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Eddy Currents in the NSLS Vacuum Chamber

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Eddy Currents in the NSLS Vacuum Chamber*

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As the applied magnetic fields are increased during acceleration, eddy currents are induced in the vacuum chamber. These result in magnetic field perturbations which we shall estimate for the Booster and X-Ray Rings. Our calculation follows that of Asner[1], in particular, we use image currents to satisfy the boundary conditions imposed by the iron poles of the magnets. The strength of the magnetic field perturbations is roughly three times greater with the iron poles present than absent.

We shall use mks units in this note. Writing the applied magnetic field as

$$B = \nabla \times A,$$

the eddy current density is

$$j_e = -\sigma \frac{\partial A}{\partial t} + c(t),$$

where σ is the conductivity in $\Omega^{-1}m^{-1}$, and $c(t)$ does not depend on the spatial coordinates and is determined by the condition that the net eddy current be zero. The magnetic field perturbation is $\Delta B = \nabla \times A_e$, where

$$A_e(x,y) = -\frac{\mu}{4\pi} \iint dx'dy' j_e(x',y') \ln\left[(x-x')^2 + (y-y')^2\right].$$

Introducing the skin depth $\delta_s^{-2} = \frac{1}{2}\sigma\mu\ (dB/dt)/B$,

the thickness of the vacuum chamber wall δ, and the effective radius R equal to the circumference of the chamber divided by 2π, dimensional arguments indicate

$$\Delta B/B \sim -\delta R/\delta_s^2.$$

For a 2n-pole field applied to a circular chamber in the absence of iron[2],

$$\Delta B/B = -n^{-1}\ \delta R/\delta_s^2,$$

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and for a dipole field applied to two parallel plates[1] of width 2a, separated by 2b,

$$\Delta B(x,o)/B = -2(\delta R/\delta_s^{\,2})\left[1 - \frac{b}{a}\tan^{-1}\frac{a}{b} - \frac{a^2x^2}{(a^2+b^2)^2} + 0(x^4)\right],$$

where $R = 2a/\pi$.

	Booster Dipole	Booster Quad	X-Ray Dipole	X-Ray Quad
σ	$8.3 \times 10^5\ \Omega^{-1}m^{-1}$	8.3×10^5	3.5×10^7	3.5×10^7
δ	0.75 mm	2.37	4.0	4.0
R	43 mm	43	65	41
$B\frac{dt}{dB}$	0.4 sec	0.4	60	60
δ_s	870 mm	870	1600	1600
$\delta R/\delta_s^{\,2}$	0.4×10^{-4}	1.2×10^{-4}	1×10^{-4}	0.6×10^{-4}

We see that a 60 sec rise time in the aluminum chamber of the X-ray ring results in comparable field perturbations as produced by a 0.4 sec rise time in the Inconel chamber of the booster. The results of numerical calculations including the detailed geometry of the vacuum chamber and the boundary conditions due to iron poles are given in Figures 1 thru 5.

Booster Quadrupole (Fig. 1) and X-ray Quadrupole (Fig. 2)

The variation of the gradient across the aperture is less than 0.1%, and for $x \leq 2.0$ cm the variation is predominantly octupole. This gradient variation should not be a problem. The horizontal asymmetry of the X-ray vacuum chamber in the quadrupoles, due to the water cooling channels, results in a small dipole and sextupole component of the field perturbation.

Booster Dipole (Figs. 3 and 4)

In Fig. 3 we consider the regular booster chamber, and in Fig. 4 the booster chamber with the vacuum pump takeoff port.

tune shift: $\Delta\nu_y = -\frac{N}{4\pi}\frac{L\Delta B'}{B\rho}\bar{\beta}_y$

chromaticity change: $\Delta\xi_y = -\frac{N}{4\pi}\frac{L\Delta B''}{B\rho}\bar{\beta}_y\,\bar{\eta}$

For the booster N = 8, $B\rho$ = 3.33 KG-m (E = 100 MeV), $\bar{\beta}_y$ = 4.5m, $\bar{\eta}$ = 0.3m. The regular chamber has L = 1.2m,

$$\frac{L\Delta B'}{B\rho} = 5.7 \times 10^{-4} m^{-1}, \quad \frac{L\Delta B''}{B\rho} = 0.25 m^{-2},$$

$$\Delta\nu_y = -1.6 \times 10^{-3},$$

$$\Delta\xi_y = -0.2,$$

and the chamber with pump has L = 0.3m,

$$\frac{L\Delta B'}{B\rho} = 4.7 \times 10^{-3} m^{-1}, \quad \frac{L\Delta B''}{B\rho} = -0.073 m^{-2},$$

$$\Delta\nu_y = -0.013,$$

$$\Delta\xi_y = 0.06.$$

In these calculations we have included the quadrupole and sextupole component of the applied magnetic field in the Booster bending magnet.

