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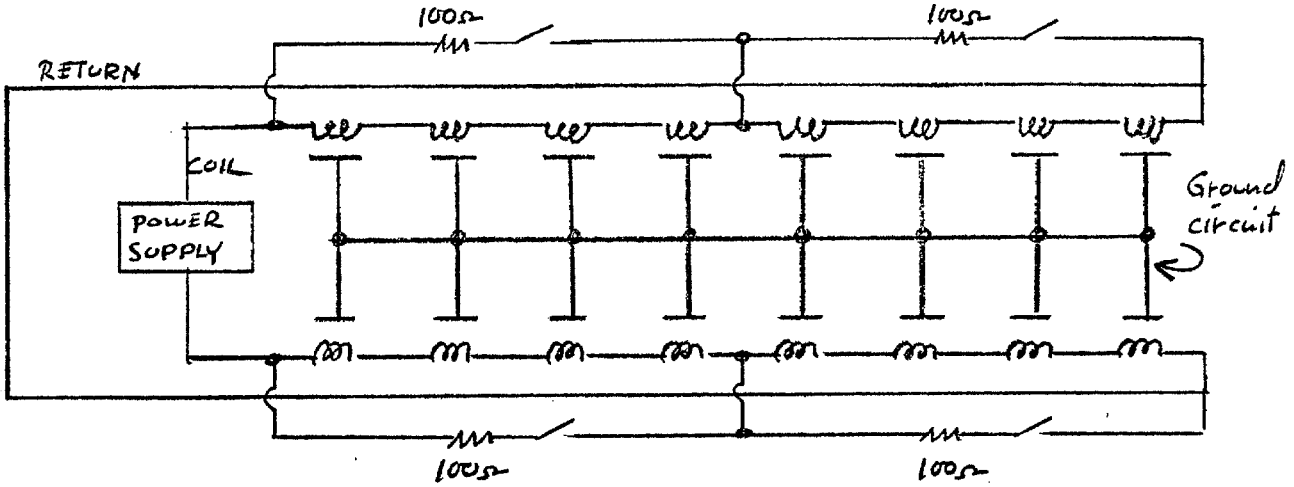
E.D. Dipole String Electrical Impedance Measurements at B12

shafer

Electrical characteristics and determination of the required damping resistor for the Energy Doubler magnets were based on electrical measurements of individual dipoles. Measurements at B12, with 16 dipoles connected in series, allows verification of certain transmission line properties predicted in UPC # 37, specifically that the model used is correct, and that standing waves do exist in the magnet strings.

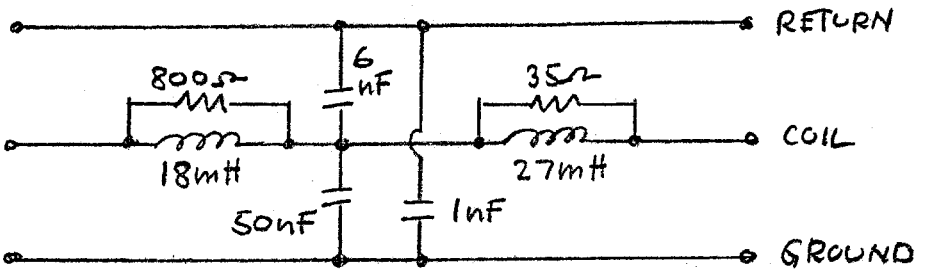
A conceptual model of the center-driven 16 dipole string is shown below:



the power supply is in the center of a string of 16 E.D. dipole coils. At each end the coil is connected to the Return bus which is also internal to the dipoles, and completes the D.C. circuit. A large capacitance between the coil and the collar assembly (grounded) produces a shunt impedance, which when combined with the series inductance of the coils leads to standing waves. Damping resistors, specifically 100 Ω 100 watt resistors connected across each half-cell (shunting the bypass SCR)

are shown. Measurements discussed here are made without the damping resistors installed in order to see the standing waves which otherwise would be damped (switches in CKT closed).

the specific model used for each dipole magnet for computer simulation is:



The values of the components are based on actual measurements, the resistances representing eddy current losses (see UPC 31). Computer program SPICE is used to calculate the impedance of 16 such dipoles as seen by the power supply in the circuit on page 1. |Z| as a function of frequency is plotted in Fig 1 for measurements at B12 and for the computer model.

