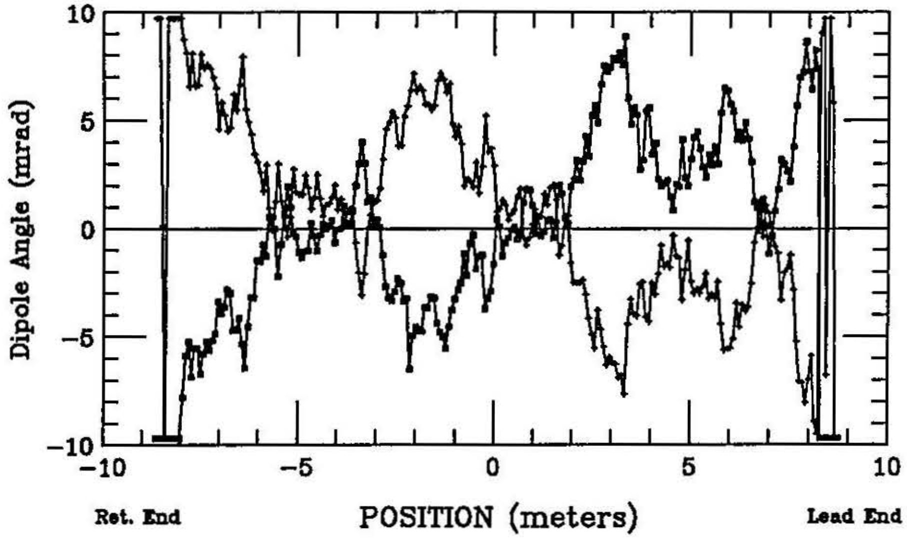
Angle S. Dev. = 2.35 mrad

Integral Extrema = −12.16 mrad−m

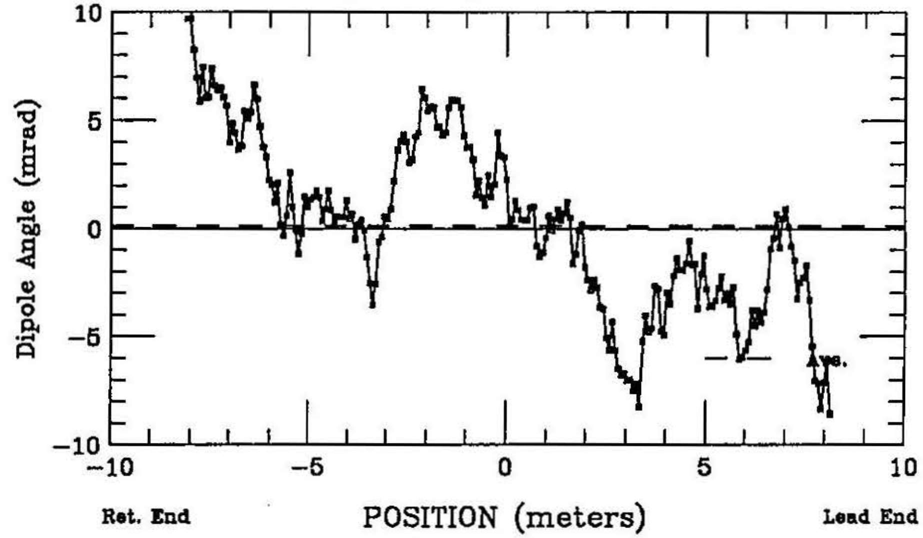
Measurement in Cryostat at ICB

DD0011 File 880625

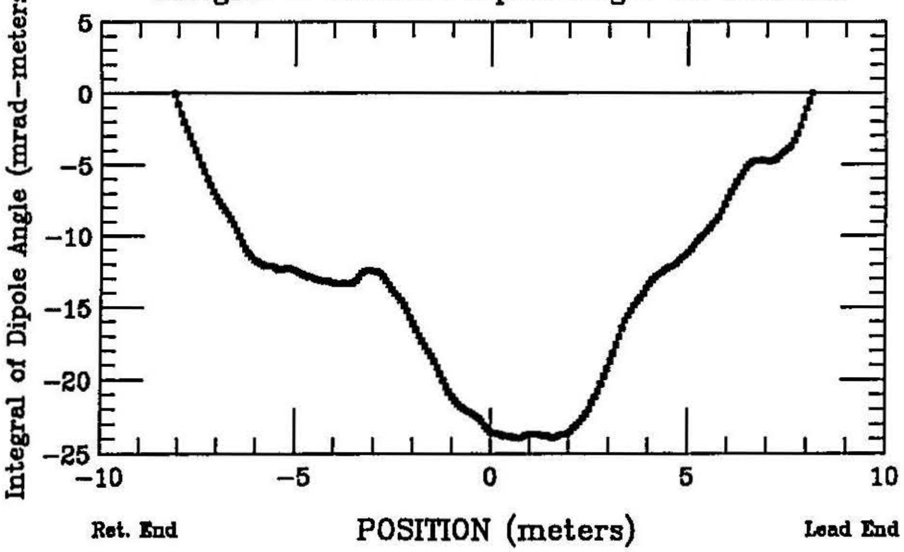
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



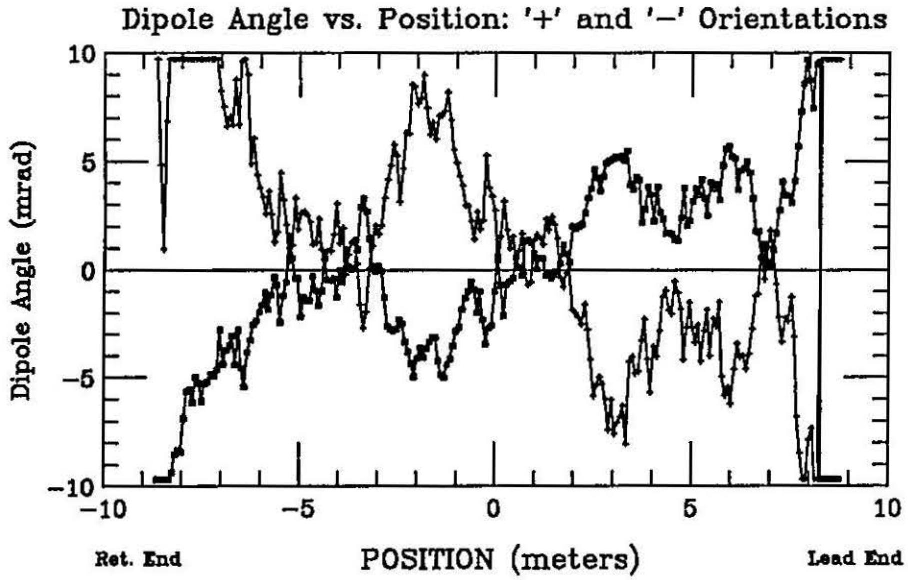
Angle Extrema = 9.57 mrad
(Relative to Average)

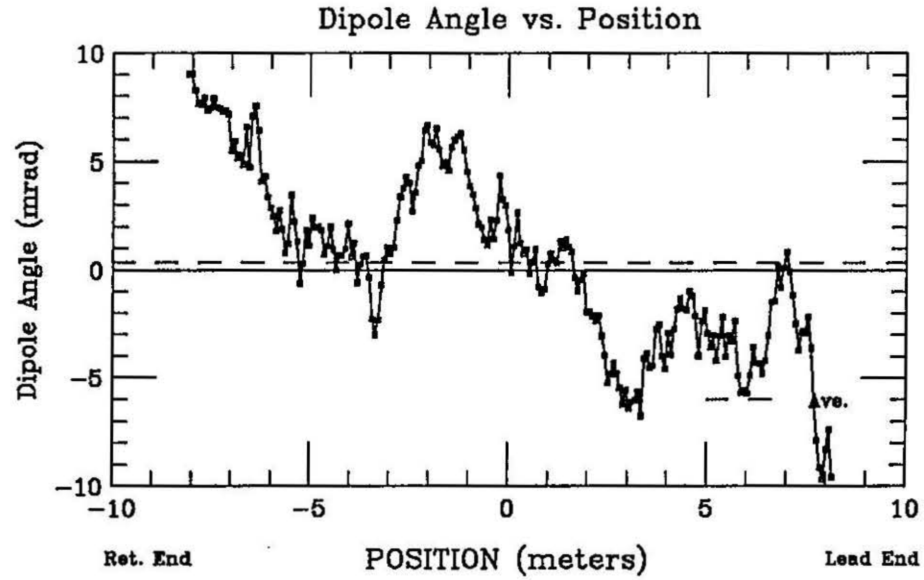
Angle S. Dev. = 3.94 mrad

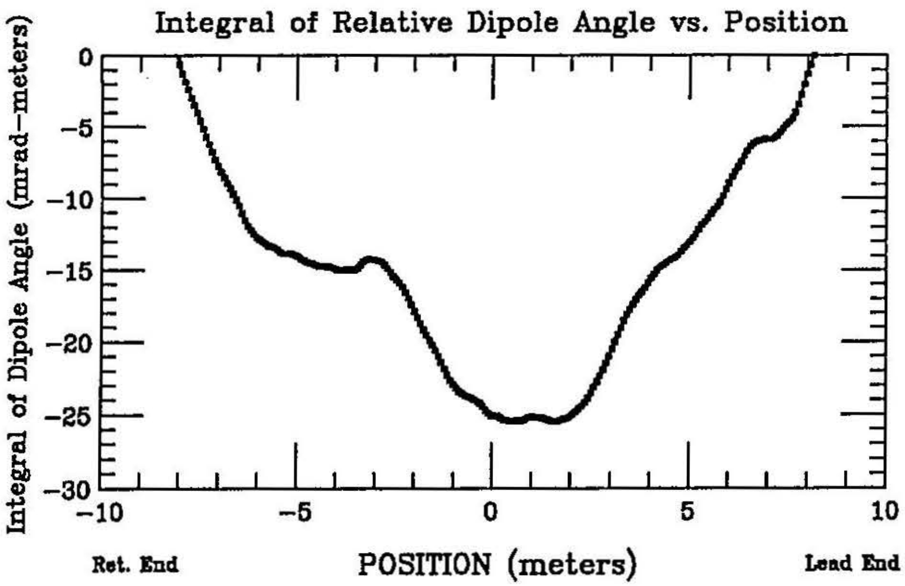
Integral Extrema = −23.96 mrad−m

Measurement before Test at MTF

DD0011 File 880531







Angle Extrema = −10.06 mrad
(Relative to Average)

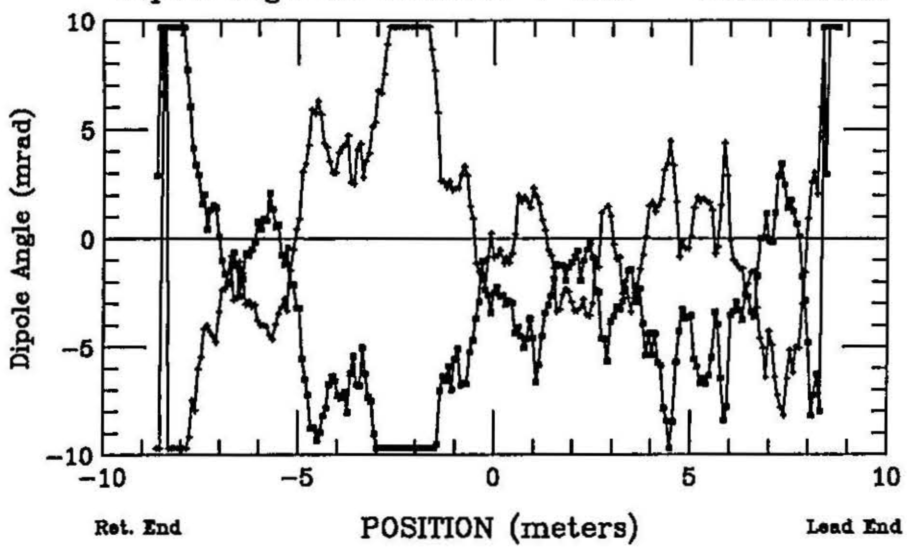
Angle S. Dev. = 4.12 mrad

Integral Extrema = −25.49 mrad−m

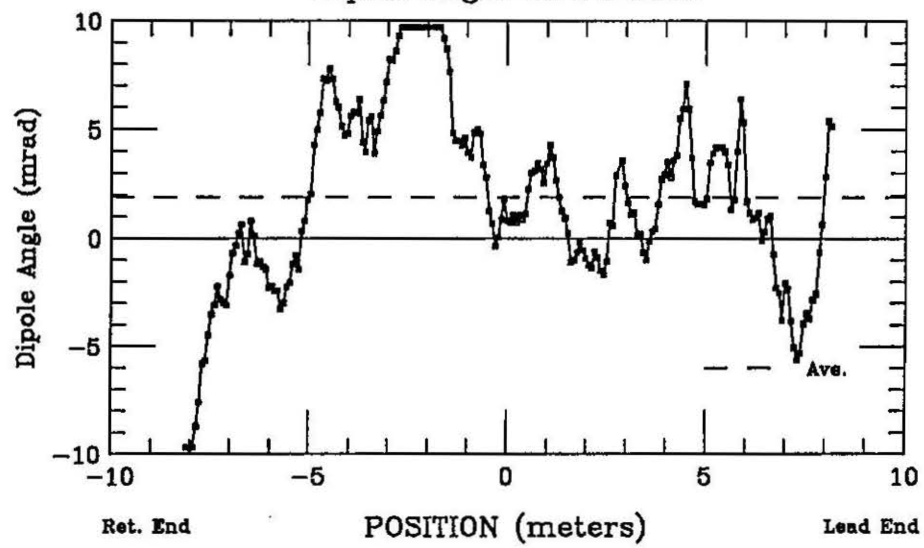
Measurement out of Cryostat at ICB

DD0012 File 880122

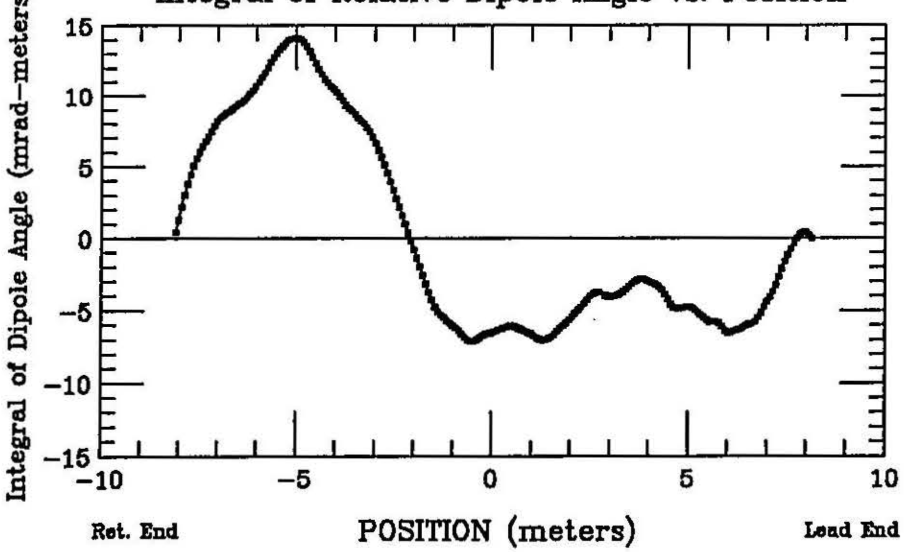
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



Angle Extrema = −11.61 mrad
(Relative to Average)