X-Ray Dipole (Fig. 5)

N = 16, $B\rho$ = 23.3 KG-m (E = 700 MeV), $\bar{\beta}_y$ = 16 m, $\bar{\eta}$ = 0.25 m,

$$\frac{L\Delta B'}{B\rho} = 1.9 \times 10^{-3} m^{-1}, \quad \frac{L\Delta B''}{B\rho} = 0.088 m^{-2},$$

$$\Delta\nu_y = -0.04,$$

$$\Delta\xi_y = -0.45.$$

The relatively large gradient error is due to the asymmetry in the vacuum chamber introduced by the distributed pump.

Slow Bump in the VUV-Ring

Consider a 4 mrad kick applied in 0.1 sec by a back leg winding on the bending magnet. This corresponds to a 62 G field change in 0.1 sec or

$$\frac{dB}{dt} = 620 \text{ G/sec}.$$

Scaling our previous result for the X-ray bending magnet by 620/146, we obtain the magnetic field perturbation due to eddy currents,

$$\Delta B = -19.6\ \mathrm{G} + (70\ \mathrm{G/m})x + (1625\ \mathrm{G/m^2})x^2 + \quad .$$

We see that this is a significant effect.

References

1. A. Asner, Calculation of Eddy Current Effects in the Vacuum Chamber of the Booster Synchrotron Quadrupole and Bending Magnets, MPS/Int. MA 67-11.

2. J. C. Herrera, Eddy Current Effects in the ISA Vaccum Chamber, BNL 19513.

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Figure 1. BOOSTER QUADRUPOLE

$\delta = 2.37\ mm$

$\sigma = 8.3 \times 10^5\ \Omega^{-1} m^{-1}$

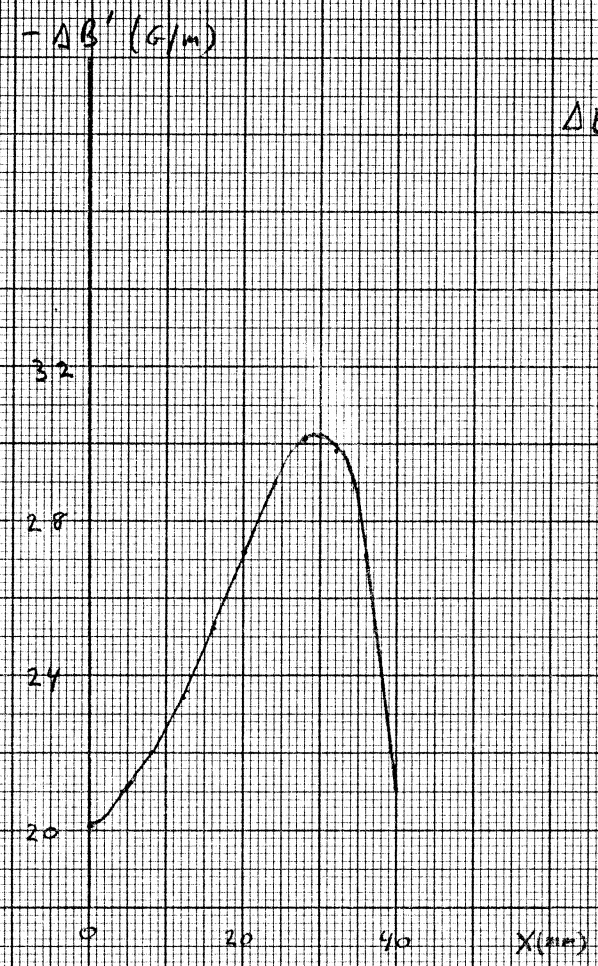
$B_0' = 14.3\ KG/m$ $(E = 100\ MeV)$

$B_f' = 100\ KG/m$ $(E = 700\ MeV)$

$\Delta t = 0.4\ \mu sec$

$dB'/dt = 214\ KG/m/\mu sec$

(symmetric)

