Fermilab

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From: Jim Strait
Subj: Notes on Tangential Probes: Example Calculations

In this note I give some example calculations of the probe sensitivity factors F_n and γ_n for a particular DDL probe that Peter Mazur had made for measuring main ring magnets several years ago. I also show the effects of several manufacturing errors. The calculations were done for a probe with a radius $r = 14.78$ mm, a length $l = 1.524$ m, a tangential winding half opening angle $\beta = 11.54^{o}$, 20 turns in the tangential winding, and 4 turns in the dipole bucking winding. The ratio of numbers of turns and the opening angle give a bucking factor of -1, as shown at the bottom of page 5 in reference [2]. This allows the two windings to be wired in series and out of phase to yield a probe with no sensitivity to the dipole signal. In the calculations below the tangential and dipole windings are assumed to have the same radii and lengths.

A FORTRAN program TANGENTIAL was used to calculate F_n and γ_n for the tangential winding alone (unbucked) and with the tangential and dipole windings wired in series (bucked). A series of runs were made with the windings at their nominal positions and with individual windings moved by 0.025 mm azimuthally and radially. The latter give a feeling for the sensitivity to plausible manufacturing errors.

On page 3 of Reference [1] the factors C_n, S_n, F_n and γ_n are defined. The first three are proportional to lr^{n+1}. This means that their values depend on the units of measure and, more annoyingly, the ratios of values for different harmonics depend also on the units of measure. For high harmonics r^{n+1} becomes sufficiently large or small, depending on the units chosen, to make numerical calculations difficult. It makes sense to redefine C_n, S_n and F_n by dividing them by the reference radius ρ^{n+1}. In this case the value of F_n still depends on the the units through the probe length but the ratio of F_n's for different values of n does not. With this modified definition the probe voltage for harmonic n at the bottom of page 3 of Ref. [1] becomes

$$V_n = B_o \omega \rho h_n F_n \sin(\bar{n}\omega t + \alpha_n + \gamma_n)$$

and the integrated voltage on page 4 becomes

$$\Phi_n = (1/\bar{n}) B_o \rho F_n h_n \cos(\bar{n}\omega t + \alpha_n + \gamma_n - \pi).$$

The multipole amplitude h_n and phase α_n are given in terms of the Fourier amplitude A_n and phase δ_n by

$$h_n = \frac{\bar{n} A_n}{B_o \rho F_n} \qquad \text{and} \qquad \alpha_n = \delta_n - \gamma_n - \bar{n}\psi + \pi,$$

where $\bar{n} = n+1$.

Figure 1 shows the sensitivity factor F_n for the example probe as a function of the multipole number n, where n = 0 is the dipole. The reference radius ρ is set to the probe radius. The sensitivity of the unbucked tangential winding varies smoothly with harmonic number and peaks at n = 7 (the 16-pole). This makes sense because the opening angle of 23.08° is close to the 22.50° spacing between windings of a 16-pole Morgan coil. The probe sensitivity goes to zero between n = 14 and n = 15. (F_n is exactly zero for $n+1 = 180^\circ/\beta$ or n = 14.6.) With the dipole coil signal subtracted from the tangential winding (bucked signal) the sensitivity to all allowed harmonics is affected; sensitivity to every other allowed multipole is enhanced or suppressed.

Figure 2 shows the phase factor γ_n. It advances by 90° from one harmonic to the next, except for an additional 180° advance as the sensitivity F_n goes through zero. The phase factor is unaffected by the bucking.

To determine the sensitivity of the probe to manufacturing errors the tangential winding segment at $90^\circ - \beta$ (#1 on page 1 of Ref [1]) and the dipole winding segment at $\phi = 0$ were moved azimuthally and radially by 0.025 mm

(1 mil). The fractional change in F_n for each of the four distortions is shown in Figure 3 as a function of n up to the zero in F_n. The effect stays within about ±1% for n up to 11 (24-pole). The change in the phase factor γ_n is shown in Figure 4. The phase shift is less than $\pm 1^o$ for $n \leq 11$, corresponding to a normal-skew mixing of ≤ 2%. The current SSC multipole specification extends to the 18-pole and in the near future will be extended to the 22-pole. Therefore this probe would be suitable for measuring the SSC dipoles.

If the probe were perfectly made the bucked signal would have no sensitivity to the dipole field. The effect on F_o of the four manufacturing errors is give in the table below.

