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Cost Study of Ferrite Kicker Magnets

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Summary

A ferrite kicker magnet has been proposed as part of a new one-turn beam abort system for the main ring accelerator. A first order approximation of costs for various configurations of magnets and power supplies has been made based on known design and cost of the existing fast extraction kicker system in the main ring.

Introduction

The present beam abort system is a half sine wave current waveform magnet which in five milliseconds moves the beam into a target edge.[1] As part of an effort to reduce residual radiation downstream of the abort target and to protect the entire ring from localized severe damage in the case a sudden magnet failure a single turn extraction abort system has been proposed.[2] One component of such a system is a ferrite kicker magnet similar to the one presently used for fast extraction of the beam and located at C-48 in the main ring. This note tabulates the cost of such a ferrite kicker magnet and several variations intended to increase the magnetic field from the present 400 gauss.[3]

Description of the Fast Extraction Kicker[4]

The present fast extraction kicker is made up of six magnets which are powered by a single energy storage network which is in turn powered by a single power supply. Three magnets and a resistor are connected in series and these two sets are driven in parallel by the energy storage network through a thyratron (see Figure 1). Figure two is a schematic of the energy storage network. The capacitors are charged slowly through the resistor R and the network is discharged through the thyratron into the cables. The pulse is approximately 21 μsec long and the pulse height is half the charging voltage since the source impedence to the left of the switch is nearly equal to the load impedence (see Figure 3).[5] Figure 4 is a simplified cross section of the kicker magnet showing the dimensions of the field region and the location of the conductors and ceramic beam pipe.

The magnet sections are actually built in half section pieces split along the vertical plane, as is better shown in Figure 5. The current pulse from the storage network enters on the left from the coaxial cable (RG-220) travels down the left half-section conductor across on two short pieces of bar into the right half section and then back along the inner conductor where it is connected to the case. The current returns via the case and coax braid to the power supply.

Table one lists dimensions and electrical parameters of the Fast Extraction Kicker. In column one for comparison purposes are the CERN SPS kicker parameters[6] for a lumped element delay line type.[5] In column three is a kicker composed of one 12.5Ω resistor and 3 magnets but driven by the full current of the energy storage network (3234 Amps). This would increase the field from 400 to 800 gauss, but does not reach the 1000 gauss proposed by L. Teng.[2]

Vertical Kicker Magnet

For kicking the beam vertically the magnet gap height must be made larger to accommodate the horizontal dimension of the beam pipe and the magnetic field decreases from 800 to 533.

$$B = \mu_o \ H = \mu_o \ \frac{I}{\text{height}}$$

for a constant current of 3234 Amps (column 4). By doubling the current to 6468 Amps, the magnetic field becomes 1066 gauss (column 5), slightly above the one kilogauss design aim.[2]

The gap height of 76.2 mm comes from measurements made by Sho Ohnuma which indicate that ±35 mm horizontal aperture at B-50 is enough for the beam.

Column 6 lists a magnet of 1500 gauss, the field proposed for the Tevatron vertical abort kicker[7] but again with a 76.2 mm gap (the proposed gap is 60 mm). The last column (7) gives the data for the CERN SPS abort kicker. As for the CERN SPS extraction kicker, this is a lumped-element transmission line magnet.

The increase in magnetic field proceeding from column 2 to column 6 is due to increasing the current by keeping the voltage constant and decreasing the resistance by sub-multiples of 50Ω. The coaxial cables from the energy storage network to the magnet are 50Ω characteristic impedence. By adding cables in parallel the apparent characteristic impedence becomes 50/2, 50/3, 50/4, ... ohms. Lowering this resistance increases the rise time

$$T_{rise}\ (10\text{-}90\%) = 2.2\,\frac{L}{2R}$$

this may become a problem at high beam intensities. The rise time can be reduced by splitting the magnet in two and lowering L to L/2 in the time constant, but then twice the current is needed from the power supply which increases the cost considerably. To make cost comparisons understandable, decreasing the rise time was not considered here.

Cost Estimates

Table two lists the costs of the components for the kicker systems. Three power supplies are listed. The first is the present extraction supply, the second is the same supply but with twice the output current, and the third a 10KA supply for the Tevatron vertical abort kicker.[7]

Table three lists the cost of seven different kicker schemes - three horizontal with two inch gaps and four vertical with 76.2 mm gaps. Also listed is the B field, the integrated kick strength, Bℓ and these two quantities divided by the cost.