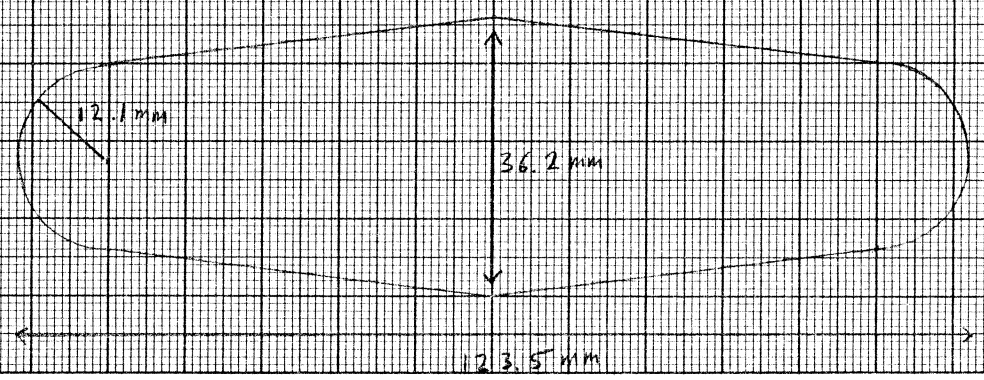


$$\Delta B = \sum_n b_n x^n$$

n	bn
	-20.7 G/m
3	6.83 KG/m³

POWER DISSIPATION

$P/\ell = 0.11\ watt/m$



Quadrupole Aperture

$a = 50\ mm$

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Figure 2. X-RAY QUADRUPOLE

$\delta = 4\,mm$

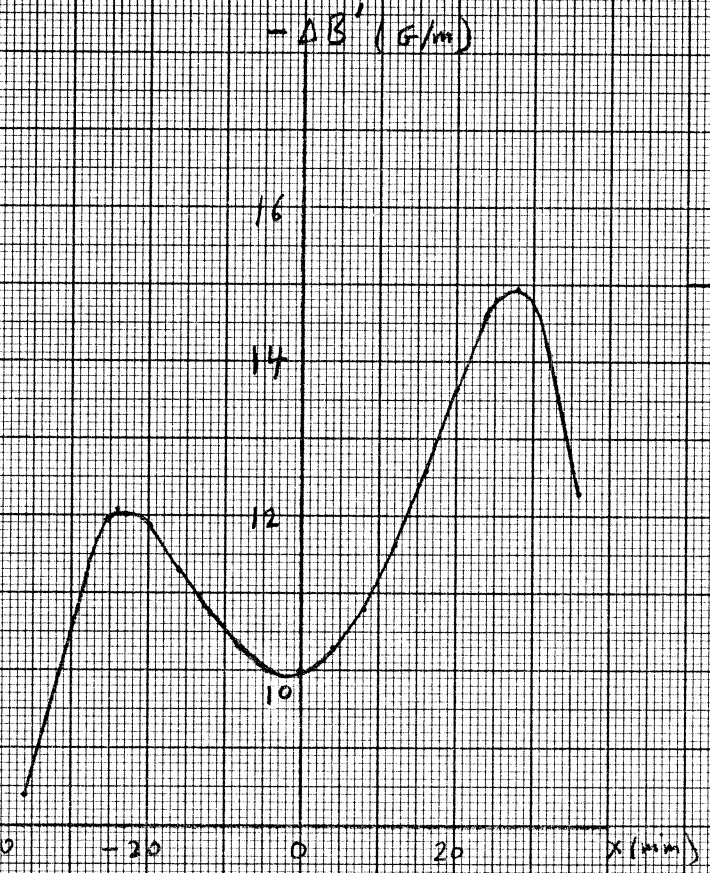
$\sigma = 3.5 \times 10^{7}\ \Omega^{-1} m^{-1}$

