Main Injector Quadrupoles: Magnetic Design Issues

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1 Introduction

The Main Injector uses 202 conventional iron core magnets. Of the latter, N will be recycled from the Main Ring. M of these N magnets have been modified by shaving 0.010 inch off the top half-core to improve the field quality in the horizontal plane at high current. From the standpoint of harmonic content, the principal effect of this modification is the introduction of a sizable octupole component. In Fermilab jargon, the M modified magnets are referred to as "new-style" quadrupoles. The remaining $M-N$ are known as "old style" quadrupoles [1].

At least $(202-N)$ quadrupoles will have to be fabricated. These new magnets will be identical to the so-called "old style" Main Ring quadrupoles, except for a redesigned conductor insulation scheme which will require minor modifications to the laminations. Essentially, the conductor slots must be made 0.116 inch thicker and 0.031 inch deeper. In principle, given the high permeability of the laminations, the effect on field quality is expected to be negligible. However, the pole profile in the neighborhood of the inner sides of the horizontal conductor slots has a dramatic effect on field quality. **It is critical not to modify the pole profile and to be especially careful with the mechanical tolerances near the inner edges of the horizontal slots.** In this note, a qualitative explanation of the magnetic behavior of the MR quadrupole magnets will be presented, followed by quantitative results. Finally, it is shown that the thicker insulation scheme can easily be accomodated without affecting field quality.

[1] This modification was done in the pre-Tevatron era, when the Main Ring was the principal accelerator. For this reason, the Main Ring quadrupoles have been designed to operate at currents in excess of 7000 Amperes (8 conductors/pole).

2 Qualitative Explanation of the Magnetic B̃ehavior

The most distinctive characteristic of the MR quadrupoles is unquestionably their asymmetric aperture. As shown in figure 1, The horizontal aperture is approximately twice the vertical aperture. To the extent that the harmonic content of the field results from the moments of the source distribution (current and induced dipole moment), it is obvious that a breaking of the 4-fold symmetry will result in the generation of higher harmonics. This symmetry breaking is also exacerbated by the fact that the regions situated at both extremes of the horizontal aperture tend to saturate first. The hyperbolic pole profile is therefore terminated in the horizontal plane by a "flat" constant gap region which is meant to retard the onset of saturation by preventing field concentration. This flat region is followed by a flared region whose purpose is to compensate for the multipoles induced by the horizontal-vertical symmetry breaking. Increasing the flare angle introduces a perturbation opposite to that induced by the symmetry breaking. This is a subtle effect which can be partially understood by considering figures 2 and 3. In these figures, only one of the four conductor groups is excited. When the topmost conductors are excited, one can see by tracking the flux lines that the flux density near the bottom horizontal slot is controlled by the flare angle. Similarly, when the leftmost conductors are excited, the flux density near the slot on the right-hand side is controlled by the same angle.

3 Quantitative Results

The harmonic content of the existing main ring quadrupoles has been determined using the code PE2D. The results are presented in tables 1 and 2. Since the conductors are positioned relatively to the lamination, the "new style" quadrupoles have non-zero skew multipoles; however, the latter remain negligible. Note that the skew multipoles of the "old style" quadrupoles must be zero by symmetry. The fact that they are not zero is due to numerical error; the values of the non-zero skew multipoles can be considered as some kind of a measure of this error. As expected, the modified magnets have a sizable octupole component. The on-axis gradient of the modified magnets is about 0.3% larger.

Table 3 summarizes the effect of a proposed modification to accomodate the new insulation scheme on the pole profile near the inner section of one of the horizontal slots. The effect of the proposed modification on the angle of flared sections is shown in figure 4. One can see that the perturbation of the harmonic content of the field is dramatic. It should also be noted that the sign of the pertubation is opposite to that resulting from the transition from "old style" to "new style". If, instead of trying to preserve the distance between the conductor and the magnetic axis of the quadrupole one makes the horizontal slots a bit deeper and preserve the angle of the flared region, the field quality remains essentially unchanged. The results are summarized in table 4. Figures 5-6 compare the field gradients $\partial B_y/\partial x$ and $\partial B_x/\partial y$ along the horizontal and vertical axes respectively for both versions of the modified lamination profile.

