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General design feasibility curves for Booster ferrite cavities

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Collider Accelerator Department

Brookhaven National Laboratory

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AD

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No. 77

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ACCELERATOR DEVELOPMENT DEPARTMENT

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GENERAL DESIGN FEASIBILITY CURVES FOR BOOSTER FERRITE CAVITIES

Martin Plotkin

INTRODUCTION

For any particular ferrite, the method of establishing the feasibility of constructing a ferrite cavity is very straightforward. The curves presented in this note are intended to facilitate the selection, or rejection, of a ferrite material based upon an initial sample measurement. It is still essential to measure (small and large samples) ferrite thoroughly, and do more detailed computations, for any potentially acceptable ferrite.

The curves are in two groups for two different approaches. The first is very specific for Booster cavities I and II at 17 Kv. The second is more general for Booster cavities I, II, III for varying gap voltages.

GENERAL DESIGN FEASIBILITY CURVES FOR BOOSTER FERRITE CAVITIES

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Design Criteria:

1. 17000 volts/cavity
2. Frequency Range
   a. Cavity I - 178.5 - 675 KHz
   b. Cavity II - 675 - 2500 KHz
3. Total axial length available/cavity - 250cm.
4. These designs predicated on small samples of TDK Ferrite SY-7 (Mike Goldman data - Fig. I)

$V = \omega BA \times 10^8$ (B-gauss A-cm^2, V-volts $A = N(r_2 - r_1) \times 2.5$, N=number of 2.5cm thick rings).

Using the data in appendix I, Fig, II represents a set of design curves for SY7 and V=17KV. For any r_2-r_1, (10cm, 12.5cm and 15cm) as shown and a power loss level selected, the number of rings is determined. The power loss level is a function of the method of cooling, the duty factor and the requirement for temperature control of the ferrite. For example, with water cooling and a 250 mw/cc power loss and a 50% duty factor, we look at the 500 mw/cc line and see that we can use 48 rings at r_2-r_1=15cm or 56 rings at r_2-r_1=12.5cm.

Available length of ferrite for a double cavity/station:

gaps (2) + clearance: 2 x 15cm	30cm
center plates:	6cm
end plates: 2@ 1.5cm	3cm
end spaces: 4@ 2.5cm	10cm
	49cm

For 250cm total - 200cm available for ferrite and cooling plates (or cooling spaces for air cooling). Cooling plates may range from 0.3cm (for edge cooling) to 0.6cm for overall cooling plates. Air cooling requires about 0.6cm between ferrite rings.

Maximum number of rings of 2.5cm thickness for various cooling $N = \frac{200}{2.5+c}$

c = cooling thickness requirement.

		N max
edge cooling	(.3cm)	71.4 (72)
overall cooling	(.6cm)	64.5 (64)
air cooling	(.6cm)	64.5 (64)

All the previous numbers are for the starting frequency. As the ferrites are dc biased to tune to the top frequency of 675 KHz the losses (at the same voltage level) may increase or decrease. This must be measured specifically for each ferrite. In general, when a ferrite is used within its normal frequency range, the impedance over the tuning range remains fairly uniform.

Since $P = V_{pk}^2/2Z$ the power loss does not vary too much. The top frequency for cavity I is well within the operating frequency range of TDK SY-7.

It is fortuitous that as the frequency rises by a factor of, let us say 3, the inductance decreases by a factor of 9 and the Q increases by about a factor of 3. Thus $Z = \omega LQ$ remains relatively constant.

Similarly for the heavy ion cavity II, the data in appendix II provides the curves in Figure III.

In Fig. III, for the same number of rings as in Cavity I, the power losses are considerably smaller. However, the top frequency of 2.5 MHz is above the normal, unbiased, operating frequency of SY7. With bias the ferrite behavior above its normal operating frequency is significantly improved. There may be larger losses at 2.5 MHz than at 675 KHz. for this reason, and also for the simplicity of making Cavity I and Cavity II identical, as many rings should be used in Cavity II as in Cavity I.

The sequence of steps in the cavity design necessitate a selection of the cooling method, which limits the maximum number of rings allowed. The diameter of the rings, commensurate with the manufacturer's capability of fabrication, should be kept as small as possible. The important criterion for the ferrite is the cross section area of the ferrite, not the ferrite volume. A ring 40cm OD - 20cm ID will perform exactly the same as one 50cm OD - 30cm ID. The smaller ring has 25% less weight and, for the same mw/cc, 25% less total power loss. Since the cost is influenced by total weight the smaller rings may be cheaper. Also cavity structures will be smaller and the rings will be easier to handle.

Having selected the cooling method, which dictates the maximum number of rings, the ferrite ring size and the duty factor, the number of rings required can be read off the curves.

40cm x 20cm rings are closer to the size rings used in the old AGS cavities. these rings were 35cm x 20cm and ran successfully with edge cooled copper plates. The voltage on the old AGS cavity was 8 KV/gap compared to the 8.5 KV/gap in the Booster cavities. If they can be manufactured, and if the duty cycle allows, 40cm x 20cm rings seem to be a viable solution.

The ferrite rings experience a thermal shock if the temperature rise during the pulse, irrespective of the duty factor, is excessive. For the case of 1w/cc the temperature rise is

$$\Delta T = \frac{\text{w/cc x duty factor}}{\text{4.186 x sp.gr. x sp.heat}}$$

ferrite specific grav ≈ 5
ferrite specific heat ≈ .17

$$\Delta T = \frac{\text{w/cc x duty factor}}{3.56}$$

If duty factor = 50% at 1 W/cc ΔT = .14°C/pulse
= 25% at 1 W/cc ΔT = .07°C/pulse

These values are not large but a mechanical analysis should be made.

If we consider using the old AGS cavities and rebuilding them for the vacuum requirements we can estimate the cavity behavior. The cavity will require a high vacuum flange in the center and an additional section can be added allowing for about 10% more ferrite (Peter Cameron information). We can use rings which are 42 cm OD and 20 cm ID and use the 1/8" copper, edge cooled, cooling plates.

If N is the number of rings in each of 4 stacks in the double cavity, and the thickness of the ferrites is 2.5 cm, then 4N(2.5) + (4N+4) (0.3) = L, the available length for the stacks. (0.3 cm ≈ 1/8" the cooling plate thickness.) Cameron indicates enough space for 88 rings at 2.1 cm which yields an available length of 214 cm. Solving for N for 2.5 cm rings we get N = 18, or 72 rings in four stacks.

$$B_{gauss} = \frac{V \times 10^8}{\omega A}$$

B = 765 gauss

V = 17000 volts

$\omega = 2\pi \times .1785 \times 10^6 = 1.122 \times 10^6$

$A = 72 \left(\frac{42.20}{2}\right) 2.5 = 1980 \text{ cm}^2$

For SY7, at 0.1785 MHz, P = 390 mw/cc.

With a 50% duty cycle the average power loss is 195 mw/cc. This is an acceptable value for water cooling with edge cooled plates.