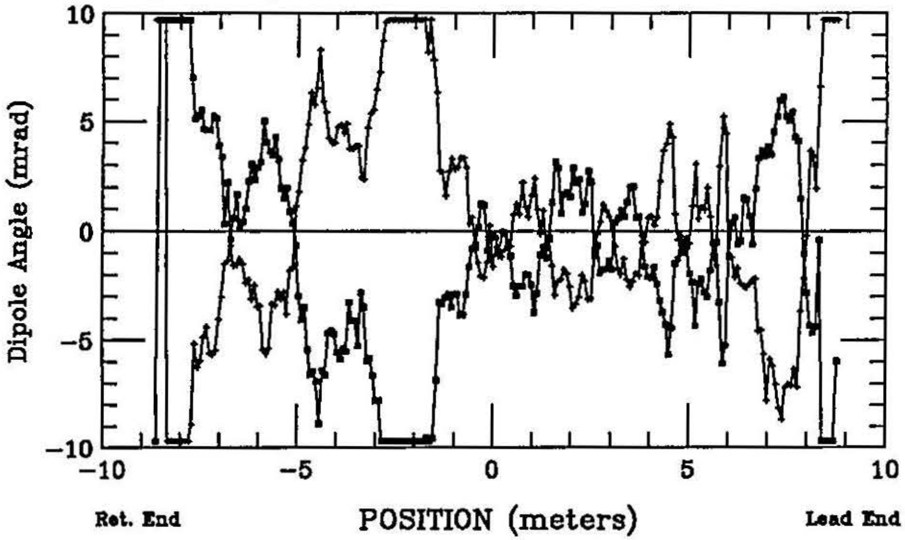
Angle S. Dev. = 4.13 mrad

Integral Extrema = 14.11 mrad−m

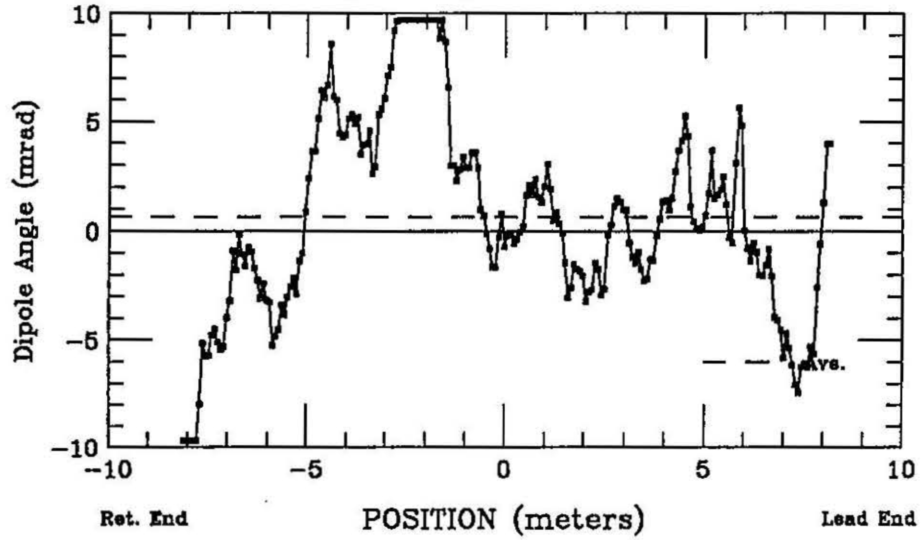
Measurement out of Cryostat at ICB

DD0012 File 880203

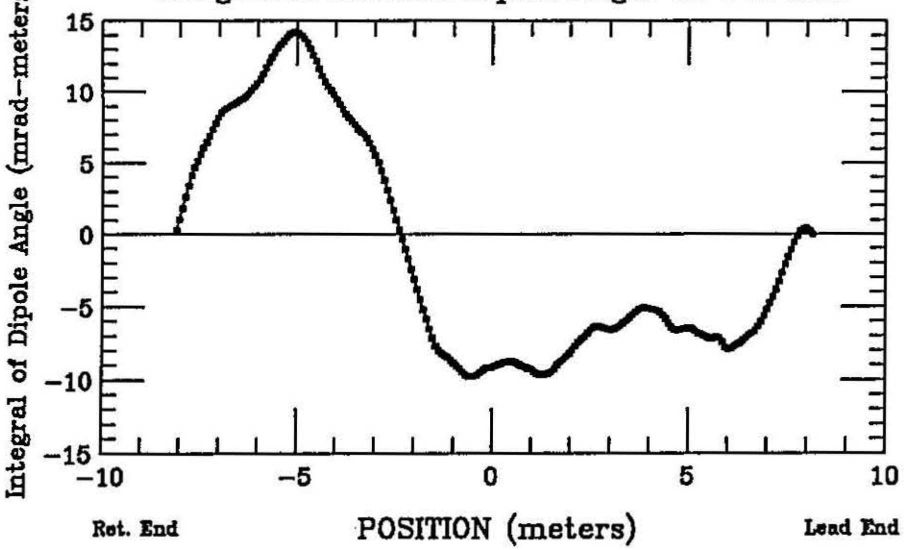
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



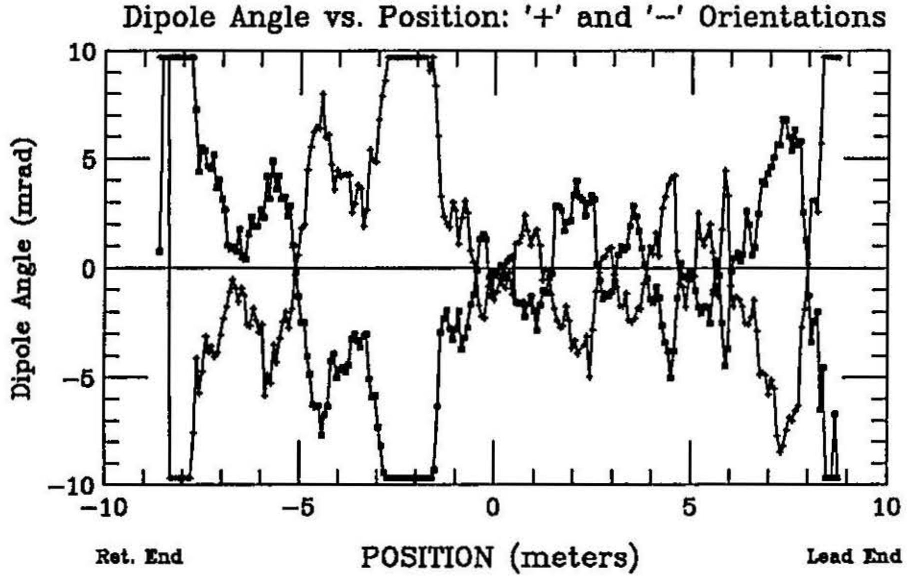
Angle Extrema = −10.33 mrad
(Relative to Average)

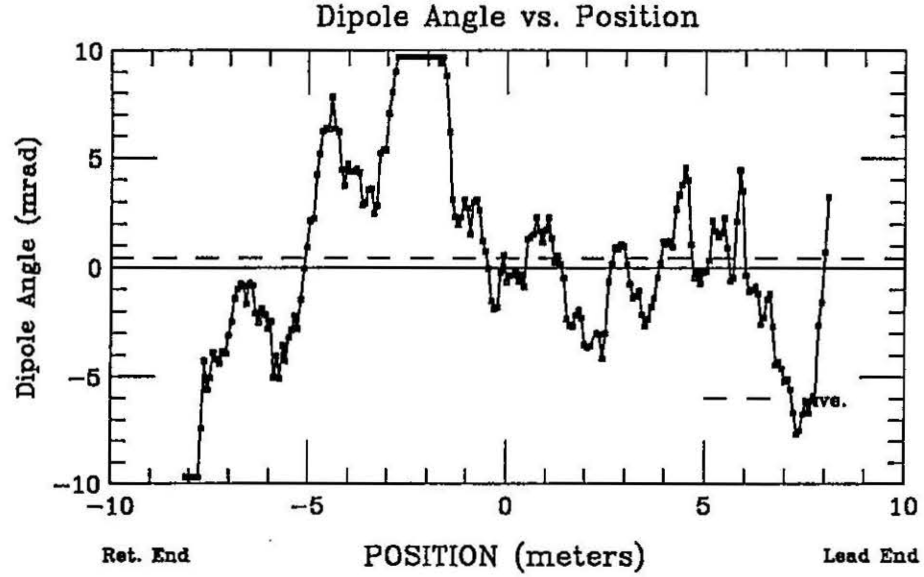
Angle S. Dev. = 4.48 mrad

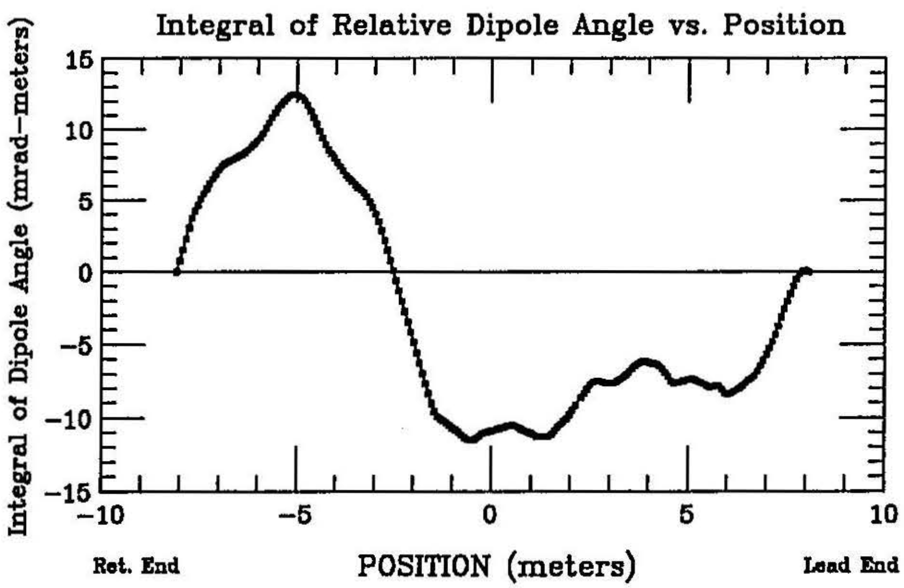
Integral Extrema = 14.23 mrad−m

Measurement before Test at MTF

DD0012 File 880211







Angle Extrema = −10.12 mrad
(Relative to Average)

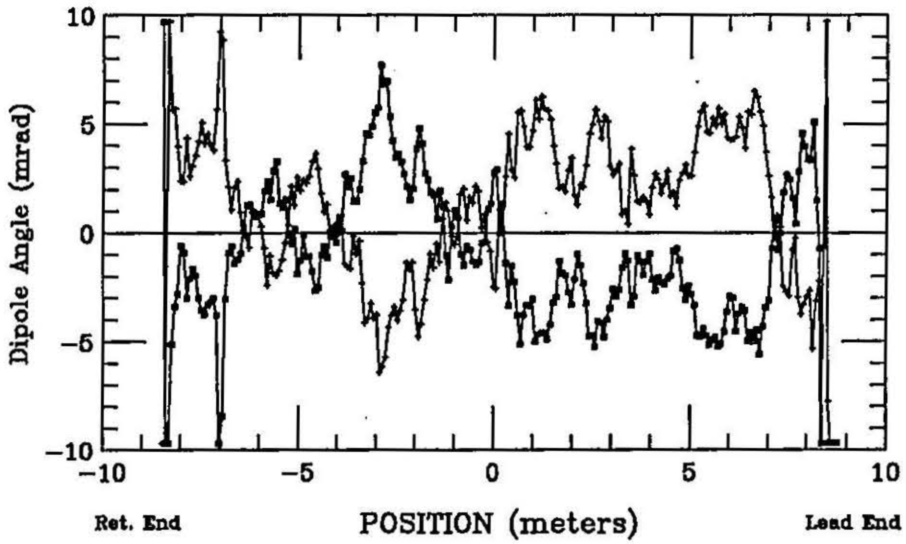
Angle S. Dev. = 4.43 mrad

Integral Extrema = 12.48 mrad−m

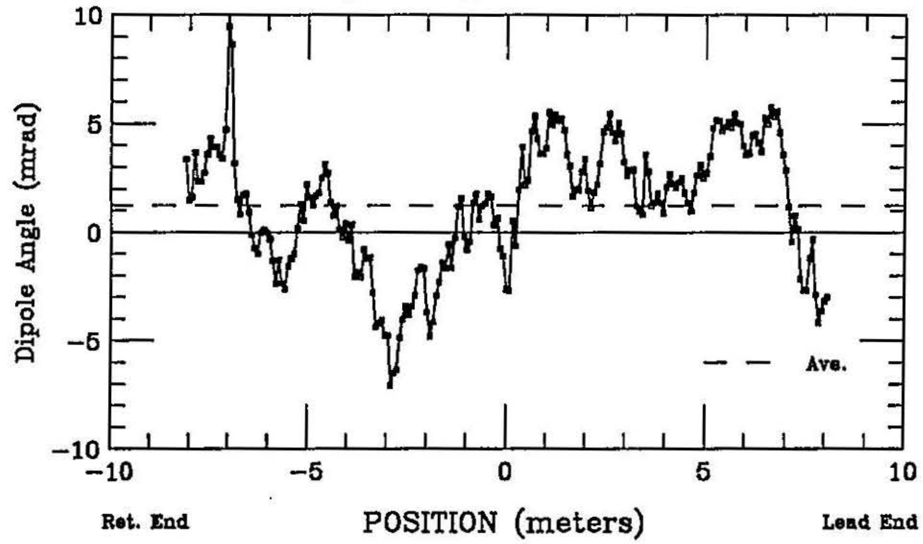
Measurement before Test at MTF

DD0013 File 880708

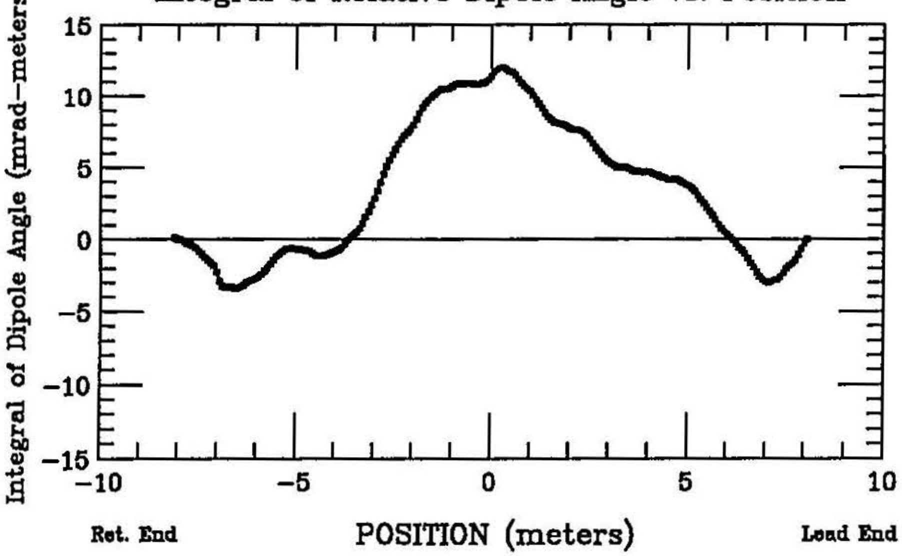
Dipole Angle vs. Position: '+' and '–' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



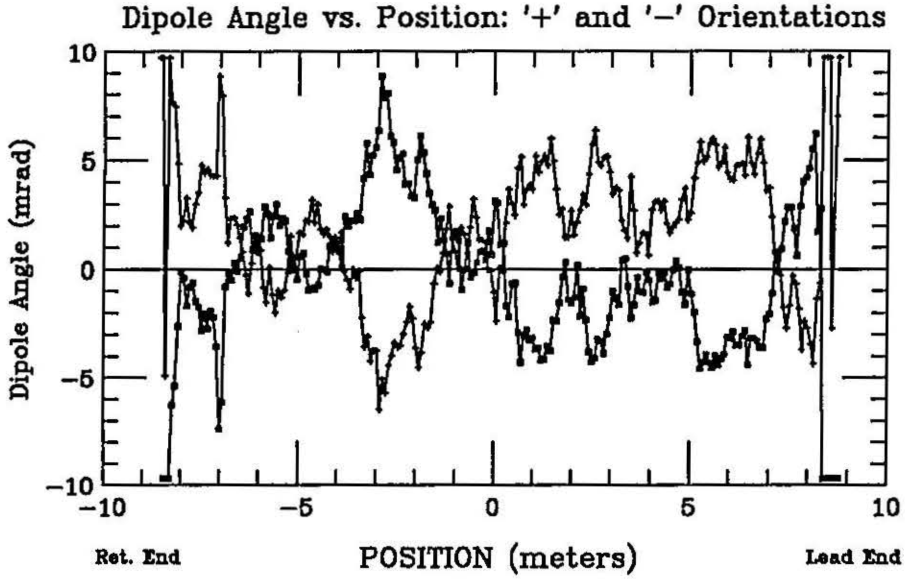
Angle Extrema = –8.30 mrad
(Relative to Average)

