national accelerator laboratory

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Measurements of Inductance and Resistance Main Ring Dipole and Quadrupole Magnets

R. Juhala and J. Pachnik

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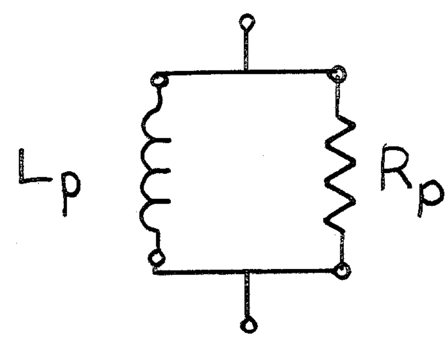
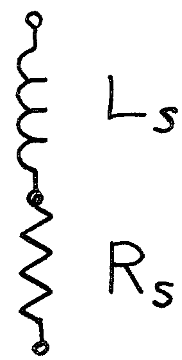
Measurements of inductance as a function of frequency and d.c. resistance have been made on main ring dipole and quadrupole magnets. The inductance measurements were made using a General Radio Model 1650-B bridge which is accurate to ± 1%. The d.c. resistances were made using a Rubicon Instruments Model 1622 Kelvin Bridge. The data presented here represent averages over several magnets of each of the four different types.

A complex impedance such as an iron core magnet can be represented electrically by either a series or a parallel combination of resistance and reactance as shown in the following diagrams:





The quantities L_s and L_p are referred to as series and parallel inductance; just as R_s and R_p are the series and parallel resistances. The values of these quantities are functions of the frequency of the applied voltage. Therefore, measurements of them have been made over a range of frequencies from 40 Hz to 4000 Hz. For magnets that are to be operated in a pulsed mode it is frequently of interest to know how the resistive losses vary as a function of frequency and what the ratio of reactive impedance is to the ohmic losses. This ratio, known as the quality factor or Q, has also been determined. Using the GRC impedance bridge direct measurements were made of the quantities Lp and Q. L_s, R_s and R_p were then calculated from the easily derived relationships given in equations (1) through (3).

$$L_s = \frac{Q^2}{1+Q^2} L_p \qquad (1)$$

$$R_s = \frac{Q\omega L_p}{1+Q^2} \qquad (2)$$

$$R_p = Q\omega L_p \qquad (3)$$

A GRC 1310-B power amplifier was used to generate a sinusoidal signal over the 40Hz to 4000Hz frequency range. Although frequencies below 40Hz can also be generated, it was very difficult to determine just where the bridge was in balance at these lower frequencies: therefore measurements below 40Hz were not taken.

The d.c. resistances of the four different types of magnets are shown in Table 1. These measurements were made at room temperature (approximately 25°C). No corrections have been made for small temperature differences that might have existed between the various measurements.

Table 1

D.C. resistances of Main Ring Dipoles and Quadrupoles

Type	Number Measured	Average (mΩ)	Low (mΩ)	High (mΩ)
B1 (1000 series)	14	5.78	5.69	5.87
B2 (2000 series)	3	6.93	6.85	6.98
7 ft. quadrupole (7000 series)	4	4.76	4.70	4.85
4 ft. quadrupole (4000 series)	7	3.37	3.25	3.58

The low and high data represent the lowest and highest resistance measurements recorded for magnets of a given type.

The average values of Q, Lp, L_s and R_s are tabulated for the different magnets in Table 2.

Table 2

Average values of a.c. resistance, inductance, and Q at 100Hz and 1000Hz with average deviations (units are millihenrys and ohms)

Magnet Type	Quantity	100Hz	1000Hz
B1	Q	3.55 ± .16	1.04 ± .03
	L_p	4.51 ± .04	3.09 + .06
	L_s	4.18 ± .05	1.61 ± .08
	R_p	10.1 ± .5	20.1 ± 1.1
	R_s	.74 ± .02	9.7 ± .2
B2	Q	3.45 ± .23	1.34 ± .04
	L_p	5.45 ± .06	4.14 ± .03
	L_s	5.03 ± .01	2.66 ± .05
	R_p	11.8 ± .7	34.8 ± .9
	R_s	.92 ± .06	12.5 ± .1
7 foot quadrupole	Q	2.9 ± .5	3.1 ± .2
	L_p	1.46 ± .08	1.10 ± .01
	L_s	1.30 ± .02	.99 ± .01
	R_p	2.7 ± .4	21.0 ± .7
	R_s	.28 ± .06	2.04 ± .06
4 foot quadrupole	Q	2.86 ± .07	3.22 ± .04
	L_p	.89 ± .01	.68 ± .01
	L_s	.80 ± .01	.62 ± .01
	R_p	1.61 ± .03	13.8 ± .2
	R_s	.18 ± .02	1.21 ± .02

The frequency dependence of L_p, L_s, R_p, R_s, and Q are shown in Figure 1 through Figure 5. Measurements were taken in 10 Hz increments from 40Hz to 100 Hz, in 100 Hz steps from 100 Hz to 1000 Hz, and in 1000 Hz steps from 1000Hz to 4000Hz. These same quantities are shown in Figure 6 through Figure 14 with more resolution in the frequency range of 40Hz to 1000Hz.