Kicker Magnets in Vacuum

No consideration was given to placing the magnet inside the vacuum. While this does eliminate the ceramic vacuum pipe and removes the danger of the pipe imploding, the cost and complexity of construction does not justify the advantage. There is an increase in the B field because the magnet gap could be made smaller at least by twice the wall thickness of the vacuum pipe and probably slightly more (the vertical beam oscillation amplitude is the minimum distance) and this increase in B field may justify putting the magnet inside the vacuum, but the additional cost would probably be about the same as building a larger energy storage network to produce the same field with a vacuum pipe.

Additional costs for an in-vacuum system would be for high voltage vacuum feedthrough connectors and for a process to bake the ferrites so that they would not produce a localized pressure bump in the accelerator. The ferrites used at the SPS have a density close to the theoretical density of 5.1 g/cm^3, therefore, the porosity and outgassing rate are low. The presently used Stackpole ferrite has a density of about 4.8 g/cm^3 giving a porosity of about 6%.

Inductance and Rise Time Calculations

$$L = \frac{\int \bar{B} \cdot \overline{ds}}{\int \bar{H} \cdot \overline{dl}}$$

assuming $\mu_f >> \mu_o$,

$$L = \frac{B\left(\frac{w}{2} \cdot \text{length}\right)}{\int_{\text{ferrite}} \frac{B}{\mu} dl + \int_{\text{air}} \frac{B}{\mu_o} dl}$$

$$L = \frac{B\left(\frac{w}{2} \cdot \text{length}\right)}{0 + \frac{B}{\mu_o} \cdot h}$$

for two half-magnets

$$L = \mu_o \frac{w \cdot \text{length}}{h}$$

$$L = 4\pi 10^{-7} \left(\frac{H}{m}\right) \frac{5.5 \text{ inches } (1 \text{ meter})}{2 \text{ inches}}$$

$$L = 3.456 \ \mu H$$

for 3 magnets L = 10.36 μH

$$\text{time constant } \tau = \frac{L}{R} = \frac{10.368\ \mu H}{25\Omega} = 415 \text{ nsec}$$

but the mismatch at the end of the transmission line gives a reflection coefficient of one, so the total voltage is twice the incident voltage which gives an apparent time constant of

$$\tau_a = \frac{\tau}{2} = \frac{415}{2} = 208 \text{ nsec}$$

and the rise time from 10% to 90% of the final current is

$$T_{rise} = 2.2\ \tau$$
$$= 457 \text{ nsec}$$

For the SPS lumped element transmission line magnets the rise time of the total magnetic field is the propagation time through the magnet

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = \text{length} \sqrt{L_o\ C_o}$$

$$\text{but } Z_o = \sqrt{\frac{Lo}{Lc}} \text{ or } \sqrt{Co} = \frac{\sqrt{Lo}}{Zo}$$

$$T = \text{length} \sqrt{Lo} \sqrt{\frac{Lo}{Zo}} = \ell\ \frac{Lo}{Zo}$$

for SPS horizontal extraction

$$T = 1.674 \text{ meter}\ \frac{8.9\ \mu H}{1.674 \text{ meter}}\ \frac{1}{10\ \Omega} = 0.89\ \mu\text{sec}$$

$$T = 890 \text{ nsec}$$

1) Main Accelerator Abort System; Carrigan, et al, Page 240 PAC 1973

2) External Abort for MR memo from L. Teng to F. Turkot, March 21, 1977.

3) Private communication with J. McCarthy

4) Private cummunications with J. McCarthy & B. Brown

5) See Fast Kickers, Forsyth & Fruitman in Particle Accelerators 1970, Vol 1, Page 27, for a general description of such circuits.

6) The SPS Fast Pulsed Magnet Systems, Faugeras et al, CERN publication number CERN/SPS/BT/76-1, March 12, 1976.