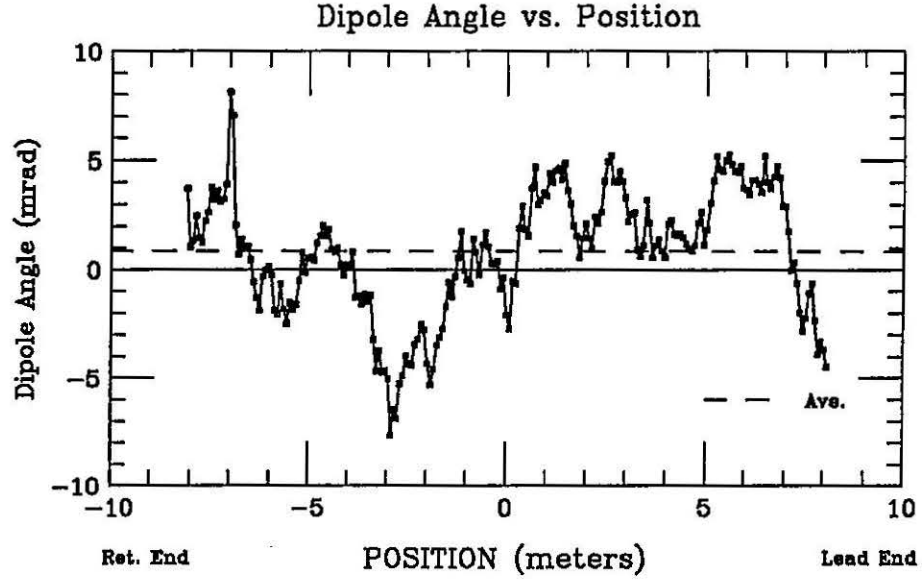
Angle S. Dev. = 2.96 mrad

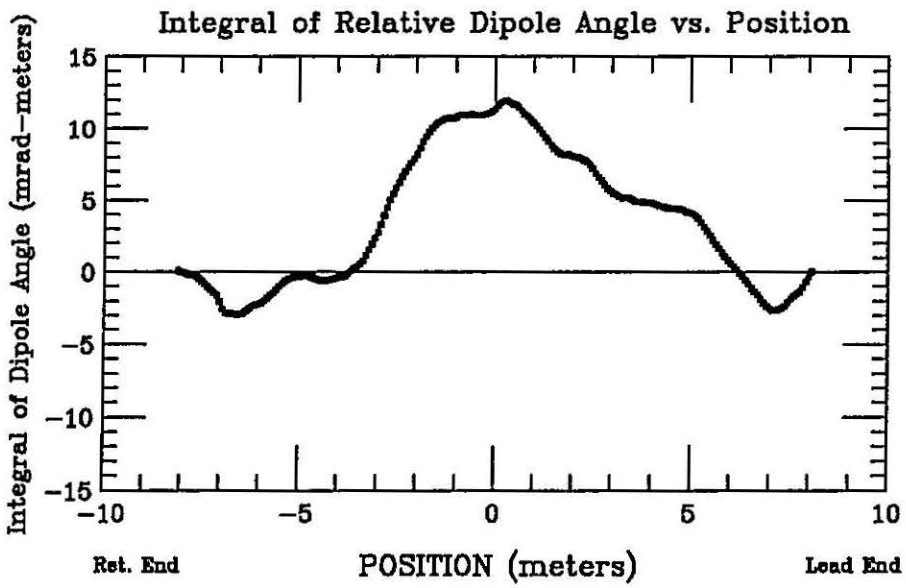
Integral Extrema = 12.01 mrad–m

Measurement out of Cryostat at ICB

DD0013 File 880909







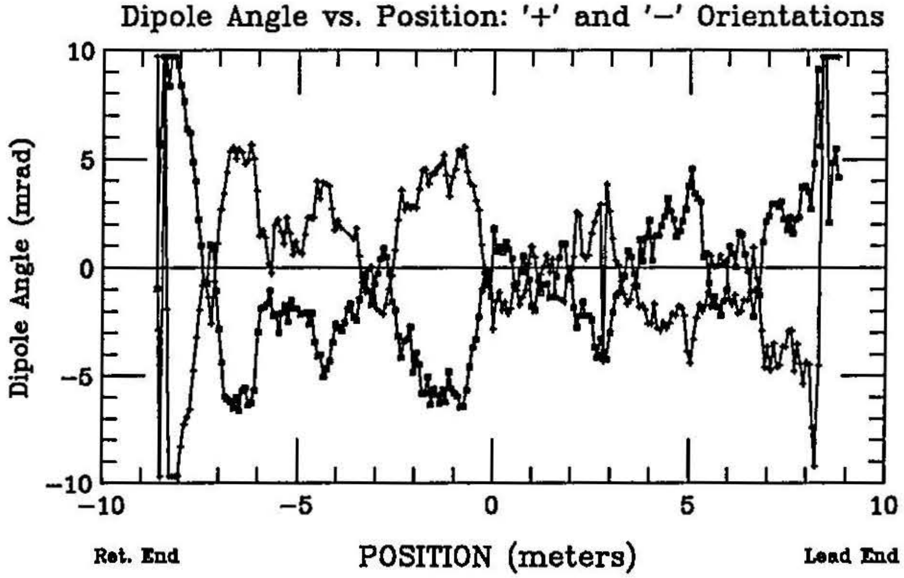
Angle Extrema = −8.50 mrad
(Relative to Average)

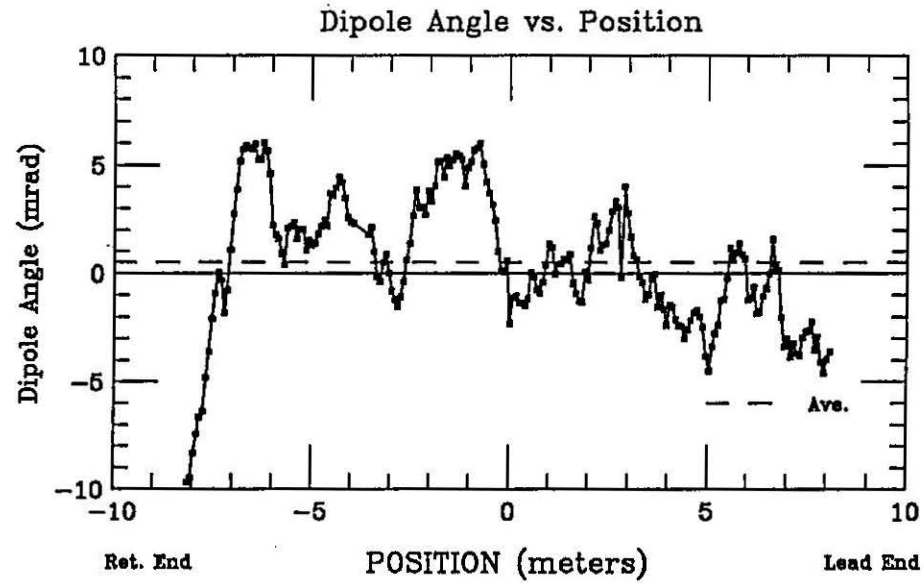
Angle S. Dev. = 2.85 mrad

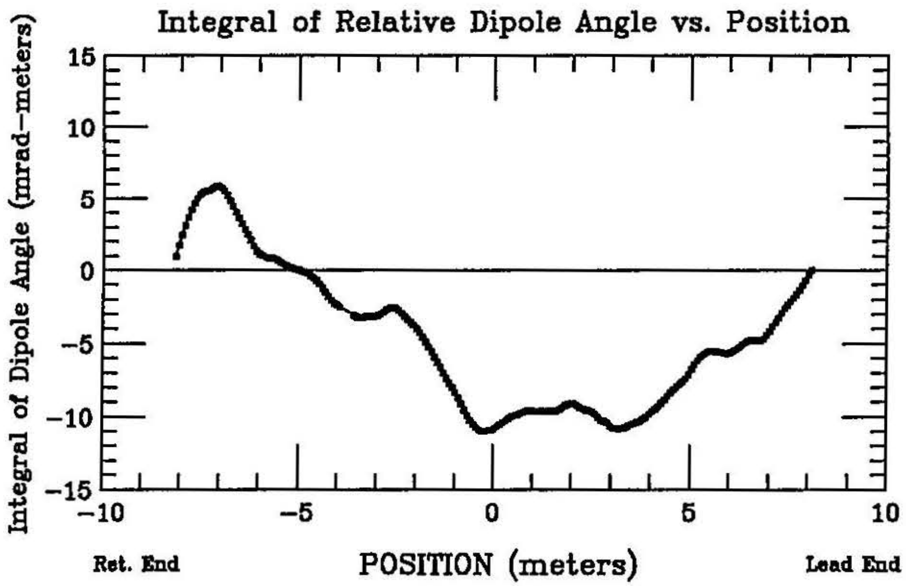
Integral Extrema = 11.94 mrad−m

Measurement before Test at MTF

DD0014 File 880302







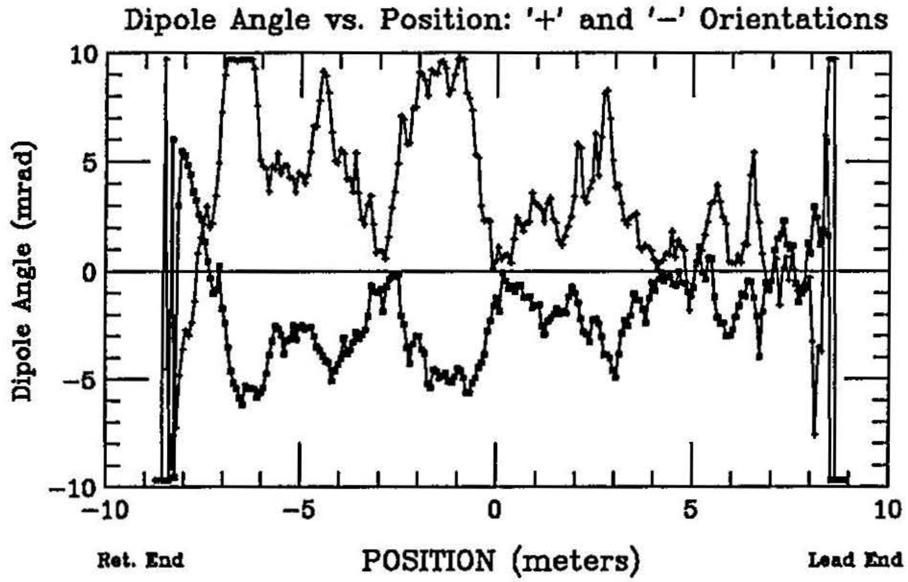
Angle Extrema = −10.21 mrad
(Relative to Average)

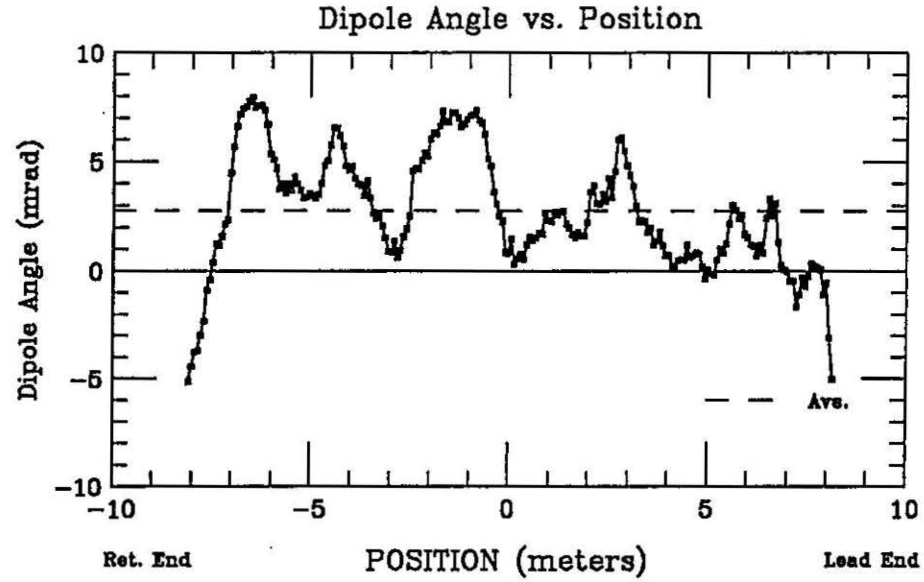
Angle S. Dev. = 3.06 mrad

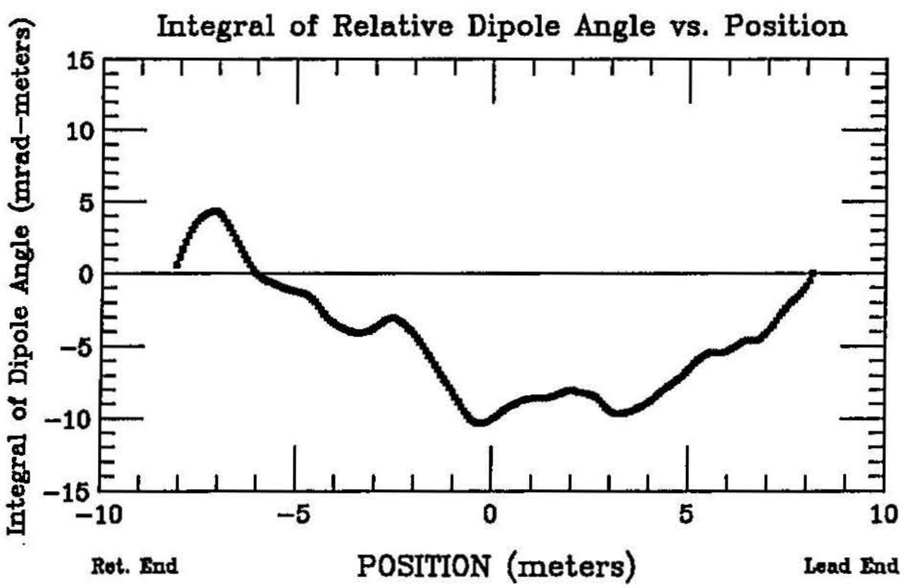
Integral Extrema = −10.97 mrad−m

Measurement out of Cryostat at ICB

DD0014 File 880527







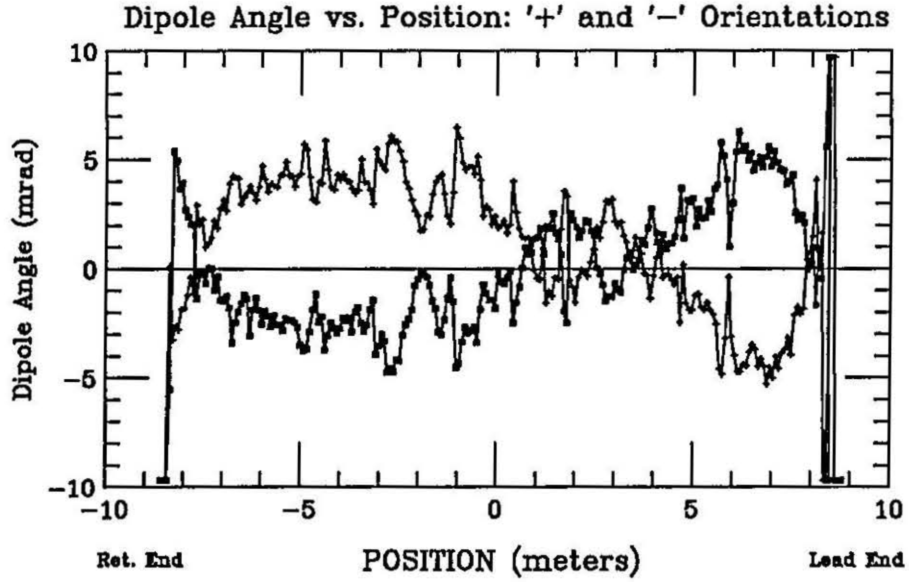
Angle Extrema = −7.89 mrad
(Relative to Average)