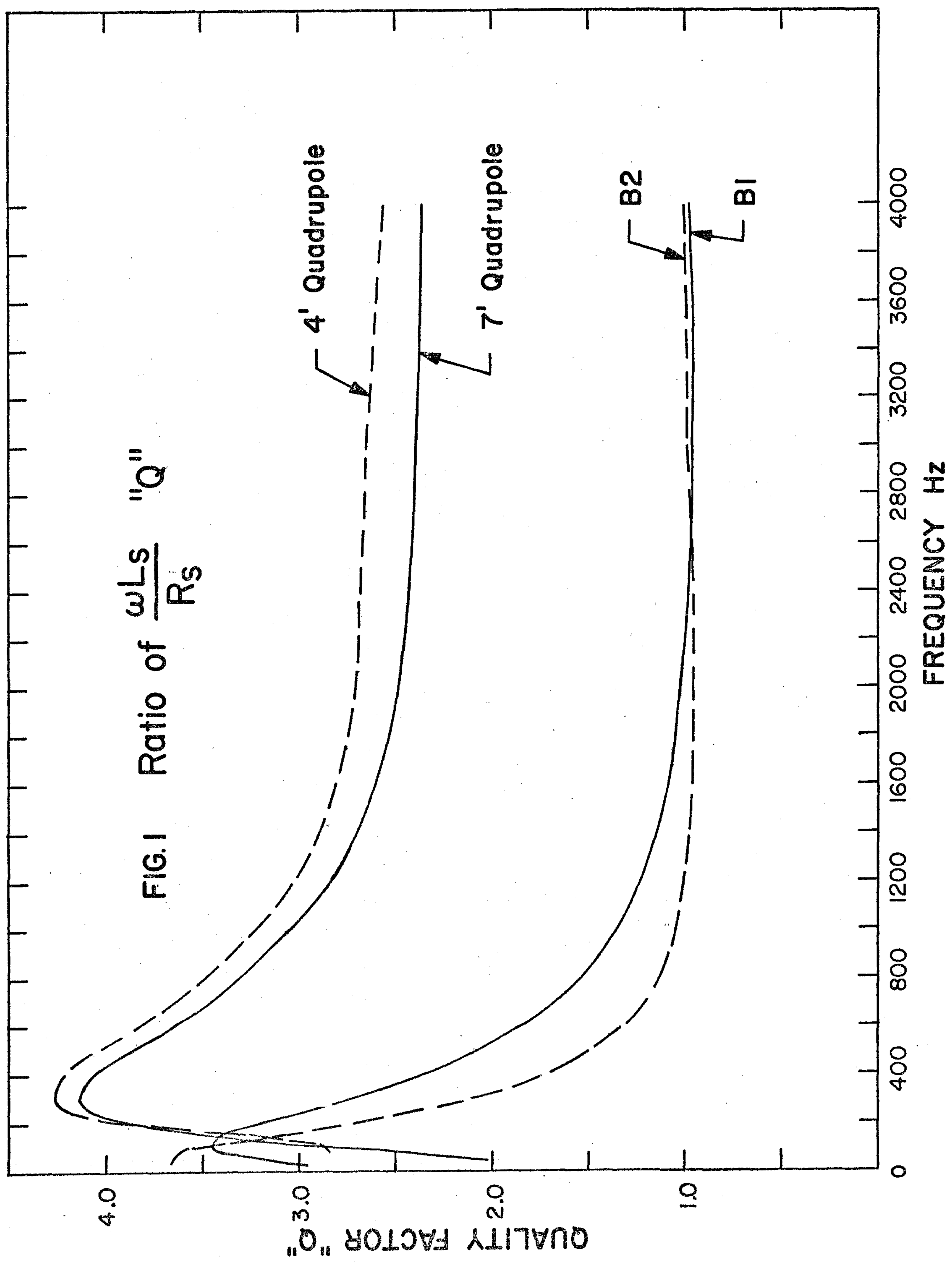


FIG. I
Ratio of $\frac{\omega L_s}{R_s}$ "Q"
4' Quadrupole
7' Quadrupole
B2
BI
FREQUENCY Hz
QUALITY FACTOR "Q"
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
1.0
2.0
3.0
4.0

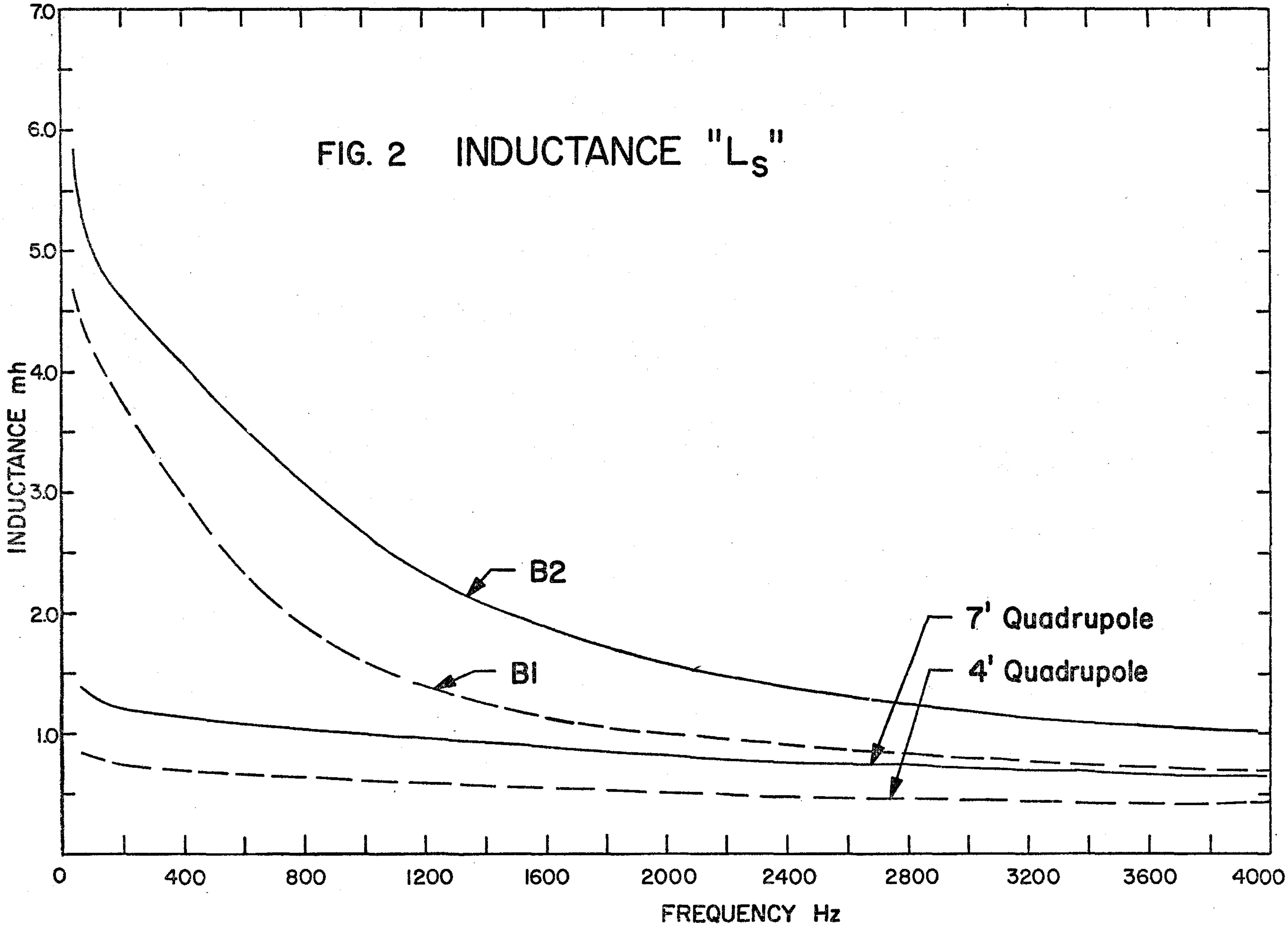


FIG. 2 INDUCTANCE "L_S"