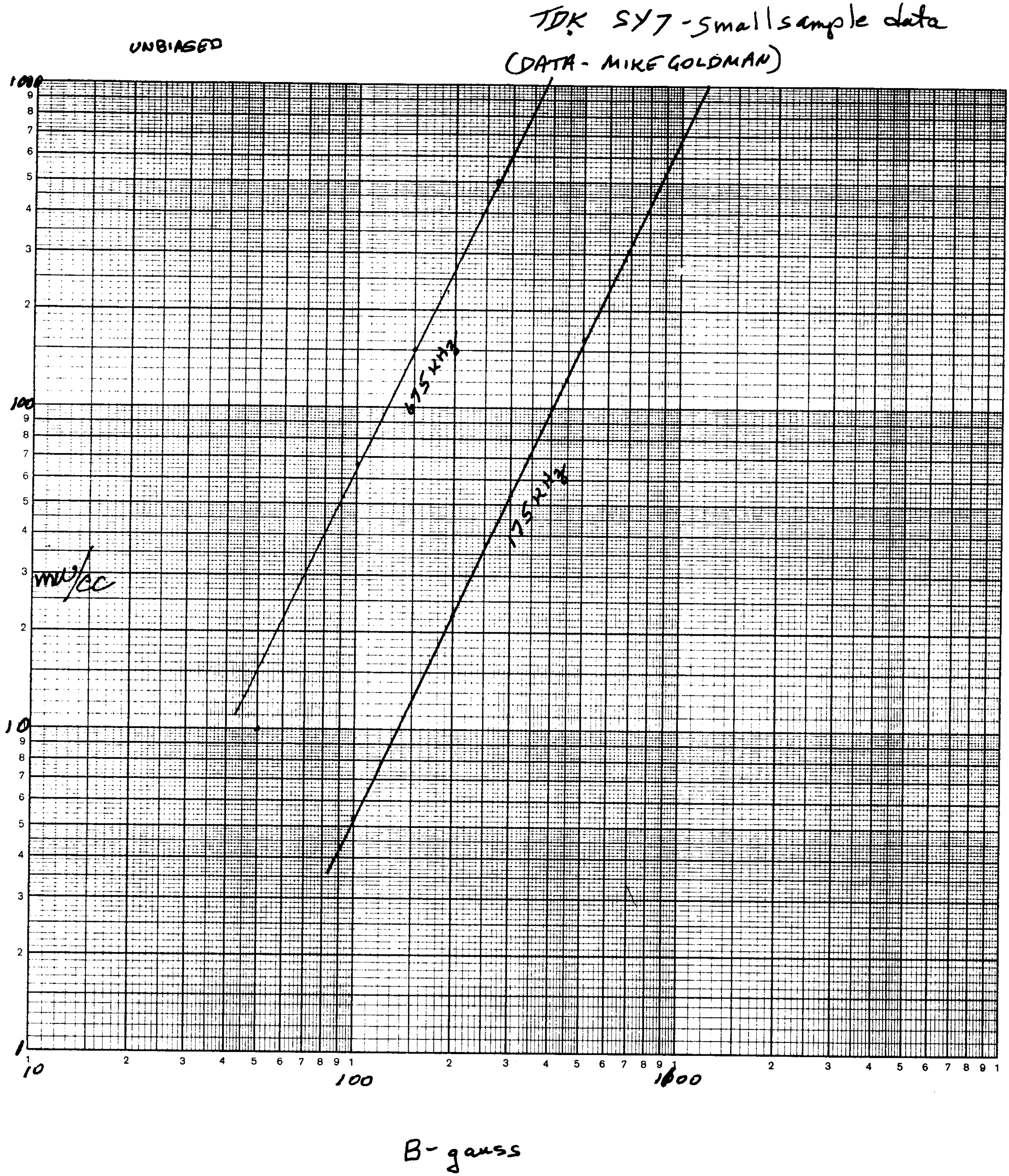
Another approach to generate a more useful set of curves is to have plots of flux density vs number of rings at a given frequency (the starting frequency) with peak voltage as a parameter. Three curves are presented for each starting frequency for the difference in inner and outer radii of 10 cm, 12.5 cm and 15 cm, for 178.5 KHz and also for 675 Hz.

The curves are used by selecting a power level which considers the cooling system and the duty cycle. The flux density for this condition is found from measured data and, for the voltage desired, the number of rings are determined. Similar curves can be readily made for any set of conditions.

Figure IV A,B,C is for a starting frequency of 0.1785 MHz.
Figure V A,B,C is for a starting frequency of 0.675 MHz.
Figure VI A,B,C is for a starting frequency of 2.5 MHz.

The data are presented in appendix III.

Fig I


TDK SY7 - small sample data
(DATA - MIKE GOLDMAN)
UNBIASED
675 KHz
175 KHz
mW/cc
B - gauss
10
100
1000
1
10
100
1000