Manufacturing Error	F_o
None	0.000
$r\Delta\phi$(tangential) = 0.025 mm	0.010
$r\Delta\phi$(dipole) = 0.025 mm	0.010
Δr(tangential) = 0.025 mm	0.051
Δr(dipole) = 0.025 mm	0.000

The largest F_o results from moving the tangential winding radially, which is the distortion that makes it and the dipole winding most non-parallel. In this case F_o is $2\text{x}10^{-3}$ times the smallest F_n for $1 \leq n \leq 11$. However, since the dipole field is 10^4 times larger than the typical harmonic, the dipole signal will still be the dominant component of the probe voltage. Depending on the manufacturing precision of the actual probe the use of additional bucking coils, added through resistor dividers, may still be required.

The warm bore tube that Charlie has ordered for use with the 50 mm SSC dipoles has an I.D. of 1.180 inches or an inner radius of 14.99 mm. The largest coil that can be put in this tube probably has a radius about 1 mm smaller (0.5 mm at the surface of the coil form and another 0.5 mm that the wires are recessed into the surface). This is sufficiently close to the 14.78 mm radius of the probe used in these examples that the effect of manufacturing errors on a probe we build will be similar to what is shown here.

References

[1] J. Strait, Notes on Tangential Probes: Basic Equations, TS-SSC 90-082, 11/9/90.

[2] J. Strait, Notes on Tangential Probes: Basic Equations II, TS-SSC 90-092, 11/27/90.

cc: S. Gourlay
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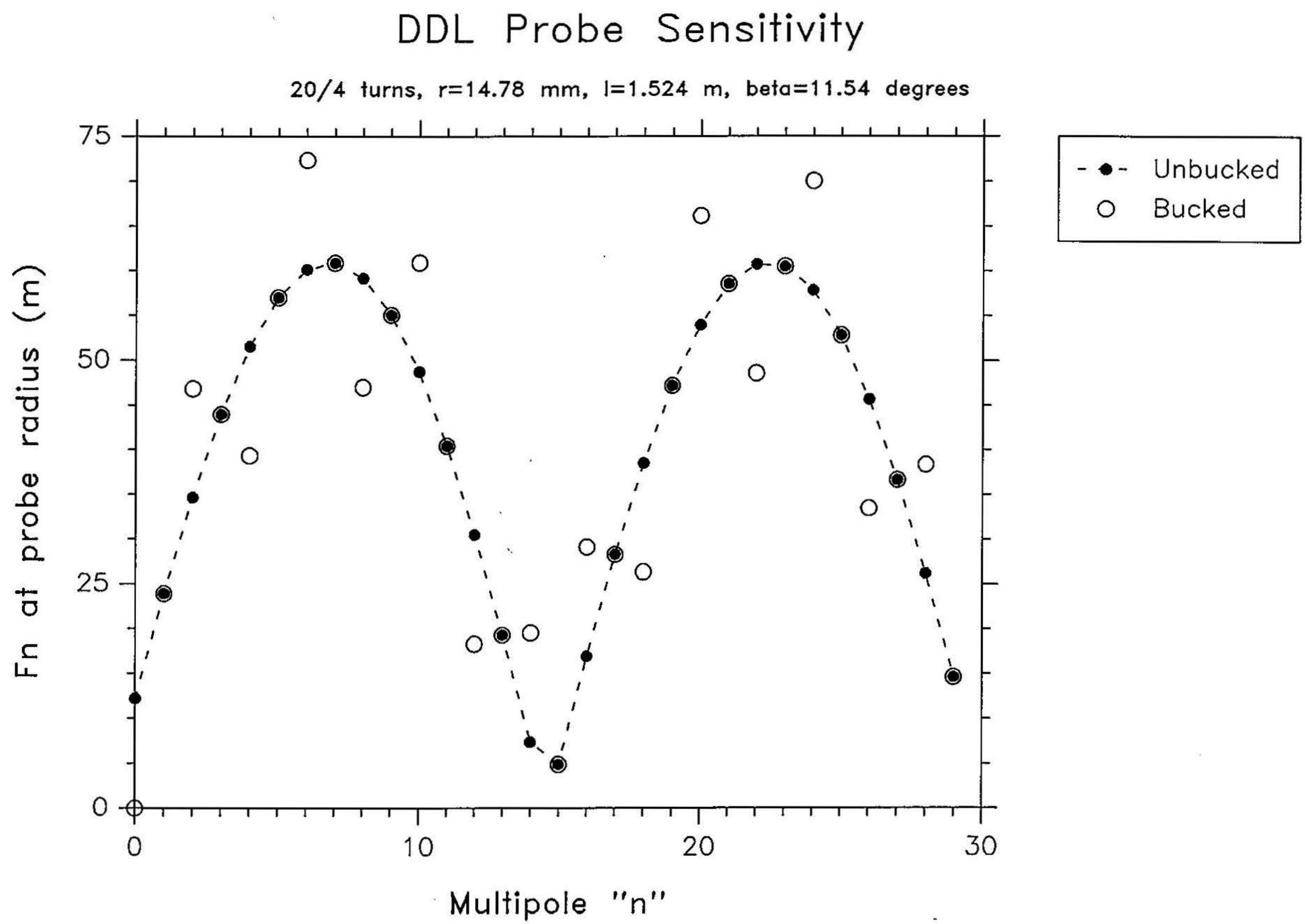
DDL Probe Sensitivity
20/4 turns, r=14.78 mm, l=1.524 m, beta=11.54 degrees
Unbucked
Bucked
Fn at probe radius (m)
Multipole "n"
75
50
25
0
0
10
20
30