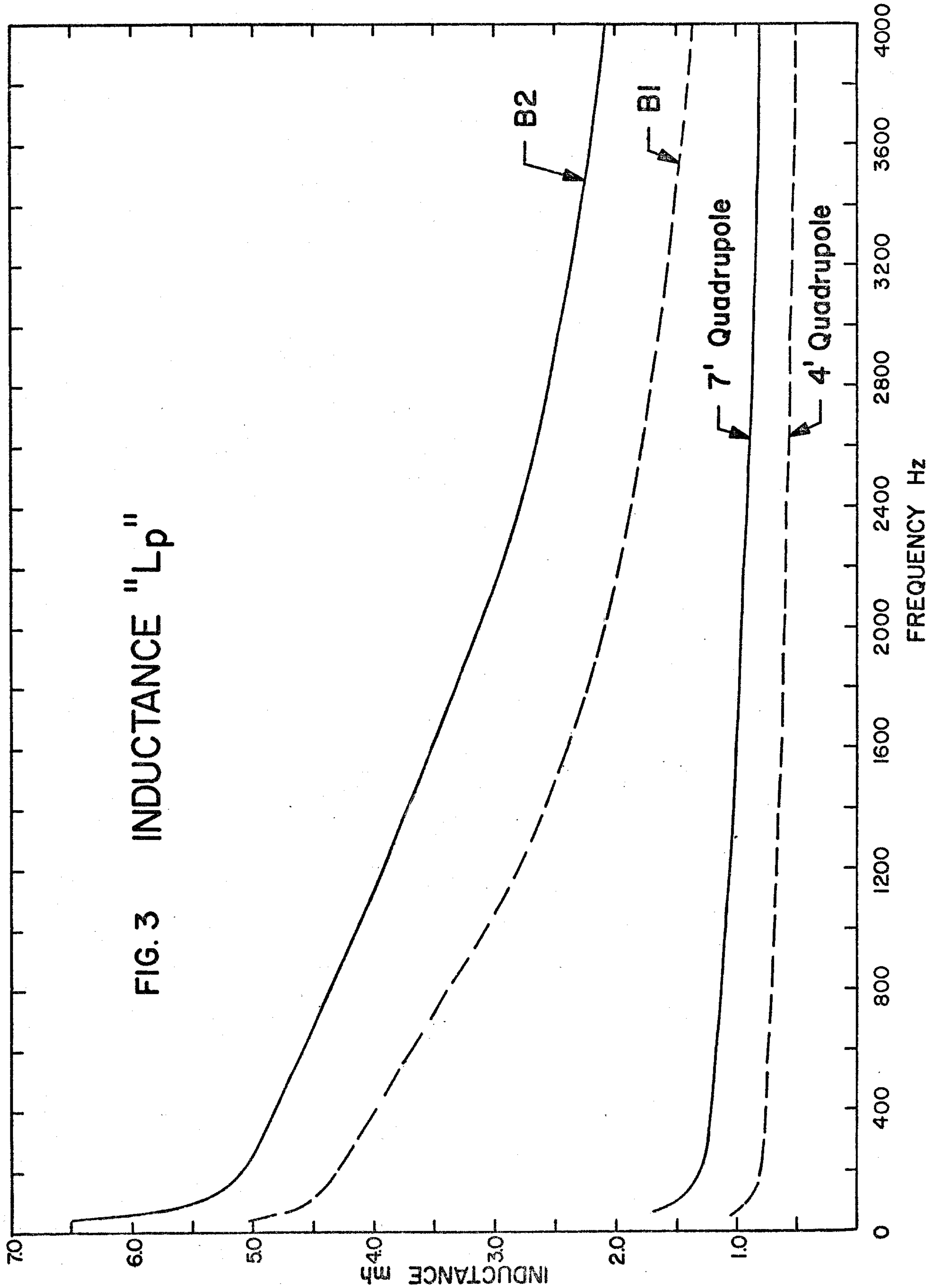


FIG. 3 INDUCTANCE "Lp"

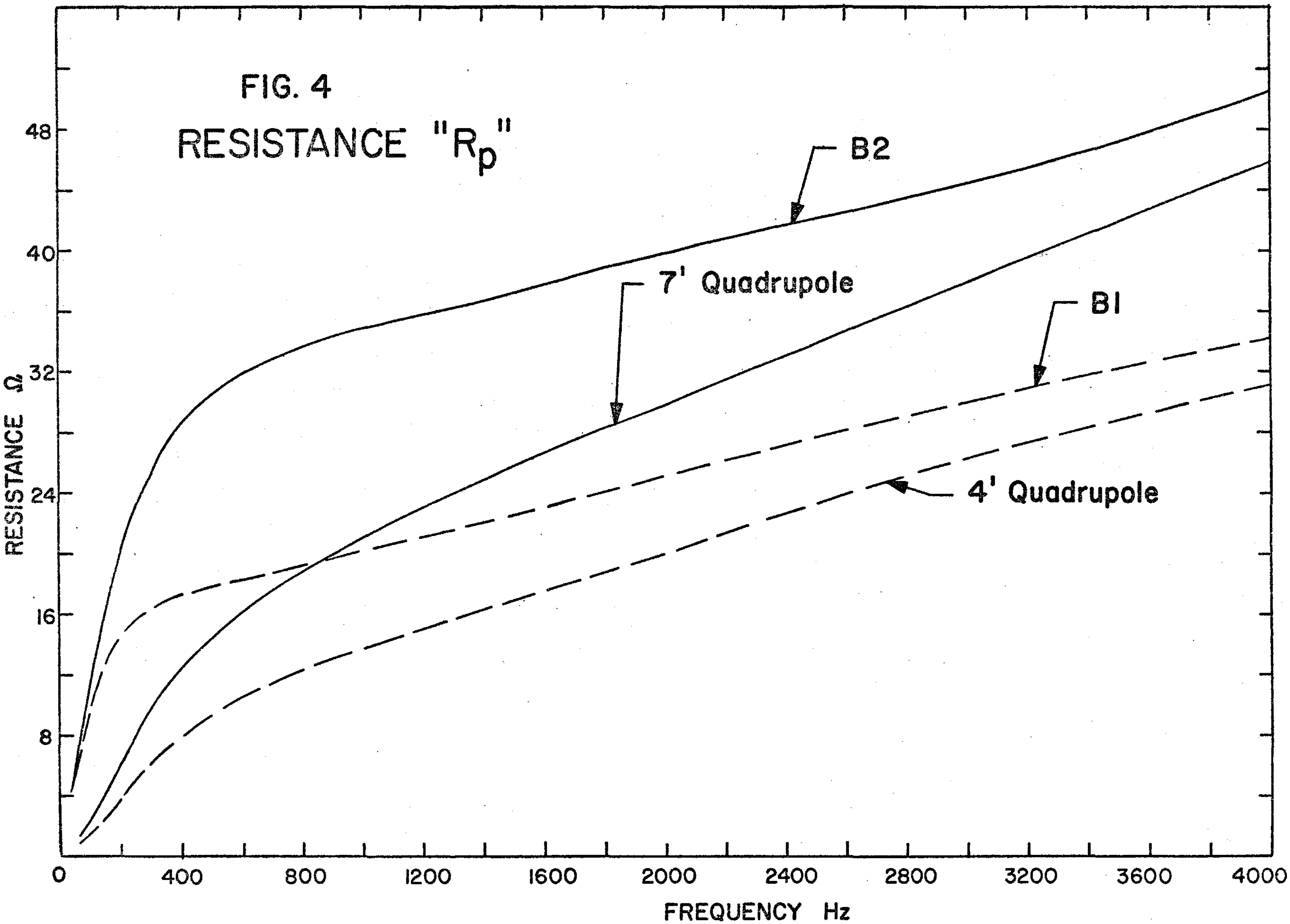


FIG. 4
RESISTANCE "R_p"
B2
7' Quadrupole
B1
4' Quadrupole
RESISTANCE Ω
48
40
32
24
16
8
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
FREQUENCY Hz