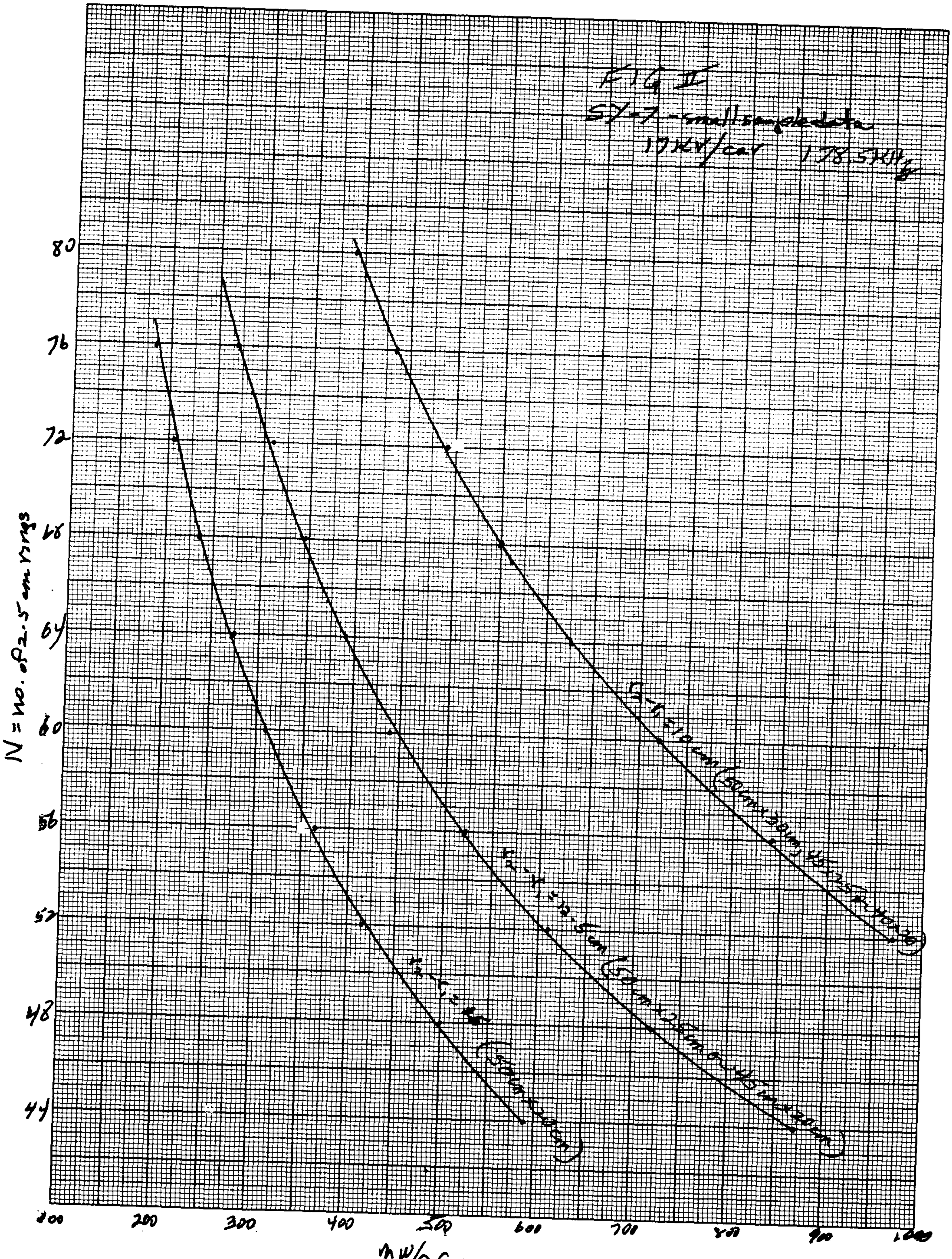
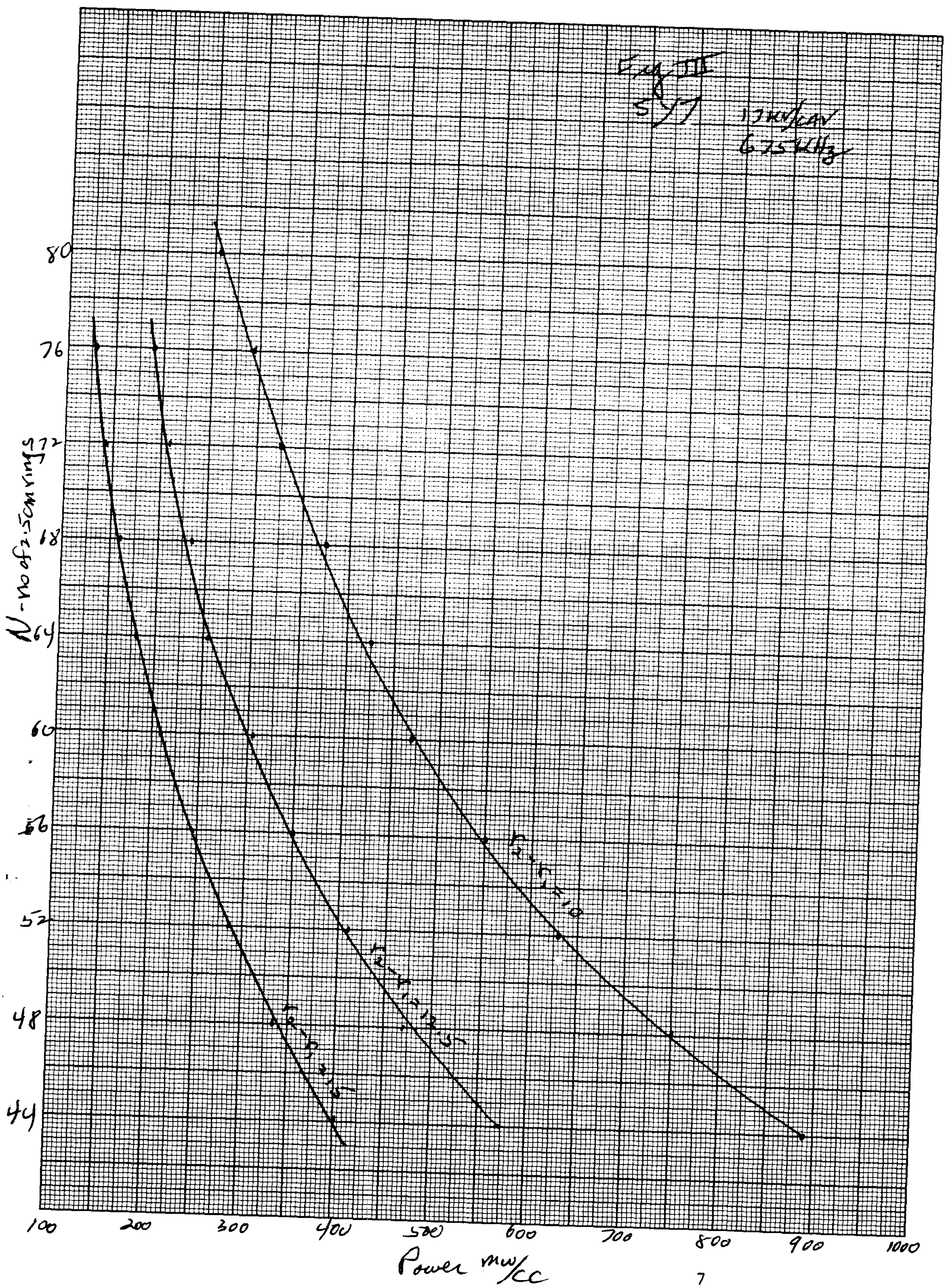
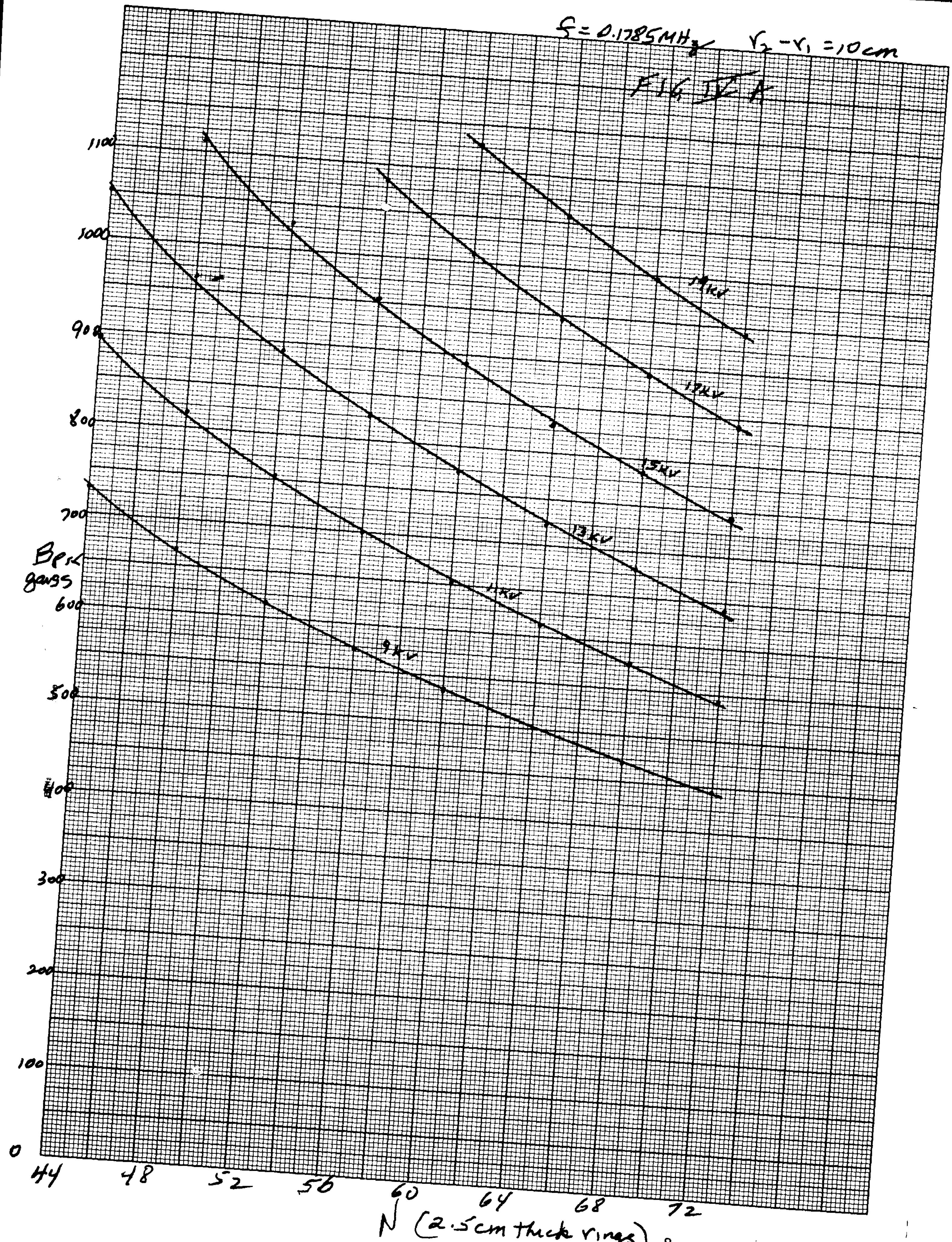