$B_i' = 36.4\ KG/m$ $(E = 0.2\ GeV)$

$B_f' = 130\ KG/m$ $(E = 2.5\ GeV)$

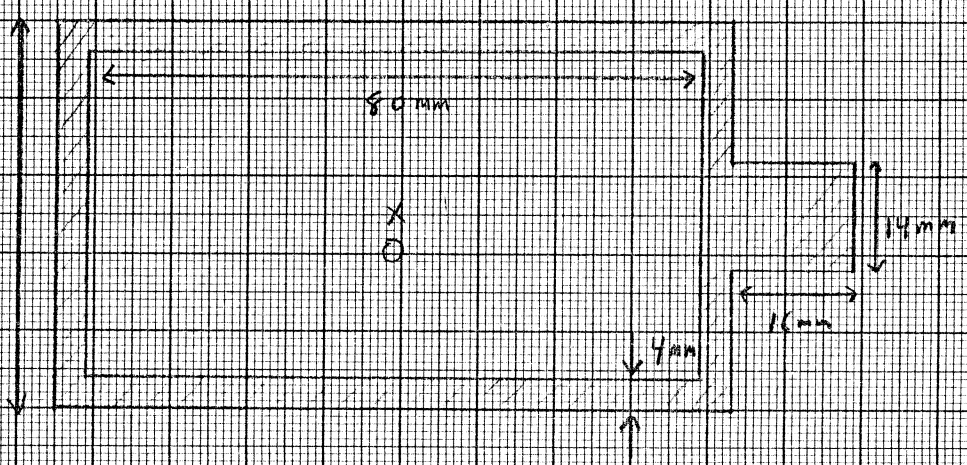
$\Delta t = 60\ sec$

$dB'/dt = 1.56\ KG/m/sec$



$$\Delta B = \sum_n b_n x^n$$

n	b_n
0	-0.039 G
1	-10.0 G/m
2	-15.6 G/m^2