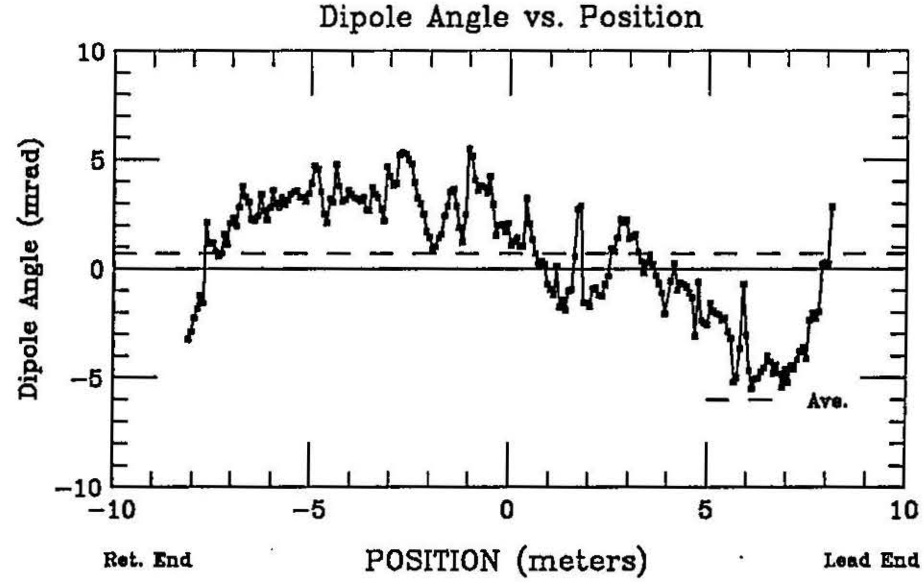
Angle S. Dev. = 2.66 mrad

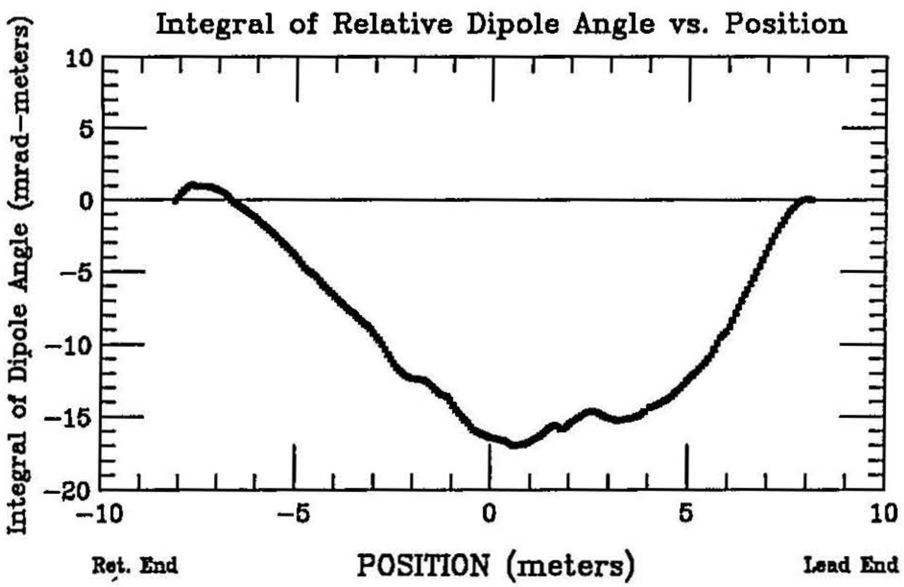
Integral Extrema = −10.34 mrad−m

Measurement before Test at MTF

DD0015 File 880910







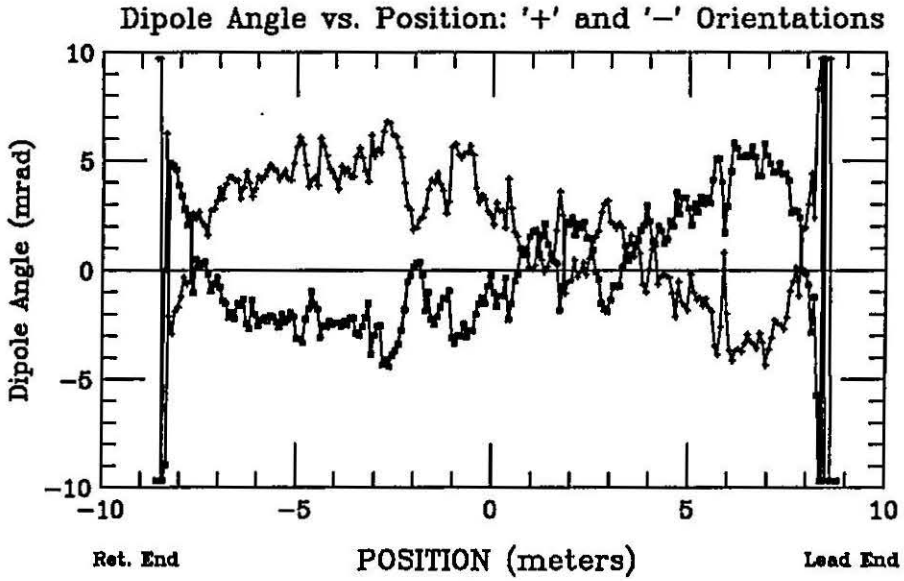
Angle Extrema = −6.20 mrad
(Relative to Average)

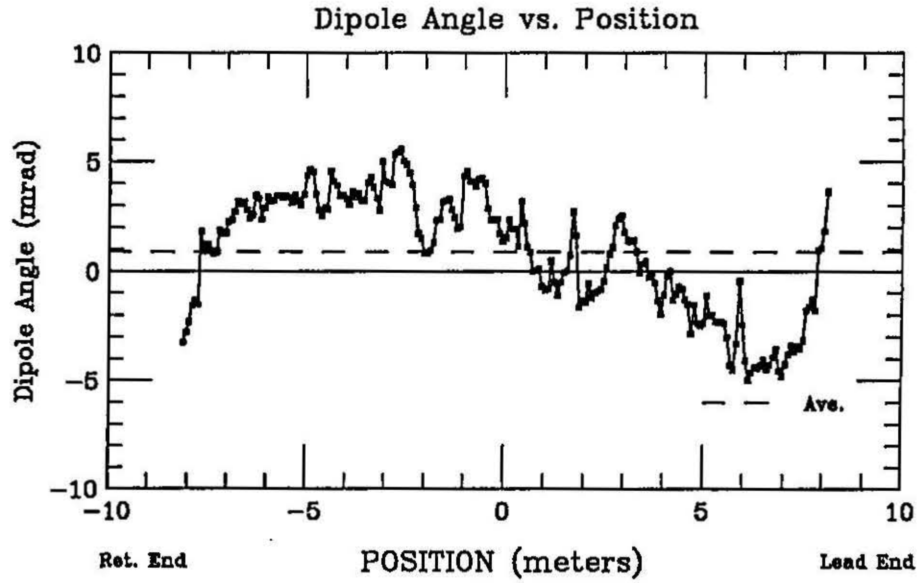
Angle S. Dev. = 2.79 mrad

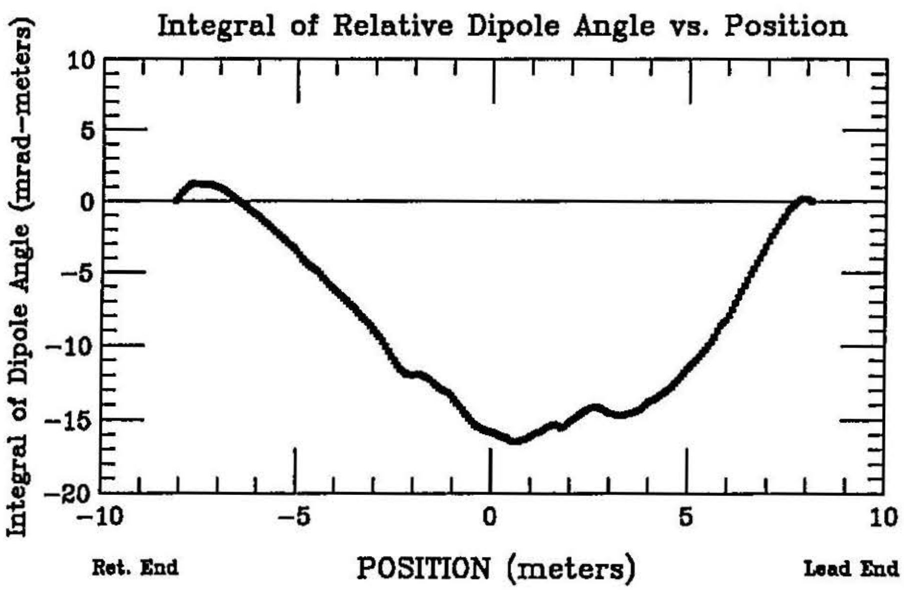
Integral Extrema = −16.97 mrad−m

Measurement out of Cryostat at ICB

DD0015 File 880928







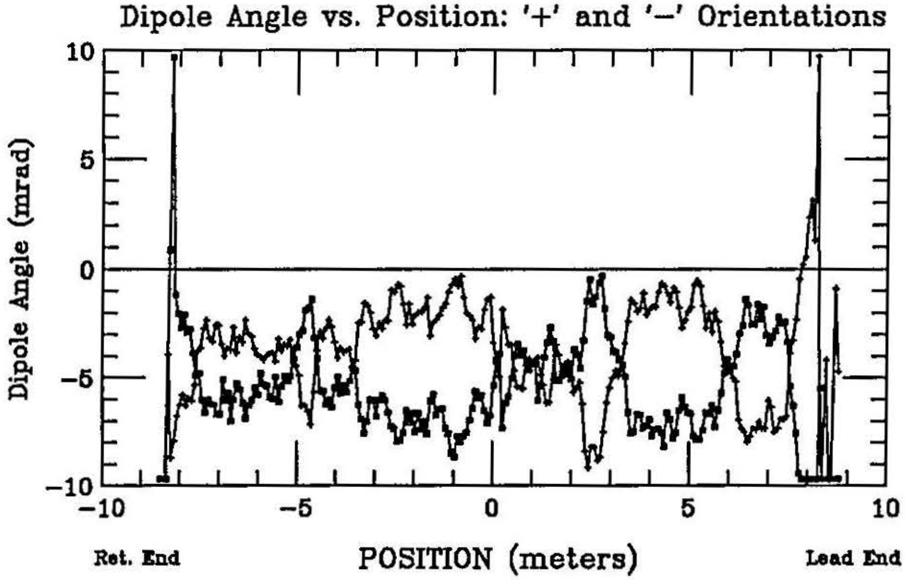
Angle Extrema = −5.84 mrad
(Relative to Average)

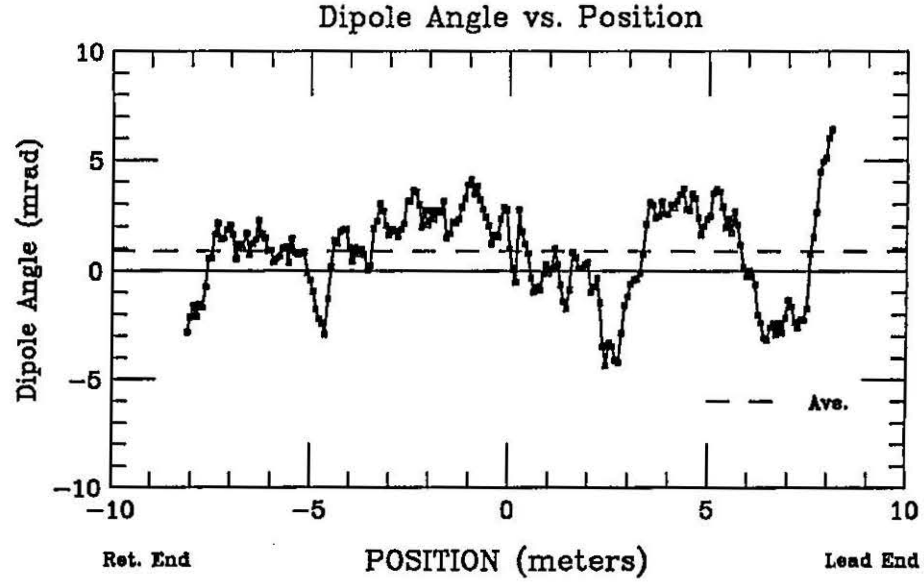
Angle S. Dev. = 2.69 mrad

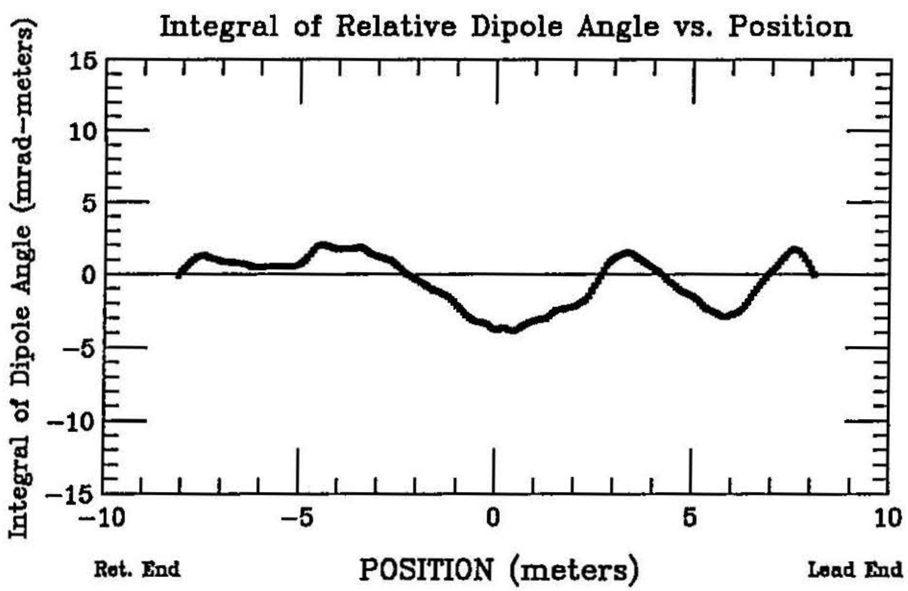
Integral Extrema = −16.44 mrad−m

Measurement before Test at MTF

DD0016 File 881230







Angle Extrema = 5.53 mrad
(Relative to Average)

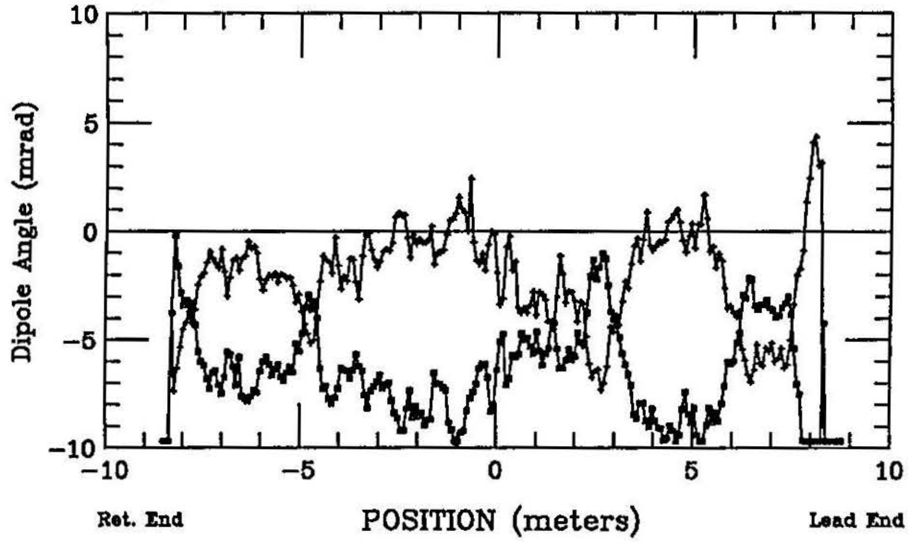
Angle S. Dev. = 2.05 mrad

Integral Extrema = −3.84 mrad−m

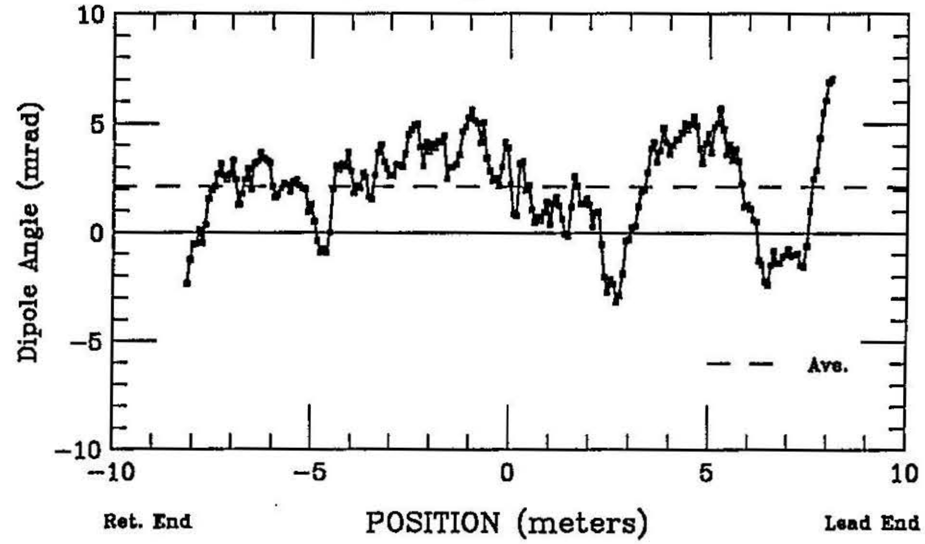
Measurement out of Cyostat at ICB

DD0016 File 890119

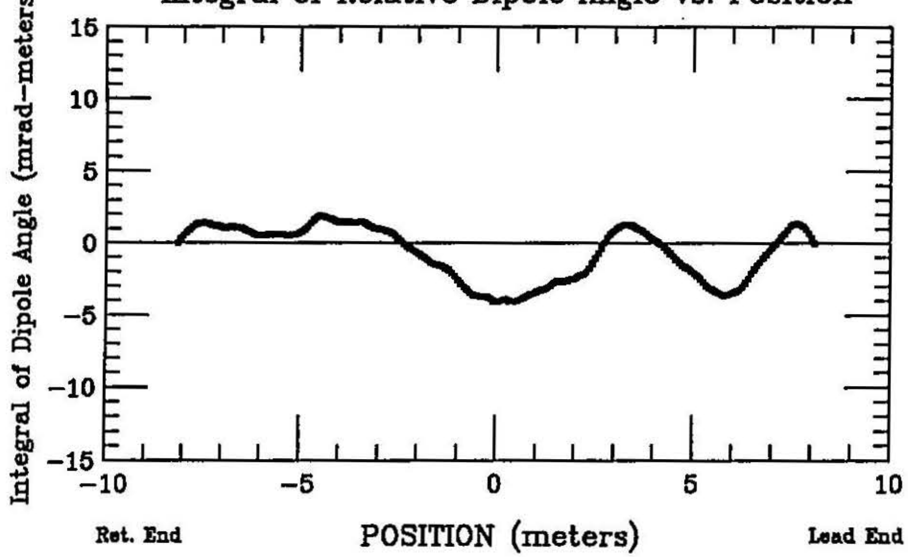
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