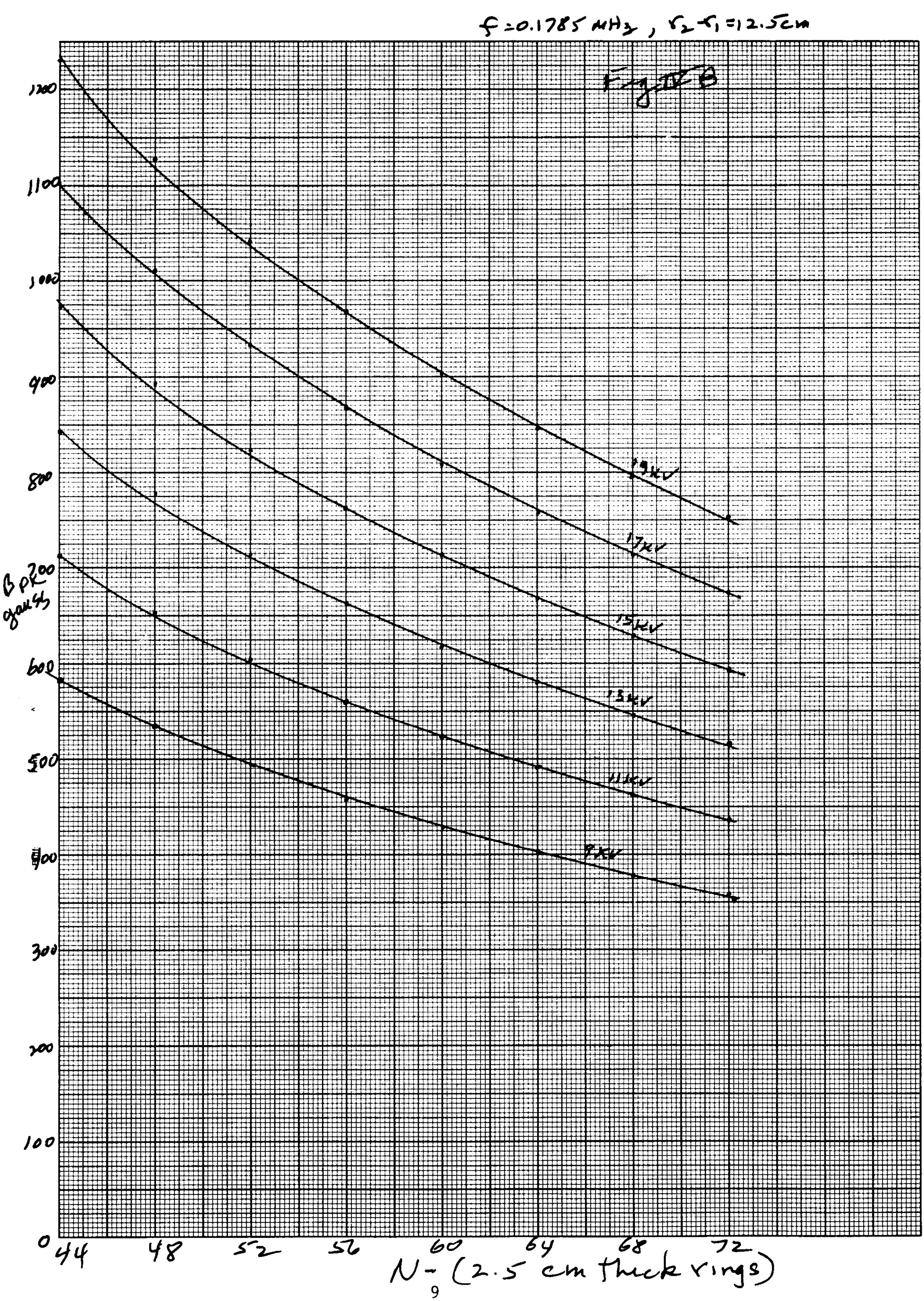
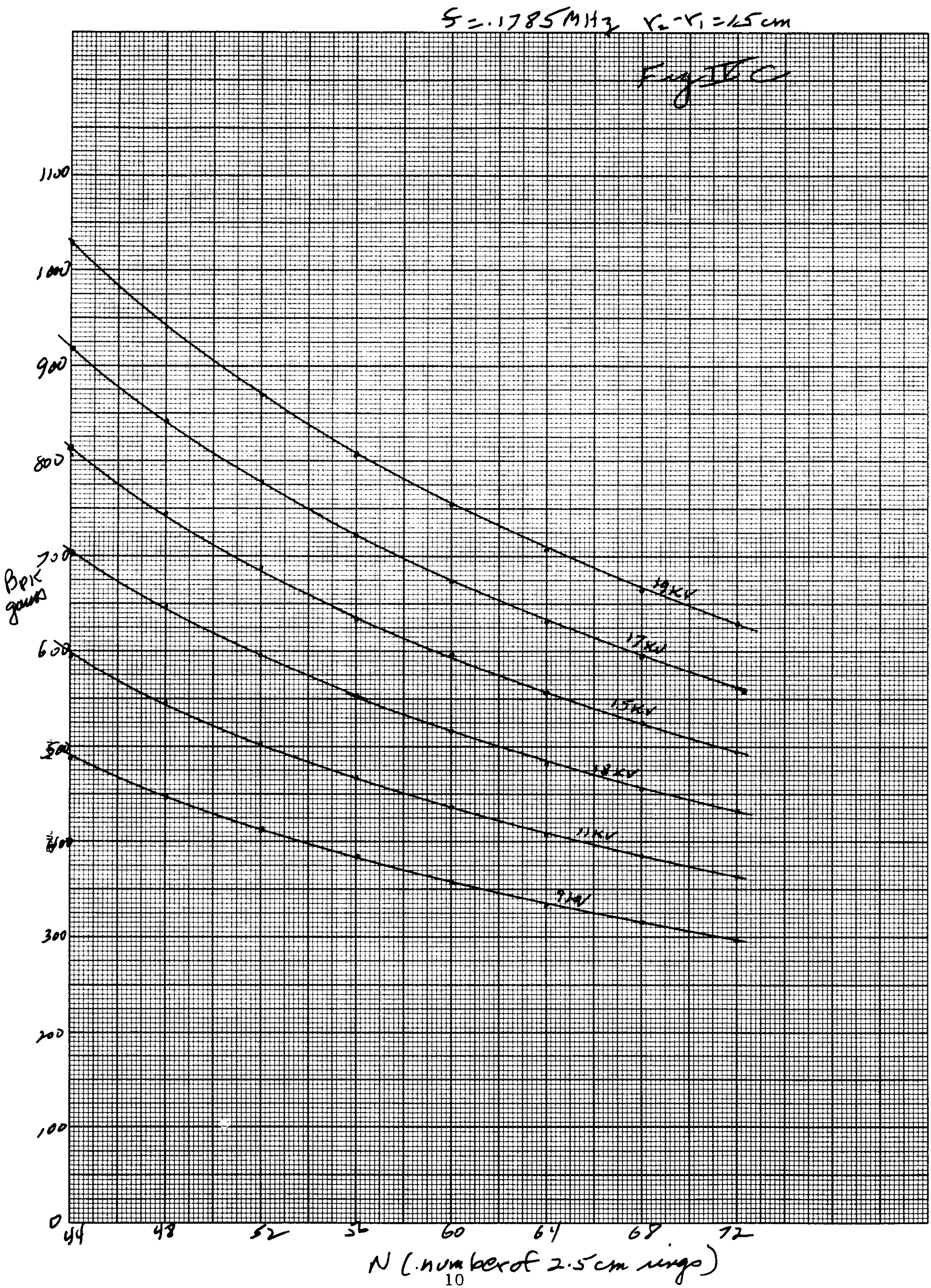