Table I presents other characteristics based on computer model. Note specifically that the impedance becomes capacitive at 900 Hz, inductive at 2100 Hz, and capacitive again at 2700 Hz. In scaling from 16 to 774 dipoles, these frequencies scale to multiples of 12 Hz. See for example Fig 1 of UPC 37. Table II presents the same variables when the damping resistors are installed. In this case the impedance becomes capacitive at 1000 Hz and remains so, behaving as a lossy transmission line.

B12 Impedance — NO DAMPING RESISTOR

F (Hz)	|Z| ohms	Re Z	Im Z	θ
50.00	222.1	32.03	219.8	81.71
100.0	423.2	113.3	407.8	74.47
150.0	596.0	215.5	555.7	68.81
200.0	745.9	319.0	673.7	64.66
250.0	881.2	417.8	775.8	61.69
300.0	1013.	513.8	872.9	59.52
350.0	1148.	612.0	971.7	57.79
400.0	1294.	719.1	1075.	56.24
450.0	1456.	842.7	1187.	54.64
500.0	1640.	992.2	1306.	52.78
550.0	1854.	1180.	1430.	50.48
600.0	2103.	1421.	1551.	47.51
650.0	2395.	1735.	1652.	43.59
700.0	2736.	2144.	1699.	38.39
750.0	3117.	2658.	1628.	31.49
800.0	3506.	3239.	1341.	22.49
850.0	3825.	3752.	748.8	11.29
900.0	3963.	3965.	-105.1	-1.518
950.0	3865.	3742.	-967.3	-14.49
1000.	3562.	3206.	-1566.	-26.07
1050.	3158.	2582.	-1836.	-35.41
1100.	2771.	2044.	-1871.	-42.46
1150.	2414.	1629.	-1781.	-47.55
1200.	2104.	1324.	-1629.	-51.07
1250.	1847.	1102.	-1482.	-53.36
1300.	1628.	942.1	-1327.	-54.63
1350.	1443.	826.2	-1182.	-55.06
1400.	1285.	742.3	-1049.	-54.72
1450.	1151.	681.9	-927.7	-53.58
1500.	1037.	639.3	-816.9	-51.95
1550.	940.5	610.2	-715.8	-49.55
1600.	859.5	591.8	-623.4	-46.49
1650.	792.8	581.8	-538.5	-42.78
1700.	739.5	578.8	-460.2	-38.49
1750.	699.2	581.8	-387.8	-33.69
1800.	671.3	589.9	-320.4	-28.51
1850.	655.6	602.8	-257.6	-23.14
1900.	651.4	620.3	-199.1	-17.80
1950.	659.2	642.0	-144.8	-12.71
2000.	674.7	668.0	-94.53	-8.054
2050.	699.8	698.2	-48.53	-3.977
2100.	732.3	732.3	-7.032	-.5501
2150.	770.9	770.3	29.62	2.202
2200.	814.2	811.9	60.95	4.293
2250.	861.1	856.8	86.40	5.758
2300.	910.5	904.4	105.4	6.644
2350.	961.2	954.1	117.2	7.001
2400.	1012.	1005.	121.3	6.882
2450.	1062.	1055.	117.2	6.339
2500.	1109.	1104.	104.9	5.424
2550.	1153.	1150.	84.30	4.192
2600.	1192.	1191.	56.16	2.699
2650.	1226.	1226.	21.48	1.004
2700.	1253.	1253.	-18.25	-.8347