Figure 1

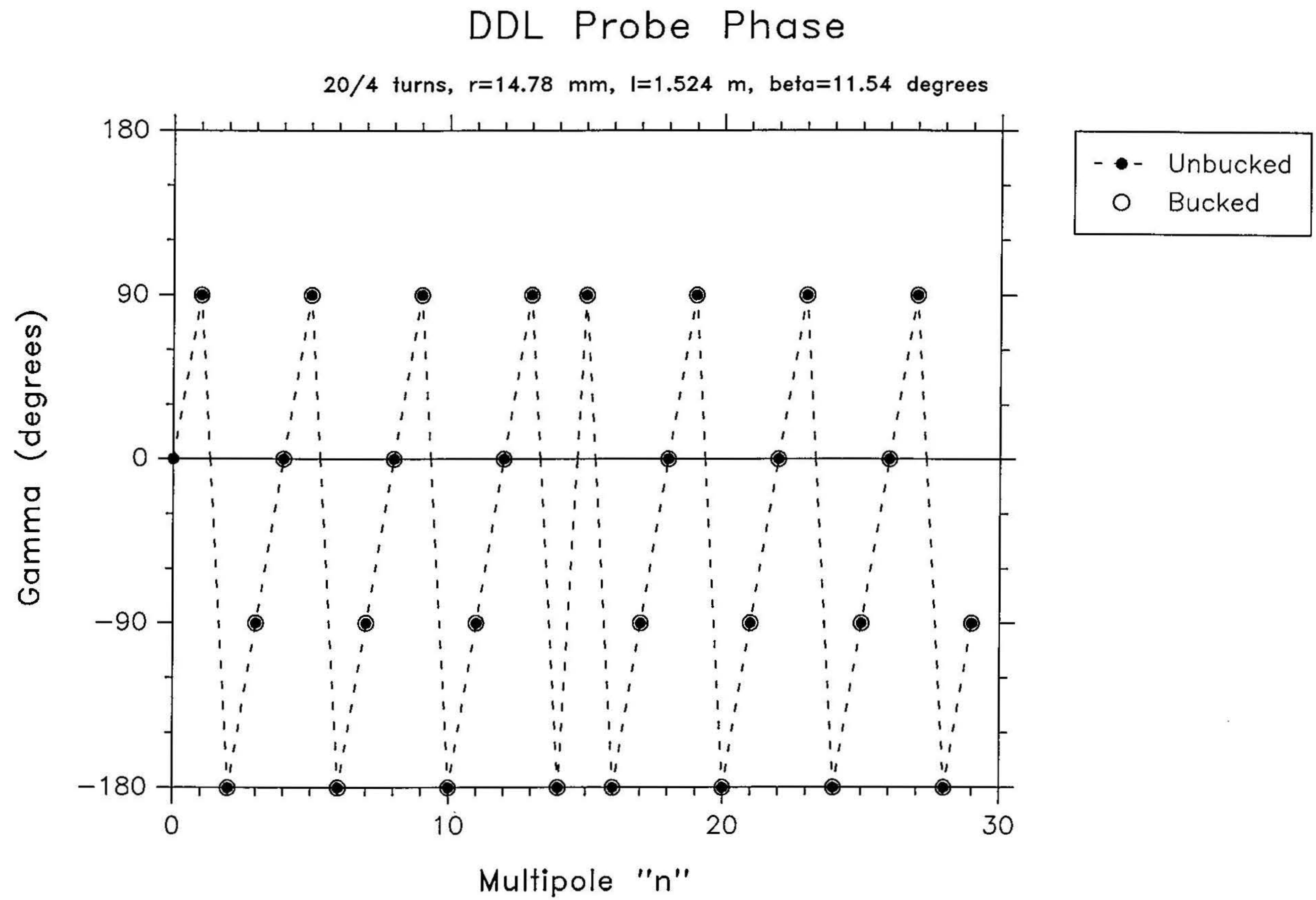
DDL Probe Phase
20/4 turns, r=14.78 mm, l=1.524 m, beta=11.54 degrees
Unbucked
Bucked
180
90
0
−90
−180
Gamma (degrees)
0
10
20
30
Multipole "n"