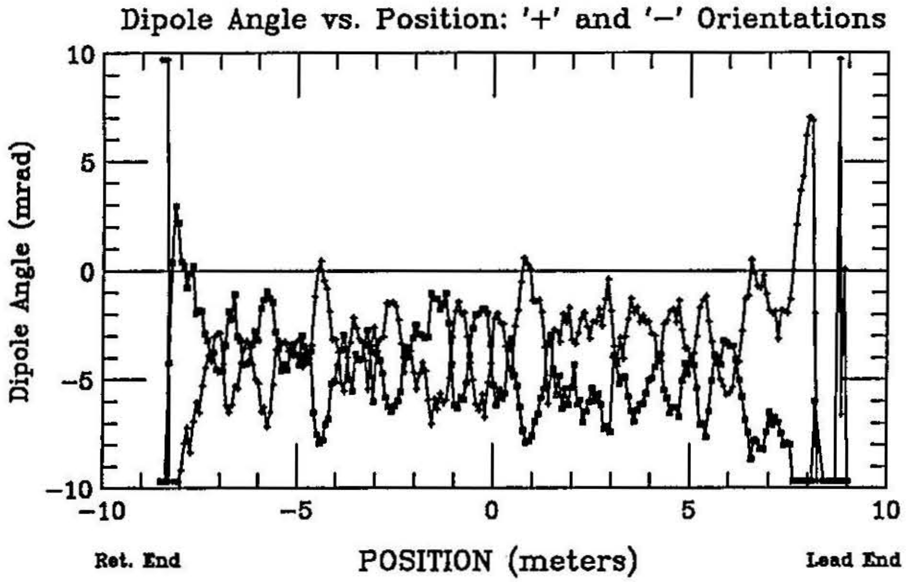
Angle Extrema = −5.28 mrad
(Relative to Average)

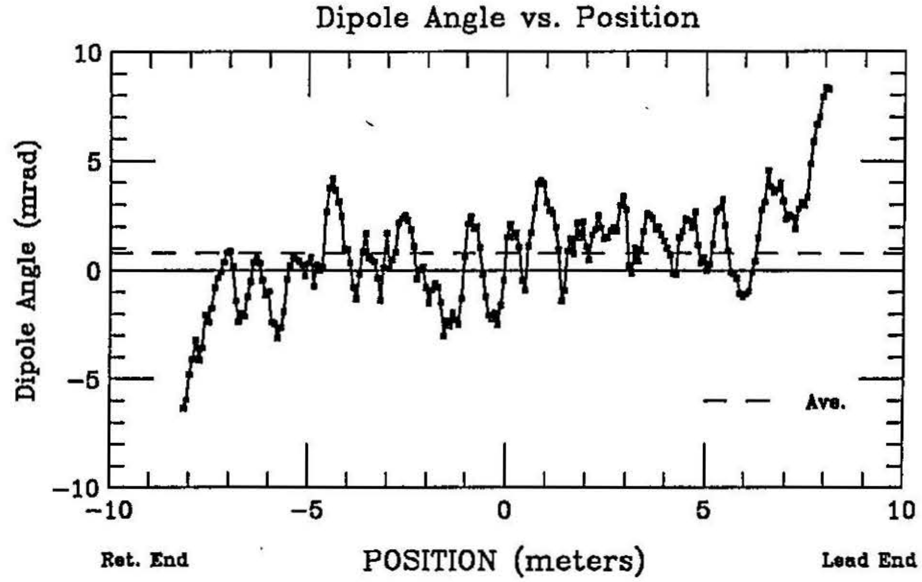
Angle S. Dev. = 2.09 mrad

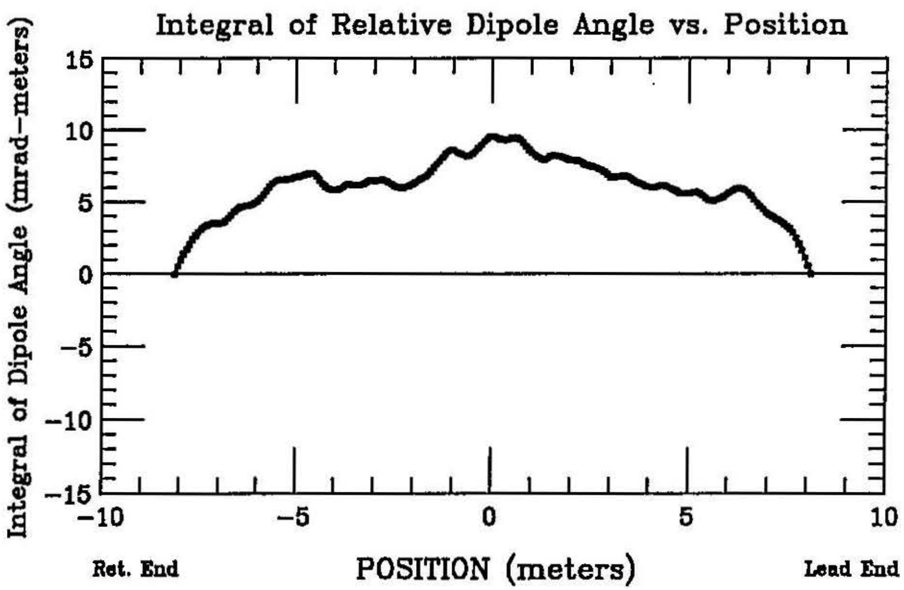
Integral Extrema = −4.09 mrad−m

Measurement before Test at MTF

DD0017 File 890203







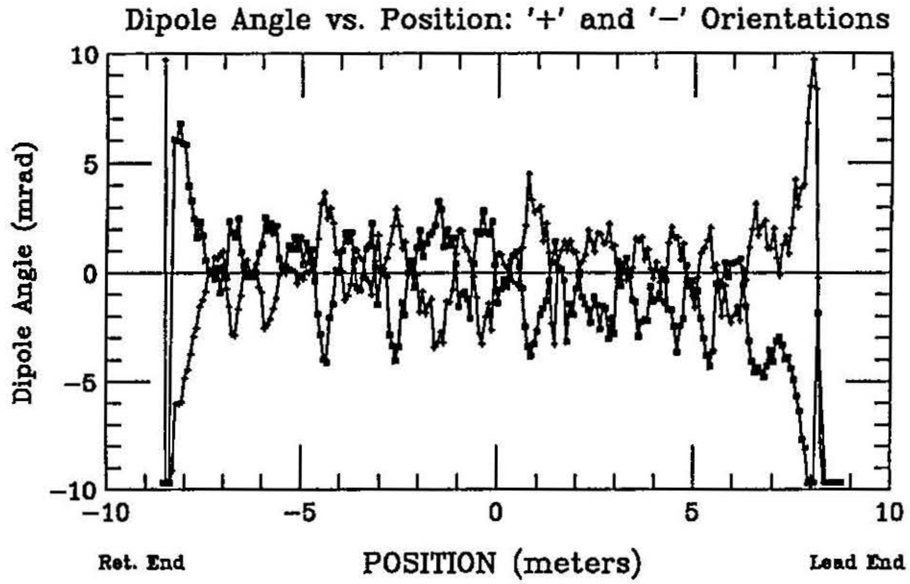
Angle Extrema = 7.56 mrad
(Relative to Average)

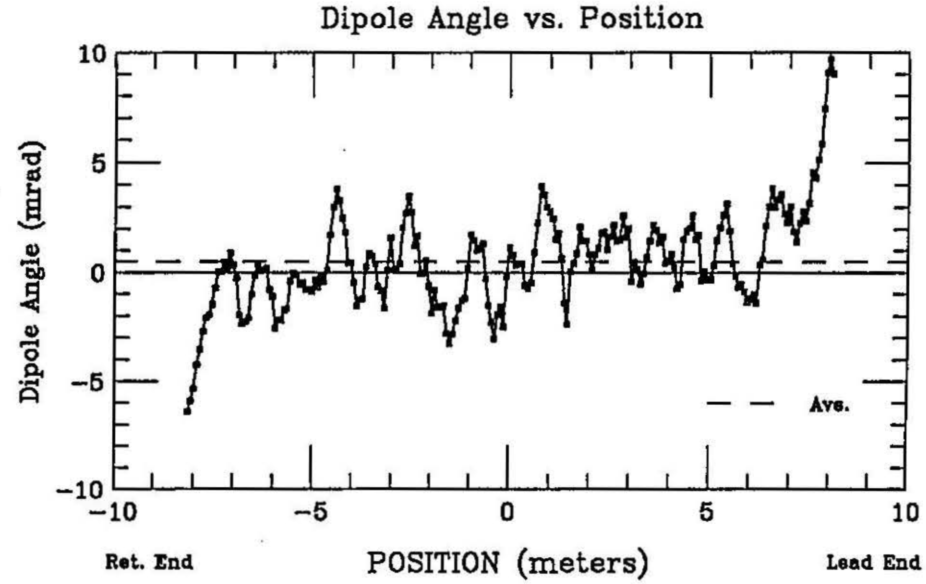
Angle S. Dev. = 2.26 mrad

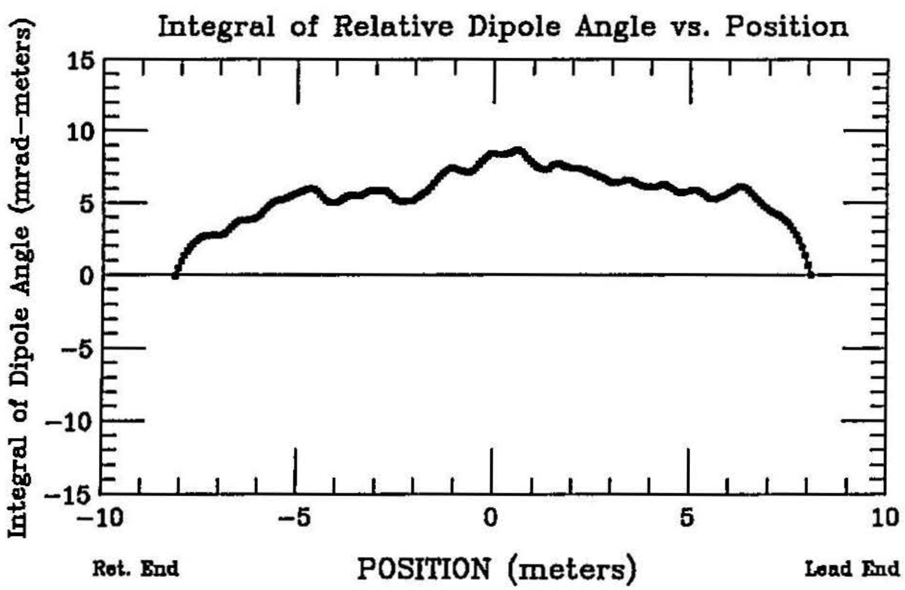
Integral Extrema = 9.55 mrad−m

Measurement before Cold Test at MTF

DD0017 File 890927







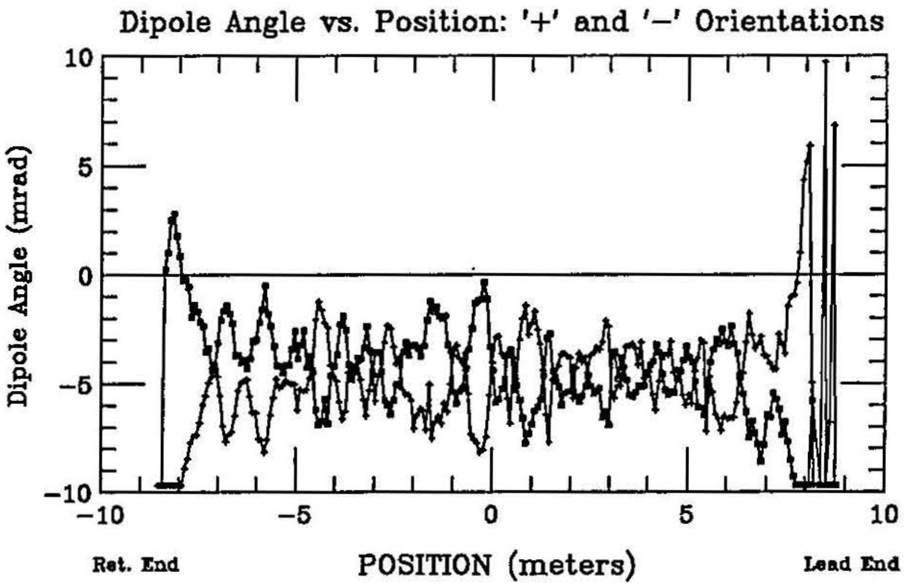
Angle Extrema = 9.19 mrad
(Relative to Average)