MAIN RING QUADRUPOLES ("OLD STYLE") FIELD HARMONICS AT $r = r_0 = 2.54$ cm ARMCO B3 laminations Magnetic Field in Gauss				
	Multipoles		Multipoles/Quadrupole $\times 10^4$	
Pole	Normal	Skew	Normal	Skew
$I = 215$ Amperes ($E \simeq 8.9$ GeV)				
4	$+0.317748 \times 10^{+3}$	$+0.227224 \times 10^{-3}$	+10000.000000	+0.007151
8	$+0.613866 \times 10^{-1}$	-0.249187×10^{-3}	+1.931927	−0.007842
12	-0.569236×10^{-1}	-0.349162×10^{-3}	−1.791470	−0.010989
16	$+0.458262 \times 10^{-1}$	-0.184547×10^{-4}	+1.442219	−0.000581
20	-0.237989×10^{-1}	$+0.329926 \times 10^{-3}$	−0.748987	+0.010383
24	$+0.100163 \times 10^{-1}$	$+0.227224 \times 10^{-3}$	+0.315228	+0.007151
$I = 2904$ Amperes ($E \simeq 120$ GeV)				
4	$+0.426396 \times 10^{+4}$	-0.520101×10^{-2}	+10000.000000	−0.012198
8	$+0.720226 \times 10^{+0}$	$+0.138136 \times 10^{-1}$	+1.689101	+0.032396
12	$-0.788976 \times 10^{+0}$	-0.185395×10^{-1}	−1.850336	−0.043480
16	$+0.604282 \times 10^{+0}$	$+0.697204 \times 10^{-2}$	+1.417185	+0.016351
20	$-0.334338 \times 10^{+0}$	-0.467039×10^{-2}	−0.784102	−0.010953
24	$+0.148524 \times 10^{+0}$	$+0.438530 \times 10^{-2}$	+0.348324	+0.010285
$I = 3630$ Amperes ($E \simeq 150$ GeV)				
4	$+0.530103 \times 10^{+4}$	-0.329340×10^{-2}	+10000.000000	−0.006213
8	$+0.772933 \times 10^{+0}$	$+0.642628 \times 10^{-2}$	+1.458081	+0.012123
12	$-0.995743 \times 10^{+0}$	-0.116553×10^{-2}	−1.878395	−0.002199
16	$+0.750000 \times 10^{+0}$	$+0.139179 \times 10^{-2}$	+1.414819	+0.002626
20	$-0.404405 \times 10^{+0}$	$+0.241065 \times 10^{-2}$	−0.762880	+0.004548
24	$+0.154577 \times 10^{+0}$	$+0.116495 \times 10^{-2}$	+0.291598	+0.002198
$I = 7000$ Amperes ($E \simeq 289$ GeV)				
4	$+0.784391 \times 10^{+4}$	-0.364470×10^{-1}	+10000.000000	−0.046465
8	$-0.290231 \times 10^{+1}$	$+0.531473 \times 10^{-1}$	−3.700081	+0.067756
12	$-0.351710 \times 10^{+1}$	-0.533295×10^{-1}	−4.483860	−0.067988
16	$+0.806742 \times 10^{+0}$	$+0.352193 \times 10^{-1}$	+1.028495	+0.044900
20	$-0.643578 \times 10^{+0}$	-0.529958×10^{-1}	−0.820481	−0.067563
24	$+0.223671 \times 10^{+0}$	$+0.300074 \times 10^{-1}$	+0.285152	+0.038256

Table 1: Harmonic content of the "old style" quadrupole magnets. The skew multipoles are zero by symmetry. The non-zero values can be considered as a rough measure of the computational error.