FIG II
SY-7 - small sample data
17KV/cm 178.5KHz
N = no. of 2.5 cm rings
80
76
72
68
64
60
56
52
48
44
100
200
300
400
500
600
700
800
900
1000
mW/cc
r2-r1 = 10 cm (50cm x 30cm, 45x25 or 40x20)
r2-r1 = 12.5 cm (50cm x 25cm or 45cm x 20cm)
(50cm x 20cm)

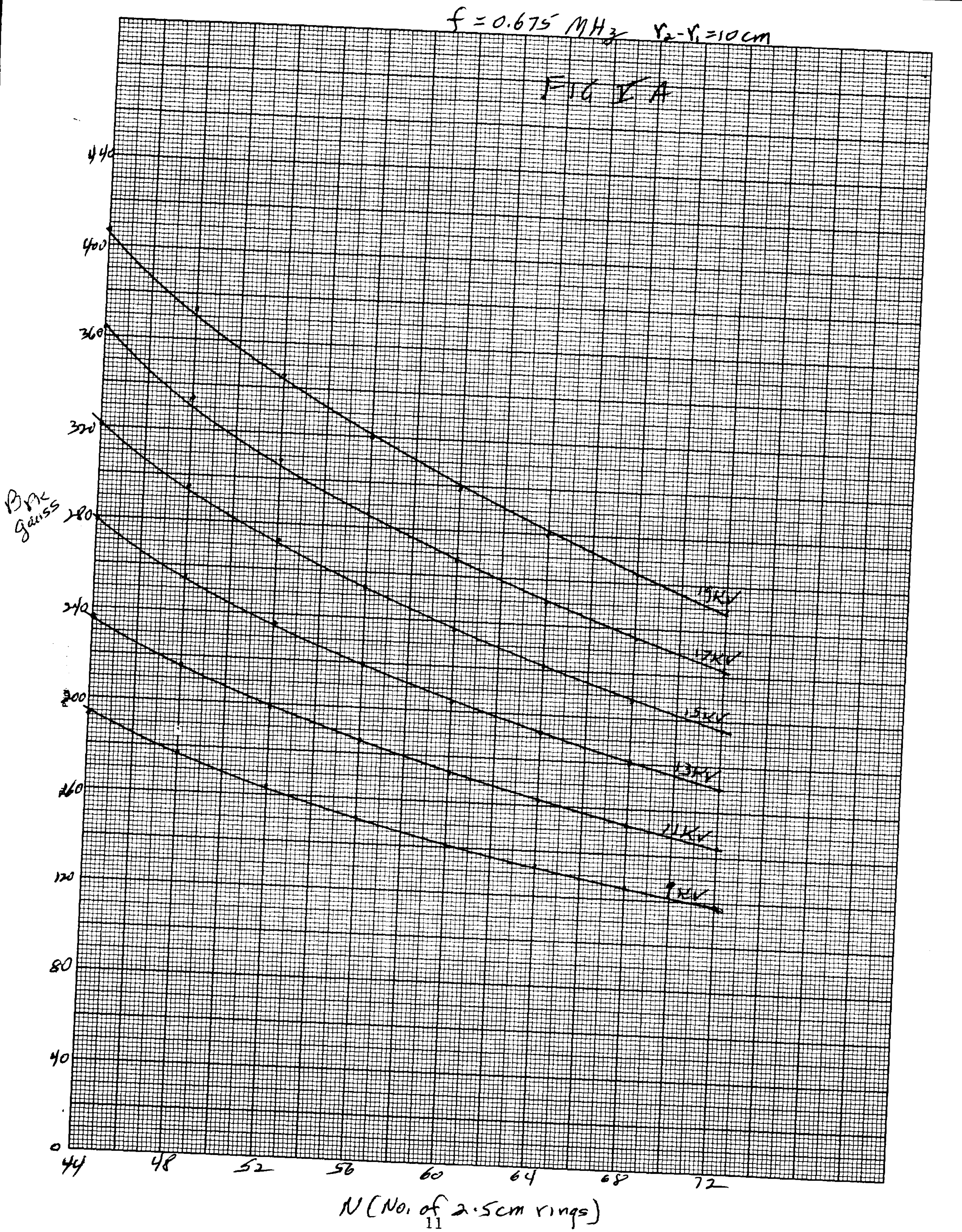

N - no of 2.5cm rings
80
76
72
64
60
52
48
44
100
200
300
400
500
600
700
800
900
1000
Power mW/cc
r2 - r1 = 10

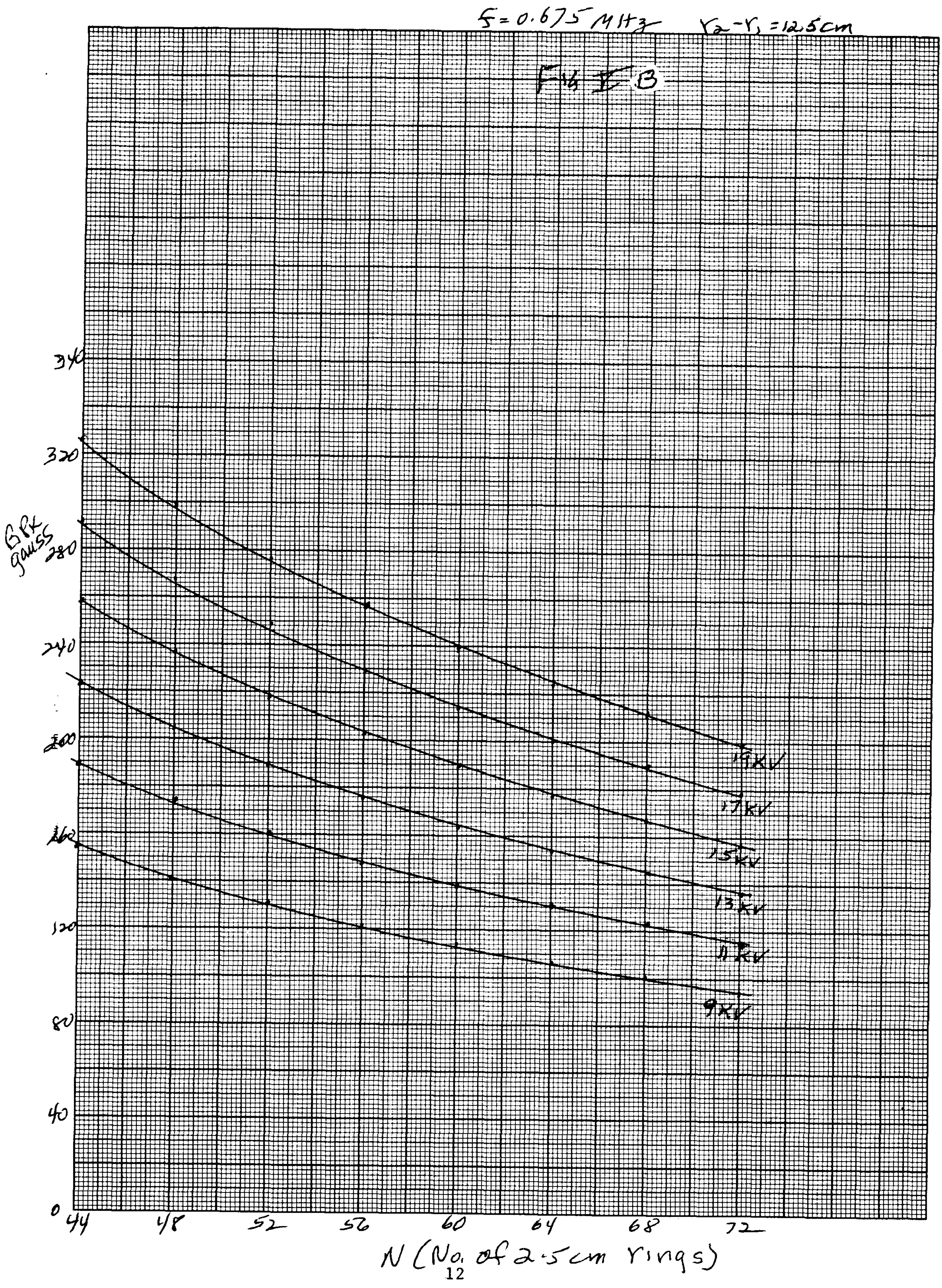

f = 0.1785 MHz $r_2 - r_1$ = 10 cm
FIG IV A
19 kV
17 kV
15 kV
13 kV
11 kV
9 kV
B_{esr} gauss
0
100
200
300
400
500
600
700
800
900
1000
1100
44
48
52
56
60
64
68
72
N (2.5 cm thick rings)


f = 0.1785 MHz , r2 - r1 = 12.5 cm
Fig IV B
B pk gauss
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
44
48
52
56
60
64
68
72
N - (2.5 cm thick rings)
19 kV
17 kV
15 kV
13 kV
11 kV
9 kV