	Fast Extraction Kicker			Beam Abort Kicker			
	SPS	Fermilab		Fermilab proposed		Tevatron	SPS
		present	possible				
gap height (mm)	32	50.8	50.8	76.2	76.2	76.2	75
B (gauss)	1200	400	800	533	1066	1500	1600
Z_0, R (ohms)	10	25	12.5	12.5	6.25	3.125	3.125 $\frac{50}{16}$
I (Amps)	3000	1617	3234	3234	6468	9096	10,000
V_p (=2IR) (K Volts)	60	80.8	80.8	80.8	80.8	59.1	62.5
T_{rise} (10%-90%) nsec	712	456	228	342	684	1824	800
length (meters)	1.674	3.0	3.0	3.0	3.0	4.0	2.560
$B\ell$ (Tm)	0.02	0.24	0.24	0.16	0.16	0.600	0.4096
number of magnets	2	2	1	2	1	1.333	2
Total length (meters)	3.35	6	3	6	3	4.0	5.12
total $B\ell$ (Tm)	0.402	0.240	0.240	0.3198	0.3198	0.600	0.9192
column number	1	2	3	4	5	6	7

KICKER MAGNET PARAMETERS

(Table 1)

TABLE 2

Component Cost in Kilodollars

I Power Supplies

(a) present power suplly (3234 Amps)

Thyratron & accesories	17		
capacitors	10		
coax	2		
control system	5		
load resistor	6		
charging supply	10		
labor	10		
	60	(X 1.1)	66

(b) new PS (6468 Amps)

present PS	60		
20 capacitors	10		
extra labor	5		
	75	(X 1.1)	82.5

(c) Tevatron PS (10 K Amps)

present PS	60		
40 capacitors	20		
extra labor	5		
	75	(X 1.1)	99

II Magnets

3 meter unit	15		15
4 meter unit	20		20

TABLE 3

System Cost in Kilodollars

(TYPE)		COST (K$)	B gauss	B gauss-meter	$\frac{B\ell}{C}$	$\frac{B\ell}{C}$
I Extraction (2 inch qq)						
(a) present (I in two magnets)						
one PS	66	96	400	2400	4.2	25.0
two magnets	30					
(b) possible (2I in one magnet)						
one PS	66	81	800	2400	9.9	29.6
one magnet	15					
(c) new PS (4I in one magnet)						
one new PS	82.5	97.5	1600	4800	16.4	49.2
one magnet	15					
II Vertical Abort (76.2 mm gap)						
(a) identical to extraction		96	267	1602	2.8	16.7
(b) possible (2I in one mag)		81	533	1602	6.6	19.7
(c) new PS (4I in one mag)		97.5	1066	3204	10.9	32.8
(d) Tevatron						
PS	99	119	1500	6000	12.6	50.4
4 meter magnet	20					