MAIN RING QUADRUPOLES ("NEW STYLE") FIELD HARMONICS AT $r = r_0 = 2.54$ cm Laminations midplane $\neq$ Coils midplane Origin = Laminations midplane ARMC0 laminations Magnetic Field in Gauss				
	Multipoles		Multipoles/Quadrupole $\times 10^4$	
Pole	Normal	Skew	Normal	Skew
$I = 215$ Amperes ($E \simeq 8.9$ GeV)				
4	$+0.319162 \times 10^{+3}$	$+0.177236 \times 10^{-3}$	+10000.000000	+0.005553
8	$+0.299695 \times 10^{+0}$	$+0.355590 \times 10^{-3}$	+9.390059	+0.011141
12	-0.407296×10^{-1}	-0.229567×10^{-3}	−1.276142	−0.007193
16	$+0.450326 \times 10^{-1}$	-0.409368×10^{-3}	+1.410964	−0.012826
20	-0.240219×10^{-1}	$+0.650241 \times 10^{-3}$	−0.752655	+0.020373
24	$+0.114788 \times 10^{-1}$	-0.119350×10^{-2}	+0.359654	−0.037395
$I = 2904$ Amperes ($E \simeq 120$ GeV)				
4	$+0.428251 \times 10^{+4}$	$+0.437089 \times 10^{-2}$	+10000.000000	+0.010206
8	$+0.390118 \times 10^{+1}$	-0.695724×10^{-2}	+9.109565	−0.016246
12	$-0.574938 \times 10^{+0}$	$+0.892401 \times 10^{-2}$	−1.342526	+0.020838
16	$+0.589764 \times 10^{+0}$	-0.332185×10^{-2}	+1.377146	−0.007757
20	$-0.343750 \times 10^{+0}$	$+0.243179 \times 10^{-2}$	−0.802683	+0.005678
24	$+0.138853 \times 10^{+0}$	-0.447758×10^{-2}	+0.324233	−0.010456
$I = 3630$ Amperes ($E \simeq 150$ GeV)				
4	$+0.532276 \times 10^{+4}$	$+0.762545 \times 10^{-2}$	+10000.000000	+0.014326
8	$+0.470930 \times 10^{+1}$	-0.508754×10^{-2}	+8.847478	−0.009558
12	$-0.716339 \times 10^{+0}$	$+0.159581 \times 10^{-1}$	−1.345804	+0.029981
16	$+0.756447 \times 10^{+0}$	-0.617849×10^{-2}	+1.421156	−0.011608
20	$-0.416831 \times 10^{+0}$	$+0.159518 \times 10^{-1}$	−0.783111	+0.029969
24	$+0.165650 \times 10^{+0}$	-0.125884×10^{-1}	+0.311211	−0.023650
$I = 7000$ Amperes ($E \simeq 289$ GeV)				
4	$+0.740301 \times 10^{+4}$	$-0.380734 \times 10^{+1}$	+10000.000000	−5.142962
8	$+0.392987 \times 10^{+1}$	$+0.343221 \times 10^{+1}$	+5.308476	+4.636236
12	$-0.205017 \times 10^{+1}$	$-0.329361 \times 10^{+1}$	−2.769373	−4.449015
16	$+0.812303 \times 10^{+0}$	$+0.319516 \times 10^{+1}$	+1.097260	+4.316028
20	$-0.605438 \times 10^{+0}$	$-0.315056 \times 10^{+1}$	−0.817827	−4.255783
24	$+0.205659 \times 10^{+0}$	$+0.312611 \times 10^{+1}$	+0.277805	+4.222755

Table 2: Harmonic content of the "new style" quadrupoles. 0.010 inch has been shaved off the top half core.

MAIN INJECTOR QUADRUPOLE (PROPOSED MODIFICATION) NORMAL FIELD HARMONICS AT $r = r_0 = 2.54$ cm ARMCO laminations Magnetic Field in Gauss		
	Multipoles	Multipoles/Quadrupole $\times 10^4$
Pole	Normal	Normal
$I = 215$ Amperes ($E \simeq 8.9$ GeV)		
4	$+0.316736 \times 10^{+03}$	+10000.000000
8	$+0.131997 \times 10^{+01}$	+41.674137
12	$-0.737910 \times 10^{+00}$	−23.297321
16	$+0.260663 \times 10^{+00}$	+8.229662
20	$-0.619534 \times 10^{-01}$	−1.955995
24	$+0.976741 \times 10^{-02}$	+0.308377
$I = 215$ Amperes ($E \simeq 120$ GeV)		
4	$+0.425412 \times 10^{+04}$	+10000.000000
8	$+0.175915 \times 10^{+02}$	+41.351677
12	$-0.990488 \times 10^{+01}$	−23.283028
16	$+0.350294 \times 10^{+01}$	+8.234229
20	$-0.839240 \times 10^{+00}$	−1.972770
24	$+0.117123 \times 10^{+00}$	+0.275317
$I = 215$ Amperes ($E \simeq 150$ GeV)		
4	$+0.529833 \times 10^{+04}$	+10000.000000
8	$+0.217582 \times 10^{+02}$	+41.066147
12	$-0.123563 \times 10^{+02}$	−23.321123
16	$+0.435043 \times 10^{+01}$	+8.210945
20	$-0.103300 \times 10^{+01}$	−1.949671
24	$+0.154091 \times 10^{+00}$	+0.290829