Inductive

Capacitive

Inductive

F (Hz)	|Z| ohms	Re Z	Im Z	θ
2750.	1273.	1271.	-51.21	-2.757
2800.	1285.	1281.	-105.4	-4.704
2850.	1291.	1282.	-148.9	-6.623
2900.	1290.	1276.	-189.9	-8.467
2950.	1283.	1263.	-227.1	-10.19
3000.	1272.	1245.	-259.5	-11.78
3050.	1255.	1223.	-286.6	-13.19
3100.	1238.	1199.	-308.3	-14.42
3150.	1217.	1173.	-324.7	-15.47
3200.	1196.	1148.	-336.3	-16.33
3250.	1174.	1123.	-343.5	-17.01
3300.	1153.	1099.	-347.1	-17.52
3350.	1132.	1077.	-347.6	-17.88
3400.	1112.	1057.	-345.5	-18.10
3450.	1094.	1039.	-341.5	-18.20
3500.	1076.	1023.	-336.0	-18.19
3550.	1061.	1009.	-329.4	-18.09
3600.	1047.	996.3	-322.0	-17.91
3650.	1035.	985.8	-314.3	-17.69
3700.	1024.	977.0	-306.3	-17.41
3750.	1015.	969.7	-298.4	-17.10
3800.	1007.	963.8	-290.7	-16.73
3850.	1000.	959.0	-283.3	-16.46
3900.	994.5	955.3	-276.4	-16.13
3950.	990.1	952.6	-269.9	-15.82
4000.	986.5	950.5	-264.1	-15.53
4050.	983.8	949.1	-258.8	-15.25
4100.	981.7	948.2	-254.2	-14.99
4150.	980.1	947.7	-250.1	-14.78
4200.	979.0	947.4	-246.7	-14.59
4250.	978.2	947.4	-243.8	-14.43
4300.	977.6	947.4	-241.5	-14.30
4350.	977.2	947.4	-239.6	-14.19
4400.	976.8	947.3	-238.2	-14.12
4450.	976.5	947.2	-237.2	-14.06
4500.	976.1	947.0	-236.6	-14.03
4550.	975.6	946.5	-236.2	-14.01
4600.	975.0	945.9	-236.1	-14.02
4650.	974.2	945.1	-236.2	-14.03
4700.	973.3	944.1	-236.4	-14.06
4750.	972.2	942.9	-236.8	-14.09
4800.	970.9	941.5	-237.2	-14.14
4850.	969.5	939.9	-237.6	-14.19
4900.	967.9	938.2	-238.0	-14.24
4950.	966.1	936.3	-238.4	-14.29
5000.	964.3	934.2	-238.9	-14.34

Capacitive

Table I

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B12 Impedance — 100 Ω / Hall coil damping resistor