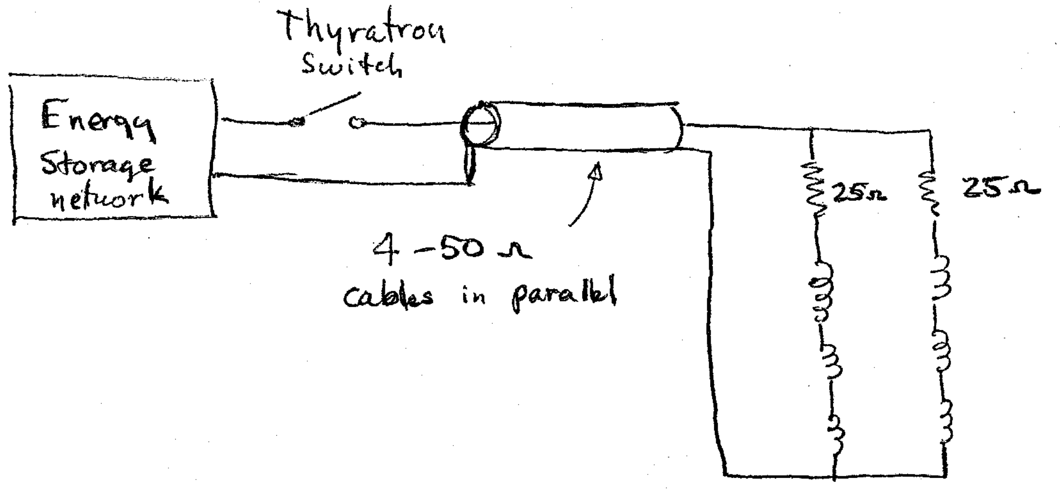
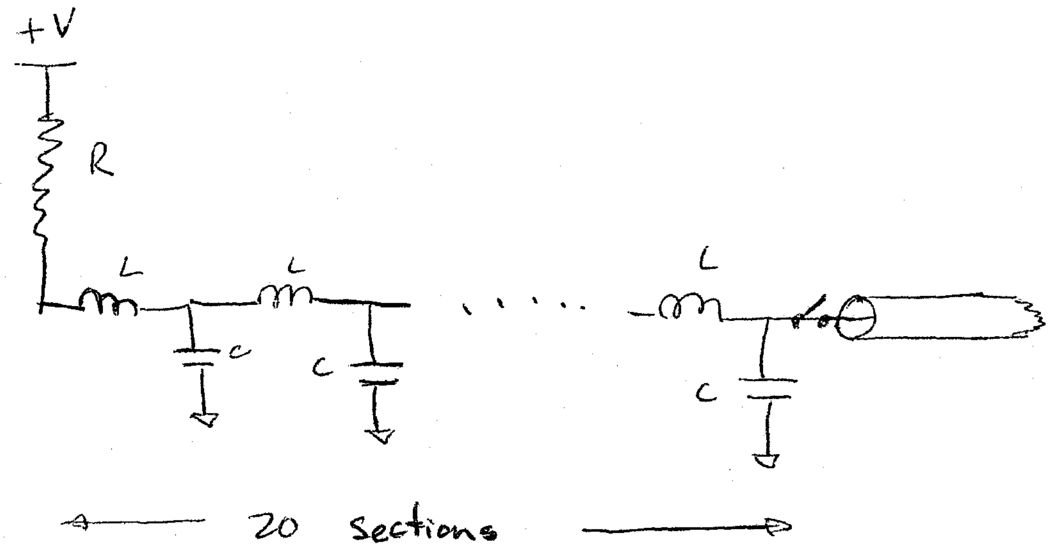