Table 3: Harmonic content of the field of the newly fabricated quadrupoles, assuming a proposed modification which would make the conductor slots 0.116 inch thicker and 0.011 inch deeper. The distances between the innermost conductors and the magnetic axis have been preserved.

MAIN INJECTOR QUADRUPOLE (IMPROVED MODIFICATION) NORMAL FIELD HARMONICS AT $r = r_0 = 2.54$ cm ARMCO laminations Magnetic Field in Gauss		
	Multipoles	Multipoles/Quadrupole $\times 10^4$
Pole	Normal	Normal
$I = 215$ Amperes ($E \simeq 8.9$ GeV)		
4	$+0.317910 \times 10^{+03}$	+10000.000000
8	$+0.125440 \times 10^{-01}$	+0.394577
12	$-0.444405 \times 10^{-01}$	−1.397896
16	$+0.411760 \times 10^{-01}$	+1.295209
20	$-0.231162 \times 10^{-01}$	−0.727130
24	$+0.111915 \times 10^{-01}$	+0.352034
$I = 2904$ Amperes ($E \simeq 120$ GeV)		
4	$+0.426752 \times 10^{+04}$	+10000.000000
8	$+0.411515 \times 10^{-01}$	+0.096430
12	$-0.600582 \times 10^{+00}$	−1.407333
16	$+0.561689 \times 10^{+00}$	+1.316195
20	$-0.315323 \times 10^{+00}$	−0.738891
24	$+0.130687 \times 10^{+00}$	+0.306236
$I = 3630$ Amperes ($E \simeq 150$ GeV)		
4	$+0.530870 \times 10^{+04}$	+10000.000000
8	$-0.632951 \times 10^{-01}$	−0.119229
12	$-0.766256 \times 10^{+00}$	−1.443397
16	$+0.692673 \times 10^{+00}$	+1.304788
20	$-0.410233 \times 10^{+00}$	−0.772756
24	$+0.177653 \times 10^{+00}$	+0.334645

Table 4: Harmonic content of the field with an improved version of the modification required to accomodate the thicker insulation. The angle of the flared section on the inner side of the horizontal slots has been preserved. The horizontal slots have been made 0.086 inch deeper than in the proposed modification and the horizontal conductors have been moved 0.097 inch away from the axis. The vertical slots are as proposed.

References

[1] Main Accelerator Quadrupole Magnet Lamination, Drawing no 0424.11-ME-1042 Rev B.

[2] Main Injector Quadrupole Magnet Lamination, Proposed Lamination (J. Humbert 10/1/90)