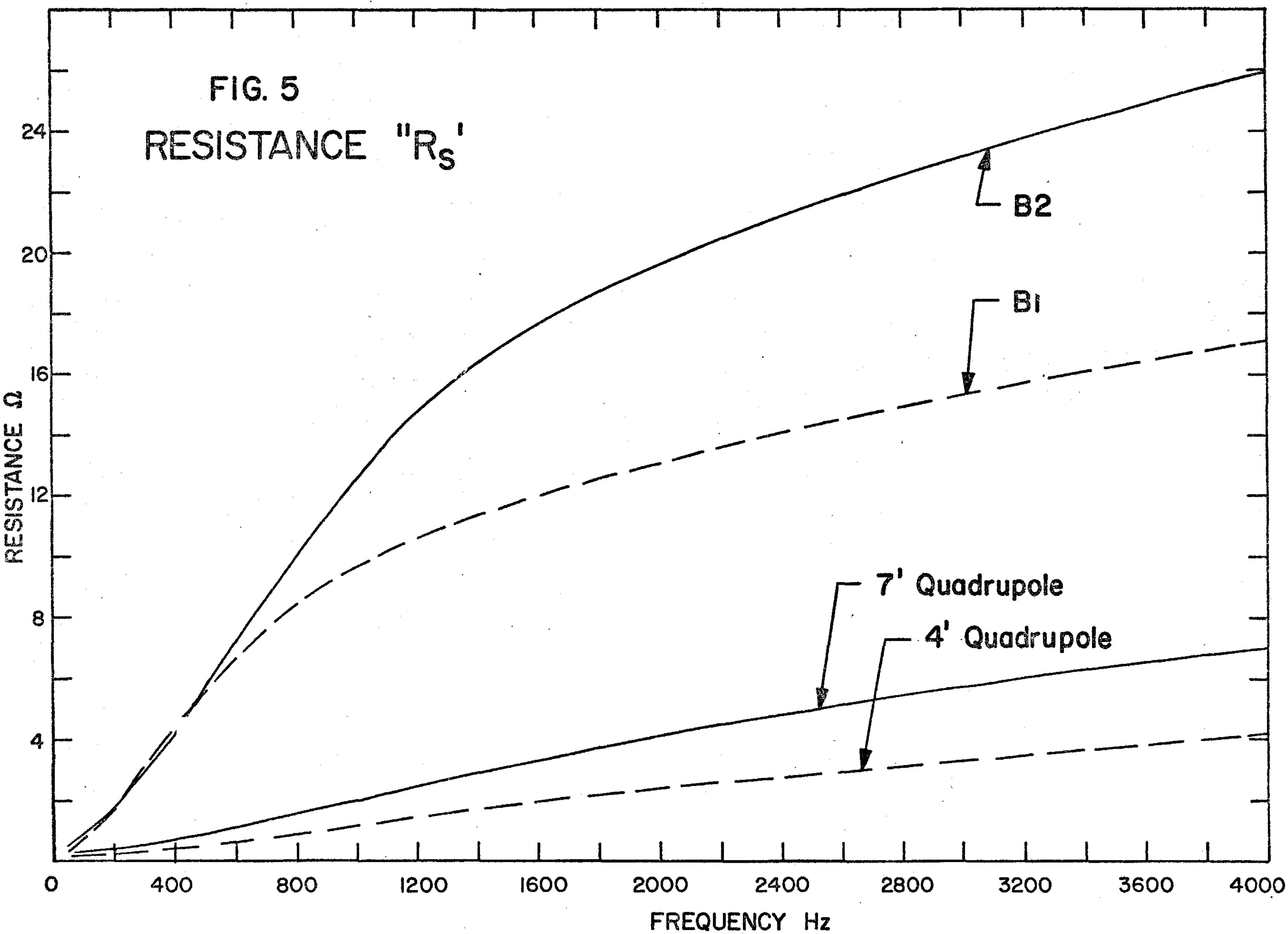


FIG. 5
RESISTANCE "R_S"

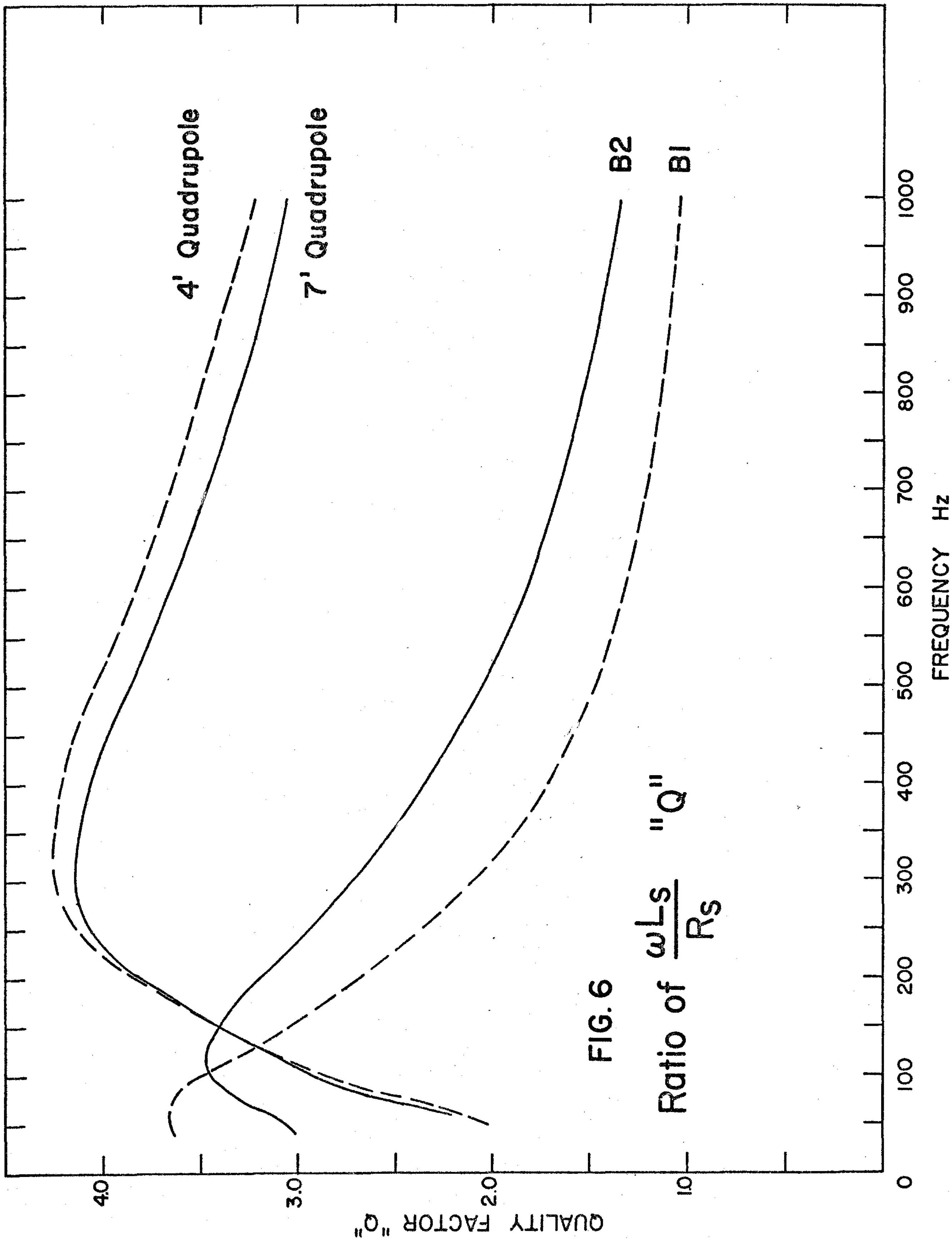


FIG. 6
Ratio of $\frac{\omega L_s}{R_s}$ "Q"