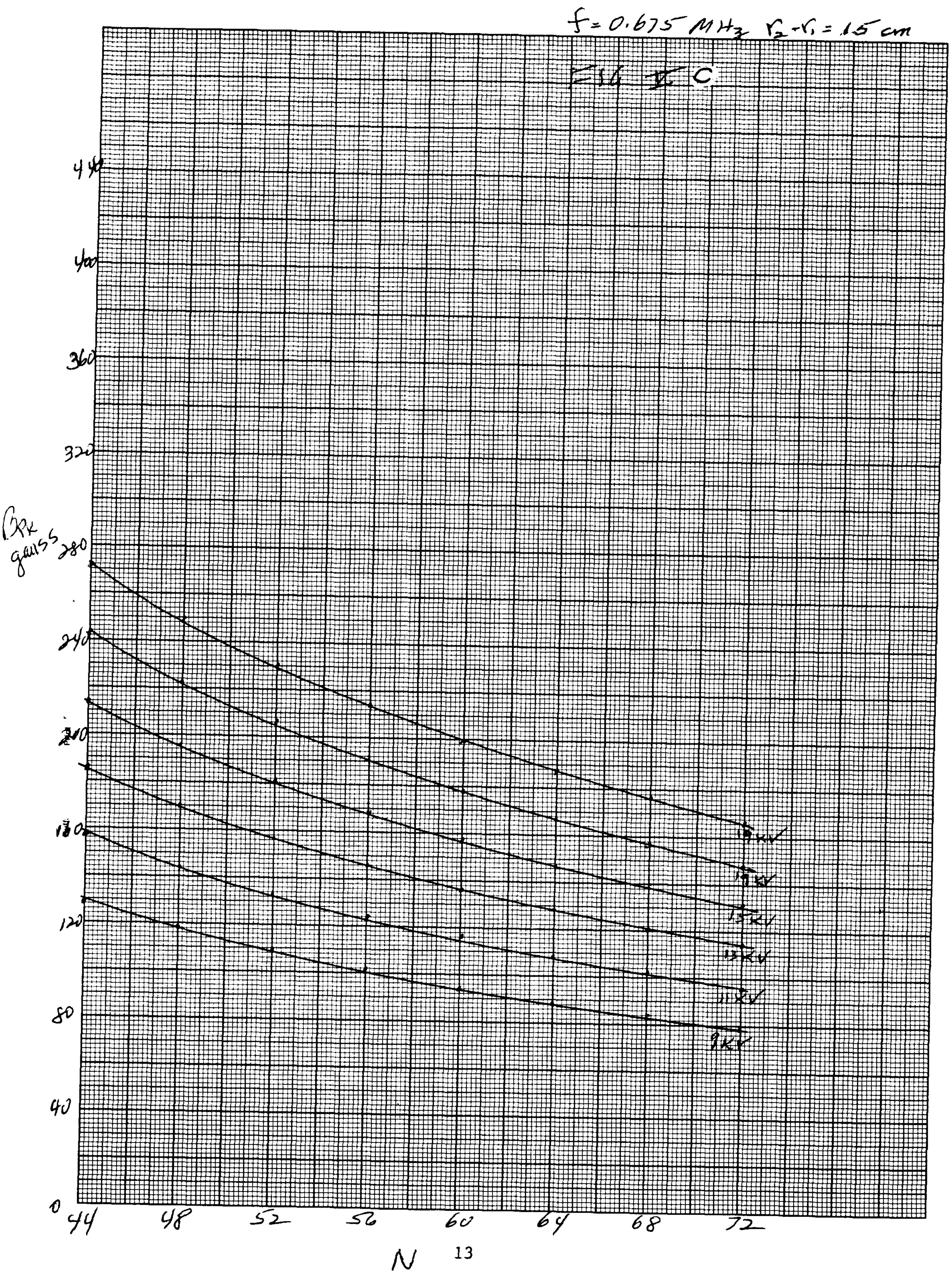


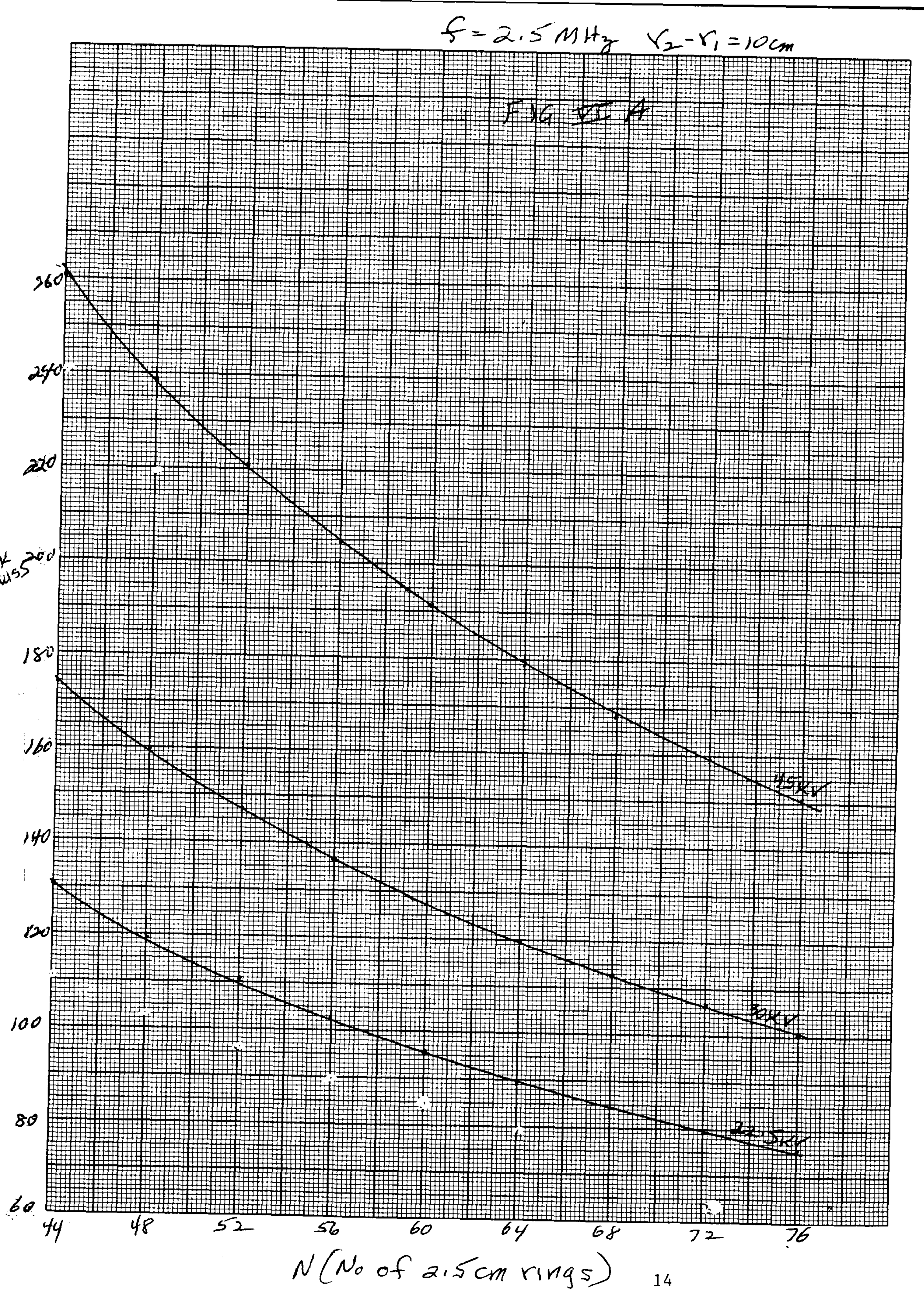
f = .1785 MHz   r2-r1 = 25 cm
Fig IV C
Bpk gauss
1100
1000
900
800
700
600
500
400
300
200
100
0
19 kV
17 kV
15 kV
13 kV
11 kV
9 kV
44
48
52
56
60
64
68
72
N (number of 2.5 cm rings)