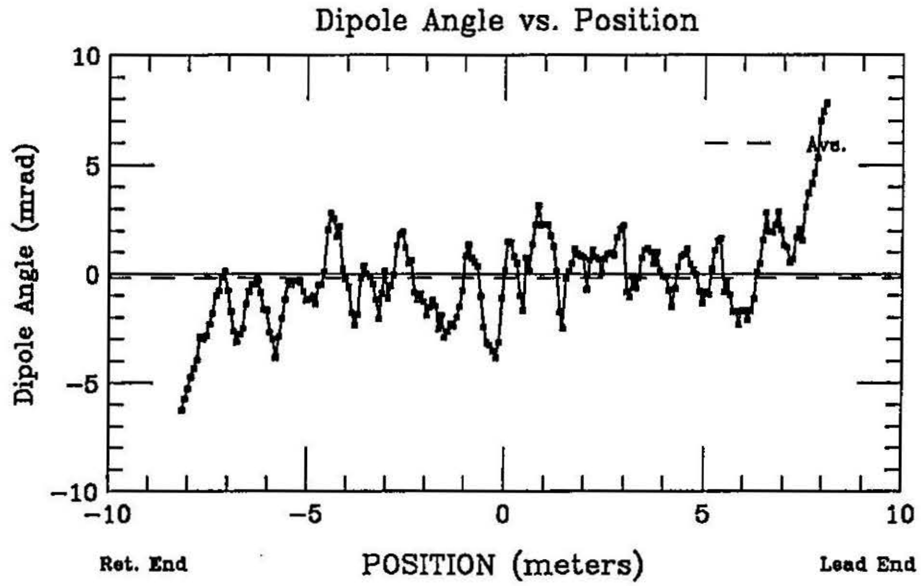
Angle S. Dev. = 2.22 mrad

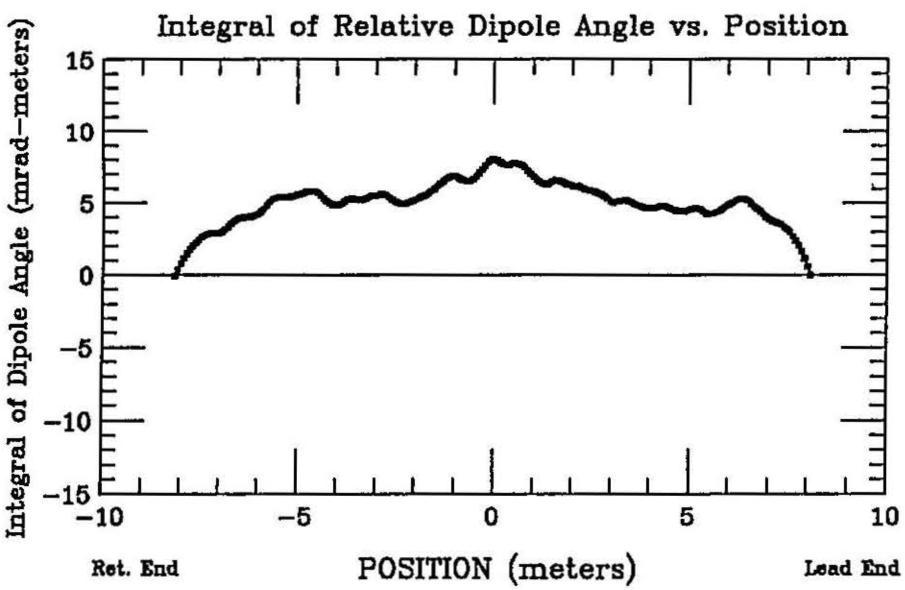
Integral Extrema = 8.64 mrad−m

Measurement after Cold Test at MTF

DD0017 File 890117







Angle Extrema = 8.00 mrad
(Relative to Average)

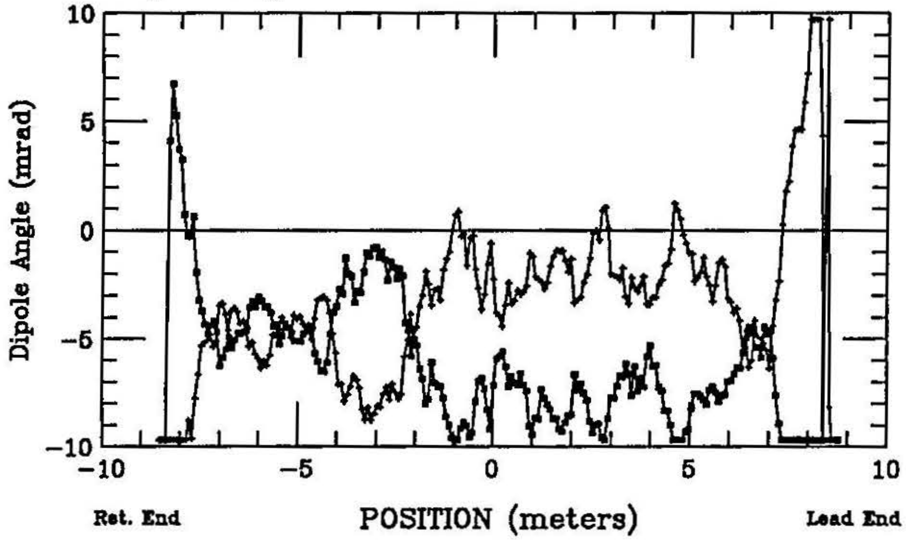
Angle S. Dev. = 2.05 mrad

Integral Extrema = 8.03 mrad−m

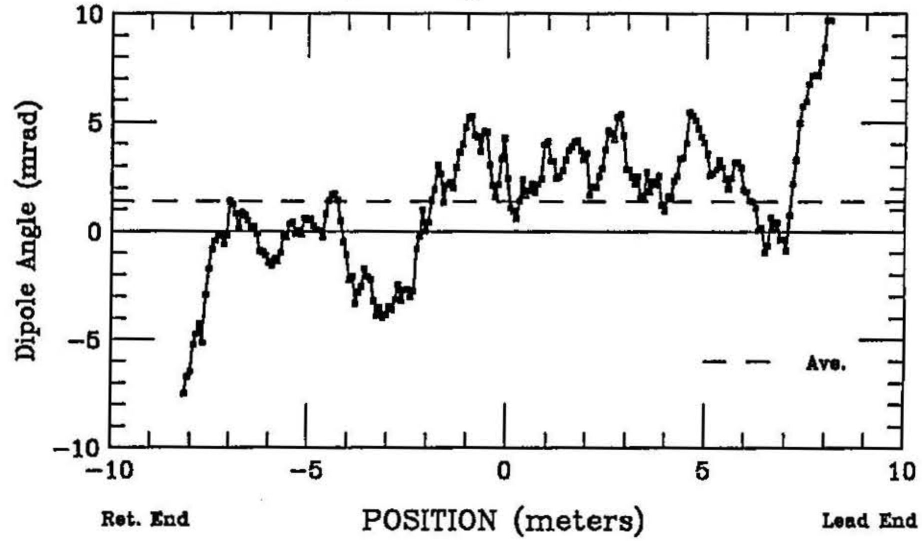
Measurement out of Cryostat at ICB

DD0018 File 890302

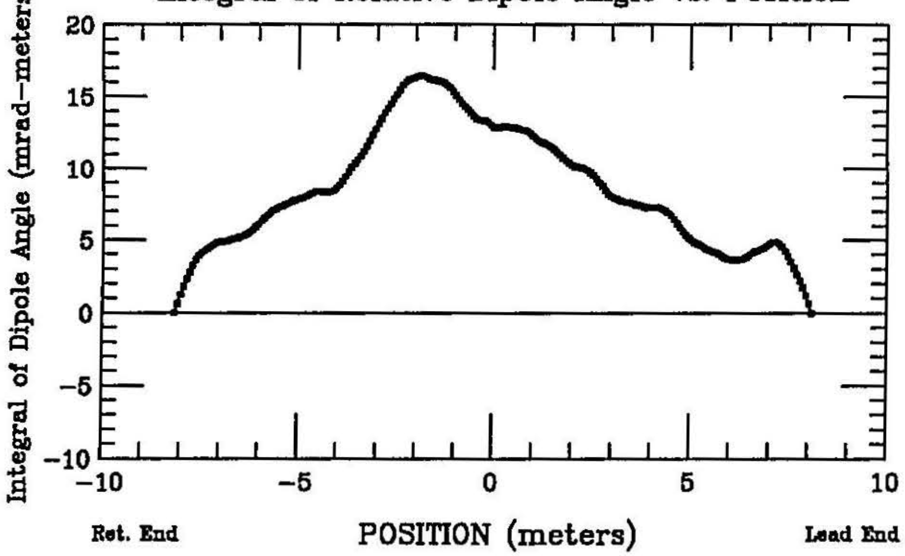
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



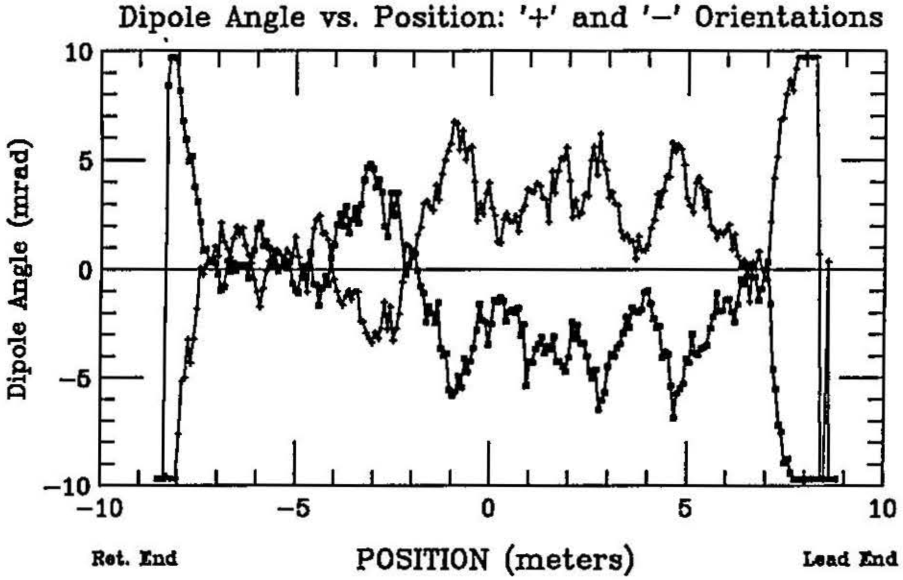
Angle Extrema = −8.87 mrad
(Relative to Average)

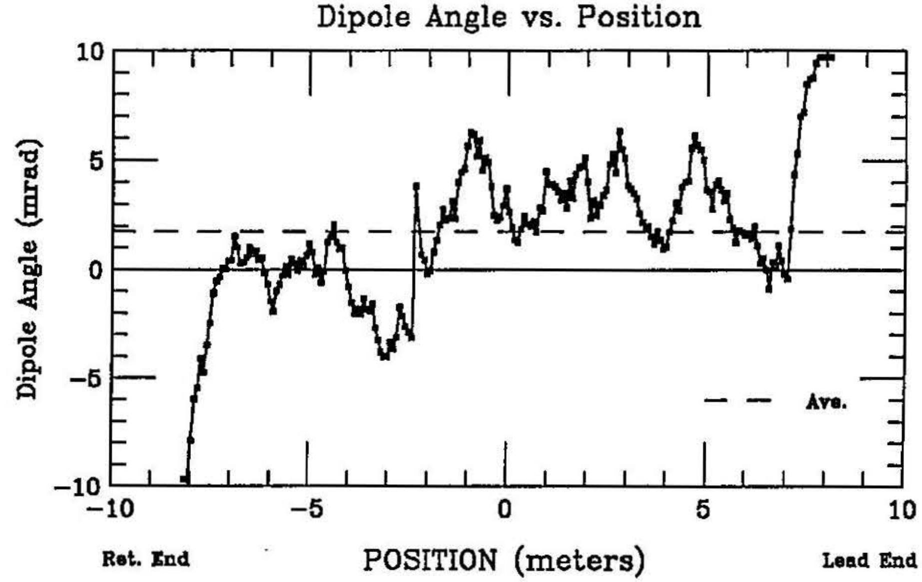
Angle S. Dev. = 2.89 mrad

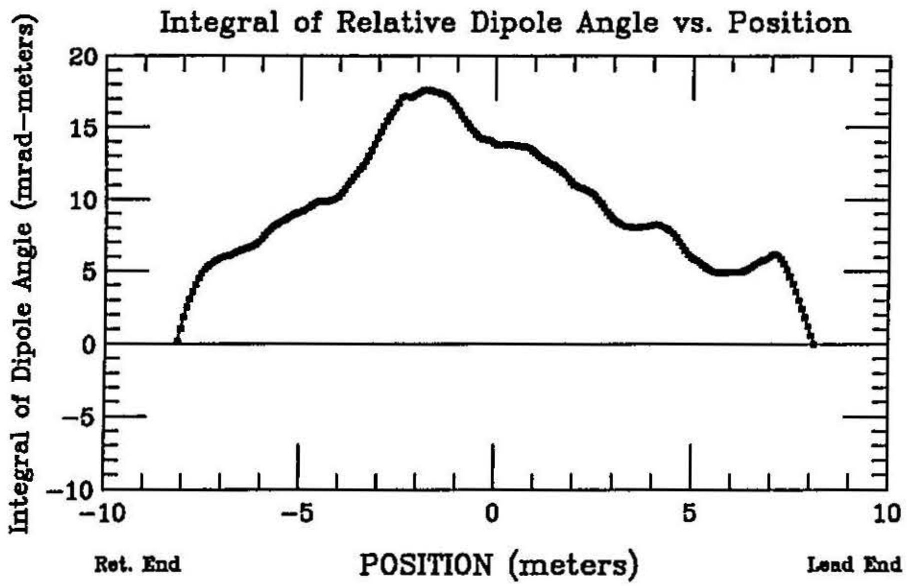
Integral Extrema = 16.44 mrad−m

Measurement out of Cryostat at ICB

DD0018 File 890721







Angle Extrema = −11.43 mrad
(Relative to Average)

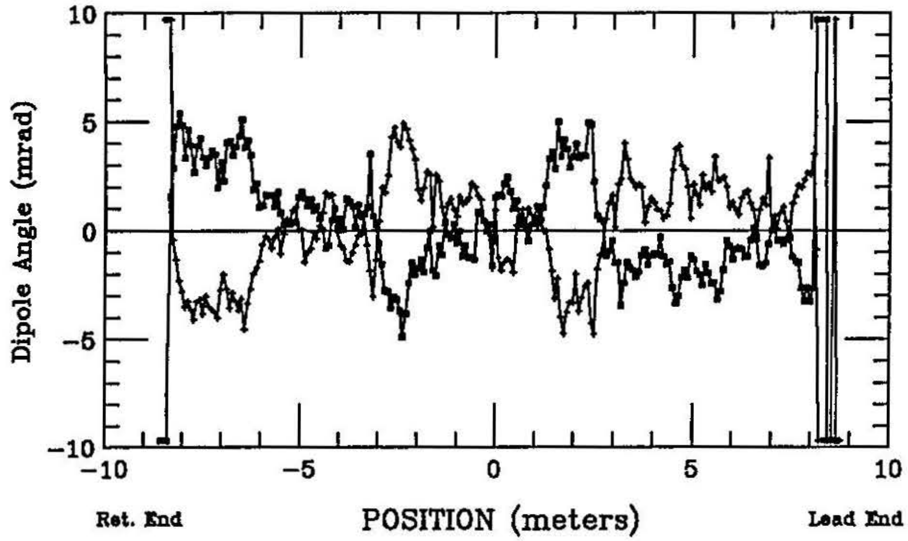
Angle S. Dev. = 3.24 mrad

Integral Extrema = 17.62 mrad−m

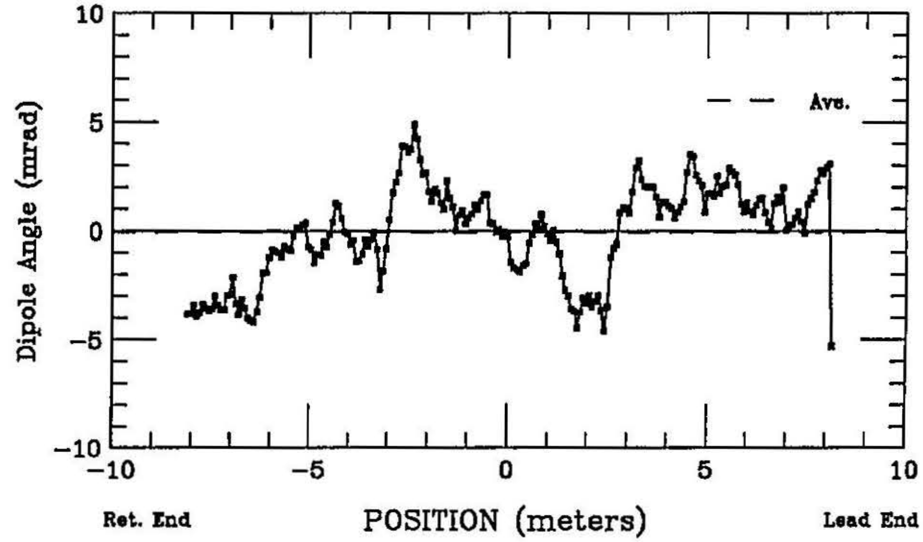
Measurement after Test at MTF

DD0019 File 890812

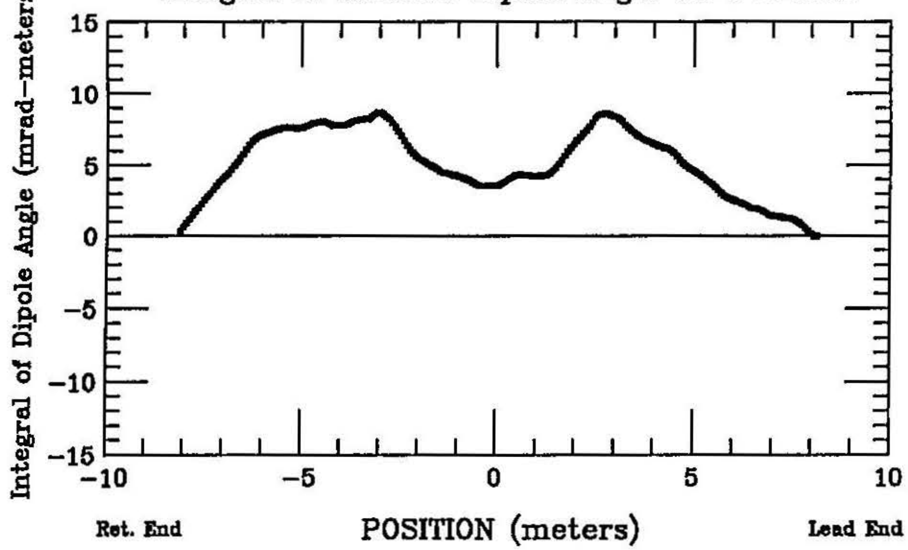
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