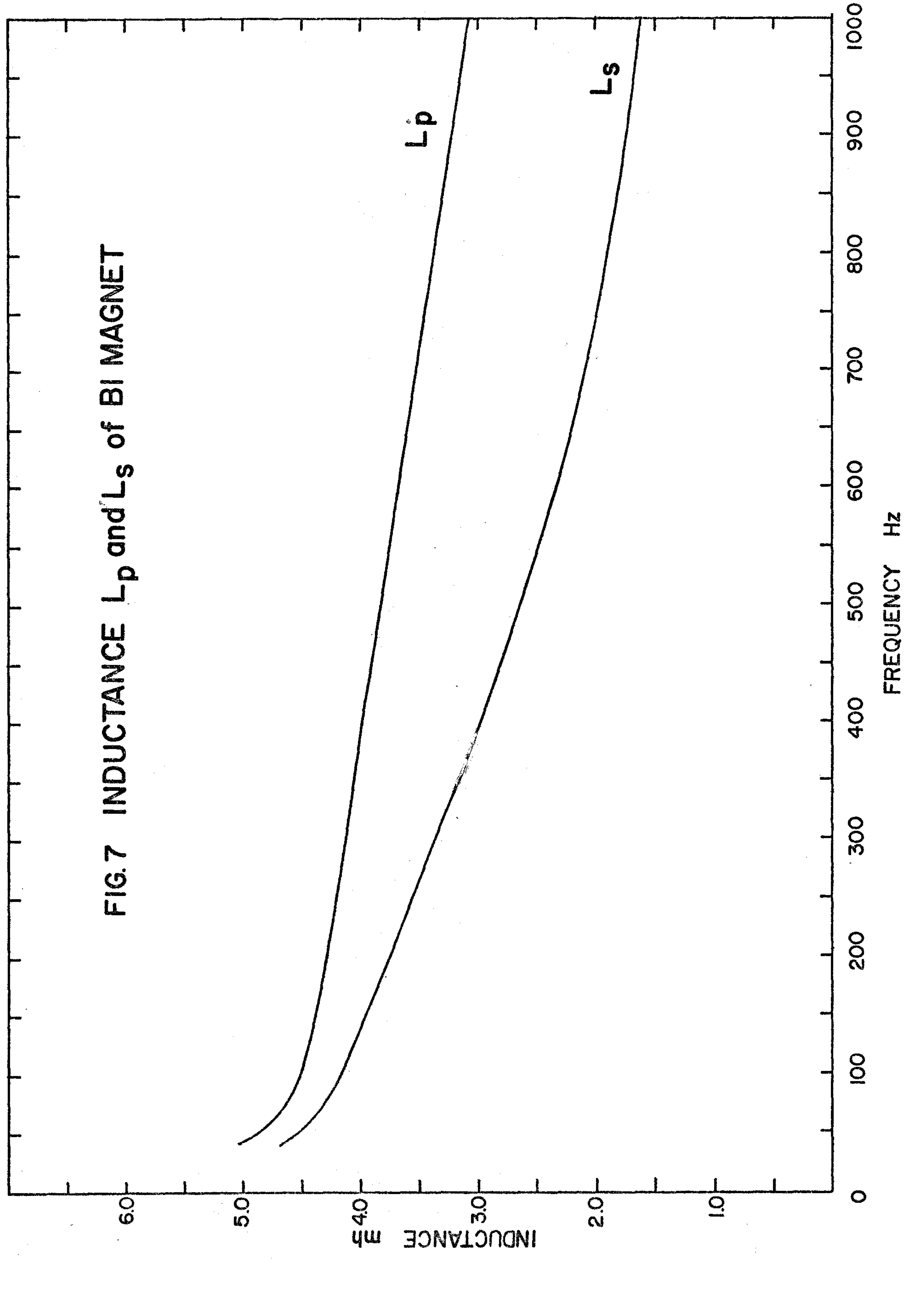


FIG. 7 INDUCTANCE L_p and L_s of BI MAGNET

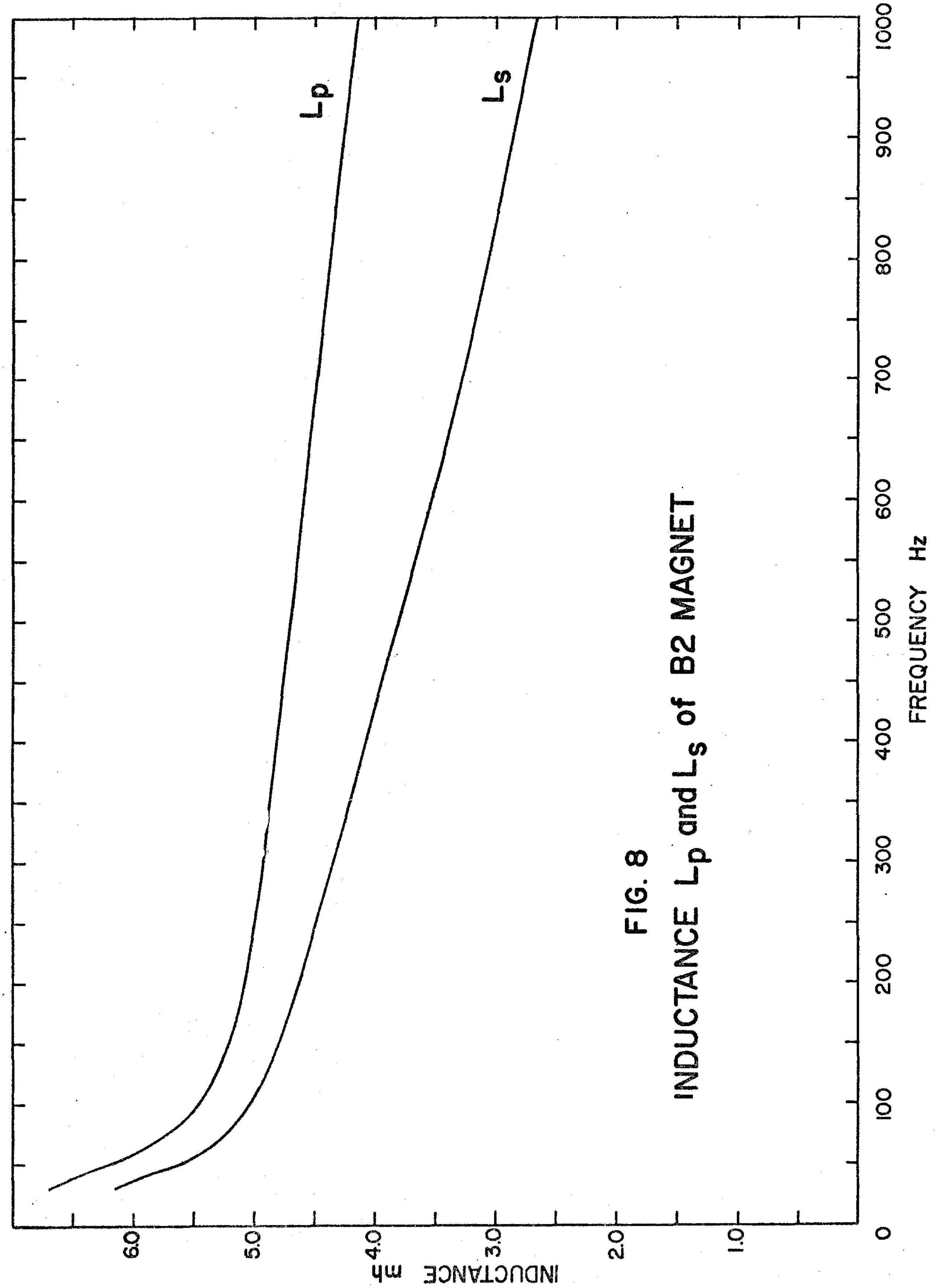


FIG. 8