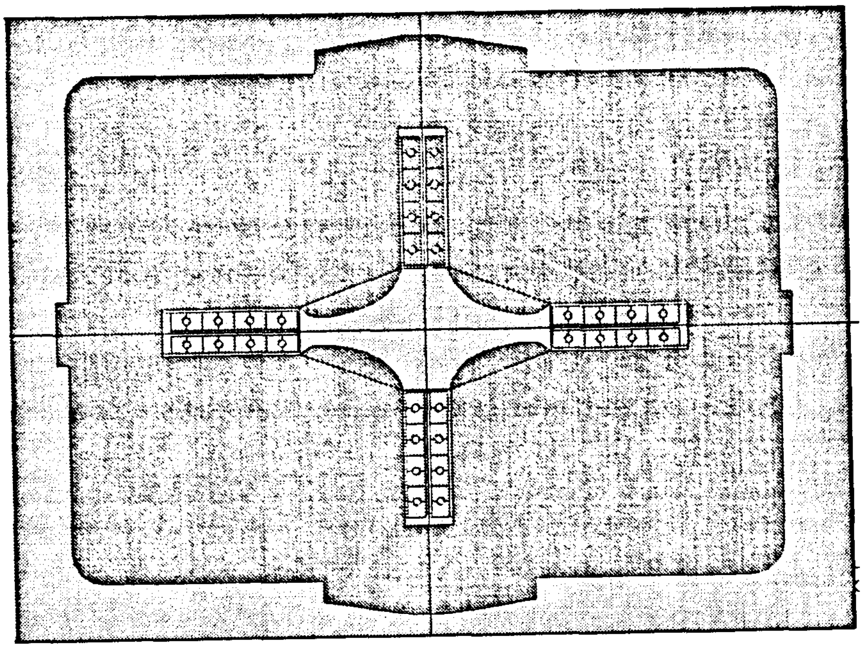

Figure 1: The Main Injector Quadrupole Magnet.

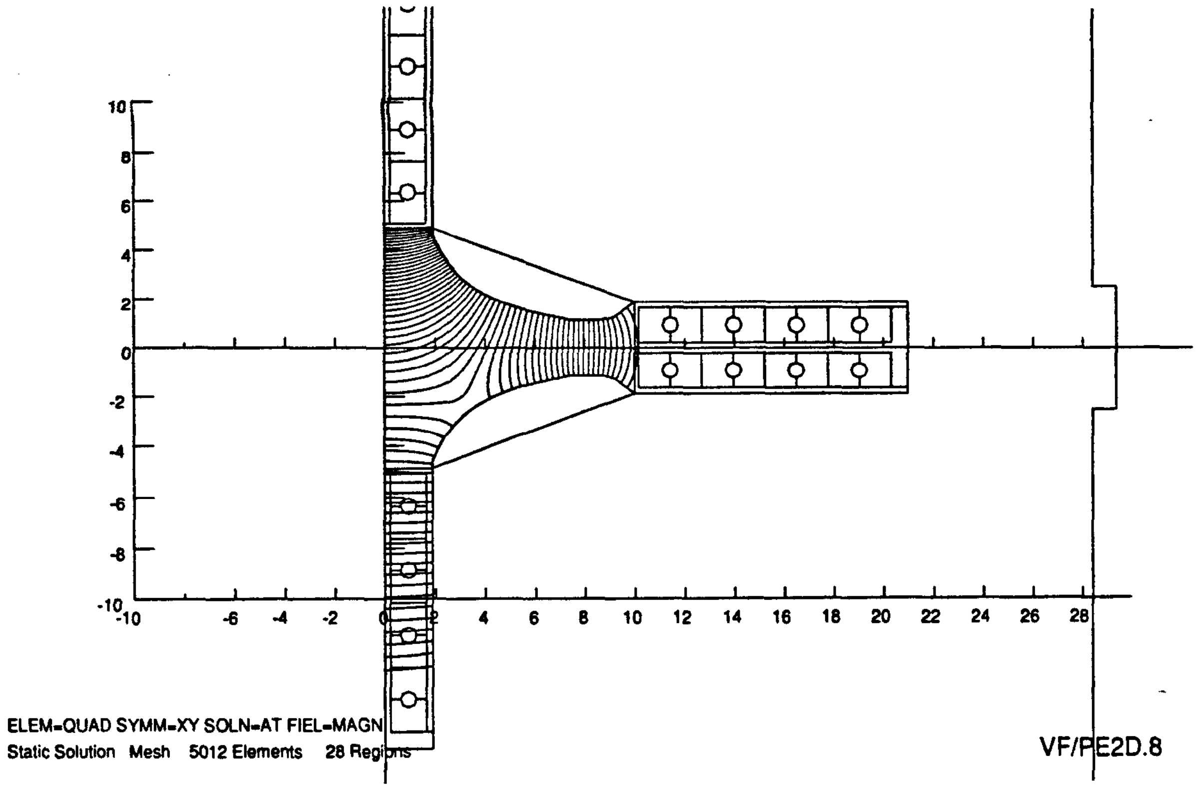

Figure 2: Effect of the flared section on field quality. Only the top conductor is energized.