3	-2.64×10^3 G/m^3



POWER DISSIPATION

$P/\ell = 3.0 \times 10^{-4}$ watts/m

Quadrupole Aperture

$a = 50\ mm$

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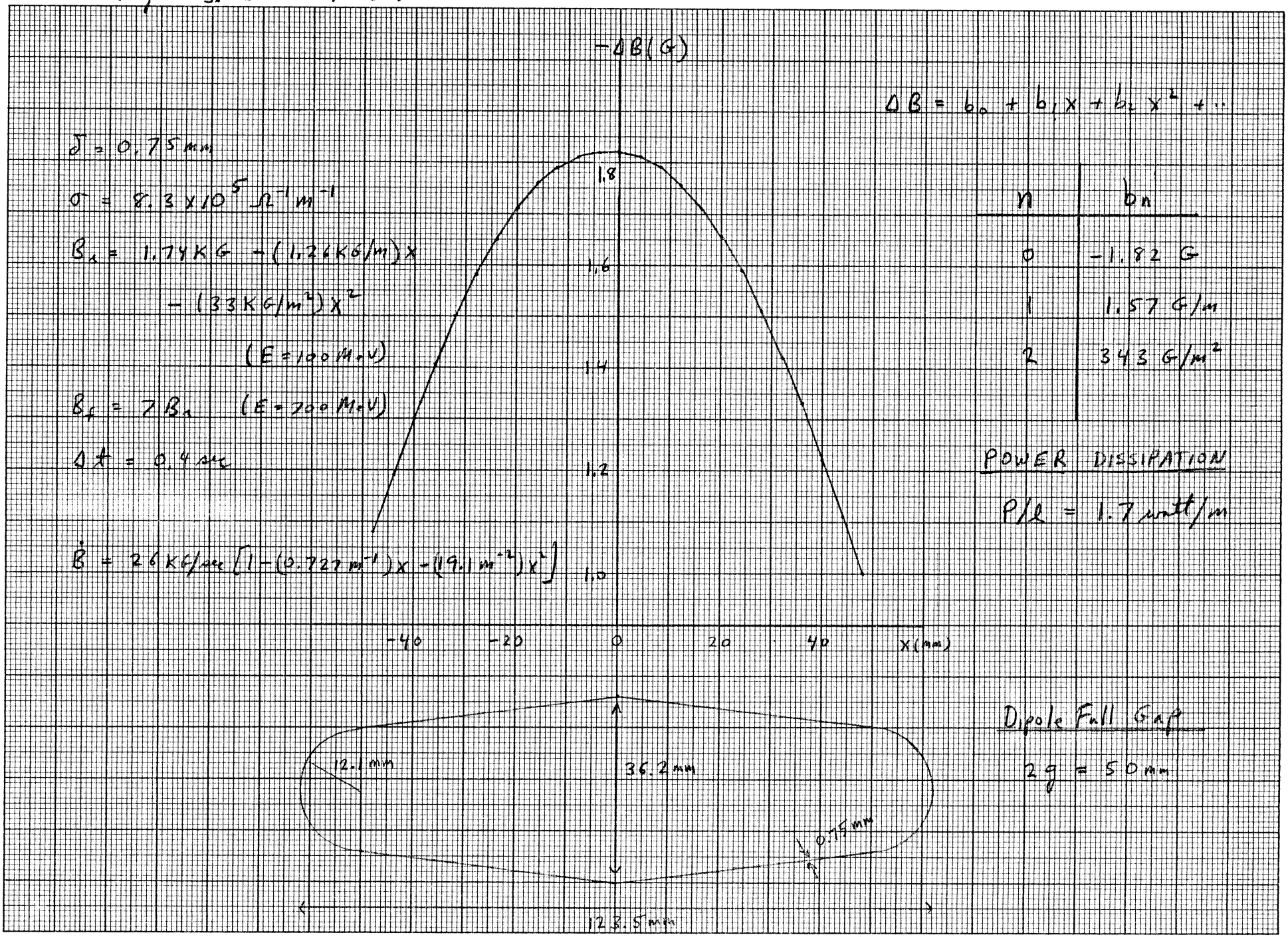
Figure 3. BOOSTER DIPOLE