INDUCTANCE L_p and L_s of B2 MAGNET

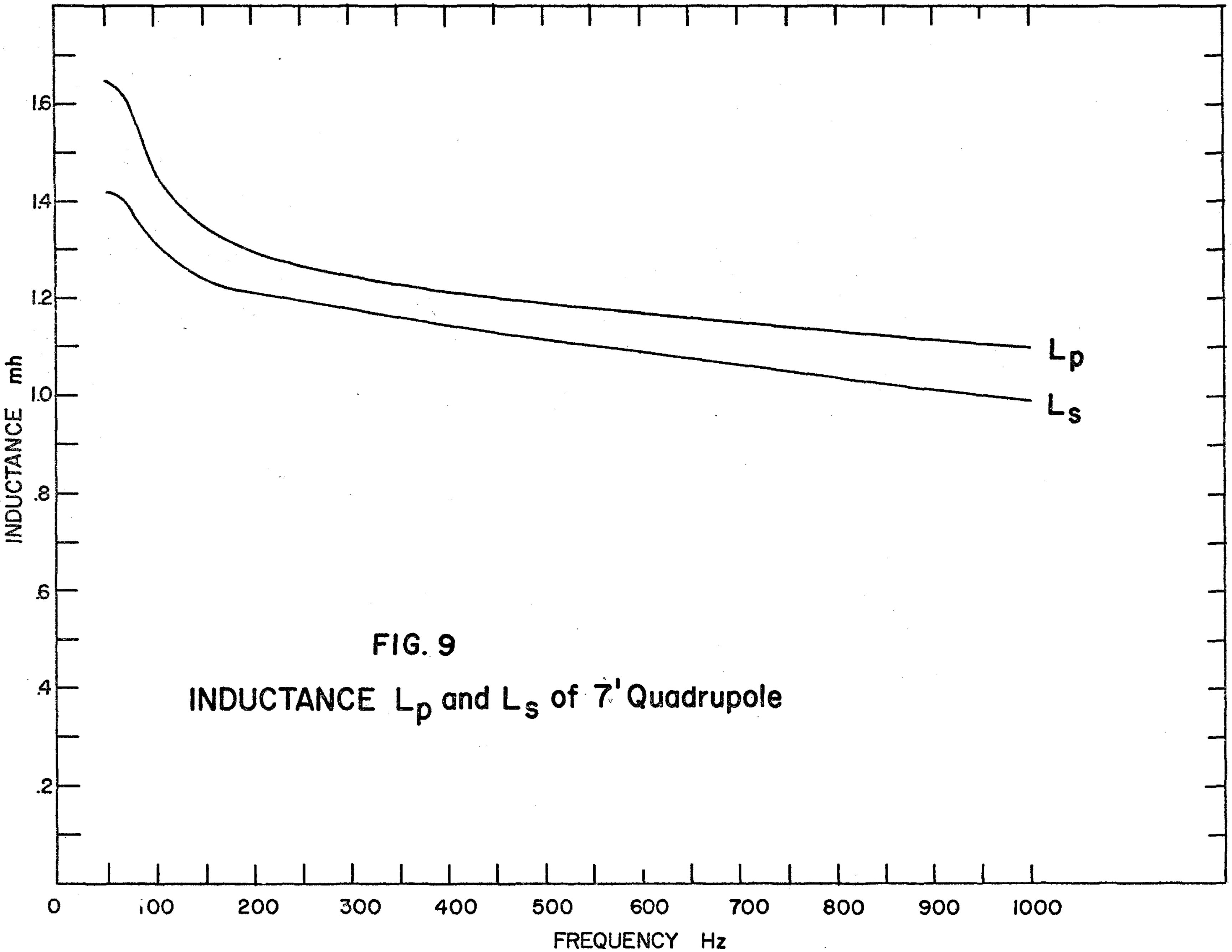


FIG. 9

INDUCTANCE L_p and L_s of 7' Quadrupole

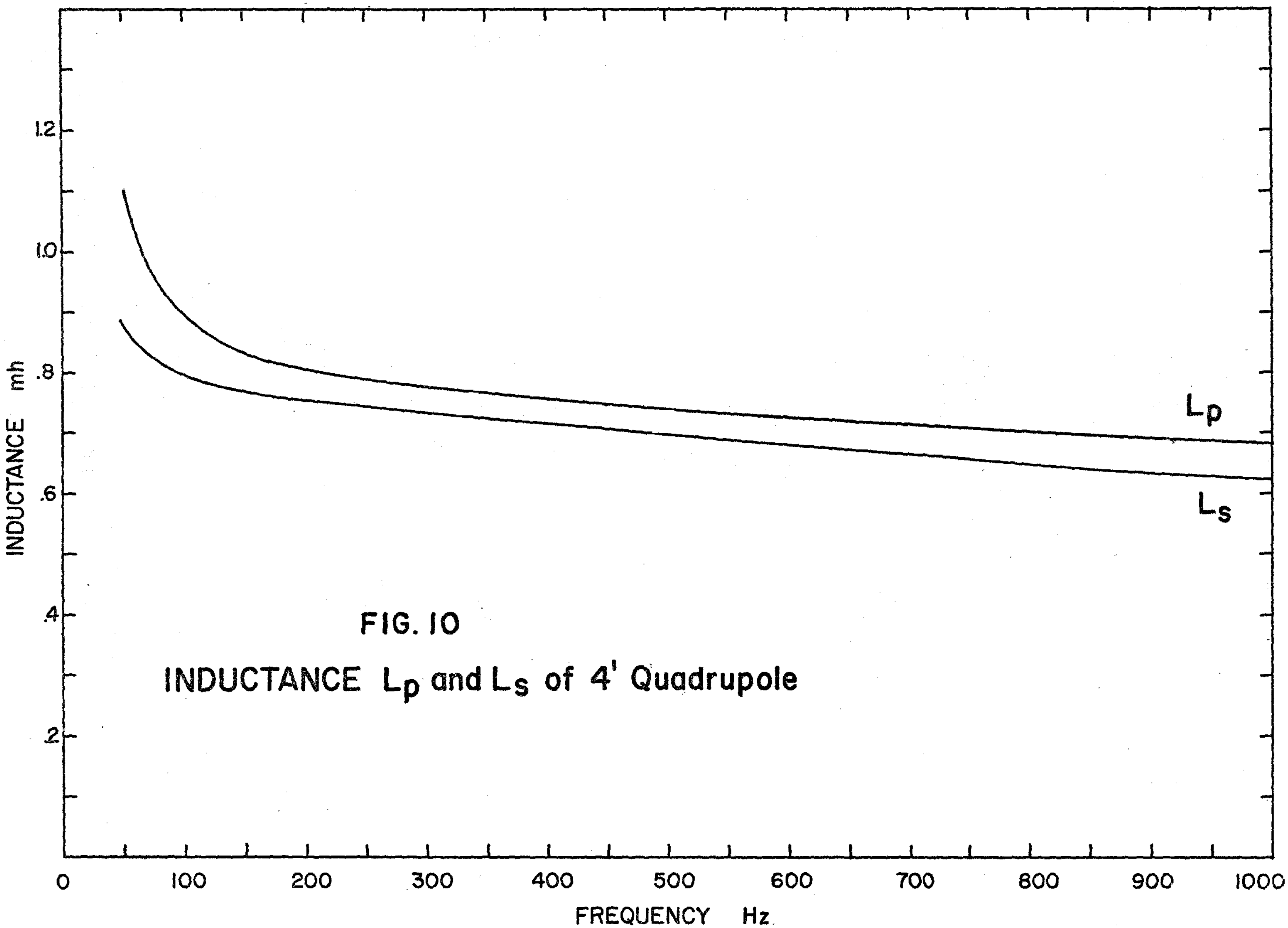