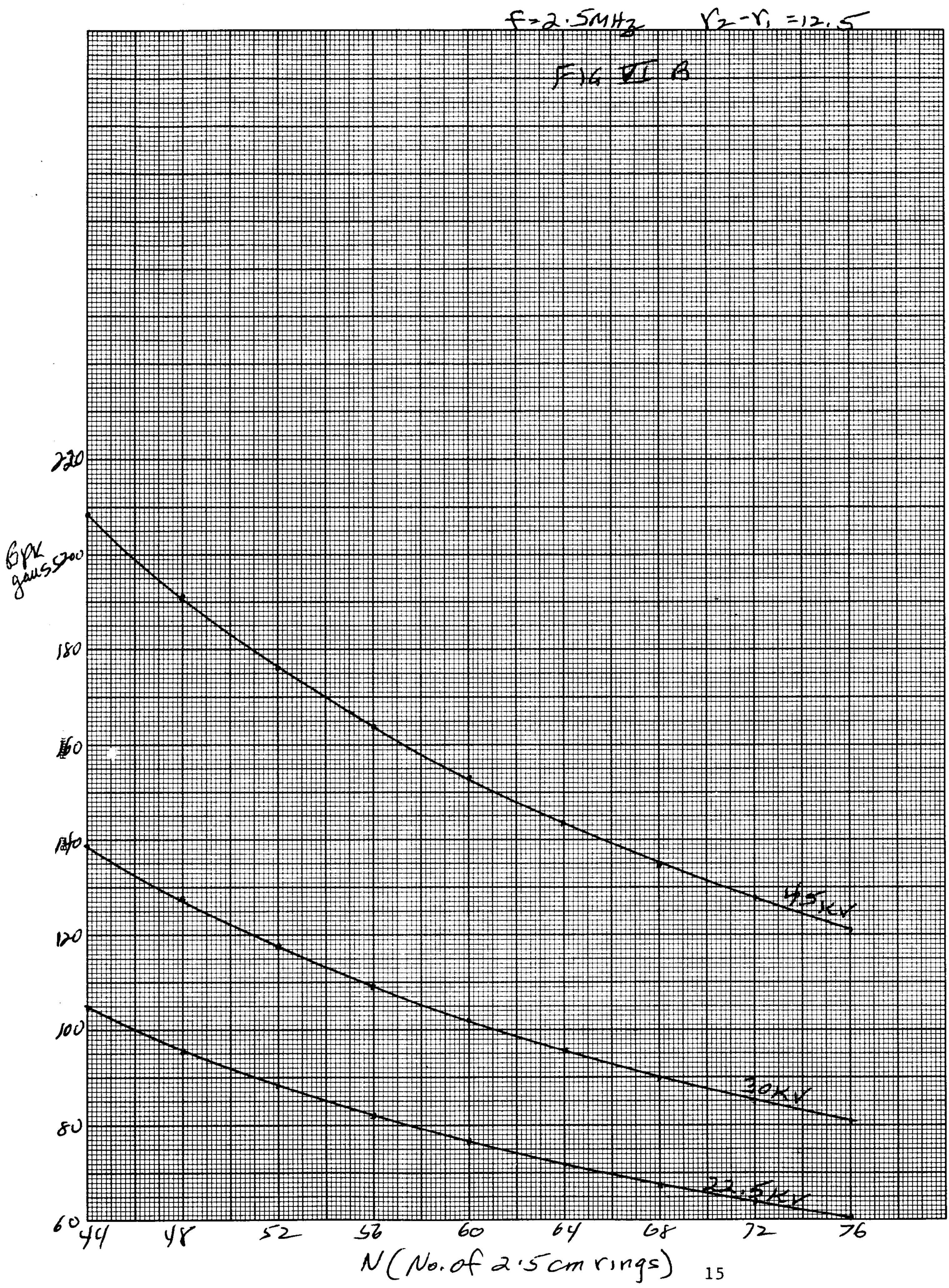

f = 0.675 MHz r2-r1=10cm
FIG V A
B_RC gauss
440
400
360
320
280
240
200
160
120
80
40
0
19KV
17KV
15KV
13KV
11KV
9KV
44
48
52
56
60
64
68
72
N (No. of 2.5cm rings)



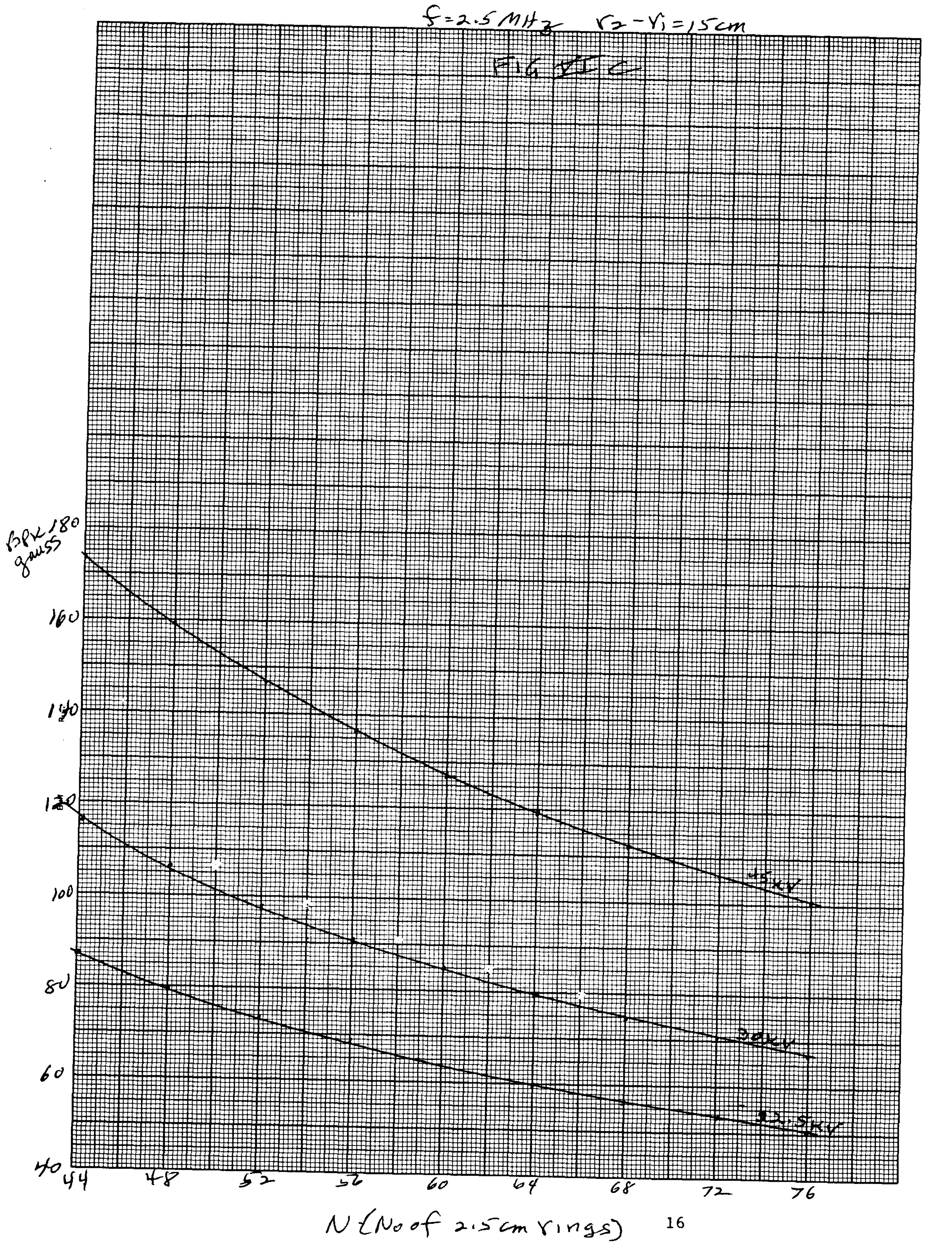
f = 0.675 MHz r2 - r1 = 12.5 cm
Fig V B
Bpk gauss
340
320
280
240
200
160
120
80
40
0
19 KV
17 KV
15 KV
13 KV
11 KV
9 KV
44
48
52
56
60
64
68
72
N (No. of 2.5 cm rings)


f = 0.675 MHz r2 - r1 = 15 cm
FIG V C
B pk gauss
440
400
360
320
280
240
200
160
120
80
40
0
44
48
52
56
60
64
68
72
N
19 KV
17 KV
15 KV
13 KV
11 KV
9 KV


f = 2.5 MHz r2 - r1 = 10cm
FIG VI A
Bpk gauss
260
240
220
200
180
160
140
120
100
80
60
44
48
52
56
60
64
68
72
76
45KV
30KV
22.5KV
N (No of 2.5cm rings)



f=2.5MHz
r2-r1=12.5
FIG VI B
Bpk gauss
220
200
180
160
140
120
100
80
60
44
48
52
56
60
64
68
72
76
45kV
30kV
22.5kV
N (No. of 2.5cm rings)


f=2.5 MHz r2 - r1 = 15 cm
FIG VI C
Bpk gauss
180
160
140
120
100
80
60
40
44
48
52
56
60
64
68
72
76
45 kV
30 kV
22.5 kV
N (No of 2.5 cm rings)