Figure 1 Fast kicker magnet circuit diagram



$$Z_0 = \sqrt{\frac{L}{C}} = 12.5\Omega$$

$$C = 40 \text{nf}$$

$$\tau = \sqrt{LC} \approx 0.5025 \mu\text{sec}$$

Figure 2 Energy Storage Network

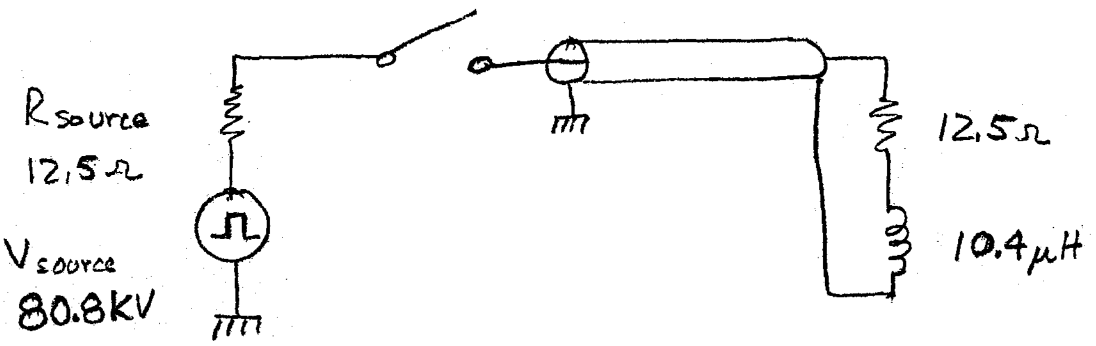


Figure 3 Equivalent Circuit of Kicker Magnet and Energy Storage Network

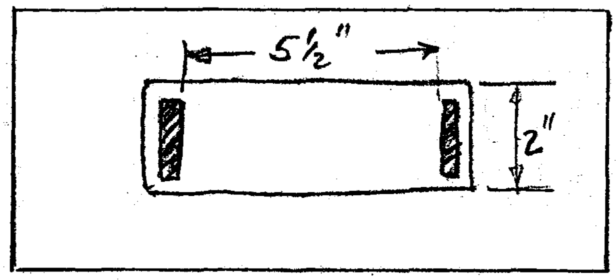


Figure 4 Simplified Cross Section of Kicker Magnet