FIG. 10

INDUCTANCE L_p and L_s of 4' Quadrupole

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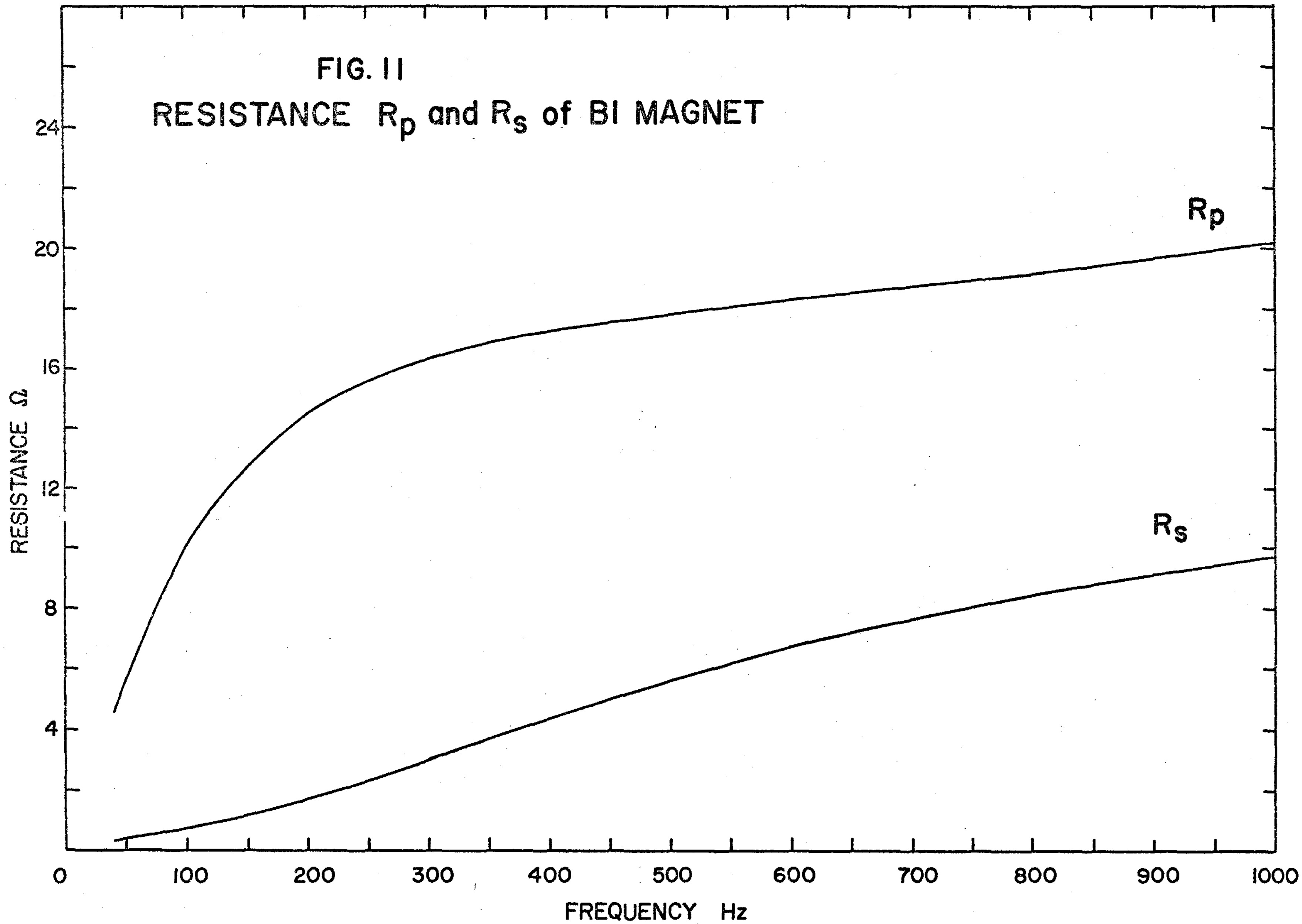