APPENDIX I

Cavity I: $\omega = 2\pi f = 1.1 \times 10^6$ (Data was taken at 175 KHz but 178.5 KHz was used in the evaluations.)

$$BA = \frac{1.7 \times 10^4 \times 10^8}{1.1 \times 10^6} = 1.515 \times 10^6$$

r_2	r_1	N	A	B	mw/cc
50	30	44	1100	1409	excessive
$r_2 - r_1 = 10$		48	1200	1292	excessive
		52	1300	1192	970
		56	1400	1107	840
		60	1500	1033	720
		64	1600	969	625
		68	1700	911	550
		72	1800	861	500
		76	1900	816	435
		80	2000	775	390
50	25	44	1375	1127	870
		48	1500	1033	720
$r_2 - r_1 = 12.5$					
		52	1625	953	610
		56	1750	886	520
		60	1875	826	440
		64	2000	775	390
		68	2125	729	345
		72	2250	689	310
		76	2375	652	270
50	20	44	1650	939	590
		48	1800	861	500
$r_2 - r_1 = 15$		52	1950	795	415
		56	2100	738	365
		60	2250	689	310
		64	2400	646	275
		68	2550	608	235
		72	2700	574	205
		76	2850	544	185

APPENDIX II

Cavity II: $\omega = 4.24 \times 10^6$, $BA = 4.01 \times 10^5$

$r_2 - r_1$	N	A	B	mw/cc
10	44	1100	364	890
	48	1200	334	750
	52	1300	308	630
	56	1400	286	550
	60	1500	267	470
	64	1600	251	425
	68	1700	236	375
	72	1800	223	325
	76	1900	211	295
	80	2000	200	255
12.5	44	1375	292	570
	48	1500	267	470
	52	1625	247	410
	56	1750	220	350
	60	1815	214	305
	64	2000	200	255
	68	2125	189	235
	72	2250	178	208
	76	2375	169	190
15	44	1650	243	400
	48	1800	223	335
	52	1950	206	285
	56	2100	191	245
	60	2250	178	208
	64	2400	167	180
	68	2550	157	160
	72	2700	148	143
	76	2850	141	130

APPENDIX III

$V = \omega BA \times 10^{-8}$ N = Number of 2.5 cm rings

$$B = \frac{V \times 10^8}{\omega A} = \frac{V \times 10^8}{2\pi f N \times 2.5\ (r_2 - r_1)}$$

$$B = \frac{6366\ V_{kv}}{f_{MHz}(r_2 - r_1)} \frac{1}{N}$$

$r_2 - r_1 = 10$ $f = .1785$

$$B = \frac{3566\ V_{KV}}{N}$$

N	B(9KV)	B(11KV)	B(13KV)	B(15KV)	B(17KV)	B(19KV)
44	729	892	1054			
48	669	817	966	1114		
52	617	754	892	1029		
56	573	701	828	955	1082	
60	535	654	773	892	1020	1129
64	502	613	724	836	947	1059
68	472	577	682	787	892	996
72	446	545	644	743	842	941

$r_2 - r_1 = 12.5$ $f = .1785$ $B = \frac{2853\ V_{KV}}{N}$

N	B(9KV)	B(11KV)	B(13KV)	B(15KV)	B(17KV)	B(19KV)
44	584	713	843	972	1102	1232
48	535	654	773	892	1010	1129
52	494	604	713	823	933	1042
56	459	560	662	764	866	968
60	428	523	618	713	808	903
64	401	490	580	669	758	847
68	378	462	545	629	713	797
72	357	436	515	594	674	753

$r_2 - r_1 = 15.0$ $f = .1785$ $B = \frac{2378 \ V_{KV}}{N}$

N	B(9KV)	B(11KV)	B(13KV)	B(15KV)	B(17KV)	B(19KV)
44	486	595	705	811	919	1027
48	446	545	646	743	842	941
52	412	503	596	686	777	869
56	382	467	554	637	722	807
60	357	436	517	595	674	753
64	334	409	484	557	632	706
68	315	385	456	525	595	664
72	297	363	431	495	561	628

$r_2 - r_1 = 10$ $f = .675$ $B = \frac{943 \ V_{KV}}{N}$

N	B(9KV)	B(11KV)	B(13KV)	B(15KV)	B(17KV)	B(19KV)
44	193	236	279	321	364	407
48	177	216	255	295	334	373
52	163	199	236	272	308	345
56	152	185	219	253	286	320
60	141	173	204	236	267	299
64	133	162	192	221	250	280
68	125	153	180	208	236	263
72	118	144	170	196	223	249

$r_2 - r_1 = 12.5$ cm $f = 675$ KHz $B = \frac{754.4 \ V_{KV}}{N}$

N	B(9KV)	B(11KV)	B(13KV)	B(15KV)	B(17KV)	B(19KV)
44	154	189	223	257	291	326
48	141	173	204	236	267	299
52	131	160	189	218	247	276
56	121	148	175	202	229	256
60	113	138	163	189	214	239
64	106	130	153	177	200	224
68	100	122	144	166	189	211
72	94	115	136	157	178	199

$r_2 - r_1 = 15$ cm   f = 675 KHz $B = \frac{628.7\ V_{KV}}{N}$

N	B(9KV)	B(11KV)	B(13KV)	B(15KV)	B(17KV)	B(19KV)
44	129	157	186	214	243	271
48	118	144	170	196	223	249
52	109	133	157	181	206	230
56	101	123	146	168	191	213
60	94	115	136	157	178	199
64	88	108	128	147	167	187
68	83	102	120	139	157	176
72	79	96	114	131	148	166

f = 2.5 MHz:

$r_2 - r_1 = 10$ $B = \frac{254.6}{N}$ Vkv   f = 2.5 MHz

N	B(22.5V)	B(30 KV)	B(45 KV)
44	130.2	173.6	260.4
48	119.3	159.1	238.7
52	110.2	146.9	220.3
56	102.3	136.4	204.6
60	95.5	127.3	191.0
64	89.5	119.3	179.0
68	84.2	112.3	168.5
72	79.6	106.1	159.1
76	75.4	100.5	150.8

$r_2 - r_1 = 12.5 \quad f = 2.5\text{ MHz} \quad B = \frac{203.7V}{N}$

N	B(22.5V)	B(30 KV)	B(45 KV)
44	104.2	138.9	208.3
48	95.5	127.3	191.0
52	88.1	117.5	176.3
56	81.8	109.1	163.7
60	76.4	101.9	152.8
64	71.6	95.5	143.2
68	67.4	89.9	134.8
72	63.7	84.9	127.3
76	60.3	80.4	120.6

$r_2 - r_1 = 15 \quad B = \frac{169.7V}{N} \quad f = 2.5\text{ MHz}$

N	B(22.5V)	B(30 KV)	B(45 KV)
44	86.8	115.7	173.6
48	79.5	106.1	159.1
52	73.4	97.9	146.9
56	68.2	90.9	136.4
60	63.6	84.9	127.3
64	59.7	79.5	119.3
68	56.2	74.9	112.3
72	53.0	70.7	106.1
76	50.2	67.0	100.5