Figure 2

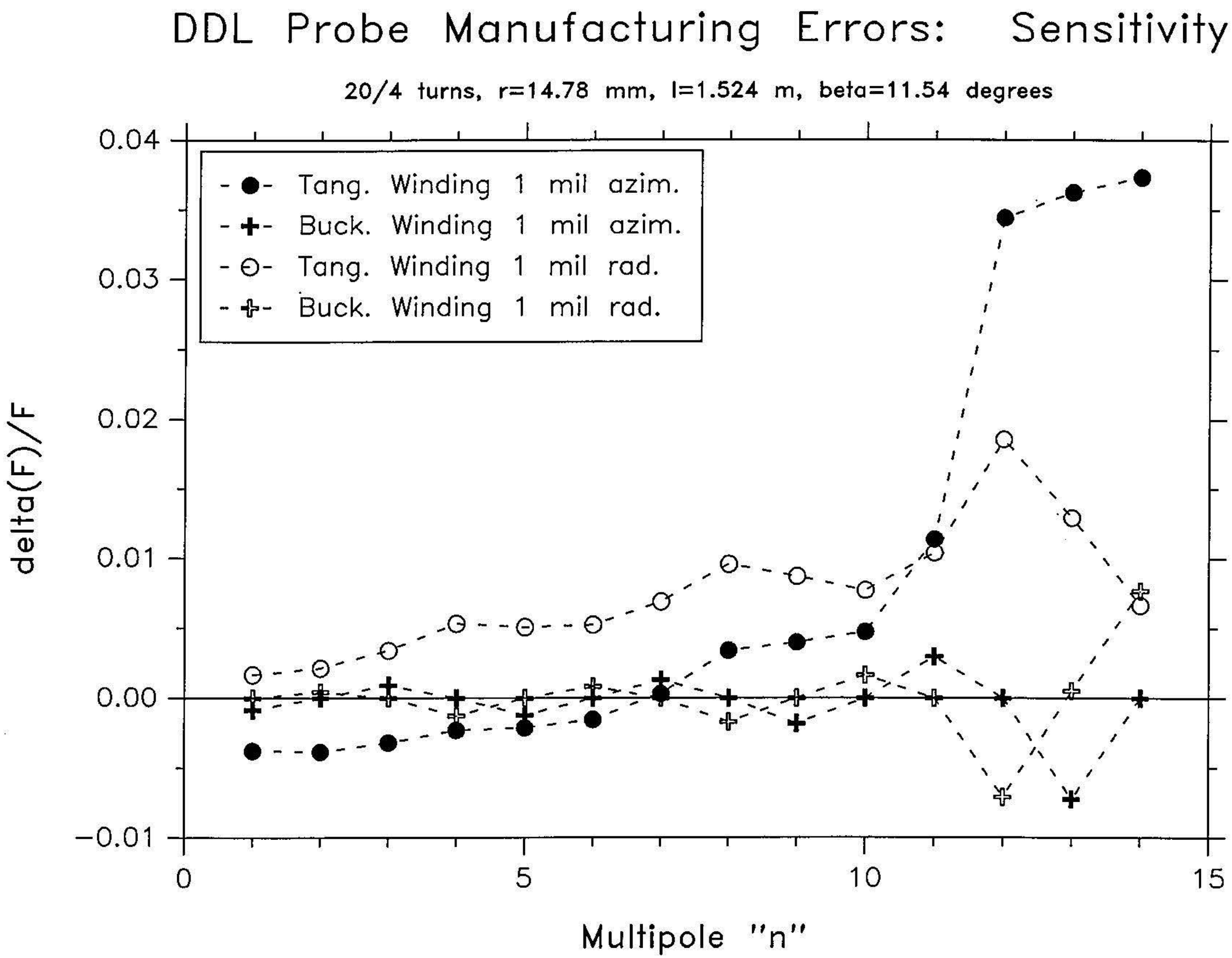
DDL Probe Manufacturing Errors: Sensitivity
20/4 turns, r=14.78 mm, l=1.524 m, beta=11.54 degrees
Tang. Winding 1 mil azim.
Buck. Winding 1 mil azim.
Tang. Winding 1 mil rad.
Buck. Winding 1 mil rad.
delta(F)/F
0.04
0.03
0.02
0.01
0.00
−0.01
0
5
10
15
Multipole "n"