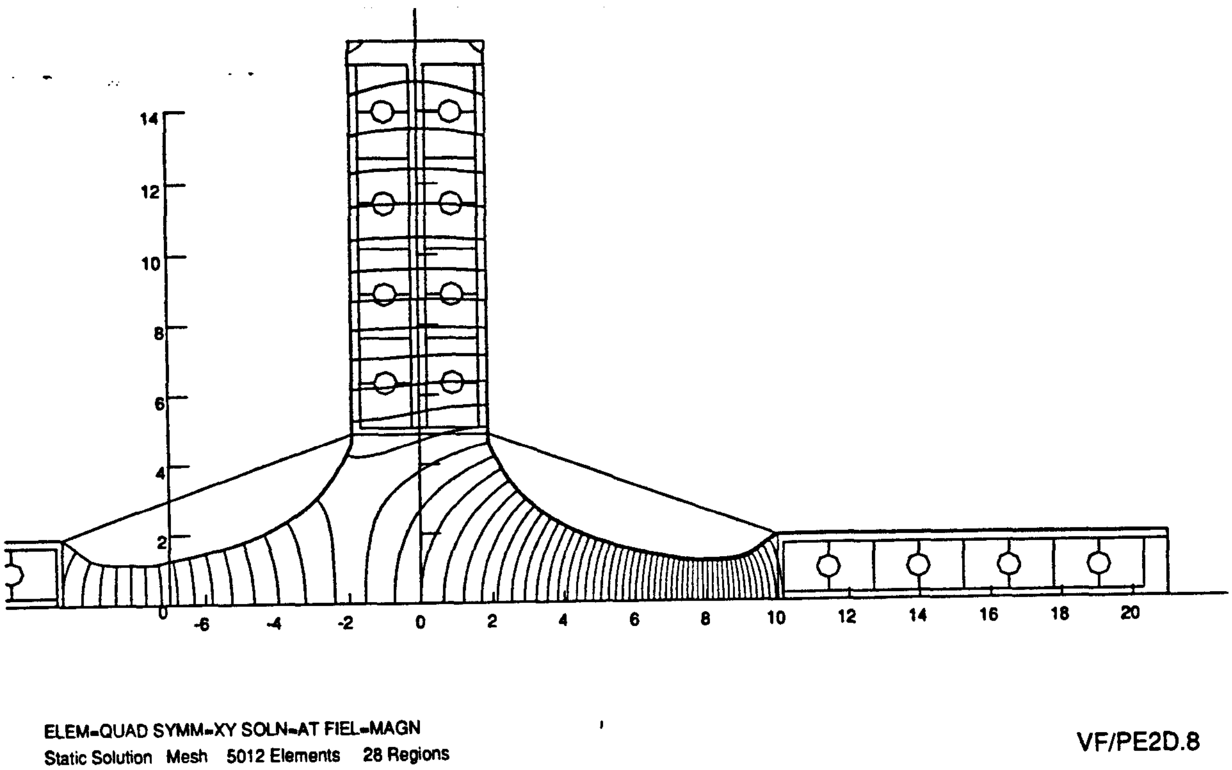

Figure 3: Effect of the flared section on field quality. Only the right horizontal conductor is energized.