$\delta = 0.75\,mm$

$\sigma = 8.3 \times 10^5\ \Omega^{-1} m^{-1}$

$B_1 = 1.74\,KG - (1.26\,KG/m)x - (33\,KG/m^2)x^2$

$(E = 100\,M.V)$

$B_f = 7B_1 \quad (E = 700\,M.V)$

$\Delta t = 0.4\,\mu sec$

$\dot{B} = 26\,KG/\mu sec\,[1 - (0.727\,m^{-1})x - (19.1\,m^{-2})x^2]$

$\Delta B = b_0 + b_1 x + b_2 x^2 + \cdots$

n	b_n
0	-1.82 G
1	1.57 G/m
2	343 G/m²

POWER DISSIPATION

$P/\ell = 1.7\,\mu watt/m$

Dipole Full Gap

$2g = 50\,mm$

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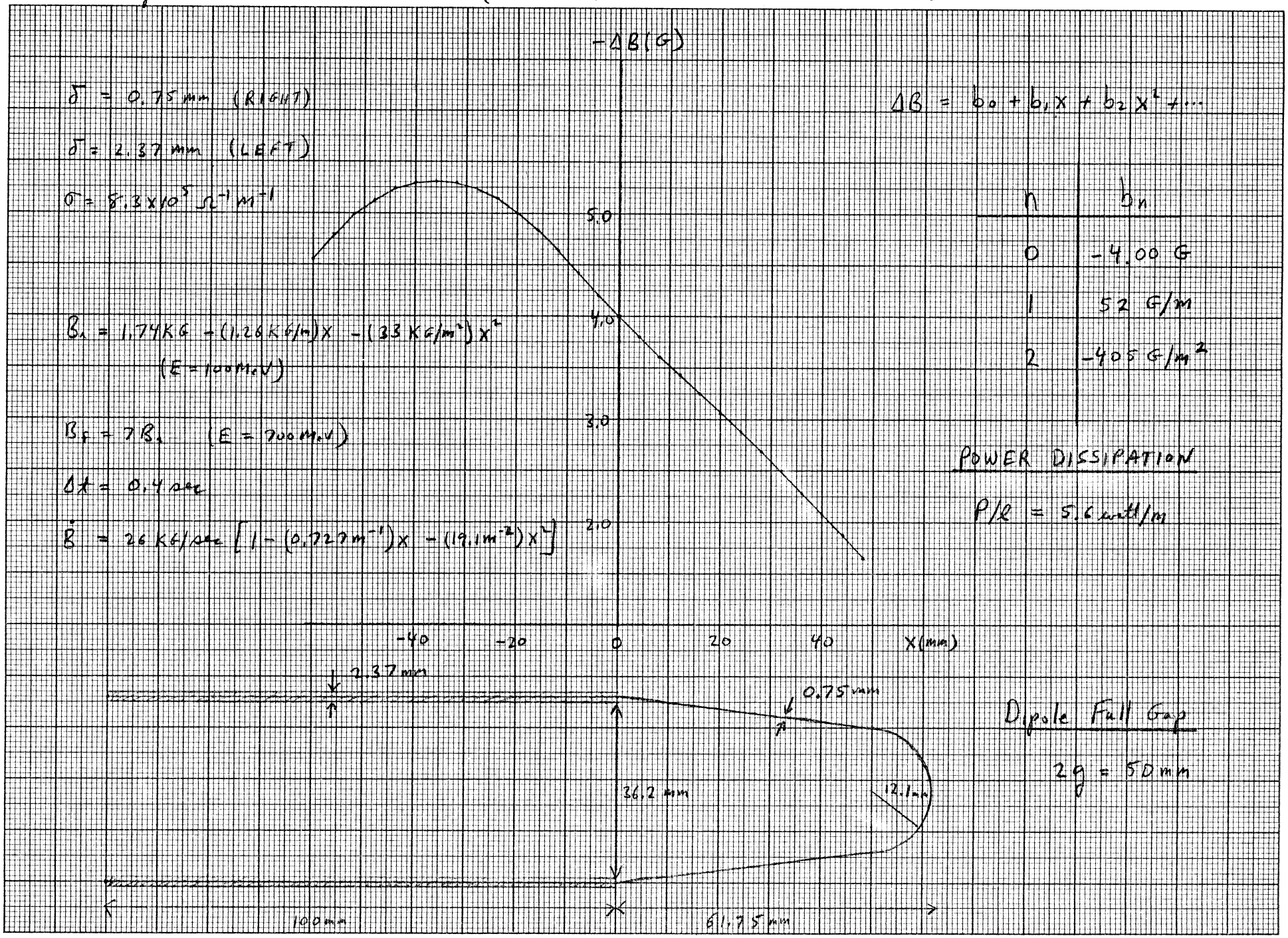
Figure 4. BOOSTER DIPOLE (WITH VACUUM PUMP TAKEOFF PORT)



$\delta = 0.75$ mm (RIGHT)

$\delta = 2.37$ mm (LEFT)

$\sigma = 8.3 \times 10^5\ \Omega^{-1} m^{-1}$

$B_1 = 1.74\,KG - (1.26\,KG/m)x - (3.3\,KG/m^2)x^2$
($E = 100$ M.V)

$B_f = 7B_1$ ($E = 700$ M.V)