FIG. 11
RESISTANCE R_p and R_s of BI MAGNET

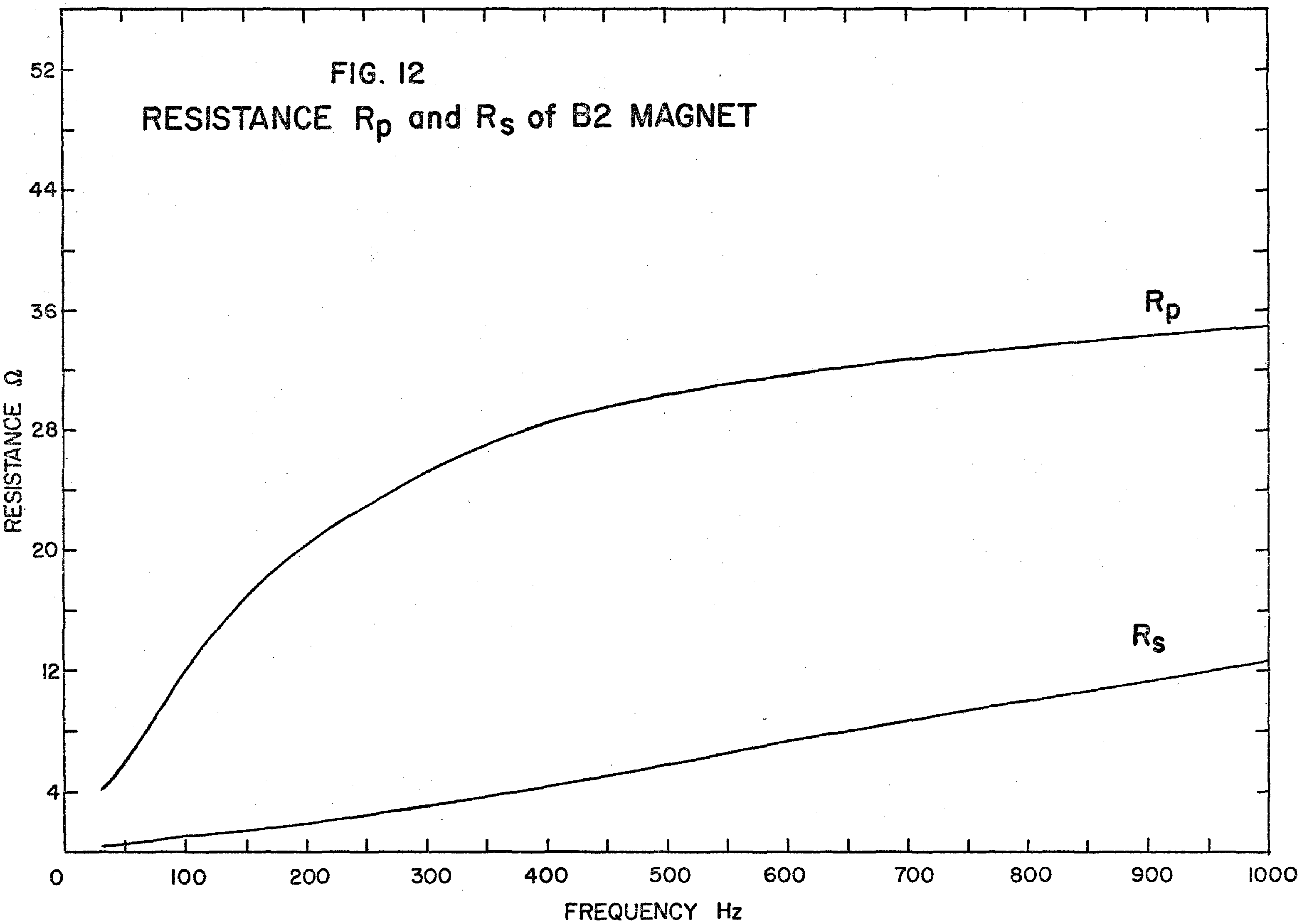

FIG. 12

RESISTANCE R_p and R_s of B2 MAGNET

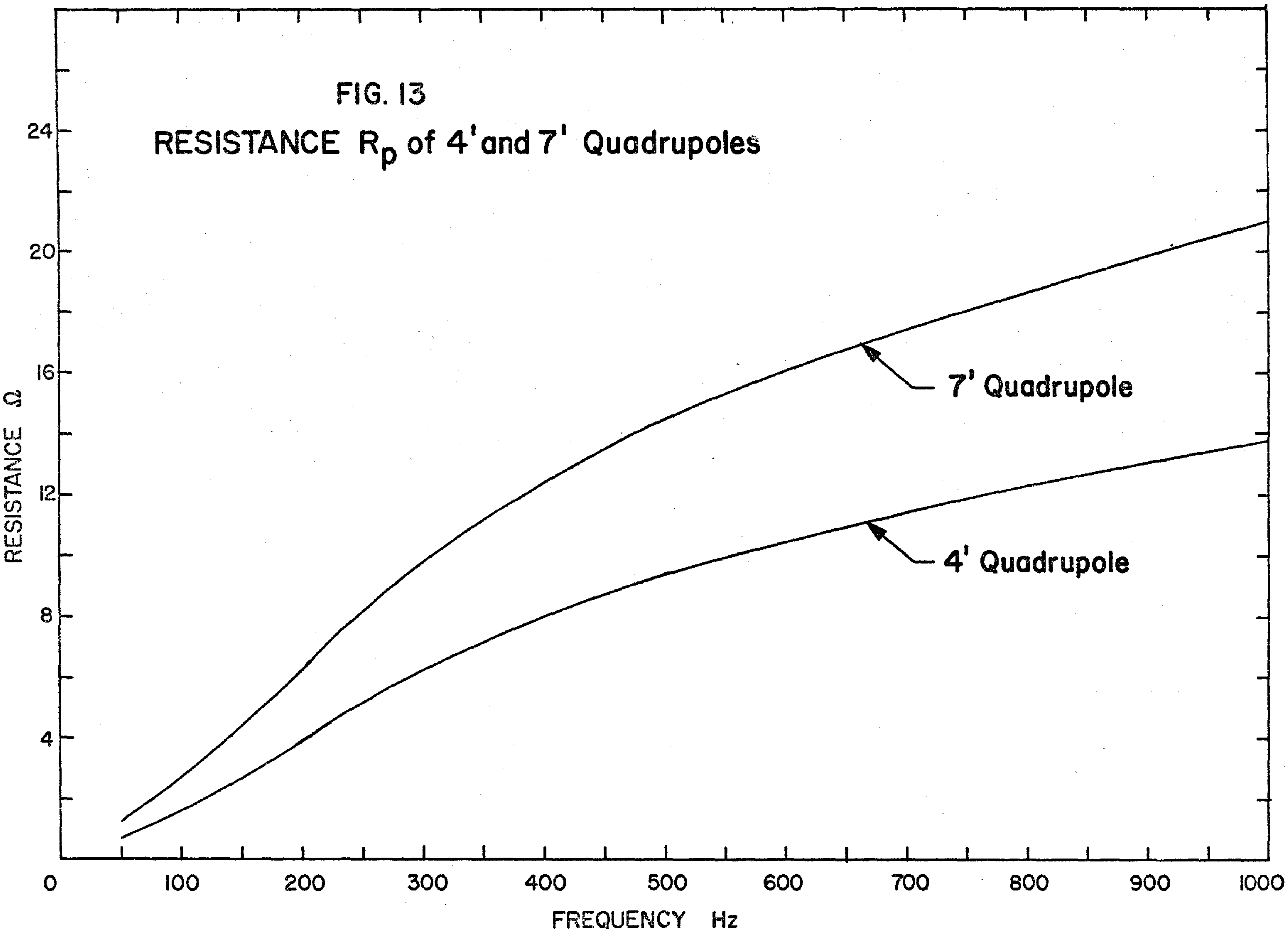

FIG. 13
RESISTANCE R_p of 4' and 7' Quadrupoles

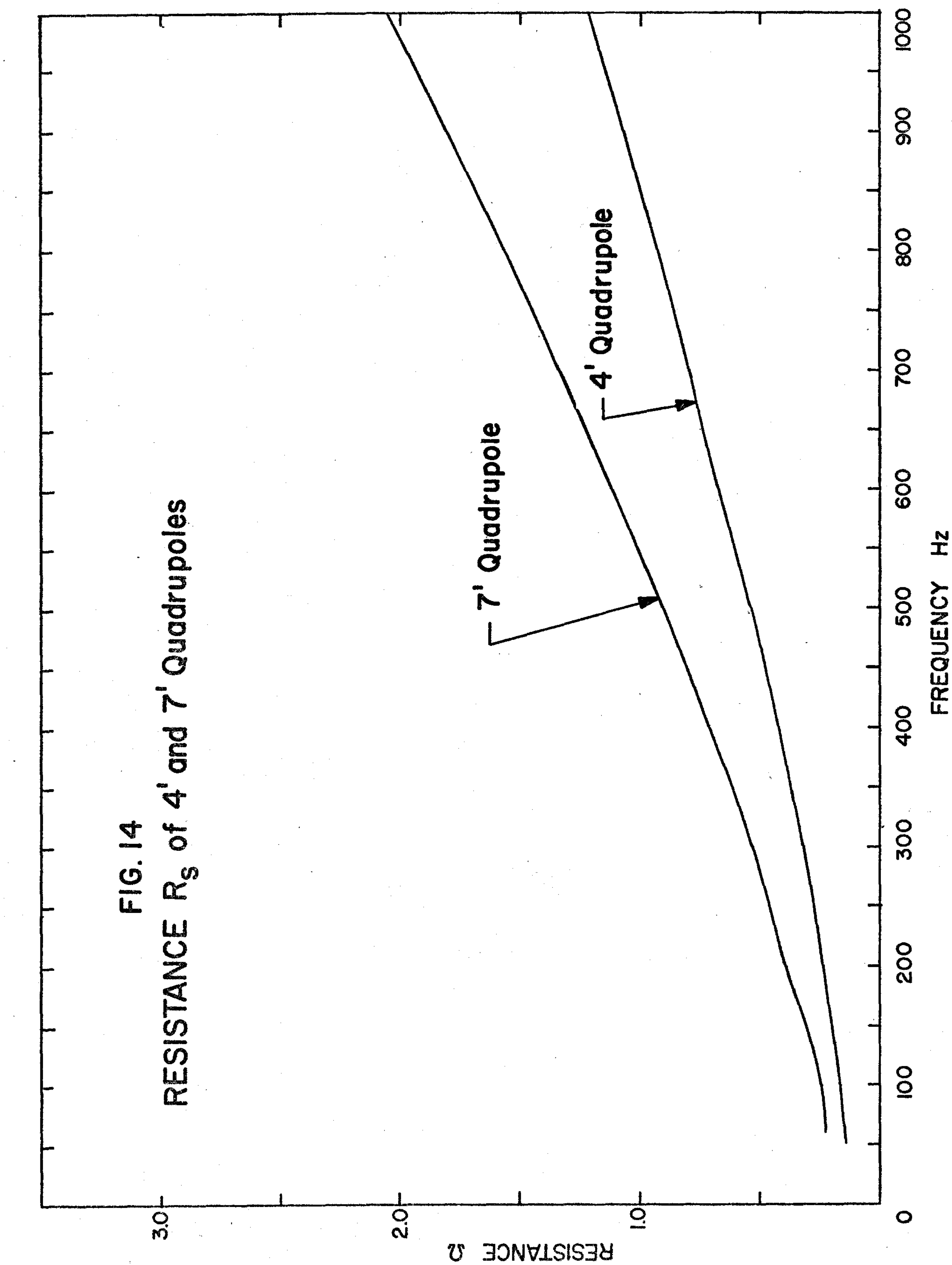

FIG. 14
RESISTANCE R_S of 4' and 7' Quadrupoles