F (Hz)	|Z| ohms	Re Z	Im Z	θ
50.00	183.3	105.8	149.7	54.75
100.0	258.2	208.9	151.8	36.01
150.0	287.5	256.8	129.3	26.73
200.0	302.6	281.5	111.1	21.54
250.0	312.7	297.0	97.79	18.23
300.0	320.6	308.4	87.65	15.87
350.0	327.4	317.6	79.31	14.02
400.0	333.4	325.6	71.93	12.46
450.0	338.9	332.6	65.04	11.06
500.0	343.8	338.8	58.38	9.777
550.0	348.1	344.3	51.82	8.560
600.0	352.0	349.1	45.28	7.391
650.0	355.4	353.3	38.76	6.261
700.0	358.3	356.9	32.24	5.162
750.0	360.9	359.9	25.75	4.091
800.0	363.0	362.5	19.28	3.045
850.0	364.7	364.5	12.96	2.021
900.0	366.1	366.1	6.511	1.019
950.0	367.2	367.2	.2346	3.661 X10^{-2}
1000.	368.0	367.9	-5.954	-.9271
1050.	368.5	368.3	-12.04	-1.873
1100.	368.7	368.3	-18.03	-2.803
1150.	368.7	367.9	-23.90	-3.717
1200.	368.4	367.2	-29.65	-4.616
1250.	367.9	366.2	-35.28	-5.502
1300.	367.2	364.9	-40.77	-6.374
1350.	366.3	363.4	-46.12	-7.233
1400.	365.2	361.5	-51.33	-8.080
1450.	363.8	359.4	-56.39	-8.915
1500.	362.3	357.1	-61.28	-9.738
1550.	360.6	354.5	-66.02	-10.55
1600.	358.7	351.7	-70.58	-11.35
1650.	356.6	348.6	-74.95	-12.13
1700.	354.3	345.4	-79.14	-12.91
1750.	351.9	341.9	-83.13	-13.67
1800.	349.2	338.2	-86.91	-14.41
1850.	346.4	334.4	-90.47	-15.14
1900.	343.4	330.4	-93.80	-15.85
1950.	340.3	326.2	-96.89	-16.54
2000.	336.9	321.8	-99.73	-17.22
2050.	333.4	317.3	-102.3	-17.87
2100.	329.8	312.7	-104.6	-18.50
2150.	326.0	308.0	-106.7	-19.10
2200.	322.0	303.2	-108.4	-19.67
2250.	318.0	298.4	-109.9	-20.22
2300.	313.8	293.5	-111.0	-20.72
2350.	309.5	288.5	-111.9	-21.20
2400.	305.1	283.6	-112.5	-21.63
2450.	300.6	278.6	-112.7	-22.03
2500.	296.0	273.7	-112.7	-22.37
2550.	291.4	268.9	-112.3	-22.67
2600.	286.7	264.1	-111.7	-22.92
2650.	282.1	259.4	-110.8	-23.12
2700.	277.4	254.9	-109.6	-23.26
2750.	272.8	250.5	-108.1	-23.34
2800.	268.2	246.2	-106.4	-23.37
2850.	263.7	242.2	-104.4	-23.33
2900.	259.3	238.3	-102.2	-23.22
2950.	255.0	234.6	-99.87	-23.06
3000.	250.8	231.2	-97.32	-22.83
3050.	246.8	228.0	-94.60	-22.54
3100.	243.0	225.0	-91.75	-22.18
3150.	239.4	222.3	-88.78	-21.77
3200.	235.9	219.8	-85.71	-21.30
3250.	232.7	217.6	-82.57	-20.78
3300.	229.8	215.6	-79.38	-20.21
3350.	227.1	213.9	-76.15	-19.59
3400.	224.6	212.4	-72.90	-18.94
3450.	222.4	211.2	-69.66	-18.26
3500.	220.4	210.2	-66.44	-17.54
3550.	218.7	209.4	-63.26	-16.81
3600.	217.3	208.8	-60.13	-16.06
3650.	216.1	208.4	-57.07	-15.31
3700.	215.2	208.3	-54.09	-14.56
3750.	214.5	208.3	-51.19	-13.81
3800.	214.0	208.4	-48.39	-13.07
3850.	213.7	208.7	-45.69	-12.35
3900.	213.6	209.2	-43.11	-11.64
3950.	213.7	209.8	-40.64	-10.96
4000.	213.9	210.5	-38.29	-10.31
4050.	214.3	211.3	-36.07	-9.687
4100.	214.9	212.2	-33.97	-9.095
4150.	215.5	213.2	-31.99	-8.535
4200.	216.3	214.2	-30.14	-8.009
4250.	217.2	215.3	-28.41	-7.516
4300.	218.1	216.5	-26.80	-7.058
4350.	219.1	217.7	-25.32	-6.634
4400.	220.2	218.9	-23.94	-6.243
4450.	221.3	220.1	-22.69	-5.884
4500.	222.5	221.4	-21.54	-5.556
4550.	223.6	222.7	-20.50	-5.259
4600.	224.8	224.0	-19.56	-4.991
4650.	226.0	225.3	-18.72	-4.750
4700.	227.3	226.5	-17.97	-4.536
4750.	228.5	227.8	-17.31	-4.346
4800.	229.7	229.1	-16.74	-4.180
4850.	230.9	230.3	-16.25	-4.036
4900.	232.1	231.5	-15.83	-3.912
4950.	233.2	232.7	-15.49	-3.808
5000.	234.4	233.9	-15.21	-3.721