$\Delta t = 0.4$ sec

$\dot{B} = 26\,KG/sec\,[1 - (0.727\,m^{-1})x - (19.1\,m^{-2})x^2]$

$\Delta B = b_0 + b_1 x + b_2 x^2 + \cdots$

n	b_n
0	-4.00 G
1	52 G/m
2	-405 G/m^2

POWER DISSIPATION

$P/\ell = 5.6$ watt/m

Dipole Full Gap

$2g = 50$ mm

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Figure 5. XRAY RING DIPOLE

$\delta = 4\,mm$

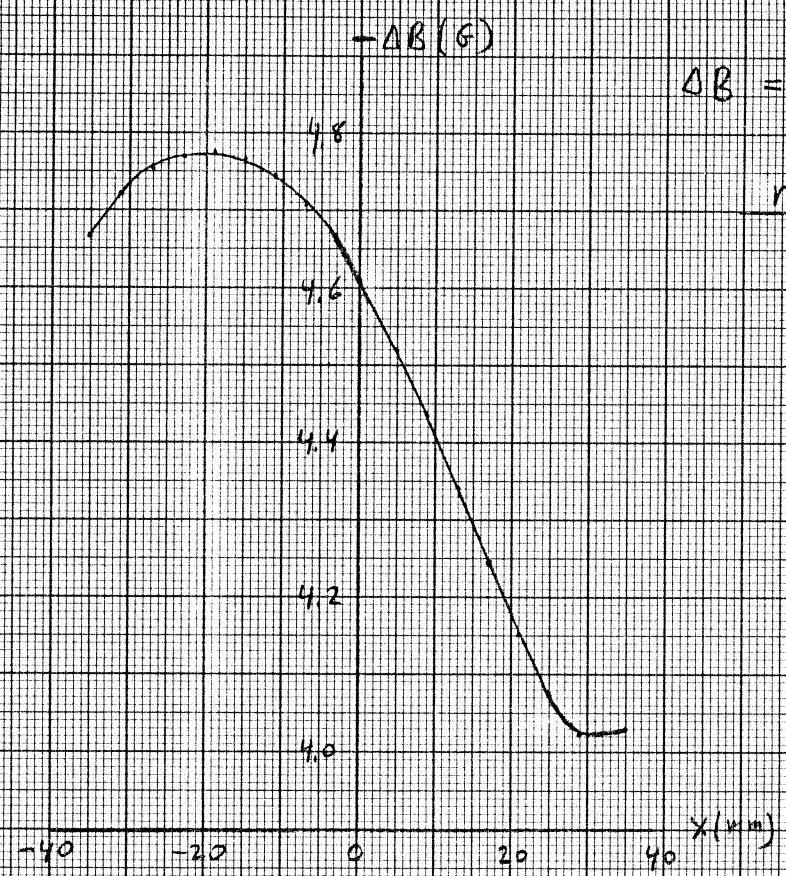
$\sigma = 3.5 \times 10^{7}\,\Omega^{-1} m^{-1}$

$B_1 = 3.4\,KG$ $(E = 0.7\,GeV)$

$B_2 = 12.2\,KG$ $(E = 2.5\,GeV)$

$\Delta t = 60\,sec$

$\dot{B} = 0.146\,KG/sec$

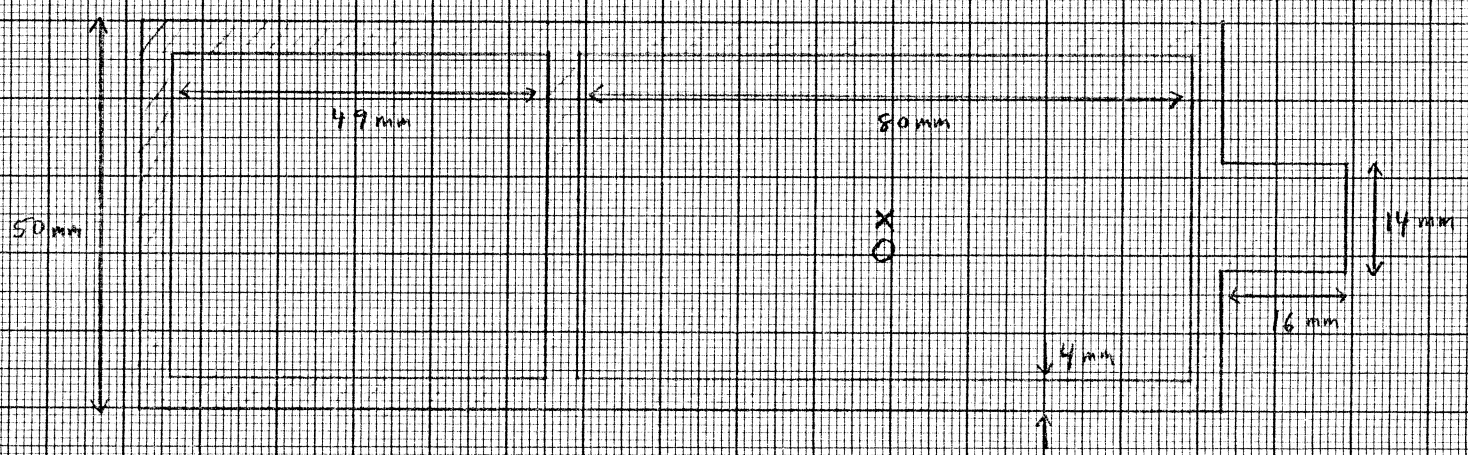


$\Delta B = b_0 + b_1 x + b_2 x^2 + \cdots$

n	b_n
0	-4.61 G
1	16.5 G/m
2	383 G/m^2

POWER DISSIPATION

$P/\ell = 0.036$ watts/m

Dipole Full Gap

$2g = 55\,mm$