Figure 3

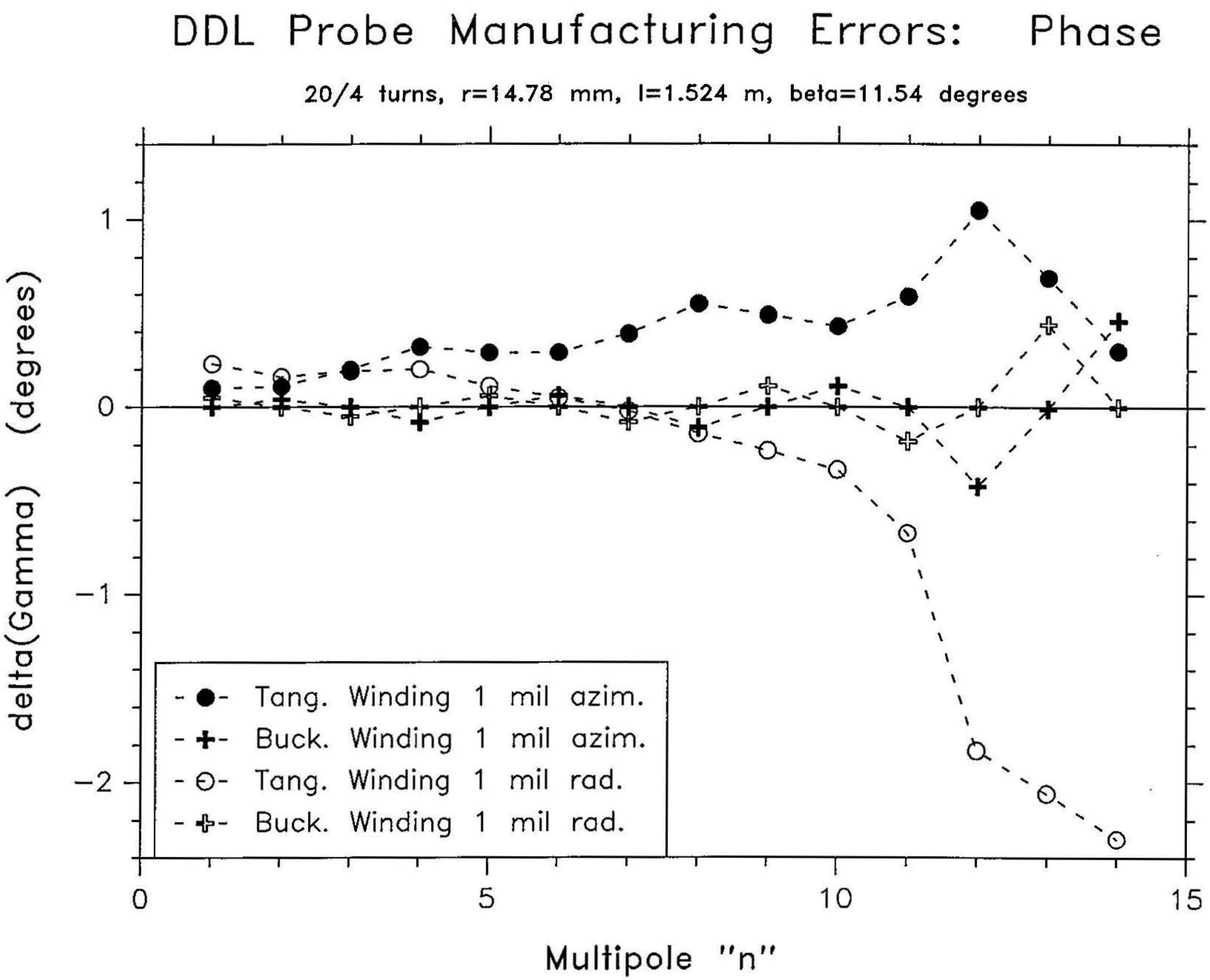
DDL Probe Manufacturing Errors: Phase
20/4 turns, r=14.78 mm, l=1.524 m, beta=11.54 degrees
delta(Gamma) (degrees)
1
0
−1
−2
0
5
10
15
Multipole "n"
Tang. Winding 1 mil azim.
Buck. Winding 1 mil azim.
Tang. Winding 1 mil rad.
Buck. Winding 1 mil rad.

Figure 4