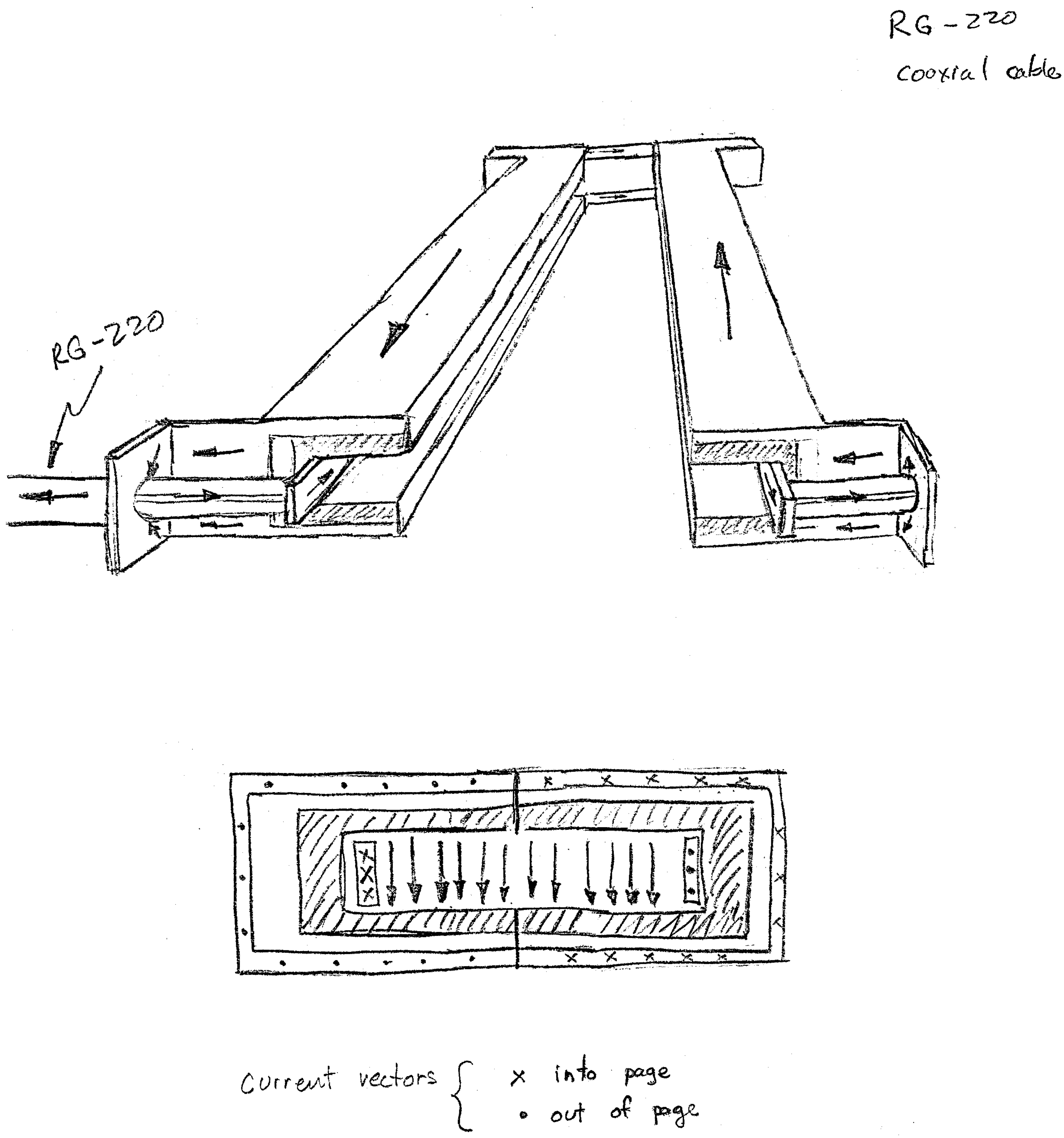
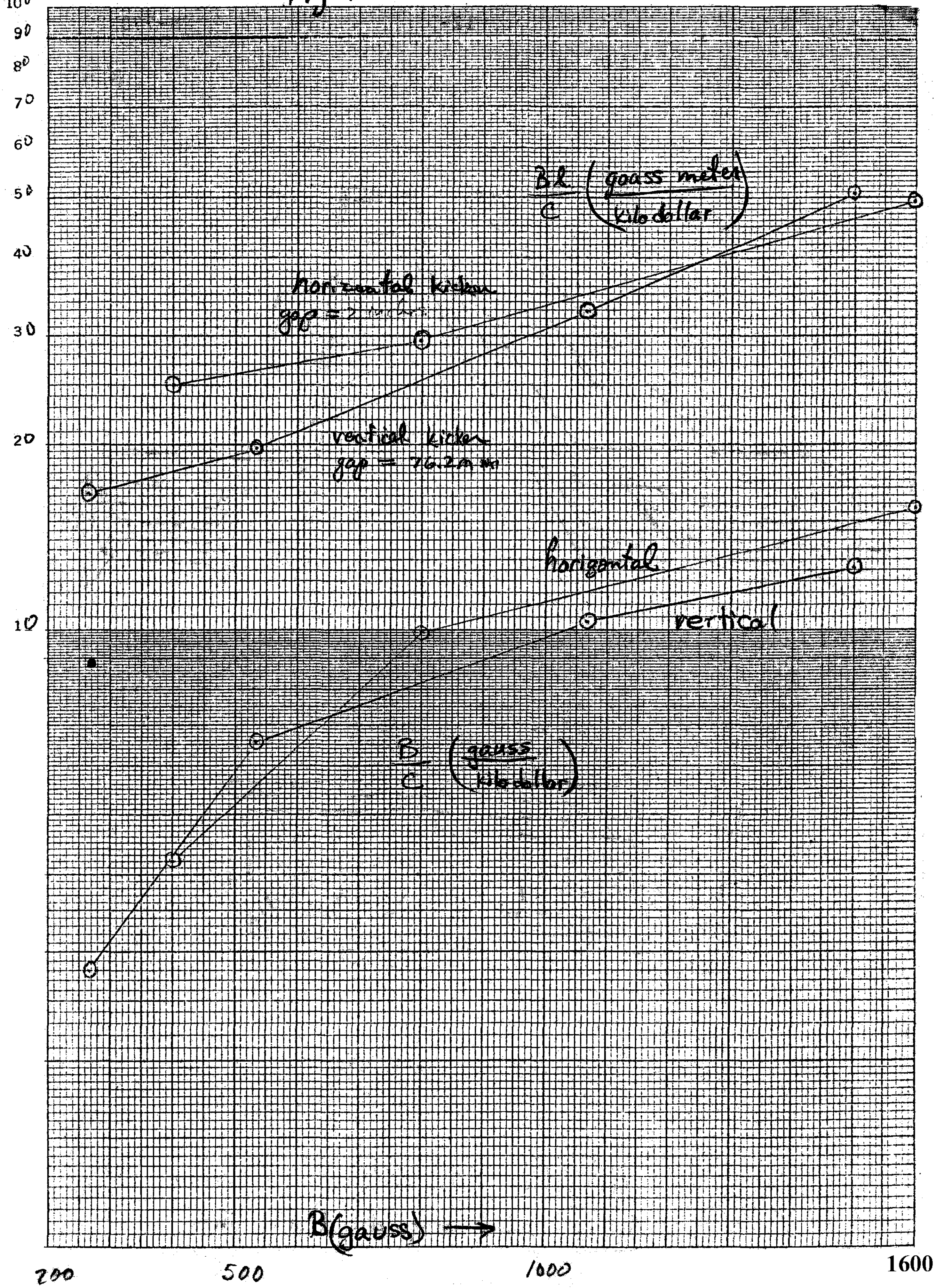


Figure 5 Magnetic half-sections showing current flow and magnetic field lines

figure 6



100
90
80
70
60
50
40
30
20
10
Bl/C (gauss meter/kilo dollar)
horizontal kicker
gap = 2 inches
vertical kicker
gap = 76.2mm
horizontal
vertical
B/C (gauss/kilo dollar)
B(gauss) →
200
500
1000
1600