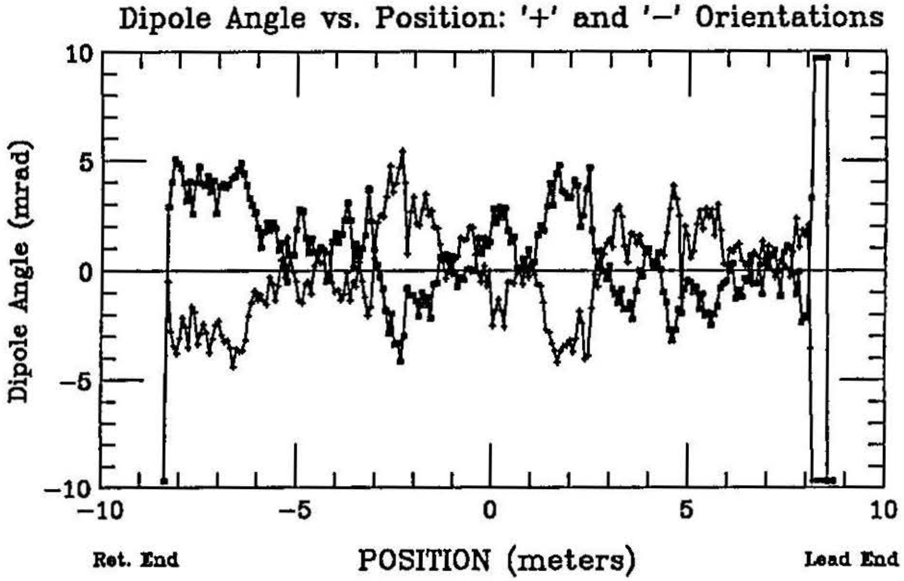
Angle Extrema = −5.22 mrad
(Relative to Average)

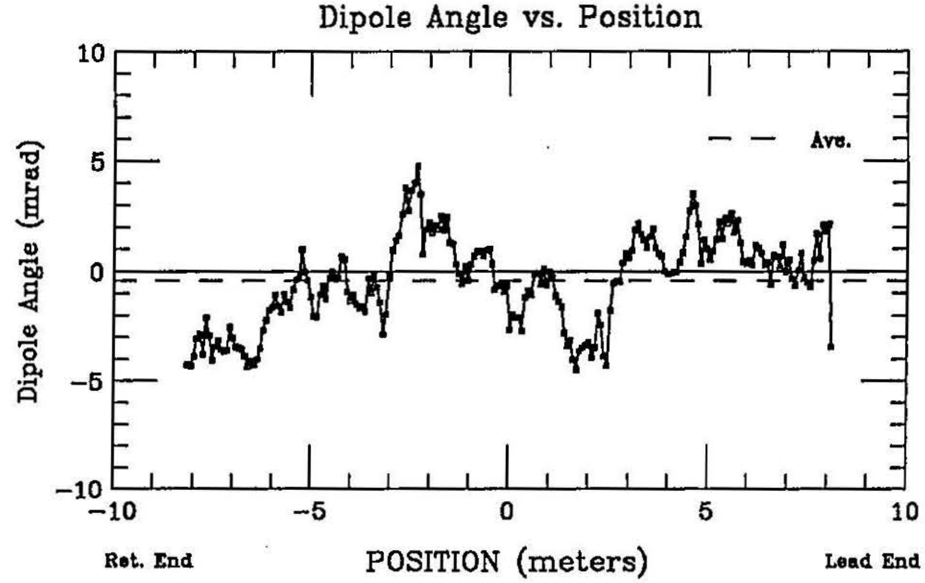
Angle S. Dev. = 2.16 mrad

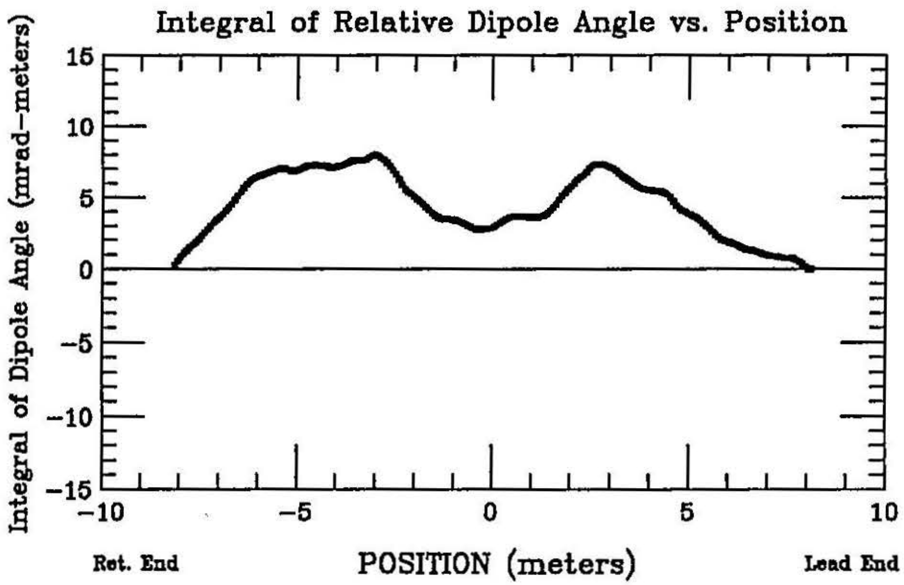
Integral Extrema = 8.63 mrad−m

Measurement out of Cryostat at ICB

DD0019 File 890828







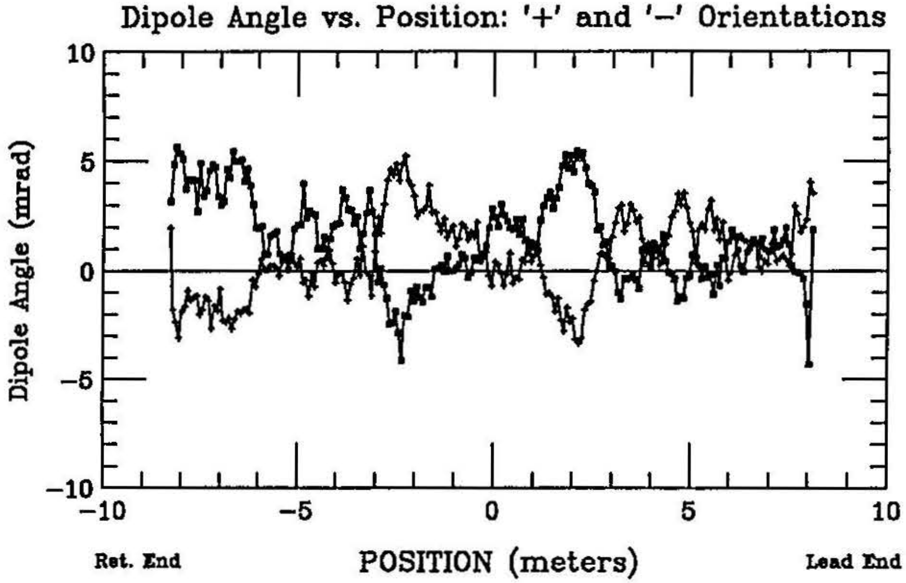
Angle Extrema = 5.22 mrad
(Relative to Average)

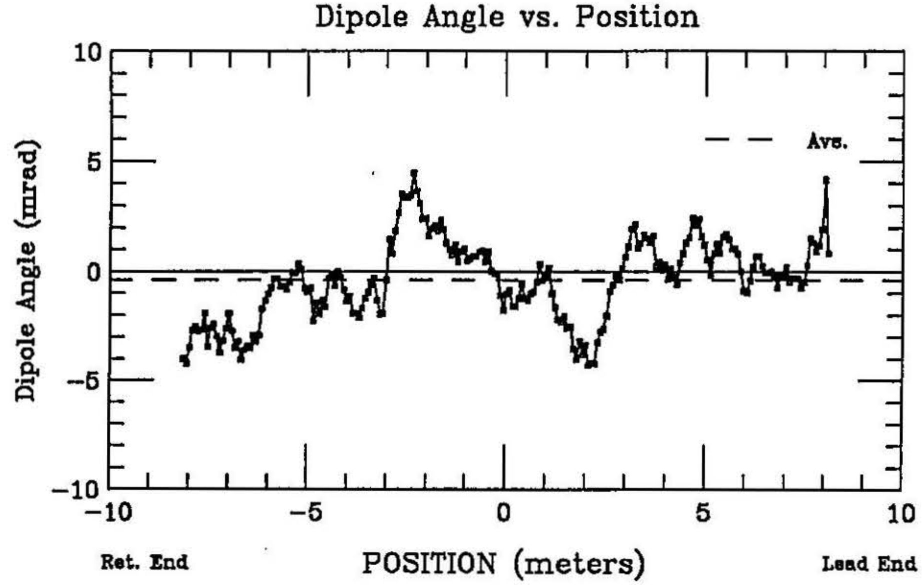
Angle S. Dev. = 2.01 mrad

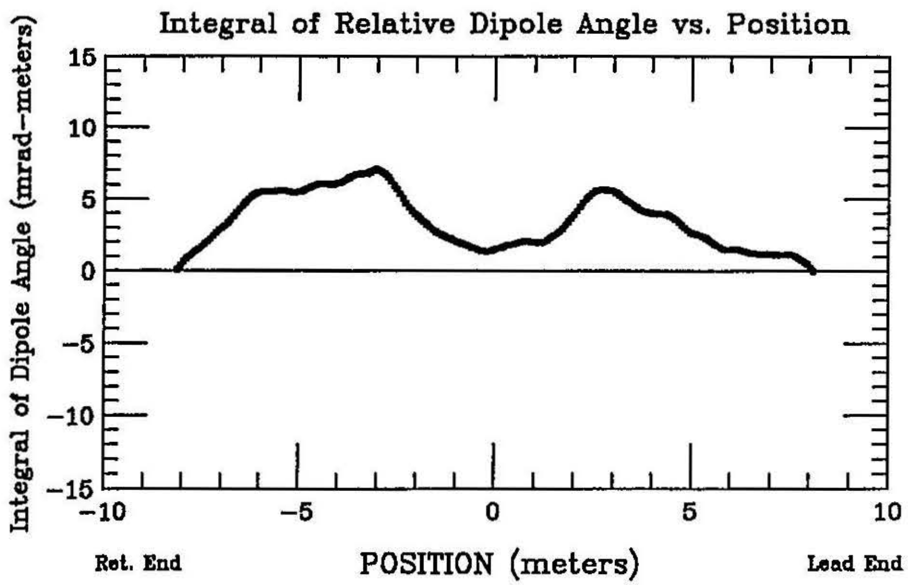
Integral Extrema = 7.99 mrad−m

Measurement before Test at MTF

DD0019 File 900209







Angle Extrema = 4.88 mrad
(Relative to Average)

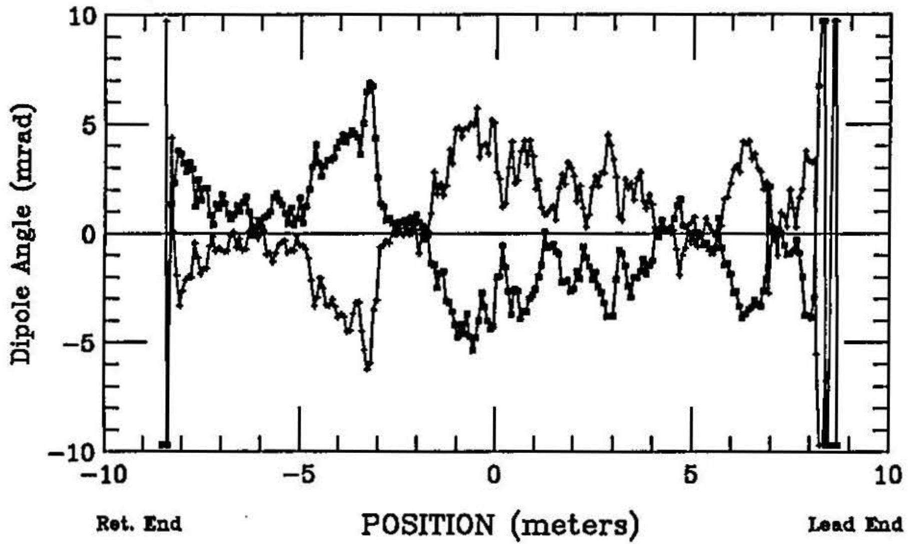
Angle S. Dev. = 1.84 mrad

Integral Extrema = 7.06 mrad−m

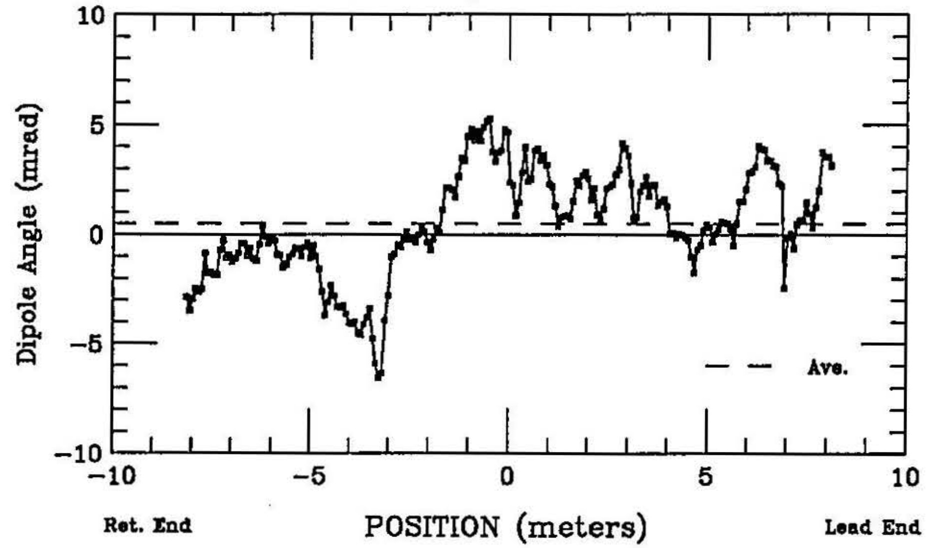
Measurement at MTF before Removal

DD0026 File 890911

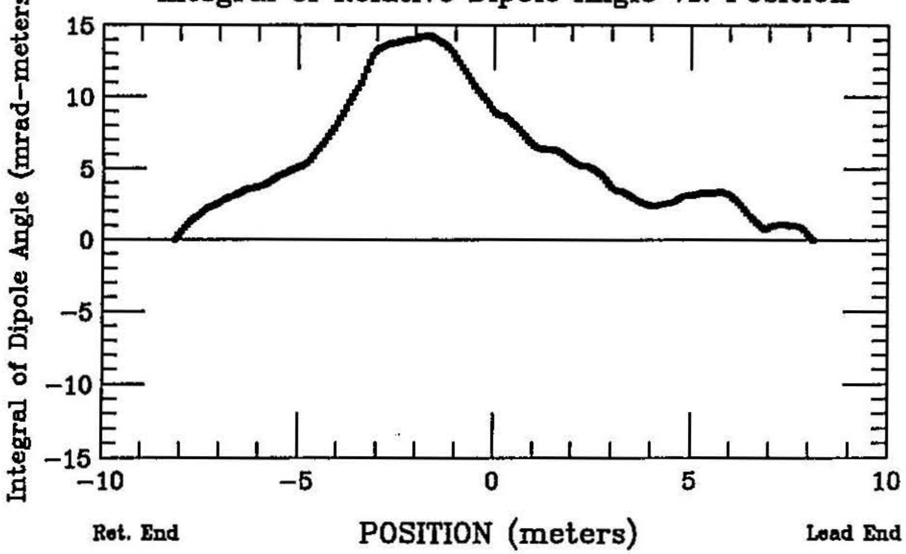
Dipole Angle vs. Position: '+' and '−' Orientations