Table II

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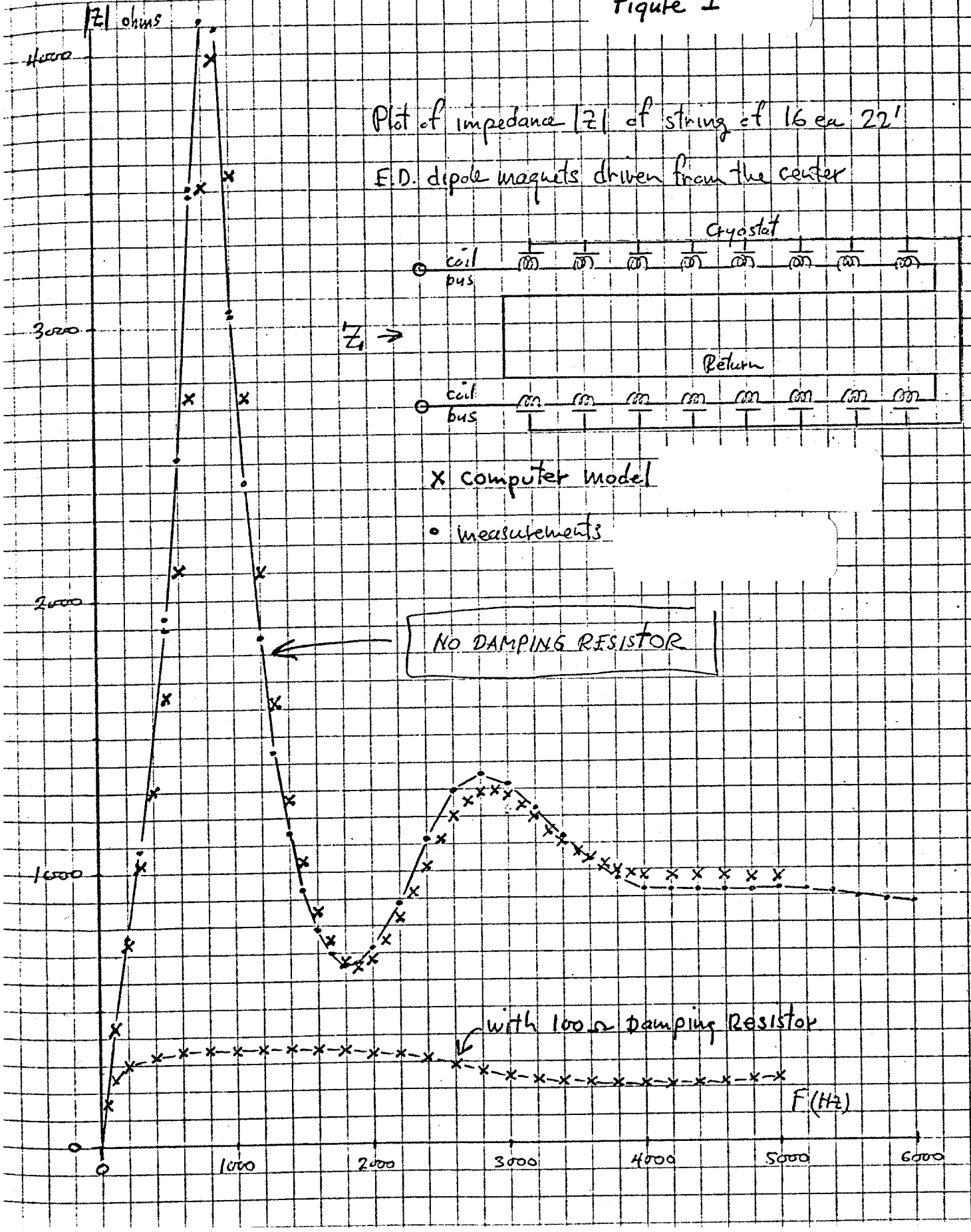
Figure 1


|Z| ohms
4000
3000
2000
1000
0
1000
2000
3000
4000
5000
6000
F (Hz)
Plot of impedance |Z| of string of 16 ea 22' E.D. dipole magnets driven from the center
Cryostat
coil bus
Return
coil bus
Z →
X computer model
• measurements
NO DAMPING RESISTOR
with 100 Ω Damping Resistor