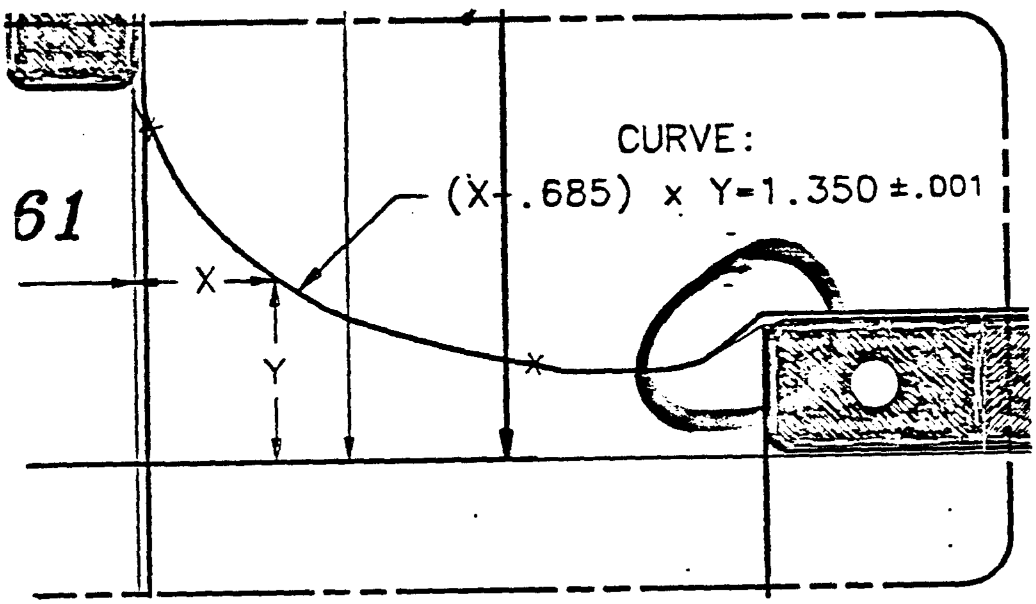

Figure 4: Effect of a proposed modification required to accomodate a thicker insulation on the flare angle.

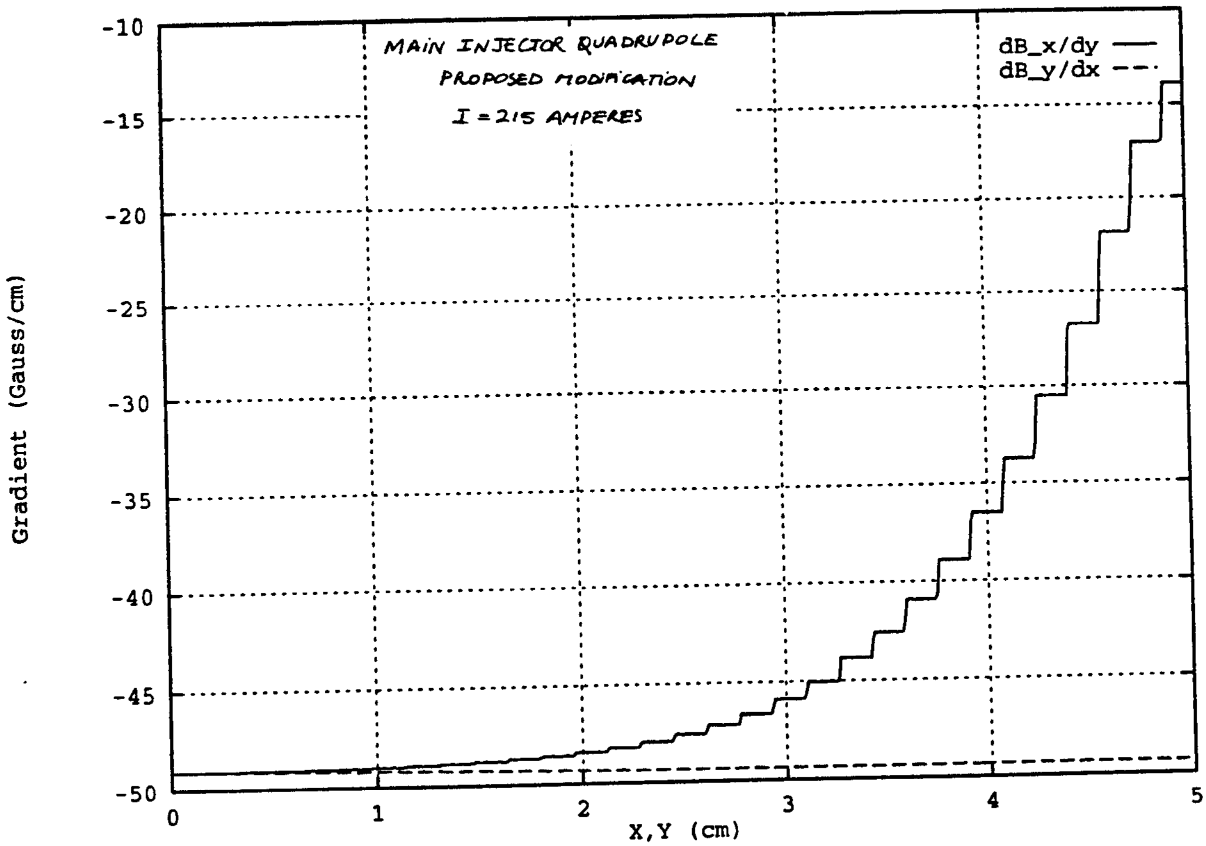

Figure 5: Field gradient along the horizontal and vertical axes for the proposed modification.