Dipole Angle vs. Position



Integral of Relative Dipole Angle vs. Position



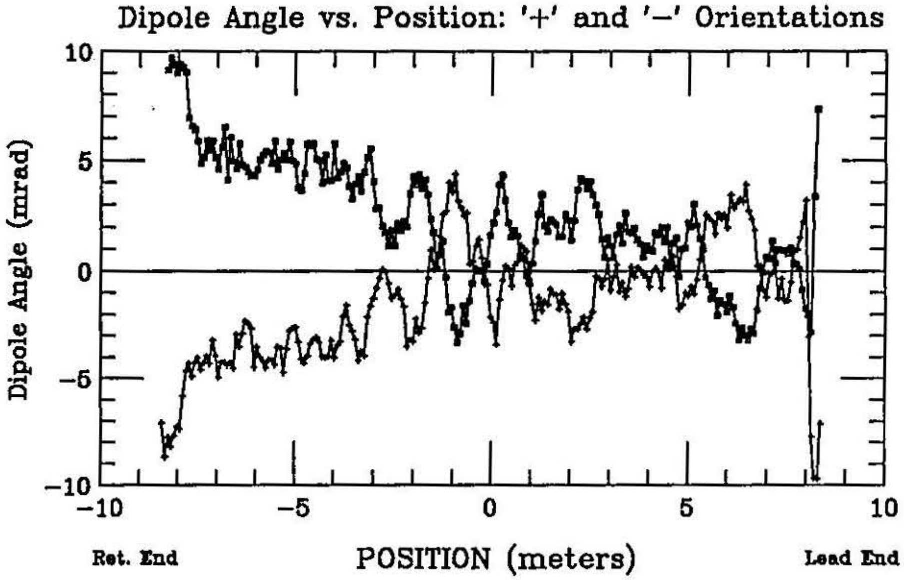
Angle Extrema = −7.04 mrad
(Relative to Average)

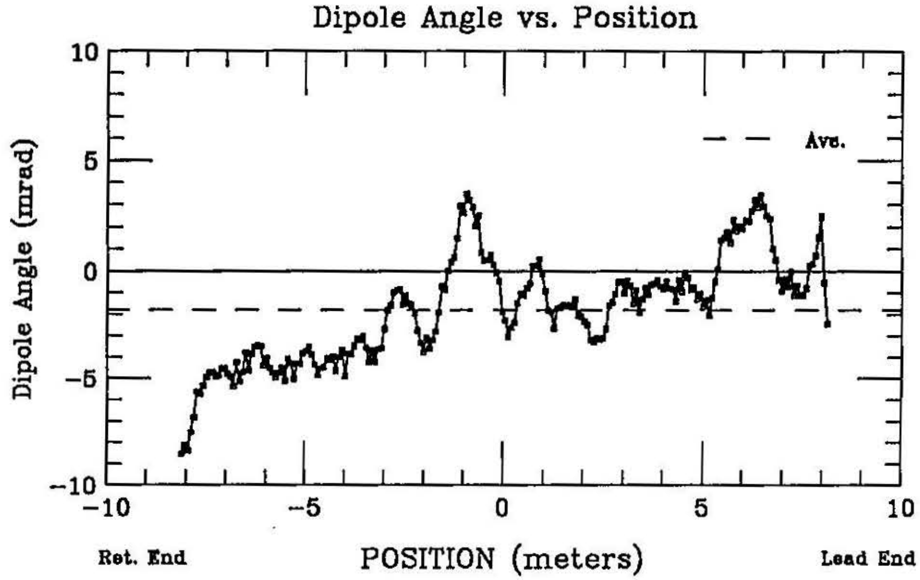
Angle S. Dev. = 2.41 mrad

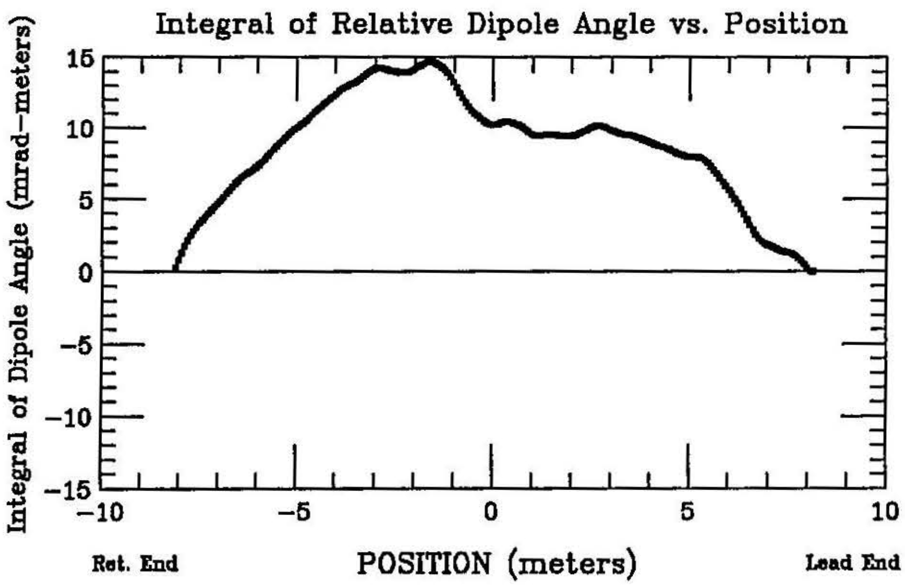
Integral Extrema = 14.26 mrad−m

Measurement out of Cryostat at ICB

DD0027 File 900208







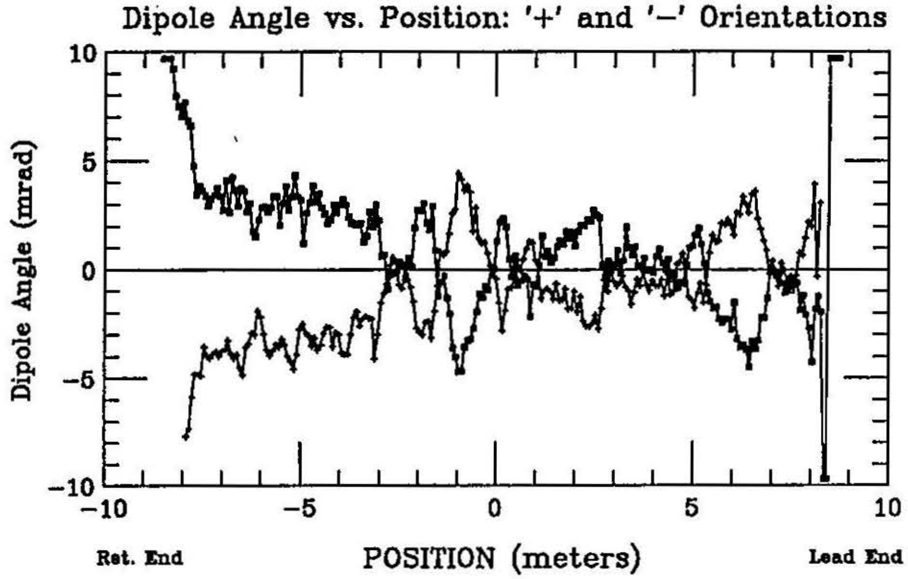
Angle Extrema = −6.74 mrad
(Relative to Average)

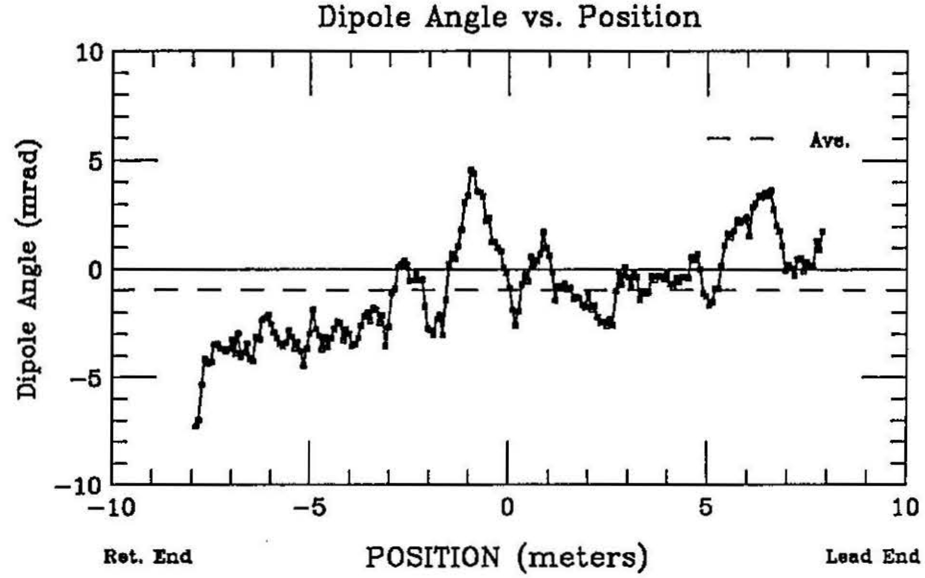
Angle S. Dev. = 2.43 mrad

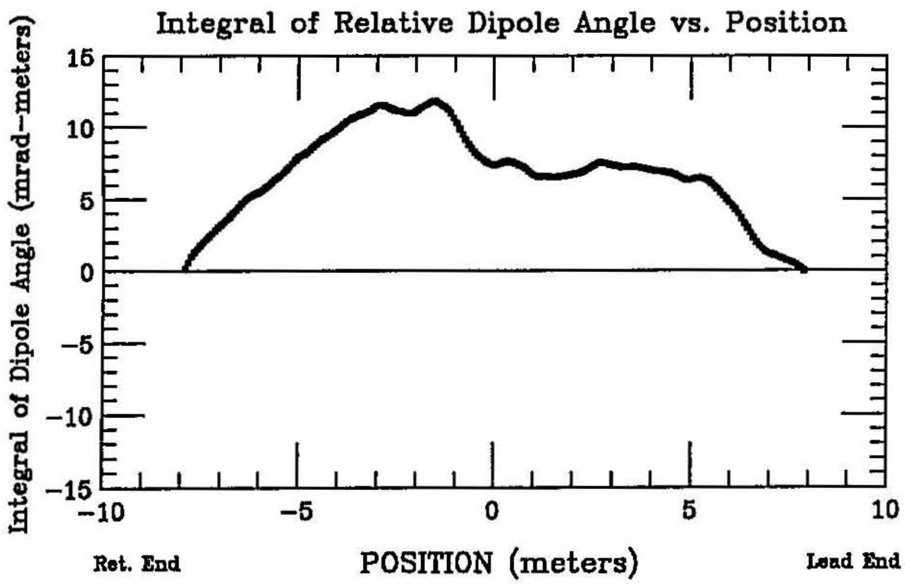
Integral Extrema = 14.69 mrad−m

Measurement aat ICB

DD0027 File 901011







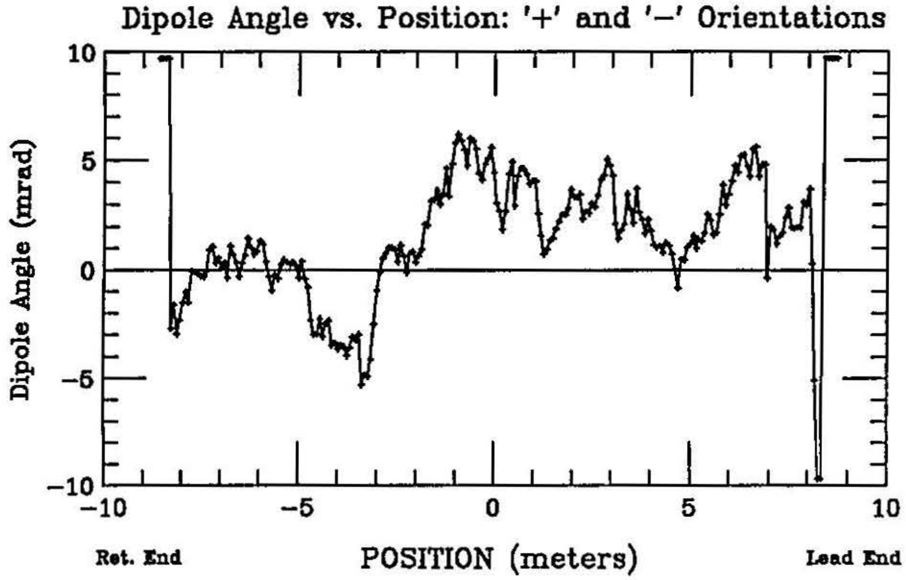
Angle Extrema = −6.30 mrad
(Relative to Average)

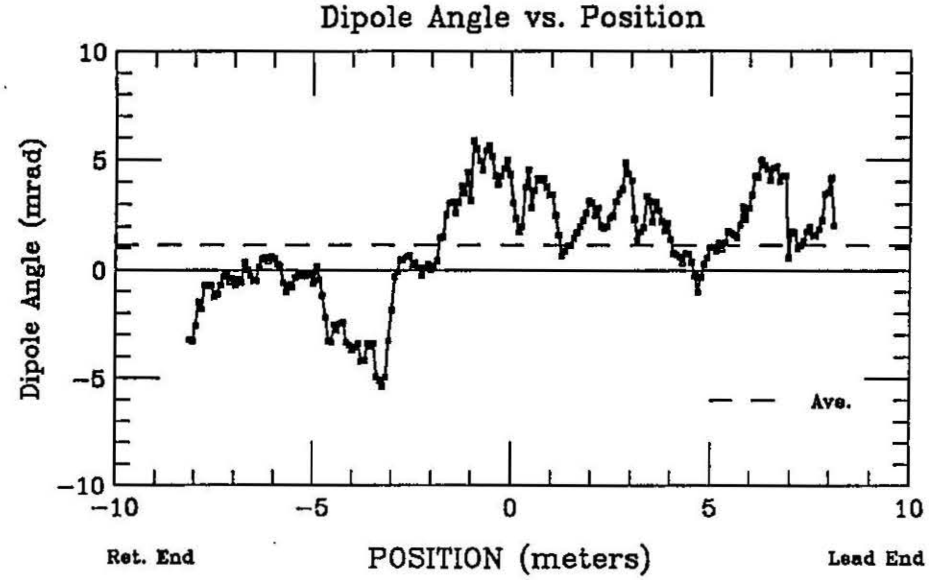
Angle S. Dev. = 2.18 mrad

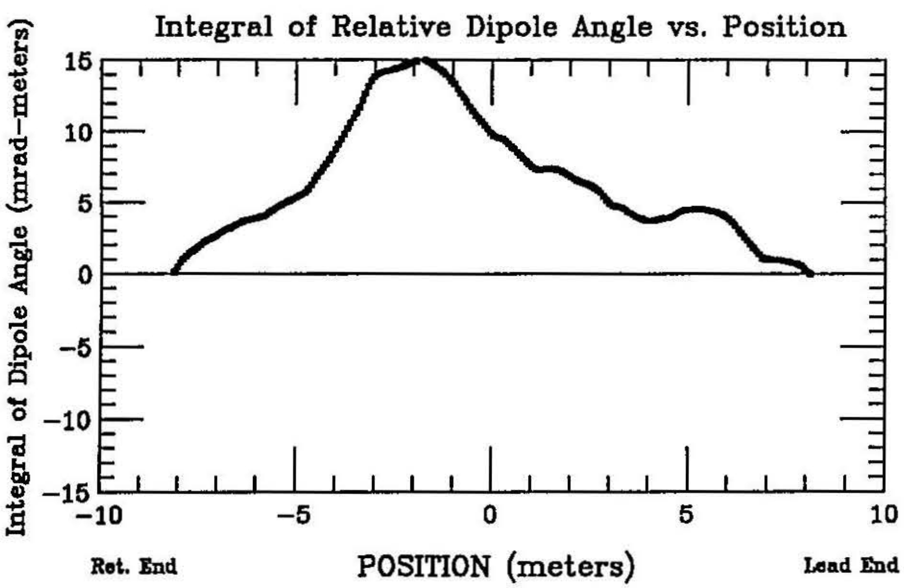
Integral Extrema = 11.82 mrad−m

Measurement after Cold Test at MTF

DD0026 File 891010







Angle Extrema = −6.51 mrad
(Relative to Average)

Angle S. Dev. = 2.43 mrad

Integral Extrema = 15.01 mrad−m

Measurement before Test at MTF